LATE CRETACEOUS TO PALEOGENE EVOLUTION OF THE GEORGIA BASIN, SOUTHWESTERN BRITISH COLUMBIA

TIMOTHY DAVID JOHN ENGLAND, B.Sc.(Hons.), M.Sc.

LATE CRETACEOUS TO PALEOGENE EVOLUTION OF THE GEORGIA BASIN, SOUTHWESTERN BRITISH COLUMBIA

BY

Timothy David John England, B.Sc. (Hons.), M.Sc.

A thesis submitted to the School of Graduate
Studies in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Department of Earth Sciences
Memorial University of Newfoundland
December, 1989

St. John's Newfoundland

ISBN 0-315-59245-1

Abstract

Georgia Basin is an elongate forearc basin that initially developed in the Late Cretaceous (Turonian - Maastrichtian). Its origin is ascribed to subduction-related lithospheric downwarping of Wrangellian crust trapped within the arc-trench gap during active convergence on the Pacific margin of North America. The sedimentary record of this period of basin development is the siliciclastic Nanaimo Group. The group is composed of distinct, alternating, dominantly coarse grained and fine grained formations, deposited during times of high and low rates of sediment delivery to the basin, respectively. The main control on grain size is believed to be local tectonic activity. Restored thicknesses exceed 5 km. Study of the group in the western part of the basin on eastern Vancouver Island and adjacent islands reveals a broad spectrum of facies associations, including alluvial, fluvial, paralic, and neritic to mid-bathyal marine deposits. A series of regional facies maps are presented for successive stages of development of the basin. Based on new paleontological data and detailed stratigraphic and structural studies, revisions are proposed to the lithostratigraphic nomenclature of the Nanaimo Group.

Vitrinite reflectance data show that much of the Nanaimo Group is mature for oil and gas generation. Vitrinite reflectance/depth gradients in the basin range from 0.17 to 0.21 log $\%R_0$/km. Thermal history modeling shows that prevailing geothermal gradients during burial were low (heat flux < 58 mW/m^2). Tectonic subsidence was up to 2.7 km in 22 m.y., occurring at essentially constant rates between 100 and 200 m/m.y.. The eastern part of Georgia Basin lies beneath Georgia Strait and/or Cenozoic deposits. The western part of the basin remained buried until mid- to late Eocene after which it was tectonically shortened and uplifted.

The southwestern part of Georgia Basin is now preserved as a southwest-verging, linked thrust system involving the Nanaimo Group and its Wrangellian basement, termed the Cowichan fold and thrust belt. The thrust system is interpreted to be a leading imbricate fan. The geometry of the belt from plan and profile perspectives illustrates its thick-skinned structural style. Thrusting was most likely in-sequence, creating an estimated minimum 20-30% shortening at the basement/cover interface. Both fault-propagation and fault-bend folding are evident, the former being more common. Kinematic indicators and the geometry of the belt show no evidence of significant transpressional or transtensional displacement fields.

The sole fault of the thrust system is interpreted to rise from northwest to southeast on a series of deep lateral to oblique ramps and merge with the eastern extension of the San Juan Fault. This explains the rapid westward thickening of the wedge of thrusted Wrangellian basement. In the east, the sole fault is interpreted to locally have permitted the Nanaimo Group to overthrust the San Juan Terrane. Investigation of the Cowichan fold and thrust belt reveals how shortening during westward-progressing terrane accretion is accommodated in a forearc region that is dominated by a large slab of rigid, semicontinental crust.

Acknowledgements

The author acknowledges with appreciation the support of the Geological Survey of Canada, BP Canada Resources Limited, BP Exploration Incorporated, and the Natural Sciences and Engineering Research Council. Although the author retains responsibility for the substance of the thesis, including possible errors and omissions, the formulation of some of the ideas has been influenced by Dr. T.J. Calon, Dr. R.N. Hiscott, and Dr. G. Quinlan (Memorial University of Newfoundland); Dr. C.J. Yorath (Pacific Geoscience Centre); and Dr. N.W. Massey (British Columbia Ministry of Energy, Mines and Petroleum Resources). A large body of geological and geophysical data on Georgia Basin was kindly made available to the author by Dr. S. Du Toit (BP Canada Resources Limited), and discussions of the study area with company personnel - in particular Dr. M.A. Cooper and N. Piggott - are acknowledged with thanks. The author appreciates reviews of various parts of the thesis by Dr. P. Cawood (Memorial University of Newfoundland), Dr. T. Lewis (Pacific Geoscience Centre), Dr. N.W. Massey, and Dr. M.A. Cooper. Field assistance was expertly provided by Ms. L.A. England, Mr. G. Linden, and Mr. M.V. Yorath.

Table of Contents

List of Tables

List of Figures

List of Photograph Plates

Chapter One

INTRODUCTION

1.1 General introduction

Basin analysis is the stratigraphic, paleogeographic, and structural study of regionally distributed packages of sedimentary rocks (Miall, 1984). The term basin analysis expresses the modern regional approach to understanding a sedimentary basin, whereby the growth of the basin is considered to be the result of a complex interplay of many contributing factors operating at various scales, and basin evolution is considered in the context of the evolution of the region as a whole, including the basement rock. It incorporates many facets of sedimentary and structural geology, and thus requires skills of integration, synthesis, and generalization, rather than specialization in any one aspect of geology. The value of such an approach (and for that matter, of any system science), in the author's view, is that by considering the whole of the problem first it becomes readily apparent what detailed work must focus on, and by analysing and integrating diverse technical data, there is as much potential for new insights to be made as in specialized studies.

The basin analyzed in this thesis is the Georgia Basin, an extensive Upper Cretaceous-Cenozoic siliciclastic sediment-filled trough in southwestern British Columbia and northwestern Washington (Figure 1.1). It is part of a series of sedimentary basins developed on the Pacific margin of North America during the Late Cretaceous, which includes those occurring in southern Alaska, in the Queen Charlotte Islands area, northern Vancouver Island, southern Washington and Oregon, and in the Great Valley, California (Dickinson, 1976). All of these basins developed in an overall convergent-margin setting. Within this type of setting, however, a large variety of forearc basins may evolve depending on the geodynamics of the local plate margin (Dickinson and Seely, 1979). Possible models of basin origin, nevertheless, may be firmly constrained by comprehensive analysis of the sedimentary succession preserved in the basin. The lack of this type of analysis for the Georgia Basin has permitted the publication of a variety of explanations for its origin as described in Chapter 2.

The thesis focuses on the Upper Cretaceous sedimentary record of the Georgia Basin - the Nanaimo Group - which is disposed in two main subbasins, the Comox and Nanaimo basins (Figure 1.2). Although the Nanaimo Group has been the subject of many studies over the last century, none of them are regional studies based on modern basin analysis principles and techniques, except for those that exist in the private domain. The main purpose of the thesis is to analyze the Cretaceous to Paleogene evolution of the Georgia Basin, to investigate its mode of origin, to describe and interpret its sedimentary record in terms of regional facies associations and depositional systems, and to consider its deformational history.

Initially it was proposed to limit the focus of the thesis to subsidence and thermal history modeling of the Georgia Basin, utilizing the information gained from a regional vitrinite reflectance sampling program, and based on measured sections and compiled stratigraphic and structural data (England, 1987). Field study commenced in May, 1987, and it soon became apparent that several changes had to be made to the thesis proposal. First, the existing 1:250,000 scale geological base map for the area by Muller and Jeletzky (1970) needed revisions to accomodate the author's views on: a) lithostratigraphic correlation in the Nanaimo Group; and b) the structural style of the region, particularly in southwestern Georgia Basin. Thus, a substantial field effort was required to construct new

1:250,000 scale geological base maps, before basin analysis could be carried out. This fieldwork was undertaken in 1987 (5 months) and 1988 (3 months), supported by Dr. C.J. Yorath, Geological Survey of Canada (Pacific Geoscience Centre), with field visits by Dr. R.N. Hiscott in 1987, and Dr. T. Calon in 1988 (both from Memorial University of Newfoundland). The geological base maps (Chapter 2) are constructed with reference to 17 1:50,000 scale geological maps generated by the author, which incorporate a large body of published and some unpublished data (Appendix A). The author concentrated on the best exposed areas, relying on "ground-truthing" traverses to the more remote parts of the basin. Study of the rocks comprising the basement of the basin is largely excluded from the thesis.

The substantial revisions made to Nanaimo Group lithostratigraphy and the structural geology of Georgia Basin required that the emphasis of the thesis shift away from analysis of a basin in a mature stage of study (adopting a more theoretical approach), to basic geological mapping to establish the basin architecture, and <u>then</u> basin analysis. As such, the study has become more well rounded and stands alone as an independent appreciation of the geology of western Georgia Basin.

Although many of the revisions to Georgia Basin geology are substantial, the thesis would not have been possible without the large amount of information gained from previous work, notably the early investigations by the Geological Survey of Canada, the publication by Muller and Jeletzky (1970), the successive theses on the Nanaimo Group contributed by students at Oregon State University, and the regional study by BP Canada Resources Limited completed prior to exploration drilling on Vancouver Island in 1986 (Bickford, 1986). In fact, the LITHOPROBE deep reflection seismic study of Vancouver Island (Yorath et al., 1985a) prompted Dr. C.J. Yorath to initially suggest the study to the author. The previous work is referred to and clearly separated from the author's interpretations in the text; the thesis merely builds on these data.

Analysis of the Georgia Basin is also based on a diverse array of new technical data, which required input from three specialists. Mr. B. Cameron, Geological Survey of Canada (Pacific Geoscience Centre), analyzed foraminiferal assemblages collected from the Nanaimo Group by the author. These data were invaluable to accurate facies analysis of the marine strata in the Nanaimo Group. Dr. J. Haggart, Geological Survey of Canada (Institute of Sedimentary and Petroleum Geology), examined macrofossil suites collected by the author, which helped to confirm and further constrain the biostratigraphic framework of the Nanaimo Group. Advice on trace fossils was obtained from Dr. G. Narbonne (Queen's University, Kingston, Ontario).

The thesis is written in about the same order that the work progressed: structural geology, stratigraphy, facies analysis, vitrinite reflectance data, and burial history analysis. The study area incorporates where the Nanaimo Group is exposed on eastern Vancouver Island and adjacent islands (Figure 1.2). A guide to locations referred to in the chapters is in Appendix A.

1.2 Regional structural style

In many of the previous studies in the Georgia Basin, structural geology was not emphasized. However, a single traverse across Nanaimo Basin (Figure 1.2) will reveal that the entire Nanaimo Group is deformed. As the region is heavily vegetated locally, and continuity between outcrops is restricted dominantly to shoreline exposures, there appeared a real danger that important structural boundaries may have been missed, such that the established stratigraphic framework of the basin might be questioned. This has happened often in studies of other sedimentary basins. In fact, because the basin stratigraphy was initially established in the least deformed parts of the basin, it has stood the test of more detailed investigation of the structural geology. In the deformed areas, however, numerous erroneous lithostratigraphic correlations have been made, mainly due to ignorance of structural complications.

The structural geology is the least emphasized aspect of most of the field-based studies of Georgia Basin made to date. This neglect is primarily born out of a lack of appreciation of the structural style of the region. Appropriately, the structural style is the first subject addressed in the thesis.

On a regional scale, the main structural element of the study area (Figure 1.2) is an elongate basin area lying between two mountain ranges: the coastal mountains of mainland British Columbia, and the mountains of Vancouver Island. This pattern probably has persisted since basin initiation, but the relative relief of the region is considered to have increased substantially during the Cenozoic, with significant uplift of the Coast Ranges and Vancouver Island (Parrish, 1981; Yorath and Hyndman, 1983). As a consequence of this uplift, the distribution of the Nanaimo Group has been considerably reduced by erosion; the group formerly may have extended over large parts of the present mountain areas, perhaps linking the Georgia Basin with basins like the Suquash Basin on northern Vancouver Island (Figure 1.2).

The study area is divisible into two provinces expressing different supracrustal structural styles. The northern province, which incorporates most of the Comox Basin, is tilted in a large homocline, cut by a few large faults with inferred normal dip slip. In contrast, the southern province, which comprises the Nanaimo Basin and southern part of the Comox Basin, is moderately deformed by large folds and thrust faults, and is referred to as the Cowichan fold and thrust belt (CFTB). The Comox and Nanaimo basins relate closely to the structural province boundaries;

however, the CFTB does encroach the southern part of the Comox Basin, the shortening presumably being accomodated on deeper, blind structures (Chapter 2).

The structural style of the study area presented by Muller and Jeletzky (1970) and Muller (1977) embraced high-angle fault blocks and strike-slip faults separating asymmetrical grabens, and deformation associated with and mostly restricted to the fault zones. The block faulting was considered to mostly reflect vertical crustal displacement caused by horizontal tension. Compressional features were only locally developed according to these authors. Much of the research on the Nanaimo Group over the last 15 years has adhered to Muller's view of the structural geology of the region (eg. Hanson, 1976; Pacht, 1980, 1984). Johnson (1985) suggested that several strike-slip faults were active in the region in the Late Cretaceous and Early Tertiary.

Deep reflection seismic profiles (LITHOPROBE), however, show that many of the inferred steep faults on Vancouver Island are listric in shape, dipping to the northeast; they have been interpreted as thrust faults, based on field relations (Yorath et al., 1985a, 1985b; Clowes et al., 1987). Subsequent mapping in the Nanoose basement culmination, which separates Nanaimo and Comox basins (Figure 1.2), has confirmed the presence of several basement-involved thrust sheets (Sutherland Brown and Yorath, 1985).

Recent fieldwork in the course of this study during 1987 and 1988, and by Massey et al. (1988) and Massey and Friday (1989), has revealed much new information about the region. Although the old perception of the structural style of the area may be applicable to parts of the northern province, it is untenable for the southern province. The view presented here for the southern province is of a linked system of folds and contractional faults constituting a thrust system, which has many characteristics in common with well known fold and thrust belts. The CFTB is thick-skinned, as both basement and its cover are intimately involved in the contractional deformation.

CHAPTER 2

STRUCTURAL GEOLOGY

2.1 Regional Geological Setting

The study area encompasses much of the Georgia Basin, which developed in the Insular Belt of the Canadian Cordillera during the Late Cretaceous, on variably metamorphosed sedimentary and crystalline rocks of the Wrangellia Terrane (Jones et al., 1977; and Figure 2.1). The origin of Georgia Basin is somewhat problematical. The author adheres to the view that the Georgia Basin evolved in a forearc position (Dickinson, 1976; Muller, 1977) due to subduction-related lithospheric downwarping (Chapters 6, 7 and 8; Yorath and Hyndman, 1983). An alternative perception is that Georgia Basin developed in a transform or obliquely convergent margin setting (eg. Umhoefer, 1987) due to extension (Pacht, 1984).

The boundaries of the study area are defined for the most part by the distribution of the Nanaimo Group in the Comox and Nanaimo basins (Figure 1.2). The eastern boundary is Georgia Strait, where the Nanaimo Group is covered by thick Cenozoic deposits of the Whatcom Basin (Crickmay and Pocock, 1963; Hopkins, 1968) and the Chuckanut Basin (Johnson, 1984; 1985). Cenozoic deformation of the mainland (Vancouver) side of the Nanaimo Basin is poorly understood, due to paucity of exposure. The Outer Islands fault (Figure 1.2), a large normal fault shown on seismic lines interpreted by Machacek (1971), downdrops the deformed Nanaimo Group ca. 3 km, where it is overlain by Tertiary deposits under Georgia Strait, effectively terminating surface expression of the Cowichan fold and thrust belt (CFTB). The southeastern boundary of the study area is the San Juan Terrane (Jones et al., 1983). The southwestern extent of the CFTB has not been delineated in detail, due to the lack of control on Cenozoic faulting within Wrangellian basement rocks on southwestern Vancouver Island. The San Juan Fault, which separates Wrangellia Terrane from Pacific Rim Terrane (Figure 2.1), constrains the maximum southwestern development of the CFTB, and may be kinematically linked to it, as discussed later in the thesis. Movement on the San Juan Fault predates the late Eocene-Oligocene Carmanah Group (which overlaps the fault) and post-dates the age of metamorphism - 40 to 44 Ma - of the Leech River Complex (Fairchild and Cowan, 1982).

Two thrust systems are recognized in the study area. The older system is the previously recognized Northwest Cascades Thrust System (NCTS) which occurs in the San Juan Islands and the Coast Ranges, and probably resulted from the collision of the Wrangellia Terrane with North America in the Cretaceous (Davis et al., 1978). The younger system is the CFTB, which probably resulted from the collision of the Pacific Rim and Crescent terranes with North America in the late Eocene.

Wrangellia Terrane had accreted to inboard terranes of the study area by mid-Cretaceous time (Monger and Price, 1979), and thereafter became the leading edge of North America as a broad continental fragment trapped within the arc-trench gap. The Lower Cretaceous Gambier Group overlaps Wrangellia and inboard terranes (Monger et al., 1985). In the study area, contraction along the eastern boundary of Wrangellia continued into the early Late Cretaceous, creating a thick, northwest-verging nappe pile in the San Juan Islands (Vance, 1977; Whetten et al., 1980; Brown, 1987; Brandon et al., 1988). The age of the leading thrusts of this part of the NCTS is bracketed between 100 and 84 Ma based on the age of disrupted strata, fission-track dates for the time of uplift of the nappe pile, and the recognition of thrust-sheet detritus in lower Nanaimo Group conglomerates (Brandon et al., 1988).

Contraction of the Georgia Basin and development of the CFTB began no earlier than in latest Cretaceous time (ca. 68-66.5 Ma) because all of the Nanaimo Group is deformed. The upper limit for the time of contraction is less certain, but is constrained by: a) mid- to late Eocene fission-track ages for the time of uplift of apatite in the Nanaimo Group and Wrangellian basement (England and Massey, in preparation); and b) thermal history modelling which requires that for calculated organic maturation levels to match measured organic maturation levels, the Nanaimo Group remained deeply buried during most of the Paleogene (Chapter 7). The contractional episode coincided with or was driven by accretion of the Pacific Rim and Crescent terranes to southern Vancouver Island in the late Eocene - at ca. 40 Ma (Clowes et al., 1987).

Extensional features in the study area are restricted to the northern structural province, aside from the Outer Islands fault (Figure 1.2) and small-scale, late extensional structures observed in the CFTB. Large faults with inferred normal dip-slip exist in the western part of the northern structural province - the Beaufort Range Fault and Mount Washington fault - and there are a number of smaller-scale faults present in the main part of the Comox Basin. This extensional episode may have been coincident with widespread intrusion of the Eocene Catface sills, dykes, and laccoliths in the Comox Basin (see Chapter 7).

Geological maps of the two structural provinces (Figures 2.2 and 2.3) are constructed from 1:50,000 scale field map data and compilation of data from many published and unpublished sources as listed by map area in Appendix A. Figure 2.2 covers the entire CFTB with the exception of the western and southwestern basement areas, where control on CFTB age structures is limited.

The basement of the study area is divided into Paleozoic, Triassic, and Jurassic rocks (Figure 2.4) which are all part of Wrangellia (Yorath and Chase, 1981). They consist of: a Paleozoic island-arc assemblage of variably metamorphosed chiefly volcanic and sedimentary rocks of the Sicker Group (Unit 1) and the Wark and Colquitz Gneisses (Unit 1a); the Upper Triassic Vancouver Group (Unit 2) divisible into the lower, thick, Karmutsen Formation basalt flows, pillow lavas, and tuffs, overlain by Quatsino Limestone and argillaceous sediments of the Sutton and Parsons Bay formations; unnamed Permian and/or Triassic volcanics (Unit 2a); Lower Jurassic calc-alkaline volcanics and sediments of the Bonanza Group (Unit 2b); and Jurassic granodiorite (Unit 3) of the Island Intrusions and Gneiss Complex (Sutherland Brown, 1966; Muller, 1977; Yorath et al., 1985a). These are predominantly highly competent, mostly crystalline rocks, with crude to strong fabrics developed prior to creation of the CFTB. Detachments related to development of the CFTB do not appear to be confined to specific units or horizons in basement.

The Nanaimo Group is comprised of a succession of conglomerate, sandstone, siltstone, and shale (Figure 2.4), which exceeds 3.6 km in exposed thickness in the eastern part of the study area; restored thicknesses, using vitrinite reflectance data (Chapter 5), may exceed 5.4 km. Competency contrasts are large, with typically thick bedded, massive conglomerate or sandstone lying between thick, silty shale units. Numerous glide horizons are present in the fine grained units, and also in the coal seams which are present in lower Nanaimo Group in the northwestern part of the CFTB; the basement/cover contact, on the other hand, does not act as a detachment horizon and can be seen in many places such as on northern Saanich Peninsula and on Saltspring Island. The 13 mapped formations (Figure 2.4) of the Nanaimo Group are grouped into 7 units chosen to simplify illustration of the structure of the southern province (Figure 2.2). The structure of the northern province is simple enough that the distribution of all of the formations present can be shown (Figure 2.3). New lithostratigraphic correlations in the Nanaimo Group (Chapter 3 and Appendix B) are an important element of the geological maps (Figures 2.2, 2.3, and A.2 to A.7).

2.2 Detailed structure of the Cowichan fold and thrust belt

In this part of the thesis, the CFTB is described, emphasizing its structural style and kinematics. Although what is presented here is a totally new perspective on the structural style of the belt compared to that of Muller and Jeletzky (1970), aspects of contractional deformation in the belt were recognized first by Clapp (1910 to 1914b), Clapp and Cooke (1917), Allan (1910), and Buckham (1947). These authors reported northeast-southwest shortening in the Nanaimo Group based on the occurrence of thrust faults, tight folds which are commonly overturned to the southwest, and thickened, sheared, and locally repeated coal seams, and thrust faults involving both Nanaimo Group and basement.

2.2.1 Plan view perspective

The macroscopic geometry of the CFTB is well displayed in the geological map (Figure 2.2) which extends over an area ca. 140 x 60 km on southeastern Vancouver Island and adjacent islands. For ease of description, the region is divided into a northern belt which comprises the CFTB northeast of the Fulford Fault, and a southern belt which comprises the CFTB south of this fault (Figure 2.5). As a result of significant uplift of Vancouver Island during the Cenozoic, the CFTB has undergone extensive erosion. From northeast to southwest, deeper levels of the CFTB are exposed, and the cover rocks are removed from the exposed ections of individual thrust sheets; the two belts afford both shallow (northern belt) and deep (southern belt) perspectives of the structure of the CFTB.

In order to set up an appropriate framework for discussion and description of the structural geology of the CFTB, it is important to consider first some major plan view aspects of the CFTB in relation to observed orientation patterns.

1) The surface traces of the main faults have a regional, northwest-southeast, curved trend. The fault surfaces dip to the northeast, where observed or inferred on the basis of hanging-wall structure. Many faults have inferred dips, but the inference is well constrained by applying principles of balanced cross-section construction to explain hanging-wall structures (see also point 7).

2) The trends of large cylindrical to subcylindrical fold systems in the Nanaimo Group are generally parallel to the fault traces in the northern belt. This feature, together with aspects of point 1 above, strongly control the distribution of lithological units in the area as indicated by the northwest-southeast, elongate map patterns of both basement and cover units.

3) Transverse faults have a general strike more or less orthogonal to the strike of the main faults, and trends of the fold axes. The transverse faults display only minor horizontal and vertical offsets.

4) A number of branch points are present, defined by fault-trace intersections (constrained and inferred), indicating a linked fault system with rejoining and connecting splays.

5) Overall, the geometry of the cover sequences in the various fault blocks is homoclinal; however, some blocks, or parts of blocks, show monoclinal structure of cover, with southwest vergence.

6) Structures within individual fault blocks have an overall southwest vergence, as indicated by the sense of asymmetry of large- and small-scale folds and the consistent bedding/cleavage relationship in homoclinal cover sequences;

cleavage generally dips more steeply to the northeast than bedding.

7) Basement culminations within individual fault blocks in the southern belt and around the western part of the northern belt, are smoothly antiformal and commonly doubly-plunging. These culminations impose a marked degree of non-cylindricity to the internal structure of fault blocks, also expressed in the structure of the cover sequences. They are interpreted as anticlines developed above hanging-wall ramps on broadly curved detachment surfaces.

Furthermore, there is no evidence of synorogenic sedimentary facies in the cover sequences related to development of significant normal-fault scarps, growth faulting, or localized pull-apart basin development.

Together, these features point strongly to the interpretation that the Nanaimo Group and its basement are part of a southwest-verging, linked thrust system with associated folds related to broadly northeast-southwest-directed, large-scale crustal contraction. Further support is derived from the analysis of kinematic aspects of fault- and fold-related, small-scale structures (section 2.2.5) and the profile perspectives of a number of balanced sections of the belt.

It is inferred that the overall structure of the thrust system is a leading imbricate fan (Boyer and Elliott, 1982) above a northeast-dipping sole thrust in Wrangellian basement, that locally may coincide with the San Juan Fault beneath central Vancouver Island. This fan may have been overall emergent, but also contains a number of thrusts with buried tip lines, as well as inferred duplex structures comprising lower Nanaimo Group sequences.

2.2.1.1 Northern belt

The dominant structure of the northern belt is a variably exhumed, leading imbricate fan, the leading thrust being the Fulford Fault and its continuation in the southeast, the President fault (Figures 1.2, 2.2). The belt is best described in three segments: 1) the southeastern Gulf Islands area, exposing the entire cover sequence resting on basement brought up on the Fulford Fault; 2) the central area, exposing mostly deep cover structures, and a wider basement outcrop; and 3) the northwestern area, exposing mostly basement rock with minor cover rock, which forms the Nanoose culmination (Figure 2.4).

Gulf Islands area

The Gulf Islands area (Plates 9a, 13a) consists of the cover sequence which dips to the northeast, and a strip of basement brought up on the Fulford Fault (Plate 2a). In detail, the area is comprised of the Fulford, Ganges-Pender, and Swanson thrust sheets, which all include basement and cover in the hanging wall. The structure of the cover sequence is a series of normal to inclined, parallel style folds, with typically single, rounded hinge zones, that have amplitudes and half wavelengths of several kilometres, and can be traced for tens of kilometres along their axial traces in a northwest to southeast orientation (Plate 9a). The folds have open to close interlimb angles and are cylindrical. Some of the folds are asymmetrical, verging to the southwest, and are locally overturned. Axial planar cleavage is either not present or crudely developed, and contraction is considered to have been accommodated mainly by bedding-parallel slip.

The Ganges and Pender thrust faults are inferred to cut up into the lower part of the cover section in the south, and several minor thrust faults are present which repeat units 7 and 8 on Saltspring and the Pender islands. The Swanson fault, originally recognized by Clapp (1912a), is inferred to bring basement rock up to the present erosional level under Swanson Channel (between North Pender and Moresby islands, Figure A.1). Several north-trending, high-angle faults are also present which show up to 1.6 km of apparent horizontal offset of marker beds (i.e. strike separation; Hobbs et al., 1976), and may facilitate displacement transfer from one thrust fault to another.

In the east, the Fulford thrust merges with the sole fault of the CFTB; it must rise on an oblique to frontal ramp herein called the President fault, which forms part of the San Juan Terrane boundary. The pattern of curved fold-axial traces in the Nanaimo Group parallel to the inferred trace of the President fault shows that folding in this area is related to the geometry of the oblique to frontal ramp system.

Central area

The central area (between E′ and E", Figure 2.2) is also homoclinal with the Nanaimo Group dipping generally to the northeast. A large, asymmetrical, gently east-plunging fold in cover dominates the structure of the area, as can be seen by following the contact between units 7 and 8 on Figure 2.2. This fold is probably related to the plunging, oblique culmination wall in basement which is exposed to the southwest. A diverging hanging-wall splay off the Fulford Fault, identified as the Brenton fault, has an inferred tip point in basement; another thrust may be present to the north, placing unit 3 over 5.

Large, upright to steeply inclined, northwest-trending folds are present in cover, like those described for the Gulf Islands area. In addition, there are numerous smaller folds (half wavelengths of 100′s of m) which in part may define a parasitic fold envelope developed around the much larger, asymmetrical plunging fold. They are developed along or near the interfaces of units 5 and 8 with unit 7, which is an indication of the large competency contrast between the coarse grained unit 7 and fine grained units 5 and the lower part of unit 8. In addition to the generally northwest-trending folds, more east-west trending folds are present in the northern part of the area, which probably represent an irregular, blind ramp geometry in lower cover or basement.

In the southwestern part of the area in units 5 and 7, a large anticline is present, the limbs of which are broken by both southwest- and northeast-verging thrust faults with intervening minor folds. Displacements on these faults, however, are minor. Some of the faults in this area have tip points indicated on the map, and it is possible that many of the folds that occur at the base of unit 8 are thrust cored. Seismic data acquired by BP Canada Resources Limited in 1984 and 1985, mostly in the area of unit 8 outcrop, show northeast- and southwest-verging minor thrusts. Whereas most of the shortening in the competent unit 7 is taken up by brittle failure, much of the shortening in unit 5 is taken up by folding discernable at both outcrop and map scales. Northeast-trending, high-angle faults with moderate vertical and lateral offsets of marker beds, crosscut the dominant structural grain of the area.

Western area

The western area of the northern belt consists of several stacked basement thrust sheets, with a veneer of basal Nanaimo Group strata. Relict basement relief is indicated in the northern part of the area, such as across the Benson thrust, where outcrop trends of basement and lower cover locally crosscut the dominant structural grain of the thrust belt in a manner that is difficult to reconcile with simple hanging-wall ramp geometries.

Paleotopographic relief on the basement surface on which the Nanaimo Group was deposited is widely recognized in the Georgia Basin (Clapp, 1914a; MacKenzie, 1922; Muller and Jeletzky, 1970).

The contractional nature of the structural culmination in the Nanoose area (Figure 2.5) was reported by Sutherland Brown and Yorath (1985). The lower part of the Nanaimo Group is repeated in the Northwest Bay area (Figure A.1), west of the culmination, along the Nanoose thrust and subsidiary splays (Figure 2.2). Thrust faults also occur in the broad basement exposures to the south, specifically the Benson, Blackjack, Okay and Dash Creek faults, all of which appear to have only minor displacements, given the limited stratigraphic separation across them. Numerous open folds are present within cover in the footwall of the Benson thrust suggesting the presence of detachments in cover.

To the west, most of the basement-involved thrusts are considered to die out in the lower part of the cover sequence. Their cumulative displacement is thought to be transferred on to the Fulford Fault (and its continuation to the northwest, the Cameron River Fault, Figure 2.3), which then acts as the floor thrust for the Comox Basin (Figure 1.2). This explains the generally undeformed state of the cover sequence in the Comox Basin as it lies essentially in one huge basement-cored thrust sheet. Seismic data acquired by BP Canada Resources Limited in 1985 in the southeastern Comox Basin show only few significant faults in a gently northeast-dipping homocline.

2.2.1.2 Southern belt

The structure of the southern belt is dominated by several prominent thrust faults which form an imbricate fan, the highest levels of which are preserved in the southeast. The southeastern boundary of the belt is the contact with the San Juan Terrane, which is inferred to be a steep lateral ramp in Wrangellian basement, with sinistral strike-slip, and is herein called the Sidney fault (Figure 2.2). East of this fault, at depth, the Wrangellian basement is considered to underplate the San Juan Terrane (Cowan and Potter, 1986).

The southern boundary of the belt is probably the San Juan Fault, which in the study area consists of two, possibly related segments: 1) the west-southwest striking part which is probably a northwest-dipping oblique ramp in Wrangellian basement; and 2) the inferred southeast-striking part which would be the leading sole thrust of the CFTB in the eastern area. The San Juan Fault cannot be shown to be stratigraphically overlapped by the Nanaimo Group as inferred by Clowes et al. (1987, p.34), and, therefore, is not necessarily a pre-Nanaimo Group feature. Much of the contraction between the Wrangellia and Pacific Rim terranes on the western part of the San Juan Fault is probably transferred onto the Survey Mountain Fault (Figure 1.2).

A tripartite division of the southern belt facilitates description of its macroscopic structure: 1) the Saanich area in the east, including the adjacent small islands; 2) the central Cowichan Valley area, after which the thrust belt is named; and 3) the western basement dominated area surrounding Cowichan Lake (Figure 2.5).

Eastern area

The structure of the eastern area is dominated by two major thrust faults - the Fulford and Tzuhalem faults - which form prominent scarps on southern Saltspring Island (Plates 1b, 2a). The Fulford Fault is the northeasternmost thrust of the southern belt. The Tzuhalem Fault refers to the segment which extends from Mount Tzuhalem in the west to the inferred branch point with the Fulford Fault in the east. The Fulford Fault continues to the east to join the President fault. The eastern part of the San Juan Fault is inferred to form the southern boundary of the area, and the Sidney fault forms the eastern boundary. Both of these faults are obscured by water or Quaternary sediment, hence their locations are uncertain.

Several thrust faults which repeat units 4 and 5 of the Nanaimo Group, as well as basement, form either a broad footwall duplex structure or footwall imbricate fan (Section 2.2.2). The lower units are locally strongly deformed, with the development of chaotic, internally dismembered zones, and a pronounced cleavage in the incompetent beds (Plate 6a). Northwest-plunging hanging-wall anticlines are associated with several of the thrusts. The amount of throw and thickness of basement involved on these faults are much less than on the Fulford and Tzuhalem faults.

Central area

The structure of the central area is characterized by three major thrust faults - Fulford, Chemainus River, and Cowichan Lake faults - and associated blocks of lower Nanaimo Group strata and basement (Figure 2.2). The Chemainus River fault is considered to represent the western continuation of the Tzuhalem Fault, and the Cowichan Lake Fault is inferred to join the Tzuhalem Fault in the east. Minor thrust faults, map scale fault-parallel folds, and cleavage folds at outcrop scale (Plate 5a), reflect shortening in the Nanaimo Group within the main footwall blocks. Trailing footwall synclines in unit 7 are common. The North Cowichan Lake fault represents a rejoining splay. In the east, a prominent northwest-plunging hanging-wall anticline cored by basement is associated with the Tzuhalem Fault. In the western part of the central area the cover rock is replaced by basement as deeper levels of the thrust system are exposed. In the south, a broad basement block is exposed, within which CFTB age faults are poorly delineated.

Western area

The western area of the southern belt is clearly fault dominated with the presence of the East Robertson, Cowichan Lake, Chemainus River, and Fulford faults (Figure 2.2). A rejoining splay known as the Meade Creek fault is present in the hanging wall of the Cowichan Lake Fault. In the footwall, a doubly-plunging hanging-wall anticline exposes basement at the eastern end of Cowichan Lake, and is associated with the inferred McKenzie Bay fault, which is probably a footwall splay of the Cowichan Lake Fault. The most southerly thrust is the East Robertson fault, which may join the oblique ramp segment of the San Juan Fault to the southeast.

To the west, the faults lie generally within basement, with only limited control on their position afforded by the sparse distribution of units 4 and 5 of the Nanaimo Group. The Chemainus River fault probably joins the Fulford Fault which links to the Cameron River Fault. The Cowichan Lake Fault splits into several splays in the west, possibly indicating the beginning of a horsetail-splay termination to this part of the thrust fault system.

The entire western area may constitute a thick thrust stack (or sheet) of Wrangellian basement resting on the San Juan Fault. In this case, the San Juan Fault is considered to be the sole thrust of the CFTB. Alternatively, the large basement block south of Cowichan Lake may have acted as a passive footwall, with the Cowichan Lake Fault being the main sole fault of the CFTB in this area. In this case, the East Robertson thrust may be a leading splay of the sole fault. The ambiguity in delineating CFTB age faults in this part of the southern belt from pre-existing basement structure prevents the determination of a unique solution to the problem.

2.2.2 Profile perspective

The structural geometry of the CFTB is best shown on vertical sections drawn orthogonally to the trend of the belt using a balanced-section approach (Figures 2.6, 2.7, 2.8, 2.9 and 2.11). The sections are based primarily on detailed 1:50,000 scale field maps of the geology of the region, but are constrained by the limited well data (3 shallow hydrocarbon-exploration wells and many shallow coal-exploration boreholes) and seismic data (LITHOPROBE and BP Canada Resources Limited) available for the region. The surface geology places tight constraints on the location, and locally the attitude, of exhumed faults and the basement/cover unconformity, as well as the structure of the exposed cover sequence within the individual thrust sheets. These data allow for some constraints to be placed on the extrapolation to depth of the shape and position of faults and lithostratigraphic contacts, particularly in the northern belt.

The inclination of the sole fault of the thrust system is taken to be comparable to the dips of similar faults in Wrangellian crust on Vancouver Island imaged on seismic data from LITHOPROBE (Clowes et al., 1987). At the western end of Line 1 on western Vancouver Island, the Westcoast Fault is clearly imaged and has a calculated dip of 21^{0}, which is probably near true dip as the line is orthogonal to the fault trace. The Survey Mountain Fault, which thrusts Wrangellia over the Pacific Rim Terrane on southern Vancouver Island, based on line 2 of LITHOPROBE, has an inclination of 28^{0}. These dip calculations rely on the time-depth relationship presented with the seismic lines, which may not be very accurate for the shallow parts of the imaged sections. Nevertheless, a reasonable estimate for the dip of the sole fault of the CFTB is around 25^{0}.

Additional constraint on the profiles is provided by vitrinite reflectance data for estimating the maximum height of the synorogenic surface above the present day surface. The calculation of the position of the paleosurface relies on the method described by England and Bustin (1986a) to estimate thickness of removed section based on vitrinite reflectance/depth gradients. In this case, the gradients are established in the uppermost thrust sheets (Chapter 5), where nearly complete sections of the Nanaimo Group are exposed, and these gradients are assumed to apply to the entire CFTB. Given that gradients measured at 3 widely spaced localities in the CFTB are within 8% of the average gradient, the error range on the estimated maximum loading in using the average gradient is considered to be +/- 0.3 to 0.5 km over the range of 0.5 to 2.5 $\%R_0$. The measured gradients are assumed to apply to the missing section, and maximum loading is assumed to have occurred during contraction. The comprehensive vitrinite reflectance database (Appendix D) has proven to be a powerful tool in analysis of the CFTB.

All deformed-state sections feature a surface which indicates the maximum possible top of the Nanaimo Group (or Nanaimo Group plus Paleogene section), based on reflectance/depth gradients and other stratigraphic data. The profiles were drawn adopting a philosophy of using minimum displacements on the faults to explain the observed data, so that minimum amounts of contraction could be estimated for the CFTB.

The five long profiles are line length and area balanced in the cover, using the restored-state cross-section approach with thrust faults that initially propagate at 35^0 through the cover rock. Within basement the faults also branch off the sole fault at 35^0, but because the sole fault is dipping at 25^0, they propagate through basement at a high angle relative to a horizontal datum. Unit thicknesses were locally adjusted on the restored-state sections to accord with calculated or measured unit thicknesses at surface; possible volume changes due to compaction during thrust loading are negligible as the succession is considered to have been compacted preorogenically. Possible dilatational strains associated with cleavage development have been ignored.

There is an outstanding problem with internal (layer-parallel) shortening reflected by locally intense cleavage in the lower cover units in the southern belt which requires that the initial line length of the cover units is larger than that of the basement/cover contact within individual thrust sheets. This points to the presence of ramp/flat geometries of thrust trajectories in the sequences above the basement/cover contact on the restored templates. Given the depth of erosion, and the extent of the present data set, the internal strain, particularly in the incompetent units, cannot be precisely restored. It is observed, however, that a substantial amount of the shortening in the lower cover appears to be accommodated by unit thickening associated with cleavage folding. Therefore, to create more viable cross-sections, an approach is taken to compensate for this observed tectonic thickening and the development of slaty cleavage in the southern belt by using locally increased thicknesses of units 4 and 5 on the (partly) restored cross-sections. Some of the observed thickness variation in units 4 and 5 may also be depositionally controlled. A horizontal top datum was chosen for the restored-state sections which has the effect of creating locally inclined basement/cover contacts due to stratigraphic thickening and/or only partial removal of layer-parallel shortening. This is especially prominent in restored-state section D-D'.

On the whole, the balancing is loosely constrained due to the lack of foreland pin lines, limited control on the location of hanging wall and footwall cut-offs for cover, the lack of strain data related to layer-parallel shortening, and the paucity of deep seismic and well data. The curved (non-cylindrical) nature of macroscopic structures in the southern belt thrust sheets creates difficulties in locating the positions of the hanging-wall and footwall cut-offs on the plane of section, particularly for the basement/cover contact on the doubly-plunging basement culminations. Nevertheless, the deformed-state sections are judged to be admissible and viable, based on the available geological data.

Section A-A′

Section A-A′ (Figure 2.6), the most southwesterly profile, shows an imbricate fan consisting of an upper stack of three large thrust sheets overlying a duplex in the footwall of the Fulford Fault. Note that the sole fault of the duplex may be represented by the southeast-striking part of the San Juan Fault. Hanging-wall structures are related to the presence of steep hanging-wall ramps and splay fault propagation. Note the inferred intracutaneous detachment soling on top of unit 4 or the basement/cover contact in the Swanson thrust sheet (see also section B-B′, Figure 2.7). The duplex structure contains several horses, and has an inferred flat (corrugated) roof thrust in order to honour the estimated maximum altitude of the synorogenic surface. The northeastern part of the duplex structure on this profile is diagrammatic due to paucity of exposure, but is based on more detailed data available in section B-B′.

The compatibility between the structural geometry and the inferred synorogenic erosional surface suggests that the imbricate fan may have been only partly emergent in the northern belt, and emergent in the southern belt. A wedge-shaped geometry is indicated for the upper part of unit 10 (Gabriola Formation) which may be the result of early erosion of Nanaimo Group due to hinterland loading by the older thrust sheets.

Section B-B′

The structural style in section B-B′ (Figure 2.7), is similar to section A-A′. An upper stack of three large thrust sheets defines the northern belt, which overlies a more finely imbricated footwall in the southern belt. The lower part of the footwall duplex is well exposed in the area of the transect. Several geometric solutions are possible which honour the surface data; nonetheless, the overall duplex geometry with a gently dipping roof thrust is necessitated by the position of the inferred synorogenic surface. A steeply inclined roof thrust, or imbricate fan, would cause too much section to overlie the synorogenic surface. The Tzuhalem Fault is inferred to branch from the Fulford Fault. Note the marked increase in the hanging-wall load east of Coal Island, as indicated by rapidly increasing vitrinite reflectance values, and its correspondence to a thrust-stack culmination. On North Pender Island, note the overturned syncline and steeply-dipping beds to the south, as the basement in the Fulford thrust sheet is approached (Figure 2.2). This requires the presence of a relatively steep ramp across the basement-cover interface in this part of the section.

Section C-C′

Section C-C′ (Figure 2.8) shows an apparently less complex geometry to the CFTB with thicker basement-cored thrust sheets. The three large upper thrust sheets of section B-B′ have now been reduced to two, as the Swanson fault has merged with and tranferred its displacement onto the Fulford Fault, probably by way of a lateral transfer fault indicated in Figure 2.2. To the south, the Tzuhalem thrust sheet rests on a large flat on the Tzuhalem Fault. The inception of this flat is visible in section B-B′ (Figure 2.7), beneath Portland Island, and relates to the shallow depth for the Tzuhalem-Fulford branch point. A west-dipping oblique ramp on the Tzuhalem Fault, inferred to lie off the southeastern shore of Saltspring Island (Figure 2.2), places this branch point deeper in section C-C′ as required by the increased basement thickness in the hanging wall of the Tzuhalem Fault.

The change in structural style from section B-B′ to C-C′ southwest of the Tzuhalem Fault is pronounced, with a complex footwall duplex in the east (sections A-A′ and B-B′) and a more simple sheet with deeper basement section in the west. This requires that there is a northwest-dipping oblique ramp in basement in Saanich Inlet, which probably links to the San Juan Fault in the southwest, and acts partly as the roof of the footwall duplex structure in the east (Figure 2.2).

Section D-D′

Section D-D′ (Figure 2.9) is a long profile which runs from Galiano Island through the middle of the Cowichan Valley. The northeastern part of the section depicts two imbricates associated with the Ganges and Fulford faults. The major anticline in the Ganges thrust sheet is doubly-crested in this profile; on Thetis Island, to the northwest, it is faulted. In the Fulford thrust sheet there are at least three minor thrusts, which indicate brittle contraction of the interfaces of unit 4 with basement and unit 5, probably to accommodate more ductile shortening in unit 5. Underlying the upper thrust sheets of the northern belt is a broad region occupied by the Cowichan Lake, North Cowichan Lake, and Tzuhalem thrust sheets. Overall, much of the geometry of this region is controlled by the large flat on the Tzuhalem Fault which is also indicated on section C-C′.

Several small footwall splays off the Fulford Fault are developed in the Mount Prevost area. Unit 5 in the immediate footwall of the Fulford Fault is strongly deformed, and forms a large cleavage-fold fan between the Fulford Fault and one of these footwall splays. To the southwest, the footwall of the Cowichan Lake Fault defines the southern limit of exposure of the Nanaimo Group. The region between the southern limit of the Nanaimo Group and the Fulford Fault is in many areas covered by thick deposits of surficial sediments, which hamper mapping of bedrock.

Seismic data from BP Canada Resources Limited confirm the general subsurface structure of the Cowichan Valley, as shown in Figure 2.10. The line crosses two faults which correlate very well to the extrapolated positions of the Tzuhalem and North Cowichan Lake faults based on surface control, and also transects the Fulford Fault which is not imaged on the record section, possibly due to its steep dip or problems related to the presence of surficial deposits. Large anticlines visible on the section are related to the wedge-shaped cut-out of two basement imbricates and, hence, are hanging-wall anticlines. The lower Nanaimo Group probably exceeds 1500 m thickness in the footwall areas based on this line; it must be greatly tectonically thickened via folding and thrusting within cover (as ovserved in the field), very little of which can be identified with certainty on the record section. Note that the step-like geometry of the basement/cover contact in the southwestern and central parts of the restored-state section may be largely an artifact of the balancing procedure as described at the beginning of section 2.3.2.

Section E-E'

Section E-E' (Figure 2.11), from Gabriola Island to Cowichan Lake, displays the strong contrast in structural styles of the southern versus the northern belts. The overall gently homoclinal structure of the Nanaimo Group in the northern belt is locally disturbed by thin-skinned detachment faults and related folds, ultimately linked to thrusts in basement (e.g. Blackjack fault). A triangle zone is created in the central part of the northern belt associated with the Extension anticline near Nanaimo River.

Folding and the occurrence of northeast-verging backthrusts in an otherwise southwest-verging contractional system are illustrated by Clapp (1912c, 1914a) and Buckham (1947) who studied the historically important coal mining area around Nanaimo. Control on subsurface structure is available in this area from seismic, well, and shallow borehole data.

The southern belt structure is fault-dominated, as previously discussed, with 9 thrusts depicted. Footwall splays are associated with the Fulford Fault. The exposed branch points of the diverging Brenton fault with the Fulford Fault, and the Meade Creek fault with the Cowichan Lake Fault, are to the east of this profile. These branch points, therefore, are subsurface on this profile. The McKenzie Bay and possibly the East Robertson faults are footwall splays of the Cowichan Lake Fault. Note the inferred position of the synorogenic surface which indicates that more than 6 km of section has been removed over this part of the map area.

2.2.3 Detachments

Detachments in Wrangellia basement are the dominant control on the development of macroscopic structures. These detachments are present in a variety of plutonic, volcanic, and sedimentary rocks which were variably metamorphosed and deformed prior to CFTB development. No preferred detachment horizon can be identified. The presence of oblique to lateral basement ramps (as indicated by the shape of the basement culminations and best represented in longitudinal sections) clearly indicates a non-homogeneous basement response to stress. On the other hand, the across-strike regular spacing of thrust faults may intuitively suggest a fairly uniform footwall response to stress, more likely to occur in a rheologically more homogeneous basement. Notwithstanding these speculations, the basement has suffered a complex deformation history which has created an overall northwest-southeast structural grain, which controls fault orientation in the CFTB.

Wherever exposed near fault traces, the immediate hanging-wall basement rocks commonly display fault breccias and vein systems, but also local foliation and lineation fabric development. Basement thus shows a rather variable rheological response to thrust development, combining cataclasis and plasticity. Deformation in basement probably took place in a low P, T regime, compatible with the low rank metamorphic indicators observed in the cover rocks (see Chapter 5). Thick zones of pre-existing highly foliated basement tectonites, often of mylonitic aspect, seem to have played an important role in localizing CFTB age thrust trajectories in the Alberni Summit area (section 2.4.3). The extent to which brittle and plastic mechanisms are partitioned in basement within the study area is, however, by no means fully documented, and a detailed mechanical analysis of the thrust system was considered beyond the scope of this study.

The basal unit of the cover sequence, typically a conglomerate or coarse grained sandstone (unit 4, Plate 2a), responds similarly to basement during deformation (see Figure 2.10). In general, the basement/cover interface is unsheared. Unit 5, however, provides a dominant detachment horizon. It acts as an intracutaneous decollement zone, accomodating slip between rigid basal conglomerate and overlying shale which is layer-parallel shortened. This layer-parallel shortening, expressed as cleavage folding, is related to "bulldozing" of the shale by hanging-wall basement (Geiser, 1988). A good example of this is in the footwall of the Fulford Fault at Maple Bay ("M" in centre of

Figure 2.2) where pronounced cleavage in unit 5 is localized to a 0.5 km wide belt adjacent to the fault (Plate 5b); other examples are found in the Mount Prevost area.

Penetrative strain within unit 5 requires that there is brittle contraction along the contacts between units 7, 5, 4 and basement. Some of the faults will root in basement, others may root in cover. In the Nanaimo area, there are excellent examples of partitioning of kinematic responses between units 5 and 7, where unit 5 (shale) shows considerable layer-parallel shortening (with tight folding and associated cleavage development, and minor small-scale thrusting), whereas the overlying base of unit 7 (conglomerate or sandstone) is internally unstrained. Shortening in unit 7 occurred by brittle contraction to accommodate unit 5 layer parallel shortening. The seismic section (Figure 2.10) also shows the contrast in styles of deformation between unit 5 which is clearly folded at surface level, whereas unit 4 and basement show much simpler larger wavelength structures related to the development of hanging-wall ramp anticlines.

In the Nanaimo coalfield, contraction in unit 7 is facilitated by numerous coal seams. Plate 19 is an example of such brittle contraction, where the coal seam has acted as a detachment horizon and has been transformed into a tectonite. Deformation has proceeded by duplexing, and all of the splay faults emanate from plastically thickened pods in the coal seam which acts as the sole of the small duplex. Clapp (1912a, 1914b) discussed in some detail the nature of strain within the coal seams, illustrating his text with several scale drawings of deformed seams. Clapp indicates that although some of the thickness variation of the coal seams can be related to a varying depositional environment, much of it is structurally controlled, as evidenced by slickensided and contorted roof or floor rock, locally overturned roof rock, and variably contorted, slickensided, and plastically swelled seams, in response to northeast-southwest contraction.

2.2.4 Macroscopic fold systems

The various fold systems observed in the CFTB can be described in terms of two general kinematic response groups. Group 1 folds, which are the most common, are fault-propagation folds (Suppe and Medwedeff, 1984; Suppe, 1985). Good examples are present in the upper thrust sheets, where some of the faults which lie in the cores of folds are exposed at the present erosional level, while others, with inferred, blind tip lines, are present in the lower units of the cover sequence. Fold pairs are characteristically asymmetrical and consist (initially) of broad open synclines in the footwall of the propagating fault, and tighter anticlines in the hanging wall. With continued fault propagation, frontal-ramp hanging-wall anticlines develop, and the footwall syncline becomes increasingly deformed in relation to continued layer-parallel shortening ("bulldozer" effect of Geiser, 1988). In the southern belt, deep erosion has breached many examples of these, exposing basement overlying penetratively deformed trailing-edge cover sequences in the underlying footwall sheet Plates 5a, 5b). Trailing-edge synclines in unit 7 in the central southern belt are prominent features of the fault-propagation folding mechanism (Figure 2.9).

Group 2 folds are fault-bend folds (Suppe, 1983) which are inferred to be present in the CFTB. Fault-bend folds have: a) more characteristically flexural-slip style features (i.e. lack of axial planar cleavage, strict class 1b parallel profile, and often kink-style geometry with especially flat crested box fold shapes); and b) undeformed footwalls where footwall ramps exist at specific locations with respect to the hanging-wall ramp anticline geometry. Ideal examples of these in the CFTB are rare (Plate 9b).

The trajectory of the Tzuhalem Fault (Section C-C′, Figure 2.8) with underlying large flat and leading ramp is one possible example, and another example is the inferred geometry of the McKenzie Bay fault (Section E-E′, Figure 2.11).

The rest of the folds observed in the CFTB are of smaller scale. It is apparent that bending of rigid basement and plastic strain in cover must lead to basement/cover and intra-cover detachments as previously discussed. The creation of this detachment style, particularly in the lower cover sequence gives rise to a macroscopic fold group (detachment folds of Dahlstrom, 1970) that has pronounced expression in the central part of the northern belt. In this area, both foreland and hinterland-verging thrusts occur, which represent a brittle response (in competent unit 7 underlain and overlain by more incompetent units) to shortening of the cover as a whole; overall, a complex geometry is developed, with northeast- and southwest-verging folds and thrusts with associated pop-ups and triangle zones (Butler, 1982); however, few of the thrusts to which the folds are associated are considered to breach the basement/cover interface. Other detachments are known in the CFTB which may also be linked to general shortening in cover, specifically the out-of-the-syncline thrust on North Pender Island (Figure 2.7, profile B-B′). Another example of the detachment style, at a larger scale, is the leading splay off the Fulford Fault in the Mount Prevost area, which separates two footwall blocks exhibiting different mechanical responses (Figure 2.9, profile D-D′).

Slaty cleavage and folds with axial planar cleavage typically arise in thrust belts at the leading edges of thrust sheets or at footwall ramps (Plates 5a, 5b, 6a). In the CFTB, cleavage is especially well developed in the latter position (Figure 2.9), but is not observed in leading thrust sheet positions; unfortunately, most of the leading edges of the thrust sheets have been removed by deep erosion. The cleavage folds in the CFTB are related to the deformation mechanism operating to form group 1 folds, and, therefore, are also a kinematic response group, strictly related to intra-cover plastic strain that arises from the development of a broad ductile bead around the thrust's tip line (Hossack, 1983; Geiser, 1988), and is a kinematically important feature of the fault-propagation fold group 1.

Rare, late stage mesoscopic features that are considered to be related to extensional relaxation have been locally observed in the CFTB, on minor thrust faults and in areas of steeply dipping cover rock, particularly in easy glide horizons such as unit 5. Late stage, back-slip folds and intrashear-zone foliation indicating late normal sense of movement are observed in coal seams at three localities in the central northern belt. Minor northeast-dipping faults with a normal sense of shear (as identified by the relation of intrashear-zone foliation orientation to shear-zone boundaries) have been observed in the eastern part of the southern belt. Highly non-cylindrical northeast-verging F_3 minor folds with S_3 cleavage dipping less than S_0 are present in unit 5 at Fulford Harbour in the hanging-wall cover sequence of the Tzuhalem Fault.

2.2.5 Orientation data and kinematic indicators

The great circle distribution of poles to bedding in the cover rocks for the upper thrust sheets of the eastern half of the northern belt illustrates the presence of mainly cylindrical upright fold systems (Figure 2.12). The modest degree of subcylindricity is considered to relate to distortion of the original fold geometry by: a) interference from rigid basement slabs in the footwall, generally leading to back tilting of the leading edges of the thrust sheets; and b) the general curvature of the belt. There is a marked decay in cylindricity, however, in the western part of the northern belt, and the entire southern belt. This is evident in the distribution of poles to bedding lacking clear great circle patterns for orientation data for the central and eastern parts of the southern belt. Figure 2.13 shows a trend towards a non-cylindrical pattern, and Figure 2.14 shows non-cylindricity of data.

Slaty cleavage (S_1) is locally well developed in the southern belt and generally dips steeply northeast (Plate 6a). In central Cowichan Valley, its average orientation is $030^0/64^0$ (dip direction/angle of dip) although it may locally dip to the southwest. The S_1 data measured lie within a cleavage fan dipping 60^0 southwest to 45^0 northeast (Figure 2.15). In the eastern part of the southern belt, the average S_1 planes dip northeast (approximately $038^0/68^0$) but are much more variable (Figure 2.16).

In the eastern part of the northern belt, few minor folds are developed, but the average trend of large fold axes is $116^0/00^0$. In the Cowichan Valley and eastern areas of the southern belt, minor folds are common, their axes plunging variably to the northwest, northeast, and southeast, but never to the southwest (Figure 2.17). The fold system in this belt is clearly macroscopically non-cylindrical, but there is an aspect of a diffuse great circle distribution of axes, indicating that small-scale fold axes lie in a plane which may correlate to the mean cleavage plane for the area, while the diffuse spread across the mean great circle pattern may in fact reflect the S_1 fan. The variable plunge of the folds in the cover is largely related to the presence of lateral, oblique, or frontal basement-culmination walls created by hanging-wall ramps on the underlying thrust fault. For example, at Maple Bay (Figure 2.18) all the minor folds that were measured plunge to the northwest ($315^0/26^0$ approximate average) off the culmination wall of the basement slab exposed to the southeast. Other examples of the association of plunging folds to basement-culmination walls are evident in Figure 2.2. In areas of higher strain, it is also possible that folds have been rotated in the tectonic transport direction. In progressive simple shear, fold axes may rotate within a common S_1 plane, but S_1 itself may vary in dip in relation to accumulated bulk shear strain. In some areas in the eastern part of the southern belt, F_2 folds are observed that deform S_0 and S_1 planes, and have an orientation which allows for their origin to be explained in a progressive simple shear model, as late stage CFTB age features.

Fault orientation data for the eastern area of the southern belt is presented in Figure 2.19. The majority of the faults dip to the northeast with an approximate average orientation of $016^0/54^0$. Slickensides measured on these fault planes describe a general range from 50^0 to 90^0 pitch (from east or west), which is a high angle from the strike of the average fault. This confirms dominantly dip-slip motion of the various fault planes including the Tzuhalem Fault at Cape Keppel (data with solid symbols in Figure 2.19. Unfortunately, the majority of the large fault planes are not exposed due to cover by surficial sediment.

Two areas that have yielded kinematic data aside from that presented in Figure 2.19 are near Mount Prevost and at Maple Bay. Slickensides and fault grooves are at a high pitch (54^0) on a splay of the Fulford Fault in the Mount Prevost area. In the Maple Bay area (Figure 2.18), in the adjacent footwall of the Fulford Fault, the perpendicular to tension gashes on bedding planes (marked "x" in Figure 2.18) is oriented $041^0/55^0$ or about an 86^0 pitch on the adjacent Fulford Fault plane. Also, the plane containing slickensides on bedding (marked "S" in Figure 2.18) would intersect the fault plane at a pitch of 84^0 from the northwest. These two indicators of the direction of maximum elongation suggest dip-slip motion of cover rock in the near footwall of the Fulford Fault. The calculated tectonic transport direction - marked "a" in Figure 2.18 - is northeast to southwest (from 041^0), orthogonal to the trace of the Fulford Fault.

Finally, on the vast majority of minor faults observed in the cover, the steeper orientation of intra-shear zone S_1 foliation, with respect to the boundaries of the shear zones, confirms reverse sense of shear for these shear zones. Furthermore, the observation that generally, bedding is more gently inclined than cleavage, in hinterland-dipping cover sections, is a prominent shear sense indicator for this type of thrust belt.

2.2.6 Discussion

Recognition of a linked fold and thrust system on southeastern Vancouver Island is based on the macroscopic structural geometry of the belt which clearly establishes the genetic relationship between faults and folds developed in a contractional setting, thereby distinguishing it from extensional, transtensional, or transpressional belts. Additional support is provided by small-scale kinematic indicators in fault zones and intrasheet settings. All of the observed structural elements can be explained readily in terms of thrust belt tectonics.

The CFTB is a dominantly orthogonal contractional belt based on: a) parallel, frontal ramp geometry for successive thrust sheets; b) the strike-parallel nature of the strips of cover rock in the thrust sheets; c) the parallel nature of the strikes of the major thrust faults to the large-scale folds; d) the similar orientation of much of the cleavage and axial planes of the minor folds to the thrust-fault planes; e) the pattern of structural repetition of stratigraphic units; f) the lack of en echelon arrangements of thrusts, normal faults, and folds, oriented obliquely to the strike of the major faults; and g) the tectonic transport direction and dominantly dip-slip movement based on small-scale kinematic indicators.

The thrust belt verges to the southwest, based on: a) the northeast dip of all the major thrust faults; b) the asymmetry of several of the large-scale folds (which is a consequence of fault-propagation folding); c) the bow and arrow rule of Elliott (1976); d) the presence of a predominantly northeast-dipping slaty cleavage; and e) that this cleavage almost always is steeper than bedding. The overall southwest vergence of the CFTB is directly related to its position in a large accretionary wedge underlain by a northeast-dipping subduction zone.

The cylindricity of the structures in the cover sequence in the eastern half of the northern belt is considered to be controlled by the parallel basement imbricates, be they blind or emergent, which are, in turn, controlled by the parallel orientation of the frontal basement ramps. On the other hand, the decay in cylindricity in the remainder of the cover sequence in the CFTB is considered to be mostly caused by the development of plunging basement culminations reflecting the presence of lateral to oblique basement ramps on the floor thrusts. In higher strain zones, the decay in cylindricity may also be related to rotation of the axes of minor fold systems toward the thrusting direction during progressive simple shear deformation. Many of the steeply plunging folds are F_2 systems which locally fold both S_0 and S_1, and thus have formed at a later stage during development of the CFTB, probably when beds were already considerably tilted on ramp structures.

Overall, it appears that there must be a large displacement transfer from the stacked basement thrusts in the west to the fewer, thrusts in the east, as evident by the inferred positions of the branch lines in the system and the reduced width of the CFTB in the east. The thrust stack, including the sole fault, thins to the east via a number of oblique to lateral ramps. Note that this imposes a major macroscopic non-cylindricity to the system, the whole thrust system essentially plunging west, except around the eastern flank of the Nanoose culmination. The increased intra-cover strain recognized in the eastern part of the southern belt is probably related to this displacement transfer to higher levels. The sole fault of the CFTB in the east is the inferred eastern extension of the San Juan Fault, which transfers via the Sidney fault, to the President fault. Presumably then, there is significant southward displacement of the southernmost thrust sheet of the CFTB over the San Juan Terrane on the President fault. This is evident from the position of the southernmost basement/cover contact lying well south of the President fault on Sidney Island (A' on Figure 2.2).

The sequence of thrusting is envisaged to be piggy-back style from northeast to southwest. Northeastwards rotation of previously formed folds, steepening to overturning of beds, and refolding (F_2) over steeply plunging axes, are related to in-sequence thrusting of basement slabs to the southwest. The repetition of lower units 4 and 5 of the Nanaimo Group and basement, and the position of the calculated synorogenic surface in the eastern part of the southern belt, strongly indicates the presence of a footwall duplex structure with a low-relief roof thrust in this area. Such a structure is strong evidence of footwall collapse and in-sequence thrusting. In general, however, folding of higher thrust sheets over lower ones is rare. Overall, the thrust system is considered to be a leading imbricate fan based on the recognition of progressively increasing hanging-wall loading to the southwest, which is evidenced by progressively increasing levels of organic maturation in cover rock to the southwest (Chapter 5; England, 1988b).

The thrust trajectories below the basement/cover interface have been drawn so that they join the sole fault at depth in as simple a manner as possible. There are, however, other obvious ways to draw their trajectories which may be equally valid. For example, where the sole fault is deep (sections D-D', E-E'), the faults below the Fulford Fault have been drawn to link up at a shallower depth, in effect becoming propagating footwall splays of the Fulford Fault, thus creating a high-level detachment in Wrangellia crust. Alternatively, these faults may be drawn to link directly with the sole fault of the CFTB.

Shortening at the basement/cover interface has been calculated for the profiles based on initial length between local pin lines measured on the restored-state sections compared to the deformed-state sections: A-A′ is 31% (11.5 km), B-B′ is 30% (11.8 km), C-C′ is 23% (8.6 km), D-D′ is 23% (10.9 km), and E-E′ is 18% (12.0 km). The southeastern profiles show more contraction than the northwestern ones; this apparent regional pattern may not hold up if some faults have not been identified in the western part of the southern belt. As no estimate of shortening can be made for the sole fault itself, these are minimum shortening estimates for the CFTB on the whole.

Overall it appears that the amounts of removed section indicated by the vitrinite reflectance data can be accommodated by a complete section of Nanaimo Group plus basement locally. However, the synorogenic surface does not always correspond to the estimated surface of the top of the Nanaimo Group, indicating a deficit of section if the top Nanaimo Group surface lies below the synorogenic surface, and an excess of section if the top Nanaimo Group surface lies above the synorogenic surface. The latter case demands syn- or preorogenic erosion, or stratigraphic thinning of the Nanaimo Group; the former case demands thickening of the Nanaimo Group.

On section A-A′ there is a pronounced excess of Nanaimo Group in the southwest, from Stuart to Sidney islands, indicating pronounced syn- or preorogenic erosion; whereas, there is little excess from Saturna to South Pender islands. The same pattern shows up on section B-B′: excess section from North Pender Island to the Saanich Peninsula, and compatibility between the top Nanaimo Group surface and synorogenic surface over Mayne Island. On section C-C′, the two surfaces are compatible for the northern belt; whereas, excess section is indicated for the southern belt. On section D-D′, the synorogenic surface is mostly compatible with the top Nanaimo surface; slight excess is indicated in the immediate hanging wall of the Fulford thrust. On section E-E′, excess removed section is indicated between the Cowichan Lake and Fulford faults, the remainder of the section showing compatibility between the synorogenic and top Nanaimo Group surfaces.

The indication of excess Nanaimo Group section in the southeastern and central area of the CFTB is considered to be real, given that the profiles were drawn using minimum displacements on the faults. Several possibilities can account for the excess Nanaimo Group: 1) foreland bulging (and consequent erosion) due to flexural loading in the hinterland during early stages of development of the CFTB; 2) basin margin wedging of the Nanaimo Group due to local unconformities or stratigraphic thinning; 3) thinning of Nanaimo Group over paleo-topographical highs (unit 5 is known to onlap basement locally); or 4) local erosion of Nanaimo Group due to post-depositional, pre- [illegible] synorogenic uplift.

Brandon and co-workers (1988) consider the Nanaimo Basin to be the synorogenic foreland basin to the NCTS; however, this is mostly incompatible with known ages of the Nanaimo Group. The Nanaimo Group is Turonian to Maastrichtian (ca. 90 to 66.5 Ma), the large part being Campanian to Maastrichtian (84 to 66.5 Ma) and clearly is postorogenic with respect to contraction of the San Juan Terrane. Furthermore, Brandon et al. (1988) suggest that the Nanaimo Group may be locally overridden by the leading thrusts of the NCTS, a situation which is not feasible in consideration of the low levels of organic maturation of the Nanaimo Group adjacent to the nappe pile (Chapter 5). In fact, the reverse situation probably exists: the Nanaimo

Group having overthrust the NCTS nappe pile, as was initially suggested by Vance (1977).

Succeeding the deposition of the Nanaimo Group, and preceding development of the CFTB (ca. 66.5-40 Ma), there was a period for which the geological record is incomplete. Renewed basement subsidence resulted in the creation of the Whatcom Basin between the Coast Plutonic Complex and Vancouver Island (Crickmay and Pocock, 1963). Whatcom Basin sediments are deformed but how this deformation relates to deformation of the Nanaimo Group is poorly understood due to lack of data. To the south, the Chuckanut Basin (Figure 1.2) developed during this time as a strike-slip basin (Johnson, 1985). Uplift of source terranes for the Chuckanut Formation is dated as 55-62 Ma (Johnson, 1984). Massey (1986) proposes a transform-dominated margin origin for the early Eocene (56-52 Ma; Berggren et al., 1985) Metchosin igneous complex on southern Vancouver Island. Thus, the early Paleogene may have been a time of instability for the region.

Possible relaxation of thrust structures in the CFTB is locally observed. The cause of these movements is interpreted to be related to gravitational instability, particularly of cover units lying on easy glide horizons, in situations where the hanging-wall cover is steeply homoclinal due to profound basement uplift on the thrust faults, such as at Fulford Harbour, where a possible northeast-verging surge zone is developed in unit 5. Other possible gravitational collapse features are associated with coal seams in the central part of the northern belt. The Outer Islands fault, which forms the western boundary of the Whatcom Basin, may have developed by backsliding on a previous CFTB thrust fault.

The CFTB is essentially a thick orogenic wedge of semicontinental crust. It is hypothesized that such a wedge will contract to compensate for increasing width of the wedge by frontal accretion (Platt, 1986; Davis et al., 1983). The late Eocene contraction may therefore relate to addition of oceanic terranes to the southwestern edge of the wedge, specifically the final accretion of Pacific Rim and Crescent terranes. Local Eocene extension may also be related to orogenic wedge dynamics as a response to overthickening of the wedge by underplating (Platt, 1986) other oceanic terranes.

The structural interpretation of southwestern Georgia Basin and its basement presented in the preceding text is completely different from the prevailing view as presented by Muller and Jeletzky (1970). It has developed by reconsidering the regional geology in the light of deep crustal seismic data (LITHOPROBE; Yorath et al., 1985a). The underlying philosophy is that the structures observed in the region are interrelated (ie. geometrically and genetically linked).

2.3 Detailed structure of the northern province

2.3.1 Main Comox Basin

The northern structural province encompasses much of Comox Basin, the main part of which is a gently northeast-dipping homocline, showing only minor local folding and faulting, in strong contrast to the CFTB. Several high-angle faults occur, typically with less than 200 m of inferred normal dip slip, which strike parallel and orthogonal to the basin axis. Many of these faults are indicated on structure maps of old coal mines (Muller and Atchison, 1971). Although a large part of the coastal plain area is drift covered (Plate 14b), its simple structure is confirmed by seismic data acquired by BP Resources Canada Limited in central and southern Comox Basin in 1984 and 1985.

The long cross-section F-F' (Figure 2.20) extends from Hornby Island to Alberni Valley (Plate 1a), and is constructed in a similar manner as described in section 2.2.2. Minor folding and a normal fault near the surface cut-off of unit 4 are depicted. Note that even using a gentle dip for the homoclinal succession, the extrapolated base of the Nanaimo Group lies above the present erosional surface of the entire Beaufort Range, indicating an enormous amount of erosion since deposition. The elevation of lower Nanaimo Group at Forbidden Plateau (1200-1500 m), northwest of the section, fits very well with its expected elevation, estimated from the profile (just under the words "Beaufort Range"). The normal-fault geometry for the Beaufort Range Fault is based on data presented below.

2.3.2 Western Comox Basin

The western part of the northern province comprises two large outliers of Nanaimo Group, in the Quinsam area in the north, and Alberni Valley area in the south. The Quinsam area is separated from the main basin by the Mount Washington fault which consists of at least three segments from Campbell Lake in the northwest to Mount Washington in the southeast. The dip separation on the main southern segment is on the order of 500-600 m assuming the fault has a near-vertical attitude at shallow depth. Several minor faults also occur, such as those present in the outlier on Forbidden Plateau.

Nanaimo Group in Alberni Valley is distributed in a main, elongate, northwest-southeast trending outlier, and as several small erosional remnants in the southwest (plate 1a). The main outlier is bounded in the northeast by the Beaufort Range Fault, which actually comprises several large fault strands (Beaufort Range Fault Zone = BRFZ), extending from Comox Lake to Alberni Summit. How the BRFZ links to the Mount Washington fault system is unclear, but the two faults occupy similar positions with respect to the main Comox Basin. Linkages between the BRFZ and faults in northwestern CFTB are also uncertain. The northwesternmost faults of the CFTB, which encroach southeastern Alberni Valley, are clearly northeast-dipping contractional faults (Yorath et al., 1985a; Sutherland Brown et al., 1986), yet colinear faults in Alberni Valley are here inferred to be southwest-dipping extensional faults (see below), the transition occurring along an imaginary line drawn from Alberni Summit orthogonally across the main outlier.

2.3.3 Beaufort Range Fault Zone

The evidence for an extensional origin of the BRFZ consists of: a) the overall structural geometry of the fault zone, and in particular the disposition of cover strata across the various fault strands; b) kinematic indicators exposed within fault zones in the Alberni Summit road cut; c) vitrinite reflectance data; and d) the lack of a northeast-dipping axial planar cleavage or southwest-verging folds in the Nanaimo Group in Alberni Valley, and local development of a southwest-dipping cleavage system, inclined steeper than bedding, near the fault zones.

The geometry of the BRFZ is best displayed on a coulisse of vertical sections across the zone, along the length of Alberni Valley (Figure 2.21). The general components of the cross-sections are a series of fault-bounded blocks of basement and basal Nanaimo Group strata interpreted as half-grabens with typically gently northeast-dipping Nanaimo Group, truncated by southwest-dipping listric normal faults. Considerable relief (up to 800 m) has developed on the main fault scarps of the BRFZ. In several of the profiles (A-A′, D-D′, E-E′, F-F′) Nanaimo Group is distributed on several benches within the BRFZ. On some sections (eg. C-C′ and D-D′) there is an overall aspect of macroscopic roll-over into the faults. In several of the half-grabens, prominent open to close hanging wall synclines are present, with high southwest-dips of beds in narrow zones adjacent to the faults. The tightly folded cover sequence in the northeastern part of section B-B'(Figure 2.21) is more difficult to rationalize in this interpretation, but may be some sort of hanging-wall collapse feature. There is a lack of detailed data in this particular area.

Based on the preceding geometrical analysis of the CFTB, thrust faults are characterized by steeply northeast-dipping Nanaimo Group in the near footwall, but southwest-dipping beds do occur in trailing footwall synclines; thus, by itself, the geometry of the footwall (hanging wall in normal fault system terminology) does not distinguish fault type. However, in combination with other aspects (points b, c, d, noted above), an extensional fault interpretation is more acceptable. These aspects are best studied in the exposures of the BRFZ at Alberni Summit.

The best exposure of the BRFZ is the Highway 4 roadcut at Alberni Summit (Figure 2.3), which lies between sections E-E' and F-F' (Figure 2.21). A schematic surface geology map is presented in Figure 2.22. The western (lower) faults, which are strands of the BRFZ, are interpreted to be normal faults. Fault "A" is defined only by rapid changes in dip of unit 6; it is not exposed. S_1 cleavage in the shale west of this fault is $248^0/75^0$ (dip direction/angle of dip) with S_0 at $243^0/60^0$. In general, the lack of a well developed, northeast-dipping slaty cleavage in strata in Alberni Valley proper, which is such a key indicator of overall southwest vergence in the CFTB, is strong evidence against the valley strata being in a footwall situation with respect to notional BRFZ thrust faults.

Fault "B" is exposed as a shaly shear zone, separating unit 4 from basement. The inclination of cleavage in the shear zone with respect to the shear-zone boundaries suggests that this is a normal fault. The lower fault strand is interpreted, based on the map pattern. Vitrinite reflectance of a sample of unit 4 in this bench, 3 km to the northwest, is 0.75 $\%R_0$, in contrast to the much higher levels in unit 4 to the east.

To the east of fault "B", up the road, unit 4 is exposed over a broad area, resting unconformably on basement. S_1 in this block dips to the southwest or northwest, and is consistently steeper than bedding. Five minor normal faults occur along the roadcut, which dip to the northeast and to the southwest, and two minor reverse faults are also present. Fault "C" is a major thrust fault which places Sicker Group on altered conglomerate of unit 4, its contractional nature verified by the inclination of S_1 in the hanging wall with respect of the main fault plane. This relationship of cleavage dipping northeast steeper than the fault planes is also expressed at several other fault planes in the zone. The orientation of intra-shear zone foliation with respect to the shear-zone boundaries also confirms the sense of contraction. Fault "C" is expressed as a zone of deformation about 30 m wide, with several intensely foliated, high strain zones present.

In the basement rock to the east, several shear zones occur, all displaying thrust geometry, based on small-scale structures. At least one small horse is interpreted to occur, which contains the basal unconformity of unit 4. At least 3 minor normal faults also occur in this area.

The thrust system is interpreted to link up with the Cameron River Fault to the southeast, although the linkage is complicated by younger, possibly strike-slip faults which strike to the north (Sutherland Brown et al., 1986). To the northwest, the thrust system is either offset by normal fault "B" or continues to the north towards Lacy and Esary Lakes (N.W.D. Massey, personal communication, 1989).

Coincident with the thrust system are elevated vitrinite reflectance levels in the Comox Formation in the footwall. Regionally, major thrust faults in the CFTB are associated with increased levels of maturation as indicated by vitrinite reflectance data of adjacent footwall strata. It is interpreted that the increased maturation levels are due to burial beneath thrust sheets of basement and Nanaimo Group, *i.e.* tectonic loading. As such, thrust faults in the CFTB can be recognized by increased vitrinite reflectance levels in the footwall, relative to regional vitrinite reflectance levels which are expressed in the hanging wall.

Vitrinite reflectance data from Alberni Valley (Chapter 5) demonstrate that northwest of Alberni Summit, the BRFZ is not a significant thrust fault, because strata in the supposed immediate "footwall" have low levels of vitrinite reflectance. Several of the data are located right in the fault zone. In fact, all of the vitrinite reflectance data from northwest of Alberni Summit show regional levels of maturation, comparable to vitrinite reflectance data from the main Comox Basin. This relationship also holds true for the Quinsam outlier. The data from southeastern Alberni Valley show much higher maturation levels in the footwall of interpreted thrust faults; however, coincident with these locations is the occurrence of Tertiary intrusives which also may have increased the local maturation levels. Thus, in this area, the data do not distinguish between tectonic loading and contact metamorphism. At Alberni Summit, however, away from the influence of Tertiary intrusives, high maturation levels in Nanaimo Group strata persist, possibly indicating tectonic loading.

2.3.4 Discussion

It has been shown that CFTB thrust faults extend to the northwest as far as the Alberni Summit area, as indicated by small-scale kinematic indicators and vitrinite reflectance data at the Highway 4 roadcut (Figure 2.22). Northwest of this area, however, the BRFZ is a normal fault array, in contrast to Dom (1986) and Yorath et al. (1985a) who interpreted the BRFZ, in effect, as a continuation of the

CFTB. Dom (1986) interpreted all of the BRFZ faults as northeast-dipping thrusts. Unfortunately, at the surface, fault-plane exposure is minimal, and those faults that are exposed are generally near vertical. The argument developed below, is that some faults are northeast-dipping thrusts, and others are southwest-dipping normal faults.

Part of the data which guided the interpretation of Yorath et al. (1985a) is from LITHOPROBE line 1, in which the BRFZ and Cameron River Fault are interpreted as northeast-dipping listric thrust faults. The author does not dispute this interpretation; however, these faults are extrapolated to the surface because there is little data in the shallow part of the record section, between 0 and 2 seconds two-way-time, ca. 0-6.5 km subsurface (Clowes et al., 1987). In the author's view, these faults may be decapitated by the normal faults of the BRFZ, which occur at a shallow depth, and probably are strongly listric to the southwest. This relationship is suggested by the map pattern (Figure 2.3), where the Cameron River Fault is apparently truncated by the BRFZ. Whatever the timing, the interpretation presented here, is that the two fault systems developed in significantly different displacement fields.

The northern province of the study area is obviously distinct from the CFTB, based on the preceding analysis. Overall, the surficial structure of the province is characterized by extensional faults with associated minor folding. Some of these faults display strike-slip offset of marker beds suggesting that in detail the displacement field was probably complex. Evaluating the array of minor faults in the province for evidence of transtension or transpression is beyond the scope of this study. Several young faults with apparent strike-slip offsets are known from the Beaufort Range and the Port Alberni Map area (92F/2) which are associated with mineralization (Sutherland Brown et al., 1986; N.W.D. Massey, personnal communication, 1988). How these features relate to the CFTB and the extensional features of the northern province is uncertain, because they lie mostly in basement rock.

It has been demonstrated that the BRFZ is distinct from the CFTB. What has not been addressed is why does the CFTB end in southeastern Comox Basin. There are three possible explanations: 1) the CFTB faults terminate due to decreasing amounts of shortening towards the northwest; 2) the shortening is distributed along an array of smaller faults which have not been identified (horsetail-splay termination); or 3) the shortening is transferred from high in the thrust stack, via a series of branch lines, to deeper structures which lie to the southwest of the study area. Given the orthogonal contraction observed in the main part of the CFTB, rapidly decreasing amounts of shortening along strike to the northwest seem unlikely. Aspects of idea 2 above have some appeal, especially in the Alberni Summit area. Idea 3 is favoured by the author, and has previously been raised at the end of section 2.2.1.1. It elegantly explains why the main part of Comox Basin is undeformed, as the basin is inferred to be riding passively on a deep floor thrust. This idea predicts that large CFTB age thrusts may exist in basement rock southwest of Alberni Valley.

2.4 Regional synthesis

Vancouver Island is part of a broad, late Mesozoic-Cenozoic forearc region, the evolution of which has featured distinct episodes of out-building in the Middle Cretaceous (accretion of Wrangellia) and Paleogene (accretion of the Pacific Rim and Leech River terranes). Interpretation of deep seismic data from LITHOPROBE (Yorath et al., 1985a, 1985b; and Clowes et al., 1987) has illuminated much of the subsurface structure of Vancouver Island, emphasizing the western and deep (i.e. younger) parts of the accretionary wedge; this study has focused on the shallow, southeastern crustal structure of Vancouver Island, in the older part of the accretionary wedge. Contractional deformation is clearly manifested in the study area, in the form of the thick-skinned CFTB.

The CFTB is an orthogonally contracted wedge, featuring well-developed mesoscopic to macroscopic fold systems, and a number of important northeast-dipping thrust faults which root deep in Wrangellian basement and form a large-scale leading imbricate fan. Kinematic indicators at all scales show an overall southwest vergence of the deformed belt. Both fault-propagation and fault-bend folding are evident, the former being more common. Fault trajectories are generally steep at high levels of the system. A moderately northeast-dipping sole fault is inferred by comparison to other faults in Wrangellian crust on Vancouver Island and is partly confirmed by the application of balanced cross-section construction techniques. The sole fault rises to the southeast by a series of oblique to lateral ramps, where it must eventually join the San Juan, Sidney, and President faults. The latter fault probably permitted the Nanaimo Group to overthrust part of the San Juan Terrane. Shortening is an estimated minimum 20-30% (8-12 km) based on tentative line and area balancing of the cover sequence on a series of profiles through the deformed belt. The CFTB was emergent, at least locally, based on the calculation of the position of the synorogenic surface, using vitrinite reflectance data.

In the absence of synorogenic detritus which can be directly tied to the CFTB, it is difficult to date the age of thrusting for certain; it is a small area of a broad accretionary complex that has suffered a long-lived deformation history throughout the Cenozoic. The age of thrusting is younger than the youngest known Nanaimo Group (ca. 68 Ma), and based on thermal history analysis (Chapter 7) and fission tracks of detrital and plutonic apatite from the CFTB (England and Massey, in preparation) probably occurred in late Eocene time coincident with final accretion of the Pacific Rim and Crescent terranes.

The CFTB passes to the northwest into the relatively undeformed northern structural province, the main surficial part of which is characterized by minor normal faults and associated folding. Shortening is presumably accommodated on a deeply buried floor thrust, which gathers displacement from high in the CFTB thrust stack, via a series of branch lines, and transfers it to thrusts that may lie west of the study area. Large extensional faults exist in western Comox Basin, which are known as the BRFZ and Mount Washington faults. These faults are probably related to widespread Eocene extension, although there is some field evidence that suggests they post-date development of the CFTB.

Thus, the structural evolution of the study area which is preferred here can be summarized as Late Cretaceous basin development by lithospheric downwarping (see Chapter 6), local Eocene extension, regional late Eocene contraction, and significant uplift and erosion for the remainder of the Cenozoic. This plausible sequence of events has to be reconciled in any tectonic model hypothesized for this long-lived forearc region (see Chapter 8).

CHAPTER 3

STRATIGRAPHY

3.1 Introduction

During the past 130 years, several stratigraphic studies have been made of the Upper Cretaceous Nanaimo Group. The early work, which is summarized by Muller and Jeletzky (1970), was driven by the need to understand the geology of the coal measures, which were important to the economy of British Columbia, and to assess the significant coal resource remaining in the Nanaimo Group on eastern Vancouver Island. The coal resource was mostly exhausted by the late 1960's after some 72,000,000 tons had been mined (Muller and Atchison, 1971). Since the publication by Muller and Jeletzky (1970), detailed work on the Nanaimo Group has been restricted to thesis research (which includes 15+ Masters theses, and 3 Ph.D. theses); these theses are widely referred to in this thesis. The emphasis in this chapter is placed on description; paleo-environmental interpretations are left to discussions in Chapter 4.

3.2 Lithostratigraphy

As pointed out by McGugan (1979), some of the revisions to the lithostratigraphy of the Nanaimo and Comox basins proposed by Muller and Jeletzky (1970) contravene the rules of stratigraphic nomenclature (American Commission on Stratigraphic Nomenclature, 1970; 1983). Muller and Jeletzky (1970) proposed that several of the formation names of one basin be changed to formation names of the other on the basis of biostratigraphic correlation. Comox Basin formation names that Muller and Jeletzky (1970) replaced by Nanaimo Basin formation names were: lower Trent River Formation replaced by Haslam Formation, upper Trent River

Formation replaced by Cedar District Formation, Denman Formation replaced by De Courcy Formation, Lambert Formation replaced by Northumberland Formation (as revised by Muller and Jeletzky, 1970), and Hornby Formation replaced by Gabriola Formation (Figure 3.1). Furthermore, several Comox Basin names were incorporated into the revised Nanaimo Basin stratigraphy: the Benson Formation was changed to the Comox Formation (the basal conglomerate being named the Benson Member), the middle unit of the Northumberland Formation was changed to the Geoffrey Formation, and the upper unit of the Northumberland Formation was changed to Spray Formation (Figure 3.2).

Simplification of lithostratigraphic nomenclature on the basis of biostratigraphy is not in accordance with correct stratigraphic procedure. It ignores the possibility of diachronous formations, which is highly likely given the extent and large paleobathymetric range of the basin. In this thesis, the formational names established by Clapp (1912b, 1912c, 1914a), Clapp and Cooke (1917), MacKenzie (1922), and Usher (1952) are retained to describe the lithostratigraphy of the Nanaimo Group. These names refer to fundamental mappable units in each basin, and, due to the alternating coarse and fine grained nature of the formations, they can generally be distinguished with ease. Some revisions are proposed as a consequence of more detailed work completed since publication of the early schemes.

In the proposed lithostratigraphic scheme (Table 3.1), references are given to descriptions of the various units, none of which has been formally defined according to the Code of Stratigraphic Nomenclature (American Commission on Stratigraphic Nomenclature, 1970). The nomenclature followed throughout the thesis includes the new and reestablished names of units discussed above. At a later date, all of the lithostratigraphic units of the Nanaimo

Group will be formally defined and supported by type section descriptions.

3.2.1 Comox Basin

In the Comox Basin, the uppermost formation is the Hornby Formation, which is successively underlain by the Spray, Geoffrey, Lambert, and Denman formations, as described by Usher (1952); Oyster Bay formation is introduced by the author for partly equivalent upper Nanaimo Group beds exposed on the coast of eastern Vancouver Island near Oyster Bay.

Underlying the units listed above are the Trent River and Comox formations, as defined by Clapp (1912c), MacKenzie (1922) and Williams (1924). Subdivision of the Comox Formation by Bickford and Kenyon (1988) into the Dunsmuir and Cumberland members should be retained; however, their use of Benson Member for the basal unit should be discontinued as the name Benson is used in the Nanaimo Basin as a formational name. Cottam Point member is a newly proposed name for the basal conglomerate of the Nanaimo Group in the Comox Basin, after Cottam Point near Parksville where the conglomerate is well exposed (England, 1989). Usher's (1952) Qualicum Formation has been shown to overlie the Comox Formation in boreholes drilled in southern Comox Basin and can be traced to the northwest to correlate with the Trent River Formation. Therefore, the Qualicum Formation need not be retained in the lithostratigraphic scheme.

The Trent River Formation locally contains an intermediate conglomerate and sandstone unit which crops out in the area near Langley Lake, north of Tsable River; on lower Bloedel Creek; north of Trent River; and has been intersected in a number of boreholes in the western central part of the basin (Muller and Jeletzky, 1970). It is proposed that this coarse grained unit be named the Tsable member (England, 1989). Muller and Jeletzky (1970) include this unit in the combined "Extension-Protection Formation"; however, the names "Extension" and "Protection" are incorrectly transferred here from the Nanaimo Basin.

In the Parksville area, a prominent polymictic conglomerate underlies Little Mountain, and conglomerate and sandstone outcrop in the Englishman River valley, and along the coast. This coarse grained facies apparently occupies an intermediate position within the Trent River Formation shales, and may be laterally equivalent to parts of the Tsable member; it cannot be traced to the northwest in the subsurface or in outcrop, and is given separate status as the Parksville member (England, 1989).

3.2.2 Nanaimo Basin

In the Nanaimo Basin, the proposed lithostratigraphic nomenclature is as follows, from base to top. Forming the base of the Nanaimo Group is the Benson Formation, as defined by Clapp (1912b, 1914a), which can be subdivided into a basal conglomerate facies, the Tzuhalem member, and a sandstone facies, the Saanich member (England, 1989). The former is named after the prominent exposures on and near Mount Tzuhalem, the latter is named after the extensive sandstone exposures on northern Saanich Peninsula.

Overlying the Benson Formation is the Haslam Formation (Clapp, 1912b, 1914a), which Ward (1978a) divided into the Haslam Creek Member, a massive shale facies exposed on Haslam Creek, and the Cowichan Member, an interbedded sandstone and shale facies well exposed on the Cowichan River.

Overlying the Haslam Formation is the Extension Formation (Clapp, 1912b, 1914a) which Bickford and Kenyon (1988) divided into a lower Northfield member, a siltstone and fine grained sandstone unit overlying the Wellington coal seam and bounded above by the No. 2 coal seam, and an upper Millstream member, a massive lithic conglomerate exposed along the Millstream River. It is herein proposed to downgrade Clapp's (1912b) East Wellington Formation to member status and include it within the Extension Formation as did Muller and Jeletzky (1970). This East Wellington Member is a thin bedded sandstone, less than 15 m thick, which overlies the Haslam Formation and underlies the Wellington coal seam. It is only locally developed in the Nanaimo area and is part of the Nanaimo coalfield sequence.

Overlying the Extension Formation is the Pender Formation (Ward, 1978a) which in the Nanaimo area is divisible into the upper Newcastle Member coal measures (coal, conglomerate, sandstone, and shale), and the lower Cranberry Member sandstone and siltstone (Bickford and Kenyon, 1988), separated by the Newcastle coal seam. Previously, these two members had been described as formations (Clapp, 1914a). Clapp (1914a) placed the base of his Cranberry Formation at the top of the first 25' (7.6 m) conglomerate bed of the Extension Formation. His Newcastle Formation included the Douglas coal seam, which occurs 15 to 75 m below the overlying Protection Formation (Clapp, 1914a).

In the Nanaimo area, the Protection Formation (Clapp, 1914a) is divisible into a lower Cassidy member sandstone and pebble conglomerate, a middle Reserve member comprising coal measures, and an upper McMillan member sandstone (Bickford and Kenyon, 1988).

The Cedar District and the De Courcy formations (Clapp, 1912b, 1914a) successively overlie the Protection Formation and consist of dominantly shale and sandstone, respectively; these formations are distributed widely throughout the basin.

Overlying the De Courcy Formation is the Northumberland Formation, which, as described by Clapp (1914a), consists of widespread shales, which are commonly laterally replaced by medial conglomerate and sandstone. Muller and Jeletzky divided Clapp's (1914a) Northumberland Formation into a lower shale unit, for which they retained the name Northumberland, a middle coarse grained unit which they named the "Geoffrey Formation", and an upper shale succession which they named the "Spray Formation", the latter two formation names coming from Comox Basin nomenclature. The names Geoffrey and Spray, however, have priority in the Comox Basin lithostratigraphic scheme of Usher (1952), and, therefore, cannot be used in the Nanaimo Basin, for reasons already discussed. It is proposed that: a) the name Northumberland be retained for the lower shale which overlies the De Courcy Formation; b) the overlying coarse grained unit be named the Galiano formation after the exposures on Mount Galiano; and c) the succeeding shale unit be named the Mayne formation after the exposures in Miners Bay and Bennett Bay on Mayne Island (England, 1989).

At the top of the Nanaimo Group column in the Nanaimo Basin is the Gabriola Formation, originally defined by Clapp (1912b, 1914a). The Mayne and Gabriola formations locally interfinger; however, at most localities the contact is transitional over a short section.

For much of the remainder of the chapter, the formations of the Nanaimo Group are described. For brevity, detailed locality descriptions have been placed in Appendix B. To follow these descriptions, the reader is advised to obtain 1:50,000 scale topographic maps of the study area (listed in Appendix A). The detailed locality descriptions provide information on along-strike lithological variations within the succession, they substantiate area to area lithostratigraphic correlations, and they provide solutions to existing lithostratigraphic interpretation problems. Furthermore, they provide a framework for future detailed sedimentological studies. Included in the formation descriptions are macrofossil, trace fossil, and microfossil data, which form the basis for much of paleo-environmental interpretation (Chapter 4).

Stratigraphic cross-sections are provided for the upper Nanaimo Group in southeastern Nanaimo Basin and in the central Comox Basin (Figures 3.3 and 3.4). The cross-sections serve to illustrate the scale of the rock units studied, the along-strike continuity of formation boundaries, the degree of exposure, and the typical fossil control available for individual units. Measured sections are provided with the detailed locality descriptions in Appendix B.

3.3 Description of formations - Nanaimo Basin

3.3.1 Benson Formation

The Benson Formation crops out widely on eastern Vancouver Island, from Nanoose Harbour (northwest of Nanaimo) to Hatch Point (southeast of Cowichan Bay, near C' in Figure 2.3), and on northern Saanich Peninsula. It also crops out on some of the Gulf and San Juan Islands. The Benson Formation was defined by Clapp (1912b, 1914a) as the basal conglomerate of the "Nanaimo series" in the Nanaimo area, named after exposures on the northern side of Mount Benson, near Nanaimo. Clapp noted, however, that in some areas the conglomerate grades upward into sandstone that underlies shale of the Haslam Formation. Thick sandstone, intercalated with siltstone and shale, and underlying the Haslam Formation, is well exposed in the southwestern part of the Nanaimo Basin. The conglomerate and sandstone facies can be distinguished readily in the field (Plates 2a, 3a), and are assigned to the Tzuhalem member, and the Saanich member, respectively, as described below.

The Benson Formation is Turonian to Santonian in age, based on the occurrence in the formation of age-diagnostic trigoniid bivalves, gastropods, and ammonites. The basal Benson Formation in southern Nanaimo Basin contain the Turonian gastropods <u>Natica conradiana vacculae n. subsp.</u> and

Gyrodes dowelli, and the Turonian-Coniacian bivalve _Pterotrigonia klamathonia_, which is the index fossil for the herein proposed Klamathonia Zone, underlying the Elongatum Zone). The upper Benson Formation locally contains _Didymoceras (B.) elongatum_ and _Inoceramus naumanni_, index fossils of the Santonian Elongatum Zone (Muller and Jeletzky, 1970). In northern Nanaimo Basin, the Benson Formation locally consists of calcarenite with tabulate coral, bryozoa, and mollusc fragments.

Foraminifers were recovered from upper Benson Formation (Saanich member) at two localities in the basin, which are suggestive of paleowater depths of 20-200 m (Cameron, 1988a, b). The microfossil data, and the occurrences of ammonites and inoceramids, demonstrate that at least part of the formation is deep marine. Other parts of the formation are shallow marine based on the occurrence of naticid gastropods, _Ostrea_, and trigoniids. It is also clear that large parts of the formation are nonmarine, based on the occurrence of autochthonous coal beds in the formation.

The Tzuhalem member is equivalent to Clapp's (1914a) "Benson conglomerates", which he reported to be well exposed in the canyon of Haslam Creek. Clapp (1914a) described the exposures north and west of Nanaimo, and Clapp and Cooke (1917) described the basal conglomerate in the Cowichan and Chemainus river valleys, and at Mount Maxwell on Saltspring Island. The thickest sections of the Tzuhalem member occur on Mount Tzuhalem and on Mount Maxwell, where it locally exceeds 180 m in thickness (Plate 2a). Over much of southern Nanaimo Basin, the conglomerate member is thin, only 2 to 20 m of poorly sorted conglomerate resting on pre-Cretaceous rocks and underlying the Saanich member.

The Saanich member comprises the thick bedded, massive to planar laminated, medium to coarse grained sandstones of the Benson Formation which are especially well developed in southern Nanaimo Basin. Locally, the member contains abundant coal debris, coal seams, and coalified branches and stumps (Plate 4a, and Sections 273 and 351, Appendix B). The most widespread exposure occurs on northern Saanich Peninsula, where tectonic thickening has resulted in a 1.5 km-wide belt extending from Tsehum Harbour to Deep Cove (Sections 293 and 294, Appendix B). A minimum thickness of 350 m is estimated for the member in this area (Section 333, Appendix B). At Hatch Point, on the western side of Saanich Inlet (Figure 2.3), sandstones of the Saanich member are estimated to be more than 500 m thick. In the Mount Tzuhalem area, the member is at least 400 m thick, and near Mount Maxwell, Hanson (1976) estimated the unit to be more than 167 m thick (including his middle mudstone and upper sandstone units). The base of the Saanich member is placed immediately above the highest occurrence of Tzuhalem member conglomerate or above the basal unconformity; its top is placed at the top of the highest sandstone that is 5 m or more in thickness, beneath the Haslam Formation.

3.3.2 Haslam Formation

The Haslam Formation is widely exposed on eastern Vancouver Island from Lantzville to Boatswain Bank, southeast of Cowichan Bay, and on northern Saanich Peninsula (Section 350, Appendix B). It crops out on Saltspring Island, on islands adjacent to the Saanich Peninsula, and on several of the San Juan Islands. Clapp (1912b) introduced the formation name for a homogeneous shale formation occurring in the Nanaimo area, which overlies the Benson Formation and underlies the Extension Formation, and is well exposed on Haslam Creek. South of Nanaimo, the Haslam Formation is composed of thin to medium bedded mudstone, siltstone, and graded, fine grained sandstone. Locally the graded sandstone beds may be coarser-grained (Ward, 1978a). Ward (1978a) subdivided the Haslam Formation into the Cowichan Member, with graded sandstone beds, and the Haslam Creek Member of homogeneous shale. However, this stratigraphic subdivision is of limited use, as the shale and sandstone-rich facies commonly alternate (as recognized by Pacht, 1980); the stratigraphic relationships between the two members that were described by Ward (1978a) and Ward and Stanley (1982) may only be valid locally. Bearing in mind that the Haslam Formation is a prominent detachment horizon in the lower Nanaimo Group (Chapter 2), it is not possible, in general, to be sure of stratigraphic relationships within the Haslam Formation. Also, no complete section is available where both members of Ward (1978a) are developed. What is clear from Ward (1978a), is that the Cowichan Member is well developed in and seems to be restricted to southern Nanaimo Basin.

In the Nanaimo area, the Haslam Formation is about 180 m thick. In southern Nanaimo Basin, the Haslam Formation commonly exceeds 500 m in thickness, and where tectonically thickened, it may be over 1000 m thick based on seismic data and structural cross-sections in Cowichan Valley (Chapter 2).

Haslam Formation is late Santonian to earliest Campanian in age, based on the occurrence of fossils indicative of the Santonian Elongatum Zone and lowermost Campanian Schmidti Zone (Muller and Jeletzky, 1970). The formation locally is very fossiliferous, containing diverse assemblages of ammonites, pelecypods, nautiloids, gastropods, and brachiopods. The specific macrofossils occurring in the formation are described by locality in Appendix B. The author collected macrofossils from the Haslam Formation at 18 localities in the basin. Microfossils are also abundant in the Haslam Formation. Over 30 localities yielded foraminifers, which generally are indicative of paleo-water depths of 100-600 m (Cameron, 1988a, b) .

3.3.3 Extension Formation

The Extension Formation crops out widely on eastern Vancouver Island, from Lantzville to Cowichan Valley, and on the inner Gulf Islands and San Juan Islands. The name Extension was introduced by Clapp (1912b) for a conglomerate formation with minor shale, sandstone, and coal, which is typified by outcrops near the town of Extension. The lithostratigraphic nomenclature remained as described by Clapp until Muller and Jeletzky (1970) erected "Extension-Protection Formation" encompassing and demoting many of Clapp's Nanaimo coalfield formations to member status. Since then, Ward (1978a) subdivided the "Extension-Protection Formation" by raising to formation status a distinct, intermediate, fine grained interval - the Pender Formation - and resurrecting the separate Extension and Protection formations. Bickford and Kenyon (1988) divide the Extension Formation into two members: the basal Northfield member coal measures, and upper Millstream member conglomerate, which is barren of coal. In this study, it is proposed to include Clapp's (1912b, 1914a) East Wellington Formation as the lowest member of the Extension Formation (as did Muller and Jeletzky, 1970), rather than considering it as a member of the underlying Haslam Formation as did Usher (1952). Thus, the Extension Formation, where it is fully developed, encompasses 3 members in the Nanaimo vicinity: the basal East Wellington Member, medial Northfield member, and upper Millstream member.

The East Wellington Member consists of fine grained to granule sandstone, and is up to 47 m thick (Bickford, 1986). The Northfield member comprises shale, siltstone, fine grained sandstone, and coal, and is up to 30 m thick (Bickford and Kenyon, 1988); in this thesis, it includes the Wellington and Little Wellington (or No. 2) seams. The Millstream member consists of thick bedded, massive conglomerate and granule sandstone, with minor coal and siltstone, and is about 120-150 m thick (Bickford and Kenyon, 1988). Outside of the Nanaimo vicinity, the Extension Formation is generally not subdivided, and consists mostly of thick bedded, polymictic, pebble to boulder conglomerate and medium to coarse grained sandstone (Plate 6b). In southern Nanaimo Basin, the Extension Formation is up to 480 m thick (Pacht, 1980).

The age of the Extension Formation is established as early Campanian, by the occurrence of lowermost Campanian Schmidti Zone index fossils in the East Wellington Member and underlying Haslam Formation, and by the occurrence of uppermost lower Campanian Chicoensis Zone index fossils in the overlying Pender Formation. The East Wellington Member is locally fossiliferous in the Nanaimo area, containing a variety of pelecypods and gastropods. Rare fossil shells also occur in upper Extension Formation in the Nanaimo area (Bickford, 1986). On Saltspring Island, pelecypods, gastropods, and brachiopods are present in the lower and middle Extension Formation (Haggart, 1988a; Hanson, 1976). Ward (1978a) recovered Inoceramus elegans in the Extension Formation at the Cusheon Creek section. Shelly zones occur in the uppermost Extension Formation on North Pender Island, and the Extension Formation is locally highly fossiliferous on the San Juan Islands (Ward, 1978a; McClellan, 1927). Ward (1978a) suggests that the Extension Formation on Orcas, Waldron, and Skipjack islands is within the Schmidti Zone. Only one foraminifer has been recovered from an Extension Formation outcrop in the upper Chemainus River area (Cameron, 1988a).

3.3.4 Pender Formation

The Pender Formation is a dominantly fine grained formation which crops out on several of the Gulf and San Juan islands, and on eastern Vancouver Island. The formation name was introduced by Ward (1978a) for a distinct body of generally thin bedded, fossiliferous mudstone, siltstone and fine grained sandstone lying between the Extension and Protection formations. The formation is equivalent to Clapp and Cooke's (1917) Ganges Formation, and part of their Duncan Formation (Table 3.1). In the Nanaimo area, the Pender Formation includes two heterogeneous members: the Cranberry and Newcastle members. These members were originally introduced as formations by Clapp (1912b), and later were subordinated to member status by Muller and Jeletzky (1970).

The Cranberry Member comprises thin bedded, fine to coarse grained, locally pebbly sandstone, interbedded with sandy shale and minor conglomerate, overlying the Extension Formation. The Newcastle Member is a coal-bearing sequence overlying the Cranberry Member and underlying the Protection Formation. It consists of pebble conglomerate, fine grained to granule sandstone, siltstone, shale, and coal, including the basal Newcastle, upper Douglas, and Douglas Rider seams (Bickford and Kenyon, 1988). Outside of the Nanaimo coalfield, the Cranberry and Newcastle members shale out into more typical, fine grained Pender Formation (Plate 7b). According to Clapp (1912b) and Usher (1952), the thickness of the Cranberry Member ranges from ca. 45 to 185 m; the Newcastle Member ranges from ca. 40 to 120 m. The Pender Formation in southern Nanaimo Basin is locally over 320 m thick.

Macrofossils are locally abundant in the Pender Formation, as indicated by McClellan (1927), Usher (1952), Hanson (1976), and Ward (1978a). Based on ammonite biochronology, the Pender Formation is late early Campanian in age (Ward, 1978a), as Chicoensis Zone index fossils are well represented in the formation.

Microfossils are also abundant in the Pender Formation. Foraminifers were recovered from eight samples of Pender Formation collected from the Cowichan Valley area, Saltspring Island, and Pender Islands. The microfauna indicate paleo-water depths of 150-1200 m (Cameron, 1988a, b).

3.3.5 Protection Formation

The Protection Formation crops out on eastern Vancouver Island between Nanaimo and Ladysmith, near Chemainus, and in Cowichan Valley. It also crops out on Saltspring, North and South Pender islands, Waldron Island, and on a group of small islands east of Sidney. The Protection Formation was introduced by Clapp (1912b) for a ca. 200 m-thick, distinctive, light grey sandstone formation on Protection Island near Nanaimo. It consists of thin to thick bedded, medium to very coarse grained sandstone, commonly cross-bedded, intercalated with planar laminated, fine grained sandstone, siltstone, and rare mudstone and coal (Section 76, Appendix B). The formation becomes conglomeratic in the Cowichan Valley area (Plate 7a, and Section 30, Appendix B). The type area for the Protection Formation is the Nanaimo coalfield.

Age diagnostic macrofossils have not been recovered from the formation, but its age is bracketed closely by the overlying upper Campanian Cedar District Formation and the underlying lower Campanian Pender Formation (Ward, 1978a); thus, the formation is mid-Campanian.

In the Nanaimo area, the Protection Formation is divisible into a lower Cassidy member of sandstone and conglomerate (Section 90, Appendix B), a middle Reserve member comprising coal, sandstone, and shale, and an upper McMillan member sandstone (Bickford and Kenyon, 1988). This subdivision is useful for borehole correlation in the Nanaimo coalfield, but is not used in this regional study.

Invertebrate fossils have been found in the Protection Formation despite statements to the contrary (Ward, 1978a). Inoceramids and other pelecypods have been reported by Clapp and Cooke (1917), Usher (1952), and Hanson (1976), and shell debris is noted in the formation by Fahlstrom (1981) and Bickford (1986). In addition, fossil plants have been collected from the Protection Formation (Bell, 1957). Foraminifers have also been collected from an equivalent of the Protection Formation in the upper Chemainus River area, suggesting paleo-water depths of 20-50 m (Cameron, 1988b).

3.3.6 Cedar District Formation

The Cedar District Formation crops out on eastern Vancouver Island southeast of Nanaimo from Harmac to Ladysmith Harbour, and on the Shoal Islands near Crofton (Section 40, Appendix B). The formation is exposed on many of the Gulf Islands, including Thetis, Saltspring, Mayne, Saturna, and the Pender islands, and is also exposed on Little Sucia Island to the southeast. The term Cedar District was introduced by Clapp (1912b) for the dominantly shale and mudstone formation that overlies the Protection Formation and underlies the De Courcy Formation in the lower Nanaimo River area near the town of Cedar. The Cedar District Formation typically consists of thin bedded silty shale, siltstone, and fine grained sandstone, or massive to crudely laminated silty shale (Plate 8a); in southern Nanaimo Basin, minor conglomerate and sandstone beds occur. The unit commonly bears calcareous concretions. Thicknesses are variable, ranging from 300 m in the Harmac area, to almost 500 m on the Pender Islands. Much of the variability in thickness may be attributed to complex interfingering contacts with the adjacent De Courcy and Protection formations. Apparently thicker sections of Cedar District shales were penetrated in the Yellow Point, and Saturna No. 1 wells - 615 and 638 m respectively; however, these exceed the true thicknesses because of structural dip. Locally, the Cedar District Formation is expected to be tectonically thickened (Chapter 2).

Macrofossils are locally abundant in the Cedar District Formation, including upper Campanian ammonites and inoceramids, other pelecypods, and gastropods (Muller and Jeletzky, 1970). Both Vancouverense and Pacificum Zones are widely represented in the Cedar District Formation. On Little Sucia Island, the Cedar District Formation may also include part of the Suciaensis Zone. Trace fossils observed in the Cedar District Formation include Thalassinoides, Helminthoida, and indistinct burrows. References are made to these occurrences in the locality descriptions (Appendix B).

Diverse and abundant foraminiferal assemblages of middle Campanian age have been recovered from the Cedar District Formation at Dodds Narrows (Sliter, 1973), and in the Saturna No. 1 well (McGugan, 1981). Samples collected by the author at 20 localities yielded foraminifers in varying abundances, and of variable diversity. Cameron (1988a, b) interprets most of the foraminifers to be indicative of paleo-water depths of 200 to 600 m; the remainder are indicative of paleo-water depths of 30-200 m. Much down-slope transport is indicated for the deeper water assemblages.

Distinguishing the Cedar District Formation and De Courcy Formations is problematical in areas where they are both represented by interbedded coarse and fine grained facies. In their type areas, the De Courcy and Cedar District formations are uniformly coarse grained and fine grained, respectively. In the southern Gulf Islands, where upper Cedar District Formation contains numerous sandstone units and lower De Courcy Formation contains numerous mudstone units, it is difficult, at isolated sections, to assign formation names. Using the term "Cedar District-De Courcy transition" facilitates field mapping in these areas. However, where possible, the formations should be distinguished, for they do have different stratigraphic positions. The main body of the Cedar District Formation overlies the Protection Formation, and the main body of the De Courcy Formation underlies the Northumberland Formation. Sandstones in lower Cedar District Formation are clearly Cedar District Formation, and shales in upper De Courcy Formation are clearly De Courcy Formation, unless it can be demonstrated that the units in question are merely interbedded tongues of their respective formations.

3.3.7 De Courcy Formation

The De Courcy Formation is exposed widely in the Gulf Islands, and forms a broad outcrop belt in eastern Vancouver Island, southeast of Nanaimo, stretching from Jack Point in Nanaimo Harbour (Section 100, Appendix B), to Coffin Point near Ladysmith Harbour (Section 104, Appendix B). The formation was introduced by Clapp (1912b) for a thick sandstone unit exposed in the De Courcy Islands (Plate 8b). The formation overlies the Cedar District Formation and underlies the Northumberland Formation. Typically, the De Courcy Formation comprises thick bedded, medium to very coarse grained sandstone, with fine grained sandstone, siltstone, and mudstone interbeds, and minor conglomerate and pebbly sandstone. Formation thickness ranges from about 300 m at Harmac, to over 450 m in the southern Gulf Islands. However, complex interfingering relationships of De Courcy sandstone with adjacent shale formations locally complicates definition of the formation, and probably contributes to the variability of its thickness.

The De Courcy Formation is dated as late Campanian, as it is bracketed by the underlying lower upper Campanian Cedar District Formation and the overlying upper upper Campanian Northumberland Formation. The De Courcy Formation thus lies between the older Vancouverense and Pacificum Zones, and the younger Suciaensis Zone (Ward, 1978a). Ward proposed a barren interzone for De Courcy time; however, fossils are known from the De Courcy Formation, despite earlier statements to the contrary (Muller and Jeletzky, 1970). Trace fossils are reported in the formation by Simmons (1973), Sturdavant (1975), Hanson (1976), and Stickney (1976). Also, inoceramids have been noted by Sturdavant (1975) and Hanson (1976), and Stickney (1976) found Pachydiscus sp. in De Courcy mudstone near St. John Point, Mayne Island. Rinne (1973) found a shell-bearing concretion in the De Courcy Formation in the Yellow Point area. Furthermore, foraminifers were recovered from five samples taken in fine grained facies of the De Courcy Formation, most of which are sparse, low diversity faunas, indicating paleo-water depths of 100 to 300 m (Cameron, 1988a, b).

3.3.8 Northumberland Formation

The Northumberland Formation crops out throughout the Gulf Islands. It generally consists of recessive, grey, silty shale interbedded with thin, very fine grained sandstone and siltstone, and minor thick bedded, medium to coarse grained sandstone (Plates 10a, b, and Sections 168 and 251, Appendix B). The thickness of the formation varies from less than 100 m on Parker Island to greater than 350 m in the Samuel Island area. The Northumberland Formation is defined by Muller and Jeletzky (1970, p. 27) as the shale beneath the middle conglomerate member of Clapp's (1914a) "Northumberland" Formation. It overlies the De Courcy Formation and underlies the Galiano formation.

The age of the Northumberland Formation is late Campanian based on the occurrence in the formation of index fossils for the Suciaensis Zone (Muller and Jeletzky, 1970) and age diagnostic foraminifers (McGugan, 1979; Cameron, 1988a, b). The formation is variably fossiliferous, and has yielded ammonites, pelecypods, gastropods, and brachiopods to a number of collectors referred to by locality in Appendix B. Microfossils are generally abundant and diverse. The author collected samples from 14 localities which yielded microfossils, some with highly diverse and abundant foraminifers (Cameron, 1988a, b). Cameron reports that the microfauna indicate paleo-water depths of 100-1200 m.

3.3.9 Galiano formation

The Galiano formation crops out extensively in the Gulf Islands, where it consists of thick bedded, medium to coarse grained sandstone and pebble to cobble conglomerate, and associated finer-grained beds (Plates 11a, b, and Sections 156 and 170, Appendix B). In the sandstone dominant areas, conglomerate forms lenses and fills channels within thick pebbly sandstone and sandstone beds. Galiano replaces the name "Geoffrey" as used by Muller and Jeletzky (1970) to identify the middle coarse grained unit of Clapp's (1914b) Northumberland Formation. It overlies the Northumberland Formation and underlies the Mayne formation. The formation varies in thickness from 150 m on Gabriola Island to over 550 m thick on northern Saturna Island.

Inasmuch as no age diagnostic fossils have been found in the Galiano formation, its precise age is uncertain. However, it lies between two well dated units - the Maastrichtian Mayne formation and the upper Campanian Northumberland Formation - thus indicating a latest Campanian-early Maastrichtian age for the unit, within the Suciaensis Zone (Muller and Jeletzky, 1970).

Fossils have been found in the Galiano formation, but they are rare. Inoceramid shells are present in the Galiano formation at two localities on Saltspring Island (Hanson, 1976), and fossil leaves occur in the unit on southeastern Samuel Island (Stickney, 1976). Inoceramids also occur in lower Galiano formation on southwestern Samuel Island. Many trace fossils have been reported, including Thalassinoides and Zoophycus?, mostly in sandy facies of the Galiano formation on Mayne, Saturna, and North Pender islands (Hudson, 1974; Sturdavant, 1975; and Stickney, 1976).

3.3.10 Mayne formation

The Mayne formation crops out in a generally continuous belt around Gabriola Island, and then is exposed as a single belt to the southeast down Valdes Island, where it eventually lies under water off the southern end of Valdes Island. The formation reappears at Montague Harbour, continues inland on southern Galiano Island, and then is offset to the south on a transverse fault trending from Georgeson Bay to just west of Salamanca Point. The formation continues under Active Pass, coming onshore between Miners Bay and Bennett Bay, Mayne Island. To the southeast, it is covered by Georgia Strait, and lies in Tumbo Channel between Tumbo Island and Saturna Island. Northwest of the Saturna Island Indian Reserve, a basal tongue of the Mayne formation is exposed on Saturna Island, and the unit was intersected in a coal exploration hole drilled on Tumbo Island (Blakemore, 1910). The Mayne formation is also brought to the surface in the core of a tight syncline trending from Otter Bay, North Pender Island, to Ellen Bay and Annette Inlet, Prevost Island, to Long Harbour, Saltspring Island.

The Mayne formation consists of thin bedded, brownish-grey siltstone and grey mudstone, with fine grained sandstone and locally coarser-grained sandstone interbeds (Plate 12b). "Mayne" replaces the name "Spray" as used by Muller and Jeletzky (1970) to describe the upper shale unit of Clapp's (1914b) Northumberland Formation. It overlies the Galiano formation and underlies the Gabriola Formation. At Miners Bay and Bennett Bay on Mayne Island, the formation is 220 m and 340 m thick, respectively. Between Saturna and Tumbo islands the unit is estimated to be about 280 m thick. In the northwestern part of the Nanaimo Basin, the Mayne formation is much thinner; it is measured to be about 100 and 110 m thick at two localities on northern Gabriola Island (Sections 156, 166, and 167, Appendix B).

Fossil evidence clearly places the Mayne formation in the Maastrichtian stage. The macrofossil evidence is as follows. The author collected Inoceramus kusiroensis from the Descanso Bay section (Section 156, Appendix B) which ranges from lower to upper Maastrichtian in California and Alaska (Haggart, 1988a). At Bennett Bay, Mayne Island, the author collected Diplomoceras? sp. indet. which is probably uppermost Campanian to lower Maastrichtian (Haggart, 1988a). Usher (1952) collected Pseudophyllites indra and Pachydiscus suciaensis from the base of this section, near Paddon Point, Mayne Island, both Suciaensis Zone fossils which range from uppermost Campanian to Maastrichtian (Muller and Jeletzky, 1970). A specimen of P. indra, almost 0.6 m in diameter, was also collected from the upper part of the Miners Bay section, Mayne Island, by Stickney (1976).

Foraminifers representing a Maastrichtian microfauna were collected by McGugan (1979) from the Descanso Bay section, Gabriola Island; from the Montague Harbour section, Galiano Island; and from the Miners Bay section, Mayne Island. The author collected high diversity microfaunas of Maastrichtian age from Bennett Bay and Miners Bay sections on Mayne Island, and from Descanso Bay and Leboeuf Bay sections on Gabriola Island; sparser microfaunas were collected from the exposures at Long Harbour, Saltspring Island (Cameron, 1988a, b). Cameron interprets paleo-water depths ranging from 100 to 800 m for the suite of samples collected by the author. McGugan (1979) reported much shallower paleo-water depths for foraminifers recovered in a suite of samples from Descanso Bay, Montague Harbour, and Miners Bay, placing these microfaunas in inner to outer shelf environments based mainly on a diversity range model of Murray (1973, as cited by McGugan, 1979); the remainder of his evidence is equivocal. The studies by McGugan (1979,

1981) and those of his students are in general at odds with more recent ideas (Cameron, 1988a, b) concerning paleoenvironmental analysis.

3.3.11 Gabriola Formation

The Gabriola Formation crops out in an arcuate belt from Gabriola Island in northern Nanaimo Basin to Tumbo Island in southeastern Nanaimo Basin. The unit was defined by Clapp (1912b) with reference to Gabriola Island outcrops. In general, the unit is dominated by massive, thick bedded, coarse grained sandstone interbedded with fine grained sandstone, intercalated with sections of thin bedded siltstone and mudstone (with rare pyrite nodules, according to Carter, 1976). Maximum exposed thicknesses of the Gabriola Formation are over 390 m on Tumbo Island (Plate 13a), over 500 m on Mayne Island, over 1150 m on Galiano Island, and over 350 m on Gabriola Island (Section 167, Appendix B).

The Gabriola Formation is clearly Maastrichtian, based on age diagnostic foraminifers recovered from samples taken from outcrops between Orlebar and Tinson points on northern Gabriola Island (Plate 13b). These samples contain a very high diversity fauna (Cameron, 1988b). In addition, a sample from Sturdies Bay, southern Galiano Island, yielded foraminifers compatible in age with the Gabriola Island assemblage. Also, poorly preserved, large ammonites were collected from the Gabriola Formation at the head of Campbell Bay, Mayne Island, identified by Usher (1952) as probably Pachydiscus suciaensis. The contact of the Gabriola Formation with the underlying Mayne formation is transitional, sharp, or interfingering.

Foraminiferal assemblages in the samples from northern Gabriola Island indicate paleo-water depths of 600-1200 m (Cameron, 1988b). Carbonized wood, fish teeth, and fish bones are also common in the samples. The absence of planktonic foraminifers, and the large amount of down-slope transported material, suggests a fairly high energy environment (Cameron, 1988b). Small bivalve shells are present in the Gabriola Formation, on the western side of Pilot Bay on Gabriola Island, and Crickmay and Pocock (1963) reported the occurrence of <u>Inoceramus</u> in Gabriola Formation. Foraminifers recovered from southern Galiano Island are indicative of a paleo-water depth of close to 200 m (Cameron, 1988a). Pyritic residue present in this sample may indicate reducing conditions during deposition.

3.4 Description of formations - Comox Basin

In the Comox Basin, the lithostratigraphic nomenclature remains mostly as established by Clapp (1912c), MacKenzie (1922), Williams (1924), and Usher (1952). The tripartite subdivision of the Comox Formation, as described by Bickford and Kenyon (1988), is useful, except that the basal conglomerate member should not be named the Benson Member for reasons described earlier. The new name selected for the basal conglomerate in the Comox Basin is the Cottam Point member. In addition, upper Nanaimo Group beds exposed along the coast of Vancouver Island in the Oyster Bay-Shelter Point area, are referred to as the Oyster Bay formation (Table 3.1).

3.4.1 Comox Formation

The Comox Formation is the basal unit of the Nanaimo Group in the Comox Basin. The main outcrop belt extends from Campbell Lake in the northwest to Deep Bay in the southeast, along the coastal plain of Vancouver Island. The formation also forms isolated outcrops in southeastern Comox Basin and the Alberni Valley area, except for the upper Ash River and Alberni Summit areas, where it is exposed more continuously. The formation name was introduced by Clapp

(1912c) for Richardson's (1873) division A, the productive coal measures of the Nanaimo Group. Where fully developed, the formation comprises basal conglomerate, medial coal measures, and upper sandstone units, termed the Cottam Point, Cumberland, and Dunsmuir members, respectively. The Comox Formation ranges from 0 to 650 m in thickness (Muller and Jeletzky, 1970).

The Cottam Point member unconformably overlies basement and is overlain by finer-grained members of the Comox Formation, or by the Trent River Formation. It typically consists of poorly sorted, clast supported, cobble to boulder conglomerate (Plate 14b). The upper contact of the member is the top of the highest conglomerate bed that is thicker than 5 m, underlying the Cumberland member, Dunsmuir member, or Trent River Formation. MacKenzie (1922) noted that the unit infills a paleosurface with considerable relief (> 130 m) and as a result shows rapid local changes in thickness.

Overlying the Cottam Point member is the Cumberland member which consists of from 30 to 150 m of shale, siltstone, and 3 major coal seams (Bickford and Kenyon, 1988), the thickest coal seam locally exceeding 7.5 m (MacKenzie, 1922). Sandstone and siltstone are associated with the coal seams, and commonly form the roof rock of the seams. These lithologies locally contain shell debris.

Succeeding the Cumberland member is the Dunsmuir member which comprises 120 to 150 m of thick bedded, medium grained sandstone, with thin interbeds of shale and coal (Bickford and Kenyon, 1988). Intraformational conglomerate also occurs in the Dunsmuir member.

The Comox Formation is dated as probably Santonian on the basis of palynomorphs (Crickmay and Pocock, 1963). Naumanni Zone ammonites and inoceramids occurring in the upper Comox Formation date these beds as upper Santonian (Muller and Jeletzky, 1970). However, Comox Formation may be younger locally, where it lies on paleotopographic highs.

Microfossil samples taken by the author yielded no marine indicators, or foraminifers indicative of paleo-water depths of 0 to 200 m (Cameron, 1988b).

3.4.2 Trent River Formation

The Trent River Formation underlies the broad coastal plain from the Campbell River area to the Parksville area, western Denman Island, and part of western Texada Island. Due to thick drift cover, however, most exposures are restricted to river cuts or wave-cut terraces. Despite limited exposure, there is reasonable control on distribution of the formation afforded by numerous coal exploration boreholes (Muller and Atchison, 1971) and limited seismic data (BP Canada Resources Limited). The formation name was introduced by Clapp (1912c) for shales overlying the Comox Formation. The Trent River Formation consists of thin bedded, laminated or massive shale, locally interbedded with fine grained sandstone (Plate 16a), with at least two coarse grained members - the Parksville and Tsable members. No complete section is available, but the formation is at least 1000 m thick in the Denman Island area, based on map interpretation. In borehole BP#10, over 600 m of the formation was penetrated.

The coarse clastic beds within the Trent River Formation in the Tsable River area, north of Trent River, and on lower Bloedel Creek are assigned to the Tsable member. They were first noted by MacKenzie (1922), who recognised thick conglomerate and sandstone interbeds in the Trent River Formation between Trent River and Cumberland, and between Union Bay and Langley Lake. Muller and Jeletzky (1967) called these beds Tsable River conglomerate, but in later publications assigned them to the Extension-Protection Formation. The Tsable member typically consists of poorly sorted, polymictic conglomerate, intercalated with pebbly mudstone and pebbly sandstone.

Distinguishing the Tsable member from possible tongues of the Comox Formation in the lowermost part of the Trent River Formation may be problematical in some areas. Only where the coarse grained facies can be shown to be surrounded by the Trent River shale should it be considered as Tsable member.

The Parksville member is a new lithostratigraphic term to describe the pebble conglomerate and sandstone beds in the Comox Basin that occur within the Trent River Formation shales near Parksville (Plate 15a, and Section 112, Appendix B). The beds are obviously discontinuous at outcrop scale and at map scale, and are considered to be coarse grained lenses within the Trent River Formation (Plate 14a). Thick drift cover, and limited subsurface control hinder detailed definition of individual units. Aside from probable thrust-repeated sections in the Northwest Bay area (Sutherland Brown and Yorath, 1985), they appear to occupy several stratigraphic levels within the shales. Based on lithology, fossiliferous lower sandstone beds in southeastern Craig Bay, and sandstone east of Wall Beach, east of Parksville, may be correlated to the East Wellington Member of the Extension Formation occurring at Lantzville. Other units of the Parksville member, however, occupy different stratigraphic positions.

The age of the Trent River Formation is late Santonian to late Campanian, based on occurrence in the formation of Elongatum, Schmidti, Chicoensis, Vancouverensis, and Pacificum Zone index fossils (Usher, 1952; Muller and Jeletzky, 1970; Ward, 1978a). As such, the formation is the same age as much of the lower Nanaimo Group in the Nanaimo Basin: parts of the Trent River Formation are coeval with the Haslam, Extension, Pender, Protection, and Cedar District formations. However, as the coarse grained formations, which are so widespread and continuous in Nanaimo Basin, are mostly absent in Comox Basin, it is not possible to subdivide the Trent River Formation over most of the Comox Basin. Coarse grained units in the Trent River Formation are restricted to a few discontinuous members developed in the Parksville and Tsable River areas.

Macrofossils are locally abundant in the formation, including inoceramids, other pelecypods, ammonites, and gastropods (Usher, 1952; Muller and Jeletzky, 1970; Ward, 1978a), and a recently discovered plesiosaur (R. Ludwigsen, personal communication, 1989). Microfossils are common throughout the Trent River Formation, collections having been made by McGugan (1964), Langhus (1968), Scott (1974), Sliter (1973), and the author. Scott (1974) collected samples from several localities in the Comox Basin, which are suggestive of a relative range in paleo-water depth of shallow to deep. Sliter (1973) considers foraminiferal assemblages from the Trent River Formation to indicate a range in paleo-water depths of 200 to 1000 m. Samples collected by the author yielded foraminifers indicative of paleo-water depths of 50 to 1200 m (Cameron, 1988b).

3.4.3 Denman Formation

The Denman Formation crops out on Denman, Chrome, and Hornby islands, and Norris Rocks. The formation name was introduced by Williams (1924) for Richardson's (1873) Lower Conglomerate subdivision of the Nanaimo Group. The formation comprises thick bedded sandstone and conglomerate, with minor siltstone and mudstone. The age of the formation is late Campanian, as it overlies Trent River Formation that contains upper Campanian fossils, and underlies Lambert Formation with uppermost Campanian to Maastrichtian fossils. Based on map interpretation, the formation is 300-400 m thick.

The subdivision of the Denman Formation into three members by Allmaras (1978) is followed in this thesis. The lower member consists of thick to very thick bedded, fine to medium grained sandstone, interbedded with siltstone and mudstone. The middle member comprises medium to thick bedded conglomerate and fine to medium grained sandstone, with minor siltstone and mudstone (Plate 16b). The upper member comprises thick bedded, planar laminated, fine to medium grained sandstone, with medium interbeds of siltstone and mudstone.

Macrofossils are rare. Richardson (1873) collected an ammonite and pelecypod from Norris Rocks. Allmaras (1978) reported the occurrence of indistinct gastropods, inoceramids, and ammonites in the formation, and both the author and Allmaras have observed horizontal and vertical burrows in the Denman Formation. Microfossils have not been recovered from the formation.

3.4.4 Lambert Formation

The Lambert Formation is exposed on eastern Denman Island and western Hornby Island, and underlies much of Lambert Channel. The formation name was introduced by Williams (1924), and is equivalent to Richardson's (1873) middle shale subdivision. There is much confusion in the literature with regard to the northwestern Hornby Island exposures of the Lambert Formation, as a direct result of the paper by Muller and Jeletzky (1970), wherein the authors suggested that upper Lambert Formation on northwestern Hornby Island is actually the Spray Formation. This necessitated placing a fault between northwestern Hornby Island "Spray" Formation and the overlying, older Geoffrey Formation. In fact, the Geoffrey Formation clearly stratigraphically overlies the Lambert Formation, and is stratigraphically overlain by the Spray Formation, on both the northern and southern coasts of Hornby Island. There is little evidence of a large fault occurring between the Lambert and Geoffrey formations on northwestern Hornby Island, as pointed out by Fiske (1977). Furthermore, upper Lambert Formation is lithologically distinct from the Spray

Formation exposed on southeastern Hornby Island. Further discussion of the problem is presented by McGugan (1979, p. 2266). The northwestern Hornby Island section of upper Lambert Formation contains most of the Suciaensis Zone fossil localities in the Comox Basin, and due to the confusion in nomenclature, many sections that have been correlated to the "Spray" Formation (eg. Richards, 1975) should instead correlate to upper Lambert Formation.

Based on map interpretation, the formation may be up to 400 m thick. Its age is late Campanian to early Maastrichtian based on the occurrence of abundant upper Campanian and lower Maastrichtian fossils (Usher, 1952; McGugan, 1964; Muller and Jeletzky, 1970).

The formation is richly fossiliferous locally, containing a variety of well preserved ammonites (14 species), pelecypods (seven species), gastropods (six species), and nautiloids (Usher, 1952). This is in stark contrast to the Spray Formation which is sparsely fossiliferous. A variety of trace fossils occur in the Lambert Formation (Plates 17a, b, 18a) including Planolites and Teichichnus (Allmaras, 1978).

Foraminifers are also abundant and diverse in the Lambert Formation (McGugan, 1964; Sliter, 1973). Based on foraminifers recovered from 22 samples of the Lambert Formation on northwestern Hornby Island, McGugan (1964) determined that the Campanian/Maastrichtian boundary lies at about Manning Point. McGugan also recovered foraminifers from the Lambert Formation on eastern Denman Island, placing these beds in the upper Campanian. According to Sliter (1973) foraminiferal assemblages in 12 samples from the Norman Point area on southwestern Hornby Island are indicative of paleo-water depths of 300-400 m; whereas, foraminiferal assemblages in 43 samples collected from northwestern Hornby Island are indicative of paleo-water depths of 500-600 m. In addition, the author collected a sample at Manning Point, which yielded foraminifers indicative of paleo-water depths of 150-300 m (Cameron, 1988b).

3.4.5 Geoffrey Formation

The Geoffrey Formation forms prominent Mount Geoffrey on Hornby Island, and crops out on the northern shore of the island from 0.5 km west to 1.1 km southeast of Shields Point, and on the southern shore between Sandpiper Beach and 1 km northeast of Norman Point. The formation forms high bluffs along the southwestern shore between Shingle Spit and Ford Cove. Typically, the Geoffrey Formation consists of thick bedded, massive, pebble to cobble conglomerate, and interbedded sandstone (Plate 18b). The formation name was introduced by Usher (1952), replacing "Hornby" Formation of Williams (1924), and "Middle conglomerate" of Richardson (1873). Based on map interpretation, the formation is ca. 170 m thick on the northern shore, and 230 m thick on the southern shore, but on Mount Geoffrey it is 400-500 m thick. These thickness variations point to a channel-shaped morphology, with the basal contact of the formation having considerable relief (200+ m). Recognition of this geometry provides an adequate explanation of the map pattern, where mudstone of the underlying Lambert Formation on northwestern Hornby Island strikes right into Geoffrey Formation conglomerate. Previous authors have interpreted the contact as a northeast-southwest trending fault (Muller and Jeletzky, 1970); however, there is no evidence for a fault in the outcrop along the northern shore, and no such fault is observed along trend on Denman Island to the southeast.

The age of the Geoffrey Formation is Maastrichtian, as it overlies the uppermost Campanian to lowermost Maastrichtian Lambert Formation, and underlies the Maastrichtian Spray Formation. Usher (1952) reports some macrofossils from cobbles of the conglomerate, but these are reworked.

3.4.6 Spray Formation

The Spray Formation crops out on Hornby Island, from 1 to 2.9 km southeast of Shields Point on the northern shore, and from Sandpiper Beach to the beach north of Spray Point on the southeastern shore, and underlies the lowland areas in between. The formation name was introduced by Usher (1952), replacing "Tribune" Formation of Williams (1924) and "Upper shales" of Richardson (1873). The formation consists of thin bedded siltstone and mudstone, intercalated with thick to thin bedded sandstone, up to 290 m thick. The age of the formation is Maastrichtian based on foraminifers collected by McGugan (1964). Macrofossils are very rare. Usher (1952) reports the occurrence of shell debris in a conglomerate lens on the northern shore of the island, and Crickmay and Pocock (1963) report Inoceramus sp. from the formation. A microfossil sample collected from Sandpiper Beach yielded a sparse foraminiferal assemblage, probably representative of paleo-water depths of 0-30 m (Cameron, 1988b).

3.4.7 Hornby Formation

Overlying the Spray Formation is the Hornby Formation which crops out on eastern Hornby Island. The formation name was introduced by Usher (1952), replacing "St. John" Formation of Williams (1924) and "Upper conglomerate" of Richardson (1873). The formation comprises thick bedded, massive sandstone and conglomerate, ca. 170-245 m thick (Usher, 1952; Fiske, 1977), and is probably Maastrichtian, because it conformably overlies the Maastrichtian Spray Formation. The only macrofossils reported from the Hornby Formation are belemnites which occur in the basal sand member (Richardson, 1873; Usher, 1952). Poorly preserved trace fossils occur in the formation, at Whaling Station Bay.

3.4.8 Oyster Bay formation

The Oyster Bay formation is introduced here for upper Nanaimo Group beds cropping out along the coast at Oyster Bay, and between Shelter Point and 1.5 km northwest of Willow Point. The beds are lithologically similar to the Spray Formation but are locally richly fossiliferous. They consist of thick to medium bedded, medium to coarse grained sandstone, and pebble to cobble conglomerate, intercalated with fine grained sandstone and siltstone. Richards (1975) correlated the beds to upper Lambert Formation (the "Spray" Formation of Muller and Jeletzky, 1970).

3.5 Biostratigraphy

The biostratigraphy of the Nanaimo Group has developed over the past 100 years largely through the efforts of the Geological Survey of Canada (Richardson, 1872; 1873; Whiteaves, 1879; 1903; Clapp, 1912a; 1913; Clapp and Cooke, 1917; Usher, 1952; and Muller and Jeletzky, 1970). The biostratigraphic scheme erected by Muller and Jeletzky (1970) represents a coherent analysis of extant macrofossil data. It is based on range zones and teilzones of the numerous inoceramid and ammonite species occurring in the Nanaimo Group. Ward (1976a; 1978a) revised Muller and Jeletzky's biostratigraphic zonation to include two more biozones, based on further collecting. The scheme presented by Ward (1978a) is used in this thesis, with the addition of one more biozone - the Klamathonia Zone. Klamathonia Zone is proposed for that part of the lower Nanaimo Group in southern Nanaimo Basin which contains <u>Pterotrigonia klamathonia</u>. According to Jones (1960), <u>P. klamathonia</u> is indicative of Turonian to lower Coniacian strata on the western coast of North America. The author collected P. klamathonia from Hamley Point on Sidney Island, and on Goudge Island, adjacent to the Saanich Peninsula (Haggart, 1988a, b). At Hamley Point, co-occurrence of the gastropods Natica conradiana vacculae and Gyrodes dowelli limit the beds to the uppermost Turonian (Popenoe et al., 1987). On Goudge Island, co-occurrence of Pterotrigonia evansana limit the beds to the lower Coniacian (Jones, 1960).

The pterotrigoniids are restricted to marginal marine sandy deposits (P.D. Ward, personal communication, 1989), which are widespread in the basal Nanaimo Group in southern Nanaimo Basin. There are indications, however, that some of the deeper marine strata in southern Nanaimo Basin, previously assigned to the Elongatum Zone, instead belong to older biozones (P.D. Ward, personal communication, 1989). Further collecting hopefully may result in the discovery of Turonian-Coniacian inoceramids or ammonites which may aid in defining the Klamathonia Zone in these deeper water facies.

The macrofossil biozonation of the Nanaimo Group, which is more precise than extant microfossil biozonation of the group (McGugan, 1964; 1979), is used in this study for estimation of absolute ages of specific formations. This is important for subsidence and thermal history modeling (Chapters 6 and 7). No radiometric ages are available yet for the Nanaimo Group, although tonsteins have been noted in some coal seams in the Comox Basin (W. Kilby, personal communication, 1989); these may furnish age constraints in the future.

Detailed summaries of all fossil occurrences in the Nanaimo Group are provided in Tables 3.2 and 3.3 for the Nanaimo and Comox basins, respectively. These data provided the basis of the biostratigraphic zonation of the Nanaimo Group.

Index fossils for the Klamathonia Zone have already been discussed. The zone has only been recognized so far in the Benson Formation. The apparent absence of the zone in northern Nanaimo Basin and the Comox Basin suggests that the Georgia Basin initially developed in the south.

Overlying the Klamathonia Zone in the Nanaimo Basin is the Elongatum Zone, named after the local range of Didymoceras B. elongatum. The zone is recognized at 25 localities in the Benson and Haslam formations, and has been identified at 13 localities in the Trent River Formation. Two subzones have been identified in the Elongatum Zone: a) the Naumanni Subzone, based on the local range of Inoceramus naumanni, and occurrence of Eupachydiscus perplicatus and Polyptychoceras vancouverense; b) succeeded by the Haradai Subzone, based on the local range of Eupachydiscus haradai.

Overlying the Elongatum Zone is the Schmidti Zone, identified by local ranges of Inoceramus schmidti and Pachydiscus (Canadoceras) multisulcatus. The Schmidti Zone has been recognized at 13 localities in the Haslam and Extension formations, and seven localities in the Trent River Formation.

The succeeding zone is the Chicoensis Zone, identified by the local range of Baculites chicoensis, Submortoniceras chicoense, and partial ranges of Inoceramus subundatus, I. vancouverensis, and Canadoceras newberryanum. It is recognized at seven localities in the Pender Formation, and three localities in Trent River Formation. Some of the B. chicoensis specimens reported by McClellan (1927) and Usher (1952) are not B. chicoensis in the sense of Ward (1978b); B. chicoensis, according to Ward, has a much shorter local range than recognized in the earlier studies.

The overlying zone is the Vancouverense Zone, identified by the local ranges of Hoplitoplacenticeras vancouverense, H. plasticum, and Baculites inornatus, and partial range of Canadoceras newberryanum. It is suggested to be present at seven localities in the Cedar District Formation, and at only two localities in the Comox Basin - one in the Trent River Formation, the other in the Oyster Bay formation.

The Pacificum Zone succeeds the Vancouverense Zone, and is identified by local ranges of Metaplacenticeras pacificum and Baculites rex. The zone is recognized at only one locality in the Trent River Formation, and four localities in the Cedar District Formation. Both the Vancouverense and Pacificum Zones are largely covered by drift in the Comox Basin.

The Suciaensis Zone is the youngest zone recognized in the Nanaimo Group. It is identified by local ranges of Pachydiscus suciaensis, Pseudophyllites indra, Pachydiscus ootacodensis, and Diplomoceras notabile. It is recognized at six localities in the Lambert, Denman, and Oyster Bay formations; and at seven localities in the Northumberland, Mayne, and Gabriola formations. The zone is long-ranging - uppermost Campanian to Maastrichtian - and is 1 and 2 km thick in the Comox and Nanaimo basins, respectively. As such, it may be possible to establish a more precise subdivision of the upper Nanaimo Group, but given the paucity of macrofossils, the scheme may have to rely on foraminiferal zonation.

Correlation of Nanaimo Group biozones to international stages is based on inter-regional correlation of important zonal fossils (Muller and Jeletzky, 1970). In some cases, however, the local range (i.e. Teilzone) of a given fossil in the Nanaimo Group does not express the full range (i.e. complete biozone) of the fossil elsewhere; a situation which must be considered in inter-regional correlation (Ward, 1978a). Ward (1978a) provides the most up to date discussions on inter-regional correlation of Nanaimo Group biozones. These correlations, with the additional correlation of the Klamathonia Zone according to Jones (1960), are summarized in Figure 3.5.

Chapter 4

REGIONAL FACIES ANALYSIS

4.1 Depositional Environments

A broad spectrum of nonmarine to deep-marine depositional environments are interpreted for lithofacies developed in the Nanaimo Group. Early studies focused on the coal measures, thus, historically, the large part of the group was interpreted as nonmarine. The nonmarine facies are, in fact, subordinate to the marine facies in both areal extent and volume of sediment. A marine origin for the fine grained formations was never debated because typically they contained abundant macrofossils; it is the intervening coarse grained formations that have been problematical.

Muller and Jeletzky (1970) interpreted the coarse grained formations as fluvial, lagoonal, and deltaic deposits, and the fine grained formations as nearshore and offshore marine deposits. They viewed the succession as a series of transgressive cycles, each cycle displaying a progression from fluvial to marine facies as listed above.

Much of the thesis research by students at Oregon State University during the period 1972-1981 promoted a deltaic origin for the bulk of the coarse grained formations, and hypothesized that the cyclicity in the Nanaimo Group resulted from deltaic progradation and abandonment; the coarse grained deposits being prograding fluvial, delta-plain, and delta-front deposits; the fine grained formations being delta slope and prodelta deposits (Packard, 1972; Simmons, 1973; Hudson, 1974; Sturdavant, 1975; Stickney, 1976; Carter, 1976; Fiske, 1977; Allmaras, 1978; and Fahlstrom, 1981). Carter (1976) suggested that marine tongues within the coarse grained formations resulted from rapid and frequent marine transgressions. Hanson (1976) also supported a deltaic origin for coarse grained formations on Saltspring Island, except for the Extension Formation which he interpreted as a piedmont-plain deposit. Hanson recognized, however, that the prodelta sediments must have been deposited in lower neritic to upper bathyal water depths. Kachelmeyer (1978) interpreted the basal Benson Formation as fluvial or high-energy littoral deposits and the upper Benson Formation as fluvial, lagoonal, tidal flat, and barrier bar deposits. He interpreted a low energy marine to prodeltaic environment for the Haslam Formation, and a braided river environment for the Extension Formation.

Fundamental to the deltaic interpretation is that the coarse grained formations are fluvial or shallow-marine deposits. The proponents of the deltaic hypothesis maintain that the succession contains all the markings of a delta or fan-delta distributary system. However, Pacht (1980; 1984) recognized that many of the coarse grained formations are deep marine in origin, based on detailed sedimentological analysis. Ward and Stanley (1982) also described submarine-fan deposits in the Haslam Formation in southern Nanaimo Basin.

In fact, the Nanaimo Group contains a very broad spectrum of deposits, from alluvial fan to deep marine, including coastal-plain, fan-delta, barrier-bar, and submarine-fan facies (England, 1988a). The larger part of the group, however is deep marine, including many of the coarse grained formations. The recognition of a much larger paleobathymetric range (and locally much steeper paleoslopes) for the basin, and the much more heterogeneous nature of the basin fill, casts doubt on the depositional model of Muller and Jeletzky (1970) which they liken to megacyclothems in the Upper Cretaceous of Utah. The Nanaimo Group has closer analogs with various Upper Cretaceous flysch deposits on the Pacific coast of North America, which represent sedimentation in active forearc settings.

4.1.1 Trace fossils

The concentration in this thesis, with respect to facies analysis, is on the marine facies, which comprise most of the exposures of the Nanaimo Group. In examining the marine facies, it was noted that well preserved trace fossils are widespread. An understanding of the distribution and morphology of ichnogenera within a succession can be a powerful tool in facies analysis; this is the case for the Nanaimo Group.

Attention to the presence of trace fossils in the Nanaimo Group was initiated through detailed studies by graduate students from Oregon State University (Table 4.1). In addition, trace fossils are recognized by the author at 30 localities, which are referred to in the formation descriptions in Chapter 3 and Appendix B. Advice and consultation on the author's tentative identifications were obtained from Dr. G. Narbonne at Queen's University, Kingston.

Previously unreported ichnotaxa observed by the author are: _Macaronichnus_ (Plate 15b), _Paleophycus_, _Ophiomorpha_ (Plate 3b), _Phycodes_, _Ancorichnus_ (Plate 17a), _Cladichnus_, ?_Granularia_, and ?_Helminthopsis_. The most common trace fossils in the Nanaimo Group are _Thalassinoides_ (Plate 17b) and meniscate burrows, some of which may be more than 0.5 m long. According to Narbonne (personal communication, 1989), some of the branching meniscate burrows may be distinct at the specific or possibly generic levels.

Trace-fossil distribution can be useful in discriminating paleo-environments; however, many of the observed forms are known to cross facies in their world-wide distributions. These include: _Ophiomorpha_, _Planolites_, _Chondrites_, _Helminthoida_, _Teichichnus_, _Thalassinoides_, _Taenidium_ (Plate 18a), _Scolicia_ (Plate 12a), and _Granularia_ (Frey and Howard, 1970; Chamberlain, 1978; and Seilacher, 1978). Even forms that are commonly restricted to specific environments such as Zoophycus and Diplocraterion, locally have considerable range in distribution (Frey and Howard, 1970; Crimes, 1977). Nevertheless, what is important is the significance of the local distribution of trace-fossil assemblages.

To assess the local paleo-environmental significance of trace fossils observed in the Nanaimo Group, they are arranged according to biofacies of increasing paleo-water depth (Table 4.2), as determined from foraminiferal assemblages described in section 4.1.4. Shallow-water traces can thus be distinguished from deep-water traces. Shallow-water biofacies 1 features Ophiomorpha, Macaronichnus, and Skolithos; whereas, biofacies 4 and 5 feature ?Granularia, Cladichnus, Chondrites, Scolicia, ?Helminthopsis, and Ancorichnus. The rest of the forms occupy a broad range of biofacies. The usefulness of such a table can only be assessed by more detailed study. In fact, as has been found in other analyses of ichnotaxa (eg. Frey and Howard, 1970), there likely is more to be gained with respect to paleo-environmental analysis from understanding the range in morphology of individual trace fossils, rather than the distribution of ichnotaxa. For example, Chamberlain (1975, as cited by Hanson, 1976) states that Thalassinoides with well developed branches commonly intersecting at 120^0 angles are typical of shallow-water facies; whereas, longer and less regularly branching forms are more common in deep-water facies.

Aside from the obvious usefulness in discriminating deep- from shallow-water facies of the Nanaimo Group, the trace fossils are important in three other ways. First, they confirm the marine origin for many of the coarse grained formations that may be devoid of other marine indicators, and that have previously been interpreted as nonmarine. Second, the associations of ichnogenera provide independent evidence that much of the Nanaimo Group is actually deep marine. Third, representatives of the

Skolithos, Cruziana, and Zoophycus ichnofacies are present; whereas, the Nereites association is not present (see Frey and Pemberton, 1984), thereby suggesting that abyssal deposits probably are not developed in the exposed Nanaimo Group.

Comparison of ichnotaxa in the Nanaimo Group to ichnotaxa reported from Upper Cretaceous abyssal fan deposits in Alaska (McCann and Pickerill, 1988), shows that only 8 of the 38 Alaskan ichnotaxa occur in the Nanaimo Group. Furthermore, a similar comparison to Eocene deep-sea fan deposits in Spain (Crimes, 1977) shows an absence in the Nanaimo Group of many of the Spanish deep-water trace fossils. The low diversity ichnofauna of the Nanaimo Group is similar to the ichnofauna reported from the Upper Cretaceous Chatsworth Formation of California (Bottjer, 1981). Bottjer ascribes the low diversity, in part, to reduced concentration of organic matter, and frequent erosion, on a sand-rich, steep-sloped, rapidly deposited submarine fan.

4.1.2 Facies associations

One of the objectives of this study is to document the succession of marine lithofacies that exist in the Nanaimo Group, and to establish paleo-environments for these deposits, based on microfaunal, macrofaunal, and sedimentological grounds. Since the focus of the thesis is not sedimentology, the rocks are mainly described in terms of facies associations; these are groups of co-occurring facies which are considered to be environmentally or genetically related (Reading, 1978). What follows are <u>regional</u> assessments of environments of deposition based on general features normally found in these environments and general principles of interpreting the sedimentary record as described by Reading (1978) and Selley (1988).

The major contribution to understanding regional marine facies associations in the Nanaimo Group is the paleo-environmental analysis of 130 assemblages of foraminifers collected by the author from the Nanaimo Group (Cameron, 1988a, b). Most important are the foraminifers recovered from fine grained interbeds within the coarse grained formations, which tightly constrain possible paleo-environmental interpretations of these deposits. Paleo-water depths are assigned to assemblages of foraminifers based on the normal distribution of these foraminifers in modern environments and well documented ancient successions (see van Hinte, 1978). However, other factors such as oxygen levels, salinity, temperature, substrate type, and turbidity can greatly bias foraminiferal distribution; hence, absolute paleo-water depth values must be used with caution (Cameron, 1988a).

The Nanaimo Group is subdivided into 6 facies associations (Table 4.3). Three are nonmarine facies associations: paralic facies association **P**; fluvial facies association **B** (mostly braided river deposits); and alluvial facies association **A** (mostly fan deposits). The remaining three are marine facies associations: littoral and upper neritic facies association **L**; middle neritic facies association **M**; and lower neritic and bathyal facies association **S**. The marine lithofacies associations correspond to foraminiferal biofacies that are ordered by increasing paleo-water depth. Facies association **L** corresponds to biofacies 1, facies association **M** corresponds to biofacies 2, and biofacies 3, 4, and 5 are found in facies association **S** (Table 4.3). Macrofossil data are compiled from many sources which are listed in Tables 3.2 and 3.3. Although average grain size decreases from facies associations **A** and **B** (sediment source region) to **S** (basin centre), a large amount of coarse resedimented material also occurs in facies association **S** which is described as a subfacies association $\mathbf{S_F}$.

4.1.3 Nonmarine facies associations

Paralic facies association P

Nonmarine facies association P generally consists of thin bedded, massive or planar laminated, very fine to fine grained sandstone, siltstone, shale, and coal. The siltstone and shale are carbonaceous, and contain rare shell debris. Large coalified tree stumps occur, which are up to 0.3 x 0.6 m in profile, and commonly have intact root systems. The coal seams, in general, are laterally extensive, and less than 2 m thick. Some coals up to 7.5 m thick do occur locally in the Comox Basin (MacKenzie, 1922). Rare lenses or thick beds of medium to coarse grained sandstone and minor conglomerate are present locally. These coarse grained units commonly have abundant coalified log and branch imprints, and feature trough cross-bedding to ripple cross-lamination.

Nanaimo Group coals have appreciable amounts of sulphur, with averages of 0.4% for the Wellington seam (n=7), 1.0% for the Newcastle seam (n=1), 0.5% for the Douglas seam (n=4), and 1.6% for seams in the Comox Formation (n=9) (Muller and Atchison, 1971). Also, the Comox Formation coals at Quinsam range from 0.8 to 1.1% sulphur (S. Gardner, personal communication, 1987).

Facies association P is spatially associated with coarse grained fluvial deposits of facies association B, and is typically overlain by thick bedded, massive sandstone of facies association L, interpreted as barrier-bar deposits (Muller and Atchison, 1971). Specific examples of superjacent marine deposits are referred to in Chapter 3 for the Newcastle and Douglas coal seams (Pender Formation), and for coal seams in the Comox Formation at Cumberland and Quinsam.

The sedimentology of coal measures, world-wide, places some constraints on the depositional environment of Nanaimo

Group coals. Coal deposits associated with barrier bars are generally of low quality, laterally discontinuous, high in sulphur content, and only a metre or two thick (Wanless et al., 1969; Horne et al., 1978; Staub and Cohen, 1979), although some backbarrier coals up to about 3.5 m thick have been reported by Cotter (1982). Lower delta-plain coals have greater lateral continuity, but are still thin (Horne et al., 1978). In contrast, upper delta-plain coals and other paludal coals are generally of higher quality, thicker, and low in sulphur content (Bustin et al., 1983; Casagrande et al., 1977). Low relief coastal-plain coals are laterally extensive, and may be thick (Wanless et al., 1969; Bustin et al., 1983). Thus, based on sulphur content, average thicknesses, and association with marine lithofacies, most Nanaimo Group coals are probably of coastal-plain origin. Some of the less continuous seams may be backbarrier or interdeltaic coals. The local, thicker coals, may have been deposited in a rapidly subsiding portion of a mid- to lower delta plain.

Facies association P is interpreted to have been deposited in a coastal environment, which possibly includes interdeltaic, backbarrier, and coastal-plain settings. It comprises large parts of the Comox Formation in the Comox Basin (Figure 2.4), and occurs in the Benson Formation on Saanich Peninsula and adjacent islands (Figure 2.3, Plate 4a, and Sections 273 and 284, Appendix B). It is well developed in the Extension, Pender, and Protection formations in the Nanaimo area (Figure 2.3).

Fluvial facies association B

Nonmarine facies association B generally consists of well-stratified, poorly sorted, pebble to cobble conglomerate, pebbly sandstone, and medium to coarse grained sandstone. Planar and trough cross-bedding and numerous channel scours are common. The conglomerate beds usually contain cross-bedded sandstone lenses. Marine indicators are absent. Facies association **B** is spatially associated with facies associations **P** and **A**.

Based on the grain size (dominance of gravel and sand size grains over silt and clay size grains) and apparent lack of levee and overbank deposits, these are probably braided-river and braid-plain deposits (Rust and Koster, 1984). Pacht (1980) determined that fluvial deposits in the Nanaimo Group compared favourably with the Scott River and Platte River braided river types of Miall (1977). The Scott River type features flood gravels and minor cross-bedded sand bars; the Platte River type features mainly cross-bedded sands deposited from migrating longitudinal and linguoid bars, and thin channel lag gravels.

Fluvial facies association **B** is present in the Benson Formation on Saanich Peninsula (Section 333, Appendix B), and on Saltspring Island at Mount Maxwell; in the Extension, Pender and Protection formations in the Nanaimo area; and in the Extension Formation on South Pender Island (Plate 6b). Facies association **B** is also present in the Comox Formation in the Comox Basin.

Alluvial facies association **A**

The alluvial facies association in the Nanaimo Group consists of thick to very thick bedded, pebble to boulder conglomerate, pebbly sandstone, and poorly sorted coarse grained sandstone. The conglomerate is generally massive or crudely stratified, and clasts are characteristically angular to sub-angular. Typically, it is clast supported, with a sparse, granule sandstone matrix, but the matrix is muddy locally. Marine indicators are absent.

Based on the extremely coarse grain size, and poor sorting, these are probably alluvial-fan or talus deposits. Radial paleo-flow patterns have not been identified in any one deposit, and the deposits are not associated with a recognizable fault scarp. Thus, it is probably more appropriate to refer to these deposits as piedmont deposits. Facies association A is commonly spatially associated with facies association B, probably representing the proximal and distal portions of an alluvial system.

Examples of facies association A in the Nanaimo Group are found in the Cottam Point member in the Comox Basin; the Tzuhalem member at Mount Tzuhalem and Mount Maxwell (Plate 2a) and in the Nanaimo area; and the Extension Formation on southeastern Waldron Island (Pacht, 1980), South Pender Island, and in the Nanaimo area.

4.1.4 Marine facies associations

Littoral and upper neritic facies association L

Facies association L mainly consists of three facies: a) medium to coarse grained sandstone - L_1; b) fine grained sandstone and siltstone - L_2; and c) conglomerate - L_3.

Facies L_1 consists of medium to thick bedded, medium to coarse grained, well to moderately sorted sandstone, featuring abundant high-energy sedimentary structures such as planar and trough cross-bedding, bidirectional cross-bedding, numerous channel scours (up to 4 m deep), large reactivation surfaces, and symmetrical and asymmetrical ripple marks. Very large crossbed sets up to 7 m high by 60 m long are developed locally (Plate 13a). Planar laminated sandstone is also developed. Commonly present are isolated shell debris or coquinas which typically include robust pelecypods; floating, rounded cobbles or gravel lags; and shale rip-up clasts. Conglomerate lenses are common. Very thick, amalgamated channelized deposits are locally developed in this facies.

Facies L_2 consists of thin to medium bedded, fine grained sandstone, siltstone and subordinate massive shale. Coal debris, pelecypod shells, and small concretions are commonly abundant. Bioturbation is prevalent. Rare floating cobbles occur. Rare shallow-water, graded deposits also occur in this facies.

Facies L_3 consists of thick bedded, massive or poorly stratified, poorly sorted, pebble to boulder conglomerate. The conglomerate is either clast supported, with a sparse, gritty sandstone matrix, typically bearing abundant shell debris (normally robust shells), or it is supported by a medium grained sandstone matrix, with numerous sandstone lenses. Usually, the clast supported conglomerate contains angular to subrounded clasts; locally very large clasts (3 to 4 m across) are present. The matrix supported conglomerate contains more rounded clasts, and is locally normally graded. Commonly, the conglomerate beds are lenticular, and rest on well-developed scour surfaces (Pacht, 1980).

Microfossils in facies association L constitute biofacies 1 of Cameron (1988a). Planktonic foraminifers are absent, and benthic foraminifers are of low diversity, but are usually present in abundance; they include simple agglutinated forms, Ammobaculites, Haplophragmoides, Trochammina, miliolids, small infrequent species of Gavelinella, Cibicides (or related attached forms), polymorphinids, and small weakly ornamented nodosarids (Cameron, 1988a). Microfossil residues include abundant terrigeneous material - plant tissue, megaspores, coal debris, fish teeth and bone, and abundant ostracods of low diversity (Cameron, 1988a).

Macrofauna present in biofacies 1 include diverse pelecypods, gastropods, and a few brachiopods, including Pterotrigonia, Ostrea, Glycymeris, Spondylus, Modiolus, Lima, Pecten, Inoceramus (specifically schmidti and vancouverensis), Rhynchonella, Natica and Gyrodes. Echinoid and barnacle fragments, bryozoa, and tabulate corals, are locally present. Ward's (1976a) Pterotrigonia association - dominantly infaunal suspension feeding organisms, with subordinate gastropods and deposit-feeding pelecypods - is a key indicator of this facies association.

Trace fossils present in biofacies 1 are large Ophiomorpha, Macaronichnus, Skolithos, ?Asterosoma, Planolites, Paleophycus, Helminthoida, and Thalassinoides.

Facies association L is interpreted to have developed in a littoral to upper neritic environment, in water depths of 0 to 30 m based on foraminiferal assemblages. Facies L_1 is interpreted to possibly represent mixed fan delta, beach, nearshore bar, and tidally influenced shallow shelf deposits. Facies L_2 is interpreted to possibly represent low energy littoral, shallow shelf, or estuarine deposits. Facies L_3 is interpreted to possibly represent coarse fan delta, nearshore bar, beach, and talus deposits.

Examples of facies L_1 are the Oyster Bay formation at Shelter Point; the Dunsmuir member in the Cumberland area; the Parksville member at Madrona Point (Plates 15a, b, and Section 112, Appendix B); the Newcastle Member and the Protection Formation in the Nanaimo area; the Protection Formation on Round Island; the Saanich member on northern Saanich Peninsula and adjacent islands (Plate 3b) and on Moresby, Portland (Plate 3a), Brackman, and Russell islands; the Extension Formation on Waldron Island; the De Courcy Formation on Sucia Island (Pacht, 1980); and the Gabriola Formation on Tumbo Island (Plate 13a).

Examples of facies L_2 are the Saanich member at Eleanor Point, Saltspring Island, on Brackman, Portland, and Goudge islands, and on northern Saanich Peninsula. It is also commonly developed in the Comox Formation, typically in siltstone overlying coal seams, such as at Quinsam.

Examples of texturally immature facies L_3 are the Cottam Point member at Englishman River Falls, and the Tzuhalem member at Mesachie Lake, on Moresby and Russell islands, and at Beaver Point, Saltspring Island. More mature facies L_3 occurs in the Oyster Bay formation at Shelter Point; the Parksville member at Madrona Point (Plate

15a); the Tzuhalem member on northern Saanich Peninsula; the Extension Formation on Waldron Island; De Courcy Formation on Sucia Island; and the Gabriola Formation on Tumbo Island.

Middle neritic facies association **M**

Facies association **M** is comprised of fine grained sandstone, siltstone, and mudstone; with subordinate coarser grained sandstone and conglomerate, and rare graded beds. The fine grained beds comprise thin to medium bedded, planar laminated to convolute laminated, fine grained sandstone, siltstone, and silty shale; overall, the grain size is finer than in facies association **L**. Thin calcareous bands, concretions, and layers occur locally. Fine grained sandstone lenses and pods are common. Rare pebble lenses and coal debris are present in the sandstone.

Coarse grained sandstone in this facies association is medium to thick bedded, generally planar laminated, locally pebbly, or contains mudstone rip-up clasts, and commonly infills shallow scour surfaces. It occurs as interbeds within fine grained beds described above, and is usually richer in clay size particles than sandstone of facies association **L**. Sedimentary structures include current ripple marks, shallow channels, and bioturbation. Shell fragments are common.

Locally, pebble to cobble conglomerate bodies occur in this facies association, typically as channel fill, interbedded with pebbly sandstone. Clasts are subangular to subrounded and supported by a coarse grained sandstone matrix. Shell debris is common in the conglomerate.

Graded beds are locally developed in this facies association, typically as thin to medium Bouma $T_{(B)CDE}$ sequences.

Microfossils in facies association **M** constitute biofacies 2 of Cameron (1988a). Planktonic foraminifers present are few, and consist of small, non-keeled species, normally Hedbergellinidae, and moderately diverse benthic forms, including nodosarid and textularid taxa, small non-keeled Gyroidinoides, Nonionella, Citharina, Praebulimina (carsayae and aspera types), aragonitic genera such as Hoeglundina and Ceratobulimina (although they can extend to deeper facies), and small species of Brizalina (Cameron, 1988a). Microfossil residues contain some terrigenous material, a few megaspores and some plant tissue, rare fish teeth and bone, and, compared to biofacies 1, more diverse ostracods which are more ornate, with thicker, heavier shells; many have eye tubercles (Cameron, 1988a).

Macrofossils represented in biofacies 2 are Inoceramus and Canadoceras, and pelecypods and brachiopods, notably Anomia, Cucullaea, Acila, Neretina, Arctica, Dosinia, Arcoida, Modiolus, and Rhynchonella. Ward's (1976a) Anomia association of epifaunal suspension feeders is represented in this facies association.

Trace fossils presented in biofacies 2 are Planolites, Thalassinoides, Phycodes, ?Diplocraterion, ?Teichichnus, and ?Taenidium.

Facies association **M** is interpreted to have been deposited in a middle neritic environment, in water depths of 30 to 100 m, based on foraminiferal assemblages. Coarse grained beds are interpreted to possibly represent deep fan delta, feeder channel, or offshore bar deposits; fine grained beds are interpreted to possibly represent low-energy shelf deposits; graded beds may represent prodelta, distal fan delta, or interdelta turbidites.

Examples of facies association **M** are the Saanich member in the Chemainus area; part of the Haslam Formation in Marie Canyon (Section 21, Appendix B); the Protection Formation south of the upper Chemainus River; the Cedar District Formation on the Shoal Islands, and in Ladysmith Harbour; the Dunsmuir member on Tsable River; and the Trent River Formation on Ship Peninsula (Plate 16a).

Lower neritic/upper and middle slope facies association S

Facies association S comprises thin to medium bedded, or massive, very fine grained sandstone, siltstone, and shale or mudstone; coarse grained beds are restricted to subfacies association S_F (section 4.1.5). The shale is either laminated or massive, silty, bears abundant concretions, and is locally fossiliferous. Lenses of fine grained sandstone are common in the siltstone. Stratification is dominantly planar, even, and continuous, although wavy bedding does occur locally. Fine ripple cross-lamination, ferruginous banding and colour lamination, and locally intense bioturbation, are evident. Concretions and concretionary layers are common, especially in the siltstone. Small-scale scour and fill structure, and soft-sediment deformation are locally developed. Rafted coal debris is present. The mudstones generally have a higher organic content than those in facies associations L and M. Soft-sediment deformation and large-scale, low-angle, downlapping beds are locally developed.

Graded beds are well developed in this facies association, ranging from thick Bouma $T_{ABCD(E)}$ to thin $T_{CD(E)}$ sequences. Granule layers and mudstone rip-up clasts are common in T_A divisions. T_B divisions are coarse grained, planar laminated sandstone. Sedimentary features observed in this facies include planar and convolute lamination, asymmetrical and climbing ripple cross-lamination, and load, tool, prod, and groove casts.

Sandstone and conglomerate occurring in this facies association are assigned to the coarse resedimented facies discussed below.

Microfossils occurring in facies association S constitute biofacies 3, 4, and 5 of Cameron (1988a), ordered by increasing paleo-water depth.

Biofacies 3

Foraminifers constituting biofacies 3 occur as large numbers of planktonic Hedbergellinidae and significant numbers of Heterohelicidae; benthic species are highly diverse, (although individual taxa are not abundant), and include _Neoflabellina_, _Palmula_, _Gaudryina_, large _Brizalina_, _Coryphostoma_, _Hoeglundina_, _Pseudonodosaria_, some biumbonate _Gavelinella_, and diverse nodosarids of more robust and ornamented type than occurring in biofacies 2 (Cameron, 1988a). Microfossil residues normally lack terrigeneous material, and ostracod species are like those of biofacies 2, with much reduced diversity (Cameron, 1988a). Cameron reports indications of oxygen deficiency in 30% of the samples and rare down-slope transport in one sample from this biofacies.

Macrofossils occurring in biofacies 3 are abundant and diverse. Pelecypods include Ward's (1976a) _Anomia_ association as listed under facies association M, and his _Inoceramus_ association of epifaunal suspension feeding inoceramids and many ammonites. Inoceramids found in this facies are _I. elegans_, _I. orientalis_, _I. naumanni_, _I. chicoensis_, _I. japonicus_, _I. sachalinensis_ and _I. ezoensis_. Ammonite genera present are _Epigoniceras_, _Didymoceras_, _Glyptoxoceras_, _Canadoceras_, and _Pachydiscus_. Nautiloids and brachiopods are also present in this facies.

Trace fossils present in biofacies 3 include _Thalassinoides_ (longer, less regularly branching forms), _Helminthoida_, _Paleophycus_, _Planolites_, _Teichichnus_, _Taenidium_, ?_Zoophycus_, and ?_Asterosoma_. This facies is dominated by chiefly horizontal burrows.

Biofacies 4

Foraminifers constituting biofacies 4 include many planktonic Hedbergellinidae and Heterohelicidae, and keeled

Globotruncanidae make their first appearance; benthic foraminifers are abundant and diverse, and include Dorothia, Osangularia, Chilostomella (the latter suggesting oxygen deficiency), Cribrostomoides, Silicosigmoilina, more lenticular and diverse Gavelinella, keeled Gyroidinoides, and Stilostomella and Ammodiscus (Cameron, 1988a). Cameron suggests that benthic foraminifer diversity remains high, because of strong upwelling of more oxygenated water at a possible shelf/slope edge; however, oxygen deficiency is indicated in 18% of the samples examined, and the hypothesized upwelling is apparently not ubiquitous. Cameron reports evidence of down-slope transport of shallower water forms in over 40% of the samples from this biofacies, and a flyschoid microfauna in almost 20% of the samples. The flyschoid microfauna is usually composed of exclusively fine grained, agglutinating species of Rhizammina, Reophax, Ammodiscus, Glomospira, Pelosina, Recurvoides, and Haplophragmoides, indicating a fairly high energy, deep-water environment (Cameron, 1988a). Microfossil residues from this biofacies contain authigenic glauconite, and, compared to biofacies 3, the ostracods are much reduced in abundance and diversity, are thinner-shelled, are typically more reticulate and spinose, and lack prominent eye tubercles (Cameron, 1988a).

Macrofossils in biofacies 4 include the pelecypods Acila, Cucullaea, Anomia, Nucula, Crassatella, and Inoceramus, specifically I. lobatus, I. orientalis, I. subundatus, I. vancouverensis, I. schmidti, I. elegans, I. ezoensis, and I. balticus. The ammonite fauna is most diverse in this facies including species of Hauericeras, Canadoceras, Gaudryceras, Baculites, Glyptoxoceras, Polyptychoceras, Pseudophyllites, Diplomoceras, Pachydiscus, (Neo)Phylloceras, Schluteria, Didymoceras, Anisoceras, and Hamites.

Trace fossils present in biofacies 4 are Thalassinoides, Teichichnus, Taenidium, Zoophycus, Ancorichnus, Scolicia, Chondrites, ?Helminthopsis, ?Helminthoida, and ?Cladichnus.

Biofacies 5

Microfossils constituting biofacies 5 include dominant Globotruncanidae and subordinate Hedbergellinidae and Heterohelicidae as planktonic forms; the diversity of benthic forms is reduced compared to biofacies 4, largely composed of spinose Praebulimina, keeled Gyroidinoides, lenticular Pullenia, Stensoina, Silicosigmoilina, finer grained Trochammina, Dorothia, and Gaudryina, and Allomorphina, an abundance of which can imply an oxygen deficient environment (Cameron, 1988a). Microfossil residues include locally diverse ostracods with a dominance of blind, spinose, or reticulate types; members of the Trachyleberididae and Krithe and related forms are common (Cameron, 1988a).

Macrofossils present in biofacies 5 include large, indistinct inoceramids and ammonites, and a few gastropods and other pelecypods. Inoceramus kusiroensis, and two species of Pachydiscus occur in this facies. The apparent reduced abundance and diversity of macrofossils is marked, but may be influenced, in part, by the reduced exposure of biofacies 5 versus biofacies 4 in the basin.

Trace fossils observed in this facies include Thalassinoides, Cladichnus, ?Helminthoida, and ?Granularia.

Facies association 8 includes a large group of sediments interpreted to have been deposited in lower neritic to bathyal water depths, based on foraminiferal assemblages. The facies association may be subdivided into three biofacies based on the foraminifers which indicate deposition in paleo-water depths of: a) 100 to 200 m - biofacies 3; b) 200 to 600 m - biofacies 4; and c) 600 to 1200 m - biofacies 5 (Cameron, 1988a).

Fine grained beds in facies association S are interpreted as low energy shelf or slope deposits; the graded beds possibly represent higher energy, deep prodelta, distal fan delta or interchannel turbidites. Coarse grained beds are resedimented and constitute subfacies association S_F as described below.

Examples of facies association S with biofacies 3 are: the Haslam Formation over much of the Cowichan Valley (Sections 21 and 40, Appendix B), on Saltspring Island, and in the Nanaimo area; the Pender Formation on upper Chemainus River (Plate 7b); the Cedar District Formation on Shoal Islands (Plate 8a, and Section 46, Appendix B); the De Courcy Formation on eastern Saltspring Island and southern Mayne Island; the Northumberland Formation on part of Saltspring Island; the Mayne formation at Long Harbour, Saltspring Island; the Gabriola Formation on Galiano Island; and the Trent River Formation on the Englishman River and on French Creek.

Examples of facies association S with biofacies 4 are: the Haslam Formation in many parts of Cowichan Valley (Plate 5b, and Section 40, Appendix B), and lower Chemainus River valley, and in the northern Saanich Peninsula area (Plate 4b); the Pender Formation on the Pender Islands; the Cedar District and Northumberland formations over much of the Gulf Islands (Section 251, Appendix B); the Mayne formation on Mayne Island (Plate 12a); the Trent River Formation in southern Alberni Valley, on Denman Island, and on Texada Island; and the Lambert Formation on Hornby Island (Plates 17a, b, 18a).

Examples of facies association S with biofacies 5 are: the Trent River Formation on southwestern Denman Island; the Pender Formation at Booth Bay, Saltspring Island; the Northumberland Formation at False Narrows (Plate 10a, and Section 168, Appendix B), Gabriola Island, and at Village Bay, Mayne Island; the Mayne formation at Descanso Bay (Section 156, Appendix B); and the Gabriola Formation at

Tinson Point, on Gabriola Island (Plate 13b, and Section 167, Appendix B).

4.1.5 Coarse grained subfacies association S_F

Coarse grained, resedimented deposits comprise a large part of facies association S. Common subfacies associations in these deposits that were observed by the author are described below. They are similar to but not identical to those described by Pacht (1980).

Channelized conglomerate and sandstone, subfacies association S_{F1}

This subfacies association is comprised of thick channel fill conglomerate and sandstone, interbedded with sandstone and minor mudstone. The conglomerate is typically clast supported, massive to crudely graded, locally imbricated, and contains pebble to boulder size clasts. It commonly contains lenticular sandstone beds. Some scours are completely filled by sandstone only. Moderately chaotic beds locally occur with these facies, consisting of large (3 to 4 m) blocks of sandstone, siltstone, and mudstone, in a disorganized, muddy, pebbly sandstone. Associated beds consist of alternations of thick bedded, coarse to medium grained sandstone, and thin bedded, fine grained sandstone and siltstone, locally exhibiting full and partial Bouma sequences.

Examples of subfacies association S_{F1} are: the Galiano formation on Gabriola, Galiano, Mayne, Prevost islands; the Cedar District Formation on Mayne Island; the Extension Formation on part of Saltspring Island; the Denman Formation on Denman Island; and the Geoffrey Formation on Hornby Island.

Sandstone, pebbly sandstone and conglomerate, subfacies association S_{F2}

This subfacies association consists of medium to thick bedded, coarse grained sandstone, pebbly sandstone, and matrix supported pebble conglomerate, intercalated with thin bedded to massive, shaly siltstone, mudstone, and fine grained sandstone. The sandstone is typically massive, or crudely planar laminated. Normal and inverse grading are observed. Sedimentary features of the sandstone include loaded bases, shale rip-up clasts, dish structure, and sheet structure. The conglomerate is clast supported or matrix supported, and locally contains abraded fossil debris. Associated fine grained beds are: a) graded beds featuring full or partial Bouma sequences and numerous sandstone dykes, or b) massive, fossiliferous mudstone or siltstone, with thin sandstone lenses.

Examples of subfacies association S_{F2} are: the De Courcy Formation on North Pender, and Mayne islands; and the upper Trent River Formation on Denman Island.

Thick bedded sandstone, subfacies association S_{F3}

This subfacies association consists of thick to very thick bedded, typically massive, coarse grained sandstone, with thin fine grained sandstone or siltstone tops. Contacts generally are sharp, planar, and continuous for tens to hundreds of metres. The fine grained tops are commonly graded or convolute laminated. Medium-scale planar and trough cross-bedding are locally developed. Full Bouma sequences are rarely developed. Sedimentary features include groove casts, load casts, flute casts, dish structure, sheet structure, dewatering pipes, coal debris, shale rip-up clasts and other pebbles, and large concretions. This sandy subfacies association locally includes a few interbedded sections of thin bedded mudstone, siltstone, and very fine grained sandstone. Some of these fine grained beds are graded.

Examples of subfacies association S_{F3} are: the Gabriola Formation on Gabriola, Galiano, and Mayne islands; the Galiano formation on Saturna and North Pender islands; the De Courcy Formation in the Yellow Point area, and on Thetis, Saltspring, and Saturna islands; the Cedar District Formation on part of Saltspring Island; the Protection Formation, on the Pender Islands; and the Denman Formation, on Denman Island.

4.1.6 Discussion

Within facies association S, there is a large range in the grain size of the facies present, from shale to cobble conglomerate. In the past, the coarse grained deposits had been interpreted as shallow-water deposits, but the occurrence of biofacies 3, 4, and 5 interbedded with the coarse grained beds establishes their deep-water origin. The coarse grained, resedimented facies comprising subfacies association S_F are interpreted to be deposits of high-concentration turbidity currents or debris flows. The fine grained, graded beds in facies association S are interpreted to represent the deposits of high- to low-concentration turbidity currents (Pickering et al., 1986). Subfacies associations S_{F1}, S_{F2}, and S_{F3} could be interpreted to represent a progression from upper to lower fan deposits (Walker, 1984). Facies classes A, B, C, and D in the terminology of Pickering et al. (1986) are common in facies association S; facies class E is rare, due to the high silt content of the shales; facies class F is also rare.

Pacht (1980) had previously described the sedimentology of the resedimented, coarse grained deposits in detail, alluding to their deep-water origin, but did not have the microfossil data in support of his conclusions. He proposed a multiple source, elongate, amalgamated, submarine-fan model for the deposits, rather than the standard, point source, lobate fan model (Walker, 1984). Pacht argued against a standard fan geometry for two reasons: 1) he recognized coarsening-upward and non-cyclic sequences in what he interpreted to be inner-fan deposits; and 2) he interpreted multiple sources and transport of detritus along the longitudinal axis of the basin, based on petrographic and paleocurrent data. Neither of these two points preclude the notion of standard fan geometry. First, in a very coarse grained fan deposit it may be difficult to differentiate between true inner-fan deposits and mid-fan or suprafan lobe deposits. Second, multiple sources and an elongate basin geometry only affect the architecture of the fan system; the system could still be made up of coalesced lobate fan deposits that are forced by basin geometry to take on a more elongate shape than in a basin without boundary constraints (Pickering, 1982). In fact, the paleocurrent data are not sufficient to define the orientation of individual fan bodies; nor is the geometry of the basin itself well constrained.

The author does not disagree with Pacht's (1980) amalgamated submarine-fan model, but believes that extant data are insufficient to discount a more simple lobate fan model (Walker, 1984). Indeed, the submarine-ramp facies model of Heller and Dickinson (1985) - with multiple feeder channels and dominance of sheet-flow deposits - holds some appeal as a model to explain some of the Nanaimo Group deposits (e.g. those in the Gabriola Formation). The main difference between the submarine-ramp facies model and the standard model (Walker, 1984) is an absence of deeply channelized inner- and middle-fan deposits in the ramp model (Heller and Dickinson, 1985). However, these particular deposits probably do exist in parts of the Nanaimo Group. Also, it can be seen that individual conglomeratic, channelized fan deposits are not as wide in profile view as the sandy fan deposits are, which suggests that the outer fan was wider than the inner fan, thus supporting a more standard, lobate fan geometry (Walker, 1984).

Given the volume of lower neritic and bathyal sediments in the basin, it is surpising that few feeder channels or submarine-canyon deposits are preserved in the Nanaimo Group. This may be a reflection of the paucity of nonmarine and shelf deposits that are coeval with the bulk of the submarine-fan deposits (upper Campanian to Maastrichtian), due to extensive post-depositional erosion. Three possible submarine-valley or feeder-channel deposits have been identified however. The oldest is the paleo-valley fill identified in the Benson Formation on Saltspring Island (Figure 4.1). The valley is estimated to have been 1.2 km wide, with several hundred meters of relief (Hanson, 1976). The valley fill consists of locally channelized, thick bedded conglomerate, sandstone, siltstone, and mudstone. Most of the valley fill, however, is nonmarine or shallow marine, not deep marine. Nevertheless, this example is probably similar in size to the channels that fed the submarine fans.

A second channel deposit is indicated in the Geoffrey Formation on Hornby Island (Fig. 4.13). The formation has a channel shape over 4 km wide, with 200 m of relief (compacted), and consists of thick bedded, channelized conglomerate and sandstone, with rare, fine grained, graded interbeds. The channel is scoured into the Lambert Formation which was deposited in water depths of 150-400 m. This explanation for the geometry of the Geoffrey Formation has strong support from paleocurrent data (Fig. 4.13), which indicate transport parallel to the channel wall. The formation contains at least some fining-upward sequences, which are typical of some submarine-canyon deposits (Morris and Busby-Spera, 1988), although canyon deposits are generally fine grained.

A third candidate for a feeder channel is the Little Mountain conglomerate (of the Parksville member), which appears to have filled a channel scoured into lower neritic shale deposits (100-200 m paleo-water depth) of the Trent River Formation (see Appendix B and Plate 14a). This body is in excess of 2 km wide and 150 m thick.

The Nanaimo Group channel deposits discussed above are generally coarse grained, indicating that the head of the canyon was proximal to the shoreline, where abundant coarse grained material could be captured (Morris and Busby-Spera, 1988).

4.2 Basin Development

To illustrate the development of the Nanaimo and Comox basins, a series of facies maps with annotated paleo-environmental interpretations are presented for successive time-stratigraphic units of the Nanaimo Group (Figures 4.1 to 4.13), based on the biochronological scheme of Fig. 3.5. These maps are summaries of the stratigraphic data, in terms of distribution of lithofacies, paleocurrent data, and paleo-environmental interpretation.

For a better appreciation of possible basin topography, paleo-water depth data derived from foraminiferal assemblages are related to morphological terms, based on the normal environment in which the foraminifers are found in the Pacific realm (Cameron, personal communication, 1989). In this way, upper neritic corresponds to nearshore, middle neritic corresponds to middle shelf, lower neritic corresponds to outer shelf, upper bathyal corresponds to upper slope, and middle bathyal corresponds to middle slope. Note that these correlations are <u>assumed</u>. There is some evidence, however, which suggests that the assumed correlations may be correct. First, down-slope indicators (i.e. transported shallow-water fauna) are mostly restricted to upper and middle bathyal foraminiferal assemblages, and rarely occur in neritic assemblages. Second, the resedimented coarse grained deposits are concentrated in the lower neritic to bathyal facies association, not in the upper and middle neritic facies associations. Third, the paleocurrent data show re-orientation of dominant flow directions from neritic to bathyal facies associations, such that bathyal paleocurrents are aligned parallel to the axial trend of the basin, perhaps parallel to a shelf/slope break, in some cases orthogonal to paleocurrents in neritic facies. Finally, there is at least one example of deep canyon erosion in lower neritic/upper bathyal facies which indicates scouring at a possible shelf/slope break.

It can be seen that the sedimentary record is incomplete, either because of erosion or burial beneath succeeding deposits. For example, the Gabriola Formation contains some of the deepest water facies of the Nanaimo Group, which requires significant net subsidence during sedimentation, inferring that the basin was still large; yet only a small part of the sedimentary record is preserved. In Chapter 5, estimated amounts of erosion are calculated using vitrinite reflectance data.

The base for the maps is not palinspastic. Estimated Tertiary shortening in the basin is a minimum of 8-12 km, northwest to southeast (Chapter 2), which, if restored, would not alter significantly the relative distribution of facies belts, as many of the facies belts trend parallel to many of the contractional faults. The main part of the Comox Basin lies within a single thrust sheet, and much of the northern belt of the Nanaimo Basin lies within a single thrust sheet; thus, facies tracts in these areas should not be displaced relative to each other. There are a few anomalies in facies tracts which are wholly due to the present structure of the basin; these are addressed in the text.

In addition, a brief examination is made of the Tertiary Whatcom and Chuckanut basins which overlie the eastern part of the Nanaimo Basin.

4.2.1 Nanaimo Basin

Klamathonia Zone, Turonian - Coniacian (Figure 4.1)

Initial subsidence is recorded by widespread, sandy, littoral and upper neritic (inner shelf) deposits, and local paralic deposits in the southern Nanaimo Basin. Deeper facies are not exposed, but may lie beneath younger units in the northeast. A broad terrigeneous source area in the south is inferred from the facies distribution. Paleocurrent data suggest that sediment transport was generally south to north. A large, partly submarine, valley-fill sequence is present in the central southern part of the basin, which has been referred to in section 4.17.

Elongatum Zone, Santonian (Figure 4.2)

The sandy littoral and upper neritic (inner shelf), and paralic sediments of the Klamathonia Zone are overlain by extensive fine grained, lower neritic (outer shelf) to upper bathyal (upper slope) sediments. In the northwest, the sandy littoral and upper neritic (inner shelf) deposits comprise part of the Elongatum Zone, inferring continued northwestward progression of the pattern of sedimentation occurring during Klamathonia time. A widespread transgression is interpreted from the facies progression, with deep-marine shale facies eventually covering even the younger shallow-marine sandy deposits in the northwest. Two areas feature bathyal (slope) deposits, with intervening lower neritic (outer shelf) deposits, which is evidence of some topography on the sea-floor during deposition. In the southeastern area, there is ample evidence of down-slope transport indicated from foraminifers. However, there is little evidence of down-slope transport in the western area, suggesting that this may have been just a deep part of the shelf. The extensive lower neritic (outer shelf) deposits presumably pass into bathyal (slope) deposits further to the northeast, based on succeeding maps. Shallower water sediments are expected to have lain to the southwest, based on the previous map, but are now beyond the zero-edge of the Nanaimo Group. The few paleocurrent data indicate dominant transport of sediment to the west and northwest.

Schmidti Zone, Campanian (Figure 4.3)

This biozone consists of middle to lower neritic (mid-shelf to outer shelf) sediments of the upper Haslam Formation overlain by coarse grained terrigeneous and upper neritic (inner shelf) sediments of the Extension Formation. The facies distribution indicates a major influx of coarse grained material from the southeast and northwest. Based on the facies progression, a marked regression is interpreted, such that fluvial and paralic sediments overlie older neritic (shelf) deposits. Coarse grained sediments in the southern central portion of the basin are dominantly marine, but paleo-water depth is uncertain. The younger deposits show a shift in paleocurrents from dominantly east-west, northwest-southeast, to more southwest-northeast. Deeper water facies are expected to lie to the northeast, based on successive maps.

Chicoensis Zone, Campanian (Figure 4.4)

This biozone is represented by paralic and shallow-marine deposits in the northwest, and upper neritic (inner shelf) deposits in the southeast, with lower neritic and upper bathyal (outer shelf and upper slope) deposits intervening. Compared to the previous maps, it is interpreted that the basin deepened, with bathyal (slope) deposits overlying lower neritic (outer shelf) or shallower deposits. Coarse grained material is present in the northwest, but not in the southeast, implying that the southeastern sediment source was not active, or that coarse sediment was bypassing the shelf area, during Chicoensis time.

Vancouverense Zone, Campanian (Figure 4.5)

This biozone is represented by sandy sediments of the Protection Formation overlain by fine grained sediments of lower Cedar District Formation. The distribution of sandy, paralic and upper neritic (inner shelf) sediments shows that the northwestern neritic (shelf) area expanded to a maximum during early Vancouverense time. These nonmarine and neritic (shelf) deposits are overlain by upper bathyal (upper slope) deposits of the Cedar District Formation, the overlap being at least 5 km, which is interpreted as a marked transgression. The upper/middle neritic (inner/mid-shelf) boundary refers to the lower Vancouverense biozone; whereas, the neritic/bathyal (shelf/slope) boundary refers to the upper Vancouverense biozone. The biofacies 1 symbol to the east of the neritic/bathyal (shelf/slope) boundary, in the north, is in the Protection Formation.

Pacificum Zone, Campanian (Figure 4.6)

This zone consists of the upper Cedar District and De Courcy formations. Facies present are mainly upper bathyal (upper slope) deposits, with some shelf deposits in the northwest and southeast. The dominant paleocurrent indicators in the deep-water sediments are aligned northwest to southeast. Note the concentration of down-slope transport indicators in the upper bathyal (upper slope) area in the southeastern part of the basin. Oxygen deficient facies are locally developed in this area.

Suciaensis Zone, Campanian and Maastrichtian (Figures 4.7, 4.8)

The Campanian deposits of this biozone consist of lower neritic (outer shelf) and upper bathyal (upper slope) facies, and minor neritic (shelf) facies in the southeast. There are several down-slope and oxygen-deficiency indicators in the upper bathyal (upper slope) deposits. Paleocurrent data cover all sectors of the compass; the data from the neritic (shelf) area suggest that sediment transport was to the southeast, which may be due to tidal influence.

Maastrichtian deposits of this biozone consist of neritic (shelf) and bathyal (slope) deposits in much the same position as in the previous map, except that the southeastern neritic (shelf) area appears to have expanded, based on facies progression. Bathyal (slope) facies, with strong evidence of downslope transport are present in the northern part of the basin.

4.2.2 Comox Basin

Elongatum Zone, Santonian (Figure 4.9)

In the Comox Basin, the initial record of sedimentation is extensive nonmarine to shallow-marine facies of the Comox Formation, overlain by fine grained, deeper water sediments of the Trent River Formation. The facies progression is evidence of a marked transgression, with lower neritic (outer shelf) facies overlying nonmarine and shallow-marine sediments. Source areas for coarse grained material are interpreted to have lain to the southwest and to the east, based on facies distribution.

Schmidti Zone, Campanian (Figure 4.10)

This biozone is represented by lower neritic (outer shelf) and shallow-marine facies in the southeastern part of the basin, and upper bathyal (upper slope) facies elsewhere. Based on facies progression, the upper neritic (inner shelf) area has been preserved, but in the other areas lower neritic (outer shelf) facies of the Elongatum biozone are overlain by upper bathyal (upper slope) deposits of the Schmidti biozone. Thus, continued transgression is evident.

Chicoensis and Vancouverense Zones, Campanian (Figure 4.11)

These biozones consist of middle neritic (mid-shelf) to middle bathyal (mid-slope) fine-grained sediments preserved in three areas. Note that separation of middle neritic (mid-shelf) and middle bathyal (mid-slope) facies is interpreted to be only about 5 km in a down-slope direction, which infers a very steep paleo-slope.

Pacificum Zone, Campanian (Figure 4.12)

The stratigraphic record for this biozone is restricted to the Denman Island area. It consists of upper to middle bathyal (upper to mid-slope) fine grained facies of upper Trent River Formation overlain by coarse grained facies of the Denman Formation. Paleocurrent indicators are dominantly oriented north-south or southwest-northeast.

Suciaensis Zone, Campanian and Maastrichtian (Figure 4.13)

This biozone consists of a thick succession of formations, mainly on Hornby Island. Coarse clastic deposits are present in Geoffrey and Hornby formations, and in part of the Oyster Bay formation. Sandstones on northwestern Lasqueti Island are included in this biozone, but their age is uncertain. The Oyster Bay formation is restricted to the northwestern part of the basin, and consists of littoral to upper neritic (inner shelf) facies. This formation may be coeval with the Lambert Formation which consists of lower neritic (outer shelf) to upper bathyal (upper slope) fine grained facies in the central part of the basin. Thus, the upper to middle neritic (inner to mid-shelf) boundary is placed between the two areas. A submarine-channel deposit (Geoffrey Formation) is interpreted to infill a channel several hundred meters deep. This feature is referred to in section 4.1.6. It occurs more or less at the neritic/bathyal (shelf/slope) facies boundary. Paleocurrent data indicate sediment transport to the northeast, parallel to the northwestern channel margin. Fine grained shallow-marine facies of the Spray Formation overlie the Geoffrey Formation, indicating major regression in this part of the basin. Overlying deposits are still marine facies, but the paleo-water depth of their environment of deposition is uncertain.

4.2.3 Whatcom and Chuckanut basins

Although these basins fall outside of the study area, they are important in evaluating the hydrocarbon potential of the Nanaimo Basin, as discussed in Chapter 5. The southeastern part of the Georgia Basin is the locus of deposition of considerable thicknesses of Paleogene sediments in two subbasins, the Whatcom and Chuckanut basins (Figure 4.14). The division between the two subbasins is the east- to northeast-striking Lummi Island-Boulder Creek fault system (Johnson, 1985). Over 3 km of Tertiary, mainly nonmarine section is present in the central part of the Whatcom Basin, which as previously discussed (Chapter 2) may have developed in an extensional or transtensional regime. Over 6 km of Eocene nonmarine sediments are preserved in the Chuckanut Basin, which is believed to be a strike-slip basin

(Johnson, 1985). Upper Cretaceous strata are present on the periphery of the Whatcom Basin, and were intersected in a few deep wells drilled on the Fraser Delta (Hopkins, 1968; Rouse et al., 1970). The overall distribution of these strata beneath the Tertiary deposits, however, is poorly known, due to lack of good seismic and well data. The exposed Cretaceous sections, although apparently the same age as the Nanaimo Group, do not contain its characteristic marine shales, and, therefore, cannot be correlated to the Nanaimo Group with confidence.

4.3 Sequence Analysis

The Nanaimo Group is composed of distinct, alternating, dominantly coarse and fine grained formations, evidently deposited during times of high and low sediment delivery to the basin, respectively. Coinciding with the variations in sediment influx are transgressions and regressions, which, in the neritic areas, are respectively marked by superposition of deep-water facies over shallow-water and nonmarine facies (Figure 4.2), or vice-versa (Figures 4.3 and 4.8). Influx of coarse grained material to the basin resulted in progradation of nonmarine and shallow-marine deposits over subjacent neritic deposits, and probably extended the neritic area basinward during times of regression (Figure 4.5). Curtailment or cessation in delivery of coarse grained material to the deeper part of the basin coincided with significant landward expansion of the neritic (shelf) area. In the deeper part of the basin, in bathyal paleo-water depths, variations in sediment influx are marked by alternating coarse and fine grained sediments, but these are all deep-water deposits, and within the precision afforded by foraminiferal assemblages, water depth changes cannot be recognized.

Based on facies progressions, relative sea-level rises in the basin evidently occurred during Klamathonia, Elongatum, Chicoensis, and middle Vancouverense time, and relative sea-level drops evidently occurred during Schmidti and upper Suciaensis time. This does not exclude the possibility that other transgressions and regressions occurred, which have not been identified, due to an incomplete stratigraphic record. The noted coincidence of transgression with cessation of sediment influx to the deep part of the basin suggests a cause and effect relationship. This relationship has been noticed in other sedimentary basins.

According to Vail et al. (1977), Von der Borch et al. (1982), and Normark (1985), during highstands of sea level, sediment is trapped on the shelf, or if sediment influx is high, progrades across the shelf as a series of clinoform lobes into deeper water; whereas, during lowstands of sea level, sediment is delivered directly onto the slope, bypassing the shelf through river-fed submarine canyons, and depositing as submarine fans. This model provides an elegant explanation for the absence of deep-water, coarse grained deposits during highstands of sea level, but does not consider variations in sediment supply to the deeper part of the basin from the source areas.

Delivery of large amounts of coarse detritus to the deep part of the basin must be related to: 1) relative uplift and erosion at the head of the sediment distribution system, which provides a large amount of sediment to the basin margin, and which is directly linked to local tectonics; and 2) processes which govern release of sediment from the basin margin to the deep part of the basin, such as relative sea-level changes, as discussed above.

Seaward progradation of deltaic and marginal marine deposits, and shelf bypass via rivers and canyons provide an adequate explanation for delivery of sediment into the deeper part of the basin; however, resedimentation of large volumes of coarse grained material into the deeper part of the basin is accomplished only by shelf collapse in response to tectonic uplift or relative sea-level fall, or both (Mutti, 1985). In addition to slope instability due to relative sea-level drop (Coleman et al., 1983), large retrogressive slides may be triggered by strong earthquakes (Booth et al., 1985).

Thus, the development of alternating coarse and fine grained deposits in the Nanaimo Group depends on primary sediment influx (governed by timing of tectonic uplift and erosion) and/or secondary processes which redistribute the sediment, which may be strongly influenced by sea level.

4.3.1 Correlation to absolute time

Direct dating of the Nanaimo Group is not possible due to the lack of radiometrically dated horizons in the succession, or magnetostratigraphy. However, good age control is afforded by the abundant macrofossils occurring in the group. Correlation to absolute time, therefore relies on the macrofossil zonation of the Nanaimo Group that is described in section 3.5, and its correlation to international stages. There are several obvious sources of error in this method.

First of all, there are several correlations of absolute time to stages (Kent and Gradstein, 1985; Haq et al., 1987; Gradstein et al., 1988). What is important in this thesis is not the absolute ages of the stage boundaries, but the amount of time between the stage boundaries. Depending on which of the four time-scales compared in Kent and Gradstein (1985) is used, the Maastrichtian Stage ranges from 5 to 8 m.y., Campanian Stage is 8 to 11 m.y., Santonian Stage is 3 to 4.5 m.y., and the Turonian and Coniacian Stages comprise 4.5 to 10 m.y. In this thesis, the time-scale used is that of Haq et al. (1987) because their sequence stratigraphy is used to correlate the Nanaimo Group to absolute time. Although their time-scale has been criticized by Gradstein et al.

(1988) the criticisms mostly pertain to problems in the Jurassic and Cenozoic parts of the scale. In fact, the time-scale of Kent and Gradstein (1985) shows little difference (less than 0.5 m.y.) to that of Haq et al. (1987) over the Late Cretaceous time considered in the thesis.

Second, the biozonation itself is imprecise. The Klamathonia Zone is Turonian to Coniacian, by definition. The Elongatum Zone is Santonian to lowermost Campanian; the Naumanni Subzone is Santonian only. The Schmidti Zone is lower lower Campanian, and the Chicoensis Zone is upper lower Campanian. The Vancouverense, Pacificum, and lower Suciaensis Zones comprise the upper Campanian. The upper Suciaensis Zone comprises the Maastrichtian. Within these constraints, there is room to shift zone boundaries up and down, depending on how much time is assigned to each zone. Using realistic lengths of time for each biozone, bearing in mind thicknesses of the formations and macrofossil control points, most of the boundaries may be fixed to a position +/- 1.5 m.y., whereas the top of the group may be fixed to a position +/- 2.5 m.y.. If these time ranges of the formation boundaries are plotted versus decompacted sediment thicknesses (from Chapter 6), it can be seen that the permissible correlations of formations to absolute time are actually quite limited (Figure 4.15). The range in permissible correlations of the Nanaimo Group to absolute time is shown in Figure 4.16. There is not much difference in the range of correlations of stratigraphy to absolute time (as evident in Figure 4.15) derived from the different possible decompacted burial curves; the different fits merely shift the formation boundaries to slightly younger or older ages.

Another method of correlating the stratigraphy to absolute time is by comparison to stratigraphy in other nearby sedimentary basins. However, there are no other Santonian to Maastrichtian sections available on the western coast of North America which are subdivided as finely as the

Nanaimo Group is. The most finely subdivided sections for comparison are those in southern France, central Texas, and the western interior of the United States which form part of the basis for the coastal onlap curves of Haq et al. (1987) as shown in Figures 3.5 and 4.16. The sequence-stratigraphic framework is derived from integrating seismic stratigraphy, stratotypes, and other reference outcrop sections, with all available magnetostratigraphy, biostratigraphy, and radiometric age dating (Haq et al., 1987).

Some scientists argue that the sequence stratigraphy of Haq et al. (1987) is more finely resolved than is permissible given the imprecision in magnetobiostratigraphic age dating that, in part, forms the basis for their coastal onlap curves (eg. Miall, 1986; Gradstein et al., 1988). There is no doubt, however, that seismic stratigraphy furnishes very fine resolution of stratigraphic successions, much finer than most biostratigraphy. It is the collective approach that Haq et al. (1987) take that validates their sequence stratigraphy; they have used an enormous amount of seismic and outcrop data in their compilations - unfortunately much of it is proprietary.

Notwithstanding the controversy surrounding the interpretation of coastal onlap curves of Haq et al. (1987), it is important to note that global correlations of depositional sequences are often possible. Miall (1986) suggests that the many synchronous unconformities and sequence boundaries in different basins are caused by regional tectonics, overprinted by eustatic sea-level changes, the latter in response to global tectonics. Link et al. (1988) state that tectonically-induced sedimentary cycles are very similar to the depositional sequences of Vail et al. (1977).

As an example of global correlation of a stratigraphic succession to the coastal onlap curves of Haq et al. (1987), consider the Nanaimo Group (Figure 4.16). The coarse grained formations of the group can be arranged relative to the absolute time-scale such that they occur at lowstand positions of the third order cycles. Within the constraints of the biostratigraphy, the coarse grained Extension, Protection, De Courcy, and Galiano formations fit well with lower parts of third order cycles UZA-3.5, 4.1, 4.3, and 4.4, respectively. The Gabriola Formation may range through cycles UZA-4.5, TA-1.1, and TA-1.2. The Benson Formation may range through cycles UZA-3.1, 3.2, 3.3, and part of UZA-3.4. Fine grained formations fit into mid- and highstand positions of the third order cycles, generally extending over longer intervals of time than adjacent coarse grained formations. It is remarkable that the average fit of the Nanaimo Group to absolute time (column A, Figure 4.16) corresponds so well to the fit provided using the method described above (column V, Figure 4.16)

It has been suggested that at active margins, submarine fans occur during times of maximum flooding, not during sea-level lowstands (R.N. Hiscott, personal communication, 1989). If this was the case for the Nanaimo Group, the correlation of formations to the absolute time-scale would shift to younger ages, which is not significant for the purposes of this study.

It is interesting to note that now that the base of the Nanaimo Group has been extended down into the Turonian, the enormous eustatic sea-level rise (100+ m) at the base of UZA-3.1 (base Turonian) may correspond with initial transgression and sedimentation in the Nanaimo Basin.

The correlation used in the thesis between Nanaimo Group stratigraphy and absolute time is the one achieved by fitting the coarse grained formations into the lowstand positions of the coastal onlap curves of Haq et al. (1987), because: a) the correlation is remarkably similar to that which results from using the average of the range in permissible correlations (column A, Figure 4.16); and b) there may be some validity to the global correlations, whatever their cause - eustacy, global tectonics, etc...

Although global eustacy has been appealed to as an explanation for local relative sea-level rises and falls (Haq et al., 1987), there is no reasonable driving force known yet which would effect large enough eustatic changes at the rate required for many depositional sequences, aside from glacio-eustatic effects (Pitman, 1978). The maximum rates of relative sea-level rises and falls in the Nanaimo Group succession are between 5 and 10 cm/1000 years. Therefore, the primary cause of local relative sea-level changes must be tectonics, which controls factors such as basement subsidence, sediment influx, and sedimentation rate; however, eustatic changes may also be influential, especially towards those processes which redistribute sediment to the deep part of the basin from the basin margins.

4.4 Provenance Data

Provenance studies provide important data regarding the evolution of a sedimentary basin and its highland sediment sources. Inasmuch as the sedimentary fill of a basin records the uplift history of its source regions, provenance studies link tectonic evolution to basin evolution, and may well provide the only means by which the tectonic history of the surrounding regions can be addressed. Provenance analysis of the stratigraphic succession, from base up, provides a reverse profile of the exhumed source rocks. In the context of this study, provenance data are particularly important with regard to basin origin, because sandstones from forearc basins in the circum-Pacific region have a characteristic compositional range. These data provide additional constraints on possible interpretations of the origin of the Georgia Basin, which is controversial (see Chapter 2).

It is suggested by Muller and Jeletzky (1970) that lower Nanaimo Group sediments were derived from the Vancouver Island region, and middle and upper Nanaimo Group sediments were dominantly sourced from the Coast Plutonic Complex (CPC). Pacht (1980) verified that detritus from the CPC dominated the composition of sediments deposited during middle to late stages of Nanaimo Basin development, and that during initial development, much of the material was derived from Wrangellian rocks. Ward and Stanley (1982) have postulated that eastern and southern source areas were also active during deposition of part of the lower Nanaimo Group (the Haslam and younger formations), and recognized three petrological intervals: the "Comox" (i.e. Benson) petrologic interval, derived from Wrangellian rocks; the Haslam petrological interval, derived from melange sources such as in the San Juan Terrane and northwestern Cascades; and the Extension-Gabriola petrological interval, derived from crystalline and supracrustal rocks which lay to the east. Thus, it is important to note that Nanaimo Group sediments can be linked to known local source areas as indicated by Muller and Jeletzky (1970), Pacht (1980, 1984); and Ward and Stanley (1982). There are no "missing" source terranes which are commonly interpreted from the sedimentary record of strike-slip basins.

In some cases, the source regions have been located by identifying particular source rocks for a certain petrologic interval, such as chert-rich strata in the San Juan Terrane (Pacht, 1980). In other cases, however, the geographic linkage has been made using paleocurrent data. Here, the danger is in interpreting source-area directions from paleocurrent data from the deep axial parts of the basin, in view of the significant shift in paleocurrent directions from shallow-water to deep-water deposits, as indicated in section 4.2; the paleocurrent directions in neritic areas may be orthogonal to those in bathyal areas.

The data examined here are compiled from a number of sources referred to in the figure captions. Raw detrital framework mode data comprise Appendix C. Most important are calculated Q, F, L, and Qm, F, Lt data, which express volumetric proportions of: monocrystalline quartz - Qm; chert grains - Qp; total quartz - Q equal to Qp plus Qm; feldspar - F, equal to plagioclase plus K-feldspar; unstable polycrystalline lithic fragments (volcanic, metavolcanic, sedimentary, metasedimentary) - L; and total lithic fragments - Lt, which equals L plus Qp (Dickinson and Suczek, 1979). These data are presented as Q-F-L and Qm-F-Lt plots which are used to distinguish key provenance types for detrital sediment.

The majority of Nanaimo Group sandstones (Figures 4.17 to 4.22) fall into the forearc sandstone compositional range (Dickinson, 1982, Figure 3). Typical forearc sandstones of the circum-Pacific volcanic-plutonic suite range in composition from feldspatholithic to lithofeldspathic, with intermediate quartz contents, semiconstant feldspar to quartz ratios, and lithic components dominated by volcanic rock fragments (Dickinson, 1982). The provenance is distinct from continental block and recycled orogenic provenance types (Dickinson et al., 1983). However, there are deviations from the typical forearc sandstone composition which reflect provenance from lithologically heterogeneous source areas, specifically uplifted oceanic terranes and arc-trench complexes (Pacht, 1984).

The average composition of lower Nanaimo Group sandstones is distinct from that of upper Nanaimo Group sandstones: for the Nanaimo Basin, compare Figure 4.17 with Figure 4.19; for the Comox Basin, compare solid symbol data with open symbol data in Figure 4.21. In both basins, there is a marked shift on Qm-F-Lt diagrams of sandstone composition from the lithic sandstone field to the arkosic sandstone field. This shift can also be seen on the Q-F-L diagrams. It is very pronounced in the Comox Basin data

(Figure 4.22), and less pronounced in the Nanaimo Basin data (Figures 4.18 and 4.20). Comparing Q-F-L versus Qm-F-Lt data for individual data sets, it can be seen that the Qp content of lower Nanaimo Group sandstones is significant. The shift from chert-rich lithic sandstone to feldspar-rich sandstone in succeeding formations of the Nanaimo Group is attributed to progressive unroofing of the volcano-plutonic arc, initially providing provenance from Wrangellian and San Juan-Northwest Cascades rocks, ultimately releasing large volumes of arkosic sediment from the arc.

In summary then, provenance data from the Nanaimo Group indicate local sediment source areas, and generally typical forearc sandstone compositions with some deviations ascribed to lithologically heterogeneous sources. Furthermore, the data show that older sediment sources were dominated by Wrangellian rock, and in the south by the San Juan Terrane and northwestern Cascades, and that younger sediment sources were dominated by rocks of the Coast Plutonic Complex. Thus, it is interpreted that uplift of the Vancouver Island area and the San Juan Island area coincided with basin initiation, and as the basin developed eastern sediment sources were accessed, marking the uplift (and growth?) of the arc region.

CHAPTER FIVE

VITRINITE REFLECTANCE ANALYSIS

5.1 Introduction

Thermal maturation studies were initially restricted to using coal rank to assess levels of organic maturity, and were based on the observed increase in coal rank with increasing depth of burial as recognized by Hilt (1873). White (1915) recognized that general levels of organic maturity increased with greater depth of burial, and since then, thermal maturation studies have expanded in scope to include a variety of organic materials as maturation indices, such as conodonts, pollen, spores, bitumen, and specific macerals of coal, such as vitrinite (Staplin, 1975). Important publications describing the correlation of alteration of organic matter to thermal history include papers by Karweil (1956), Tissot et al. (1974), Gray and Boucot (1975), Stach et al. (1975), Cassou et al. (1977), Epstein et al. (1977), Bostick (1979), and Lerche et al. (1984). Alteration of organic matter in response to temperature changes is primarily dependent on the type of organic matter. In general, as temperature progressively increases, there is a darkening in the colour of kerogen (in transmitted light) due to an increase in the amount of carbon relative to oxygen and hydrogen. The correlations of temperature-dependent changes of various organic materials are compiled by Heroux et al. (1979) and Bustin et al. (1985).

There is little evidence that organic matter is altered in response to pressure changes, except at very low ranks (Bustin, 1983); temperature is usually the dominant control. However, time may also be important. For example, a rock that sustains a temperature of $100^{0}C$ for 10 m.y. may attain the same maturity as a rock that has sustained a temperature of $80^{0}C$ for 20 m.y. (Karweil, 1956). It has been shown by Shibaoka and Bennett (1977) that strata at identical present-day temperatures may have different levels of organic maturation depending on their age. The length of time that organic matter resides at the maximum temperature is especially important in analysis of uplifted basins. The significance of the role that time plays in organic matter maturation is documented by laboratory experiments (Epstein et al., 1977)

Of all the methods of measuring organic maturity, vitrinite reflectance has proven to be the most useful and direct, for a wide variety of sediments and rocks (see Bostick, 1979). It is a precise method that entails measuring the amount of a certain wavelength of light reflected from a polished surface of vitrinite, under a reflected-light microscope, using a calibrated photometer; this property of vitrinite changes uniformly over a broad range of catagenesis and metamorphism (Koetter, 1960; Bostick, 1974; 1979). The details of the method are provided by Bustin et al. (1983; 1985).

Vitrinite reflectance is an appropriate method of determining levels of organic maturation for this study in particular, because vitrinite is very common and widely dispersed in the Nanaimo Group. It occurs in detrital and in situ coal seams; as coalified higher plant material such as branches, spars, and tree trunks and roots (Plate 4); and it occurs as finely dispersed matter, particularly in the finer grained rocks. Coal - mostly pure vitrain - was available at the large majority of sample sites; only about twenty samples had to be acidized to obtain dispersed organic matter.

5.2 Vitrinite reflectance database

The vitrinite reflectance database comprises over 614 measurements of strata in the Georgia Basin, 590 of the

Nanaimo Group, and 24 of strata in the Whatcom and Chuckanut basins (for comparative purposes). The database includes a compilation of data from four unpublished sources, two of which are studies carried out for Dr. C.J. Yorath at the Pacific Geoscience Centre (Pearson, 1984; 1985), comprising 35 values; one of which is a 1986 study by Dr. R. M. Bustin at the University of British Columbia, comprising 40 values; and the other source is data from BP Resources Canada Limited, consisting of 222 values. The remaining 317 values were measured by the author at the Coal Laboratory, Department of Geological Sciences, the University of British Columbia.

The database is presented in Appendix D, organized by NTS map sheet, sample number, locality, latitude, longitude, formation, mean reflectance, standard deviation, number of readings to calculate the mean reflectance, NTS map sheet, and a quality factor, Q. The reflectance measurements are of mean random reflectance (abbreviated as $\%R_0$). The Q factor is a visual estimate of how well the readings are normally distributed. Not all of the compiled data include a Q factor because some of the raw data from which the mean values were calculated are not available. The N value, number of readings used to calculate the mean, should be at least 20, preferably 50 or 100, to accurately establish the mean random reflectance (Bustin et al., 1985). There is less confidence that mean values calculated from fewer than 20 readings accurately express the true mean reflectance of the sample; in some samples it is not possible to take many readings due to small sample size.

5.3 Levels of organic maturation

Levels of organic maturation of Nanaimo Group are presented as surface $\%R_0$ maps which cover the northern, central, and southern parts of the study area (Figures 5.1, 5.2, 5.3). The data comprise mostly outcrop samples, except for the southern and central area where $\%R_0$ estimates based on borehole data are included, and the northern area where some shallow coal-mine samples are included. No isoreflectance contours are drawn due to uncertainty or complexity related to post-depositional structural deformation; posted values alone adequately express the levels of maturation.

5.3.1 Northern area

The northern area covers the Comox Basin north of $49^0 30'$ north latitude, an arbitrary division of the basin (Figure 5.1). Measured $\%R_0$ values range from 0.38 $\%R_0$ to 4.38 $\%R_0$. However, the high $\%R_0$ values in the Nanaimo Group are only associated with the Catface Intrusions; thus, it is interpreted that the elevated levels of maturation are related to local high heat flow and contact metamorphism during the intrusive phase. As such, regional or background levels of maturation range from 0.38 $\%R_0$ to only 0.86 $\%R_0$.

There are abundant $\%R_0$ data in the southern part of the map area, from the western erosional edge of the Nanaimo Group to the centre of the basin near Hornby Island. A consistent, but gradual decrease in rank - from 0.85 to 0.48 $\%R_0$ - is observed to occur towards the centre of the basin, corresponding to the direction of younging of strata. This is a normal burial history pattern where older strata have been buried to greater depths than younger strata, by virtue of stratigraphic position, and thus have higher rank. The data between this southern transect and the area influenced by intrusives show that the base of the Nanaimo Group ranges from 0.64 to 0.85 $\%R_0$. North of the area of intrusives, the base of the group ranges from 0.42 to 0.68 $\%R_0$ (albeit with many fewer samples) attesting to lesser amounts of burial in these areas, assuming similar paleogeothermal gradients. In fact, these values are not much higher than those on Hornby Island in the southeast, which occur in much younger strata.

Lower Nanaimo Group on Texada Island in the far east appears to be at about the same level of maturation as the western exposures, based on only one sample.

Using the reflectance-rank classification of McCartney and Teichmüller (1972), regional levels of maturation correspond to subbituminous to high-volatile bituminous coal rank. Where influenced by the young intrusives, coal rank ranges from high- to low-volatile bituminous to as high as anthracite.

5.3.2 Central area

This map encompasses the Comox Basin south of $49^{0}30'$ north latitude, including the Alberni outlier, and the northwestern part of the Nanaimo Basin (Figure 5.2). Measured $\%R_0$ values range from 0.32 to 2.49 $\%R_0$. The range in maturation levels in the southern part of the main Comox Basin and northwestern Nanaimo Basin, along the coastal plain, is 0.32 to 1.11 $\%R_0$, which sets the regional or background level of maturation for the map area. Note the normal burial history signature expressed by decreasing rank upsection (i.e. towards the basin centre) in the southern area. Elevated levels of maturation in the Nanaimo Group are associated with the Catface Intrusions in the southern part of the map, and are interpreted to be related to local high heat flow and contact metamorphism established during the intrusive phase. For example, in the Moriarty Lake-Dash Creek intrusive centre at the southern end of the main Comox Basin, maturation levels increase from the maximum regional value of 1.11 $\%R_0$ to a range from 1.60 to 2.49 $\%R_0$. These increased levels occur in an area not considered to have suffered significant tectonic burial.

In the southern Alberni area, the Nanaimo Group has also been intruded locally by the Eocene Catface sills and consequently shows elevated levels of maturation of 0.91 to 1.70 $\%R_0$. However, in this area, tectonic burial due to southwest-directed overthrusting may also have influenced the thermal history of the Nanaimo Group. The amount of throw on the thrust faults in this area is unknown; therefore, the component of maturation due to tectonic burial cannot be determined (see Chapter 2).

A distinct reduction in levels of maturation (to regional levels) occurs in the Alberni outlier northwest of the area influenced by the intrusives. As some of the samples in this area are located close to the eastern bounding faults (Beaufort Range Fault Zone - see Chapter 2), enhanced maturation due to tectonic burial must not be significant; if the faults are thrusts, their throw is minor. Alternatively, these faults are normal faults. The latter interpretation is favoured here (see Chapter 2), whereby the exposed strata in Alberni valley have been down-dropped to their present position.

Regional levels of maturation in the central area range from subbituminous to high-volatile bituminous rank. Where influenced by Tertiary intrusives or tectonic loading, the rank increase to medium- and low-volatile bituminous rank, and locally attains semi-anthracite and anthracite rank.

5.3.3 Southern area

The southern map covers the entire Nanaimo Basin (Figure 5.3). The sample density is necessarily much higher in this area versus northwestern areas due to the increased structural deformation level. The subdivisions of the Cowichan fold and thrust belt (CFTB, Figure 2.6) are followed in this description. The vitrinite reflectance data in the northern belt show an overall consistent, orderly progression from higher to lower levels of maturation from southwest to northeast, in the direction of younging of strata. Hence, a strong normal burial history signature is interpreted from the data. Lower Nanaimo Group beds generally range from ca. 0.65 to [illegible]5 $\%R_0$; the middle and upper parts of the group generally range from 0.75 to 0.40 $\%R_0$. Exceptions are the western and extreme eastern parts of the northern belt, where lower values - ca. 0.54 to 0.67 $\%R_0$ - exist in lower Nanaimo Group, attesting to the fact that these beds were buried less than correlative strata in the remainder of the area, reflecting the positive nature of these areas during sedimentation (see Chapter 4).

Low levels of maturation in the Nanaimo Group on Orcas, Waldron, Johns, and Stuart Islands, in the southeastern part of the Gulf Islands area, are significant in that they preclude part of the structural interpretation of Brandon et al. (1988), who suggested that the leading edge of the San Juan thrust stack overrode the Nanaimo Group. The reverse situation is actually favoured here, with the Nanaimo Group overthrusting the older San Juan thrust stack, based on structural arguments raised in Chapter 2, which are substantiated by the low levels of maturation in the Nanaimo Group in this area. This scenario was originally proposed by Vance (1977).

In strong contrast to the northern belt, strata in the southern belt have much higher levels of organic maturation, as evident in vitrinite reflectance values ranging from 0.65 to 2.66 $\%R_0$. The elevated levels of maturation are interpreted to reflect greater depths of burial due to tectonic loading based on: a) the association of elevated vitrinite reflectance values with footwall blocks of the thrust faults; b) the absence of post-depositional intrusives in this area; and c) the lack of evidence for increased paleogeothermal gradients in this area, as compared to the northern belt.

In the western, Cowichan Lake area, reflectance values range from 1.40 to 2.66 $\%R_0$. In the central, Cowichan Valley area, reflectance values generally range from 1.26 to 1.93 $\%R_0$. In the eastern, Saanich area, reflectance values range from 0.65 to 1.71 $\%R_0$. As such, there is a decrease in levels of maturation longitudinally within the belt, such that regional levels of maturation are attained locally in the Saanich area. This overall southeasterly decrease, along the strike of the pronounced thrust faults which segment the belt, is attributed to an overall decrease in the amount of tectonic burial in relation to reduced hanging-wall load. This pattern is substantiated by the recognition of increasingly thinner basement overthrust sheets towards the southeast, and the inference of a southeast-rising sole fault of the CFTB as previously discussed in Chapter 2.

Within individual fault blocks, a common pattern is for the reflectance levels to be highest in the immediate footwall of the thrusts. This pattern is strongly developed in the Saanich area and at the eastern end of the Cowichan Valley area, where in near footwall positions below the Tzuhalem Fault, reflectance values reach maxima of 1.24 to 1.71 $\%R_0$; whereas, further away from the main fault, maximum values range from 0.90 to 1.13 $\%R_0$. This pattern is attributed to the maximum hangingwall load having developed adjacent to the fault. The marked decrease in maturation levels away from the faults is interpreted to be due to rapid hangingwall cut-out of basement and Nanaimo Group along a steeply inclined thrust.

In the northern belt, the regional levels of maturation are, in general, high-volatile bituminous rank, locally ranging into subbituminous and medium-volatile bituminous ranks. In the southern belt, the general maturation levels of the Nanaimo Group are: medium- to low-volatile bituminous rank, locally attaining semi-anthracite and anthracite rank, in the Cowichan Lake and Cowichan Valley areas, and; between high- and low-volatile bituminous coal in the eastern (Saanich) area.

5.4 Reflectance/depth gradients

Establishing reflectance/depth gradients for the Nanaimo Group is important to correctly assess its thermal history (Chapter 6) and to estimate the amount of eroded (removed) section (see section 5.5). The reflectance/depth gradient is a signature of the average geothermal gradient that prevailed during coalification. Unfortunately, due to the lack of deep wells, degree of unroofing, and structural deformation, reflectance/depth gradients are difficult to obtain. Fortunately, in the Gulf Islands area, exposures of the Nanaimo Group can be stacked in a composite manner to form nearly complete sections, which provide good control on reflectance/depth gradients over several kilometres of section. Shorter sections, including well data, are also available locally.

Reflectance/depth plots are presented for four composite stratigraphic sections, six short sections, and ten boreholes (Figures 5.4 to 5.17 - note that the depth scale varies between some plots). On selected profiles, reflectance/depth gradients have been calculated by linear regression (Table 5.1), where depth is taken to be the dependent variable, and log reflectance is taken to be the independent variable. Linear regression can only be applied correctly to data in individual fault blocks The regression lines are best fit lines to the %R_0 data, assuming that each data point is of the same quality (i.e. the data were not weighted according to Q factor as described in section 5.2). Correlation coefficients expressing the goodness of fit of the regression line to the data (Table 5.1) range from 0.26 to 0.99.

To graph the reflectance changes occurring in the stratigraphic sections, an arbitrary datum is selected at the top of each section to which the "depth" scale is related; the format of presentation is simply to facilitate comparison to the well data.

5.4.1 Sucia Islands

The southwestern section (Figure 5.4) is exposed along the southern shore of the Sucia Islands. Stratigraphic thicknesses are estimated from field maps, based on average bedding inclinations. The data are sparse, but show an overall increase from 0.4 to 0.6 $\%R_0$ throughout the 1000 m of section. The reflectance-gradient is calculated to be 0.28 log $\%R_0$/km. This profile is important because the beds overlying the Cedar District Formation have been variously interpreted as the Eocene Chuckanut Formation (e.g. Johnson, 1985) or as the De Courcy Formation (Ward, 1978a; Pacht, 1980). If maximum burial of the Cedar District Formation was reached during Nanaimo Group deposition, there should be a profound unconformity separating middle Nanaimo Group from the Chuckanut Formation, possibly with 2 km of the Nanaimo Group missing. If true, a break or step in the reflectance/depth gradient should be visible at this level. In fact, the gradient is continuous across the boundary, suggesting that there is no significant unconformity present, and that overlying beds are indeed Nanaimo Group. The reader should be aware, however, that if maximum burial of the Cedar District Formation was not reached until after deposition of the Chuckanut Formation, then it is possible that the proposed unconformity could be masked.

5.4.2 Saanich Peninsula area

On Coal Island, adjacent to the Saanich Peninsula, a 700 m-long section was measured in lower Nanaimo Group (Figure 5.5; Sections 273, 351, Appendix B) The section features at least 3 thrust faults, beneath which there are successive decreases in reflectance. This pattern is normal for thrust-faulted sections where maturation was preorogenic (England and Bustin, 1986b); more deeply buried, older sections overthrust less buried, younger sections. Although the back-steps are minor, and the data are sparse deeper in the section, it is clear that the gradient is discontinuous, and overall, is low.

A short section was measured in the Saanich member at Bryden Bay on northeastern Saanich Peninsula (Figure 5.6; Sections 284, 294, Appendix B), which yielded a smooth reflectance/depth gradient in the section overlying the fault. The reflectance/depth gradient is calculated to be 0.32 log %R_0/km. Beneath the fault, there is a minor back-step in reflectance, similar to the pattern observed on Coal Island.

A longer section was measured along Pat Bay Highway at Swartz Bay ferry terminal (Figure 5.7; Section 350, Appendix B). At least two thrusts in the section disrupt the reflectance/depth gradient. The data are sparse, but firmly establish that strata of higher rank overlie lower rank strata. A similar pattern is evident in the Coal Point section, on western Saanich Peninsula (Figure 5.8; Section 333, Appendix B) where the lowest beds have the lowest reflectance value.

5.4.3 Northern Nanaimo Basin

In northern Nanaimo Basin, a 420 m section in upper Nanaimo Group yielded a coherent pattern of increasing vitrinite reflectance with increasing age of strata (Figure 5.9; Section 167, Appendix B). The gradient calculated by linear regression (0.71 log %R_0/km), however, is much higher than that obtained for the composite section from the same area, thus underscoring the danger in interpreting average (regional) gradients based on short sections.

Data from the Yellow Point and Harmac wells (plotted as circles on Figure 5.3) are insufficient to establish good gradients, due to the local poor quality of the samples, caving contamination, and possible structural complications within the shale units (Figures 5.10 and 5.11). The gradient established for the Harmac well (0.28 log $\%R_0$/km) is slightly higher than the gradient calculated for the composite section from the same area. No gradient is calculated for the Yellow Point well due to poor data. Although the well data are poor, they serve to illustrate the general levels of maturation of the Nanaimo Group in the area, and overall low increase in reflectance with depth.

5.4.4 Composite sections - Nanaimo Basin

The most complete Nanaimo Group profiles comprise composite sections (Figures 5.12, 5.13, 5.14) built from outcrop data from certain areas of the basin. Stratigraphic thicknesses and relative position of the data are established from map interpretation. Reflectance/depth gradients established for the composite sections are very similar, although the correlation coefficients of the linear regression lines differ markedly (r^2 ranges from 0.36 to 0.82, Table 5.1). The average difference between the observed and estimated depths for given $\%R_0$ values, known as the standard error of the estimate, ranges from 0.2 to 0.5 km for the composite sections (Table 5.2).

The southern Nanaimo Basin area encompasses Tumbo, Saturna, Samuel, Mayne, North Pender, South Pender, southern Galiano, Prevost, northeastern Saltspring, and Moresby islands. The zero depth datum in Figure 5.12 is 1165 m above the base of the Gabriola Formation (limit of exposed section). The reflectance/depth gradient is calculated to be 0.18 log $\%R_0$/km.

The central Nanaimo Basin area encompasses northern Saltspring, Galiano, Prevost, Parker, Wallace, Secretary, Norway, and Tent islands. It overlaps slightly with the southern area. The arbitrary zero depth datum in Figure 5.13 is 1000 m above the base of the Gabriola Formation. The reflectance/depth gradient is calculated to be 0.17 log $\%R_0$/km.

The northern Nanaimo Basin area encompasses northern Galiano, Thetis, Gabriola, Mudge, and De Courcy islands, and the eastern part of Vancouver Island between Ladysmith and Nanaimo. The arbitrary zero depth datum in Figure 5.14 is 400 m above the base of the Gabriola Formation. The reflectance/depth gradient is calculated to be 0.20 log $\%R_0$/km.

5.4.5 Comox Basin

Reflectance/depth data are presented for a series of shallow boreholes in Comox Basin, arranged in a northwest-southeast oriented cross-section for boreholes BP10 to BP3 inclusive, with borehole BP4 from Port Alberni area added to the end (Figure 5.15). The locations of the boreholes are indicated by open circles in Figure 5.2. Reflectance data from outcrops near the boreholes, plotted at the tops of the profiles, are consistent with the subsurface reflectance data. For BP10 to BP6, maturation levels range from 0.50 to 1.16 $\%R_0$. In BP5, a distinct back-step in maturation levels occurs below 250 m, which may indicate the presence of a minor thrust fault. Less obvious reflectance gradient breaks in BP10 and BP6 may be interpreted in the same way.

In BP8, BP3, and BP4 (Figure 5.15) and BP1 and BP2 (Appendix C), elevated levels of maturation are obviously associated with the Catface sills. Vitrinite reflectance values of 0.90 to 4.6 $\%R_0$ occur in samples examined from these boreholes. Marked increases in maturation levels towards the sills or sill-affected sediments documents the thermal aureoles associated with some of the sills.

As the reflectance data from the short boreholes is poor locally, the profiles are short, and some boreholes are influenced by intrusives, there is limited control on reflectance/depth gradients. Nevertheless, gradients may be estimated for boreholes BP10, BP7, BP5, and BP6, which range from ca. 0.25 to 0.55 log $\%R_0$/km, with an average of 0.38 log $\%R_0$/km.

A composite section of the upper Nanaimo Group is constructed from field data from Hornby and Denman Island (Figure 5.16). The zero depth datum is 170 m above the base of the Hornby Formation (that is the limit of exposure). The reflectance/depth gradient calculated for this profile is 0.21 log $\%R_0$/km, which is lower than that indicated from the short borehole profiles.

5.4.6 Data comparison

A comparison of selected reflectance/depth gradients is presented in Table 5.1. Most important are the gradients for the composite sections which are based on large reflectance data sets extending over large stratigraphic thicknesses. The gradients range from 0.17 to 0.21 log $\%R_0$/km. Thus, a regional reflectance/depth gradient for western Georgia Basin is calculated to be 0.19 log $\%R_0$/km, based on the average of the four composite sections. Locally, however, the gradient may exceed the average, as on Sucia Islands and at Bryden Bay, where gradients of 0.28 and 0.32 log $\%R_0$/km are indicated, respectively, and in southwestern Comox Basin as indicated by short borehole sections; these data, however, are not so firmly established as in the composite sections.

The range in reflectance gradients of 0.17 to 0.21 log $\%R_0$/km compare favourably with gradients from Cooper Basin in Australia - 0.18 to 0.26 log $\%R_0$/km (Shibaoka and Bennett, 1977), and from the Front Ranges of the Western Canadian Sedimentary Basin - 0.1 to 0.3 log $\%R_0$/km (England and Bustin, 1986b). Average paleo-heat flow is inferred for the Georgia Basin based on these reflectance/depth gradients (Chapter 6).

5.5 Amounts of eroded section

The degree of erosion may be assessed for the entire study area based on the reflectance maps (Figures 5.1 to 5.3) and knowledge of reflectance/depth gradients. Estimates of eroded section can be made using the simple graphical method described in England and Bustin (1986a). The reflectance gradient is extrapolated from its surface intercept to a "zero" maturation level (0.15 or 0.20 $\%R_0$) and the elevation of this point above the surface intercept is taken as the thickness of removed section. Such a method should produce accurate results where the basin is mature and there is good control on reflectance gradients. Control on reflectance/depth gradients is, however, limited to the eastern parts of the study area. In practice, then, these gradients are assumed to apply to the region on the whole, from which amounts of removed section are estimated for individual surface reflectance values.

The most complete sections in the study area are the areas from which the composite sections were constructed. Even in these areas there is considerable "missing" section. This "missing" section is estimated to be 1.3 to 1.4 km (+/- 0.5 km) for the southern Nanaimo Basin area, 1.3 to 1.6 km (+/- 0.3 km) for central Nanaimo Basin area, 1.5 to 1.6 km (+/- 0.5 km) for northern Nanaimo Basin area, and 2.0 km (+/- 0.2 km) for central Comox Basin area. The "missing" section includes any preserved section which lies offshore (as northeast dipping beds) and the section removed by erosion.

Overall, a significant unroofing of the Nanaimo and Comox Basins is documented by the vitrinite reflectance data (Table 5.2). The amount of removed section is estimated to range from 1.6 to 6.6 km (+/- 0.5 km). The elevation of the zero maturation level (interpreted as the synorogenic surface) calculated using the reflectance data is more than accounted for by the estimated maximum thickness of the

Nanaimo Group (and possible Paleogene section), which is up to 5.4 km (+/- 0.5 km). This is best illustrated by the structural cross-sections of Chapter 2, where the estimated synorogenic surface generally lies below the estimated top surface of the Nanaimo Group for a complete section. Locally, overthrust wedges of basement may account for some of the removed section.

5.6 Hydrocarbon maturation

One of the factors to consider in assessing hydrocarbon prospectivity in any basin is the level of organic maturation. In terms of vitrinite reflectance, the oil generation threshold (OGT) is about 0.6 $\%R_0$ (England and Bustin, 1986a) and the oil generation floor is about 1.3 $\%R_0$ based on Dow (1977). Actually, the OGT boundary is affected by the type of kerogen present, and ranges from 0.4 to 0.7 $\%R_0$ (Barnes et al., 1984). The wet gas zone extends from the floor of the oil window to about 2.0 $\%R_0$ and the dry gas window continues from there to 4 or 5 $\%R_0$ (Barnes et al., 1984).

It is clear from the vitrinite reflectance data that most of the surface exposures and shallow parts of the Nanaimo Group lie within the oil window. Overthrust strata are generally within the wet gas window, and areas affected by Tertiary intrusive activity may lie within the dry gas window. As such, there is potential that significant volumes of hydrocarbons have been generated sometime in the history of the Georgia Basin, a topic which is addressed in Chapter 7. This optimism, however, is countered by the observed paucity of good hydrocarbon source rocks in the basin (England, 1988b).

Chapter 6

SUBSIDENCE HISTORY ANALYSIS

6.1 Introduction

The subsidence history of a basin, as recorded by the ages and thicknesses of basin strata, preserves a signature of the driving mechanism for basin formation. Basin subsidence is generally considered to be due to basement subsidence related to tectonic factors (tectonic subsidence) amplified by sediment loading (Steckler and Watts, 1978). To evaluate tectonic subsidence of a basin, therefore, the component of subsidence related to sediment loading has to be removed. If the lithosphere is assumed to respond only to the sedimentary load above it, then tectonic subsidence can be estimated by careful back-stripping of the basin fill (i.e. correcting for compaction and sequential removal of sediment and water loads) using a simple Airy, local compensation type model (Steckler and Watts, 1978). In other situations, it may be appropriate to remove the sediment load using a flexural model (Watts and Ryan, 1976; Steckler and Watts, 1978). In these cases, it is assumed that the lithosphere provides some support to the sedimentary load, exhibiting time- and load-dependent flexural rigidity (Beaumont, 1978).

Where lithospheric flexure is concerned, aside from the amount, age, and type of sedimentary infill, there are many other factors that need to be examined, eg. the constitution of the lithosphere, its physical properties, the profile of the basement/cover contact, extrabasinal loads, temperature distribution in the lithosphere, etc... (Beaumont, 1978; Beaumont et al., 1982). Although downwarping of the lithosphere is appealed to, to explain the origin of the Late Cretaceous Georgia Basin, it is beyond the scope of this study to build a model based on lithospheric flexure; the available data are insufficient for the task. Primarily, good seismic and deep well data are lacking for the region underlying Georgia Strait, so that a complete across-basin profile cannot be constructed.

As a first approach to subsidence modeling of the Georgia Basin, a local compensation type model was chosen for the analysis. The main goal is to evaluate the resulting tectonic subsidence curves, for these may relate to distinct basin-forming mechanisms. For example, tectonic subsidence in flexurally formed basins varies with position in the basin (i.e. proximity to the load), and is episodic; it is very rapid in response to emplacement of thrust sheets, and stalled as the basin is filled up between thrusting episodes (Beaumont et al., 1982). Where tectonic subsidence is driven by extension, with initial attenuation of the lithosphere and passive upwelling of the asthenosphere, followed by lithospheric cooling (McKenzie, 1978), initial subsidence (e.g. the syn-rift episode) may be very rapid and follow a linear or stepped pattern (Cochran, 1983; Hegarty et al., 1988); subsequent subsidence (e.g. the post-rift episode) follows an exponential decay pattern (Steckler and Watts, 1978; Royden and Keen, 1980).

Tectonic subsidence rate may range from 10 m/m.y. to 10 km/m.y. depending on tectonic setting (Pickering et al., 1989, p. 75). However, based on subsidence rates alone, different types of orogenic basins cannot be distinguished. Forearc basins in particular show a large range in tectonic subsidence rates: 20 m/m.y. to greater than 5 km/m.y. (Pickering et al., 1989). A few examples of rates of tectonic subsidence follow. Basins on Australia's rifted southern margin have tectonic subsidence rates of 50 m/m.y which is regarded as rapid by Hegarty et al. (1988). Syn-rift basins of the North Atlantic have average tectonic subsidence rates of 50 to 100 m/m.y. for Triassic and Kimmeridgian rift phases; whereas, post-rift subsidence is ca. 40 m/m.y. (Hiscott et al., 1990). Very high rates of subsidence may occur in extensional basins. Tectonic subsidence in the Los Angeles pull-apart basin proceeded at rates of about 362 m/m.y. (Sawyer et al., 1987), and rates of tectonic subsidence for the Lusitanian Basin are greater than 250 m/m.y. for a syn-rift phase (Hiscott et al., 1990).

Subsidence history is a key element to consider in the analysis of the Late Cretaceous Georgia Basin because different basin-forming mechanisms have been proposed for the basin (see section 2.1). Although the approach taken is preliminary - future work should focus on flexural models - it is important, because there are few published reports on the subsidence history of forearc basins.

6.2 Subsidence History Modeling

To investigate the basin-forming mechanism(s) for the Late Cretaceous Georgia Basin, four sites were selected for burial history analysis, three in the Nanaimo Basin and one in the Comox Basin. The four sites correspond to the locations of the composite sections described in sections 5.4.4 and 5.4.5. (see Appendix A). The southern Nanaimo Basin site (site 1) and the central Nanaimo Basin site (site 2) are about 20 km apart. The northern Nanaimo Basin site (site 3) lies 40 km northwest of site 2, and is about 75 km southeast of the central Comox Basin site (site 4).

A standard approach to subsidence history analysis is adopted utilizing the BURSUB computer program (Stam et al., 1987), which is based on principles of decompaction and back-stripping established by Sclater and Christie (1980) and follows Steckler and Watts (1978) for the determination of tectonic subsidence. An important part of the back-stripping method is to decompact units (original thickness restoration) utilizing depth-porosity curves for unit lithology. As sediments are progressively buried, pore fluids are expelled and compaction occurs. To compute restored thicknesses of the sediment pile at a certain time, the sediments younger than the age being considered are removed, and the remaining sediments are decompacted in a series of steps (moving along the porosity-depth gradients). The general porosity-depth equation used in decompaction, as described in Royden and Keen (1980) and Stam et al. (1987), is:

$$P = F\ e^{-Cz} \qquad [6.1]$$

where: P = porosity (% of rock volume)
z = burial depth in metres
F = initial (surface) porosity
C = constant

Values for F and C are lithology dependent. For linear porosity-depth relationships, the following equation from Stam et al. (1987) is employed:

$$P = F - 1000Cz \qquad [6.2]$$

Local porosity-depth curves could not be established for lithologies of the Nanaimo Group, because of the lack of deep borehole data. Instead, subsidence history simulations were run using three pairs of F and C values. The first run (case 1) employed equation 6.2 with default F and C values for sandstone and shale supplied with the BURSUB program, established for the Cenozoic of the North Sea and Labrador Shelf, where for sandstone, F = 0.485 and C = 0.9884 E-04, and for shale, F = 0.456 and C = 0.5582 E-04. The second run (case 2) used equation 6.1 with F and C values derived from the Baldwin-Butler power-law equation for shale:

$$z = 6.02\ (1-P)^{6.35} \qquad [6.3]$$

and the Sclater-Christie exponential curve for sandstone:

$$z = 3.7 \ln (0.49/P) \qquad [6.4]$$

(Baldwin and Butler, 1985), where for sandstone, F = 0.49 and C = 0.270 E-03, and for shale, F = 0.478 and C = 0.539 E-03. For comparative purposes, a third run (case 3) used equation 6.1 with F and C values derived in part from modifications of equations 6.3 and 6.4 by Hiscott et al. (1990), where for sandstone, F = 0.30 and C = 0.270 E-03, and for shale F = 0.543 and C = 0.617 E-03.

Calculation of tectonic subsidence (unloaded basement depth) in the BURSUB program (Stam et al., 1987) utilizes the following equation based on Steckler and Watts (1978):

$$y = z \cdot [(\rho_m-\rho_s)/(\rho_m-\rho_w)]+[(w_x+w_m)/2]+[(sl_x+sl_m)/2]- [\rho_m/(\rho_m-\rho_w)] \cdot [(sl_x+sl_m)/2)] \qquad [6.5]$$

where: y = average tectonic subsidence
z = decompacted depth (total sediment thickness)
ρ_m = mantle density
ρ_w = density of sea water
ρ_s = mean density of sediment
sl_x and sl_m = maximum and minimum eustatic sea-level estimates
w_x and w_m = maximum and minimum estimates of paleo-water depth.

Numerical input data for subsidence history simulations for the four sites are listed in Appendix F. Stratigraphic thicknesses and lithology for the 1D modeling sites are based on field data (Chapter 3 and Appendix B, plus field maps). Restored thicknesses of missing section accord with section 5.5. Correlation of stratigraphy to absolute time is described in section 4.3.1. Paleo-water depth data are based on interpretation of foraminiferal assemblages by

Cameron (1988a; b), as described in Chapter 4. Long term eustatic sea-level changes are estimated from Haq et al. (1987) as drawn in Figure 3.5.

6.3 Results

Although subsidence history simulations were run three times per modeling site using the different F and C parameters and different assumptions as to porosity-depth relationships described in section 6.2, the results of the different simulations are not significantly different. The different porosity-depth relationships are evidently very similar. Only case 2 simulations are presented in the thesis because of the limited variation in results between the three cases; they represent a good median case to consider in the analysis of the subsidence history of the basin.

6.3.1. Burial Curves

Burial curves for each modeling site are presented for the total depth (oldest) level which include a water-depth curve and a simple age versus present depth (compacted burial) curve (Figures 6.1 to 6.4), and then as a series of decompacted burial depths for each age level (Figures 6.5 to 6.8), following the format of Stam et al. (1987).

The decompacted burial curves for the oldest horizon from sites 1 and 2 (Figures 6.1 and 6.2) are similar, with more or less constant slope. The youngest parts of the curves steepen slightly. The decompacted burial curve for the oldest horizon at site 3 (Figure 6.3) shows a different pattern, where the older part of the curve (pre-79.5 Ma) has a gentle slope, and the younger part of the curve (post-79.5 Ma) has a steep slope, similar to the equivalent curves of sites 1 and 2. The decompacted burial curve for the oldest level at site 4 shows a different pattern to that for site

3, where initially (pre-80 Ma) the curve is steep, and then has a gentler slope to about 70 Ma, after which it steepens again. The gently sloping part of the decompacted burial curve for site 4 has about the same slope as the gently sloping part of the curve for site 3. The steep part has a slope comparable to the curves for sites 1 and 2.

Decompacted burial curves for all ages of strata are presented for the four modeling sites (Figures 6.5 to 6.8). At sites 1 and 2, the average water-depth curves show initial deepening and then steady, deep-water conditions prevailing for the remainder of modeled time (Figures 6.5, 6.6). The average water-depth curve for site 3 shows initial, steady, shallow-water conditions prevailing, followed by a rapid overall deepening to very deep water conditions at the end of modeled time (Figure 6.7). The average water-depth curve for site 4 shows initial rapid deepening, followed by rapid shoaling, followed by continuous shallow-water conditions (Figure 6.8). Water depth is poorly constrained, however, for the part of the curve younger than 71 Ma; it is possible that the section may actually deepen again post-71 Ma, based on the observation of possible deep-water trace fossils at this level in the succession.

6.3.2 Restored Sedimentation Rate

Restored (decompacted) sedimentation rates for strata in the Nanaimo Basin range from less than 10 cm/1000 yr (100 m/m.y.) for the Benson Formation, to greater than 105 cm/1000 yr for the Protection Formation (Figures 6.9, 6.10, 6.11). These rates are very sensitive to the correlation of the stratigraphy to the absolute time scale, especially for some of the short ranging units (with respect to time) where a slight adjustment in age range may drop the restored sedimentation rate by up to 50%. The adopted correlation of the Nanaimo Group to absolute time requires that restored sedimentation rates are low for fine grained formations and high for coarse grained formation, with respect to an average restored sedimentation rate. Average restored sedimentation rates are 39 cm/1000 yr for site 1, 41 cm/1000 yr for site 2, 31 cm/1000 yr for site 3, and 30 cm/1000 yr for site 4. The reader should bear in mind that these rates are highly sensitive to the age assignments to the Nanaimo Group, and thus are no more than first order approximations.

6.3.3 Tectonic Subsidence

Tectonic subsidence curves for sites 1 and 2 are essentially linear, with a slope of about 123 m/m.y., accumulating 2.7 km of subsidence over 22 m.y. (Figures 6.13, 6.14). The tectonic subsidence curve for site 3 consists of two segments, both broadly linear, the older part having a slope of ca. 64 m/m.y., accumulating 0.4 km of subsidence by 80 Ma, the younger part having a slope of 167 m/m.y., accumulating another 2.3 km of subsidence, for a total of 2.7 km of tectonic subsidence (Figure 6.15). The tectonic subsidence curve for site 4 consists of three parts, the older part being linear, with a slope of about 178 m/m.y., accumulating 1.3 km of subsidence by 80 Ma, followed by a gently curving part, where accumulated tectonic subsidence essentially remains constant (at 1.1 to 1.3 km) until 71 Ma, followed by a linear part with a slope of 162 m/m.y., accumulating another 0.7 km of subsidence, for a total of 2.0 km of tectonic subsidence (Figure 6.16).

For sites 3 and 4 (Figures 6.15, 6.16), note the large difference in tectonic subsidence curves when water-depth and sea level corrections are applied; this is mostly due to the large variation in water depth (see Figures 6.7 and 6.8).

6.4 Discussion

The validity of adopting a simple isostatic model for subsidence history analysis of the Late Cretaceous Georgia Basin may be questioned if a flexural origin is appealed to for its origin (e.g. Yorath and Hyndman, 1983). The rationale for the approach taken is that it is preliminary; more data is required to build a flexural model. However, if the effective elastic lithosphere was able to flex over such a narrow zone (basin width of less than 200 km), then it must be very thin, less than 10 km (Turcotte and Schubert, 1982, p. 126, eq. 3-133), or it did not behave as an intact plate (i.e. it may have been weakened by pervasive fracturing). The thickness of the lithosphere in forearc regions is undoubtedly thicker than 10 km because of low heat flow (e.g. Lewis et al., 1988); thus, the weakened plate behaviour is favoured. However, the state of Wrangellian lithosphere during basin formation (prior to contraction) is really unknown.

Burial curves and tectonic subsidence curves for sites 1 and 2 are similar, with steeply sloped decompacted burial curves, and linear tectonic subsidence over the 22 m.y. of recorded basin history. Deep-water conditions were established early, and prevailed for the remainder of basin development at these locations. The rate of tectonic subsidence is high and constant over the 22 m.y. record of sedimentation.

At site 3, the burial curves and tectonic subsidence curves differ from those at sites 1 and 2. Initially, shallow-water conditions prevailed, with corresponding reduced amounts of decompacted burial (gentle slope) <u>and</u> tectonic subsidence. The rate of tectonic subsidence is low for this period (87.5 to 79.5 Ma). Thereafter, the tectonic subsidence rate increased by a factor of 2.6, with corresponding rapid decompacted burial and establishment of very deep water conditions.

Despite the differences in timing and rates of local tectonic subsidence between sites 1 and 2 and 3, the final amount of tectonic subsidence is equal (ca. 2.7 km). Perhaps at site 3, the initially reduced amounts of tectonic subsidence indicate initial support of the sediment load by the lithosphere (i.e. some initial flexural strength).

Tectonic subsidence and decompacted burial curves for the Comox Basin (site 4) are different from those for the Nanaimo Basin sites. The initial rate of decompacted burial is high due to a very high rate of tectonic subsidence from 87.5 to 80 Ma; consequently very deep water conditions were established by 80 Ma. From 80 Ma to 71 Ma, there is minor tectonic uplift, which corresponds to reduced amounts of decompacted burial and rapid shoaling of the basin. After 71 Ma, tectonic subsidence was rapid again, and decompacted burial increased.

In comparison to other sedimentary basins, the rate of tectonic subsidence calculated is average, ranging from 64 to 178 m/m.y. (see section 6.1), with an average of about 134 m/m.y or 13 cm/1000 yr. The average restored sedimentation rate of 30 to 40 cm/1000 yr for the Nanaimo Group is also average, compared with restored sedimentation rates for other sedimentary basins (Stow et al., 1985). It compares favourably with rates calculated for the Neogene section in the Queen Charlotte Basin - 40 cm/1000 yr (Yorath and Hyndman, 1983), and the 30 to 50 cm/1000 yr rate estimated for the Paleogene southern Alberta foreland basin (England, 1984). Note that the restored sedimentation rates are approximately 2.3 to 3.0 times the tectonic subsidence rates, showing the correct degree of amplification of tectonic subsidence rates by sediment loading.

Tectonic subsidence curves for the Nanaimo and Comox basins are broadly linear in shape for the 22 m.y. record of Nanaimo Group sedimentation (e.g. Figure 4.16). They do not resemble subsidence curves generated by tectonic pulses such as in foreland basins, or by thermal cooling as in post-rift basins. By themselves, however, they do not distinguish between a basin formed by flexure and one formed by extension. The main arguments against a rift or pull apart origin of Georgia Basin are based on lines of thought other than subsidence curves, notably low heat flow, basin architecture, and lack of faults recording strike-slip motion.

An important observation is that tectonic subsidence was mostly constant during sedimentation. This implies a constant basin-forming mechanism operating in central and southern Nanaimo Basin. The northern Nanaimo Basin and Comox Basin areas behaved differently, implying spatial and temporal differences in the tectonic processes (or responses to the processes) governing the subsidence.

Chapter 7

THERMAL HISTORY ANALYSIS

7.1 Introduction

The thermal history of a basin can be extracted from the levels of organic maturation of basin strata, because maturation of organic matter is a function of time and temperature and is an irreversible process. Levels of organic maturation express a summation of the effects of the basin's temperature history. Although not representing a unique thermal history, measured levels of organic maturation provide tight constraints on possible thermal histories for basin strata. Using a time-temperature integral for maturation of organic matter (e.g. Lopatin, 1971; Hood et al., 1975; Royden et al., 1980), calculated levels of organic maturation for a model thermal history may be compared against measured levels, and by iteration, a best fit thermal history for the basin strata may be realized.

7.2 Thermal history modeling

An important approach in determining basin origin is thermal modeling, through which the subsidence history of the basin is linked to prevailing geothermal gradients, based on values for basal heat flow and thermal conductivity of the sediments. A temperature history can be calculated directly using the one-dimensional transient heat-flow equation (Carlslaw and Jaeger, 1959):

$$(\partial T/\partial t) = (1/\rho c).(\partial/\partial z).[K.(\partial T/\partial z)] + U(\partial T/\partial z) + A/\rho c \quad [7.1]$$

where: T = temperature (K)

t = time (s)

z = depth (m)
K = thermal conductivity (W/mK)
U = velocity term which is a function of the rate of deposition of the sediments (m/s)
c = specific heat (J/kgK)
= density (kg/m^3)
A = heat generation due to radioactive decay in the sediments (W/m^3)

Thermal history modeling for this study was carried out using a comprehensive interactive program - THETA (Bloomer and Richardson, 1982) - made available to the author by BP Exploration Incorporated, Houston, Texas. THETA solves equation 7.1 numerically, calculates the transient temperature field during deposition and compaction of the sedimentary column, and estimates levels of organic maturation using a time-temperature integral. The time-temperature integral used is the **C** parameter (Royden et al., 1980), where:

$$\mathbf{C} = \ln \int_0^t 2^{T(t)/10} dt \qquad [7.2]$$

where: T = temperature (^0C)
t = time (m.y.)

This is an empirical equation based on observations by Lopatin (1971) and Hood et al. (1975) that the reaction rate for thermal alteration of organic material doubles for each 10 ^0C increase in temperature, but increases only linearly with time. The organic maturation reactions are assumed to be first order in temperature and to obey the Arrhenius equation (Royden et al., 1980).

There has been considerable work in recent years attempting to calculate organic maturation directly using the Arrhenius equation (eg. Wood, 1988):

$$k = Ae^{-E/RT} \qquad [7.3]$$

where: k = the reaction rate coefficient
A = pre-exponential factor ($m.y.^{-1}$)
E = the activation energy ($kJmol^{-1}$)
R = the gas constant ($0.008314\ kJmol^{-1}K^{-1}$)
T = temperature (K)

Uncertainties remain, however, regarding the selection of activation energies (E) and pre-exponential factors (A) for kerogen maturation (Wood, 1988; Bustin et al., 1985). The series of component reactions in kerogen alteration are in themselves not well understood. Attempts to measure temperature-dependent intramolecular and chemical changes (Mackenzie and McKenzie, 1983) have met with limited success.

The C parameter equation approximates the Arrhenius equation, where the $A = 2.66 \times 10^{17}\ m.y.^{-1}$ and $E = 100\ kJmol^{-1}$ over the temperature range of 10 to 300 ^{0}C, and simulates slightly faster reactions than the Waples (1980) time-temperature integral (Wood, 1988). For type III kerogen, the Lopatin method (Lopatin, 1971), using either equations by Royden et al. (1980), or Waples (1980) as modified by McKenzie (1981), provides a good approximation of maturation for temperature fields less than 300 ^{0}C, based on favourable comparison of predicted maturation values to measured values in basins where the burial history is well known.

According to Bloomer and Richardson (1982), given a firmly established stratigraphic column, the important input variables in thermal analysis are surface temperature (T_s), basal heat flow (Q_b), thermal resistance of the rock sequence (R_z), and heat production in the sediments where:

$$Q_b = -KdT/dz \qquad (W/m^2) \qquad [7.4]$$

$$R_z = \int_0^z dz/K \qquad (m^2K/W) \qquad [7.5]$$

and K = thermal conductivity of the sediments (W/mK)
z = depth (m)

Thermal history modeling was carried out for the same 4 sites as described in section 6.2. Thermal conductivity data for rocks of the Nanaimo Group are presented in section 7.3. Regional heat-flow data are discussed in section 7.4. Surface temperature is discussed in section 7.5.

Overall, the major uncertainties in the thermal history analysis are the uplift and heat-flow history of the Georgia Basin. The latter, however, is constrained by the slope of the measured reflectance-depth curves, which relate directly to the prevailing geothermal gradient during maximum burial (England and Bustin, 1986a). Thus, an important aspect of the thermal modeling is to estimate the heat flow necessary to have produced the observed reflectance-depth gradients in the Nanaimo Group.

7.3 Thermal conductivity measurements

To determine the range in thermal conductivity of Nanaimo Group rocks, a suite of 79 samples was selected for laboratory analysis. All of these samples are from outcrops, with the exception of 5 core plugs from the Point Roberts well. These data are important for thermal history modeling (section 7.2) and determination of present day heat flow (section 7.4).

Thermal conductivity was measured on a divided bar apparatus (Beck, 1965) set up at the Pacific Geoscience Centre, under the guidance of Dr. T. Lewis. Hand specimens of Nanaimo Group outcrops were cored using a drill press. These cores were then cut precisely into 1 cm thick discs (flat to within 0.02 mm, parallel to within 0.05 mm, 1.00 +/- 0.05 cm in thickness, cut perpendicular to the axis of the core, within 3^{0}). Core diameter was either 2.5 or 3.5 cm. Cores were obtainable from fine grained to granule sandstone, but could not be recovered from shale and siltstone samples. In the latter case, conductivity was measured using rock chips packed in perspex containers (Sass et al., 1971).

The divided bar apparatus (Beck, 1965) is a composite cylinder which consists of a stack of brass and fused quartz discs, mounted between two reservoirs of constant but different temperature. The water-saturated sample is placed in the centre of the bar, and the temperature drop across the sample is measured at thermal equilibrium (constant heat flow). This temperature drop is proportional to the thermal resistance of the sample, and may be calculated knowing the precise thickness and disc-face surface area, correcting for bar resistance and contact resistance. Rock-chip samples are measured in saturated perspex containers in the same way, but the resulting thermal conductivity value is for the container plus contents; corrections are made to remove the container effects, and a geometric model is employed to back out the rock conductivity from the value obtained for the rock and water aggregate. Details of the methodology employed are described in Leslie (1984), Sass et al. (1971), and Beck (1965).

Thermal conductivities determined for Nanaimo Group samples are listed in Appendix E. The values obtained range from 1.15 to 6.0 $Wm^{-1}K^{-1}$. Average thermal conductivity values for the Nanaimo Group (Table 7.1) range from 1.56 to 1.76 $Wm^{-1}K^{-1}$ for shales and 2.42 to 3.62 for sandstones.

These values are consistent with the mineralogy of the samples (section 4.4). Constituent minerals consist dominantly of mixtures of feldspar - 2.30 $Wm^{-1}K^{-1}$, quartz - 7.12 $Wm^{-1}K^{-1}$, and clay - 1.2 to 3 $Wm^{-1}K^{-1}$ (Turcotte and Schubert, 1982). For comparison, thermal conductivity values reported by Royden and Keen (1980) are 1.92 $Wm^{-1}K^{-1}$ for mudstone and 5.44 $Wm^{-1}K^{-1}$ for quartz sandstone.

7.4 Heat flow

Active convergent margins have a characteristic heat-flow pattern with low heat flow in the forearc region - generally less then 40 mW/m^2 - and high heat flow in the arc and backarc region - 75 to 100 mW/m^2 (van den Beukel and Wortel, 1986). Present day heat flow in southwestern British Columbia fits this pattern very well, with low heat flow recorded in the coastal regions and high heat flow recorded in the Coast Plutonic Complex (Hyndman, 1976). However, recent work by Lewis et al. (1988) has shown the heat-flow pattern to be more complicated, whereby on the shelf, heat flow is slightly elevated - 50 mW/m^2 - steadily decreasing landwards to about 25 mW/m^2 on the western flank of the Coast Plutonic Complex, before rising to 80 mW/m^2 in the west central part of the Coast Plutonic Complex (arc massif).

The standard explanation for low heat flow in forearc regions is that the subducting slab of oceanic lithosphere is cold and wet, and acts as a regional heat sink; whereas, high heat flow in arc and backarc regions is attributed to magmatic activity and lithospheric thinning related to induced convection in the asthenosphere wedge above the down-going slab (Andrews and Sleep, 1974; van den Beukel and Wortel, 1986). Elevated heat flow on the shelf of southwestern British Columbia is postulated by Lewis et al. (1988) to be due to redistribution of heat by water (generated by dehydration of subducting oceanic crust) flowing updip through the subduction complex.

Within the study area on eastern Vancouver Island, heat flow ranges from 34 to 52 mW/m^2 (Lewis et al., 1988; see also Table 7.2). In addition, basal heat flow for the Yellow Point and Harmac wells was calculated utilizing a subroutine in the THETA program, using bottom hole temperature data recorded during well logging runs, and thermal conductivity data for well cuttings, provided by Dr. T. Lewis, (personal communication, 1988). Average thermal conductivities for formations penetrated in these wells are presented in Appendix E. Borehole temperature data were corrected for thermal disturbance due to drilling.

The equation used in THETA for the calculation of basal heat flow is:

$$Q_b = ((T_z - T_s)/R_z) - A_z/2 - A_{zb} \qquad [7.6]$$

where: Q_b = basal heat flow (mW/m^2)

T_z = equilibrium temperature (K) at z

T_s = surface temperature (K)

R_z = total thermal resistance (m^2K/mW) between z and the surface

A_z = the heat production between z and the surface (mW/m^2)

A_{zb} = the heat production between z and the basement (mW/m^2)

This expression is an approximate steady-state solution to the full differential equation for transient heat flow (Equation 7.1). The actual contribution of radiogenic heat from the sedimentary column is considered to be negligible: the wells are shallow (<1600 m) and measured heat generation from crustal samples in the region is only 0.6 to 0.8 uW/m^3 (Lewis et al., 1988). Surface temperature T_s is taken as 10 ^0C based on mean annual air temperature records for Nanaimo

City (9.3 ^{0}C) and Nanaimo Harbour (10.3 ^{0}C) from Environment Canada (1982). Ground surface temperature is slightly cooler: ca. 8 to 9 ^{0}C, based on borehole data (Lewis et al., 1988, Figure A4). Thus, true basal heat flow would be slightly greater than that calculated.

Initially, temperatures within the column are determined using an approximate basal heat flow. During this run, the thermal resistance of the succession is calculated. The true basal heat flow is calculated next, using the equilibrium formation temperatures calculated from the borehole temperature data. Basal heat flow for the Yellow Point well is 34 mW/m^2 and for the Harmac well is 36 mW/m^2. These values correspond to average geothermal gradients of 21 ^{0}C/km and 28 ^{0}C/km, based on the equilibrium formation temperatures at the bottom of the holes.

7.5 Surface temperature history

Surface temperatures for the Late Cretaceous and the Paleogene were undoubtedly warmer based on oxygen isotope data (Savin, 1977). Uncertainties exist in applying regional paleo-temperature data to the study area, but possible deviations from the regional pattern are not considered to be significant. Surface temperatures during Nanaimo Group sedimentation are simply taken as 20 ^{0}C for emergent and shallow-water facies, and 15 ^{0}C for lower neritic-upper bathyal facies (Priest et al., 1985; Savin, 1977, Figure 1c, p. 329). During the Tertiary, land surface temperature is taken to gradually cool through 15 ^{0}C at 40 Ma, cooling to the present day 10 ^{0}C.

7.6 Results and discussion

The best fit burial history simulations described in the following sub-sections were obtained by maximizing the fit between the model C (from equation 7.2) versus ln %R_0

correlation for the study areas with the C versus ln $\%R_0$ correlation established from modeling studies of basins distributed world-wide (supplied in the THETA program, Priest et al., 1985). The relationship between C and ln $\%R_0$ for the Georgia Basin compared to the world standard curve is plotted in Figure 7.1.

The curve-fitting procedures in the modeling are iterative. Heat flow or amount and duration of burial are varied until the modeled curve matches the measured curve. The margin of error on the match obtained is difficult to address because it is affected very much by what error is assigned to the correlation of C versus ln $\%R_0$. The component of the error which can be attributed to the initial reflectance/depth gradients is about +/- 1 unit of C. The reader should be cautioned that these are only best-fit simulations of the thermal history using standard procedures. The results may change significantly if the relationship between C and ln $\%R_0$ is modified.

7.6.1 Simulation A - Cretaceous burial, Paleocene Uplift

In the first run, the temperature history of each modeling site was calculated based on present day heat flow and the following subsidence history: subsidence from initial deposition of the Nanaimo Group through to the end of the Cretaceous (66.5 Ma) followed by rapid uplift in the Paleocene (Appendix F). Maturation levels are calculated then for the period from initial deposition to maximum burial at 66.5 Ma, and thereafter there is no appreciable further gain in maturation, due to rapid uplift.

The results of the first run are the following. For all of the sites, calculated maturation levels are far too low compared to the measured values (e.g. compare line "a" to line "c" in Figure 7.2). Measured C values are estimated using a correlation of C to ln $\%R_0$ based on global studies (Figure 7.1). For calculated values to be anywhere near measured values of C, the heat flow used in the simulation has to be increased from 36 mW/m^2 to 60-70 mW/m^2, or just about doubled. Then, however, there is a large discordance in slopes between the measured data and the calculated data (line "b" in Figure 7.2).

The main conclusion reached as a result of simulation A, is that there is a major component of the burial history that is missing. The measured values of maturation with depth indicate low paleo-heat flow, but substantially more or longer burial than has been considered in the simulation. As the Nanaimo Group stratigraphy is well constrained, and the total amount of removed section is firmly established by the reflectance-depth data (section 5.5), the only significant changes that can be made to the burial history are the age of the missing section, the duration of maximum burial and time of uplift.

7.6.2 Simulation B - Cretaceous to mid-Eocene burial, late Eocene uplift

In simulation B, the burial history considered is extended to 40 Ma, and a part of the missing section (Section 5.3) is assigned a late Paleocene-Eocene age (i.e., Upper Burrard Formation or Chuckanut Formation equivalent). Post-40 Ma, the sites are considered to have been uplifted rapidly, with no appreciable further gain in maturation. Several iterations were run, varying the amount of missing section assigned a Late Cretaceous age versus an early Paleogene age, varying time of uplift, and varying the thermal history.

Two major conclusions result from this broad sensitivity analysis of the above mentioned variables. First, as long as the Cretaceous section remains at or near maximum burial depth for the Paleocene and much of the Eocene, calculated values match measured values of maturation. Variations in the partitioning of the missing section into Maastrichtian and early Paleogene components, and uplifting the section beginning between 46 Ma and 40 Ma, have little effect overall. Second, compared to the present day heat flow at the modeling sites, slightly elevated heat-flow levels are required for calculated values to match measured levels of maturation, and these elevated levels must prevail during maximum burial.

The results of the best fitting runs in simulation B are presented as burial history plots with **C** value isopleths superimposed (Figures 7.3 to 7.6). The match obtained between measured and calculated maturation levels for site 1 is shown in Figure 7.7.

The thermal history used in the best fitting iterations has a heat flow of 40 mW/m^2 from 88.5 Ma until 60 Ma, increasing exponentially to the maximum basal heat flow (Q_{max}) at 55 Ma, holding steady at Q_{max} until 50 Ma, and then decreasing exponentially to 40 mW/m^2 at 40 Ma. Calculated Q_{max} values are 48 mW/m^2 for site 1, 50 mW/m^2 for site 2, 54 mW/m^2 for site 3, and 58 mW/m^2 for site 4. The elevated heat flow pulse must coincide with maximum or near maximum burial of the Nanaimo Group, and is probably related to one of the following events: a) the inception of the Whatcom and Chuckanut Basins, which have elements of a pull-apart origin (Johnson, 1985) with possible shallow intrusions; and b) envisaged high heat flow related to the 50 Ma magmatic episode in the Coast Crystalline Complex (Armstrong, 1987), and parts of the Catface magmatic episode on Vancouver Island. Thus, there is a valid geological explanation for elevated heat flow during maximum burial in a setting otherwise characterized by low heat flow. The low heat flow probably prevailed in the Late Cretaceous and certainly prevails today.

Redistribution of heat by convection of water in the basin and lateral heat flow in spatially limited basins are important considerations in assessing paleo-heat flow in sedimentary basins. The influence of these factors on estimates of paleo-heat flow in the Late Cretaceous to Paleogene Georgia Basin cannot be addressed because the restored basin geometry is unknown.

7.6.3 Timing of Hydrocarbon Maturation

Hydrocarbon generation begins at 0.6 $\%R_0$ (section 5.6) or a **C** value of about 11 (Figure 7.1). The oil floor of 1.3 $\%R_0$ (section 5.6) correlates to a **C** value of about 14. With reference to figures 7.3 and 7.4, any hydrocarbons generated at the base of the section at sites 1 and 2 would have been expelled between ca. 63 Ma and 45 Ma. Furthermore, a large amount of the Nanaimo Group would have entered the oil window prior to inferred uplift at 40 Ma. The same pattern holds true for site 4 (Figure 7.6). At site 3 (Figure 7.5), hydrocarbon generation at the base of the section would have been later, not beginning until the end of the Paleocene.

Notwithstanding the paucity of good source rock in the Nanaimo and Comox basins, hydrocarbons could have been generated over about 25 m.y. in the Paleogene. However, the formation of the main structures in the mid- to late Eocene (Chapter 2) is thought to be coincident with or to slightly predate the uplift of the basins (ca. 40 Ma), thereby post-dating the main phase of hydrocarbon generation. This sequence of events greatly reduces the hydrocarbon potential of the study area, for the structural traps would not have formed in time to catch the hydrocarbons. Only in parts of the basins which have remained buried (under Whatcom Basin) does the hydrocarbon potential remain positive. In tectonically overthrust areas (Figure 2.2), there is also the possibility of a second hydrocarbon generation phase (mostly wet gas or dry gas).

Chapter 8

EVOLUTION OF THE GEORGIA BASIN

8.1 Introduction

In this study, several aspects of the geology of the western part of the Georgia Basin have been investigated. Major advances have been achieved in understanding its structural history, the distribution of lithofacies and biofacies in the Cretaceous sequence of the basin, the subsidence and thermal history of the basin, and the magnitude and extent of its uplift history. These are reviewed in section 8.5. The geological database is now substantial within the study area, and should serve well for comparison to other forearc basins.

Despite the progress made in understanding the evolution of Georgia Basin, the study remains hindered by two major problems: 1) the basin has been substantially exhumed so that its maximum extent in the Late Cretaceous and early Paleogene is unknown; and 2) the relations between western and eastern parts of the Nanaimo Group are obscured by Georgia Strait and Tertiary deposits of the Whatcom Basin. The latter problem may be solved, in part, by acquiring new seismic and/or well data from Georgia Strait. The former problem is insoluble. Very few basin-margin deposits are preserved, being represented only in some of the oldest formations; much of the basin fill is deep marine. Nonetheless, the Late Cretaceous Georgia Basin possibly rivals the Late Cretaceous Great Valley of California in size, being at least 100 km wide and a minimum of 250 km long, possibly 400 km long if originally connected to the Suquash Basin. Its sediment thickness, however, is less than half of the Great Valley sequence, ca. 5 km maximum for the Nanaimo Group, compared to 12-15 km for the Great Valley sequence (Dickinson, 1971). However, the Great

Valley sequence ranges from Jurassic to Late Cretaceous, whereas the Nanaimo Group is only Late Cretaceous.

The Late Cretaceous Georgia Basin is not a foreland basin to the northwestward-verging nappe system in the San Juan Islands as proposed by Brandon et al. (1988), because: a) the age of the Nanaimo Group mostly postdates the thrusting (Chapter 2); b) vitrinite reflectance data show that the nappes did not overthrust the southern part of the basin (Chapter 5); c) facies maps show that the deep part of the basin is elongate in a direction which is orthogonal to the nappe front; and d) there is little difference in the amount of tectonic subsidence from southern to northern Nanaimo Basin (Chapter 6) - in a foreland basin the amount of tectonic subsidence should decrease with increasing distance from the thrust front. Furthermore, it is shown in this chapter (section 8.3) that the Late Cretaceous Georgia Basin was not a strike-slip basin as advocated by Pacht (1980; 1984). Rather, it is the opinion of the writer, that the basin is one of the best exposed forearc basins in the world. As such, it is an important record of the evolution of the North American Pacific margin at the latitude of the study area during the Late Cretaceous. The presence of the forearc basin confirms that subduction was occurring on this part of the Pacific margin from 88.5 Ma to at least 68 Ma, and the detrital record of the basin confirms the growth of the adjacent arc massif. The presence of the arc is independently known. It is evident from the occurrence of plutonic and volcanic rock suites in the Coast Crystalline Complex which establish a magmatic episode for the period 84 Ma to 64 Ma based on radiometric-age dating (Armstrong, 1987).

The analogy of the Great Valley forearc basin for the Georgia Basin has been previously raised (Dickinson, 1976; Muller, 1977). The comparison becomes more important, however, now that some models for the tectonic evolution of the Cordillera suggest large northwards displacement of the outer Canadian Cordillera during the Late Cretaceous (Umhoefer, 1987). It is clear from the present study that the Georgia Basin and its surrounding highland sediment source regions are an intact, albeit contracted, remnant of a Late Cretaceous arc-trench system. The main difference between the Great Valley forearc region and the Georgia Basin forearc region is that in the former the subduction complex is separated from the main forearc basin by a trapped wedge of oceanic crust, whereas, in the latter, the subduction complex was separated from the main forearc basin by a thick block of semicontinental crust of the Wrangellia Terrane.

8.2 Review of arc-trench systems

To understand the tectonic setting of the Georgia Basin it is necessary to review what is known about arc-trench systems in general. The arc-trench system is a fundamental feature of convergent-plate boundaries. If crust is created at ocean ridges, and lithospheric plates move away from these spreading centres, then lithosphere has to be consumed somewhere in order to maintain the constancy of the surface area of the globe. The oceanic lithosphere is consumed by subduction in arc-trench systems.

A generalized arc-trench system consists of an outboard trench, a medial accretionary prism, and an inboard arc massif, which is a composite volcanic and plutonic highland area (Figure 8.1). The arc-trench system is an area of complex structural and stratigraphic relations, reflecting the dynamic nature of convergent-margin deformation. Yet there are some consistencies in the overall morphology of forearc regions, as described by Dickinson and Seely (1979) who recognized nine different types of forearc regions. Although each of the arc-trench systems developed around the world is unique, their development can be synthesized in a general way.

Initially a subduction zone is established at a convergent-plate boundary, where one plate descends beneath the other and lithosphere is consumed. This may be between continental and oceanic plates, Andean-type subduction, or between two oceanic plates, intra-oceanic subduction. Presumably subduction arises when the lithosphere begins to yield as a result of global tectonic forces. The plates yield where the lithosphere is weakest, in oceanic or transitional oceanic-continental crust, potentially trapping a piece of this weaker crust between the arc and the trench. The width of this crustal piece is determined by such factors as the rate of plate convergence, angle of plate subduction, and thickness of the continental lithosphere (Seely, 1979; Dickinson and Seely, 1979). The trench is established primarily due to downflexing and subduction of oceanic lithosphere. The accretionary prism develops by: a) seaward accretion of oceanic sediments scraped off the downgoing slab; b) accumulation of sediments derived from the arc massif or medial positive features of the arc-trench gap; and c) landward understuffing of oceanic sediments and slices of oceanic crust (Farhoudi and Karig, 1977; Dickinson and Seely, 1979). Very rapid growth of the accretionary prism may be accomplished by large-scale underplating of oceanic material (Platt et al., 1985). The underplated imbricate slices of upper oceanic crust are subsequently elevated and rotated upward as the next slices of ocean floor are stuffed under the prism. This understuffing forces the imbricate stack to rise, providing a dam (or dams) for sediments to pond behind. A consequence of elevating the leading edge of the overriding plate is the creation of a downwarp within the arc-trench gap, which forms the inner trough.

The gap between the arc and the trench is from inception primarily a depositional site because of: a) the downwarping effect of subducting oceanic lithosphere at the trench and also up to 200 km inboard (eg. Yorath and

Hyndman, 1983) where the downgoing plate commonly steepens its descent, perhaps by slab-pull (Turcotte et al., 1977); and b) the sediment trap created by the growing subduction complex and medial ridge. As the outboard region is elevated, a large inner trough develops in the arc-trench gap. Ultimately a large sedimentary basin may form, rapidly accumulating sediments derived from the uplifting arc-massif; the older the arc-trench system is, the more sediment will have gathered there. Sedimentary piles over 15 km thick are known from mature arc-trench systems (Dickinson, 1971). These sediments record the tectonic history of the system, marking the successive unroofing of rocks in the highland areas with successive sedimentary layers in the basin.

The arc massif grows mainly by expansion and thermal doming related to injection of large amounts of magma, derived, at least in part, from partial melting of the downgoing slab (see section 7.4). The growth of the arc and its contemporaneous erosion provide more and more sediment for the inner trough forearc basin. Thus, the inner trough commonly widens through time, as exemplified by the Great Valley sequence in California (Dickinson, 1971, 1973; Dickinson and Seely, 1979). The final stage in the evolution of the forearc region is reached when, due to changes in the tectonic regime (trench jump, plate motion reorganization, rapid convergence, etc...), the arc-trench system is abandoned. Commonly, at this stage, forearc basins, medial ridge, and subduction complex are complexly contracted.

Arc-trench systems may be very extensive, as shown by the system that extends for over 3000 km from Sumatra to Burma (Curray et al., 1979). The late Mesozoic to Paleogene arc-trench system in California, in which the Great Valley sequence was deposited, stretched a minimum of 500 km along the Pacific Coast of North America.

The structural style of a forearc region is variable (Dickinson and Seely, 1979). The stable inner flank of the forearc basin, and the arc massif basins, are characteristically block faulted as a result of arc uplift, and possible extension related to rising plutons or magmatic withdrawal beneath the basins (Dickinson and Seely, 1979). Most of these faults are normal; however, some reverse faults do occur. On the other hand, the subduction complex is a dominantly compressional regime characterized by a fan of landward-dipping thrust faults and seaward-verging folds in highly sheared and internally dismembered oceanic sediments and volcanics, where the toe of the slope of the subduction complex is the seaward edge of the active fold and thrust belt, and the intensity of surface deformation diminishes progressively upslope from the toe. The medial ridge and the outer part of the inner trough have a structural style transitional between that exhibited in the subduction complex and that of the arc massif. For the most part, however, the inner-trough forearc basin remains mostly undeformed until the final stage of evolution of the forearc region.

An alternative appreciation of the structural style of the forearc region is presented by Platt (1986) who views the whole accretionary prism as an orogenic wedge which may dynamically extend or contract in response to overall thinning or thickening of the wedge due to terrane accretion or underplating, respectively, thereby maintaining an equilibrium wedge geometry or taper. It would thus be possible to have extensional faulting occurring at a high level in the accretionary prism during plate convergence.

Using the general appreciation of arc-trench systems, a valid geological explanation is provided for many of the attributes of the Georgia Basin, as outlined in the foregoing chapters: constant, downwarping basin forming process; northwest-southeast orientation of basin elongation; possible orthogonal asymmetry to the basin;

basin architecture; sediment source history; low heat flow; connections to the open ocean; and eventual contraction of the basin. A forearc-basin origin for the Georgia Basin is the most acceptable based on the observed data. In the classification scheme of Dickinson and Seely (1979), the basin is considered to have been developed in a broad-ridged forearc region, where the ridge would have been mostly composed of a large block of Wrangellian lithosphere.

8.3 Evidence against a strike-slip fault origin

The proposal by Pacht (1980; 1984) that the Nanaimo Basin developed as a pull-apart basin within a broad zone of normal and transcurrent faulting in a transform margin or as an intra-massif forearc basin developed in an obliquely convergent-margin setting, is disputed in this thesis. The evidence for Pacht's (1984) proposal is based on sandstone petrography, a supposed magmatic gap in the Coast Crystalline Complex, the lack of trench deposits, the fault geometry in the Nanaimo Basin, and evidence of large-scale, Late Cretaceous, dextral transcurrent motion in the Canadian Cordillera. In the following, each of these points is examined.

Pacht (1984) states that typical forearc sandstones are not present in the Nanaimo Group in the Nanaimo Basin and suggests that the high-plagioclase arkoses that are derived from the Coast Plutonic Belt average only 3.4% volcanic rock fragments, and that no contemporaneous volcanic rock fragments occur. As shown in section 4.4, and Figures 4.17 to 4.22, the <u>majority</u> of Nanaimo Group sandstones fall into the forearc sandstone compositional range typical of the circum-Pacific (Dickinson, 1982, Figure 3). Furthermore, the average component of volcanic rock fragments for Nanaimo Group sandstones actually ranges from 4% to 24% varying by formation and location. In consideration of the fact that the active arc lay 120 to 200 km inboard of the Georgia

Basin on the eastern side of the Coast Crystalline Complex (Armstrong, 1987), without considering the amount of Cenozoic contraction between the two areas, it is not surprising that much of the coeval arc detritus did not reach the Georgia Basin. The provenance from the arc massif is dominated by plutonic detritus (see section 4.4).

The supposed magmatic gap in the Coast Crystalline Complex during the Late Cretaceous is not substantiated for the relative latitude of the study area in the most recent compilation (Armstrong, 1987), nor in a previous compilation by Muller (1977). Roddick (1983) showed that the only magmatic gap in the Coast Crystalline Complex in the Cretaceous occurred from 140 Ma to 115 Ma.

The lack of trench deposits that Pacht (1984) refers to is not too surprising given the degree to which the western margin of Vancouver Island has been underplated and is truncated by the West Coast and San Juan Faults which separate Wrangellia from the Pacific Rim Terrane (Clowes et al., 1987). Correlatives of the Franciscan terrane of California do exist in the Pacific Rim Terrane, representing inferred trench deposits as young as Valanginian (Muller, 1977). It is quite conceivable that the younger trench deposits, coeval with the Nanaimo Group, have been underplated.

The structural style of the Nanaimo Basin as related by Pacht (1984) is characterized by steeply dipping normal faults, some of which have dextral displacement, obviously following Muller and Jeletzky's (1970) perception of the local structural geology. This perception has been dismissed in Chapter 2, based on the evidence that: a) the faults clearly are thrusts; and b) they developed <u>after</u> basin formation. Small-scale structures in the Nanaimo Group between these faults record evidence for orthogonal contraction only. The absence of bounding strike-slip faults for the Nanaimo Basin makes it difficult to demonstrate a pull-apart origin for the basin.

The final point Pacht (1984) appeals to is the noted dextral transcurrent motions in the Late Cretaceous Canadian Cordillera. These motions, however, take place on faults far removed from the Nanaimo Basin. Strike-slip displacement fields present inboard of the study area in no way constrain possible displacement fields established in the study area, for the displacement fields established in any area are as much controlled by the orientation of (micro)plate boundaries with respect to the prevailing stress field, as they are to the orientation of the prevailing stress field itself.

Pull-apart basins develop at releasing bends or at stepped-fault discontinuities in strike-slip systems, and are synonymous with rhombochasms and wrench grabens (Mann et al., 1983). Aside from the close association with a strike-slip fault structural style - which is clearly dismissed in Chapter 2 - strike-slip basins are recognized by the following criteria from Reading (1980) and Hempton and Dunne (1984): 1) extremely rapid vertical movements; 2) high sedimentary input (commonly episodic); 3) facies with limited geographical extent; 4) spectacular unconformities of limited lateral extent; 5) limited metamorphism and sparse igneous activity; 6) discordance between lithofacies present (type and grain size) and source areas (displaced source terranes); 7) extreme lateral facies variations; 8) thick basin fill relative to basin size; 9) asymmetrical sedimentary sequences and facies patterns; 10) migration of depocentres; and 11) Z-shaped, S-shaped, or almond shaped basin geometry.

Criteria of points 1, 3, 4, 7, 9, 10, and 11 above clearly are not present in the Nanaimo Group. The formations of the Nanaimo Group are remarkably consistent in thickness and lithology over tens of kilometres in the Georgia Basin. The subsidence history is markedly steady and linear. Unconformities do not feature prominently in most of the group. Source terranes are accounted for, and depocentres were stable (see facies maps, Chapter 4). Criteria of points 2 and 5 are present, but these are not really unique to pull-apart basins. Point 6 has already been addressed in the discussion of provenance data (section 4.4).

Particularly telling is point 8. Hempton and Dunne (1984) describe a relationship of the length of a pull-apart basin versus the thickness of sediment fill. For a 100 km long basin, the true sediment thickness is on average over 8 km. Furthermore, Aydin and Nur (1982) showed that the length to width ratio of pull-apart basins is approximately 3:1, such that a 100 km long pull-apart basin is no wider than 30 km. Considering the Nanaimo Basin by itself, it is much wider (ca. 60 to 70 km) than normal pull-apart basins of 100 km length, and about half as deep (5 km maximum). Considering the Georgia Basin, it is about three times larger than the average pull-apart basin, and its length to width ratio based on the preserved sedimentary record, is 2.5:1; the ratio for the uneroded basin limits would have been less.

8.4 Summary of basin evolution

The evolution of the Georgia Basin is illustrated in Figure 8.2. The Wrangellia Terrane apparently accreted to inboard terranes of the study area by Mid-Cretaceous (Monger and Price, 1979), although contraction along the eastern boundary of Wrangellia continued to about 84 Ma resulting in the Northwest Cascades Thrust system (Brandon et al., 1988). Initial subsidence of the Georgia Basin began at about 88.5 Ma, represented by the accumulation of widespread sandy neritic deposits in southern Nanaimo Basin, and possibly slightly younger coastal-plain and neritic deposits in northern Nanaimo Basin and the Comox Basin. This event closely follows the enormous sea-level rise in the early Turonian (Haq et al., 1987). Deep-water conditions were established early on (by 85 Ma) in the Comox and Nanaimo basins, except for the northern and southeastern Nanaimo Basin, where paralic and shallow-marine deposition persisted. For central and southern Nanaimo Basin, deep-water conditions persisted for the remainder of the Cretaceous. Northern Nanaimo Basin foundered at about 79.5 Ma, with very deep water sedimentation prevailing for the remainder of the Cretaceous. Shallow-water conditions prevailed in southeasternmost Nanaimo Basin for the duration of Nanaimo Group deposition. In the Comox Basin, deep-water conditions were replaced by increasingly shallow-water conditions, from about 80 Ma to 71 Ma, due to stalled tectonic subsidence, after which the area probably rapidly subsided. Tectonic subsidence of 2.7 km in the Nanaimo Basin and 2.0 km in the Comox Basin, occurred at a rapid, linear, or stepped-linear rate. The total sediment thickness may have been in excess of 5 km at the end of the Cretaceous.

The facies spectrum preserved in the Nanaimo Group is wide, from alluvial-fan, braided-river, and paralic deposits (including extensive coal measures), to upper neritic to mid-bathyal (1200 m) facies. The group is composed of distinct, alternating, dominantly coarse grained or fine grained formations, evidently deposited during times of high or low sediment delivery to the marine basin, related to local tectonic activity and/or secondary, sediment-redistribution processes. Coinciding with variations in sediment influx are real transgressions and regressions marked by superposition of deep-water facies over shallow-water facies, and vice-versa. The transgressions are noted to coincide with cessation of sediment influx to the deeper part of the basin, suggesting that during sea-level highstands, sediment was trapped on the basin margins. Paleo-slopes were steep where measurable (section 4.2.2), and the neritic areas were narrow. Much of the Nanaimo Group consists of amalgamated, coarse grained, sandy, resedimented deep-water sequences for which correlative neritic deposits are absent due to erosion. The eastern parts of Georgia Basin are poorly understood due to paucity of exposure, but the Nanaimo Group clearly onlaps the western flank of the Coast Crystalline Complex in a nonmarine facies, analagous to the onlap of the Sierra Nevada by the Great Valley sequence.

The Paleogene record of sedimentation in the Georgia Basin is confined to the Whatcom Basin, where up to 3 km of Tertiary section is preserved. This Tertiary depocentre developed at about the same time as the Chuckanut Basin to the southeast, and, in a similar manner, may be fault bounded. Extensional faulting in the Comox Basin may also have developed during this time. The Paleogene section is known to overlie the Nanaimo Group in the Whatcom Basin, based on seismic data and well control, but is estimated to have been thin (<1 km) or absent over western Nanaimo Basin and the Comox Basin. From the end of the Cretaceous to at least the mid-Eocene, the Nanaimo and Comox basins remained at or near maximum burial.

In mid- to late Eocene, the Georgia Basin was contracted, probably in response to accretion of the Pacific Rim and Crescent terranes to Vancouver Island at 40 Ma (Clowes et al., 1987). The southwestern Nanaimo Basin and part of southern Comox Basin developed into a thick-skinned fold and thrust belt; whereas, the remainder of the Comox Basin probably rode passively on a deep thrust system, such that it remained mostly undeformed during the contraction. The fold and thrust belt is surmised to have developed by footwall collapse from northeast to southwest, and is now preserved mainly as a leading imbricate fan, exhibiting up to about 30% contraction (10 to 12 km minimum). Subsequent uplift of the entire region during the Cenozoic has resulted in deep exhumation of the western part of the Georgia Basin, and the Cowichan fold and thrust belt, with inferred thicknesses of eroded section generally ranging from about 2 km to 6.6 km. The current erosion level is markedly asymmetrical due to the progressive uplift of Vancouver Island relative to Georgia Strait for the remainder of the Cenozoic. Much of the detritus from the exhumed western part of the Georgia Basin may now lie in the marginal Tofino Basin.

8.5 Summary of conclusions

This intensive analysis of the Nanaimo Group in western Georgia Basin has taken many directions, with much new information gathered along the way. The most important conclusions and contributions are summarized in this section, following the order of presentation in the thesis.

Structural Geology

The deep crustal architecture of Vancouver Island was revealed following the results of deep seismic profiling across the study area (Yorath et al., 1985a) and field studies by Sutherland Brown and Yorath (1985). Several large, northeast-dipping faults were recognized, which field relations show to be thrusts. The study of these and related faults in southwestern Georgia Basin by the author has led to the recognition of a large, southwest-verging, linked fold and thrust belt - the Cowichan fold and thrust belt - involving both the Nanaimo Group and Wrangellian basement rocks. The macroscopic structural geometry of the belt clearly establishes the genetic relationship between faults and folds developed in an orthogonal contractional setting, thereby distinguishing it from extensional, transtensional, or transpressional belts. Additional support is provided by small-scale kinematic indicators in the Nanaimo Group in the fault blocks. Thus, the previous perception of the structural style of southwestern Georgia Basin by Muller and Jeletzky (1970), involving high-angle fault blocks and strike-slip faults separating asymmetrical grabens, is shown to be erroneous.

Five tentatively balanced profiles of the thrust belt (Figures 2.6 to 2.9, and 2.11) display its overall geometry as a leading imbricate fan that was at least partly emergent during orogenesis. Contraction is estimated to be a minimum of from 18 to 31% (9 to 12 km). Fault propagation by footwall collapse is evidenced by deformed footwall synclines and possible footwall duplexes. The faults are interpreted to sole on a moderately northeast-dipping sole fault, and hence cut the surface at a high angle. The sole fault is interpreted to be a southeast-trending segment of the San Juan Fault, extending from north of Shawnigan Lake to Haro Strait. It must then be offset along a north-striking lateral ramp, the Sidney fault, linking to the President fault, which forms the boundary between the San Juan Terrane and the Nanaimo Basin (and its Wrangellian basement), within the northern San Juan Islands (Figures 1.2 and 2.2).

Overall, there appears to be large displacement transfer from stacked basement thrust sheets in the northwest, to the fewer, higher thrusts in the east, as evident by the inferred position of the branch lines in the system and the reduced width of the thrust belt in the southeast. This imposes a major macroscopic non-cylindricity to the system, the whole thrust system essentially plunging to the west.

The timing of contraction is estimated to be mid- to late Eocene, coincident with or driven by accretion of the Pacific Rim and Crescent terranes to southern Vancouver Island (Clowes et al., 1970). This timing is supported by thermal history modeling of the Nanaimo Basin, which requires that it remained buried from Late Cretaceous to mid-Eocene, and preliminary fission-track dating of uplift of detrital and plutonic apatite from the study area (England and Massey, in preparation).

To the northwest, the CFTB passes into the relatively undeformed part of the Comox Basin, which exhibits a contrasting structural style, and thus is considered as a separate structural province in the thesis. Contraction in this province is suggested to have occurred along a deeply rooted thrust, such that the entire Comox Basin is in essence an undeformed thrust sheet. The surface structural style in the northern province is characterized by extensional faults with associated minor folding as illustrated by one long profile (Figure 2.20) and a coulisse of vertical sections across Alberni Valley (Figure 2.21). In the western part of the province, several large faults occur with inferred normal dip slip, that have previously been interpreted as thrusts. The Beaufort Range Fault Zone, for example, is interpreted as a large normal fault system, based on its macroscopic geometry, small-scale kinematic indicators, and vitrinite reflectance data. The timing of this extensional episode is unknown, but there is some indication that it post-dates the contractional episode. It may have coincided with the Catface magmatic episode, which ranges from early Eocene to Oligocene (Armstrong, 1987).

Most importantly, the structural deformation of the Georgia Basin occurred in the Cenozoic, for it involved even the very youngest Nanaimo Group. Therefore, it post-dates the Cretaceous episode of basin formation, and the prominent faults in the basin did not exist during sedimentation. Thus, they could not have influenced sedimentation at all. The concept of an older history of movement on these faults is dismissed due to the lack of fault scarp detritus, facies and bed thickness continuity across the faults, and the lack of an early movement record based on analysis of small-scale kinematic indicators in the Nanaimo Group. As such, in considering the paleogeography of the Georgia Basin, it is important to realize that much of the present day relief in the basin is due to post-depositional deformation.

Stratigraphy

A thorough study of Nanaimo Group stratigraphy, based on eight months of fieldwork and compilation of extant data from many sources, has led to a reexamination of the validity of some of the changes in stratigraphic nomenclature introduced by Muller and Jeletzky (1970). These authors "simplified" the existing lithostratigraphy of the group on the basis of biostratigraphic correlation, which is completely inadmissable according to the North American stratigraphic code. It is proposed to reinstate previously established formation names such as the Benson, Trent River, Denman, and Lambert formations. It is also necessary to create new names for units in the Nanaimo Basin - the Galiano and Mayne formations - to replace the use of "Geoffrey" and "Spray" formations in the Nanaimo Basin: these are Comox Basin formations which cannot be correlated with confidence to the Nanaimo Basin. As a result of more detailed work, the Benson Formation is subdivided into the basal coarse grained Tzuhalem member, and the upper fine grained Saanich member. The "Benson" Member of the Comox Formation is replaced by the Cottam Point member, as Benson is a formation name in the Nanaimo Basin. Coarse grained units of limited geographical extent within the Trent River Formation are referred to as the Tsable and Parksville members. The Oyster Bay formation is introduced for coastal Nanaimo Group exposures near Campbell River.

The intent of making these changes is to clearly separate the concepts of litho- and biostratigraphy in the Nanaimo Group, and to remove from the literature the obvious inaccuracies of lithostratigraphic correlations made over distances of up to hundreds of kilometres. The addition of new formation names facilitates accurate description of discrete rock units within the group. It is hoped that these changes will be incorporated in the scheme when the stratigraphy of the Nanaimo Group is formally defined.

The fieldwork contribution is significant, with the collection by the author of 130 foraminiferal assemblages (Cameron, 1988a, b), 55 macrofossil assemblages (Haggart, 1988a, b), and the recognition of trace fossils at 30 localities in the Nanaimo Group. The microfossil data are crucial to the paleo-environmental interpretation, and confirm the Maastrichtian age for much of the Gabriola Formation. The macrofossil data confirm the extant biostratigraphic scheme for the Nanaimo Group, as reviewed in section 3.5. Important contributions from the macrofossil collection are that the base of the Nanaimo Group has been pushed back in time to include Turonian-Coniacian strata in southern Nanaimo Basin, and several new species were discovered, some of them in the youngest parts of the Nanaimo Group, where there is little macrofossil control. Finally, the concept of condensed neritic sections has been introduced to explain the apparently closely stacked biozones in the Cedar District Formation on Sucia Islands and in the Oyster Bay formation at Shelter Point.

Regional facies analysis

Regional analysis of facies associations developed in the Nanaimo Group shows the broad spectrum of depositional environments that existed in the Georgia Basin during the Late Cretaceous. Alluvial (piedmont), braided-river, braid-plain, and paralic deposits occur, as well as a variety of marine deposits. The paralic deposits include significant coastal-plain coal deposits. In the marine deposits, a wide range in grain size is present, largely due to resedimentation processes, which transported large volumes of coarse grained detritus into deep-water environments. The resulting deposits are interpreted as amalgamated, coarse grained, sandy submarine-fan deposits. Three possible feeder-channel deposits have been identified (1 to 4 km wide, several hundred metres deep).

The marine biofacies scheme is constructed on the basis of foraminiferal assemblages (Cameron, 1988a). Three neritic facies and two bathyal facies are recognized. However, macrofossil assemblages are tied into this scheme and reveal much more about the environments of deposition in terms of organic diversity and richness. Open oceanic circulation during deposition is indicated.

The regional facies analysis has dispelled the notion of a deltaic origin for many of the coarse grained Nanaimo Group sandstones. The recognition of deep-water trace fossil assemblages (with the advice of G. Narbonne, personal communication, 1989), and the collection of deep-water foraminifera from shale layers within the coarse grained formations, confirms their deep-water origin. Previously, many of these units were reported to be devoid of marine indicators. Most of these sandstones were deposited in paleo-water depths of 200-600 m, some of them as deep as 1200 m (Cameron, 1988a, b). The general paleo-water depth range of many of the formations is established from Cameron's work. The recognition of a large paleo-bathymetric range in the basin accords with that observed in other coarse grained flysch basins. The concept that the cyclicity in the group was produced by deltaic progradation and regression is untenable given the constant deep-water conditions prevailing in many parts of the basins.

A series of facies maps is presented for successive time-stratigraphic divisions of the Nanaimo Group. These show the facies progression during development of the Nanaimo and Comox basins. It is clear from these maps that much of the facies record is missing due to erosion, with basin-margin facies preserved only in southeastern and northwestern Nanaimo Basin, and in western Comox Basin. An important observation based on these maps is the marked shift in paleocurrent directions from neritic to bathyal deposits.

The importance of the provenance data to the study has already been addressed in section 8.3.

Vitrinite reflectance

Vitrinite is common and widely dispersed in the Nanaimo Group, and therefore was used to determine levels of organic maturation. The vitrinite reflectance database comprises over 614 samples, 317 of which were measured by the author. Regional levels of organic maturation in the Comox Basin are attributed to a normal burial history of eogenesis and catagenesis. They range from 0.32 to 1.1 $\%R_0$. Elevated levels of maturation - up to 4.4 $\%R_0$ - are associated with the Catface Intrusions, and are therefore interpreted to be related to contact metamorphism. Regional levels of maturation in the Nanaimo Basin range from 0.40 to 1.25 $\%R_0$. Elevated levels - up to 2.66 $\%R_0$ - in southwestern Nanaimo Basin are interpreted to reflect greater depths of burial due to tectonic loading by basement and cover rock along thrust faults. The pattern of increased $\%R_0$ levels in the footwall cover rock of the faults, compared to $\%R_0$ levels in the hanging wall cover rock, is important independent evidence that the faults are thrusts.

Low levels of organic maturation in the Nanaimo Group on the northern San Juan Islands demonstrate that the Nanaimo Group was <u>not</u> overthrust by the leading edge of the San Juan Nappe pile, as hypothesized by Brandon et al. (1988).

The most complete surface sections of the Nanaimo Group examined have reflectance/depth gradients ranging from 0.17 to 0.21 log $\%R_0$/km. In these sections, there is 1.3 to 2.0 km of "missing" section which lies offshore or may have been removed by erosion. Elsewhere, the degree of erosion is much more substantial, ranging from 1.6 to 4.2 km for the

Comox Basin, and 2.0 to 6.6 km in the Nanaimo Basin. The thickness of the removed section, however, is easily accounted for in consideration of the restored thickness of the Nanaimo Group plus possible Paleogene section (up to 5.4 km) and, locally, overthrust wedges of basement rock.

Much of the Nanaimo Group at the surface and in the subsurface lies within the oil window. Overthrust strata are generally within the wet gas window in southwestern Nanaimo Basin. Where influenced by contact metamorphism, the Nanaimo Group may lie within the dry gas window. Hydrocarbon generation is estimated to have begun in the early Paleogene, prior to the development of the main structures in the Comox and Nanaimo basins, which greatly reduces the hydrocarbon potential of the region.

Burial History Analysis

Subsidence history analysis of southern and central Nanaimo Basin indicates rapid tectonic subsidence, with a linear time dependence, implying a constant tectonic driving force acting over the 22 m.y. of recorded sedimentation (88.5 to ca. 66.5 Ma). This driving force is attributed to lithospheric downwarping related to the subduction process (eg. Yorath and Hyndman, 1983). Northern Nanaimo Basin and central Comox Basin subsided with a slightly different pattern (section 8.4) consisting of several linear segments. No exponential decay pattern is present in the data, so there is no support for thermally driven subsidence.

Present day heat flow in the study area is low, ranging from 34 to 52 mW/m^2. Low heat flow is characteristic of forearc regions and is attributed to subduction of cold, wet oceanic lithosphere which acts as a regional heat sink. Thermal history modeling of sites in the Nanaimo and Comox basins shows, however, that heat flow during the time of maximum burial of the Nanaimo Group must have been slightly elevated - 48 to 58 mW/m^2 - compared to the present day, but still fairly low by global standards.

With such low heat flow the Nanaimo Group must have remained buried for at least another 20 m.y. following the 22 m.y. record of Late Cretaceous sedimentation so that calculated levels of maturation match measured levels of maturation. This part of the analysis is predicated on the correlation of the time-temperature integral employed to vitrinite reflectance, which is established from basin studies around the world. As such, it is interpreted that the Nanaimo Group remained buried until the late Eocene, after which it was rapidly uplifted with little further gain in maturation. Fission-track data for time of uplift of plutonic and detrital apatite in the study area, support this claim (England and Massey, in preparation). The slightly elevated heat flow during the time of maximum burial may be attributed to higher regional heat flow related to the 50 Ma magmatic episode of the Coast Crystalline Complex (Armstrong, 1987), coinciding with the opening of the Whatcom and Chuckanut basins, and thermal activity related to the Catface Intrusions.

8.6 Future work

This study has focused on two main phases in the evolution of the Late Cretaceous Georgia Basin: its initial development, and subsequent contraction. One element of the study that may provide scope for further research is the role that basement has played in the evolution of the basin.

If the Georgia Basin initially subsided due to flexing of the lithosphere, then the lithosphere was either thin or mechanically discontinuous (section 6.4). Also, between different areas of the basin, apparent differences in yield behaviour or in amounts of tectonic subsidence, imply that there are local differences in the constitution and/or rheology of the lithosphere. For example, the areas associated with the Nanoose Arch, central Comox Basin and northern Nanaimo Basin, display different subsidence behaviour compared to that displayed in southern and central Nanaimo Basin. Perhaps the lithosphere in the Nanoose area is thicker and/or strain hardened. Lithospheric heterogeneity is also manifested during subsequent contraction of the Georgia Basin, when a strong contrast in structural style emerged between the Comox Basin area, which possibly behaved as one large plate, and the Nanaimo Basin, where a large imbricate fan developed. The lithosphere in the Nanaimo Basin area must have been much weaker, possibly much thinner, than in the Comox Basin area.

Thus, from this study it appears that the lithosphere in this forearc region is not behaving uniformly and is probably mechanically discontinuous. Future burial history modeling of the Georgia Basin will have to reckon with this factor.

The Cowichan fold and thrust belt, which involved Nanaimo Group <u>and</u> its Wrangellian basement, is well exposed and worthy of further study. The (partly) balanced cross-sections could be reworked, utilizing a computer program, to identify different permissible solutions. Through field studies, tighter constraints could be placed on estimating the amounts of layer-parallel shortening for individual units within the fault blocks.

Stratigraphic and sedimentological studies of the resedimented, coarse grained, deep-water facies of the Nanaimo Group should be continued. Worldwide, relatively few examples of these facies are available for study. The favourable exposure and ideal working conditions should gaurantee that these rocks will form the basis for many more studies.

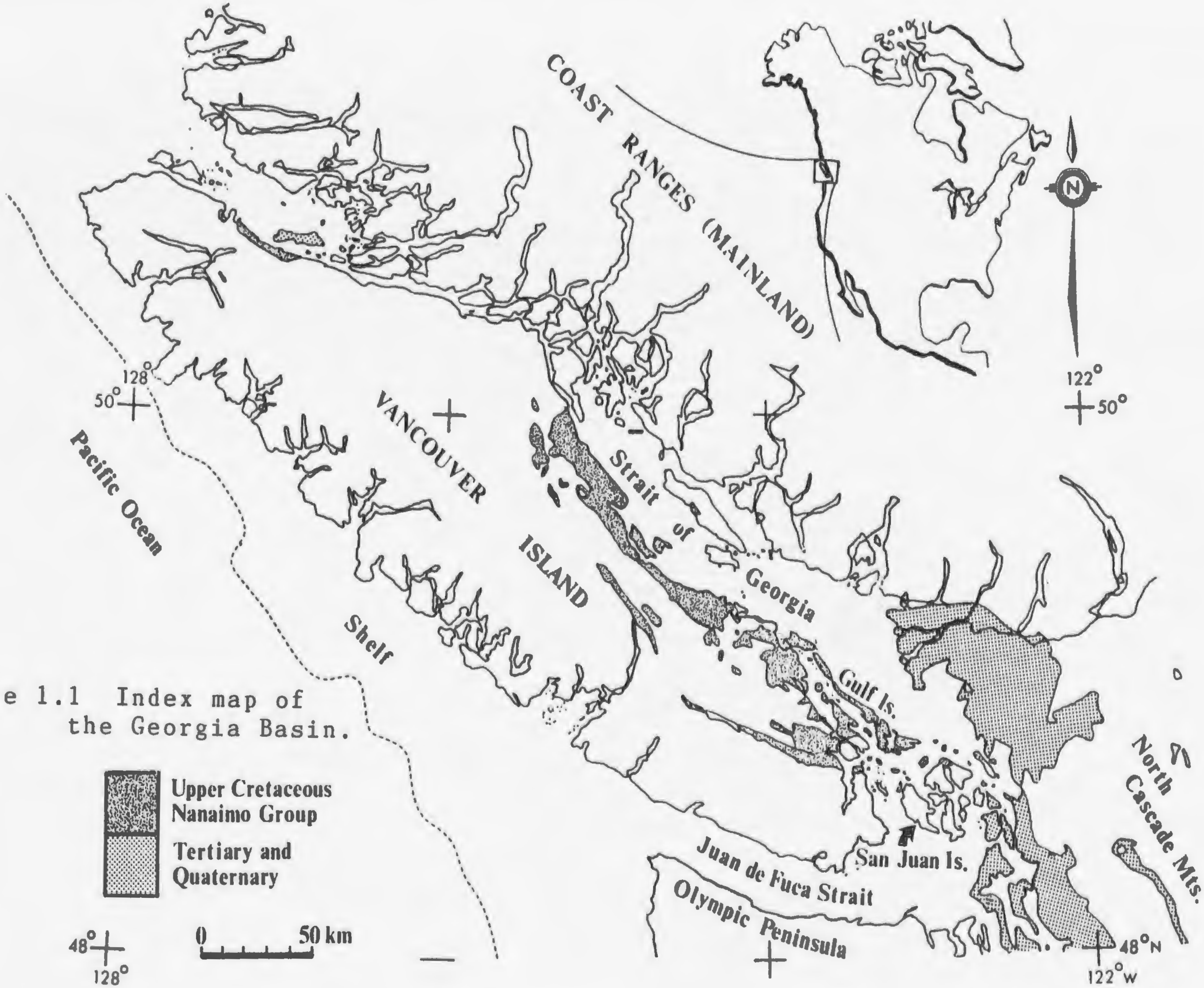


Figure 1.1 Index map of the Georgia Basin.

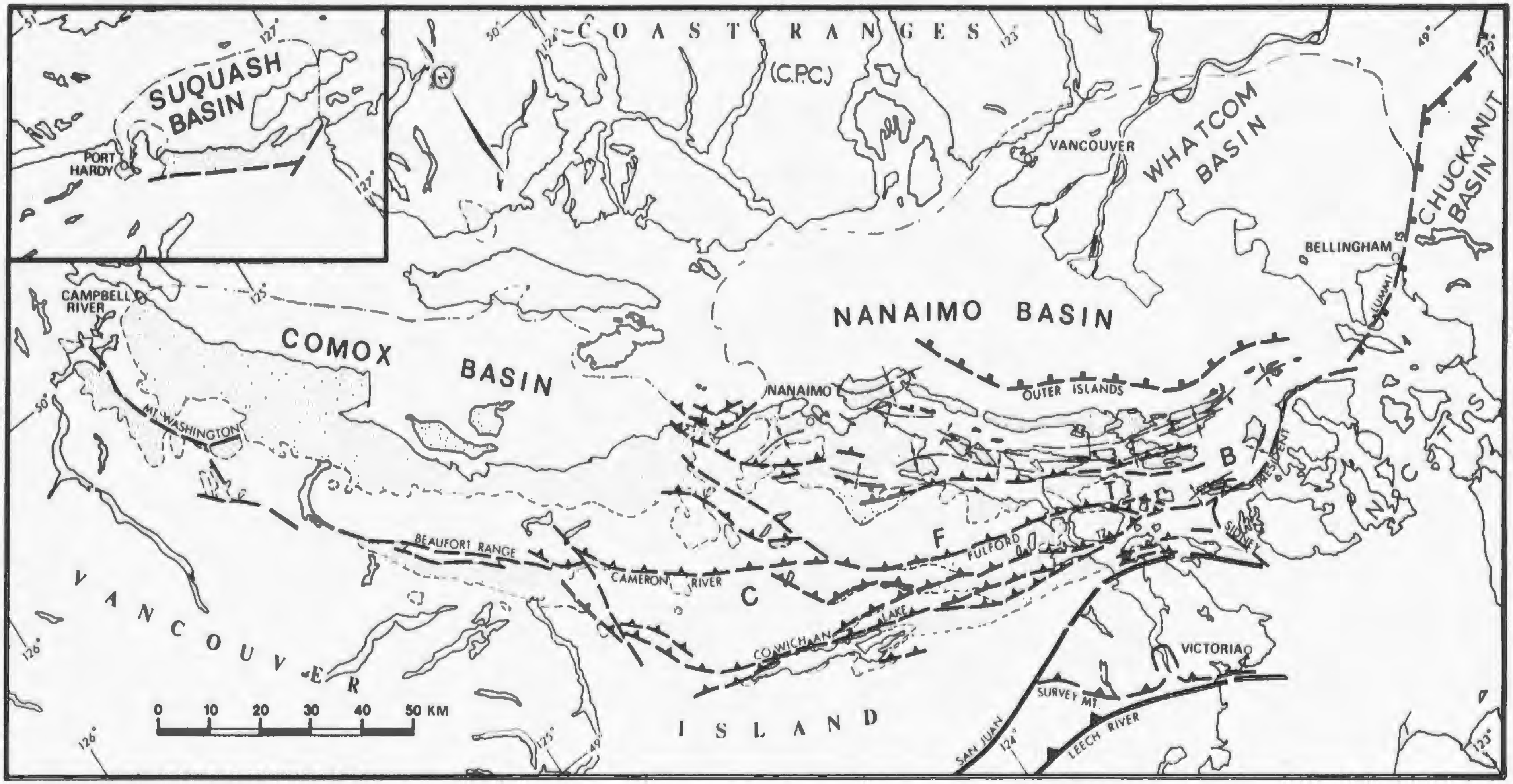


Figure 1.2 Regional map of the Georgia Basin. The Nanaimo Group outcrop areas are stippled.

WR = Wrangellia   SJ = San Juan   PR = Pacific Rim   CR = Crescent

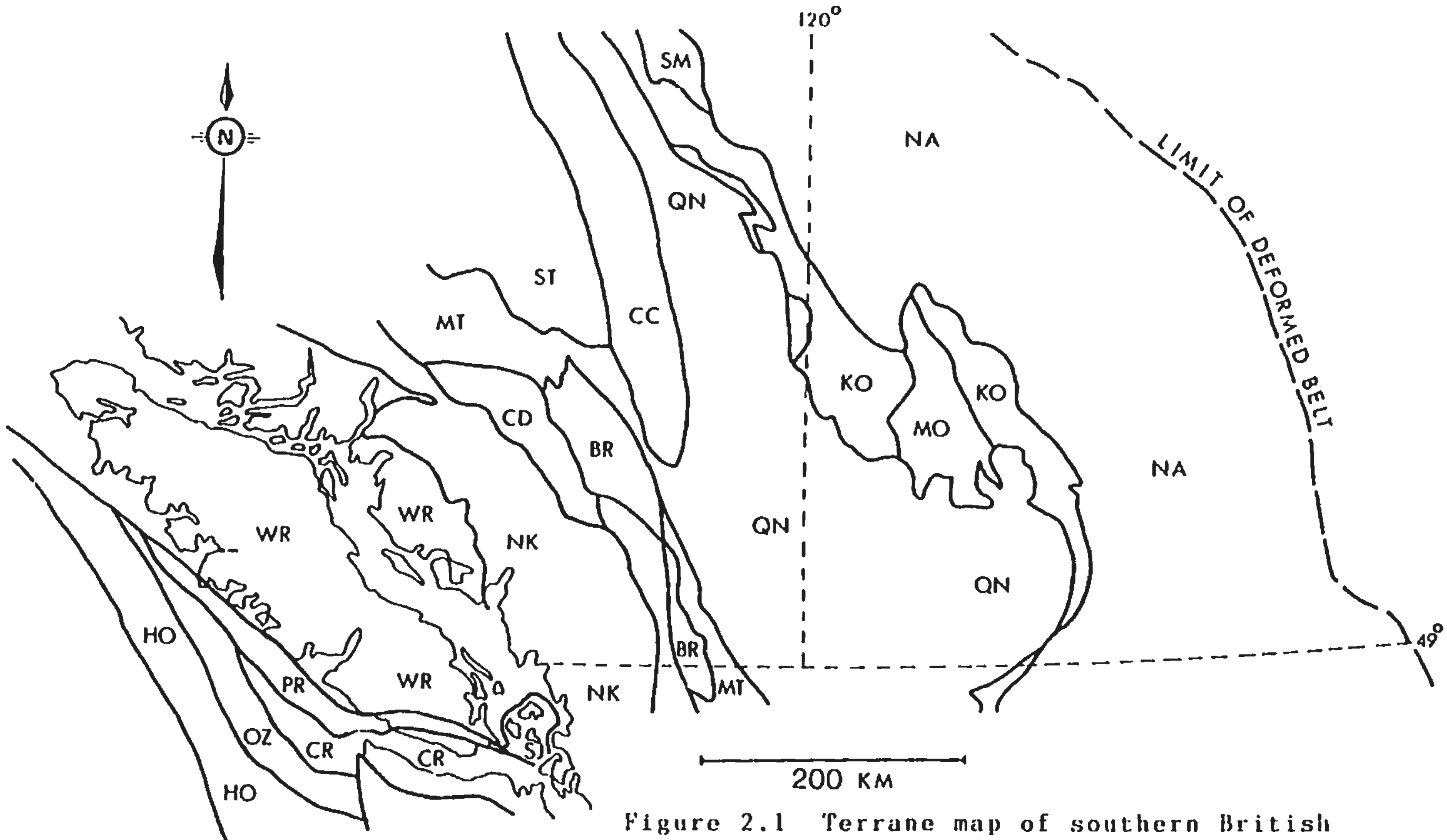
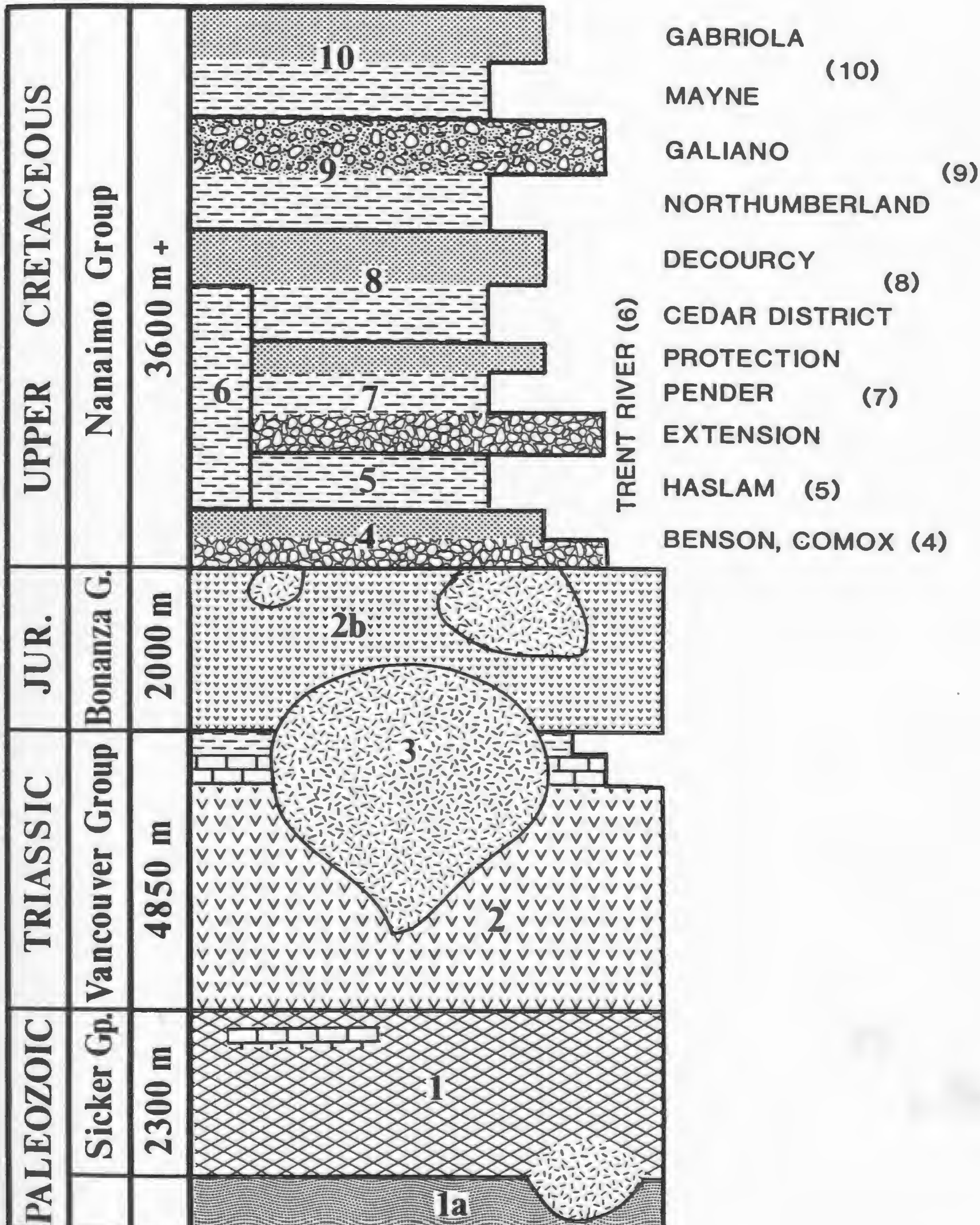


Figure 2.1 Terrane map of southern British Columbia (after Monger et al., 1985).

Figure 2.2 Geological map of the southern structural province.

Figure 2.4 Simplified stratigraphic column of the study area.



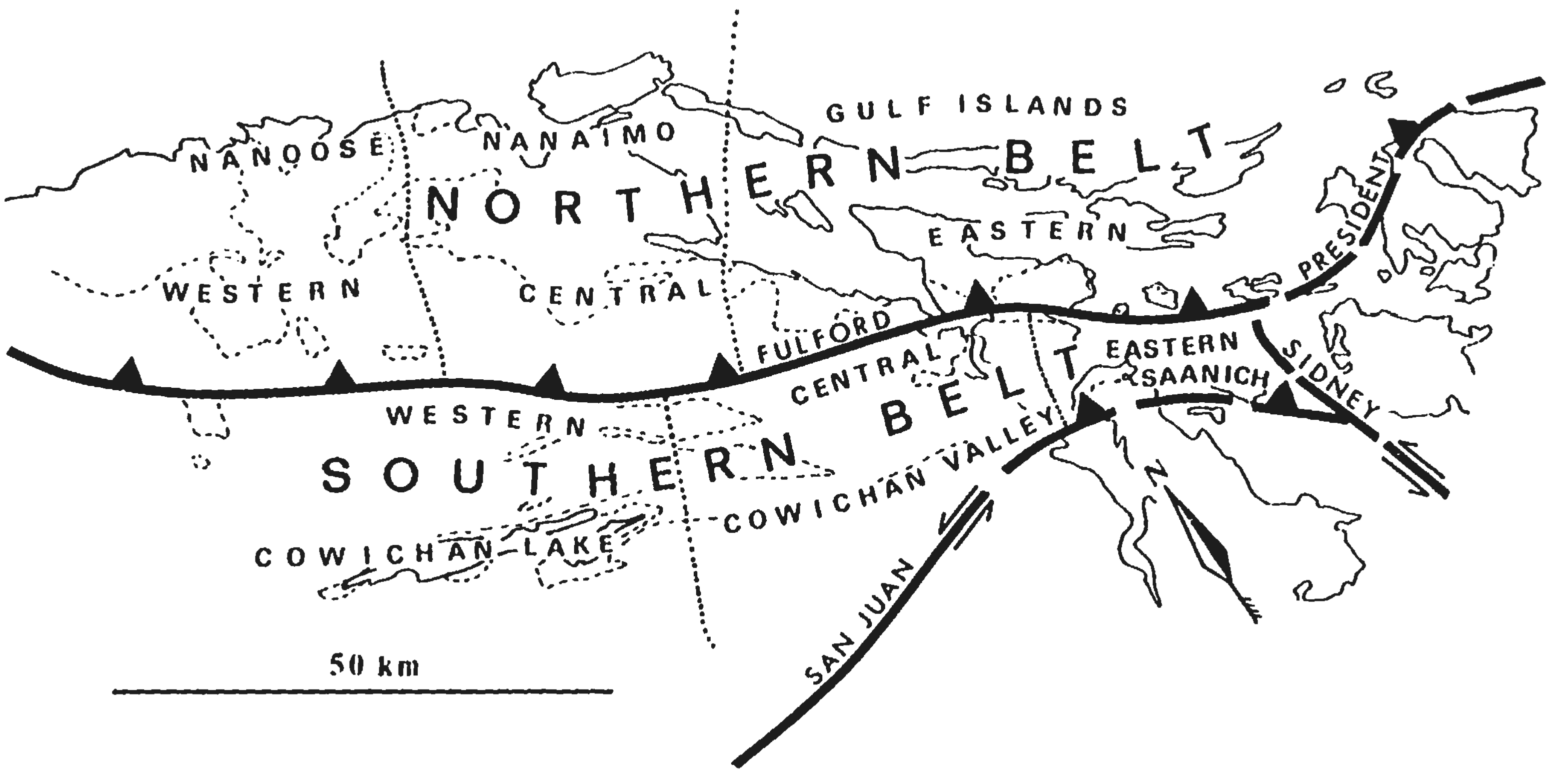


Figure 2.5 Structural and geographical subdivision of the Cowichan fold and thrust belt.

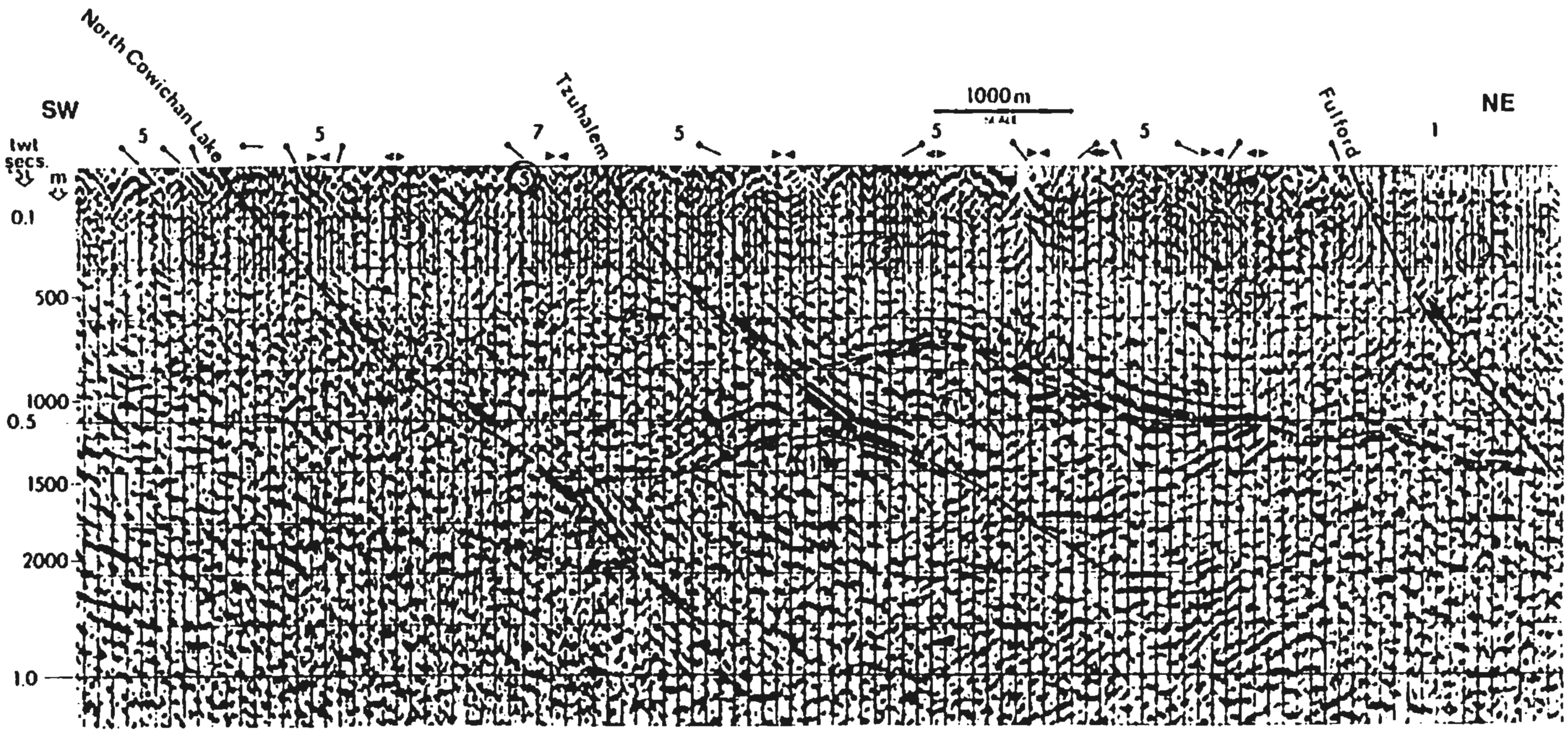


Figure 2.10 Seismic line from the Cowichan Valley (see Figure 2.2) which supports the interpretation of the structural style of the southern belt of the Cowichan fold and thrust belt. The data are provided by BP Canada Resources Limited and were acquired in 1985 using an array of 4 Mertz vibrators; CDP coverage is 3000%. The data have been migrated. Key for units is Figure 2.4.

Figure 2.12 Lower hemisphere equal area projection of poles to bedding (S_o) measured in the eastern half of the northern belt.

Figure 2.13 Lower hemisphere equal area projection of poles to S_o from the central part of the southern belt.

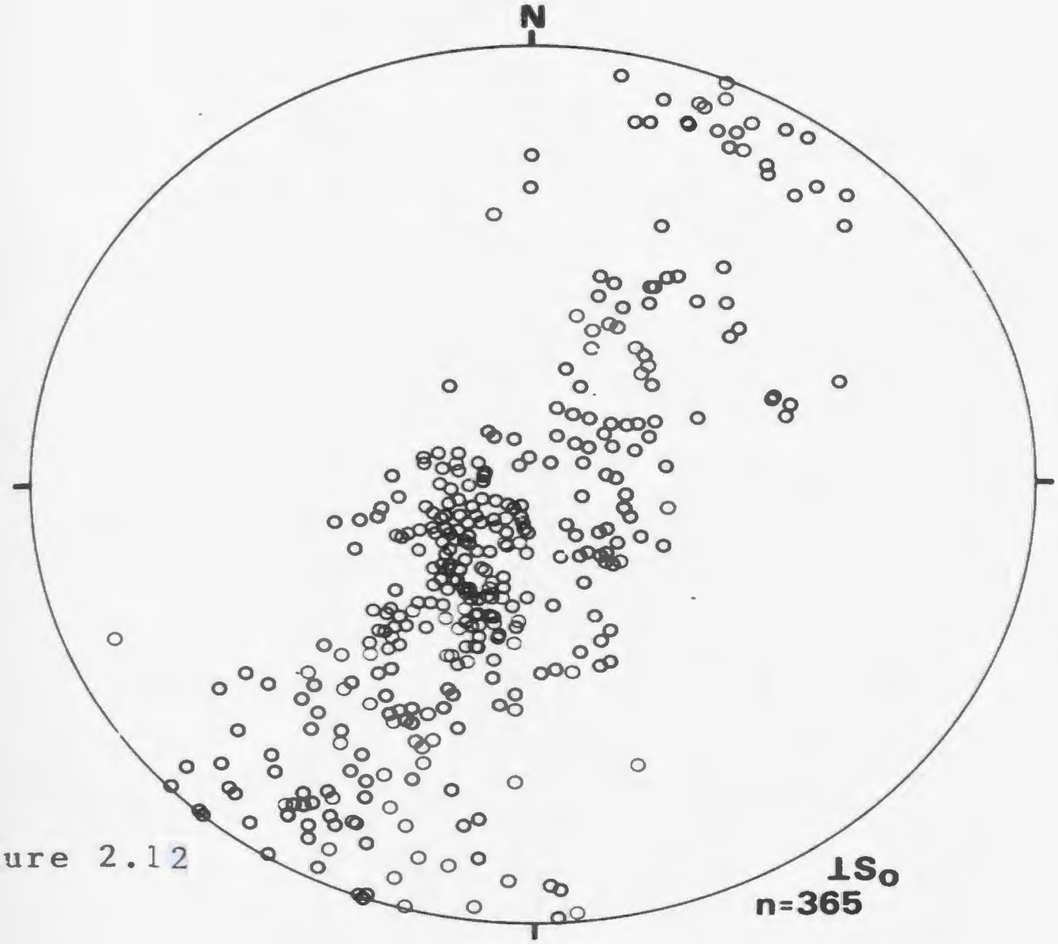


Figure 2.12

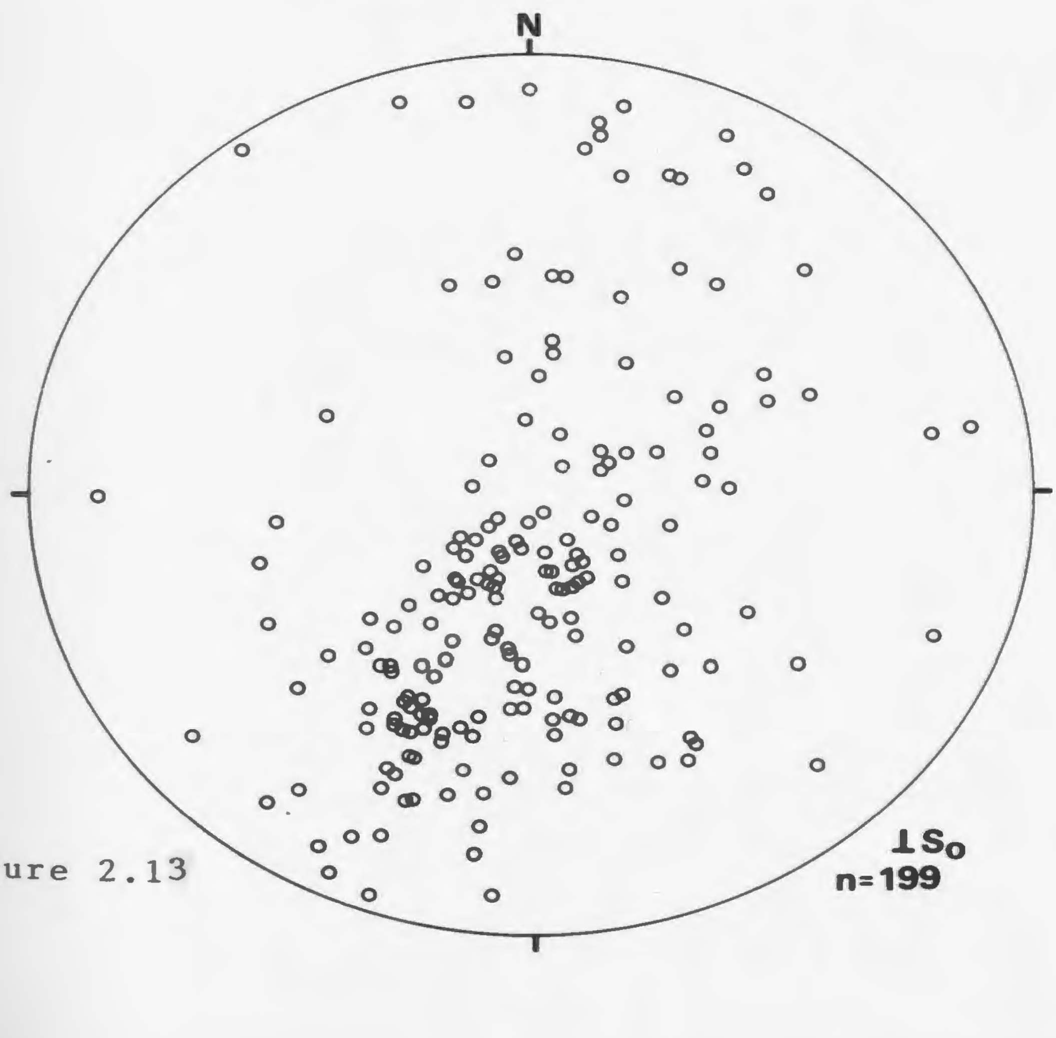


Figure 2.13

Figure 2.14 Lower hemisphere equal area projection of poles to S_o from the eastern part of the southern belt.

Figure 2.15 Lower hemisphere equal area projection of poles to cleavage (S_1) from the central part of the southern belt.

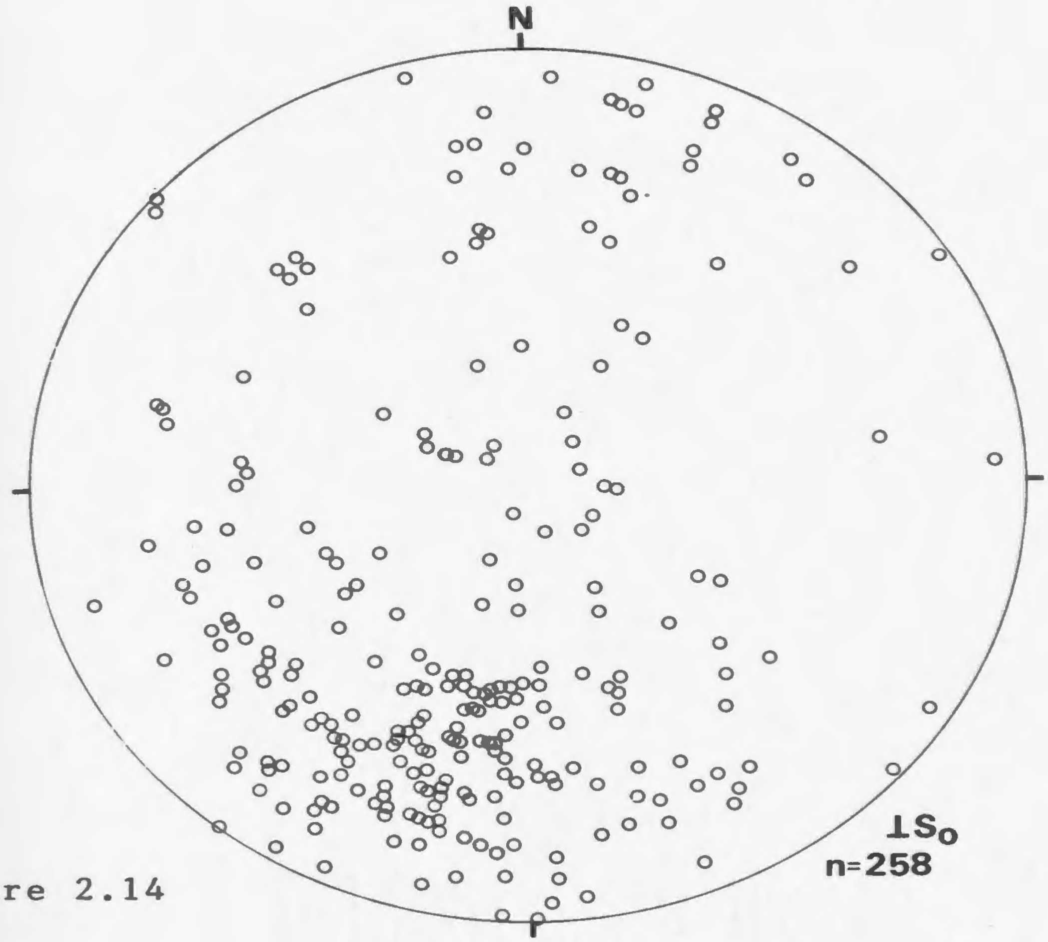


Figure 2.14

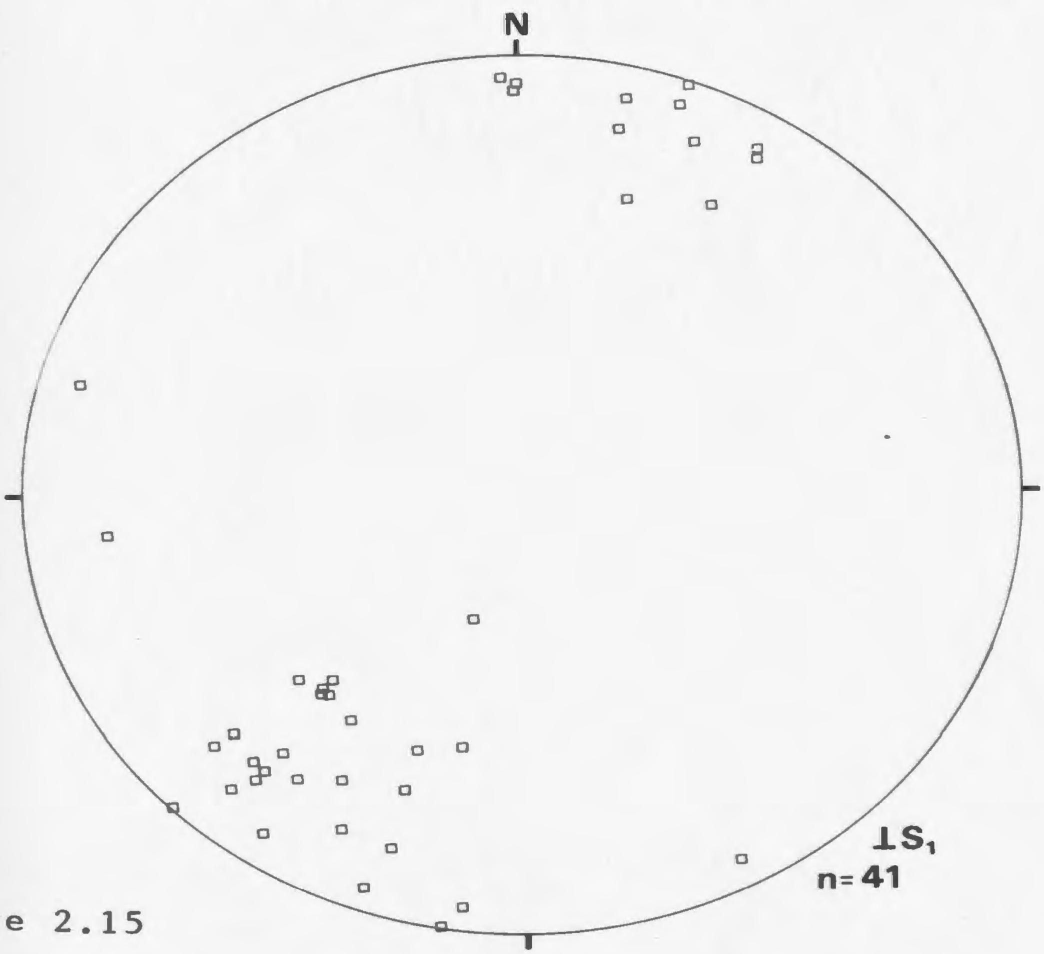


Figure 2.15

Figure 2.16 Lower hemisphere equal area projection of poles to S_1 from the eastern part of the southern belt.

Figure 2.17 Lower hemisphere equal area projection of F_1 fold axes from the central and eastern parts of the southern belt.

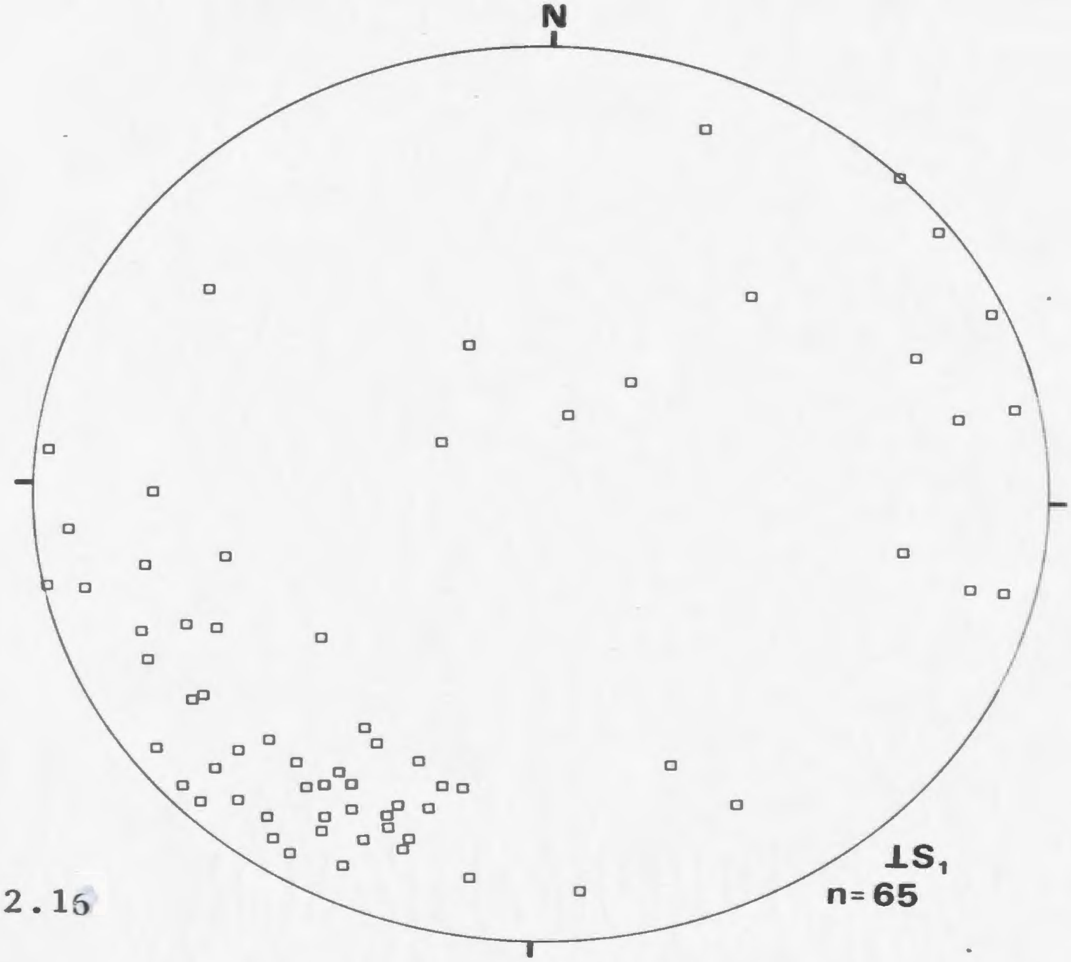


Figure 2.16

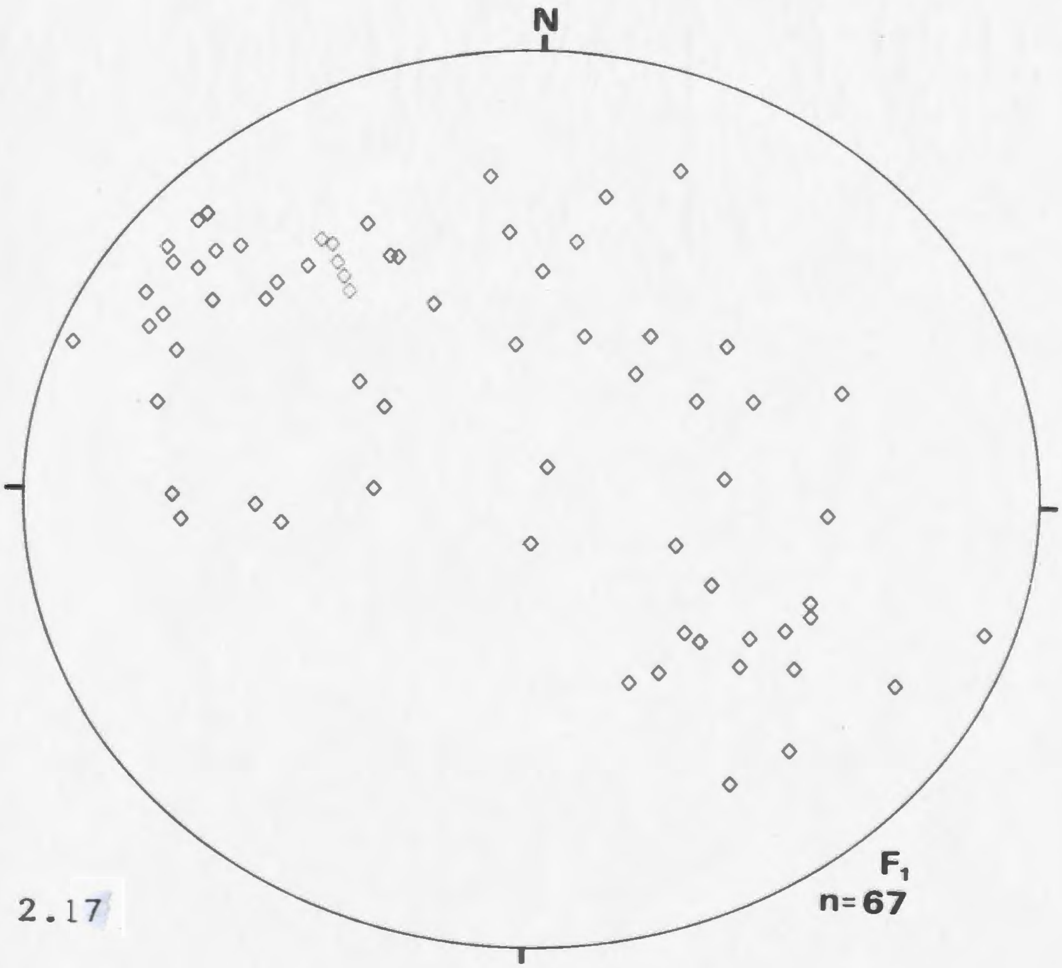


Figure 2.17

Figure 2.18 Lower hemisphere equal area projection of structural data for the Maple Bay area. Note the general northwest plunge of the fold axes. Kinematic indicators such as slickensides (s) and fault grooves, as well as tension gashes (x = perpendicular to tension gashes on S_o) indicate dip-slip motion of the Nanaimo Group in the foot-wall of the Fulford Fault. a = tectonic transport direction.

Figure 2.19 Lower hemisphere equal area projection of poles to fault planes in the eastern area of the southern belt. The majority of the fault planes dip to the northeast. Slickensides measured on these planes confirm dominantly dip-slip motion. The data with solid symbols are from Cape Keppel, southern Saltspring Island where the Tzuhalem Fault is exposed (see Figure 2.2).

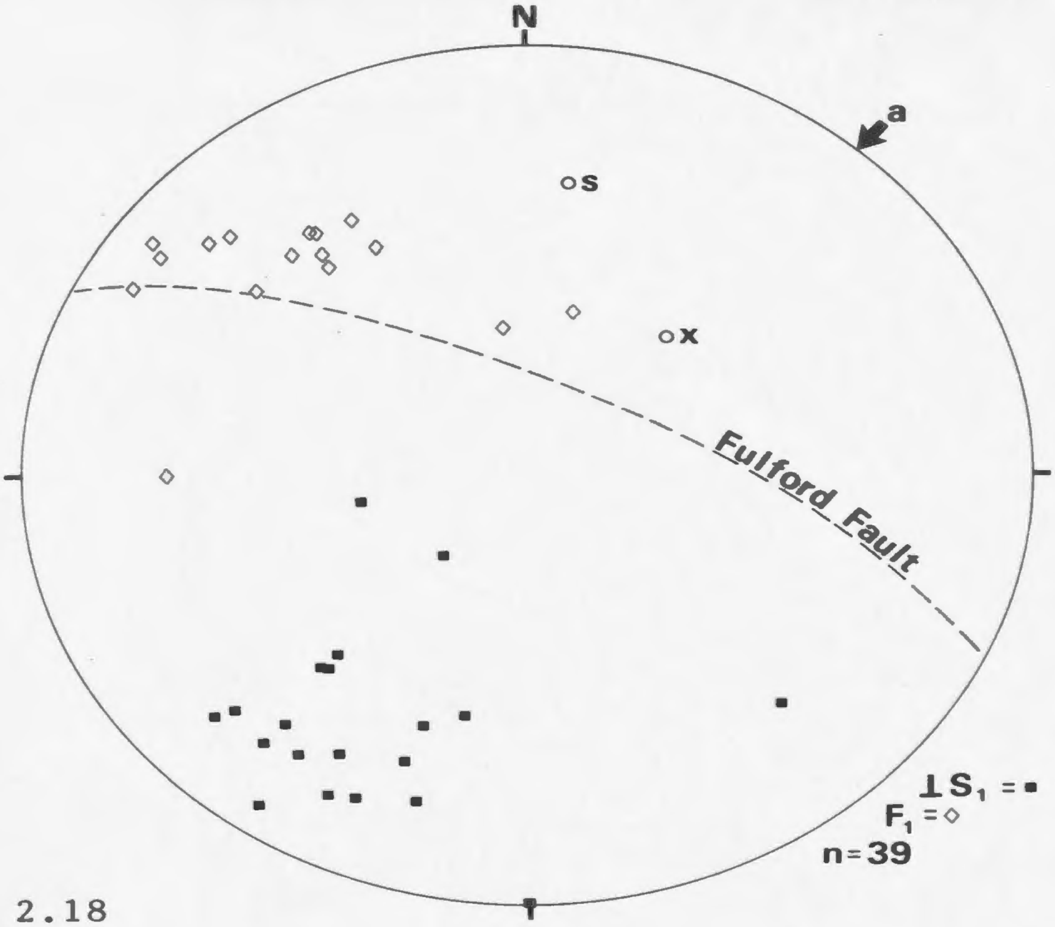


Figure 2.18

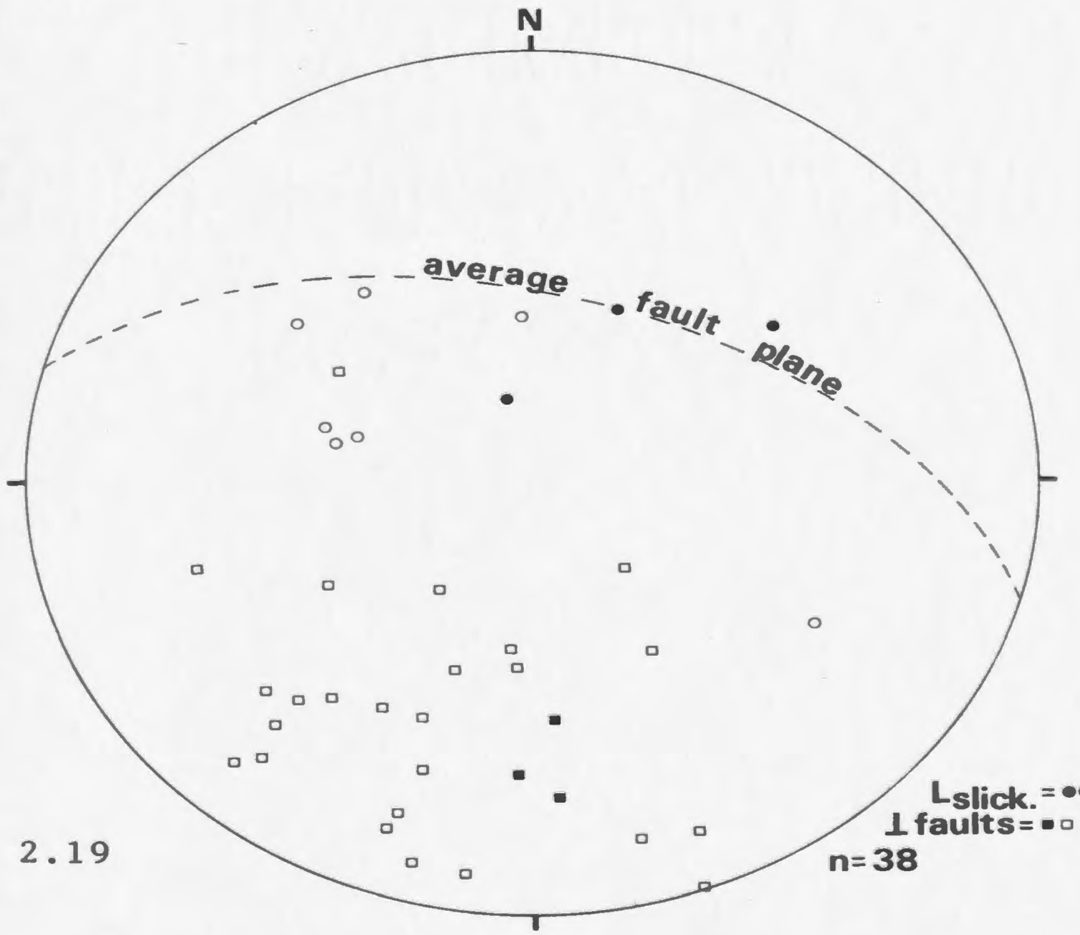
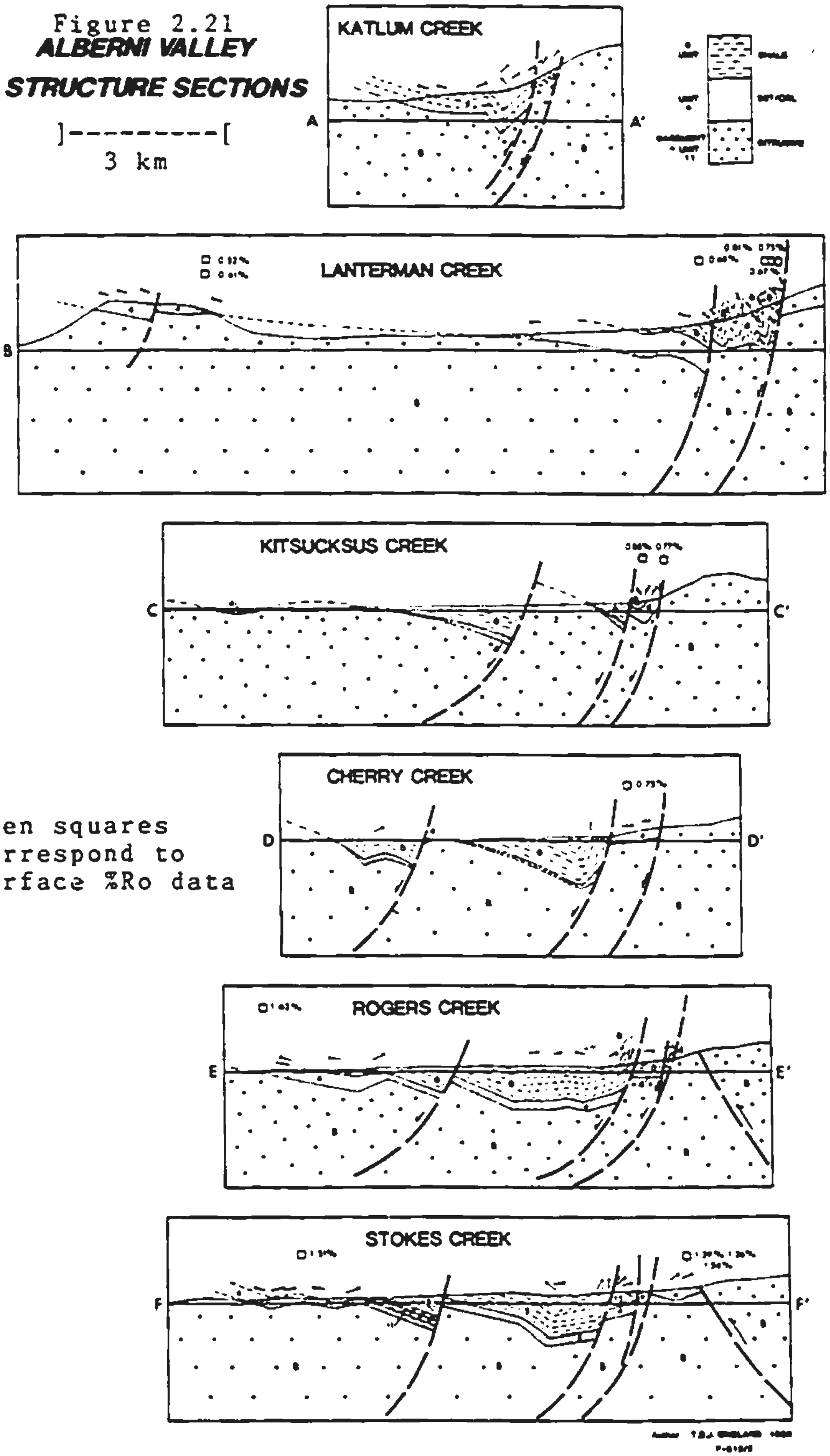


Figure 2.19

Figure 2.21
ALBERNI VALLEY
STRUCTURE SECTIONS

]---------[
3 km



Open squares
correspond to
surface %Ro data

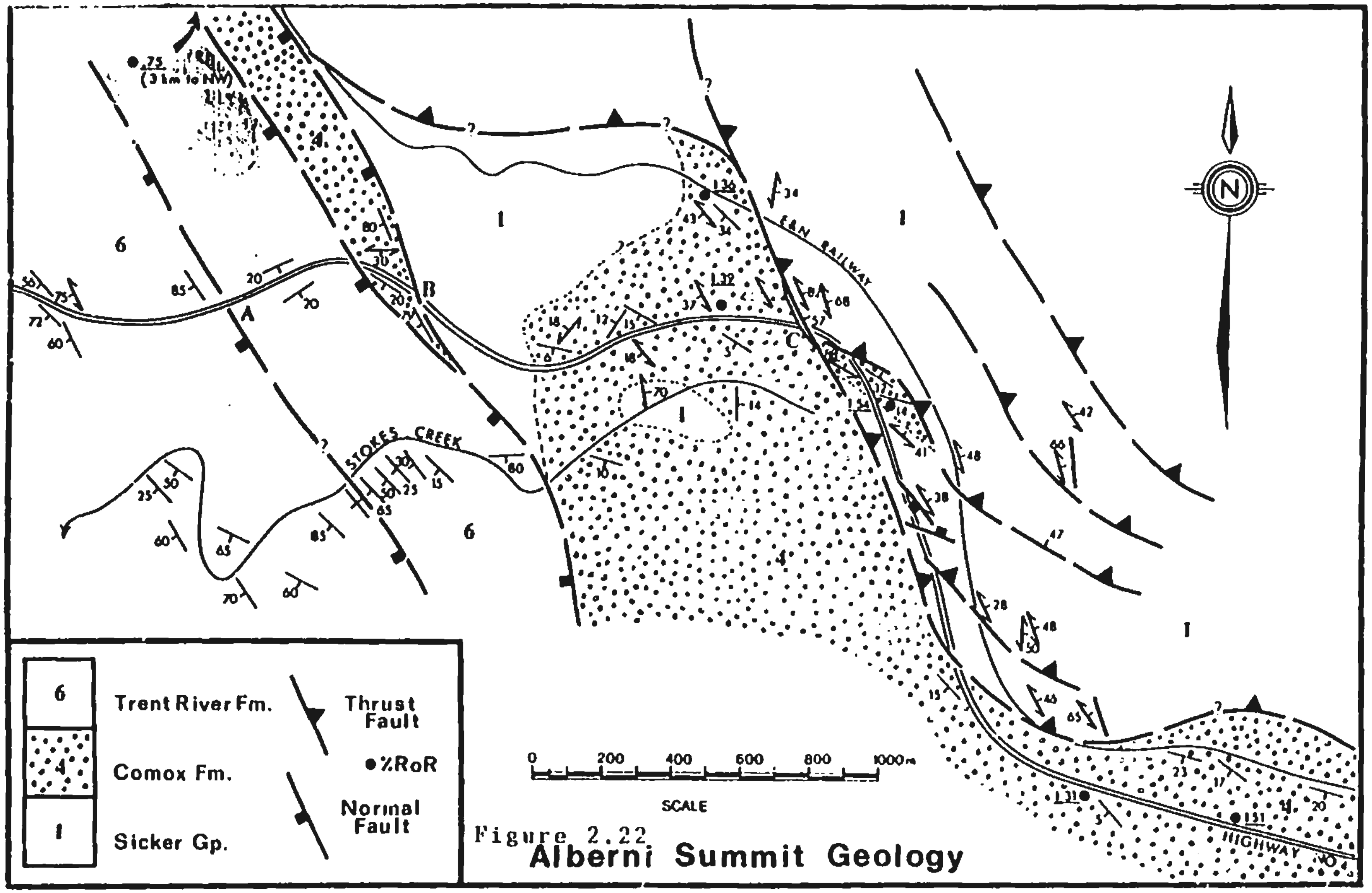


Figure 2.22
Alberni Summit Geology

Table 3.1 Lithostratigraphy of the Nanaimo Group. Numbers are keyed to references listed at the bottom of the table.

COMOX BASIN:		
Hornby Fm.	Sst. and cgl.	4
Spray Fm.	Sh. and minor sst.	4
Geoffrey Fm.	Cgl. and sst.	4
Oyster Bay fm.	Sst., sltst., and cgl.	9
Lambert Fm.	Sh. and minor sst.	4
Denman Fm.	Sst., cgl., and minor sh.	4
Trent River Fm.	Sh., minor cgl., sst. and sh.	1, 3
Tsable mbr.	Cgl., sst. and minor sh.	8
Parksville mbr.	Cgl. and sst.	8
Comox Fm.	Sst., sh. and cgl.	1
Dunsmuir mbr.	Sst. and coal	7
Cumberland mbr.	Sltst., sst., sh., coal	7
Cottam Point mbr.	Cgl. and sst.	8
NANAIMO BASIN:		
Gabriola Fm.	Sst., cgl., minor sh.	2
Mayne fm.	Sh. and minor sst.	8
Galiano fm.	Cgl., sst., and minor sh.	8
Northumberland Fm.	Sh. and minor sst.	5
De Courcy Fm.	Sst., cgl. and minor sh.	2
Cedar District Fm.	Sh. and minor sst.	2
Protection Fm.	Sst., sltst., cgl. and coal	2
McMillan mbr.	Sst. and sltst.	7
Reserve mbr.	Sltst., sst. and coal	7
Cassidy mbr.	Sst. and cgl.	7
Pender Fm.	Sh., sltst., sst., cgl. and coal	6
Newcastle Mbr.	Sh., cgl. and coal	2
Cranberry Mbr.	Sst. and sltst.	2
Extension Fm.	Cgl., sst., sltst., and coal	2
Millstream mbr.	Cgl. and coal	7
Northfield mbr.	Sltst., sst. and coal	7
East Wellington Mbr.	Sst. and sandy sh.	2
Haslam Fm.	Sh., sltst. and minor sst.	2
Cowichan Mbr.	Sh. and minor sst.	6
Haslam Creek Mbr.	Sh. and sltst.	6
Benson Fm.	Cgl., sst. and sh.	2
Saanich mbr.	Sst. and sh.	8
Tzuhalem mbr.	Cgl. and sst.	8

1. Clapp (1912c); 2. Clapp (1914b); 3. MacKenzie (1922); 4. Usher (1952); 5. Muller and Jeletzky (1970); 6. Ward (1978a); 7. Bickford and Kenyon (1988); 8. England (1989); 9. This study.

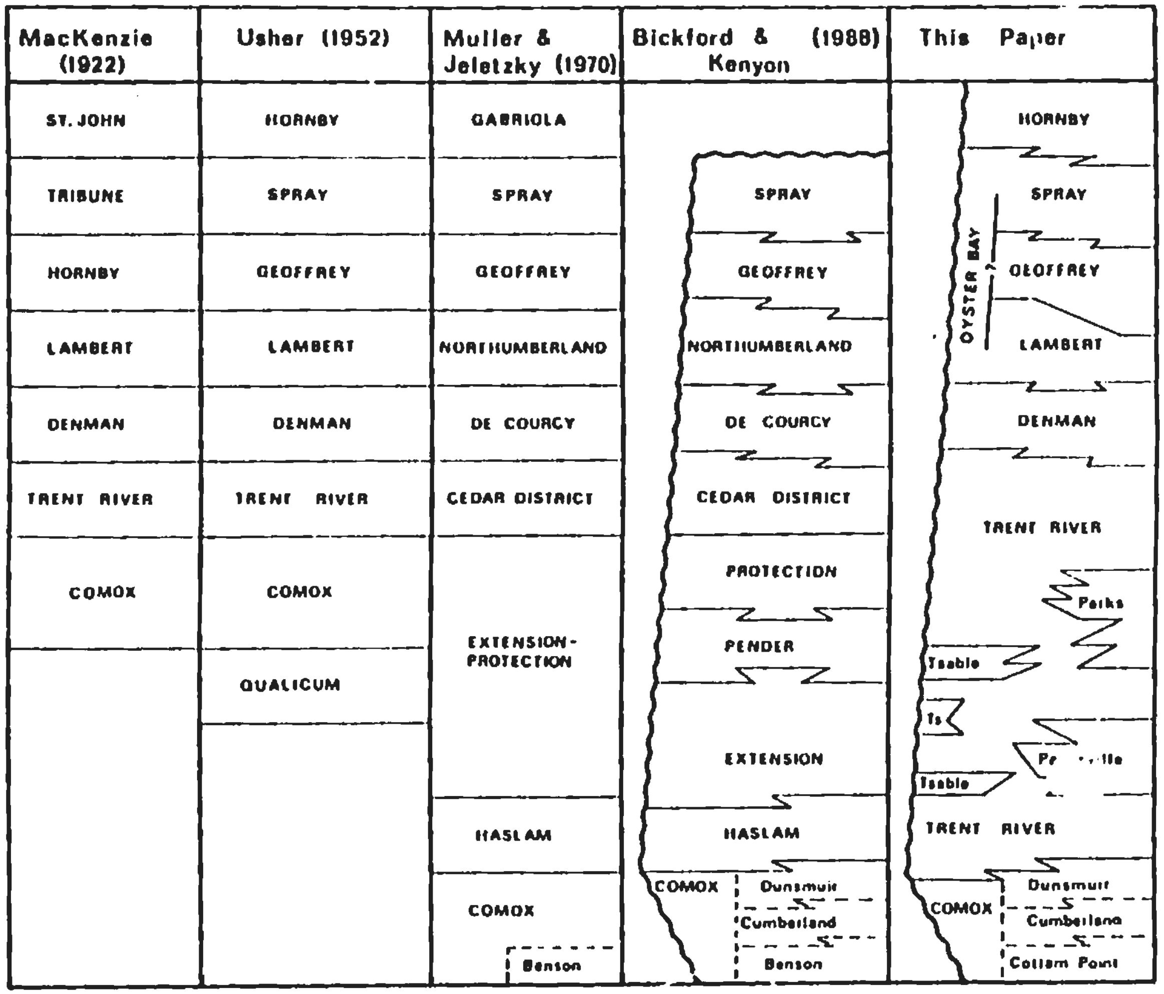


Figure 3.1 Lithostratigraphy of the Nanaimo Group, Comox Basin.

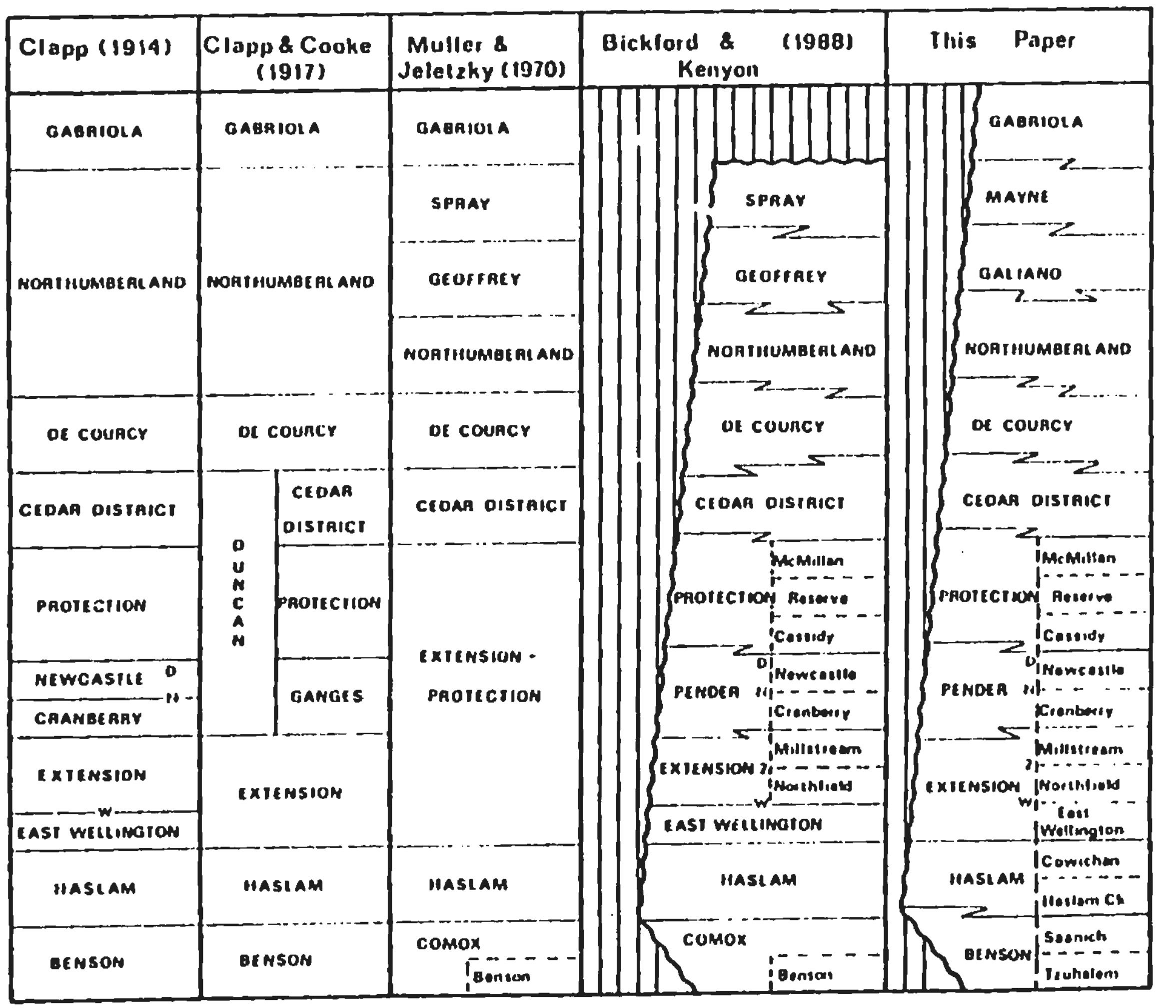
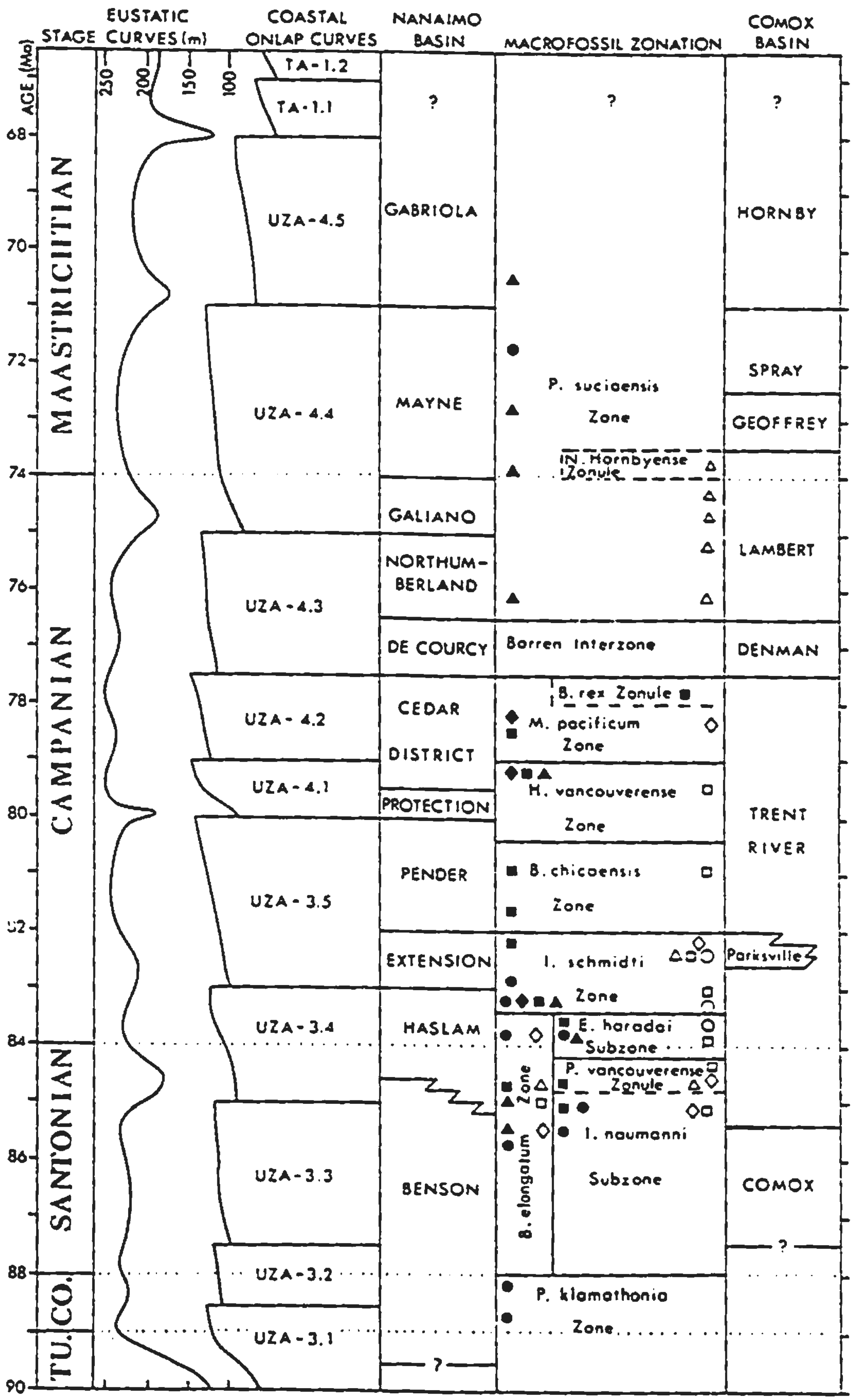


Figure 3.2 Lithostratigraphy of the Nanaimo Group, Nanaimo Basin.

Figure 3.5 Nanaimo Group sequence stratigraphy. The absolute age assignments for the stages, eustatic sea-level curves, and coastal onlap curves, are from Haq et al. (1987). The correlation of Nanaimo Group to absolute time is discussed in section 4.3.1. Macrofossil zonation is from Ward (1978a). Macrofossil control (based on occurrences listed in Tables 3.2 and 3.3) is indicated by symbols (solid for Nanaimo Basin, open for Comox Basin) which correspond to levels within formations in the respective basins. Triangles = Usher (1952); diamonds = Muller and Jeletzky (1970); squares = Ward (1978a); circles = author (Haggart, 1988a,b). For example, the lowest open diamond in the Elongatum Zone denotes that Muller and Jeletzky (1970) reported Elongatum Zone fauna occurring in the uppermost Comox Formation.

Figure 3.5



AGE (Ma)
STAGE
EUSTATIC CURVES (m)
250
200
150
100
COASTAL ONLAP CURVES
NANAIMO BASIN
MACROFOSSIL ZONATION
COMOX BASIN
MAASTRICHTIAN
CAMPANIAN
SANTONIAN
TU.
CO.
68
70
72
74
76
78
80
84
86
88
90
TA-1.2
TA-1.1
UZA-4.5
UZA-4.4
UZA-4.3
UZA-4.2
UZA-4.1
UZA-3.5
UZA-3.4
UZA-3.3
UZA-3.2
UZA-3.1
GABRIOLA
MAYNE
GALIANO
NORTHUM-BERLAND
DE COURCY
CEDAR DISTRICT
PROTECTION
PENDER
EXTENSION
HASLAM
BENSON
P. suciaensis Zone
N. Hornbyense Zonule
Barren Interzone
B. rex Zonule
M. pacificum Zone
H. vancouverense Zone
B. chicoensis Zone
I. schmidti Zone
E. haradai Subzone
P. vancouverense Zonule
I. naumanni Subzone
B. elongatum Zone
P. klamathonia Zone
HORNBY
SPRAY
GEOFFREY
LAMBERT
DENMAN
TRENT RIVER
Parksville
COMOX

Table 4.1 Previously reported Nanaimo Group ichnogenera.

Denman Formation:		
Teichichnus	Denman Is.	7
Lambert Formation:		
?Asterosoma	Hornby Is.	6
Planolites	Denman Is.	7
Trent River Formation:		
Zoophycus, Scolicia, Chondrites, Teichichnus and ?Planolites	Denman Is.	7
Mayne Formation:		
?Thalassinoides	Saturna Is.	2
Thalassinoides	Galiano Is.	5
Thalassinoides	Mayne Is.	3
Zoophycus?Helminthoida	Mayne Is.	3
Galiano Formation:		
horizontal worm burrows? & Zoophycus	Pender Is.	1
?Thalassinoides	Saturna Is.	2
Thalassinoides	Mayne Is.	3
Northumberland Formation:		
?Thalassinoides	Saturna Is.	2
Helminthoida & Tomaculum problematicum	Saltspring Is.	4
Thalassinoides & Helminthoida	Mayne Is.	3
De Courcy Formation:		
Diplocraterion	Saturna Is.	2
Planolites	Saltspring Is.	4
Cedar District Formation:		
Helminthoida & Thalassinoides	Saltspring Is.	4
horizontal worm burrows & ?Zoophycus	Pender Is.	1
?Thalassinoides	Saturna Is.	2
Thalassinoides and Helminthoida	Mayne Is.	3
Thalassinoides	Crofton	9
Haslam Formation:		
Planolites	Saanich	8
Thalassinoides	Saltspring Is.	4
Benson Formation:		
Planolites, Helminthoida or Phycosiphon, & Asterosoma-Teichichnus	Saltspring Is.	4
Planolites	Saanich	8

1. Hudson (1974); 2. Sturdavant (1975); 3. Stickney (1976); 4. Hanson (1976); 5. Carter (1976); 6. Fiske (1977); 7. Allmaras (1978); 8. Kachelmeyer (1978); 9. Fahlstrom (1981)

Table 4.2 Trace fossils versus biofacies in the Nanaimo Group. Superscripted numbers are keyed to the following references: 1. Stickney (1976); 2. Hanson (1976); 3. Fiske (1977); 4. Sturdavant (1975) and Pacht (1980); 5. Hudson (1974); and 6. Allmaras (1978).

BIOFACIES

	1	2	3	4	5
Ophiomorpha	X				
Macaronichnus	X				
Skolithos	X?			X?[1]	
Asterosoma	X?[2]	X?[3]			
Planolites	X	X	X	X	
Paleophycus	X		X	X	
Helminthoida	X		X[2]	X?[1]	X?
Thalassinoides	X	X	X	X	X
Phycodes	X?	X?			
Diplocraterion		X?	X[4]		
Teichichnus		X?	X	X	
Taenidium		X?	X	X	
Zoophycus			X?[5]	X[6]	
Ancorichnus				X	
Scolicia				X	
Helminthopsis				X?	
Chondrites				X[6]	
Cladichnus				X?	X
Granularia					X?

Table 4.3. Regional facies associations in the Nanaimo Group. Marine facies associations correspond to foraminiferal biofacies recognized by Cameron (1988a, b).

BIOFACIES	ASSOCIAT.	SETTING	LITHOLOGY
	Nonmarine A	Alluvial	poorly sorted c/g sandstone & crudely stratified cobble to boulder conglomerate
	Nonmarine B	Fluvial	poorly sorted conglomerate, pebbly sandstone, m/g to c/g sandstone, well stratified
	Nonmarine P	Paralic	massive to laminated f/g sandstone, carbonaceous siltstone & shale, coal
1 0-30 m	Marine L	Littoral & Upper Neritic	well to moderately sorted f/g to c/g sandstone, shale & siltstone, conglomerate
2 30-100 m	Marine M	Middle Neritic	laminated f/g sandstone, siltstone, shale, minor c/g sandstone & conglomerate
3 100-200 m	Marine S	Lower Neritic	laminated or massive shale, siltstone, and f/g sandstone & resedimented deposits of: channelized conglomerate & sandstone; massive and thick bedded m/g to c/g sandstone, pebbly sandstone, conglomerate; and graded beds
4 200-600 m		Upper Bathyal	
5 600-1200m		Middle Bathyal	

Key to the facies maps (Figures 4.1 to 4.13)

Standard lithology symbols are used for conglomerate (small circles), sandstone (small dots), and shale (dashes). As biozone boundaries often do not correspond to formation boundaries, the formations represented in each map are indicated, with a key to dominant lithofacies. The numbers refer to marine biofacies; letters A, B, and P refer to nonmarine facies associations as described in section 4.1. Large arrows represent probable sediment source regions; small arrows, paleocurrent data. Large letter F indicates occurrence of zone-diagnostic macrofossils; subscripts on the letter F indicate subzones (eg. F_h marks the occurrence of Haradai subzone index fossils). The thin, short dashed line indicates the approximate position of the 30 m paleo-isobath, assumed for these figures to separate inner and mid-shelf environments. The thick, long dashed line represents the approximate position of the 200 m paleo-isobath, assumed to separate shelf and slope environments. These boundaries generally represent average positions within the biozone represented in each figure. Small letters O and D designate evidence of oxygen deficiency and down-slope transport, respectively, as indicated by foraminifers. Small letters FL indicate the occurrence of a flyschoid foraminiferal assemblage.

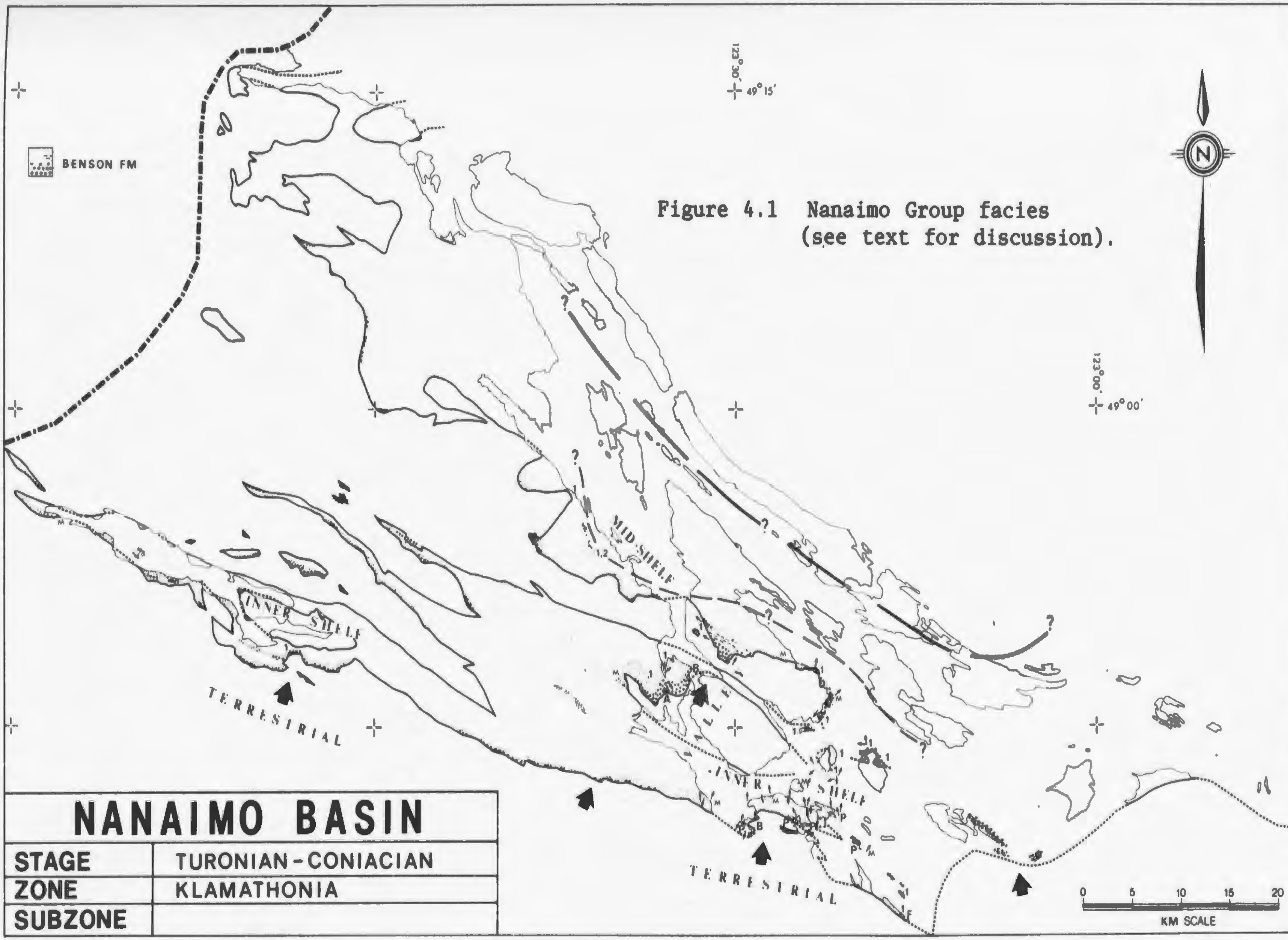


Figure 4.1 Nanaimo Group facies (see text for discussion).

NANAIMO BASIN	
STAGE	TURONIAN - CONIACIAN
ZONE	KLAMATHONIA
SUBZONE	

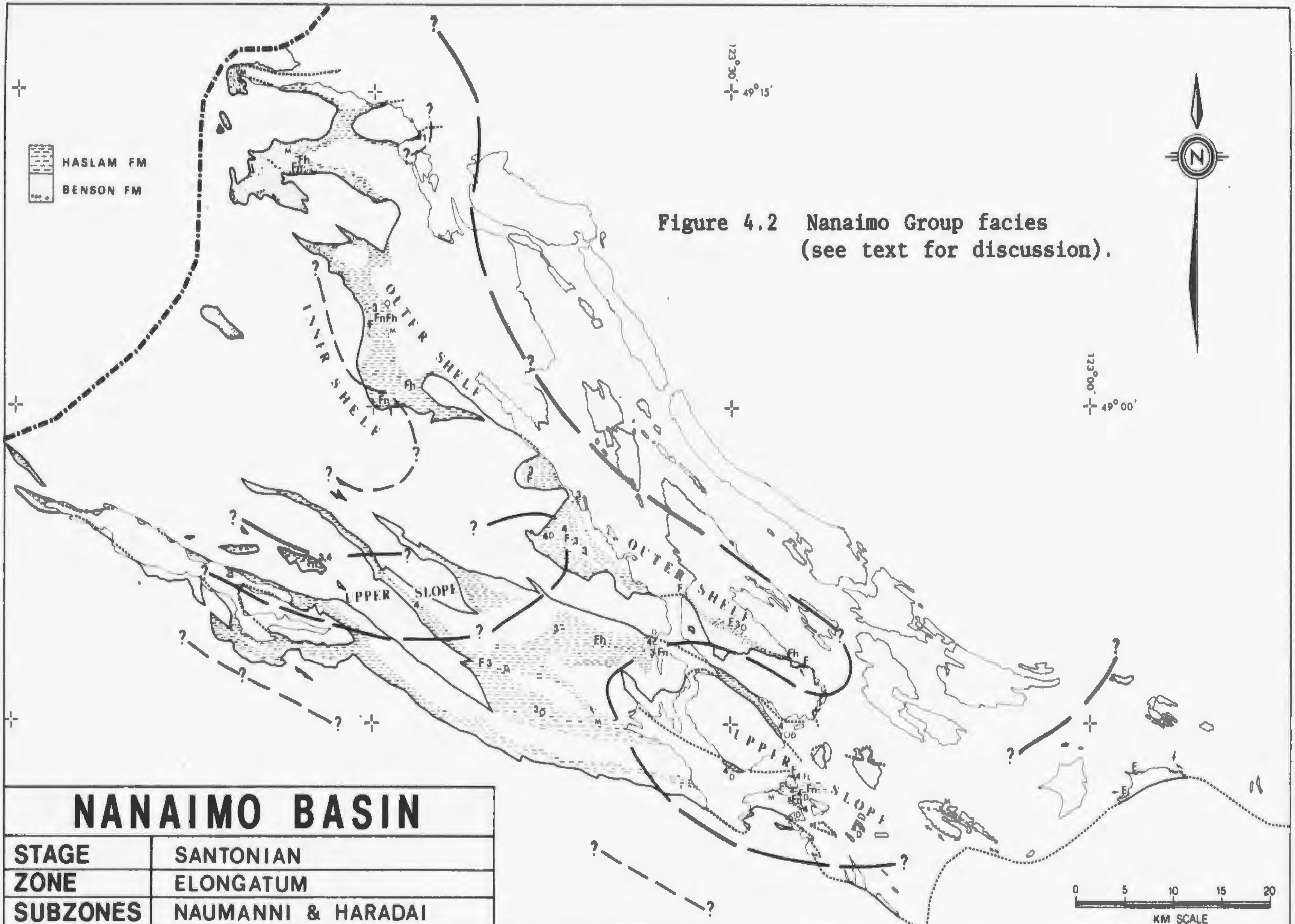


Figure 4.2 Nanaimo Group facies (see text for discussion).

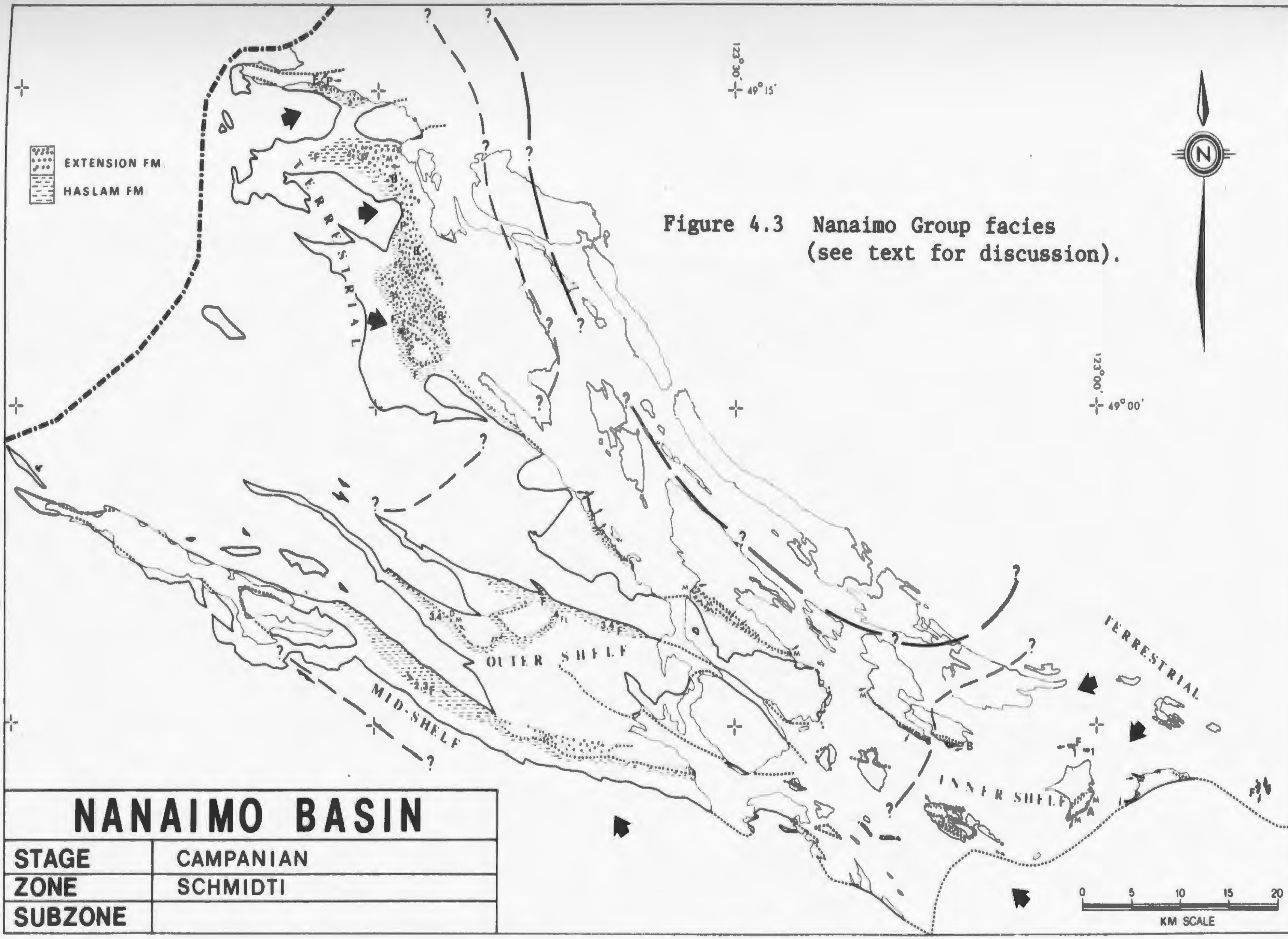


Figure 4.3 Nanaimo Group facies (see text for discussion).

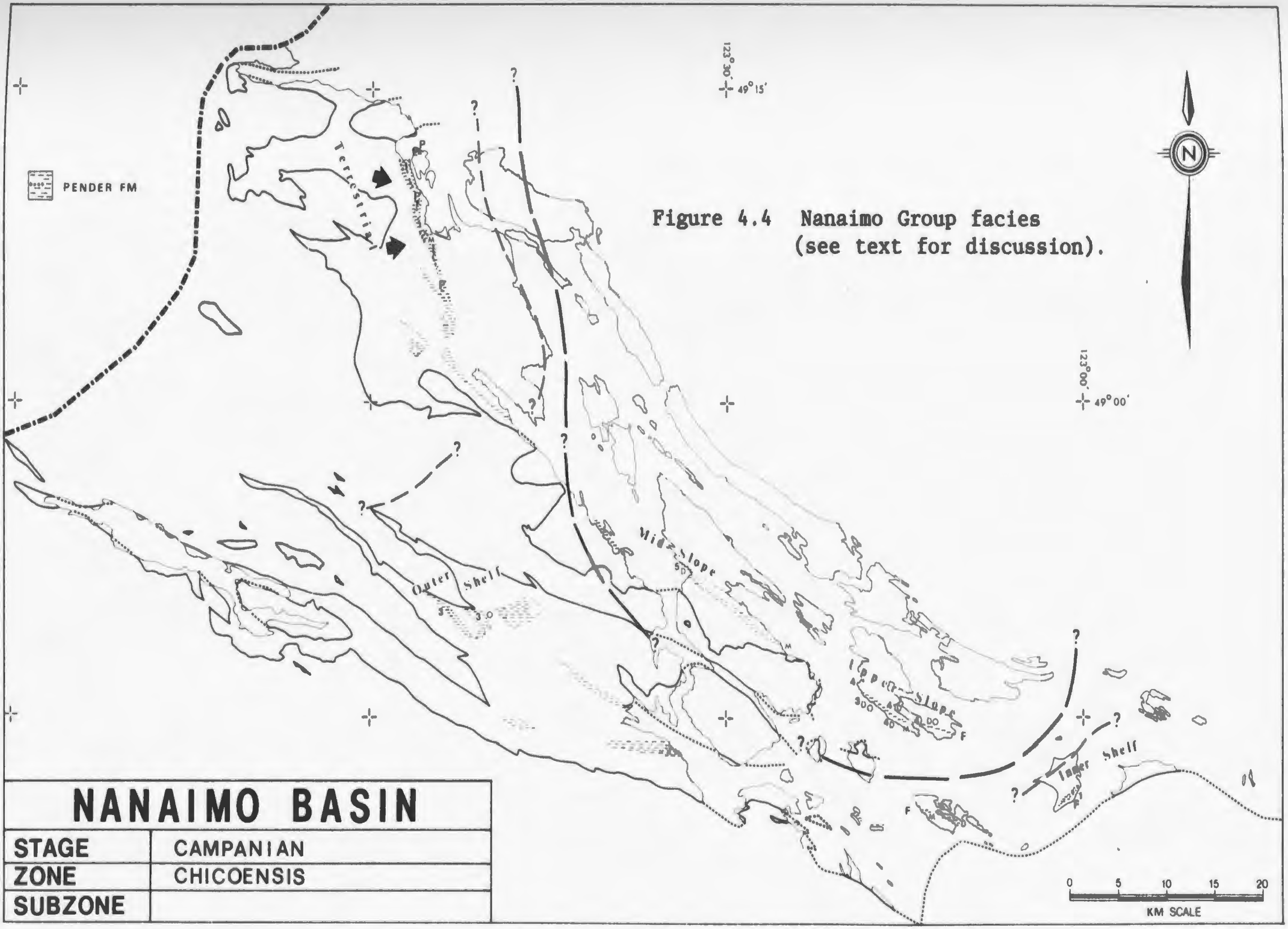


Figure 4.4 Nanaimo Group facies (see text for discussion).

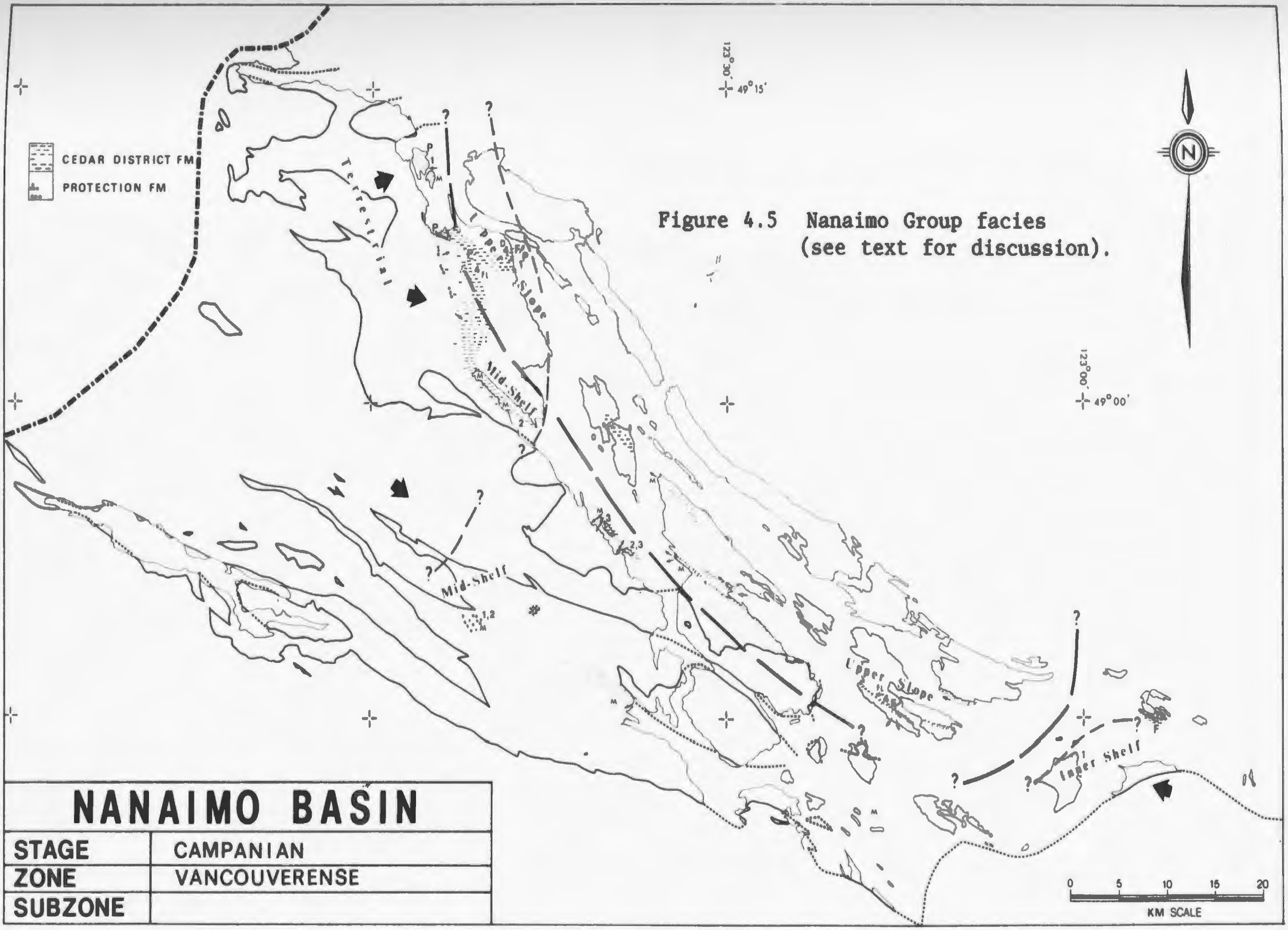


Figure 4.5 Nanaimo Group facies (see text for discussion).

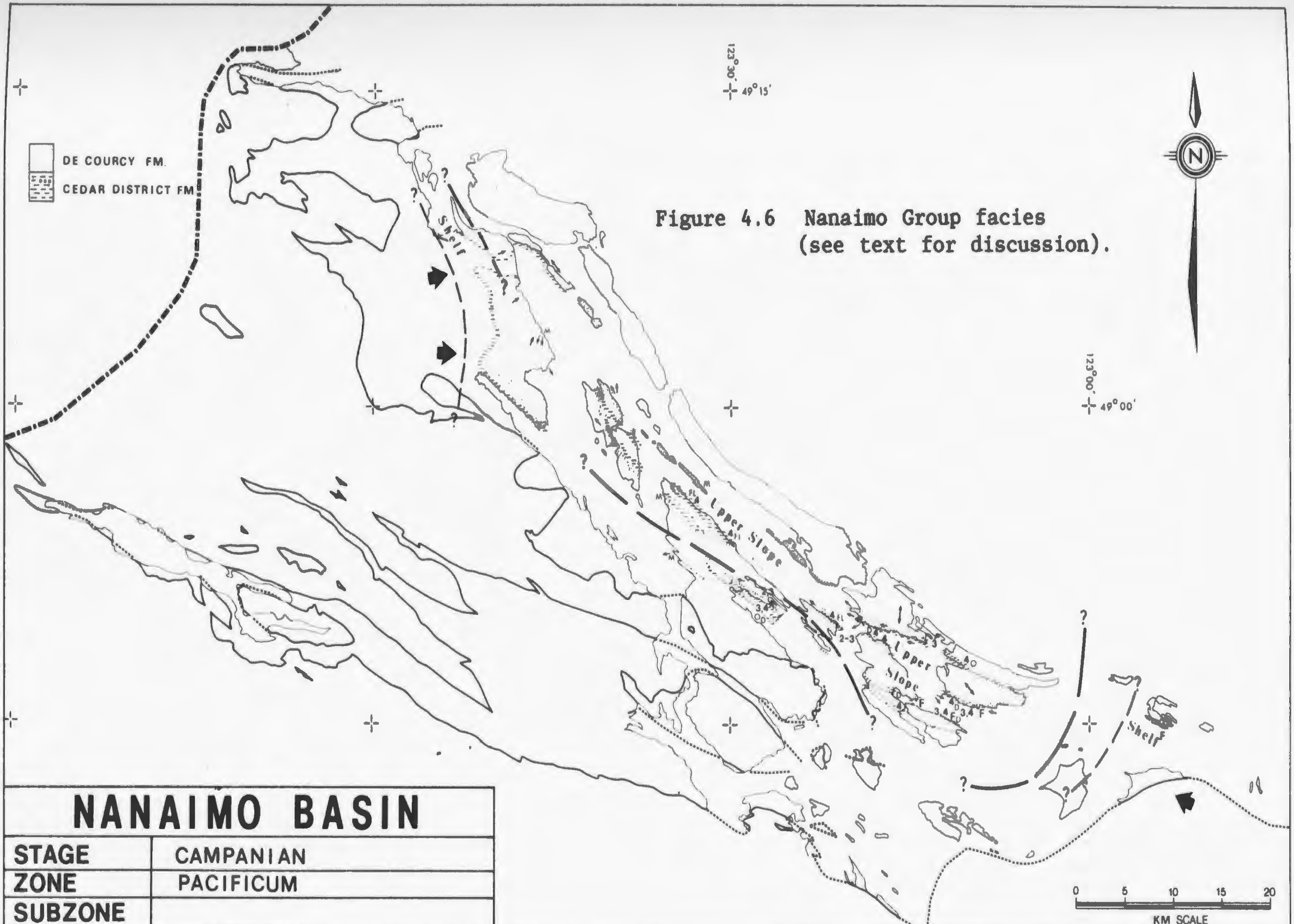


Figure 4.6 Nanaimo Group facies (see text for discussion).

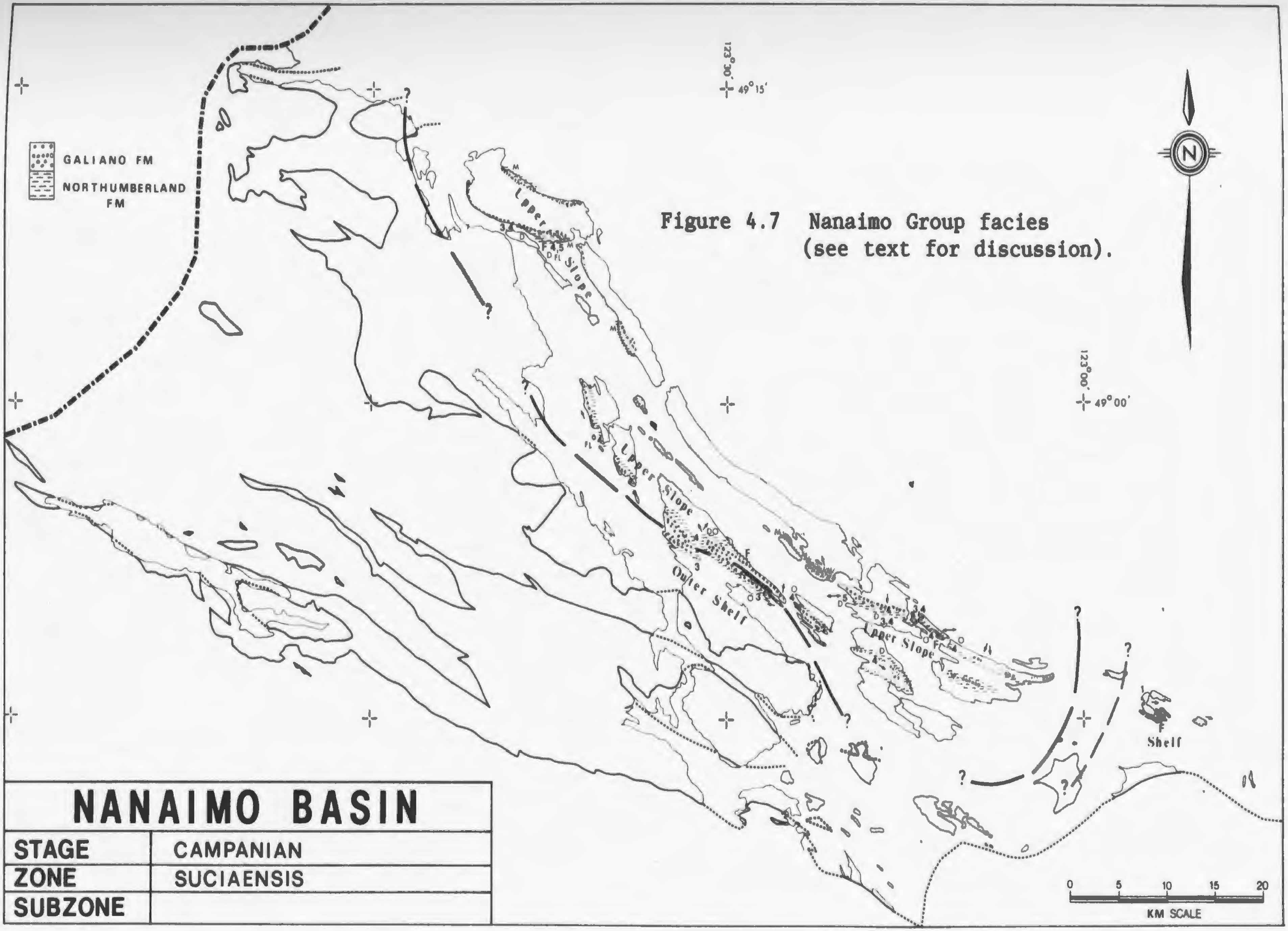


Figure 4.7 Nanaimo Group facies (see text for discussion).

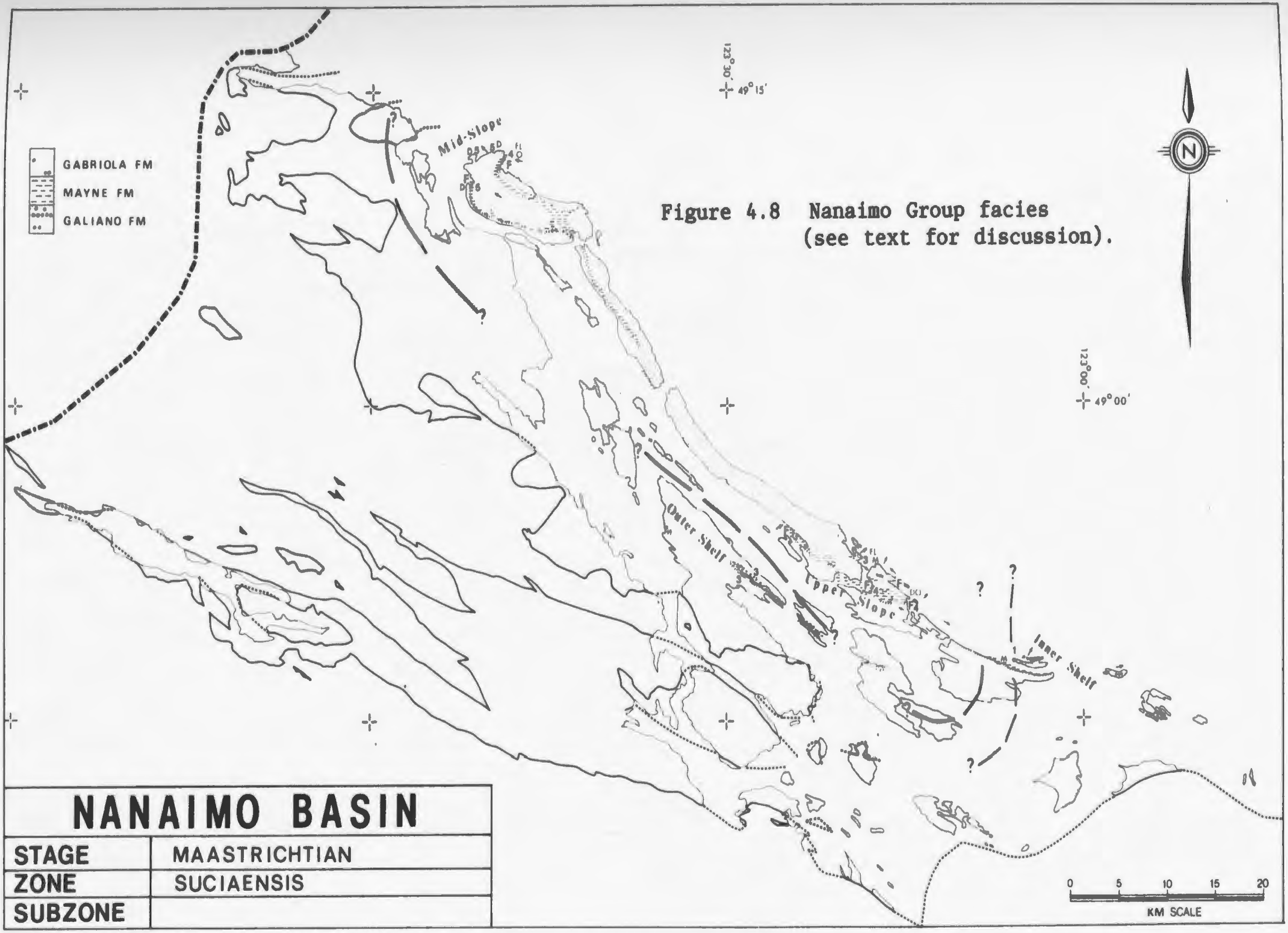


Figure 4.8 Nanaimo Group facies (see text for discussion).

Figure 4.9 Nanaimo Group facies
(see text for discussion).

COMOX BASIN

STAGE	SANTONIAN
ZONE	ELONGATUM
SUBZONE	

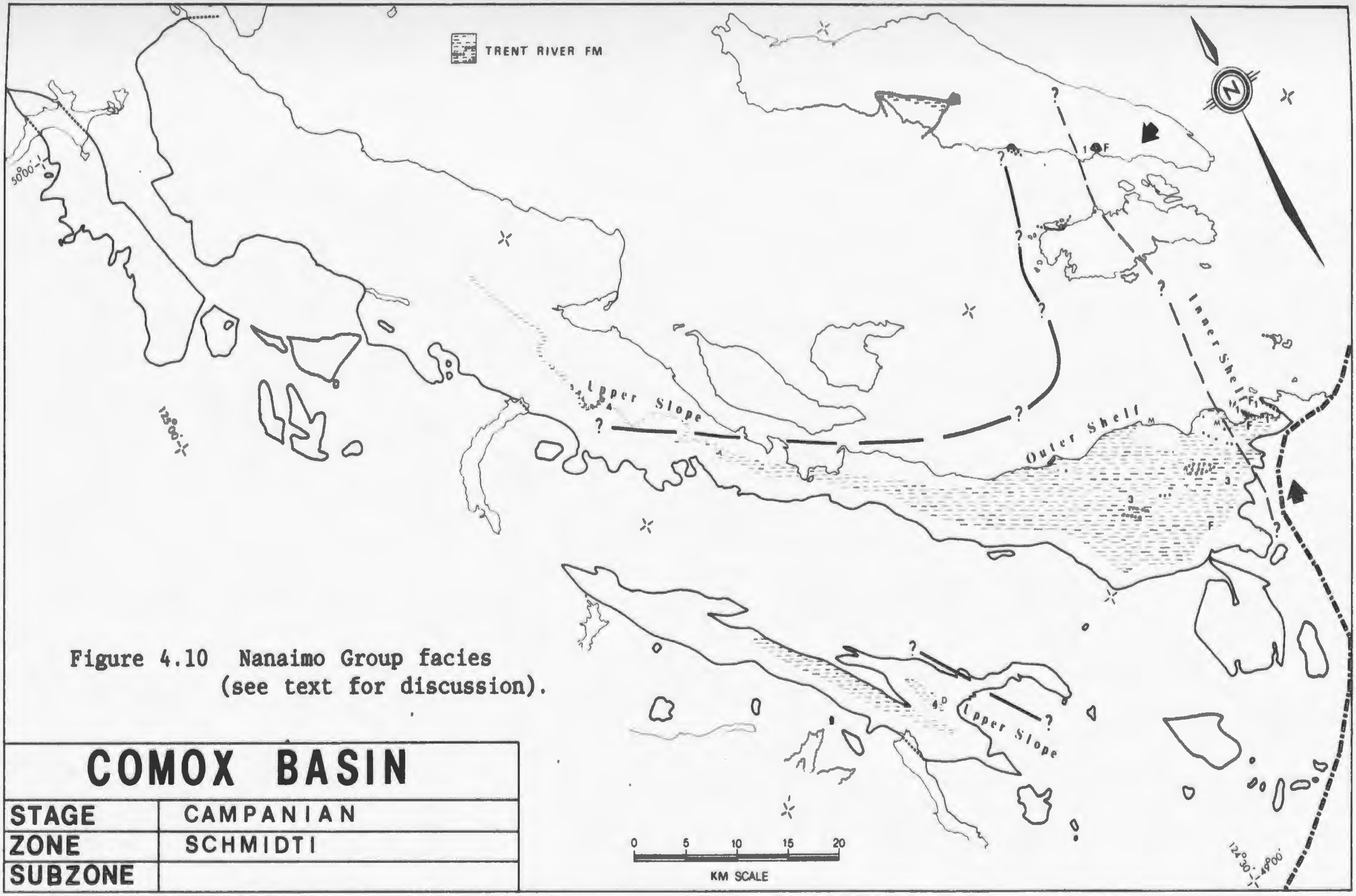


Figure 4.10 Nanaimo Group facies
(see text for discussion).

COMOX BASIN

STAGE	CAMPANIAN
ZONE	SCHMIDTI
SUBZONE	

Figure 4.11 Nanaimo Group facies (see text for discussion).

Figure 4.12 Nanaimo Group facies (see text for discussion).

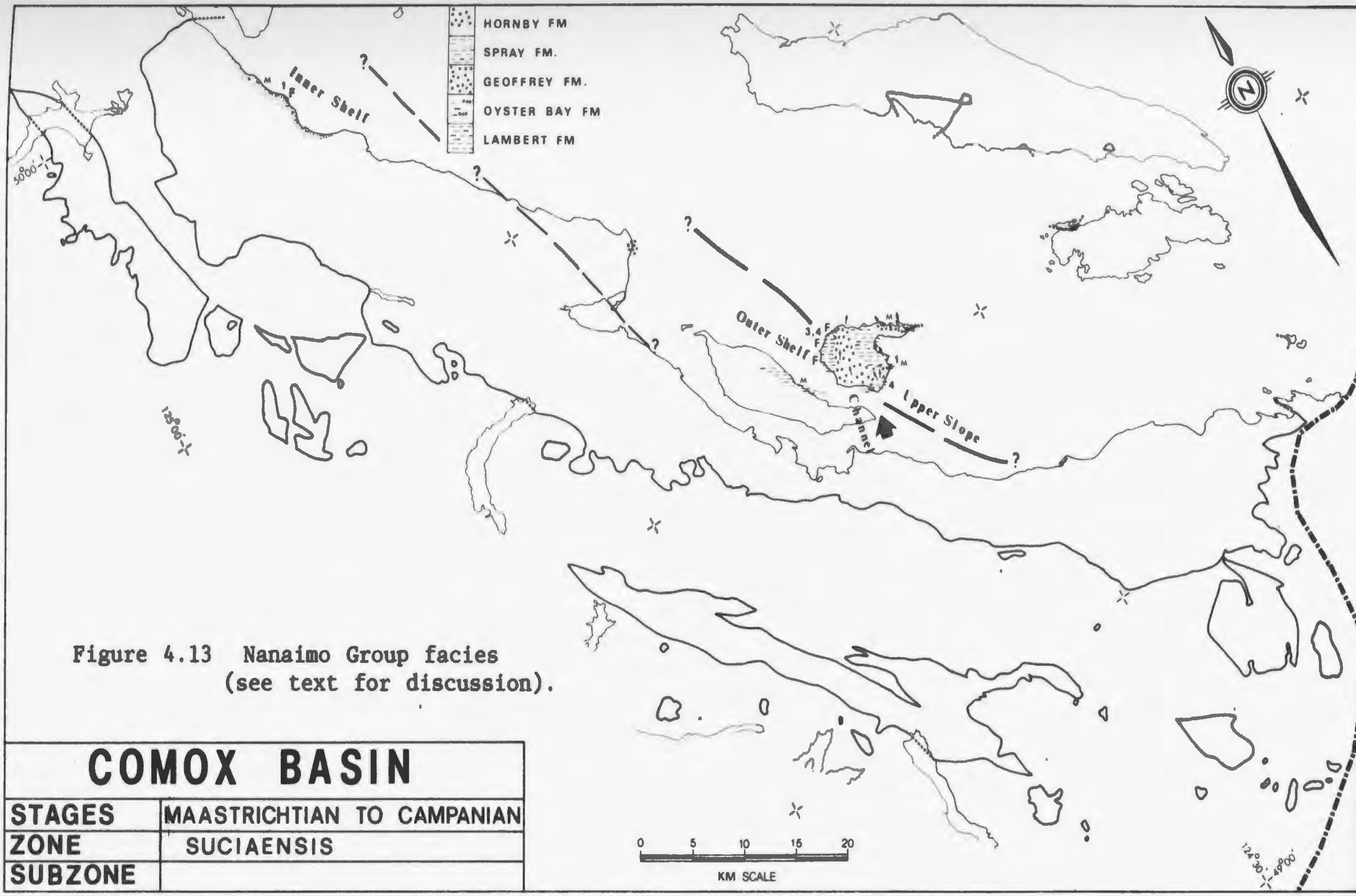
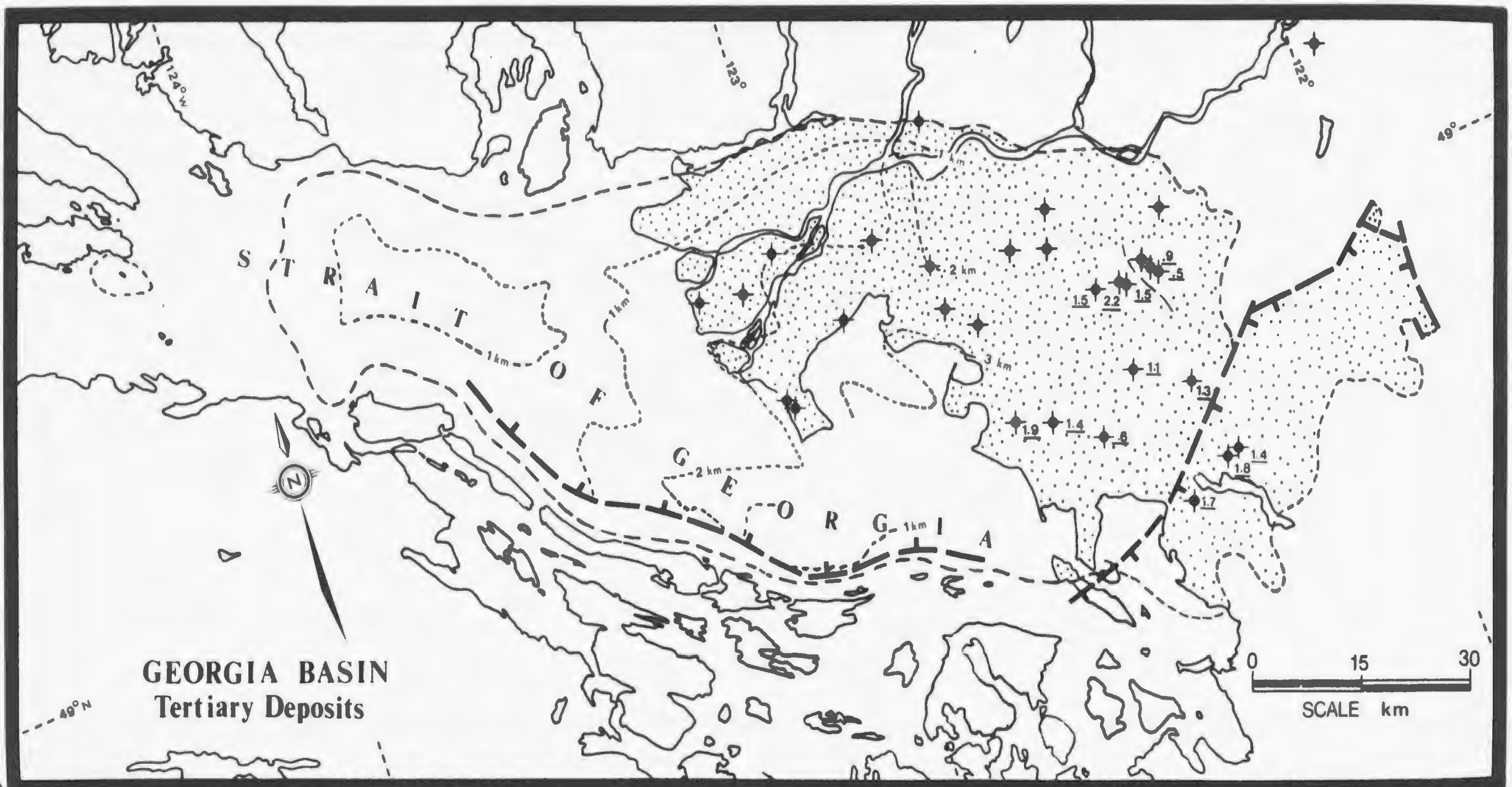


Figure 4.13 Nanaimo Group facies
(see text for discussion).

COMOX BASIN

STAGES	MAASTRICHTIAN TO CAMPANIAN
ZONE	SUCIAENSIS
SUBZONE	

Figure 4.14 Distribution of Tertiary deposits in Georgia Basin, based on data from Machacek (1970), Johnson (1985), and Bickford (1986). Underlined values posted at wells are minimum thicknesses because the base of the Tertiary was not intersected in the wells. Isopach lines (short dashes) are presented for parts of the area. The major bounding fault in the southwest is the Outer Islands fault; the eastern fault is the Lummi Island - Boulder Creek fault, separating Chuckanut Basin from Whatcom Basin.



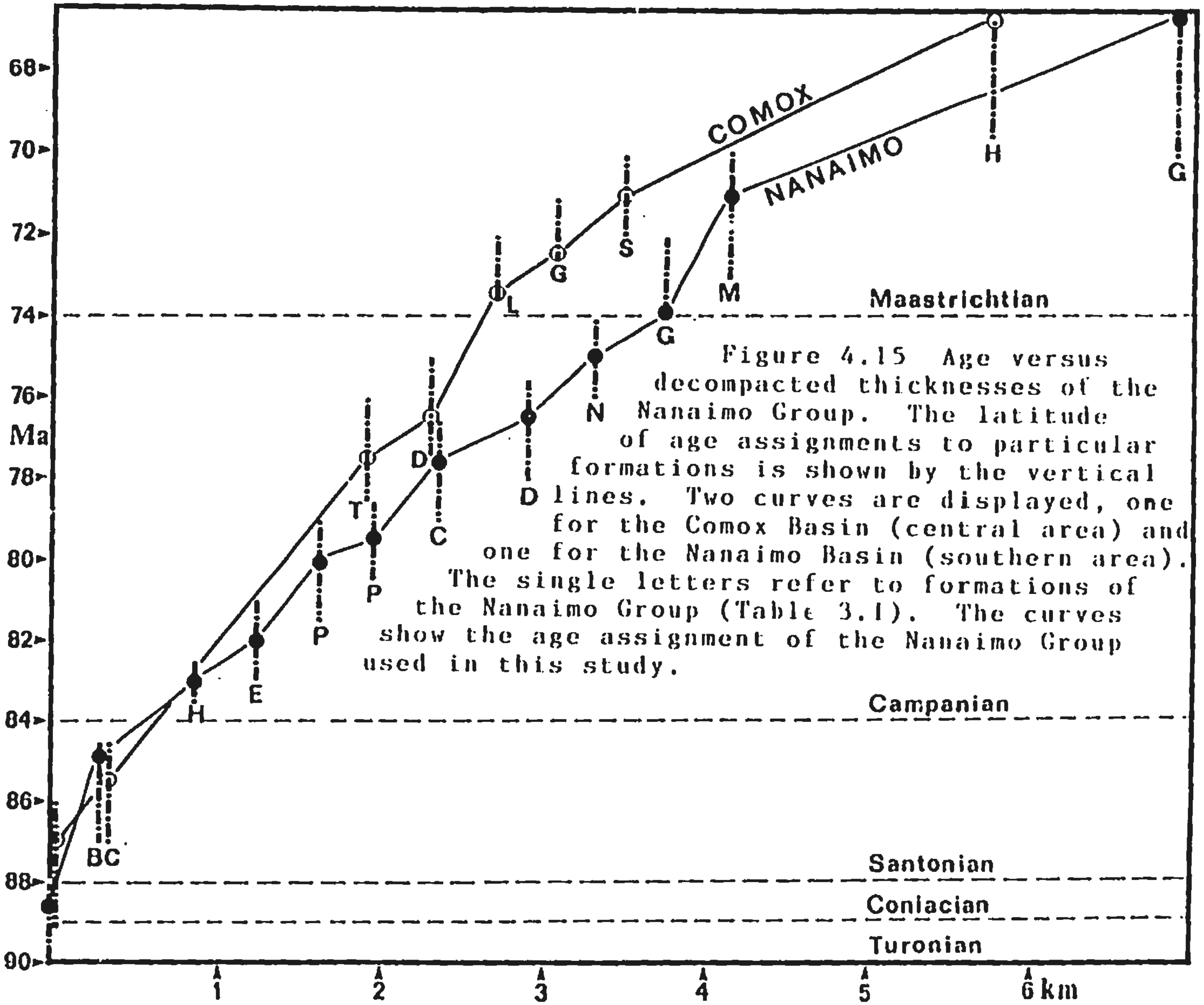


Figure 4.15 Age versus decompacted thicknesses of the Nanaimo Group. The latitude of age assignments to particular formations is shown by the vertical lines. Two curves are displayed, one for the Comox Basin (central area) and one for the Nanaimo Basin (southern area). The single letters refer to formations of the Nanaimo Group (Table 3.1). The curves show the age assignment of the Nanaimo Group used in this study.

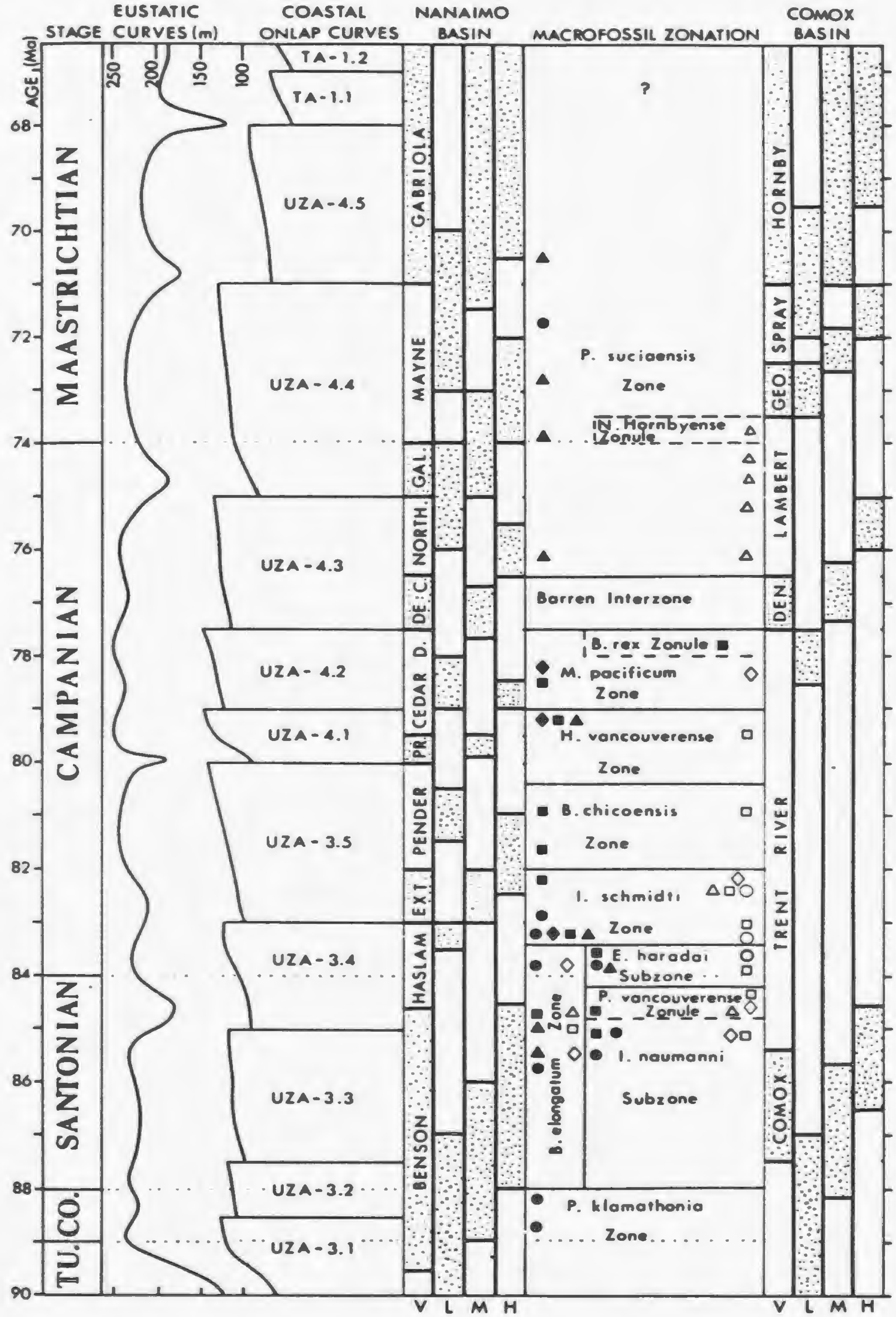


Figure 4.16 Possible correlations of formations of the Nanaimo Group to absolute time. The range of possible fits for each formation is shown by the low (L), medium (M), and high (H) position columns. The correlation assumed in the study is shown in the columns marked V. It is based on the sequence stratigraphy of Haq et al. (1987). Note that this correlation is similar to the correlation shown in column M. See text for further discussion.

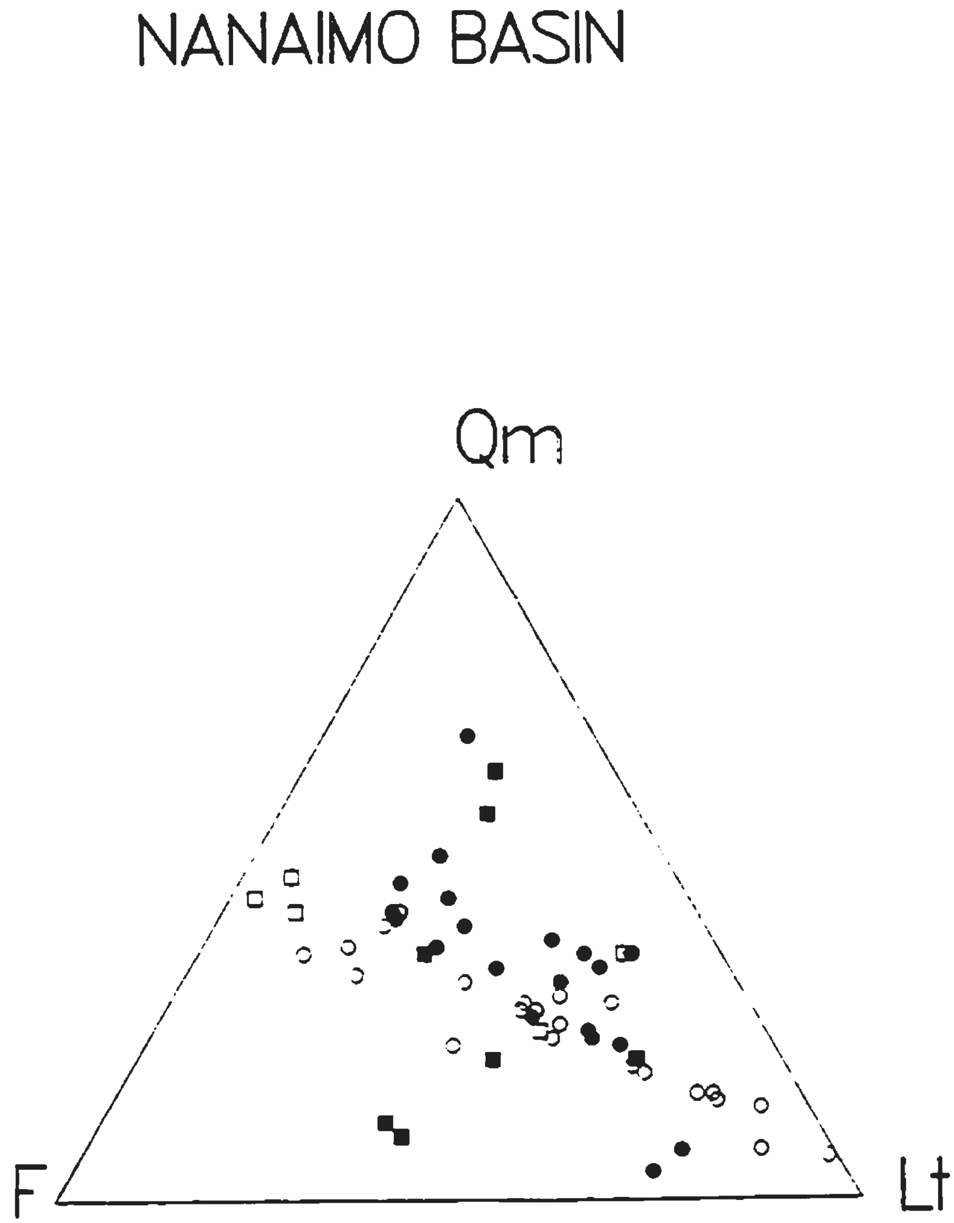


Figure 4.17 Ternary plot of detrital framework mode data for the lower Nanaimo Group expressing volumetric proportions of monocrystalline quartz (Qm), feldspar (F), and total lithic fragments (Lt). The data are divided up by formation: Benson = solid circles, Haslam = solid squares, Extension = open circles, and Pender = open squares. Data sources are Thom (1983), Fahlstrom (1981), Kachelmeyer (1978), Hanson (1976), and Hudson (1974).

NANAIMO BASIN

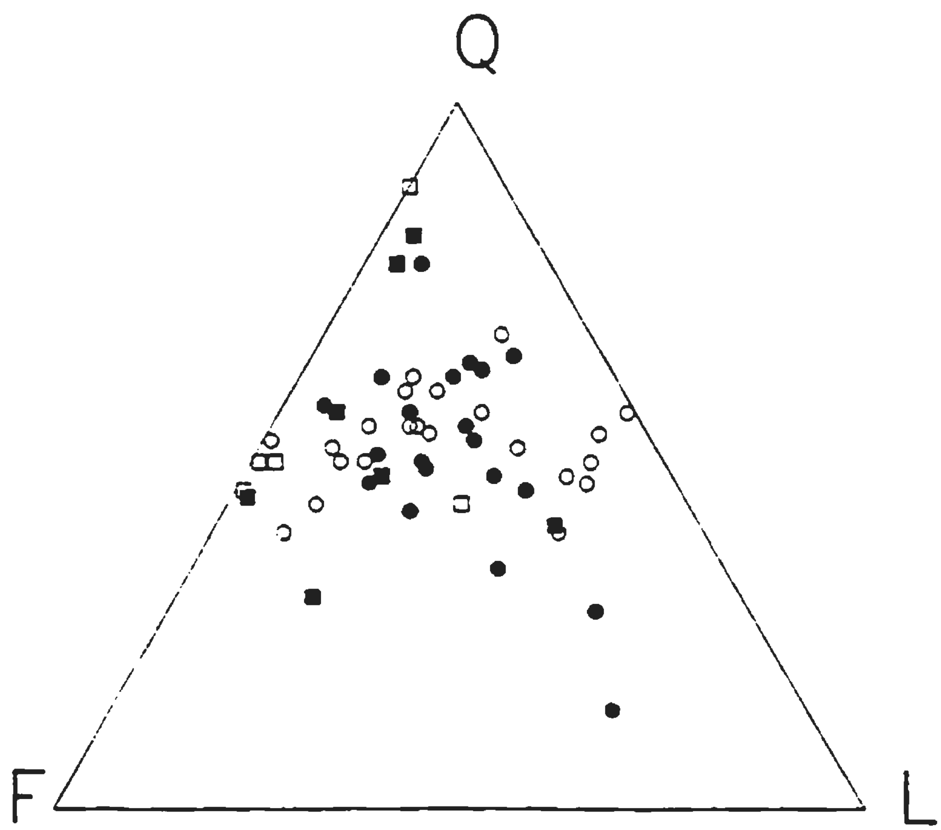


Figure 4.18 Ternary plot of detrital framework mode data for the lower Nanaimo Group expressing volumetric proportions of total quartz (Q), fe`dspar (F), and unstable polycrystalline lithic fragments (L). The data are divided up by formation: Benson = solid circles, Haslam = solid squares, Extension = open circles, and Pender = open squares. Data sources are Thom (1983), Fahlstrom (1981), Kachelmeyer (1978), Hanson (1976), and Hudson (1974).

NANAIMO BASIN

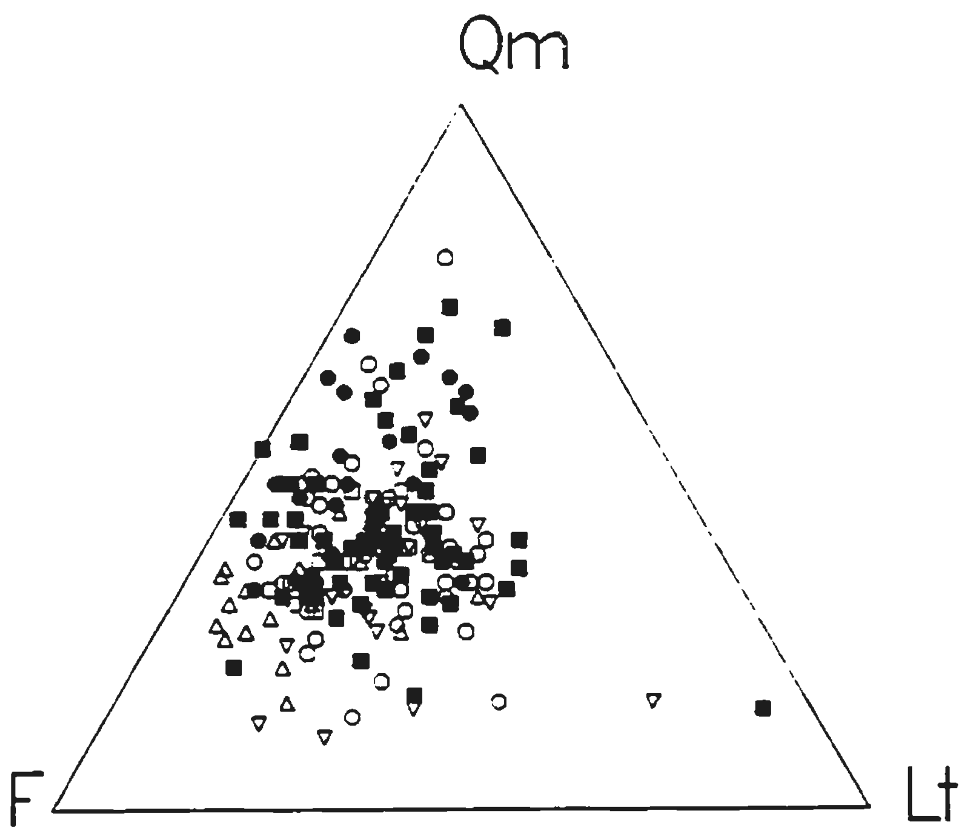


Figure 4.19 Ternary plot of detrital framework mode data for the upper Nanaimo Group expressing volumetric proportions of monocrystalline quartz (Qm), feldspar (F), and total lithic fragments (Lt). The data are divided up by formation: Protection = solid circles, Cedar District = solid squares, De Courcy = open octagons, Northumberland = open squares, Galiano = inverted triangles, Mayne = open circles, and Gabriola = upright triangles. Data sources are Thom (1983), Fahlstrom (1981), Pacht (1980), Hanson (1976), Carter (1976), Stickney (1976), Sturdavant (1975), Hudson (1974), and Simmons (1973).

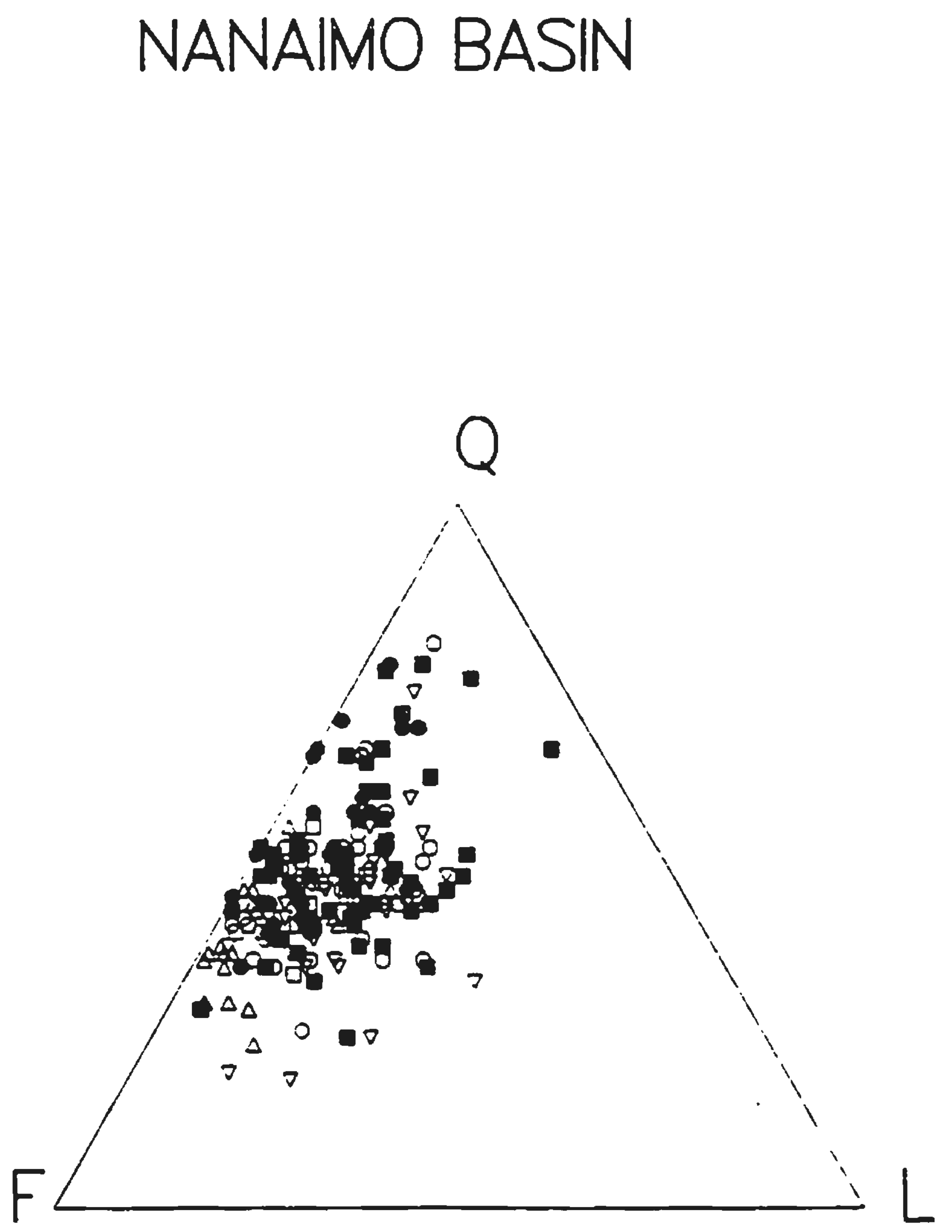


Figure 4.20 Ternary plot of detrital framework mode data for the lower Nanaimo Group expressing volumetric proportions of total quartz (Q), feldspar (F), and unstable polycrystalline lithic fragments (L). The data are divided up by formation: Protection = solid circles, Cedar District = solid squares, De Courcy = open octagons, Northumberland = open squares, Galiano = inverted triangles, Mayne = open circles, and Gabriola = upright triangles. Data sources are Thom (1983), Fahlstrom (1981), Pacht (1980), Hanson (1976), Carter (1976), Stickney (1976), Sturdavant (1975), Hudson (1974), and Simmons (1973).

COMOX BASIN

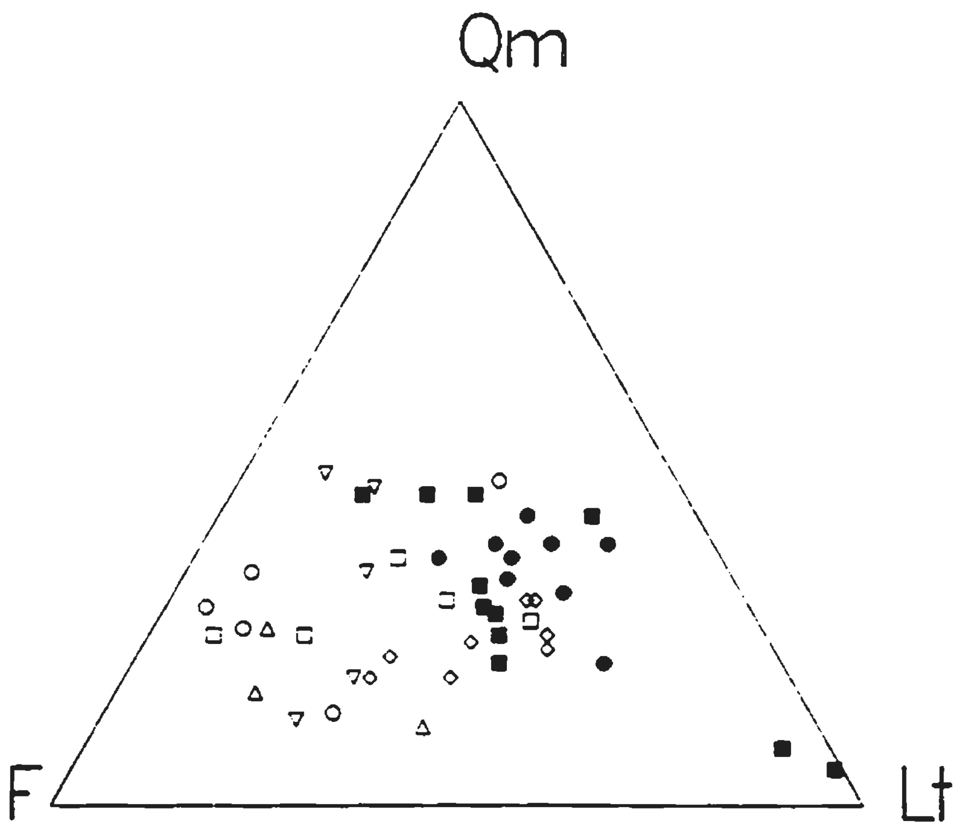


Figure 4.21 Ternary plot of detrital framework mode data for the Nanaimo Group expressing volumetric proportions of monocrystalline quartz (Qm), feldspar (F), and total lithic fragments (Lt). The data are divided up by formation: Comox = solid circles, Trent River = solid squares, Denman = open diamonds, Lambert & Oyster Bay = open squares, Geoffrey = inverted triangles, Spray = open circles, Hornby = upright triangles. Data sources are Thom (1983), Allmaras (1978), and Fiske (1977).

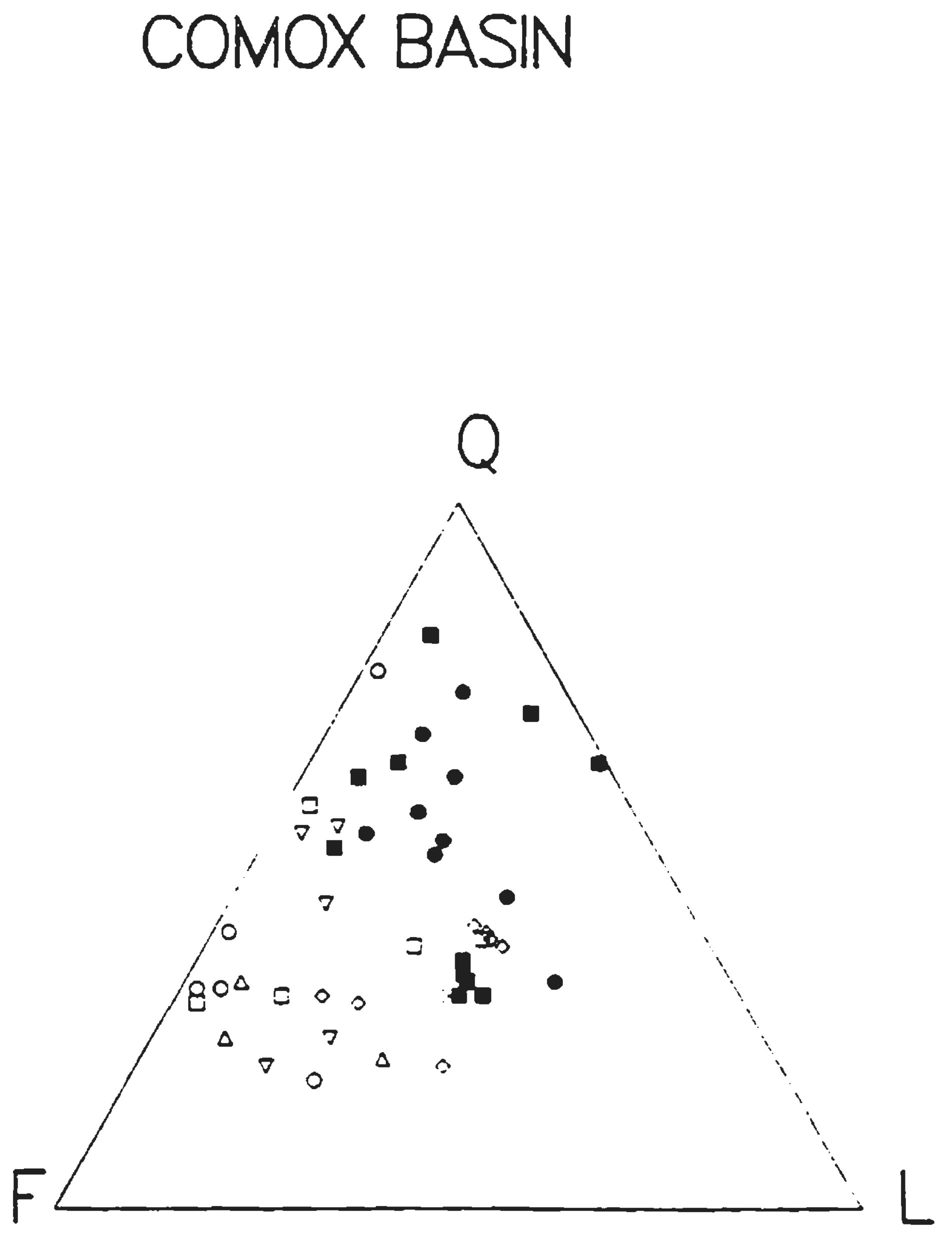


Figure 4.22 Ternary plot of detrital framework mode data for the Nanaimo Group expressing volumetric proportions of total quartz (Q), feldspar (F), and unstable polycrystalline lithic fragments (L). The data are divided up by formation: Comox = solid circles, Trent River = solid squares, Denman = open diamonds, Lambert & Oyster Bay = open squares, Geoffrey = inverted triangles, Spray = open circles, and Hornby = upright triangles. Data sources are Thom (1983), Allmaras (1978), and Fiske (1977).

Table 5.1. Reflectance/depth gradient statistics for selected localities in Georgia Basin. N = the number of $\%R_0$ data points. By linear regression, the data are described by:

$$\text{Depth} = A1\ (\log\ (\%R_0 x100)) - B,$$

with a correlation coefficient = r^2. A2 is the gradient expressed in log $\%R_0$/km. H = the estimated amount of eroded section at the locality, based on extrapolation of the gradient to 0.15 $\%R_0$. S = standard error of the estimate of H (km).

LOCALITY	N	A1	B	r^2	A2	H	S
S.Nanaimo Basin	43	-5452	7671	0.54	0.18	3.1	0.49
C.Nanaimo Basin	42	-5823	8485	0.82	0.17	3.0	0.33
N.Nanaimo Basin	67	-4964	7403	0.36	0.20	2.5	0.50
C.Comox Basin	21	-4852	7718	0.72	0.21	1.3	0.20
Harmac Well	23	-3631	5901	0.28	0.28	0.9	0.20
Gabriola Island	6	-1401	2163	0.26	0.71	0.4	0.17
Bryden Bay	5	-3129	6037	0.99	0.32	0.3	0.01
Sucia Island	6	-3563	5322	0.50	0.28	1.0	0.31

Table 5.2. Amounts of eroded section in western Georgia Basin calculated using reflectance/depth gradients as discussed in section 5.5. The reflectance values used are from areas outside of the influence of intrusives. In southern Comox Basin, two gradients are used as discussed in section 5.4.5..

Locality	Gradient (log $\%R_0$/km)	Range in $\%R_0$	Eroded section (km)
Nanaimo Basin:			
Southeastern Gulf Is.	0.18	0.35-1.05	2.0-4.6
Central Gulf Is.	0.17	0.47-1.49	2.9-5.8
Northern Gulf Is. & Nanaimo area	0.20	0.43-0.84	2.2-3.6
Northwestern area (Nanoose)	0.21	0.56-0.80	2.8-3.5
Cowichan & Saanich areas (southern belt)	0.19	0.65-2.66	3.4-6.6
Comox Basin			
Northern area (Comox to Campbell River)	0.21	0.38-0.86	1.8-3.7
Southern area (incl. Denman & Hornby Is.)	0.21	0.32-1.11	1.6-4.2
	0.38	0.32-1.11	0.8-2.3
Alberni Valley	0.21	0.61-0.88	3.0-3.7
	0.38	0.61-0.88	1.6-2.0

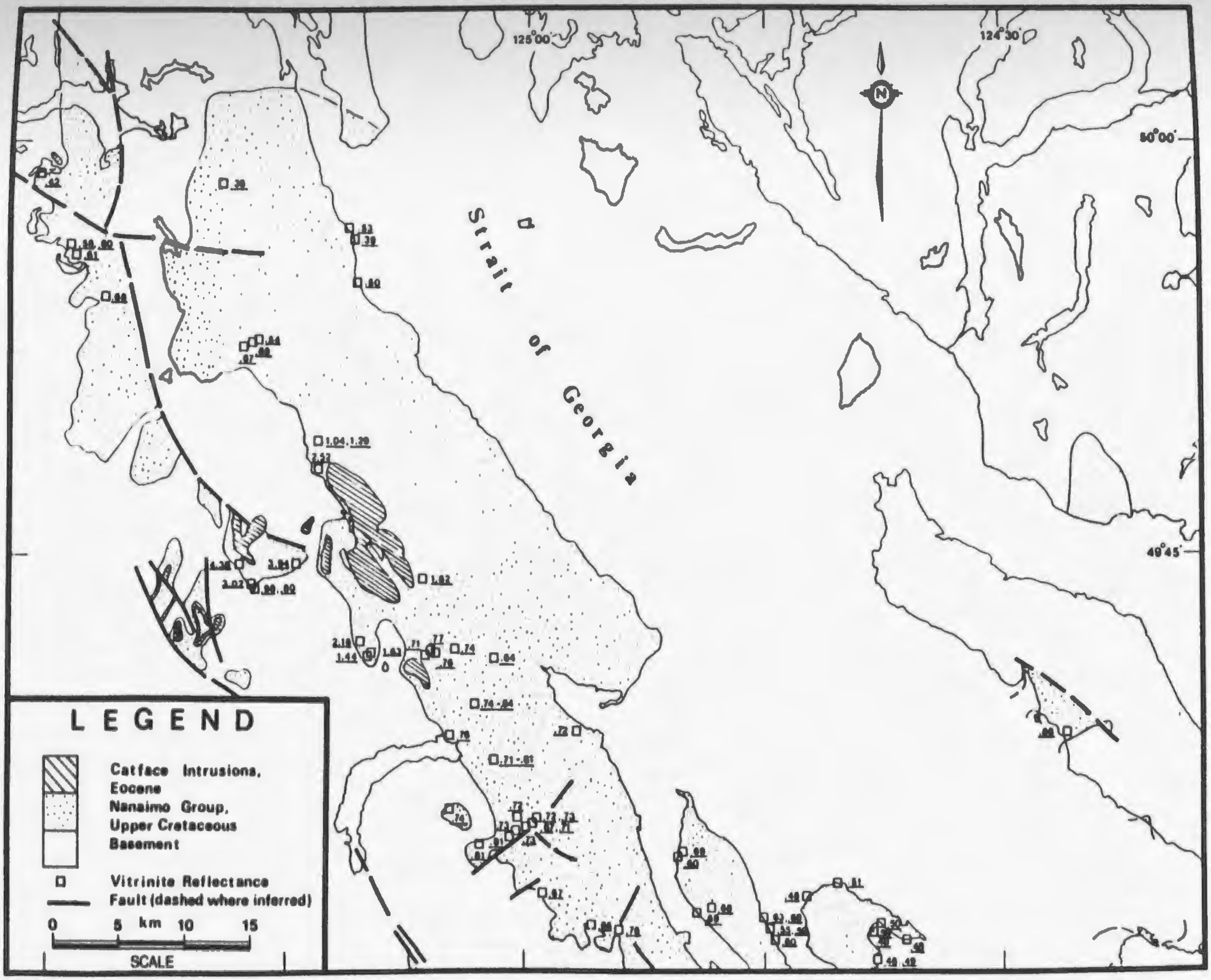
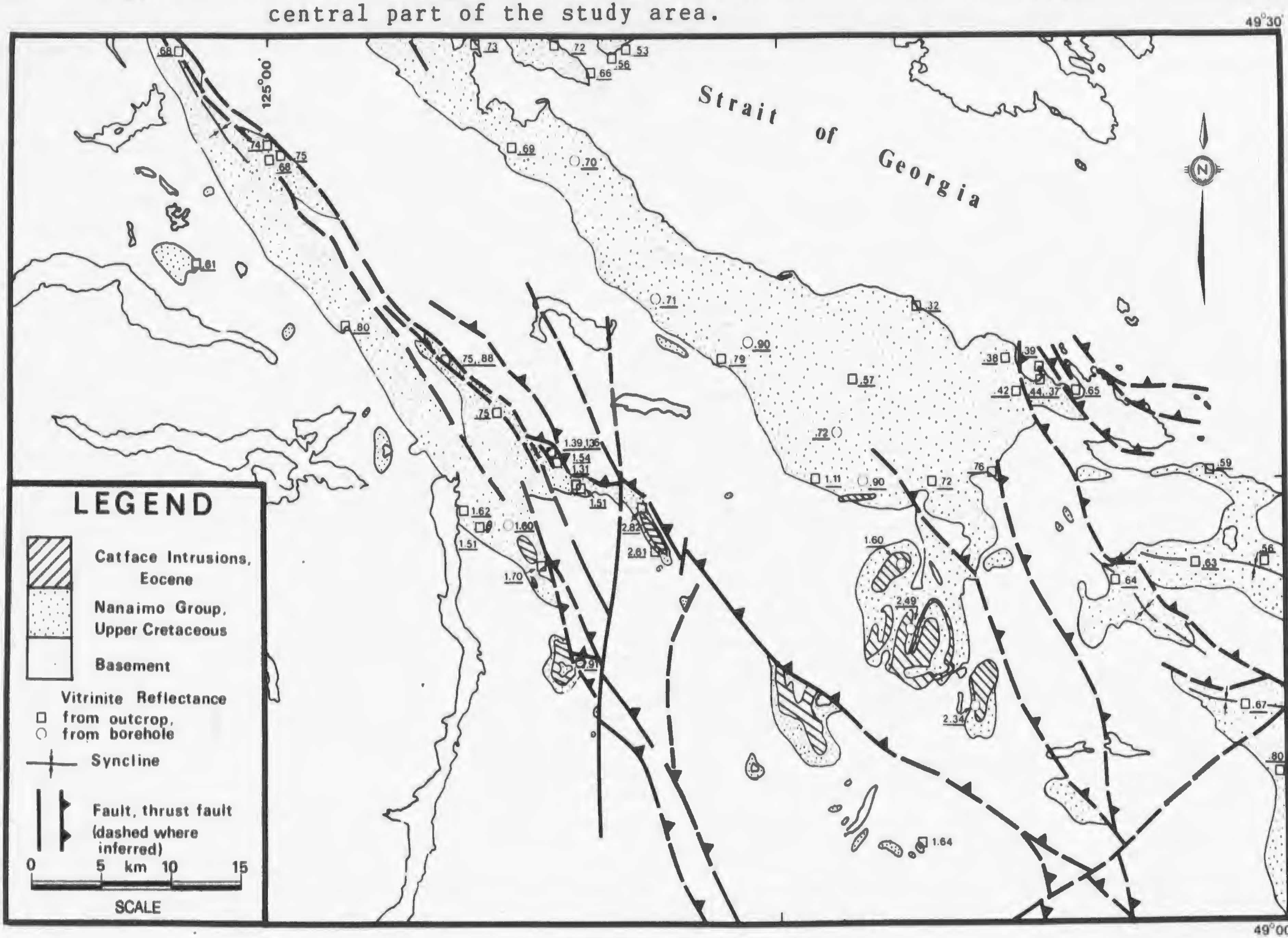


Figure 5.1 Levels of organic maturation (%Ro) of the Nanaimo Group, northern part of the study area.

Figure 5.2 Levels of organic maturation (%Ro) of the Nanaimo Group, central part of the study area.



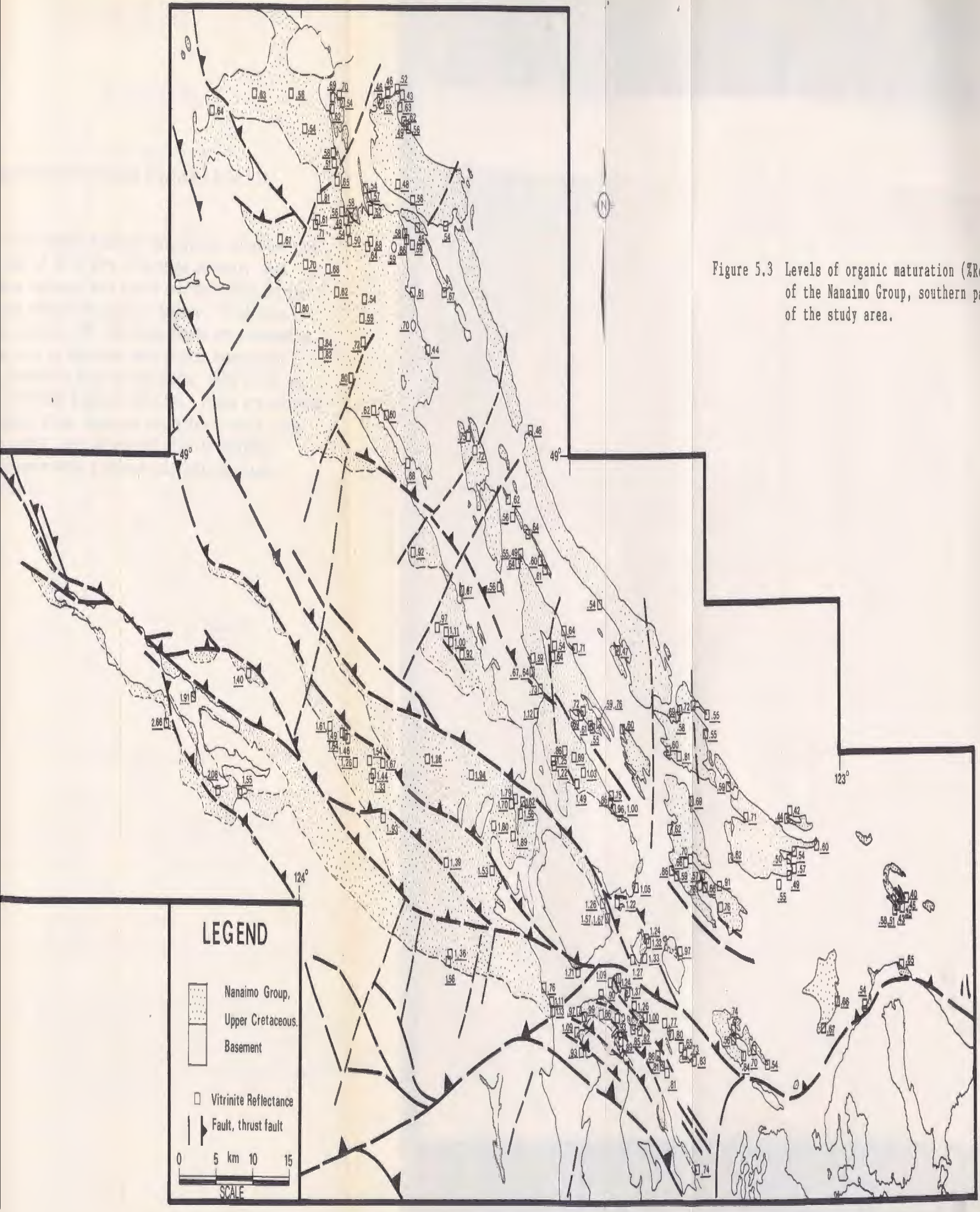


Figure 5.3 Levels of organic maturation (%Ro) of the Nanaimo Group, southern part of the study area.

Reflectance/depth plots (Figures 5.4 to 5.16)

Solid squares represent data points calculated from the mean of 20 or more reflectance readings; open squares represent data points calculated from the mean of less than 20 reflectance readings. In addition, where possible, 95% confidence limits are expressed as error bars on individual data points, based on the "t" probability distribution (Davis, 1973; p. 95) and the calculated standard deviation. Faults are indicated by dashed lines, formation boundaries by solid lines. Long dashed lines on selected profiles represent reflectance-depth gradients calculated by linear regression.

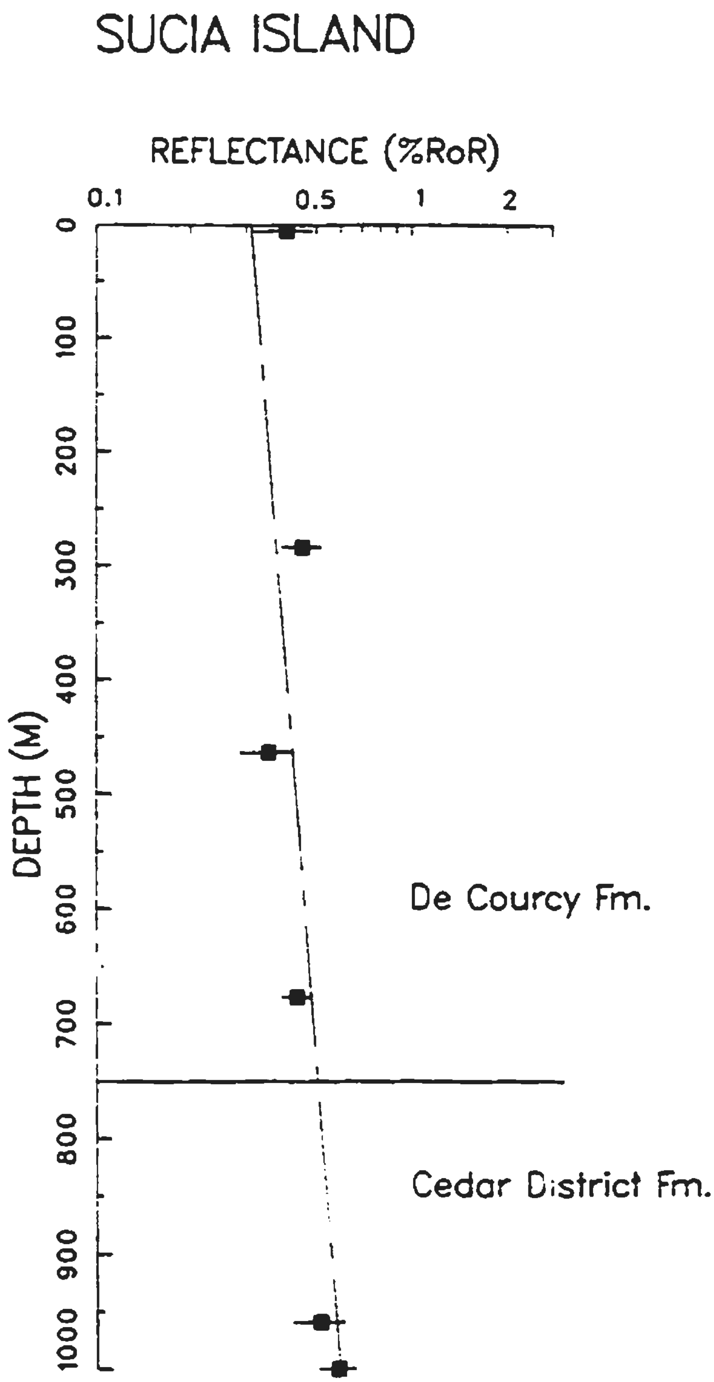


Figure 5.4 Reflectance/depth plot for middle Nanaimo Group exposed along the southern Sucia Islands. The data do not support the notion of a significant unconformity at ca. 750 m as has been suggested by Johnson (1985).

COAL ISLAND

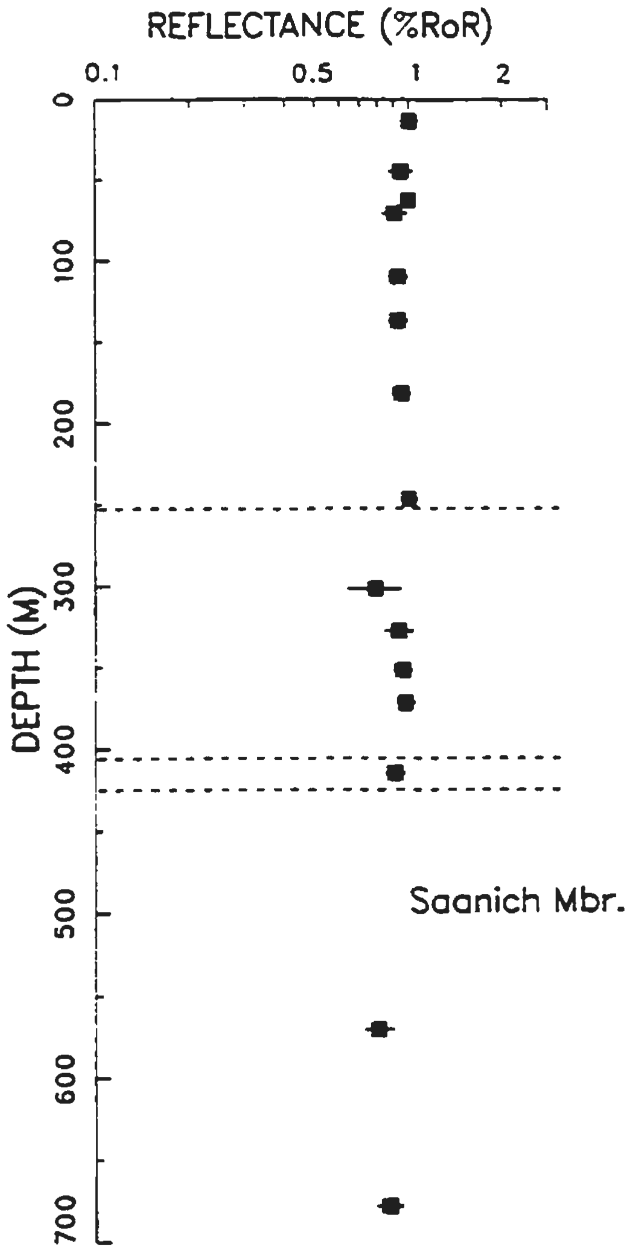


Figure 5.5 Reflectance/depth plot for lower Nanaimo Group exposed on southeastern Coal Island. This section features at least 3 minor thrusts beneath which there are consistent minor back-steps in %Ro levels.

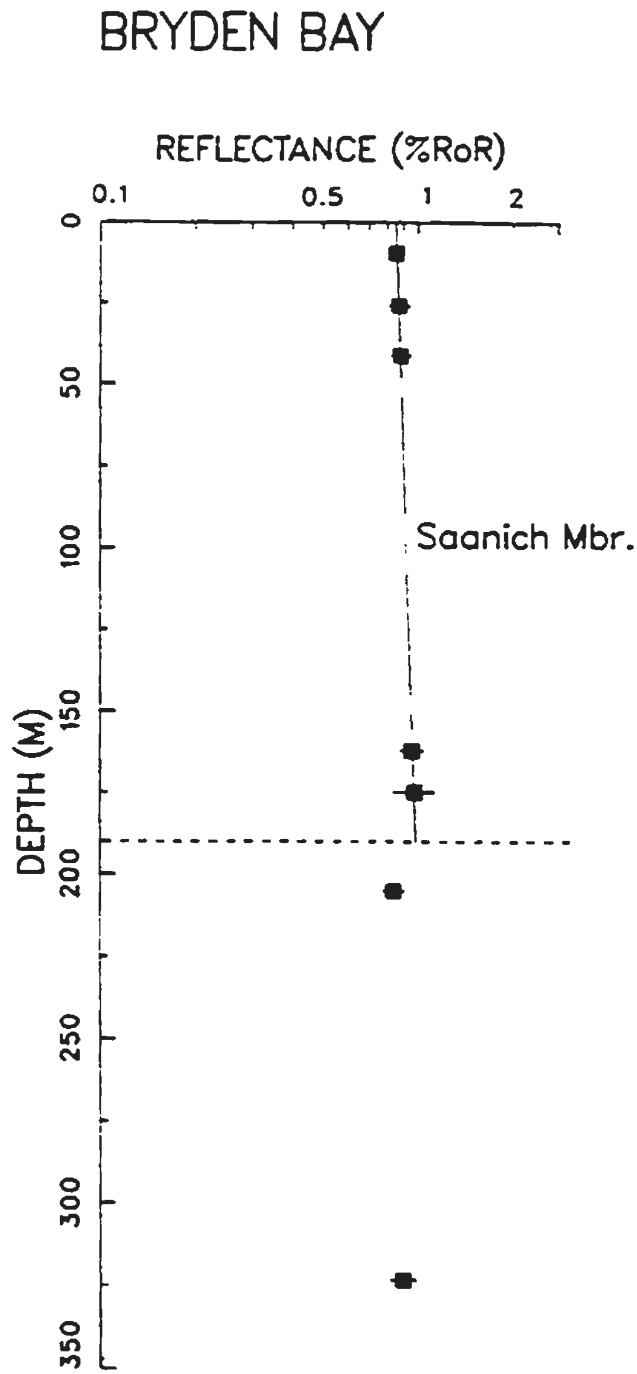


Figure 5.6 Reflectance/depth plot for basal Nanaimo Group exposed along the north shore of Tsehum harbour, northern Saanich Peninsula. A minor back-step in %Ro level occurs beneath a minor thrust fault.

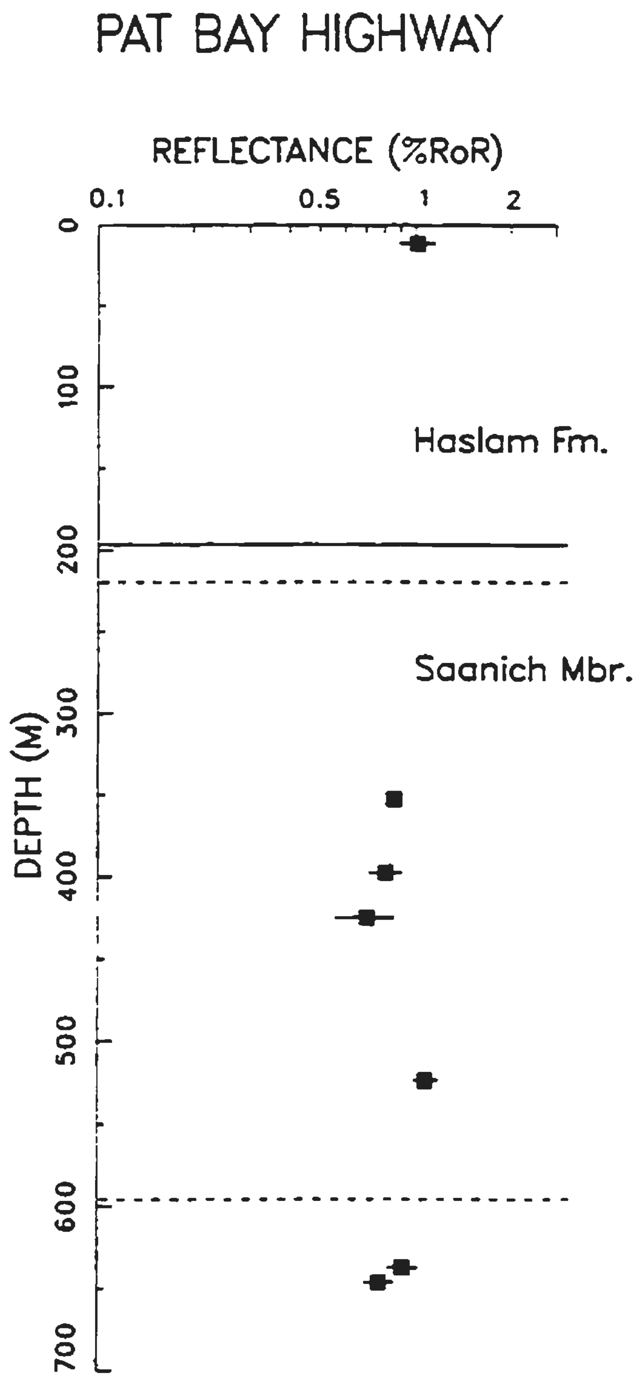


Figure 5.7 Reflectance/depth plot for lower Nanaimo Group exposed along the Pat Bay Highway on northern Saanich Peninsula. Although the data are sparse, they show that higher rank strata are probably thrust over lower rank strata.

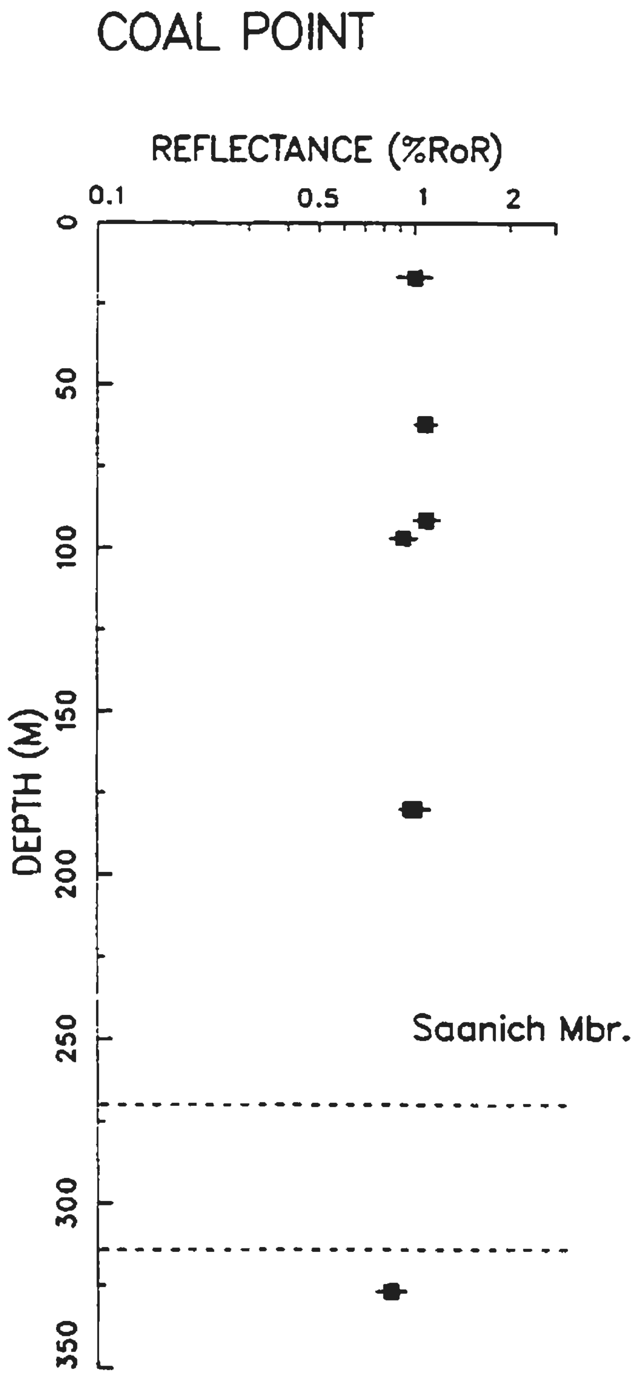


Figure 5.8 Reflectance/depth plot for lower Nanaimo Group cropping out on northwestern Saanich Peninsula near Coal Point. Rank does not increase with depth, which suggests that the section is structurally disrupted.

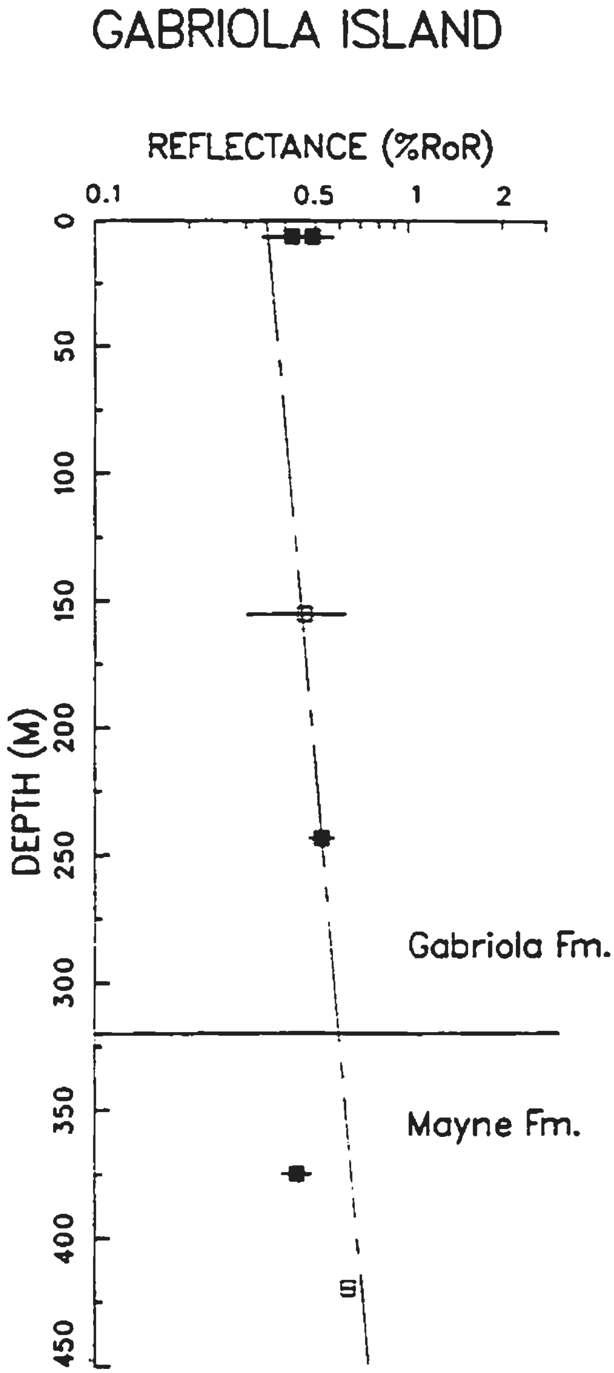


Figure 5.9 Reflectance/depth plot for upper Nanaimo Group exposed along northern Gabriola Island from Orlebar Point to Tinson Point.

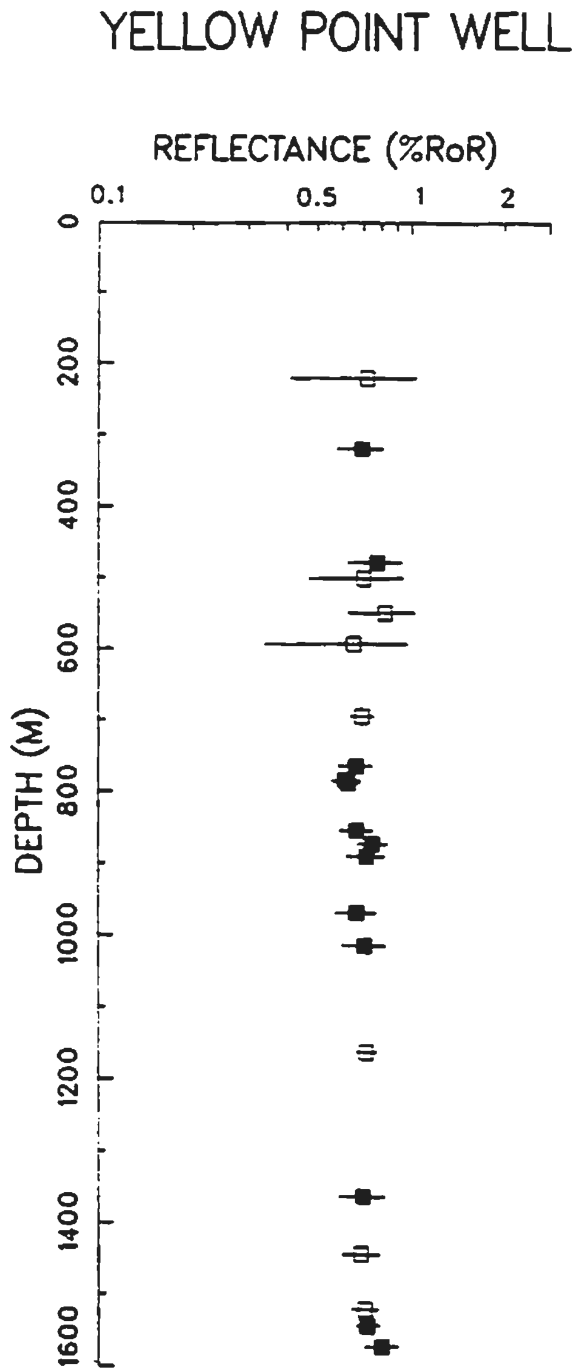


Figure 5.10 Reflectance/depth plot for middle to lower Nanaimo Group in the BP Yellow Point well. There is no observed increase in %Ro levels down the well. However, the data are poor in the upper part of the well.

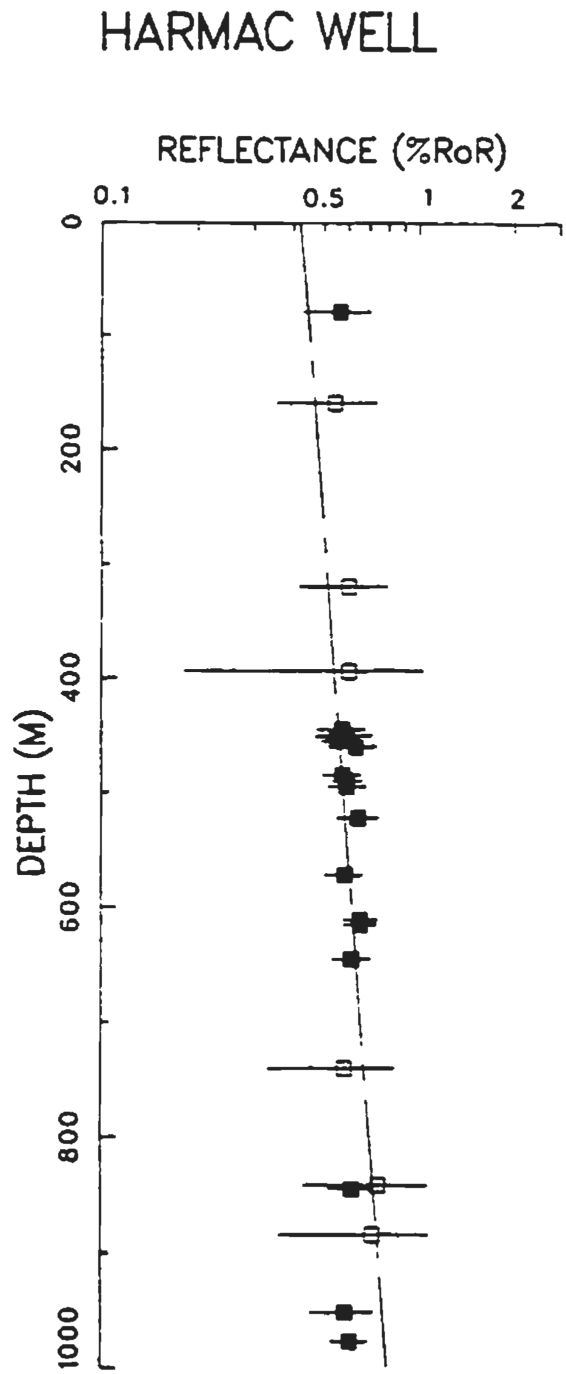


Figure 5.11 Reflectance/depth plot for middle to lower Nanaimo Group in the BP Harmac well. The data from this well are better than in the Yellow Point well, showing an overall increase in %Ro levels with increasing depth. The gradient calculated, however, has a very low correlation coefficient.

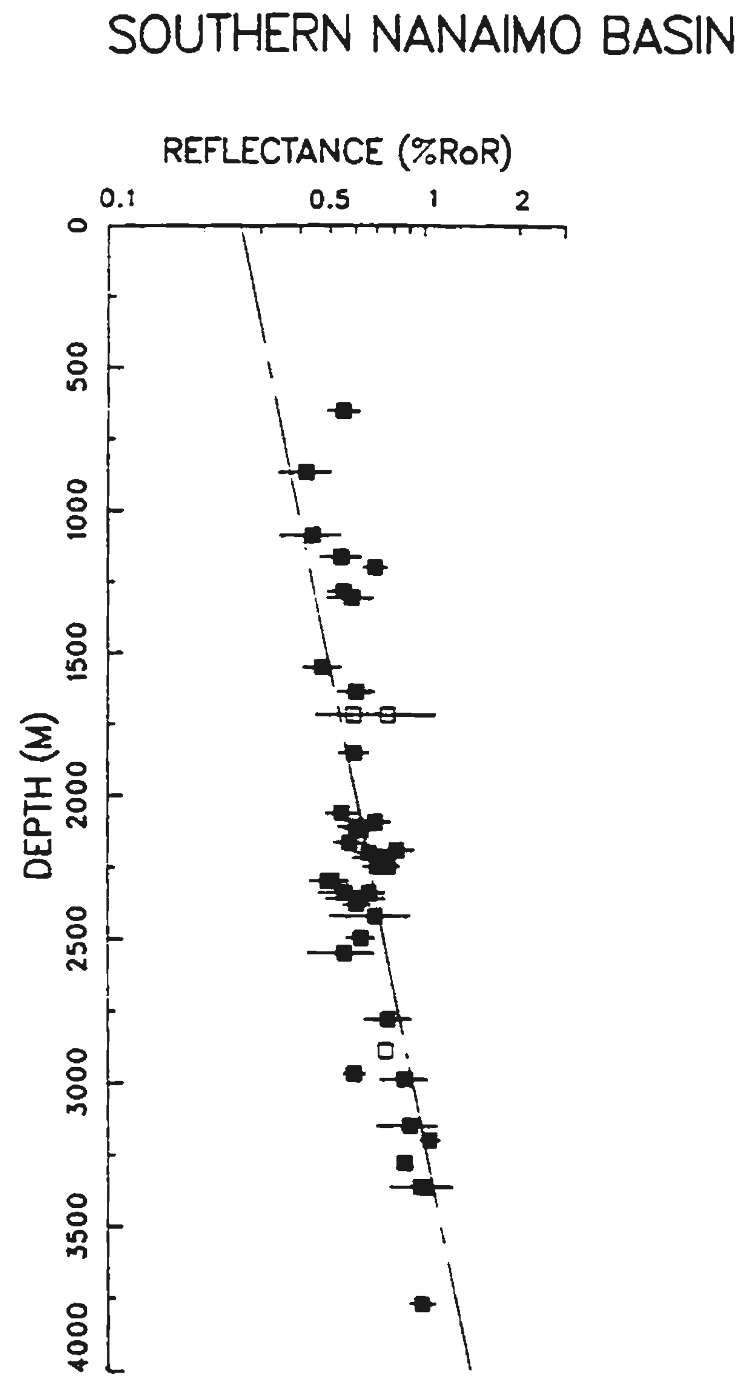


Figure 5.12 Reflectance/depth plot for the Nanaimo Group outcropping in the southern Gulf Islands. This is a composite section, the top of which is 1165 m above the base of the Gabriola Formation.

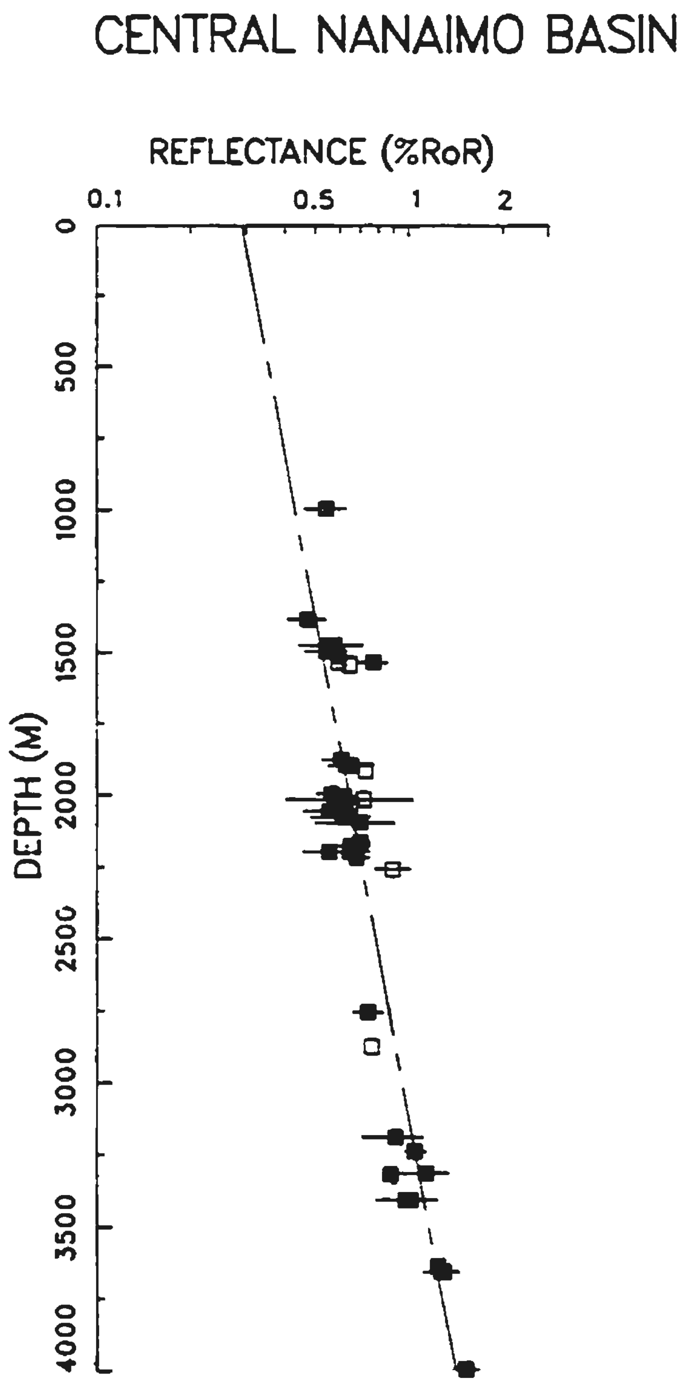


Figure 5.13 Reflectance/depth plot for the Nanaimo Group exposed in the central Gulf Islands. This is a composite section, the top of which is 1000 m above the base of the Gabriola Formation.

NORTHERN NANAIMO BASIN

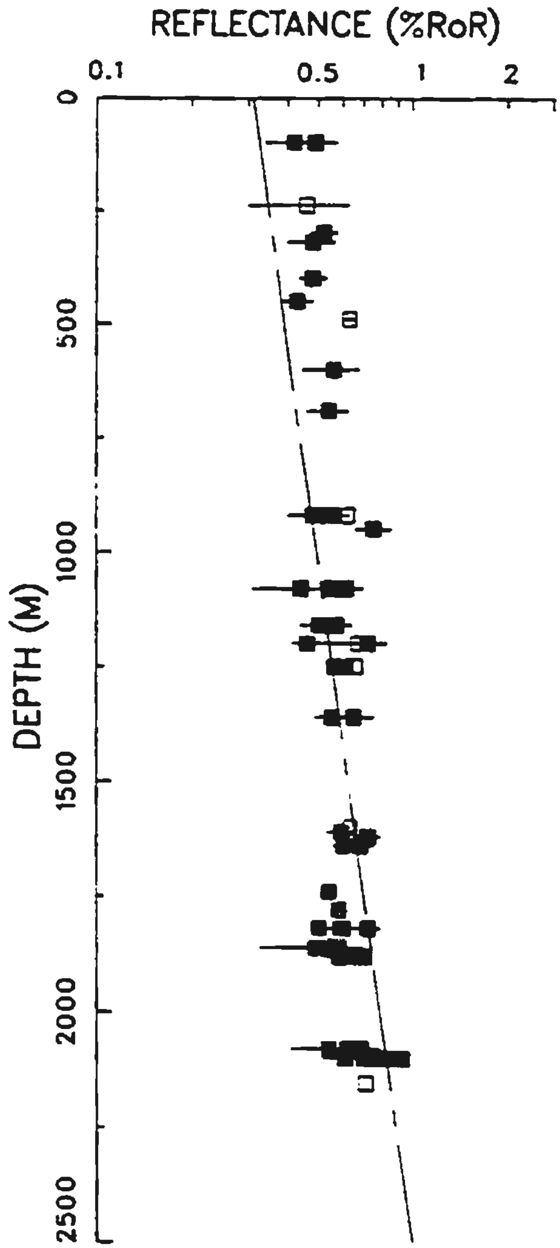


Figure 5.14 Reflectance/depth plot for the Nanaimo Group cropping out on eastern Vancouver Island and the northern Gulf Islands. The top of this composite section is 400 m above the base of the Gabriola Formation.

Figure 5.15 Reflectance/depth plots for short coal exploration boreholes drilled in the Nanaimo Group, southern Comox Basin. The formations are identified on the figure. Note the rapid increase in %Ro levels in the proximity of the sills. Except for these parts of the section, the reflectance/depth gradients are low. See Appendix A for borehole locations and text for discussion.

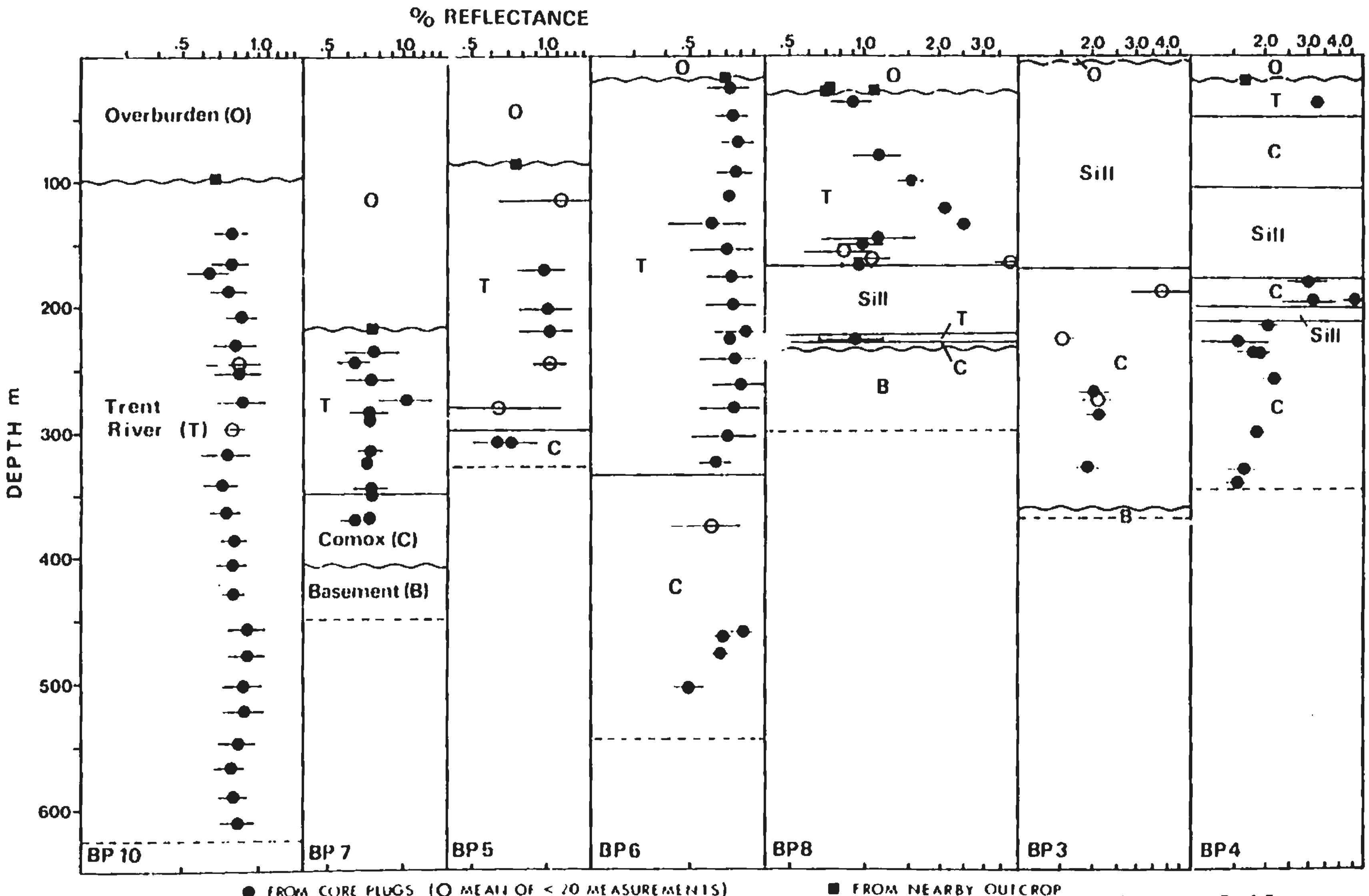

% REFLECTANCE
DEPTH m
Overburden (O)
Trent River (T)
Comox (C)
Basement (B)
Sill
BP 10
BP 7
BP 5
BP 6
BP 8
BP 3
BP 4
● FROM CORE PLUGS (O MEAN OF < 20 MEASUREMENTS)
■ FROM NEARBY OUTCROP

Figure 5.15

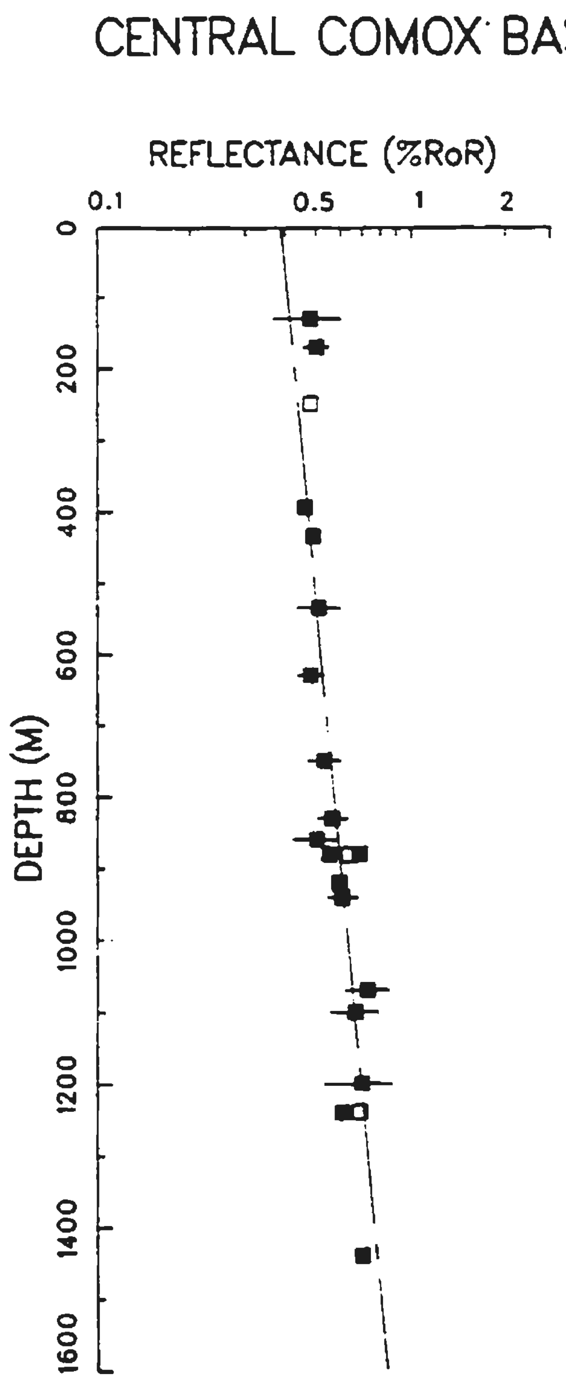


Figure 5.16 Reflectance/depth plot for the upper Nanaimo Group in the Denman - Hornby Island area. The top of this composite section is 170 m above the base of the Hornby Formation.

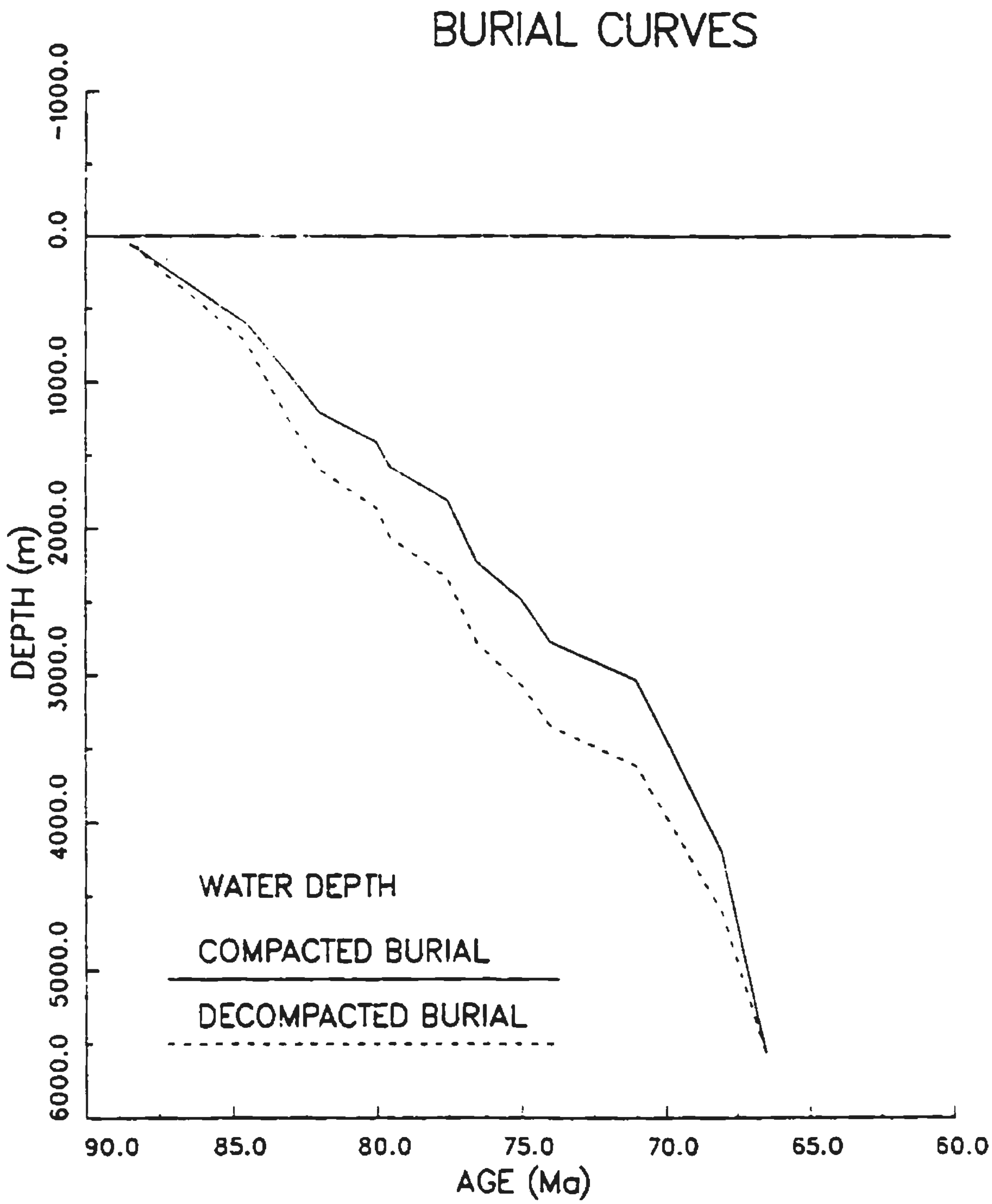


Figure 6.1 Burial curves and water-depth curve for site 1 (southern Nanaimo Basin). The burial curves are for the total depth level (oldest horizon) in the Nanaimo Group.

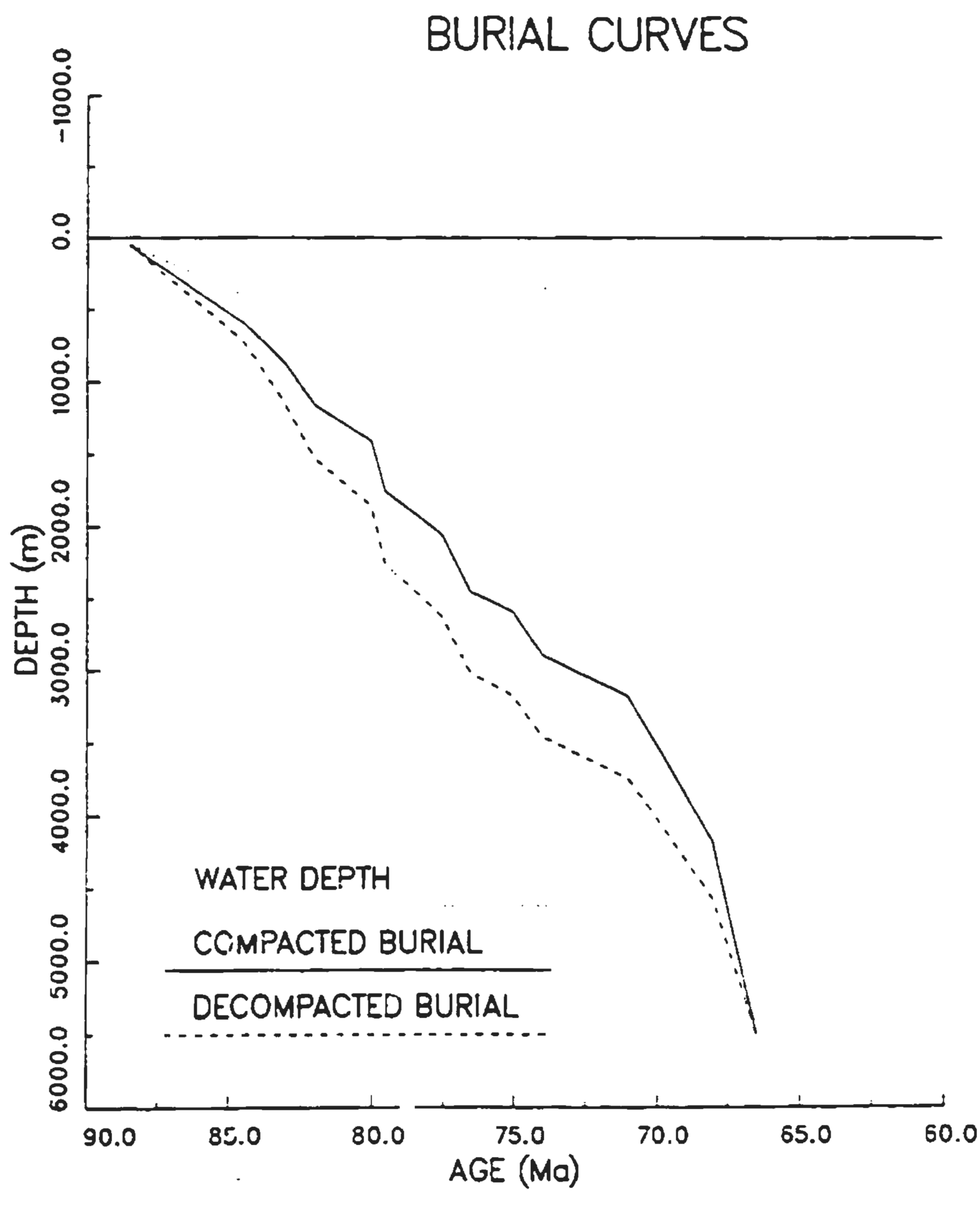


Figure 6.2 Burial curves and water-depth curve for site 2 (central Nanaimo Basin). The burial curves are for the total depth level (oldest horizon) in the Nanaimo Group.

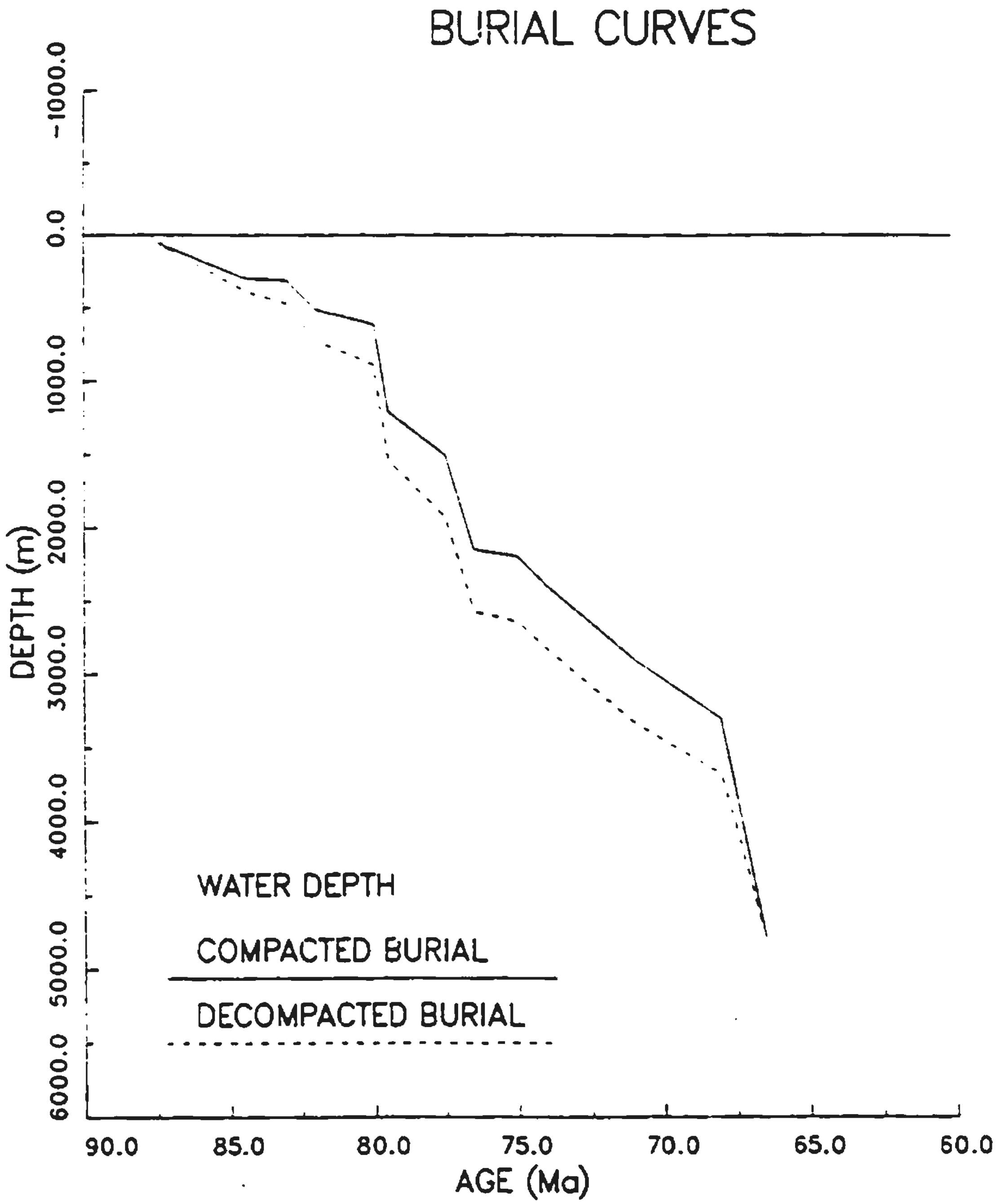


Figure 6.3 Burial curves and water-depth curve for site 3 (northern Nanaimo Basin). The burial curves are for the total depth level (oldest horizon) in the Nanaimo Group.

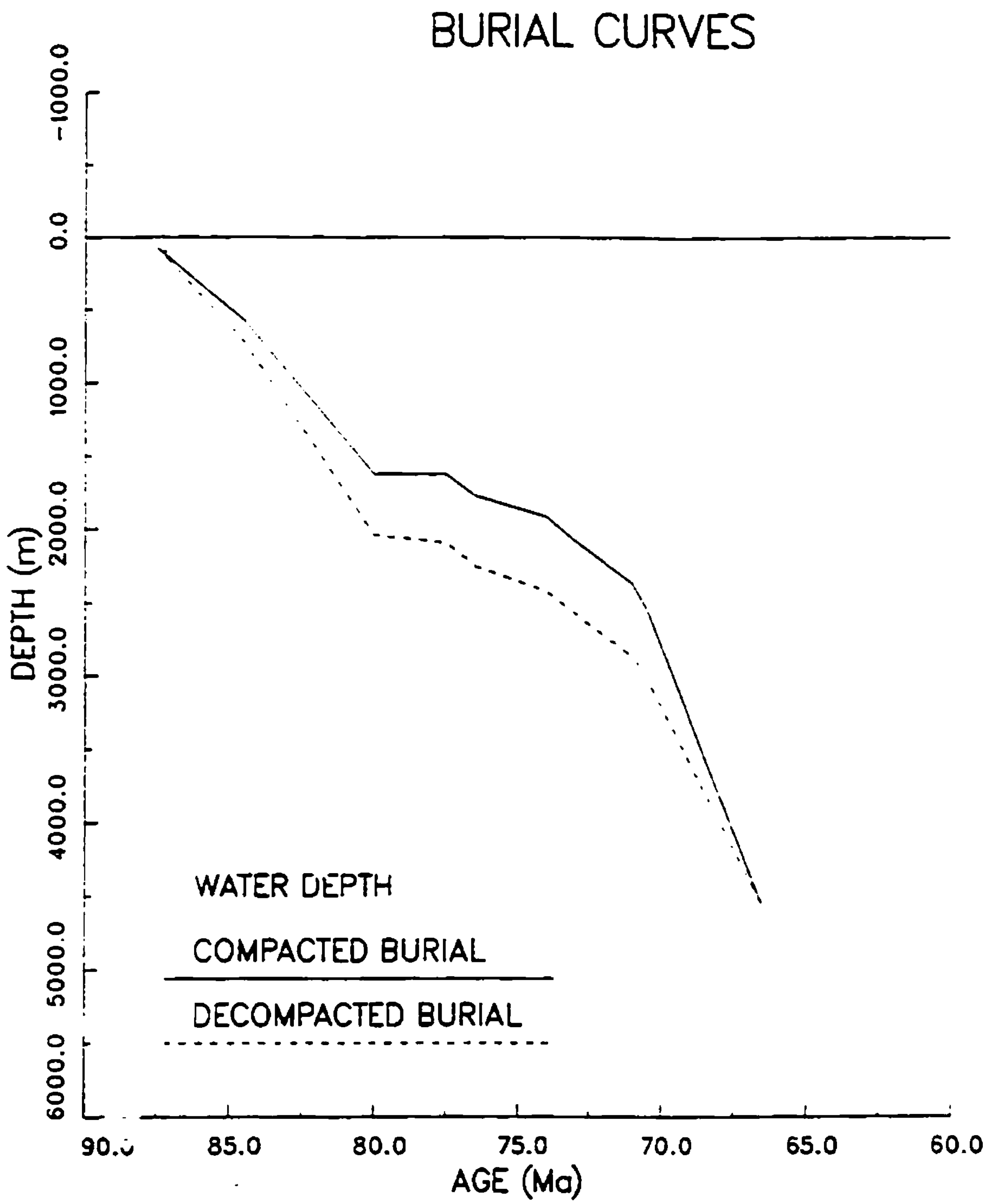


Figure 6.4 Burial curves and water-depth curve for site 4 (central Comox Basin). The burial curves are for the total depth level (oldest horizon) in the Nanaimo Group.

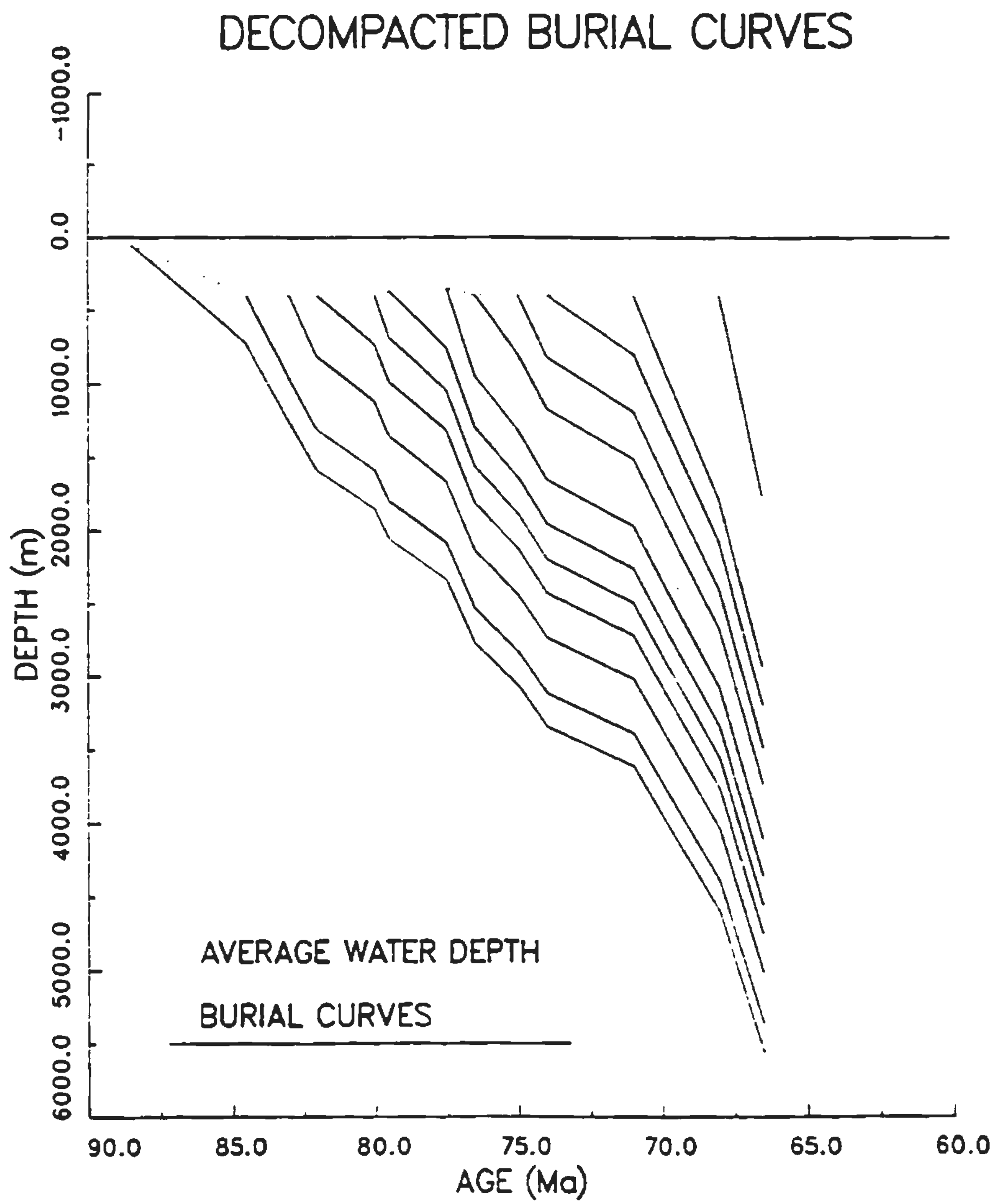


Figure 6.5 Decompacted burial curves for each age level in the composite section from site 1.

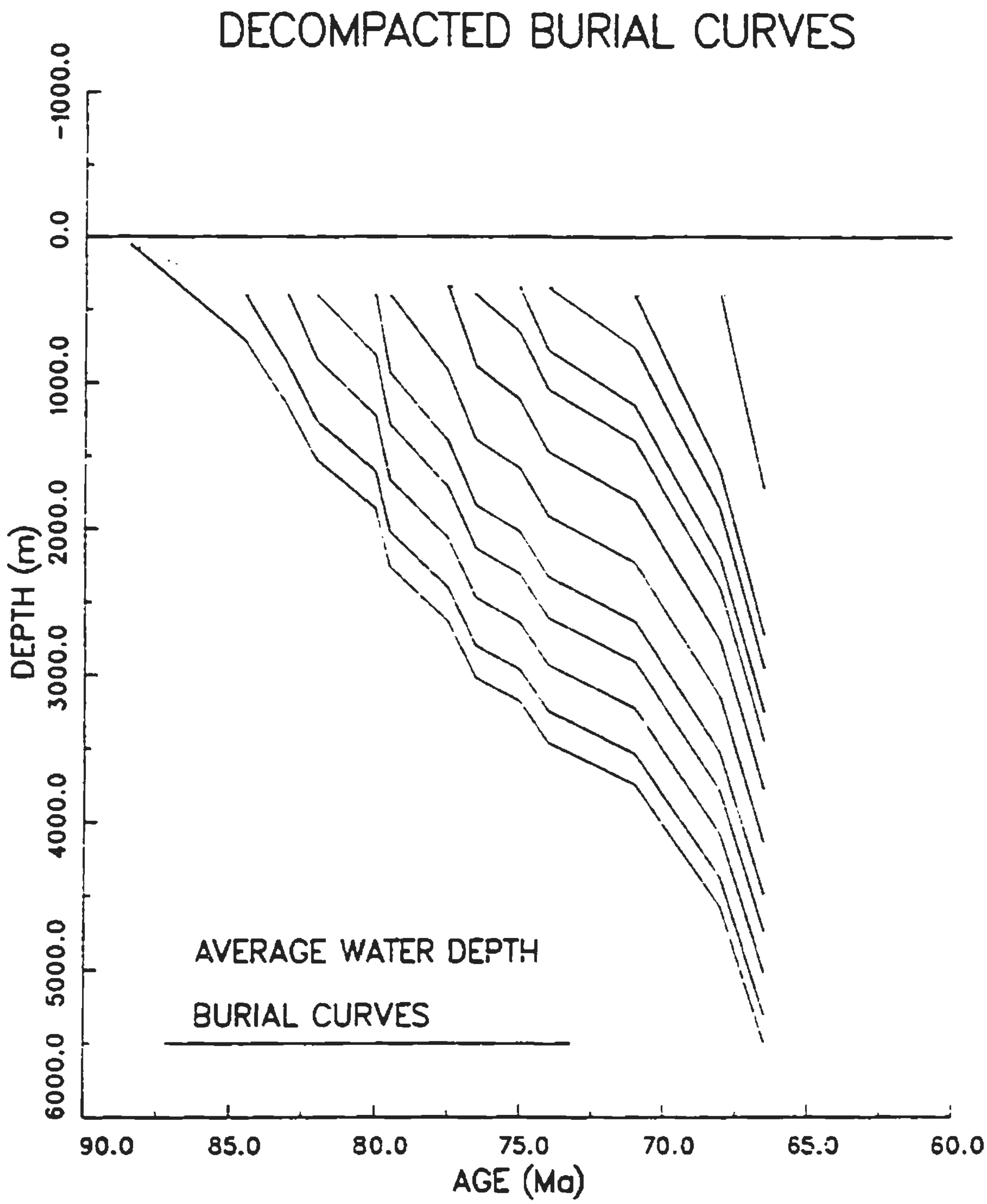


Figure 6.6 Decompacted burial curves for each age level in the composite section from site 2.

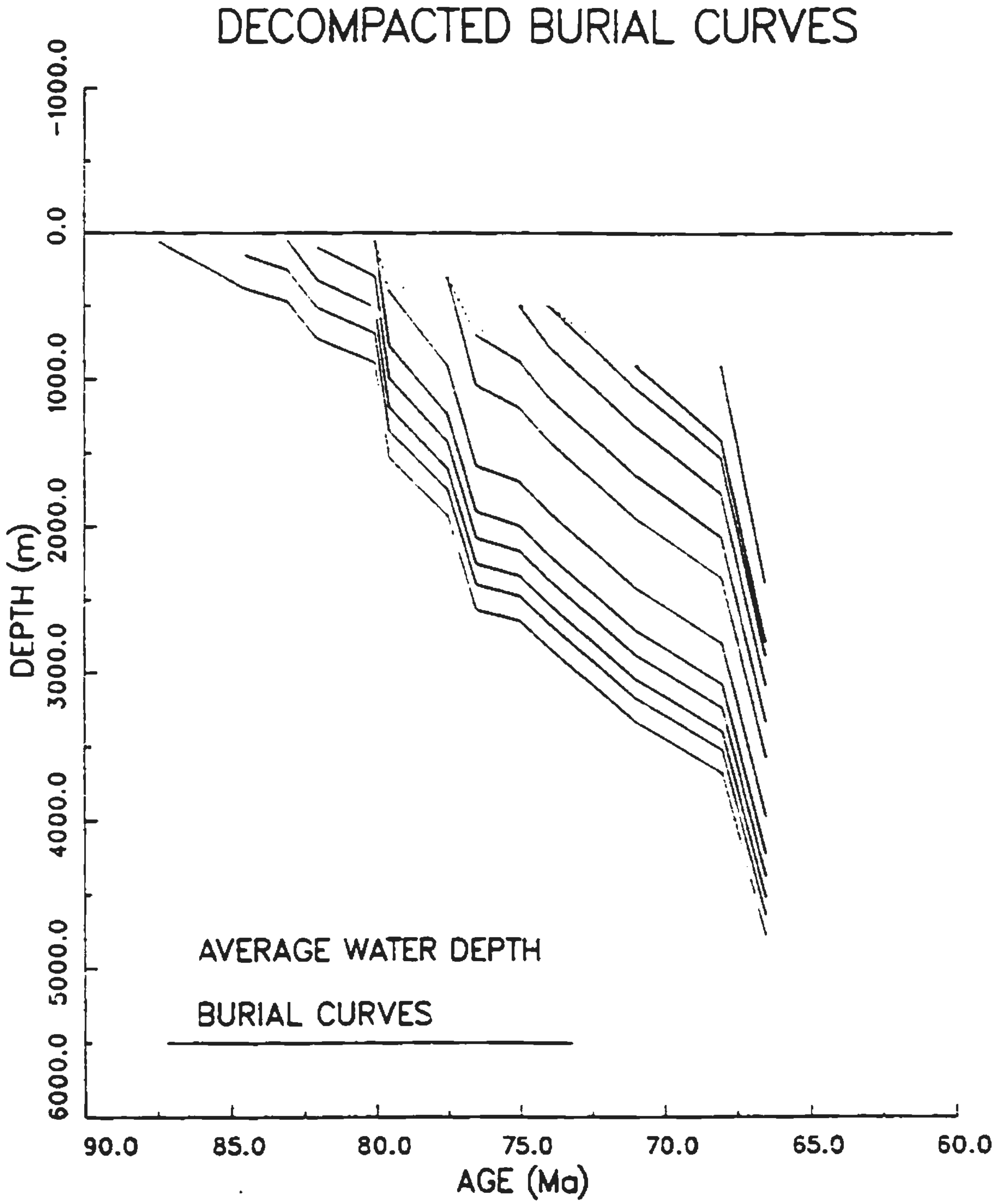


Figure 6.7 Decompacted burial curves for each age level in the composite section from site 3.

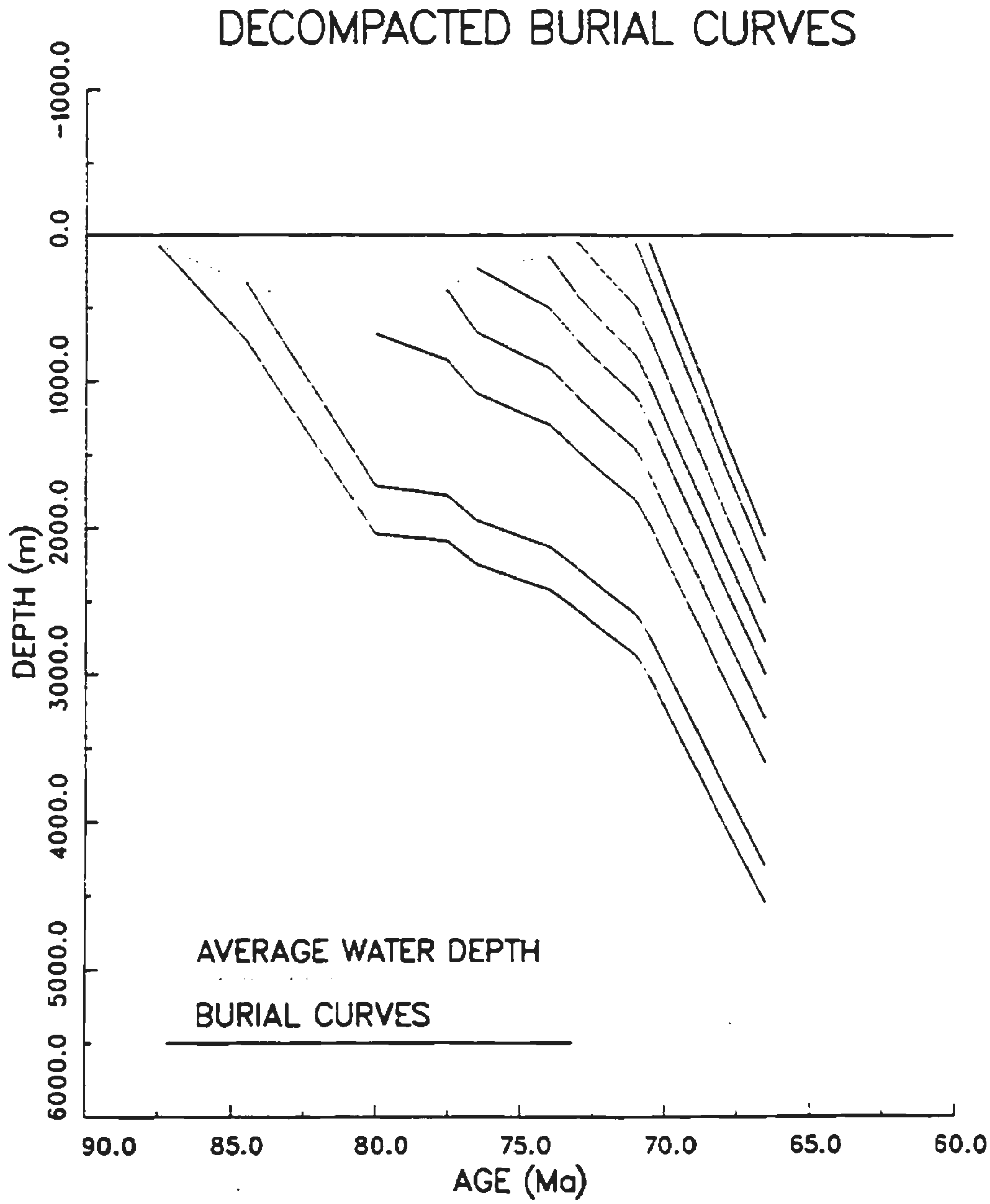


Figure 6.8 Decompacted burial curves for each age level in the composite section from site 4.

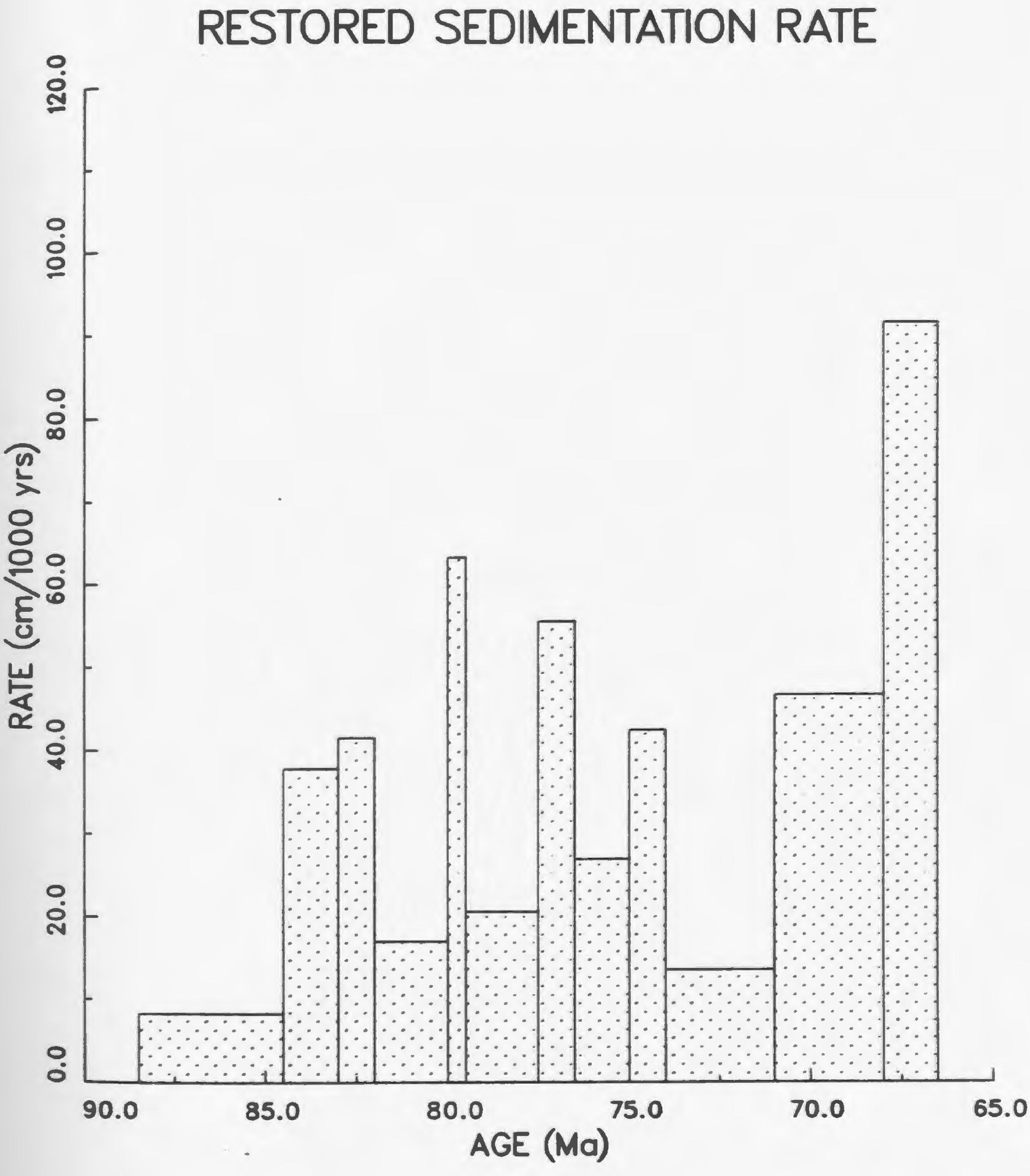


Figure 6.9 Decompacted sedimentation rates for each age level in the composite section from site 1.

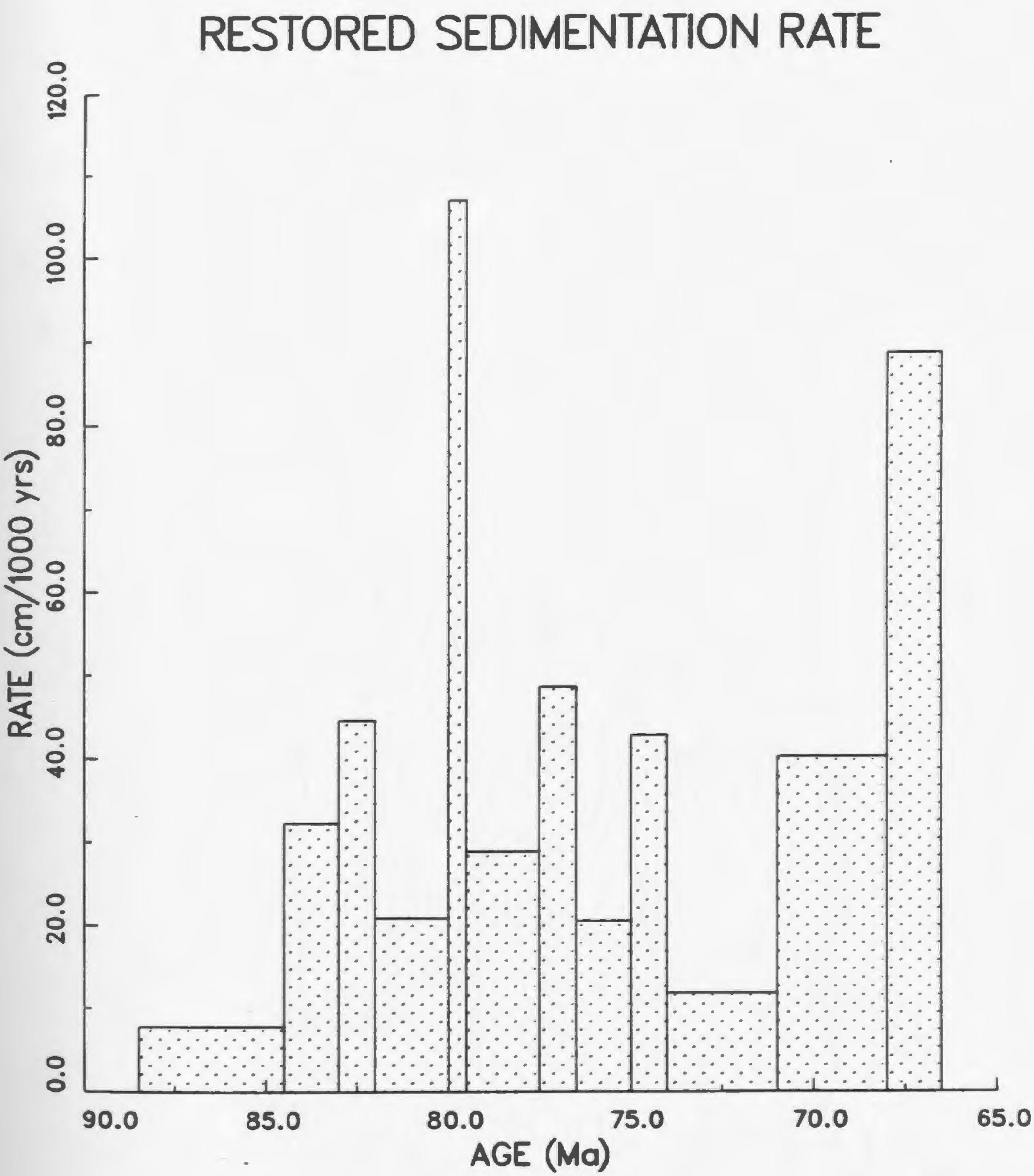


Figure 6.10 Decompacted sedimentation rates for each age level in the composite section from site 2.

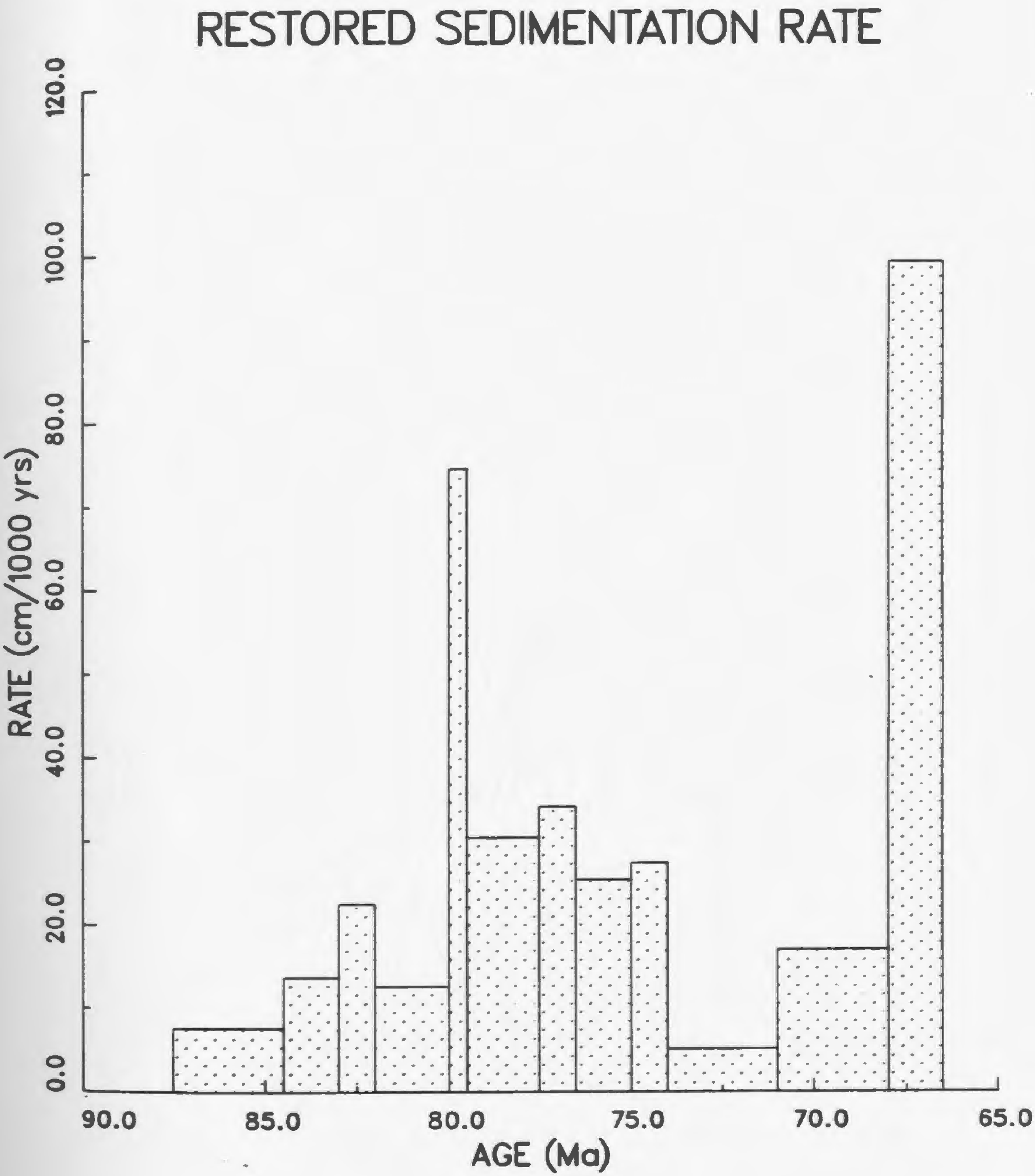


Figure 6.11 Decompacted sedimentation rates for each age level in the composite section from site 3.

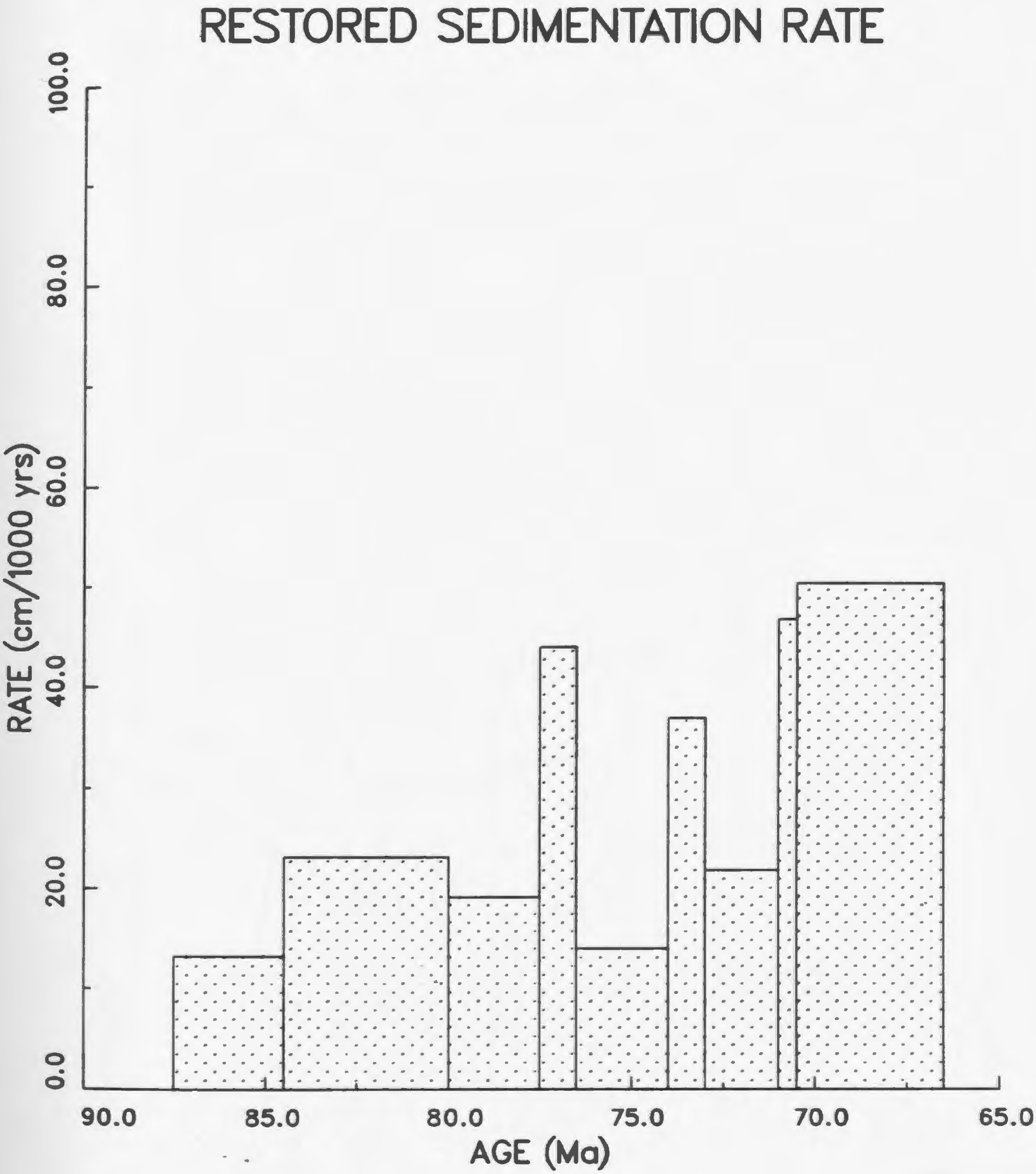


Figure 6.12 Decompacted sedimentation rates for each age level in the composite section from site 4.

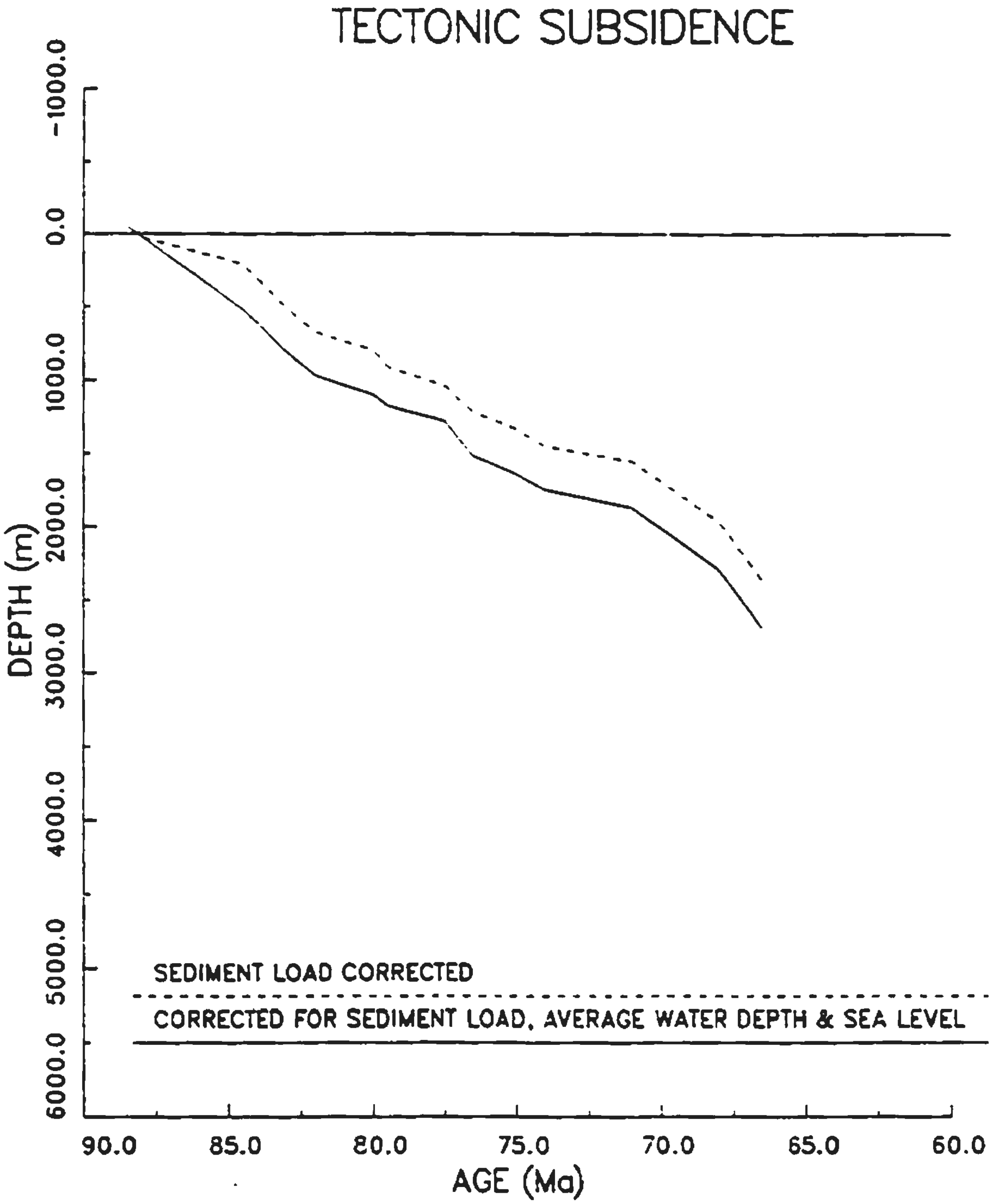


Figure 5.13 Average tectonic subsidence curves for the total depth level (oldest horizon) in the Nanaimo Group at site 1.

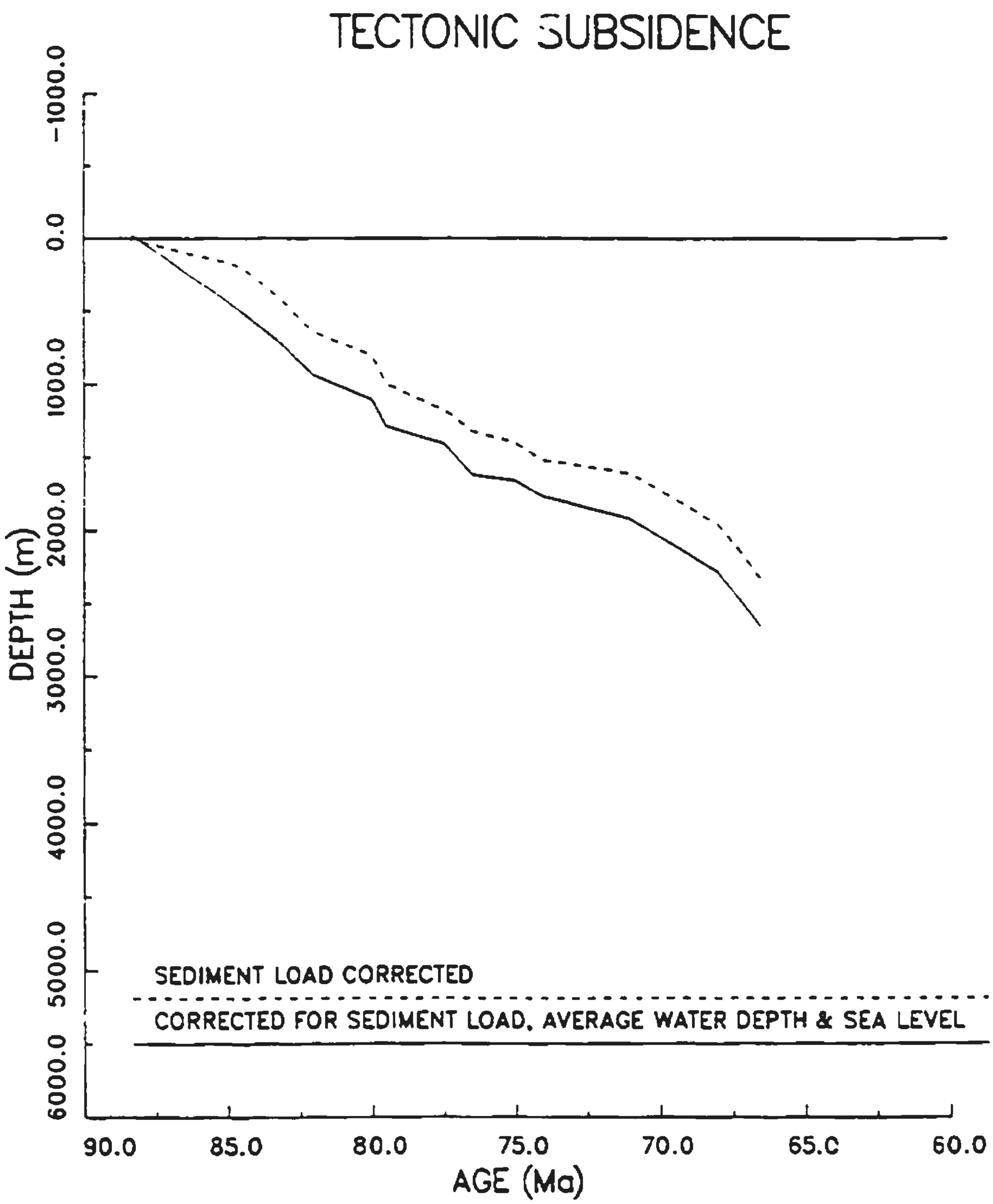


Figure 6.14 Average tectonic subsidence curves for the total depth level (oldest horizon) in the Nanaimo Group at site 2.

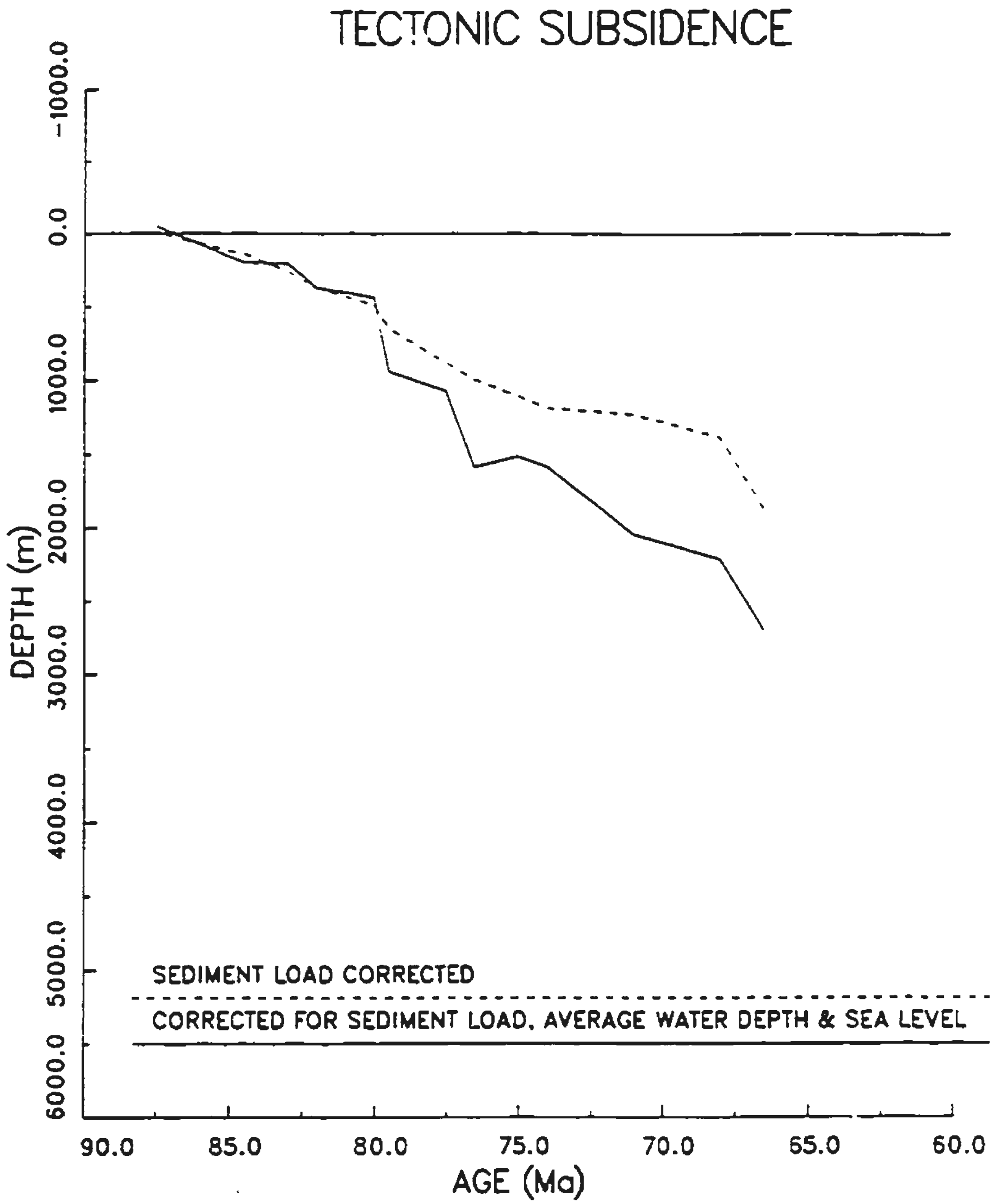


Figure 6.15 Average tectonic subsidence curves for the total depth level (oldest horizon) in the Nanaimo Group at site 3.

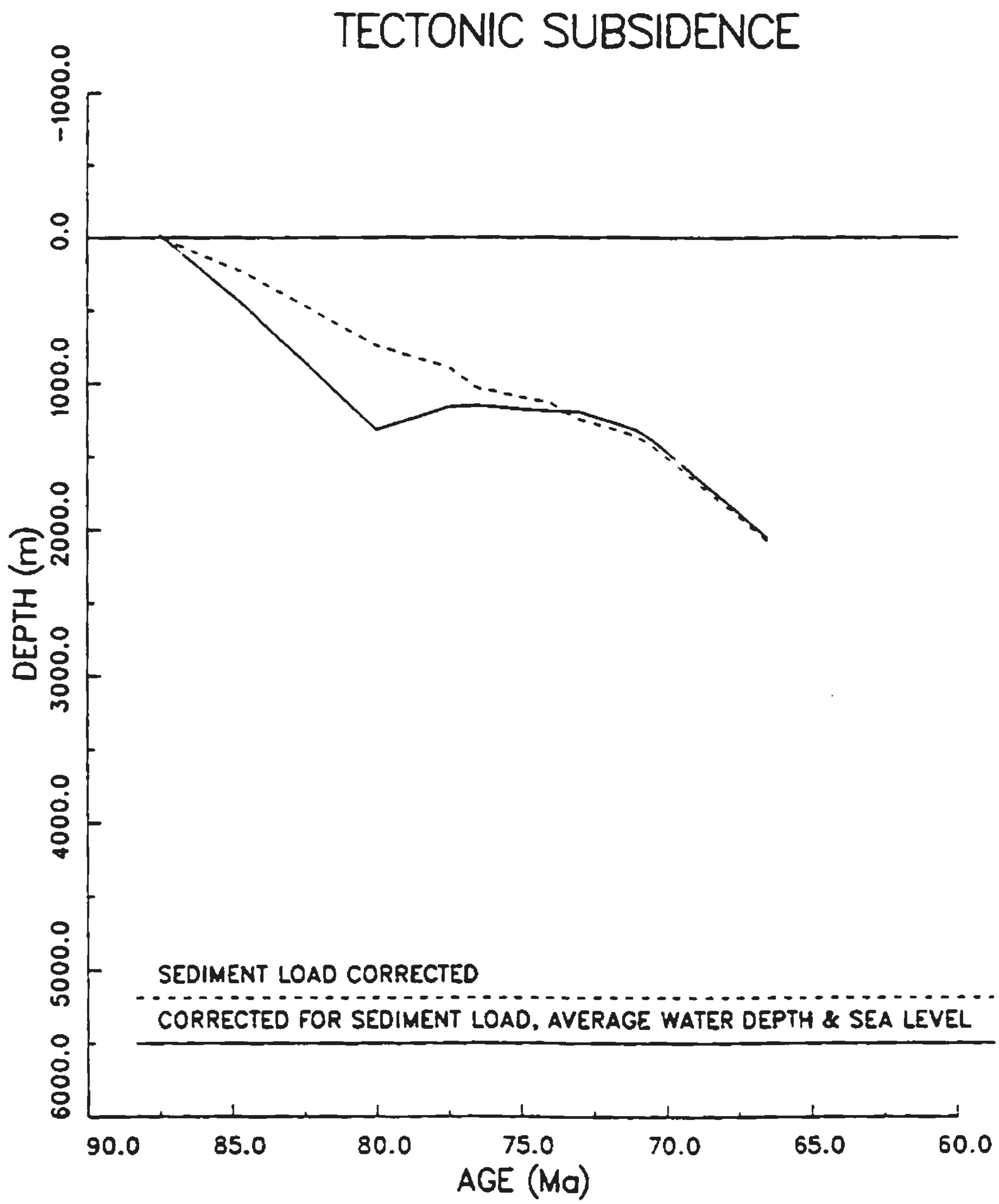


Figure 6.16 Average tectonic subsidence curves for the total depth level (oldest horizon) in the Nanaimo Group at site 4.

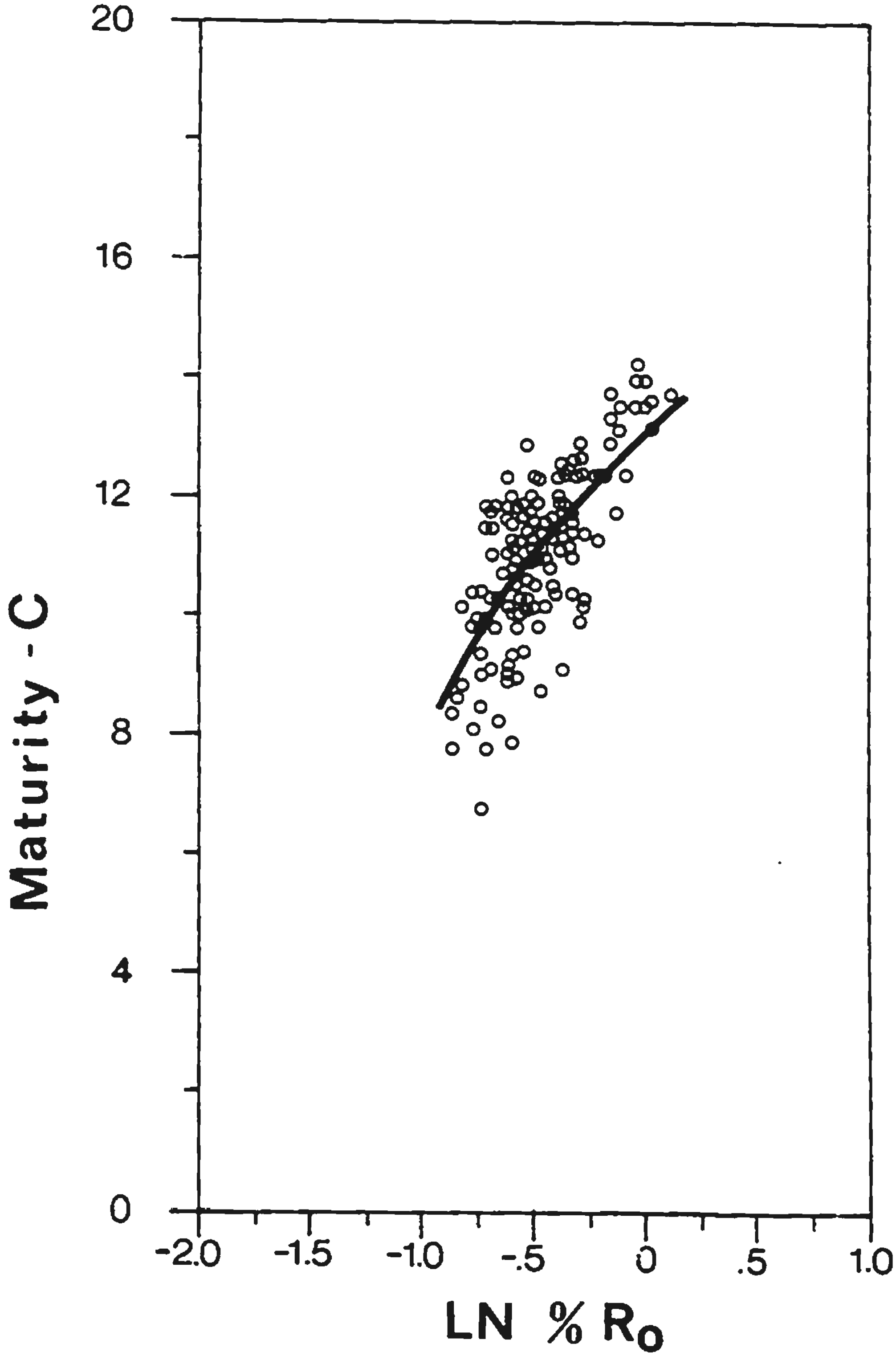
Table 7.1. Average thermal conductivity values for the Nanaimo Group based on data from outcrop samples (Appendix E).

FORMATION	CONDUCTIVITY ($Wm^{-1}K^{-1}$)	# OF SAMPLES
Gabriola	2.78	7
Mayne	1.56	4
Galiano	2.82	9
Northumberland	1.57	3
De Courcy	2.99	17
Cedar District	1.70	4
Protection	3.15	7
Pender	1.52	1
Extension	3.52	4
Haslam	1.71	4
Benson	3.62	8
Denman	2.42	1
Trent River	1.76	1
Comox	3.62	1

Table 7.2. Present day heat flow in the study area. Data from Lewis et al. (1988) and this study (*).

LOCATION	HEAT FLOW (mW/m^2)
Courtenay	38
Port Alberni	43
Nanaimo (average of 2)	45
Mount Sicker (average of 5)	35
Saanich Peninsula	34
Harmac Well*	36
Yellow Point Well*	34

Figure 7.1 Correlation of ln %Ro to the C parameter. The curve is the global average correlation (Priest et al., 1985); the circles are Nanaimo Group data from all of the modeling sites.



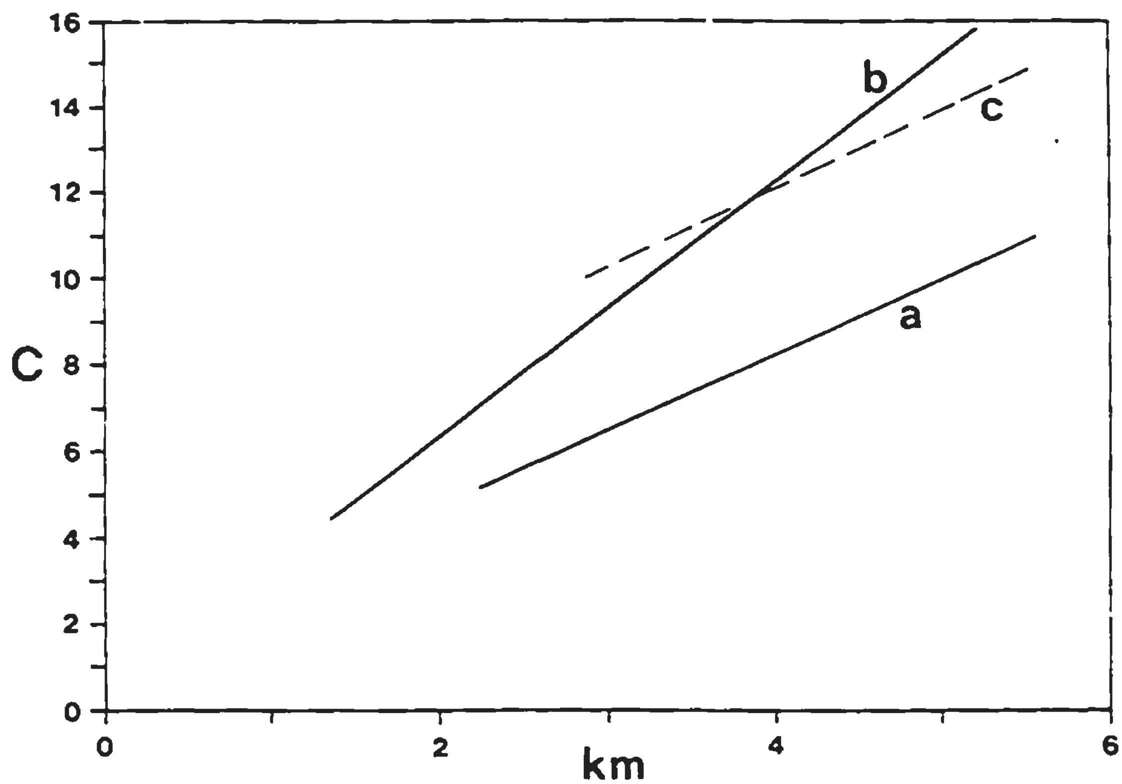


Figure 7.2 Thermal history modeling, simulation A, for site 1 (southern Nanaimo Basin). Curve "a" represents calculated maturation levels using present day heat flow of 36 mW/m^2. Curve "c" represents measured maturation levels. If higher heat flow is used in the burial history simulation, the calculated maturation gradient is too high (eg. curve "b" for 70 mW/m^2).

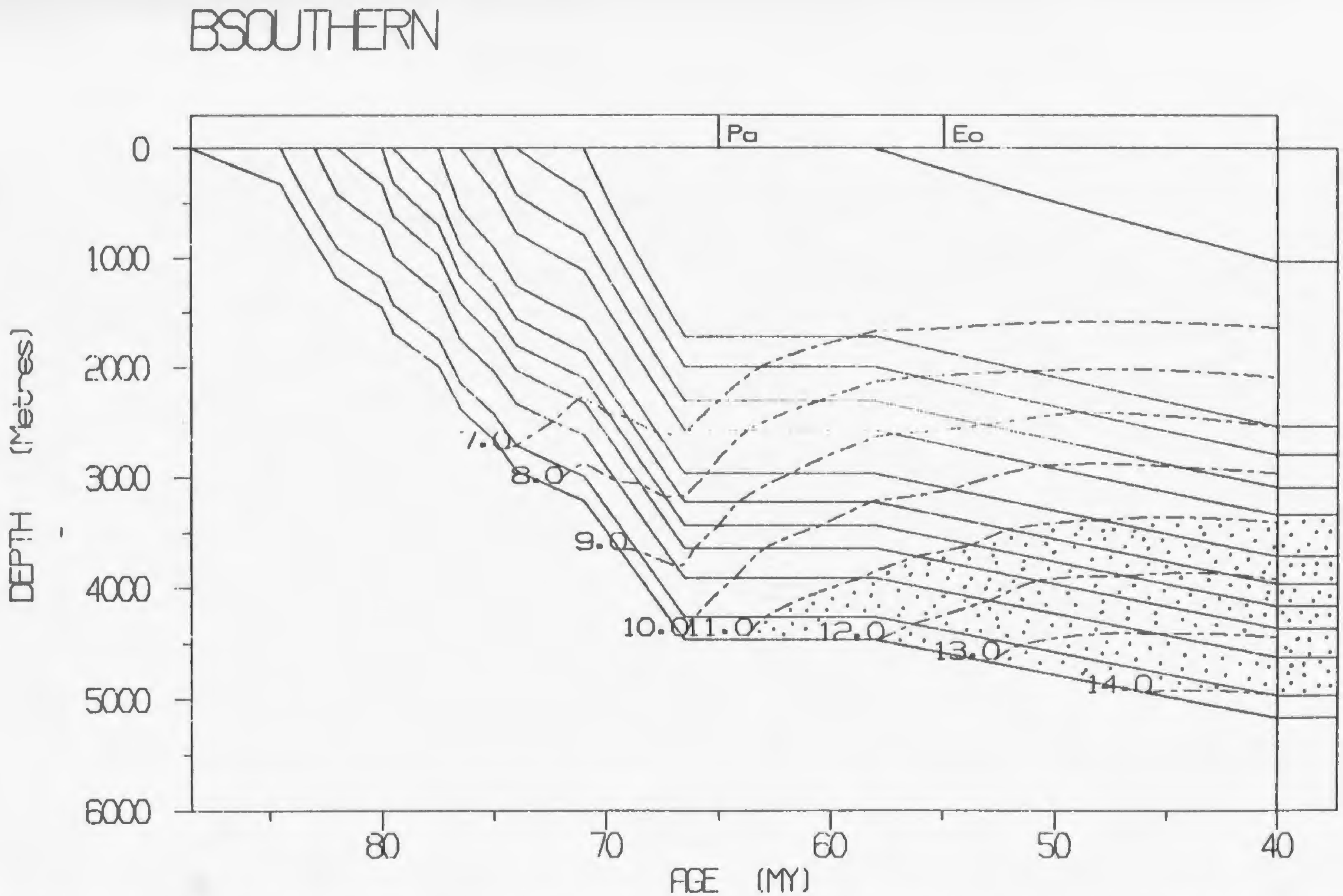


Figure 7.3 Burial history plot for simulation B at site 1. Isopleths of C values are shown by dashed lines; the oil window is shown by small dots.

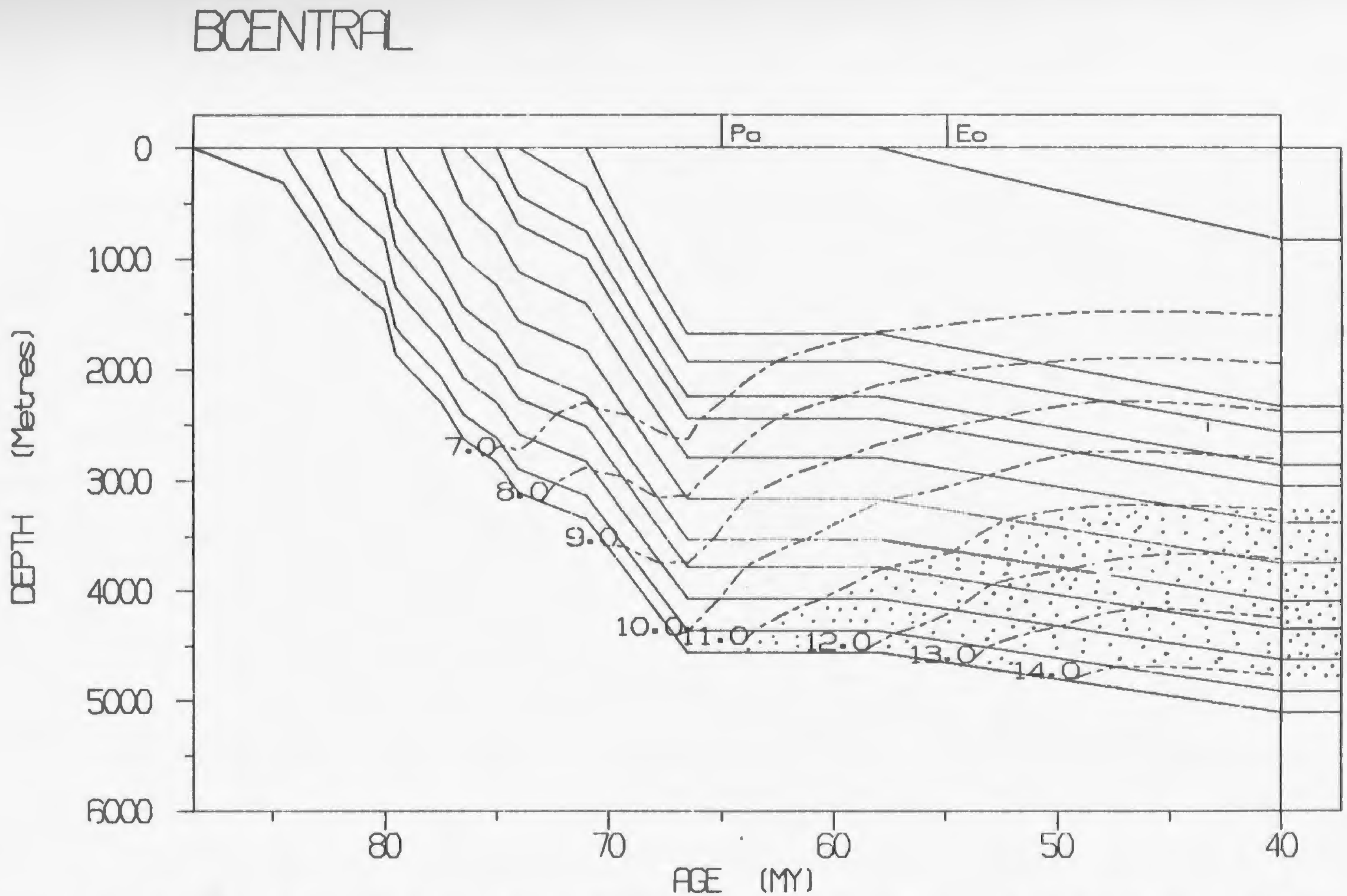


Figure 7.4 Burial history plot for simulation B at site 2. Isopleths of C values are shown by dashed lines; the oil window is shown by small dots.

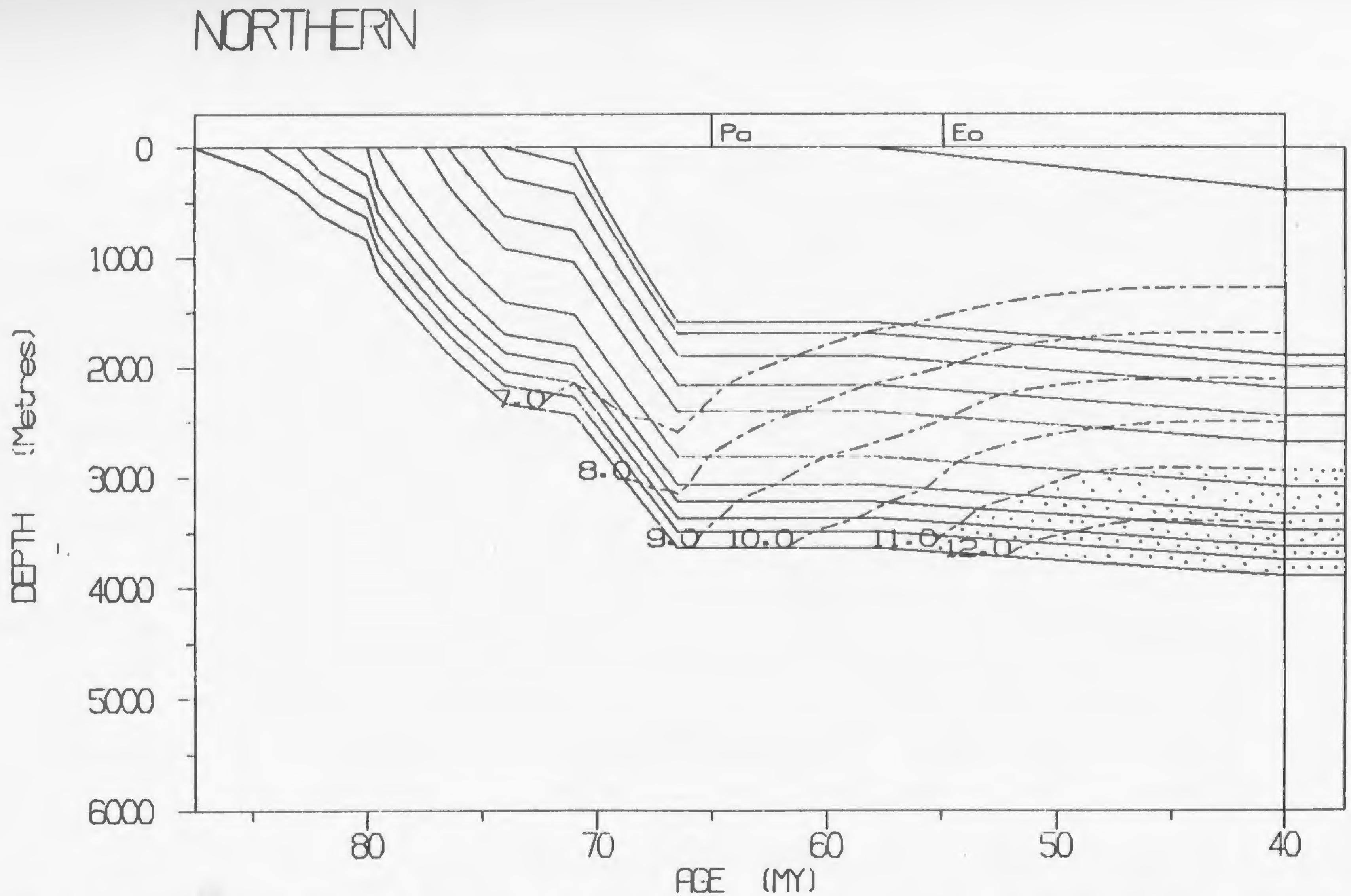


Figure 7.5 Burial history plot for simulation B at site 3. Isopleths of C values are shown by dashed lines; the oil window is shown by small dots.

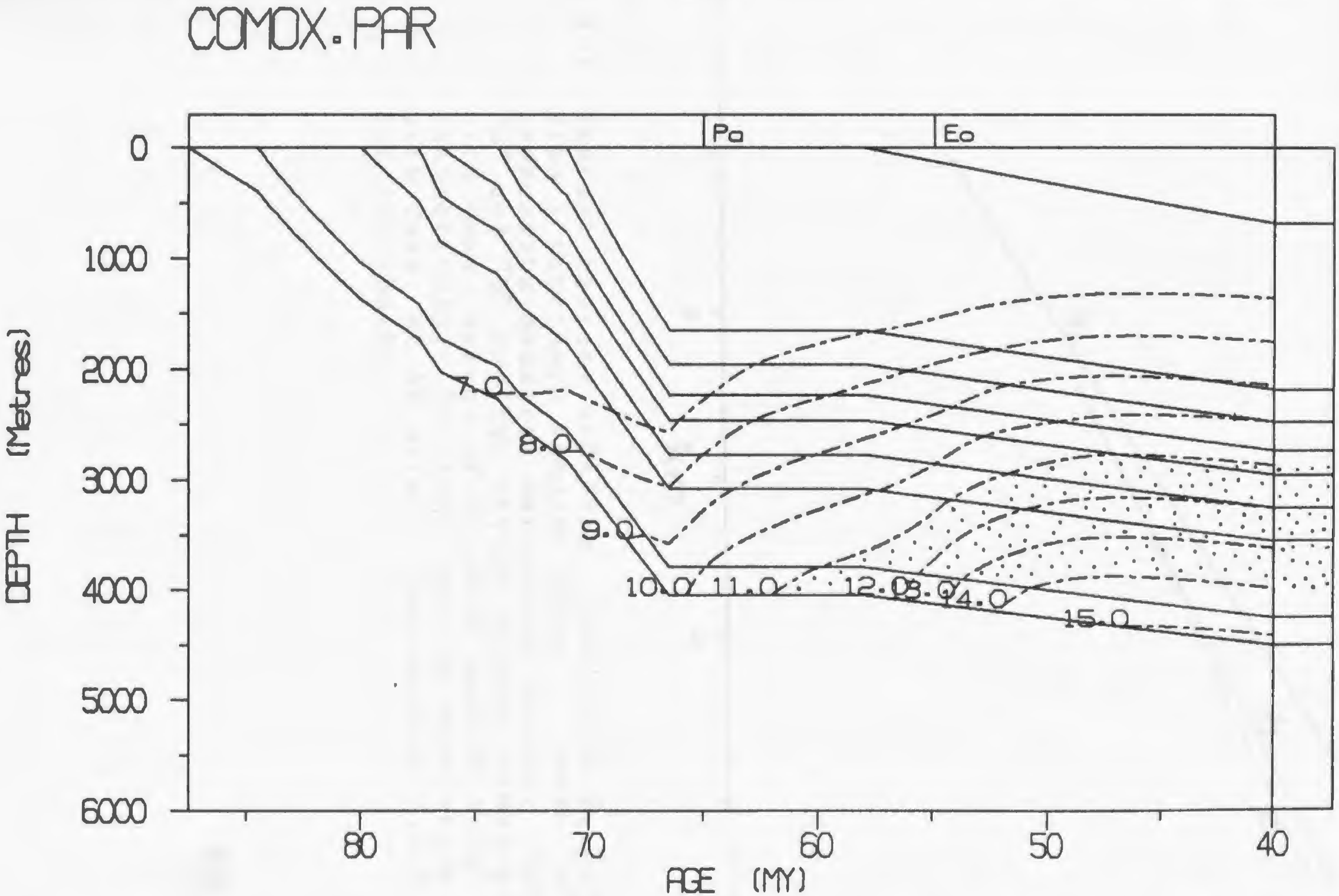


Figure 7.6 Burial history plot for simulation B at site 4. Isopleths of C values are shown by dashed lines; the oil window is shown by small dots.

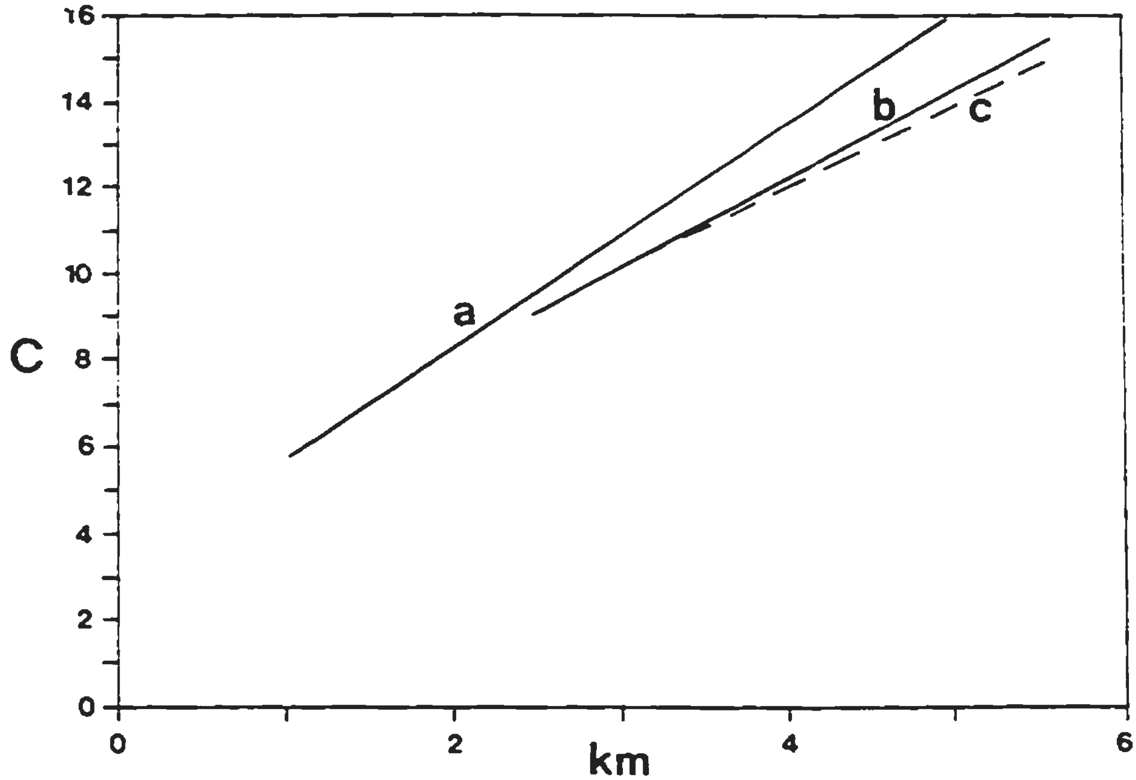


Figure 7.7 Thermal history modeling, simulation B, for site 1 (southern Nanaimo Basin). Curve "c" represents measured maturation levels. Curves "a" and "b" are for burial history simulations with Qmax. values of 60 mW/m^2 and 50 mW/m^2 respectively. The best fitting simulation is with Qmax. at 48 mW/m^2. See section 7.6.2 for discussion.

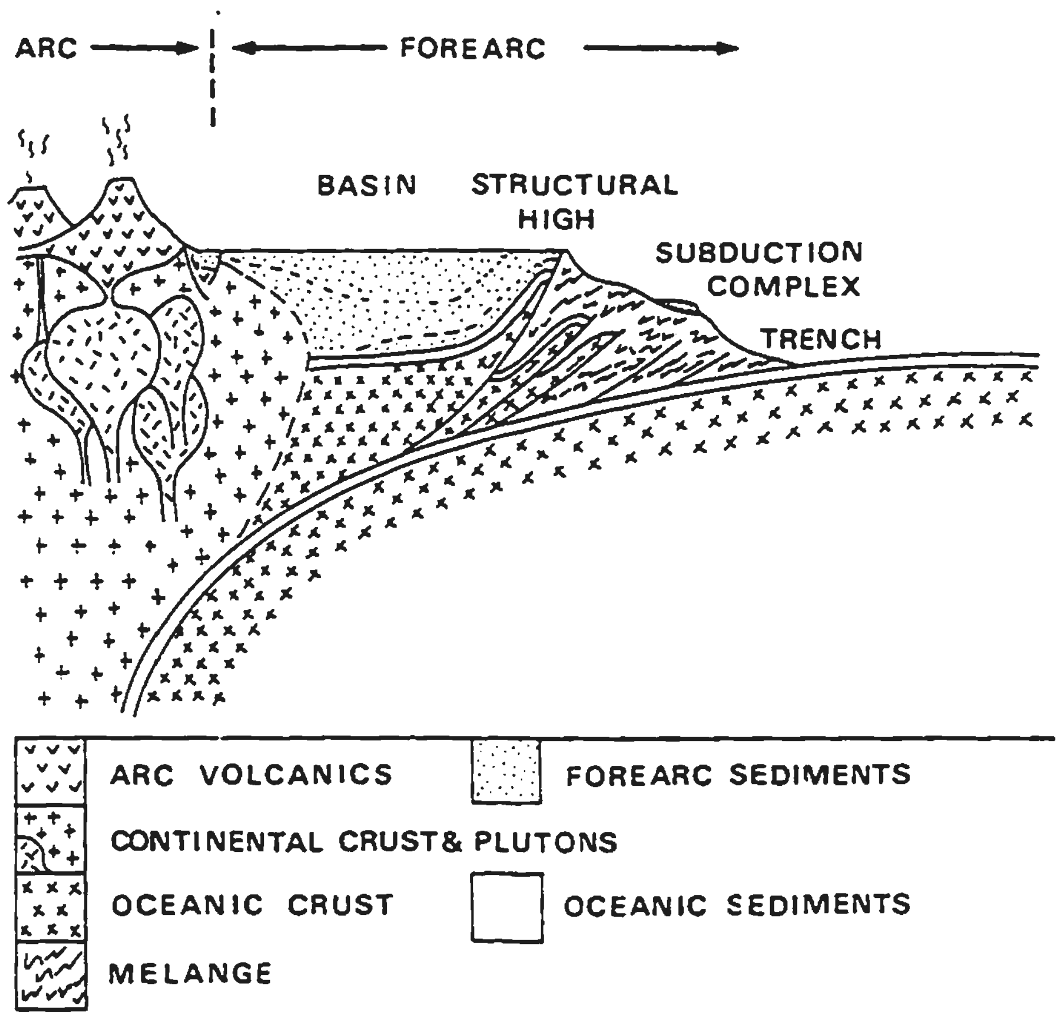


Figure 8.1 Elements of the generalized arc-trench system (after Dickinson and Seely, 1979).

Figure 8.2 Sequential tectonic evolution of the southern Georgia Basin: a) final collision of Wrangellia with inboard terranes; b) sedimentation of the Nanaimo Group; c) final sedimentation of the Nanaimo Group; d) migration of depocentre to Whatcom Basin, sedimentation of Paleogene section; e) development of the Cowichan fold and thrust belt due to accretion of oceanic terranes; and f) deep exhumation to the present.

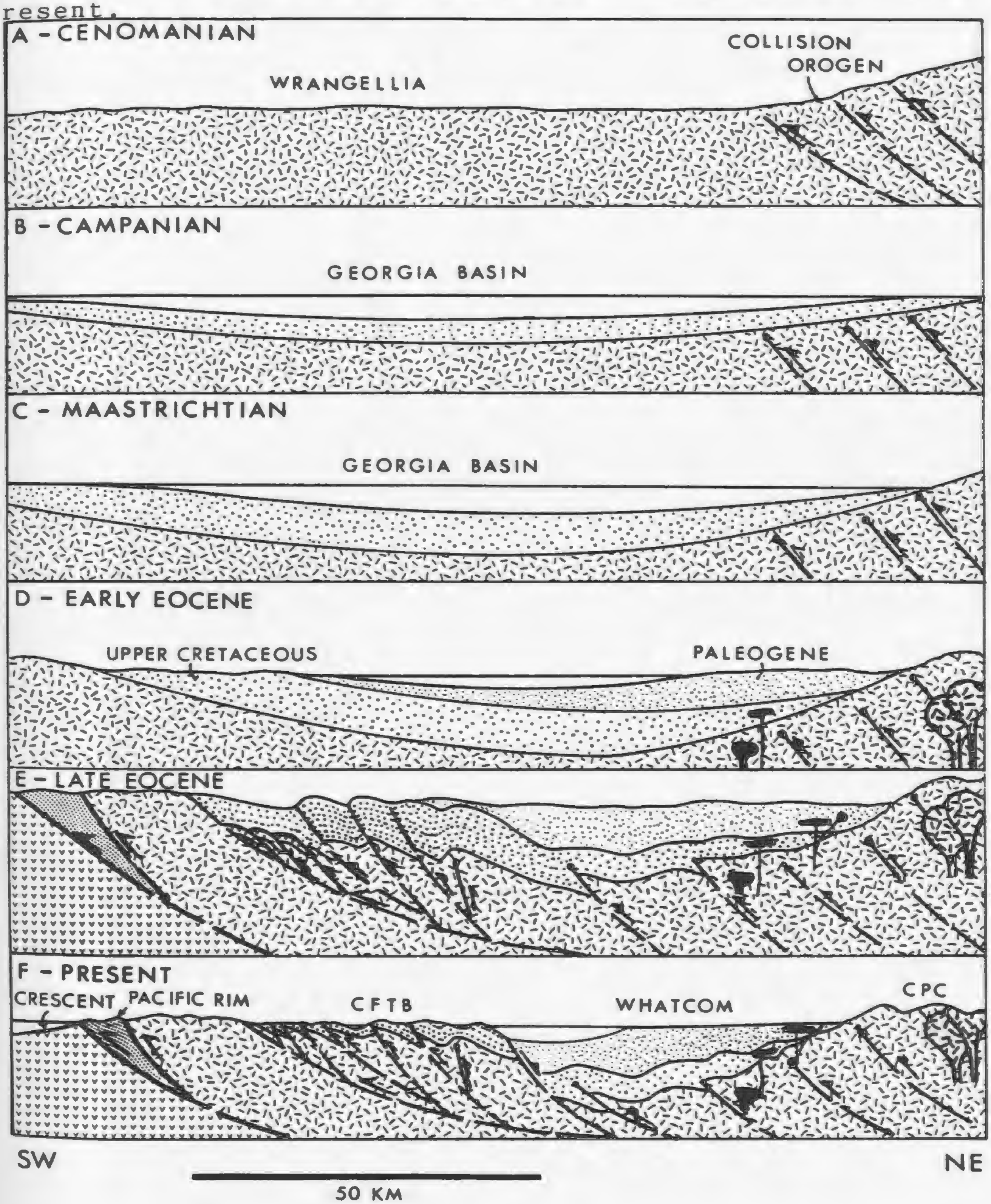


Plate 1a. Southwestern view of the Alberni Valley with Thunder Mountain in the middle background. Thunder Mountain is capped by Comox Formation conglomerate and sandstone.

Plate 1b. (below) Eastern view of the southern part of the field area, displaying the prominent cuesta at Mount Maxwell in the background. The trace of the Fulford Fault runs along the edge of the cultivated fields on the left side of the photograph.

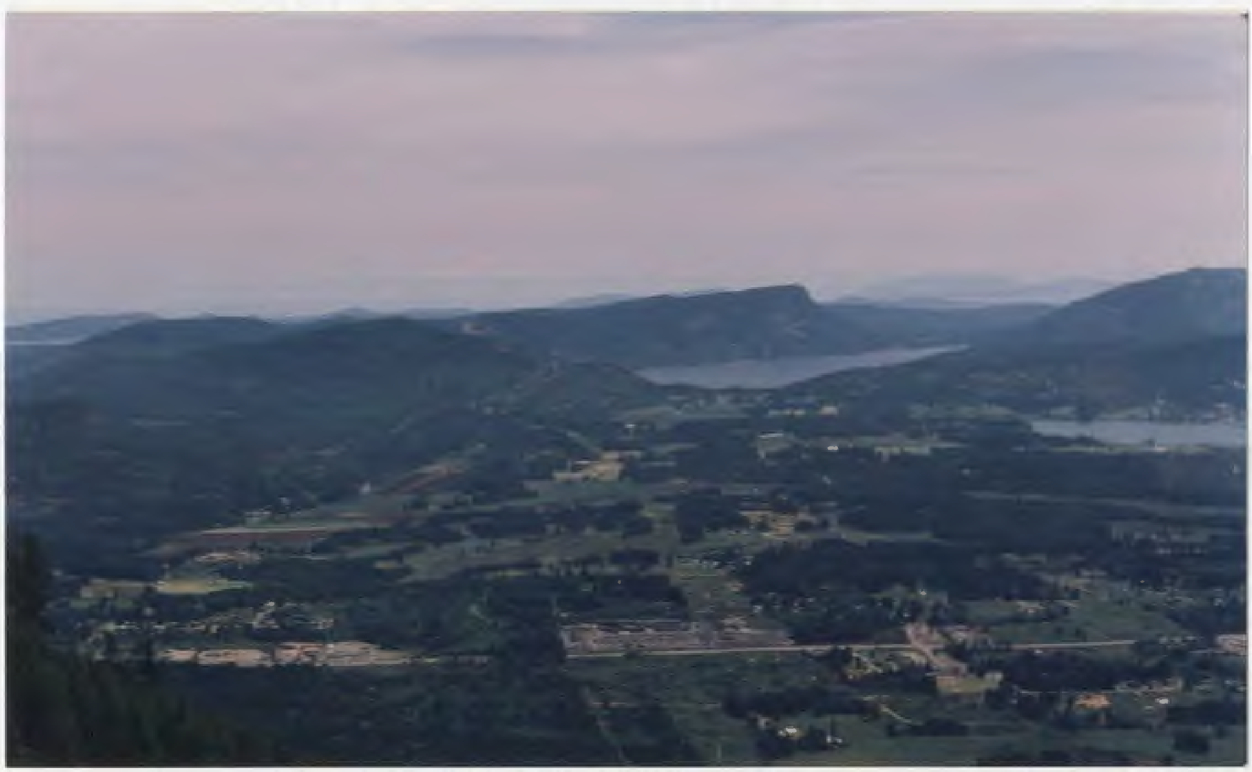


Plate 2a. Tzuhalem member conglomerate (facies association A) exposed in Sansum Narrows in the foreground and also at the top of Mount Maxwell in the background, with the Fulford Fault running along the shoreline below the mountain.

Plate 2b. Thrust fault exposed near Towner Bay, northwestern Saanich Peninsula, placing Jurassic granodiorite on the right over Saanich member siltstone and sandstone on the left.

Plate 3a. Bidirectional trough cross-bedding in sandstone of the Saanich member (facies association L_1) exposed on islets near southern Portland Island.

Plate 3b. Ophiomorpha occurring in Saanich member sandstone (facies association L_1) on Forrest Island, north of Sidney Island.

Plate 4a. Large coalified stump in siltstone of the Saanich member (facies association P) exposed on Coal Island. The hammer handle is 44 cm in length.

Plate 4b. Kink fold developed in thin bedded Haslam Formation (facies association S) cropping out on southern Piers Island.

Plate 5a. Vertical axial planar cleavage (S_1) intersecting near horizontal bedding in the hinge of a large fold in the Haslam Formation (facies association S), near Maple Bay.

Plate 5b. Cleavage refraction in alternating fine grained sandstone and shale of the Haslam Formation (facies association S) at Maple Bay.

Plate 6a. Axial planar cleavage (S_1) dipping to the northeast steeper than S_0 in thin bedded fine grained sandstone, siltstone, and shale of the Haslam Formation (facies association S) on southern Domville Island, near Saanich Peninsula.

Plate 6b. (below) Poorly sorted polymictic conglomerate of the Extension Formation (facies association B), Gowlland Point, South Pender Island.

Plate 7a. Cliff forming conglomerate and sandstone of Protection Formation equivalent at the top of Mount Prevost near Duncan.

Plate 7b. (below) Pender Formation shale and siltstone (facies association S) downlapping the top surface of Extension Formation equivalent in the upper Chemainus River canyon. The field of view is about 30 m across.

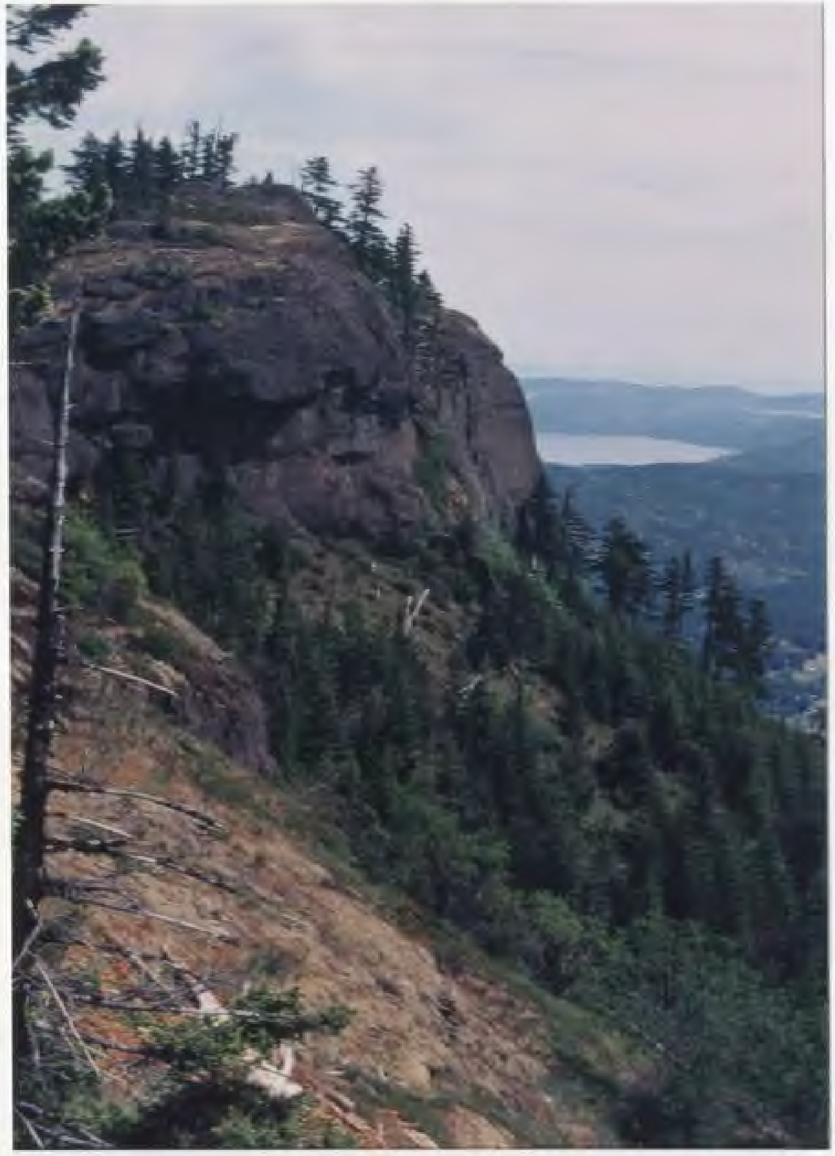


Plate 8a. Thin bedded succession of graded fine grained sandstone and siltstone, and shale (facies association M) of the Cedar District Formation, Shoal Islands. Note the man for scale.

Plate 8b. Massive medium grained sandstone, overlain by medium grained sandstone with shaly interbeds, overlain by very thick bedded, coarse grained sandstone. De Courcy Formation exposed on western De Courcy Island.

Plate 9a. Southern view of northeast-dipping beds on Mayne Island (left) and southwest-dipping beds on North Pender Island (right) on the limbs of the Navy Channel anticline, middle Nanaimo Group. The field of view is approximately 3 km.

Plate 9b. Folding associated with a minor thrust fault in the De Courcy Formation on southern Saturna Island.

Figure 10a. Large sandstone dyke crosscutting very fine grained sandstone and shale (facies association S, biofacies 5) of the Northumberland Formation, False Narrows, Gabriola Island.

Figure 10b. Dewatering structures in a coarse grained sandstone interbed of the Northumberland Formation (facies association S_{F3}), False Narrows, Gabriola Island.

Plate 11a. Large cobble conglomerate and sandstone of the Galiano formation (facies association S_{F1}) on Prevost Island. Note the local inverse grading and clasts which protrude into overlying beds. The hammer is 44 cm long.

Plate 11b. Thick bedded, medium to coarse grained sandstone of the Galiano formation (facies association S_{F3}), western Valdes Island.

Plate 12a. Scolicia in the Mayne formation (facies association S, biofacies 4), Bennett Bay, Mayne Island.

Plate 12b. Thin bedded fine grained sandstone, siltstone, and shale, displaying Bouma sequences (facies association S) in the Mayne Formation, Le Boeuf Bay, Gabriola Island.

Plate 13a. Large crossbeds developed in the Gabriola Formation (facies association L?) near Tumbo Island. Note the northeast-dipping cuestas in upper Nanaimo Group in the far background.

Plate 13b. Thick Bouma sequence developed in the Gabriola Formation (facies association S) on northern Gabriola Island.

Plate 14a. Thick pebble conglomerate of the Parksville member forming Little Mountain south of Parksville.

Plate 14b. (below) Poorly sorted, angular cobble conglomerate of the Cottam Point member (facies association A), exposed at Cottam Point east of Parksville.

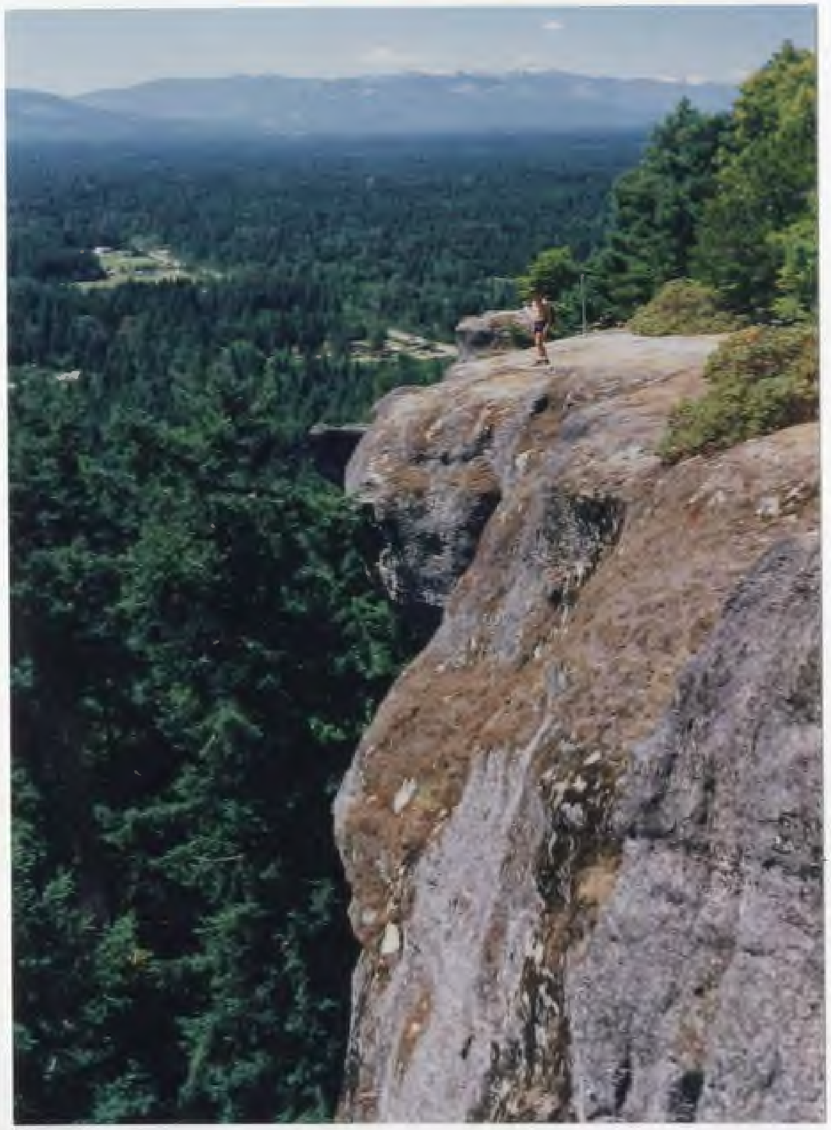


Plate 15a. Planar cross-bedded pebble conglomerate and sandstone of the Parksville member (facies association L) at Madrona Point, east of Parksville.

Plate 15b. Macaronichnus occurring in Parksville member sandstone (facies association L) at Madrona Point, east of Parksville.

Plate 16a. Alternating fine grained sandstone and shale of the Trent River Formation (facies association M) at Ship Peninsula, near Denman Island.

Plate 16b. Conglomerate-filled channel in the Denman Formation (facies association S_{F1}), Denman Island.

Plate 17a. Ancorichnus (?) occurring in the Lambert Formation, southwestern Hornby Island.

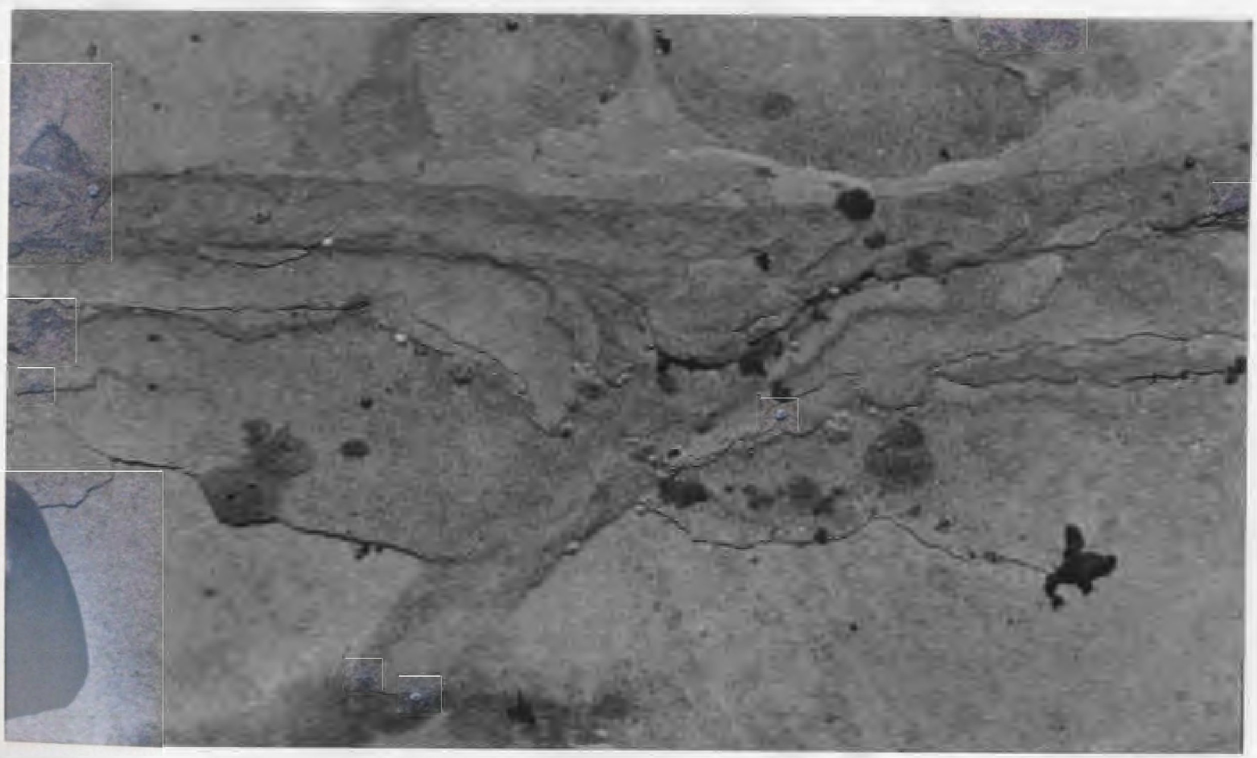


Plate 17b. Thalassinoides occurring in the Lambert Formation, northwestern Hornby Island.

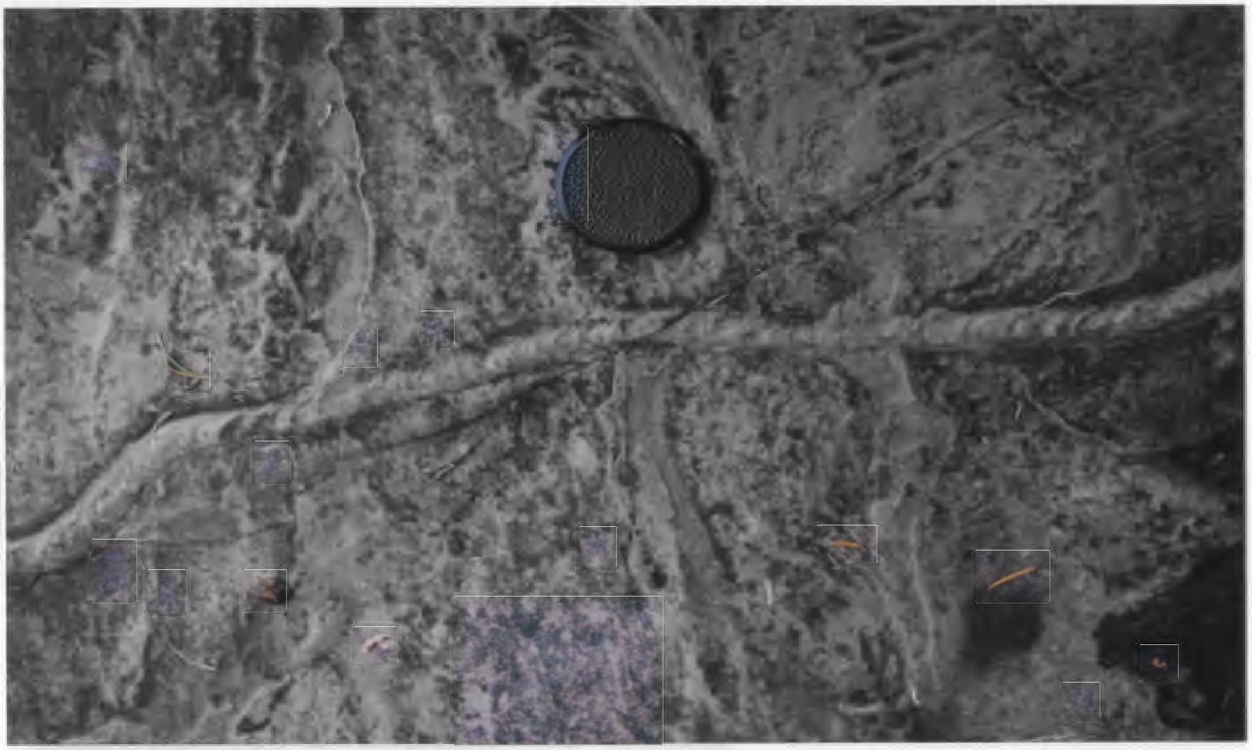


Plate 18a. Taenidium (?) occurring in the Lambert Formation (facies association S) on north-western Hornby Island.

Plate 18b. Conglomerate debris flow deposit overlying fine grained sandstone, Geoffrey Formation, northern Hornby Island.

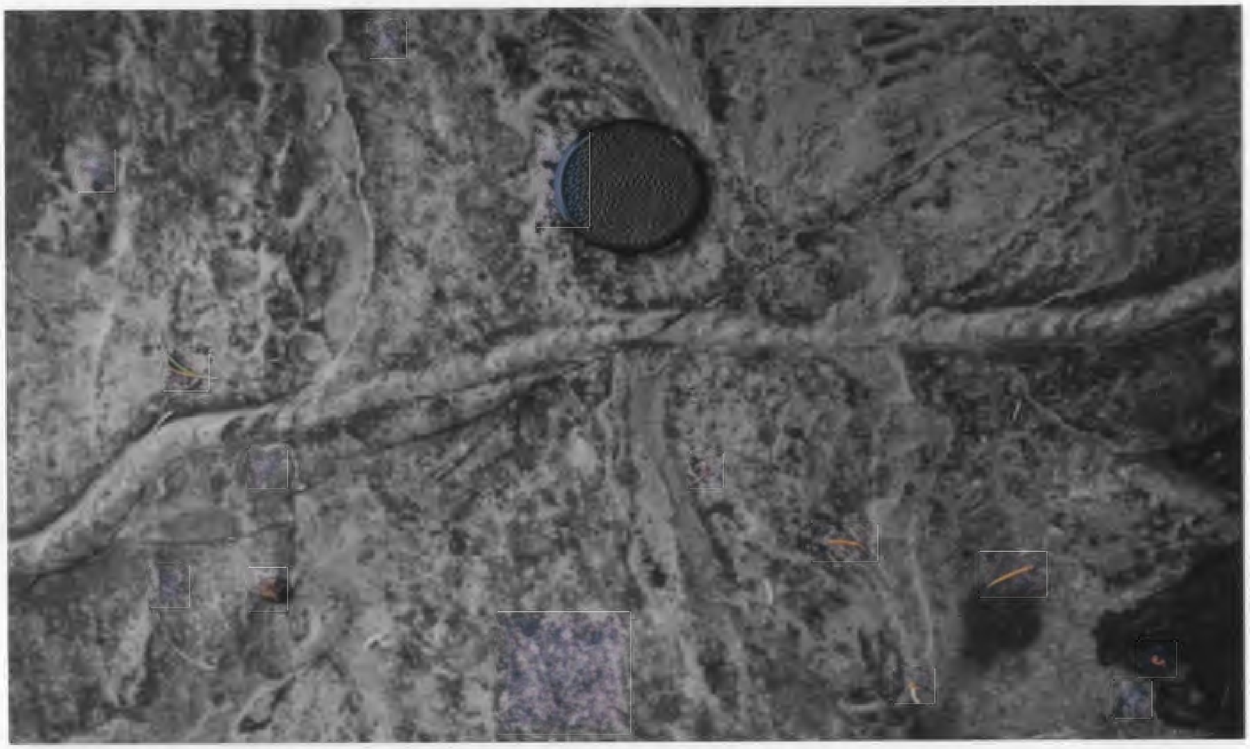


Plate 18a. Taenidium (?) occurring in the Lambert Formation (facies association S) on north-western Hornby Island.

Plate 18b. Conglomerate debris flow deposit overlying fine grained sandstone, Geoffrey Formation, northern Hornby Island.

Plate 18a. Taenidium (?) occurring in the Lambert Formation (facies association S) on northwestern Hornby Island.

deposit overlying
Geoffrey Formation,

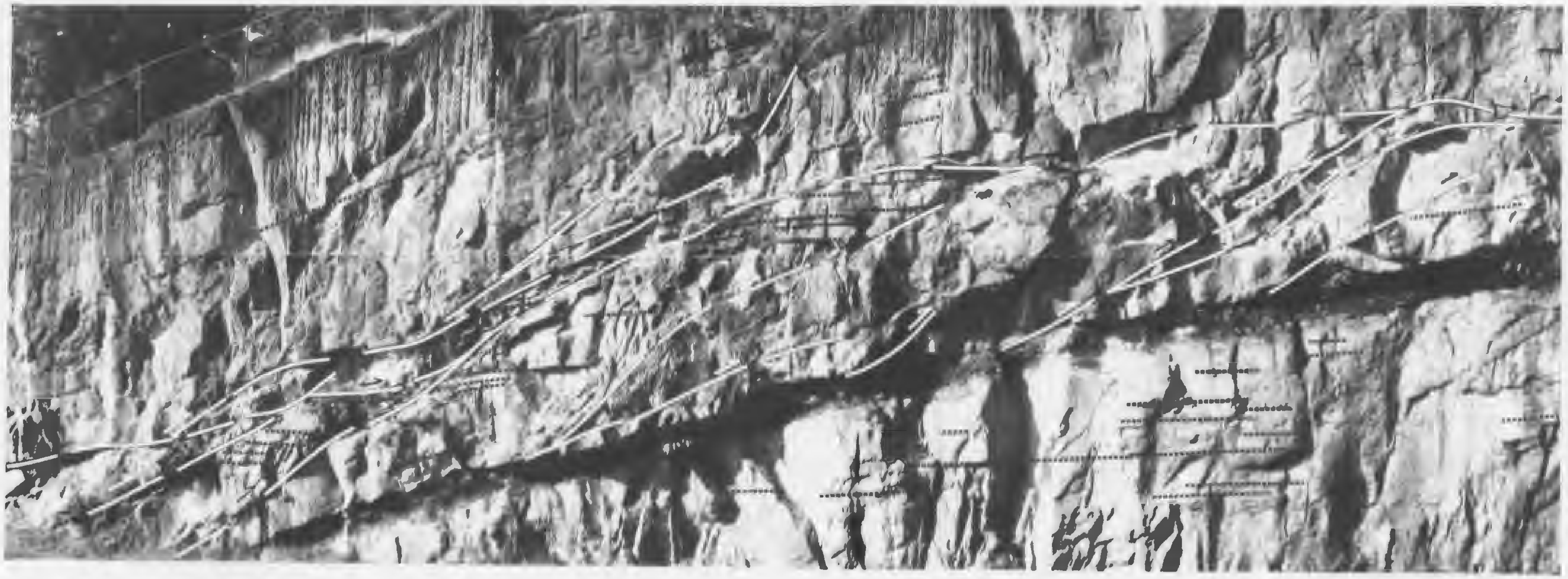


Plate 19. West-verging hanging-wall duplex in the Pender Formation exposed in a parking lot in downtown Nanaimo. The field of view is about 25 m across. Bedding is indicated by short dashed, black lines. Faults are marked by white lines.

References Cited

American Commission on Stratigraphic Nomenclature, 1970, Code of Stratigraphic Nomenclature: American Association of Petroleum Geologists, Tulsa, 22 p.

Andrews, D.J., and N.H. Sleep, 1974, Numerical modelling of tectonic flow behind island arcs: Geophysical Journal of the Royal Astronomical Society, v. 38, p. 237-251.

Allan, J. A., 1910, Saltspring Island, and East Coast of Vancouver Island: in Summary Report for 1909: Geological Survey Branch, Canada Department of Mines, p. 98-103.

Allmaras, J.M., 1978, Stratigraphy and sedimentology of the Late Cretaceous Nanaimo Group, Denman Island, British Columbia: unpublished M.Sc. thesis, Oregon State University, Corvallis, Oregon, 174 p.

Armstrong, R. L., 1987, Mesozoic and Early Cenozoic magmatic evolution of the Canadian Cordillera: in S.P. Clark, B.C. Burchfiel, and J. Suppe (eds.), Processes in Continental Lithospheric Deformation: A symposium to honour John Rodgers: Geological Society of America, Special Paper 218.

Aydin, A., and A. Nur, 1982, Evolution of pull-apart basins and their scale independence: Tectonics, v. 1, p. 91-105.

Baldwin, B., and C.O. Butler, 1985, Compaction curves: American Association of Petroleum Geologists Bulletin, v. 69, p. 622-626.

Barnes, M.A., Barnes, W.C., and R.M. Bustin, 1984, Diagenesis 8. Chemistry and Evolution of Organic Matter: Geoscience Canada, v. 11, p. 103-114.

Beaumont, C., 1978, The evolution of sedimentary basins on a viscoelastic lithosphere: theory and examples: Geophysical Journal of the Royal Astronomical Society, v. 55, p. 471-497.

Beaumont, C., Keen, C.E., and R. Boutilier, 1982, A comparison of foreland and rift margin sedimentary basins: Philosophical Transactions of the Royal Society of London, A, v. 305, p. 295-317.

Beck, A., 1965, Measuring heat flow on land: Geophysical Monograph Series, v. 8.

Bell, W.A., 1957, Flora of the Upper Cretaceous Nanaimo Group of Vancouver Island, British Columbia: Geological Survey of Canada, Memoir 293.

Berggren, W.A., Kent, D.V., Flynn, J.J., and J.A. Van Couvering, 1985, Cenozoic geochronology: Geological Society of America Bulletin, v. 96, p. 1407-1418.

Bickford, C.L., 1986, Regional geology of Georgia and Whatcom Basins: BP Canada Resources Limited, unpublished technical report TR-1319, 96 p.

Bickford, C. and Kenyon, C., 1988, Coalfield Geology of eastern Vancouver Island (92F): British Columbia Ministry of Energy, Mines and Petroleum Resources, Geological Fieldwork, 1987, Paper 1988-1, p. 441-450.

Blakemore, W., 1910, Log of bore-hole on Tumbo Island: in Robertson, W.F., Coal-mining in British Columbia, Annual Report of the Minister of Mines for 1909, Province of British Columbia, p. K161-162.

Bloomer, J.R., and S.W. Richardson, 1982, A guide to geothermal analysis of the maturity of source rocks using THETA and related programmes: BP Petroleum Development (Overseas), unpublished technical report, 102 p.

Booth, J.S., Sangrey, D.A., and J.K. Fugate, 1985, A nomogram for interpreting slope stability of fine-grained deposits in modern and ancient marine environments: Journal of Sedimentary Petrology, v. 55, p. 29-36.

Bostick, N.H., 1974, Phytoclasts as indicators of thermal metamorphism, Franciscan Assemblage and Great Valley Sequence (upper Mesozoic), California: Geological Society of America, Special Paper 153, p. 1-17.

-------------- 1979, Microscopic measurement of the level of catagenesis of solid organic matter in sedimentary rocks to aid exploration for petroleum and to determine former burial temperatures - a review: Society of Economic Paleontologists and Mineralogists, Special Publication No. 26, p. 17-43.

Bottjer, D.J., 1981, Trace fossils from an Upper Cretaceous deep-sea fan, Simi Hills, California: in Link, M.H., Squires, R.L., and Colburn, I.P. (eds.), Simi Hills Cretaceous turbidites, southern California: Pacific Section, Society of Economic Paleontologists and Mineralogists, Field Guide, p. 59-62.

Boyer, S.E., and D. Elliott, 1982, Thrust systems: American Association of Petroleum Geologists, v. 66, p. 1196-1230.

Brandon, M.T., Cowan, D.S., and J.A. Vance, 1988, The Late Cretaceous San Juan thrust system, San Juan Islands, Washington: Geological Society of America, Special Paper 221, 81 p.

Brown, E.H., 1987, Structural geology and accretionary history of the Northwest Cascades system, Washington and British Columbia: Geological Society of America Bulletin, v. 99, p. 201-214.

Buckham, A.F., 1947, The Nanaimo Coal Field: The Canadian Institute of Mining and Metallurgy, Transactions, v. L, p. 460-472.

Bustin, R.M., 1983, Heating during thrust faulting in the Rocky Mountains: friction or fiction?: Tectonophysics, v. 95, p. 309-328.

Bustin, R.M., Cameron, A.R., Grieve, D.A., and W.D. Kalkreuth, 1983, Coal petrology, its principles, methods and applications: Geological Association of Canada, Short Course Notes, v. 3, 273 p.

Bustin, R.M., Barnes, M.A., and W.C. Barnes, 1985, Diagenesis 10. Quantification and Modelling of Organic Diagenesis: Geoscience Canada, v. 12, p. 4-21.

Butler, R.W.H., 1982, The terminology of structures in thrust belts: Journal of Structural Geology, v. 4, p. 239-246.

Cameron, B.E.B., 1988a, Paleoenvironmental analysis of 70 samples from the Upper Cretaceous Nanaimo Group, from Vancouver Island and adjacent Gulf Islands: Geological Survey of Canada, unpublished report BEBC-1988-3, 32 p.

---------------- 1988b, Paleoenvironmental analysis of 61 samples from the Upper Cretaceous Nanaimo Group, from Vancouver Island and adjacent Gulf Islands: Geological Survey of Canada, unpublished report BEBC-1988-4, 26 p.

Carslaw, H.S., and J.C. Jaeger, 1959, Conduction of heat in solids: 2nd edition, Oxford University Press, Oxford, 510 p.

Carter, J.M., 1976, The stratigraphy and sedimentology of the Cretaceous Nanaimo Group, Galiano Island, British Columbia: unpublished M.Sc. thesis, Oregon State University, Corvallis, Oregon, 203 p.

Casagrande, D.J., Siefert, K., Berschinsky, C., and N. Sutton, 1977, Sulphur in peat forming systems of the Okefenokee Swamp and Florida Everglades: origins of sulphur in coal: Geochimica et Cosmochimica Acta, v. 41, p. 161-167.

Cassou, A., Connan, J., and B. Porthault, 1977, Relations between maturation of organic matter and geothermal effect, as exemplified in Canadian east coast offshore wells:

Bulletin of Canadian Petroleum Geology, v. 25, p. 174-194.

Chamberlain, C.K., 1978, Recognition of trace fossils in cores: in Society of Economic Paleontologists and Mineralogists, Short Course Notes No. 5, Oklahoma City, p. 119-166.

Clapp, C.H., 1910, Southern Vancouver Island: in Summary Report for 1909, Geological Survey Branch, Canada Department of Mines, p. 84-97.

------------ **1911**, Geology of the Victoria and Saanich Quadrangles, Vancouver Island, B.C.: in Summary Report for 1910, Geological Survey Branch, Canada Department of Mines, p. 102-109.

------------ **1912a**, Southern Vancouver Island: Geological Survey Branch, Canada Department of Mines, Memoir 13, p. 124-136.

------------ **1912b**, Geology of Nanaimo Sheet, Nanaimo coal-field, Vancouver Island, British Columbia: in Summary Report for 1911, Geological Survey Branch, Canada Department of Mines, p. 91-105.

------------ **1912c**, The Geology of the Nanaimo Coal District: Transactions of the Canadian Institute of Mining and Metallurgy, v. 15, p. 334-353.

------------ **1913**, Geology of the Victoria and Saanich map-area, Vancouver Island: Geological Survey of Canada, Memoir 36.

------------ **1914a**, Geology of the Nanaimo map-area: Canada Department of Mines, Geological Survey, Memoir 51, 135 p.

------------ **1914b**, Coal formation on Galiano, Mayne, and Saturna Islands: in Report of the British Columbia Minister of Mines for 1913, p. K292-299.

Clapp, C.H., and H.C. Cooke, 1914, Geology of a portion of the Duncan Map-area, Vancouver Island, B.C.: in Summary Report for 1913, Geological Survey Branch, Canada Department of Mines, p. 84-105.

---------------------------- **1917**, Sooke and Duncan Map-areas, Vancouver Island: Geological Survey of Canada, Memoir 96, 445 p.

Clowes, R.M., Brandon, M.T., Green, A.G., Yorath, C.J., Sutherland Brown, A., Kanasewich, E.R., and C. Spencer, 1987, LITHOPROBE - southern Vancouver Island: Cenozoic subduction complex imaged by deep seismic reflections: Canadian Journal of Earth Sciences, v. 24, p. 31-51.

Cochran, J.R., 1983, Effects of finite rifting times on the development of sedimentary basins: Earth and Planetary Science Letters, v. 66, p. 289-302.

Coleman, J.M., Prior, D.B., and J.F. Lindsay, 1983, Deltaic influences on shelf edge instability processes: Society of Economic Paleontologists and Mineralogists, Special Publication 33, p. 121-137.

Cotter, E., 1982, Upper Cretaceous coals of the Sabinas Basin, northeastern Mexico: products of back-barrier deposition and changing rates of propagation: 11th International Congress of Sedimentology, Hamilton, Ontario, Abstracts of papers, p. 57.

Cowan, D.S. and C.J. Potter, 1986, Centennial Continent/Ocean Transect #9, B-3 Juan de Fuca Spreading Ridge to Montana Thrust Belt: Geological Society of America.

Crickmay, C.H., and S.A.J. Pocock, 1963, Cretaceous of Vancouver, British Columbia, Canada: American Association of Petroleum Geologists Bulletin, v. 47, p. 1928-1942.

Crimes, T.P., 1977, Trace fossils of an Eocene deep-sea sand fan, northern Spain: in Crimes, T.P., and J.C. Harper (eds.), Trace fossils 2: Geological Journal, Special Issue 9, p. 71-90.

Curray, J.R., Moore, D.G., Lawver, L.A., Emmel, F.J., Raitt, R.W., Henry, M., and R. Kieckhefer, 1979, Tectonis of the Andaman Sea and Burma: in Watkins, J.S., Montadert, L., and P.W. Dickerson (eds.), Geological and Geophysical Investigations of Continental Margins: American Association of Petroleum Geologists Memoir 29, p. 189-198.

Dahlstrom, C.D.A., 1970, Structural geology in the eastern margin of the Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology, v. 18, p. 332-406.

Davis, J.C., 1973, Statistics and data analysis in geology: John Wiley & Sons, Toronto, 550 p.

Davis, G.A., Monger, J.W.H., and B.C. Burchfiel, 1978, Mesozoic construction of the Cordilleran Collage, central British Columbia to central California: in Howell, D.G., and McDougall, K.A., (eds.), Mesozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Symposium, p. 1-32.

Davis, D., Suppe, J., and Dahlen, F.A., 1983, Mechanics of fold-and-thrust belts and accretionary wedges: Journal of Geophysical Research, v. 88, p. 1153-1172.

Dickinson, W.R., 1971, Clastic sedimentary sequences deposited in shelf, slope, and trough settings between magmatic arcs and associated trenches: Pacific Geology, v. 3, p. 15-30.

---------------- 1973, Widths of modern arc-trench gaps proportional to past duration of igneous activity in associated magmatic arcs: Journal of Geophysical Research, v. 78, p. 3376-3389.

---------------- 1976, Sedimentary basins developed during evolution of Mesozoic-Cenozoic arc-trench system in western North America: Canadian Journal of Earth Sciences, v. 13, p. 1268-1287.

---------------- 1982, Compositions of sandstones in circum-Pacific subduction complexes and fore-arc basins: American Association of Petroleum Geologists Bulletin, v. 66, p. 121-137.

Dickinson, W.R., and D.R. Seely, 1979, Structure and stratigraphy of forearc regions: American Association of Petroleum Geologists Bulletin, v. 63, p. 2-31.

---------------- and C.A. Suczek, 1979, Plate tectonics and sandstone compositions: American Association of Petroleum Geologists Bulletin, v. 63, p. 2164-2182.

Dickinson, W.R., Beard, L.S., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A., and P.T. Ryberg, 1983, Provenance of North American Phanerozoic sandstones in relation to tectonic setting: Geological Society of America Bulletin, v. 94, p. 222-235.

Dom, K., 1986, The Beaufort Range Fault Zone in the Alberni area: unpublished B.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 35 p.

Dow, W.G., 1977, Kerogen studies and geological interpretations: Journal of Geochemical Exploration, v. 7, p. 79-99.

Elliott, D., 1976, The motion of thrust sheets: Journal of Geophysical Research, v. 81, p. 949-963.

England, T.D.J., 1984, Thermal maturation of the Western Canadian Sedimentary Basin in the Rocky Mountain Foothills and Plains of Alberta South of the Red Deer River: unpublished M.Sc. thesis, University of British Columbia, Vancouver, British Columbia, 171 p.

---------------- 1987, Evolution of the Georgia Basin, southwestern British Columbia: unpublished Ph.D. thesis Proposal, March 1987, Memorial University of Newfoundland, St. John's, Newfoundland, 42 p.

---------------- **1988a**, Stratigraphy and structure of the Nanaimo Basin, southwestern British Columbia: in Program with Abstracts, GAC/MAC/CSPG Joint Annual Meeting, St. John's, Newfoundland, May 23-25, 1988, v. 13, p. A-37.

---------------- **1988b**, Hydrocarbon potential of the Nanaimo Basin, southwestern British Columbia: Sedimentary Basins of the Canadian Cordillera, Geological Association of Canada, Pacific Section, 1988 Symposium, p. 7.

---------------- **1989**, Lithostratigraphy of the Nanaimo Group, Georgia Basin, southwestern British Columbia: in Current Research, Part E, Geological Survey of Canada, Paper 89-1E, p. 197-206.

England, T.D.J., and R.M. Bustin, 1986a, Thermal maturation of the Western Canadian Sedimentary Basin south of the Red Deer River: 1) Alberta Plains: Bulletin of Canadian Petroleum Geology, v. 34, p. 71-90.

--------------------------------- **1986b**, Effect of thrust faulting on organic maturation in the southeastern Canadian Cordillera: Advances in Organic Geochemistry, Organic Geochemistry, v. 10, p. 609-616.

Environment Canada, 1982, Canadian Climate Normals, Volume 2, Temperature 1951-1980.

Epstein, A.G., Epstein, J.B., and L.D. Harris, 1977, Conodont colour alteration - an index to organic metamorphism: United States Geological Survey, Professional Paper 995, 27 p.

Fahlstrom, B. E., 1981, Stratigraphy and depositional history of the Cretaceous Nanaimo Group of the Chemainus area, British Columbia: unpublished M.Sc. thesis, Oregon State University, Corvallis, Oregon, 115 p.

Fairchild, L.H., and D.S. Cowan, 1982, Structure, petrology, and tectonic history of the Leech River complex northwest of Victoria, Vancouver Island: Canadian Journal of Earth Sciences, v. 19, p. 1817-1835.

Farhoudi, G., and D.E. Karig, 1977, Makran of Iran and Pakistan as an active arc system: Geology, v. 5, p. 664-668.

Fiske, D.A., 1977, Stratigraphy, sedimentology, and structure of the Late Cretaceous Nanaimo Group, Hornby Island, British Columbia, Canada: unpublished M.Sc. thesis, Oregon State University, Corvallis, Oregon, 164 p.

Frey, R.W., and J.D. Howard, 1970, Comparison of Upper Cretaceous ichnofaunas from siliceous sandstones and chalk, Western Interior Region, U.S.A.: in Crimes, T.P., and J.C. Harper (eds.), Trace Fossils, Seel House Press, Liverpool, U.K., p. 141-166.

Frey, R.W., and S.G. Pemberton, 1984, Trace fossil facies models: in Walker, R.G. (ed.), Facies Models, 2nd Edition, Geoscience Canada, Reprint Series 1, p. 189-207.

Geiser, P.A., 1988, Mechanisms of thrust propagation: some examples and implications for the analysis of overthrust terranes: Journal of Structural Geology, v. 10, p. 829-845.

Gradstein, F.M., Agterberg, F.P., Aubry, M.-P., Berggren, W.A., Flynn, J.J., Hewitt, R., Kent, D.V., Klitgord, K.D., Miller, K.G., Orbradovitch, J., Ogg, J.G., Prothero, D.R., and G.E.G. Westerman, 1988, Sea level history: Science, v. 241, p. 599-601.

Gray, J., and A.J. Boucot, 1975, Color changes in pollen and spores: A review: Geological Society of America Bulletin, v. 86, p. 1019-1033.

Grieve, D.A., 1974, Stratigraphy of the Upper Cretaceous Nanaimo Group of Prevost Island, British Columbia: unpublished B.Sc. thesis, University of British Columbia, Vancouver, British Columbia.

Haggart, J.W., 1988a, Report on Upper Cretaceous fossils collected from the Nanaimo Group of Vancouver Island: Geological Survey of Canada, unpublished report no. JWH-1988-04, 18 p.

Haggart, J.W., 1988b, Report on Upper Cretaceous fossils collected from various locations of the Nanaimo Group of southern Vancouver Island and the adjacent San Juan Islands, British Columbia: Geological Survey of Canada, unpublished report no. JWH-1988-12, 5 p.

Hanson, W.B., 1976, Stratigraphy and sedimentology of the Cretaceous Nanaimo Group, Galiano Island, British Columbia: unpublished Ph.D. thesis, Oregon State University, Corvallis, Oregon, 339 p.

Haq, B.U., Hardenbol, J., and P.R. Vail, 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156-1167.

Hegarty, K.A., Weissel, J.K., and J.C. Mutter, 1988, Subsidence history of Australia's southern margin: Constraints on basin models: American Association of Petroleum Geologists Bulletin, v. 72, p. 615-633.

Heller, P.L., and W.R. Dickinson, 1985, Submarine ramp facies model for delta-fed, sand-rich turbidite systems: American Association of Petroleum Geologists Bulletin, v. 69, p. 960-976.

Hempton, M.R., and L.A. Dunne, 1984, Sedimentation in pull apart basins: Active examples in eastern Turkey: Journal of Geology, v. 92, p. 513-530.

Heroux, Y., Chagnon, A., and R. Bertrand, 1979, Compilation and correlation of major thermal maturation indicators: American Association of Petroleum Geologists Bulletin, v. 63, p. 2128-2144.

Hilt, C., 1873, Die Beziehungen zwischen der Zusammensetzung und den technischen Eigenschaften der Steinkohle: Zeitschrift Ver. Deutscher Ingen. Band 17, Ht. 4, p. 194-202.

Hiscott, R.N., Wilson, R.C.L., Gradstein, F.M., Pujalte, V., Garcia-Mondejar, J., Boudreau, R.R., and H.A. Wishart, 1990, Comparative stratigraphy and subsidence history of Mesozoic rift basins of North Atlantic: American Association of Petroleum Geologists Bulletin, v. 84, p. 60-76.

Hobbs, B.E., Means, W.D., and P.F. Williams, 1976, An outline of structural geology: John Wiley & Sons, Toronto, 571 p.

Hood, A., Gutjahr, C.C.M., and R.L. Heacock, 1975, Organic metamorphism and the generation of petroleum: American Association of Petroleum Geologists Bulletin, v. 59, p. 986-996.

Hopkins, W.S., 1968, Subsurface Miocene rocks, British Columbia - Washington, a palynological investigation: Geological Society of America Bulletin, v. 79, p. 763-768.

Horne, J.C., Ferm, J.C., Caruccio, F.T., and B.P. Baganz, 1978, Depositional models in coal exploration and mine planning in Appalachian region: American Association of Petroleum Geologists Bulletin, v. 62, p. 2379-2411.

Hossack, J.R., 1983, A cross-section through the Scandinavian Caledonides constructed with the aid of branch-line maps: Journal of Structural Geology, v. 5, p. 103-111.

Hudson, J.P., 1974, Stratigraphy and paleoenvironments of the Cretaceous rocks, North and South Pender Islands, British Columbia: unpublished M.Sc. thesis, Oregon State University, Corvallis, Oregon, 139 p.

Hyndman, R.D., 1976, Heat flow measurements in the inlets of southwestern British Columbia: Journal of Geophysical Research, v. 81, p. 337-349.

Jeletzky, J.A., 1983, Report on megafossils from Vancouver Island, British Columbia: unpublished report for B.P. Resources Canada Limited, 5 p.

Johnson, S.Y., 1984, Stratigraphy, age and paleogeography of the Eocene Chuckanut Formation, northwest Washington: Canadian Journal of Earth Sciences, v. 21, p. 92-106.

-------------- 1985, Eocene strike-slip faulting and nonmarine basin formation in Washington: in Biddle, K. T., and N. Christie-Blick, eds., Strike-slip Deformation, Basin Formation, and Sedimentation: Society of Economic Paleontologists and Mineralogists, Special Publication 37, p. 283-302.

Jones, D.L., 1960, Pelecypods of the Genus Pterotrigonia from the west coast of North America: Journal of Paleontology, v. 34, p. 433-439.

Jones, D.L., Silberling, N.J., and Hillhouse, J., 1977, Wrangellia - a displaced terrane in northwestern North America: Canadian Journal of Earth Sciences, v. 14, p. 2565-2577.

Jones, D.L., Howell, D.G., Coney, P.J., and J.W.H. Monger, 1983, Recognition, character, and analysis of tectonostratigraphic terranes in western North America: in Hashimoto, M., and S. Uyeda (eds.), Accretion Tectonics in the Circum-Pacific Regions: Terra Scientific Publishing Company, Tokyo, p. 21-35.

Kachelmeyer, J. M., 1978, Bedrock geology of the north Saanich-Cobble Hill areas, British Columbia, Canada: unpublished M.Sc. thesis, Oregon State University, Corvallis, Oregon, 153 p.

Karweil, J., 1956, Die Metamorphose der Kohlen vom Standpunkt der physikalischen Chemie: Deutsch. Geol. Gesellschaft Zeitschrift, v. 107, p. 132-139.

Kent, D.V., and F.M. Gradstein, 1985, A Cretaceous and Jurassic geochronology: Geological Society of America Bulletin, v. 96, p. 1419-1427.

Koetter, K., 1960, Die mikroscopische Reflexionsmessung mit dem Photomultiplier und ihre Anwendung auf die Kohlenuntersuchung: Brennst.-Chem., v. 41, p. 263-272.

Langhus, B.G., 1968, Vancouver Cretaceous foraminifera: unpublished M.Sc. thesis, University of Calgary, Calgary, Alberta, 77 p.

Lerche, I., Yarzab, R.F., and C.G.St.C. Kendall, 1984, Determination of paleoheat flux from vitrinite reflectance data: American Association of Petroleum Geologists Bulletin, v. 68, p. 1704-1717.

Leslie, T., 1984, Thermal conductivity measurements using a divided bar apparatus: unpublished report of Physics Co-op Summer Work Project, University of Victoria, Victoria, British Columbia, 26 p.

Lewis, T.J., Bentkowski, W.H., Davis, E.E., Hyndman, R.D., Souther, J.G., and J.A. Wright, 1988, Subduction of the Juan de Fuca plate: Thermal consequences: Journal of Geophysical Research, v. 93, p. 15,207-15,225.

Link, M.H., Abbott, W.O., Homewood, P., Labaume, P., Nilsen, T.H., Pickering, K., Ricci Lucchi, F., Stow, D.A.V., Underwood, M.B., van Vliet, A., and P. Weimer, 1988, -Tectonic control on submarine fans and turbidite systems: Comfan II, Parma, Italy, September 18-23, 1988.

Lopatin, N.V., 1971, Temperature and geologic age as factors in coalification (in Russian): Akad. Nauk SSSR Izv. Ser. Geol., no. 3, p. 95-106, English translation by Bostick, N.H., Illinois Geological Survey, 1972.

Machacek, V., 1971, Georgia Straits 1969 Project, Texaco Exploration Canada Ltd.: Petroleum Resources Branch, British Columbia Ministry of Energy, Mines and Petroleum Resources, Assessment Report No. 1529.

MacKenzie, J.D., 1922, The coal measures of Cumberland and vicinity, Vancouver Island: Transactions of the Canadian Institute of Mining and Metallurgy, v. 25, p. 382-411

Mackenzie, A.S., and D.P. McKenzie, 1983, Isomerization and aromatization of hydrocarbons in sedimentary basins formed by extension: Geological Magazine, v. 120, p. 417-470.

Mann, P., Hempton, M.R., Bradley, D.C., and K. Burke, 1983, Development of pull-apart basins: Journal of Geology, v. 91, p. 529-554.

Massey, N.W.D., 1986, Metchosin Igneous Complex, southern Vancouver Island: ophiolite stratigraphy developed in an emergent island setting: Geology, v. 14, p. 602-605.

Massey, N.W.D., Friday, S.J., Tercier, P.E., and T.E. Potter, 1988, Geology of the Duncan and Chemainus River area, NTS 92B/13 and 92C/16E: Geological Survey Branch, British Columbia Ministry of Energy, Mines and Petroleum Resources, Open File 1988-8.

Massey, N.W.D., and S.J. Friday, 1989, Geology of the Alberni-Nanaimo Lakes Area, Vancouver Island (92F/1W, 92F/2E and part of 92F/7): in Geological Fieldwork, 1988: Geological Survey Branch, British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1989-1, p. 61-74.

McCann, T., and R.K. Pickerill, 1988, Flysch trace fossils from the Cretaceous Kodiak Formation of Alaska: Journal of Paleontology, v. 62, p. 330-348.

McCartney, J.T., and M. Teichmuller, 1972, Classification of coals according to degree of coalification by reflectance of the vitrinite component: Fuel, v. 51, p. 64-68.

McClellan, R., 1927, Geology of the San Juan Islands: University of Washington Publications in Geology 2, 241 p.

McGugan, A., 1964, Upper Cretaceous Zone Foraminifera, Vancouver Island, British Columbia, Canada: Journal of Paleontology, v. 38, p. 933-951.

------------ **1979**, Biostratigraphy and paleoecology of Upper Cretaceous (Campanian and Maestrichtian) Foraminifera from the Upper Lambert, Northumberland, and Spray Formations, Gulf Islands, British Columbia, Canada: Canadian Journal of Earth Sciences, v. 16, p. 2263-2274.

____________ **1981**, Late Cretaceous (Campanian) foraminiferal faunas, Chapter et al. Saturna No. 1, Gulf Islands, British Columbia: Bulletin of Canadian Petroleum Geology, v. 29, p. 110-117.

McKenzie, D., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25-32.

------------- **1981**, The variation of temperature with time and hydrocarbon maturation in sedimentary basins formed by extension: Earth and Planetary Science Letters, v. 55, p. 87-98.

Miall, A.D., 1977, A review of the braided-river depositional environment: Earth-Science Reviews, v. 13, p. 1-62.

------------ **1984**, Principles of Sedimentary Basin Analysis: Springer-Verlag, Berlin, 490 p.

------------ **1986**, Eustatic sea level changes interpreted from seismic stratigraphy: A critique of the methodology with particular reference to the North Sea Jurassic record: American Association of Petroleum Geologists Bulletin, v. 70, p. 131-137.

Monger, J.W.H. and R.A. Price, 1979, Geodynamic evolution of the Canadian Cordillera - progress and problems: Canadian Journal of Earth Sciences, v 16, p. 770-791.

Monger, J.W.H., Clowes, R.M., and R.P. Riddihough, 1985, Continent-ocean Transect B2: Juan de Fuca Plate to Alberta Plains; explanatory pamphlet: Geological Society of America, Boulder, Colorado, 21 p.

Morris, W.R., and C.J. Busby-Spera, 1988, Sedimentologic evolution of a submarine canyon in a forearc basin, Upper Cretaceous Rosario Formation, San Carlos, Mexico: American Association of Petroleum Geologists Bulletin, v. 72, p. 717-737.

Muller, J.E., 1977, Evolution of the Pacific Margin, Vancouver Island, and adjacent regions: Canadian Journal of Earth Sciences, v. 14, p. 2062-2085.

------------- 1983, Geology, Victoria: Geological Survey of Canada, Map 1553A, 1:100,000.

Muller, J.E., and D.J.T. Carson, 1969, Geology and mineral deposits of Alberni map-area, Vancouver Island and Gulf Islands, British Columbia: Geological Survey of Canada, Paper 68-50.

Muller, J.E., and J.A. Jeletzky, 1967, Stratigraphy and biochronology of the Nanaimo Group, Vancouver Island and Gulf Islands, British Columbia: Geological Survey of Canada, Paper 67-1, Part B, p. 39-47.

-------------------------------- 1970, Geology of the Upper Cretaceous Nanaimo Group, Vancouver Island and Gulf Islands, British Columbia: Geological Survey of Canada, Paper 69-25, 77 p.

Muller, J.E., and M.E. Atchison, 1971, Geology, history and potential of Vancouver Island coal deposits: Geological Survey of Canada, Paper 70-53, 50 p.

Mutti, E., 1985, Turbidite systems and their relations to depositional sequences: in Zuffa, G.G. (ed.), Provenance of Arenites: D. Reidel, Dordrecht, p. 65-93.

Normark, W.R., 1985, Local morphologic controls and effects of basin geometry on flow processes in deep marine basins: in Zuffa, G.G. (ed.), Provenance of Arenites: D. Reidel, Dordrecht, p. 47-63.

North American Commission on Stratigraphic Nomenclature, 1983, North American stratigraphic code: American Association of Petroleum Geologists Bulletin, v. 67, p. 841-868.

Pacht, J.A., 1980, Sedimentology and petrology of the Late Cretaceous Nanaimo Group deposited in the Nanaimo Basin, western Washington and British Columbia: implications for Cretaceous tectonics: unpublished Ph.D. thesis, Ohio State University, Columbus, Ohio, 361 P.

------------ 1984, Petrologic evolution and paleogeography of the Late Cretaceous Nanaimo Basin, Washington and British Columbia: implications for Cretaceous tectonics: Geological Society of America Bulletin, v. 95, p. 766-778.

Packard, J.A., 1972, Paleoenvironments of the Cretaceous rocks, Gabriola Island, British Columbia: unpublished M.Sc. thesis, Oregon State University, Corvallis, Oregon, 101 p.

Parrish, R., 1981, Cenozoic uplift history of the Coast Mountains of British Columbia: Geological Association of Canada, Cordilleran Section Meeting, Program and Abstracts, p. 30.

Pearson, D. E., 1984, Vitrinite reflectance of twenty-six samples from Vancouver Island: unpublished report for Pacific Geoscience Centre, David E. Pearson & Associates Ltd., Victoria, British Columbia, 77 p.

--------------, 1985, Vitrinite reflectance data for Richfield's Sunnyside & Pt. Roberts Wells: unpublished report for Pacific Geoscience Centre, David E. Pearson &Associates Ltd., Victoria, British Columbia, 46 p.

Pickering, K.T., 1982, The shape of deep-water siliciclastic systems: a discussion: Geo-Marine Letters, v. 2, p. 41-46.

Pickering, K., Stow, D., Watson, M., and R. Hiscott, 1986, Deep-Water facies, processes and models: A review and classification scheme for modern and ancient sediments: Earth-Science Reviews, v. 23, p. 75-174.

Pickering, K.T., Hiscott, R.N., and F.J. Hein, 1989, Deep marine environments, clastic sedimentation and tectonics: Unwin Hyman, London, 416 p.

Pitman III, W.C., 1978, Relationship between eustacy and stratigraphic sequences of passive margins: Geological Society of America Bulletin, v. 89, p. 1389-1403.

Platt, J.P., 1986, Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks: Geological Society of America Bulletin, v. 97, p. 1037-1053.

Platt, J.P., Leggett, J.K., Young, J., Raza, H., and S. Alam, 1985, Large-scale sediment underplating in the Makran accretionary prism, southwestern Pakistan: Geology, v. 13, p. 507-511.

Popenoe, W.P., Saul, L.R., and T. Susuki, 1987, Gyrodiform gastropods from the Pacific Coast Cretaceous and Paleocene: Journal of Paleontology, v. 61, p. 70-100.

Priest, R., Allard, F., and I. Hutchison, 1985, THETA - A guide to thermal modelling: Internal report, British Petroleum, Geophysics Research and Technical Services, London, 277 p.

Reading, H.G., 1978, Sedimentary environments and facies: Elsevier, New York, 557 p.

Reading, H.G., 1980, Characteristics and recognition of strike-slip fault systems: in Ballance, P.F., and H.G. Reading (eds.), Sedimentation in oblique-slip mobile zones, Special Publication of the International Association of Sedimentologists, v. 4, p. 1-15.

Richards, B.C., 1975, Longusorbis cuniculosus: A new genus and species of Upper Cretaceous crab; with comments on Spray Formation at Shelter Point, Vancouver Island, British Columbia: Canadian Journal of Earth Science, v. 12, p. 1850-1863.

Richardson, J., 1872, Report on the coal fields of the east coast of Vancouver Island: in Geological Survey of Canada, Report of Progress, 1871-1872, p. 73-100.

Richardson, J., 1873, Report on the coal fields of Vancouver and Queen Charlotte Islands: in Geological Survey of Canada, Report of Progress, 1872-1873, p. 32-65.

Rinne, R.W., 1973, Geology of the Duke Point-Kulleet Bay area, Vancouver Island, B.C.: unpublished M.Sc. thesis, Oregon State University, Corvallis, Oregon, 63 p.

Roddick, J.A., 1983, Geophysical review and composition of the Coast Plutonic Complex south of latitude 55N: Geological Society of America, Memoir 159, p. 195-211.

Rouse, G.E., Hopkins, W.S., and K.M. Piel, 1970, Palynology of some Late Cretaceous and Early Tertiary deposits in British Columbia and adjacent Alberta: Geological Society of America, Special Paper 127, p. 213-246.

Royden, L., and C.E. Keen, 1980, Rifting process and thermal evolution of the continental margin of eastern Canada determined from subsidence curves: Earth and Planetary Science Letters, v. 51, p. 343-361.

Royden, L., Sclater, J.G., and R.P. von Herzen, 1980, Continental margin subsidence and heat flow: important parameters in formation of petroleum hydrocarbons: American

Association of Petroleum Geologists Bulletin, v. 64, p. 173-187.

Rust, B.R., and E.H. Koster, 1984, Coarse alluvial deposits: in Walker, R.G. (ed.), Facies Models, Geoscience Canada, Reprint Series 1, p. 53-69.

Sass, J.H., Lachenbruch, A.H., and R.J. Monroe, 1971, Thermal conductivity of rocks from measurements on fragments and its application to heat flow determinations: Journal of Geophysical Research, v. 76, p. 3391-3401.

Savin, S.M., 1977, The history of the earth's surface temperature during the past 100 million years: Annual Review of Earth and Planetary Sciences, v. 5, p. 319-355.

Sawyer, D.S., Hsui, A.T., and M.N. Toksoz, 1987, Extension, subsidence and thermal evolution of the Los Angeles basin - a two-dimensional model: Tectonophysics, v. 133, p. 15-32.

Sclater, J.G., and P.A.F. Christie, 1980, Continental stretching: An explanation of the post-mid-Cretaceous subsidence of the central North Sea basin: Journal of Geophysical Research, v. 85, p. 3711-3739.

Scott, J.A.B., 1974, The foraminifera of the Haslam, Qualicum, and Trent River Formations, Vancouver Island, British Columbia: Bulletin of Canadian Petroleum Geology, v. 22, p. 119-176.

Seely, D.R., 1979, The evolution of structural highs bordering major forearc basins: in Watkins, J.S., Montadert, L., and P.W. Dickerson (eds.), Geological and Geophysical Investigations of Continental Margins: American Association of Petroleum Geologists, Memoir 29, p. 245-260

Seilacher, A., 1978, Use of trace fossil assemblages for recognizing depositional environments: in Society of Economic Paleontologists and Mineralogists, Short Course Notes No. 5, Oklahoma City, p. 167-181.

Selley, R.C., 1988, Applied Sedimentology: Academic Press, San Diego, California, 446 p.

Shibaoka, M., and A.J.R. Bennett, 1977, Patterns of diagenesis in some Australian sedimentary basins: The Australian Petroleum Exploration Association Journal, v. 17, p. 58-63.

Simmons, M.L., 1973, Stratigraphy and paleoenvironments of Thetis, Kuper, and adjacent Islands, British Columbia: unpublished M.Sc. thesis, Oregon State University, Corvallis, Oregon, 114 p.

Sliter, W.V., 1973, Upper Cretaceous foraminifers from the Vancouver Island area, British Columbia, Canada: Journal of Foraminiferal Research, v. 3, p. 167-186.

Stach, E., Mackowsky, M.-TH., Teichmuller, M., Taylor, G.H., Chandra, D., and R. Teichmuller, 1975, Stach's textbook of coal petrology, second edition: Gebrueder Borntraeger, Berlin, Stuttgart, 428 p.

Stam, B., Gradstein, F.M., Lloyd, P., and D. Gillis, 1987, Algorithms for porosity and subsidence history: Computers & Geosciences, v. 13, p. 317-349.

Staplin, F.L., 1975, Interpretation of thermal history from colour of particulate organic matter - a review: Palynology, v. 1, p. 47-66.

Staub, J.R., and A.D. Cohen, 1979, The Snuggedy Swamp of South Carolina: a back barrier estuarine coal forming environment: Journal of Sedimentary Petrology, v. 49, p. 133-144.

Steckler, M.S., and A.B. Watts, 1978, Subsidence of the Atlantic-type continental margin of New York: Earth and Planetary Science Letters, v. 41, p. 1-13.

Stickney, R.B., 1976, Sedimentology, stratigraphy, and structure of the Late Cretaceous rocks of Mayne and Samuel Islands, British Columbia: unpublished M.Sc. thesis, Oregon State University, Corvallis, Oregon, 226 p.

Stow, D.A.V., Howell, D.G., and C.H. Nelson, 1985, Sedimentary, tectonic, and sea-level controls: in Bouma, A.H., Normark, W.R., and N.E. Barnes (eds.), Submarine fans and related turbidite systems: Springer, New York, p. 15-22.

Sturdavant, C.D., 1975, Sedimentary environments and structure of the Cretaceous rocks of Saturna and Tumbo Islands, British Columbia: unpublished M.Sc. thesis, Oregon State University, Corvallis, Oregon, 195 p.

Suppe, J., 1983, Geometry and kinematics of fault-bend folding: American Journal of Science, v. 283, p. 684-721.

---------- 1985, Principles of structural geology: Englewood Cliffs, New Jersey, Prentice-Hall, 537 p.

Suppe, J. and D.A. Medwedeff, 1984, Fault-propagation folding: Geological Society of America, Abstracts with Programs, v. 16, p. 678.

Sutherland Brown, A., 1966, Tectonic history of the Insular Belt of British Columbia: Canadian Institute of Mining and Metallurgy Special Volume 8, p. 83-100.

Sutherland Brown, A. and C.J. Yorath, 1985, LITHOPROBE profile across southern Vancouver Island: geology and tectonics: in Tempelman-Kluit, D., ed., Field guides to geology and mineral deposits in the southern Canadian Cordillera: Geological Society of America, Cordilleran Section Meeting, Vancouver, British Columbia, p. 8-1 to 8-23.

Sutherland Brown, A., Yorath, C.J., Anderson, R.G., and K. Dom, 1986, Geological maps of southern Vancouver Island, LITHOPROBE 1: Geological Survey of Canada, Open File 1272.

Thom, R.C., 1983, A study of the mineralogy, sedimentary provenance and diagenetic history of the Late Cretaceous Nanaimo Group sandstones in the Georgia Basin, southwest British Columbia: BP Exploration Canada Limited, unpublished technical report TR-742, 60 p.

Tissot, B., Durand, B., Espitalie, J., and A. Combaz, 1974, Influence of nature and diagenesis of organic matter in formation of petroleum: American Association of Petroleum Geologists Bulletin, v. 58, p. 499-506.

Turcotte, D.L., and G. Schubert, 1982, Geodynamics -applications of continuum physics to geological problems: John Wiley & Sons, New York, 450 p.

Turcotte, D.L., Ahern, J.L., and J.M. Bird, 1977, The state of stress at continental margins: Tectonophysics, v. 42, p. 1-28.

Twombley, B.N., 1987, Sedimentological observations on CST and conventional cores from the BP et al. Yellow Point well, Vancouver Island: BP Canada Inc., unpublished technical report, TR-1476, 22 p.

Umhoefer, P.J., 1987, Northward translation of "Baja British Columbia" along the Late Cretaceous to Paleocene margin of western North America: Tectonics, v. 6, p. 377-394.

Usher, J.L., 1952, Ammonite faunas of the Upper Cretaceous rocks of Vancouver Island, British Columbia: Geological Survey of Canada, Bulletin 21, 182 p.

Vail, P.R., Mitchum, Jr., R.M., Todd, R.G., Widmier, J.M., Thompson III, S., Sangree, J.B., Bubb, J.N., and W.G. Hatlelid, 1977, Seismic stratigraphy and global changes of sea level: in Payton, C.E. (ed.), Seismic stratigraphy -- applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 49-212.

van den Beukel, J., and R. Wortel, 1986, Thermal modelling of arc-trench regions: Geologie en Mijnbouw, v. 65, p. 133-143.

van Hinte, J.E., 1978, Geohistory analysis - application of micropaleontology in exploration geology: American Association of Petroleum Geologists Bulletin, v. 62, p. 201-222.

Vance, J.A., 1977, The stratigraphy and structure of Orcas Island, San Juan Islands: in Brown, E.H., and R.C. Ellis, eds., Geological excursions in the Pacific Northwest: Geological Society of America, Annual Meeting, Seattle, Washington, p. 170-203.

von der Borch, C.C., Smit, R., and A.E. Grady, 1982, Late Proterozoic submarine canyons of Adelaide geosyncline, South Australia: American Association of Petroleum Geologists Bulletin, v. 66, p. 332-347.

Walker, R.G., 1984, Turbidites and associated coarse clastic deposits: in Walker, R.G. (ed.), Facies Models, Geoscience Canada, Reprint Series 1, 2nd edition, p. 171-188.

Wanless, H.R., Baroffio, J.R., and P.C. Trescott, 1969, Conditions of deposition of Pennsylvanian coal beds: in Dapples, E.C., and M.E. Hopkins (eds.), Environments of Coal Deposition, Geological Society of America, Special Paper 114, p. 105-142.

Waples, D.W., 1980, Time and temperature in petroleum Formation: application of Lopatin's method to petroleum exploration: American Association of Petroleum Geologists Bulletin, v. 64, p. 916-926.

Ward, P.D., 1976a, Stratigraphy, paleoecology and functional morphology of heteromorph ammonites of the Upper Cretaceous Nanaimo Group, British Columbia and Washington: unpublished Ph.D. thesis, McMaster University, Hamilton, Ontario.

----------- 1976b, Upper Cretaceous ammonites (Santonian-Campanian) from Orcas Island, Washington: Journal of Paleontology, v. 50, p. 454-461.

----------- 1978a, Revisions to the stratigraphy and biochronology of the Upper Cretaceous Nanaimo Group, British Columbia and Washington State: Canadian Journal of Earth Sciences, v. 15, p. 405-423.

----------- 1978b, Baculitids from the Santonian-Maestrichtian Nanaimo Group, British Columbia, Canada and Washington State, U.S.A.: Journal of Paleontology, v. 52, p. 1143-1154.

Ward, P.D., and K.O. Stanley, 1982, The Haslam Formation: a Late Santonian-Early Campanian forearc basin deposit in the Insular Belt of southewestern British Columbia and adjacent Washington: Journal of Sedimentary Petrology, v. 52, p. 975-990.

Watts, A.B., and W.B.F. Ryan, 1976, Flexure of the lithosphere and continental margin basins: Tectonophysics, v. 36, p. 25-44.

Whetten, J.T., Zartman, R.E., Blakely, R.J., and D.L. Jones, 1980, Allochthonous Jurassic ophiolite in northwest Washington: Geological Society of America Bulletin, v. 91, p. 359-368.

White, D., 1915, Some relations in origin between coal and petroleum: Washington Academic Scientific Journal, v. 5, p. 189-212.

Whiteaves, J.F., 1879, On the fossils of the Cretaceous rocks of Vancouver and adjacent islands in the Strait of Georgia: Geological Survey of Canada, Mesozoic Fossils, v. 1, p. 93-190.

---------------- 1903, On some additional fossils from the Vancouver Cretaceous with a revised list of the species therefrom: Geological Survey of Canada, Mesozoic Fossils, v. 1, p. 309-415.

Williams, T.B., 1924, The Comox Coal Basin: unpublished Ph.D. thesis, University of Wisconsin.

Wood, D.A., 1988, Relationships between thermal maturity indices calculated using Arrhenius equation and Lopatin method: Implications for petroleum exploration: American Association of Petroleum Geologists Bulletin, v. 72, p. 115-134.

Yorath, C.J., and R.L. Chase, 1981, Tectonic history of the Queen Charlotte Islands and adjacent areas - a model: Canadian Journal of Earth Sciences, v. 18, p. 1717-1739.

Yorath, C.J., and R.D. Hyndman, 1983, Subsidence and thermal history of Queen Charlotte Basin: Canadian Journal of Earth Sciences, v. 20, p. 135-159.

Yorath, C.J., Clowes, R.M., Green, A.G., Sutherland Brown, A., Brandon, M.T., Massey, N.W.D., Spencer, C., Kanasewich, E.R., and R.D. Hyndman, 1985a, LITHOPROBE - Phase 1: southern Vancouver Island: preliminary analyses of reflection seismic profiles and surface geological studies: in Current Research, part A: Geological Survey of Canada, Paper 85-1A, p. 543-554.

Yorath, C.J., Green, A.G., Clowes, R.M., Sutherland Brown, A., Brandon, M.T., Kanasewich, E.R., Hyndman, R.D., and Spencer, C., 1985b, LITHOPROBE, southern Vancouver Island: seismic reflection sees through Wrangellia to the Juan de Fuca plate: Geology, v. 13, p. 759-762.

Appendix A. Field data collected during 1987 and 1988 are complemented by much extant data. Sources of this compiled data are referred to below by NTS 1:50,000 map sheet.

NTS 92	B/10	B/11	B/12	B/13	B/14	C/16	F/1	F/8	G/4
Bickford (1986)	-	x	x	x	x	x	x	x	x
Buckham (1947)	-	-	-	-	-	-	-	-	x
Carter (1976)	-	-	-	x	x	-	-	-	x
Clapp (1912a)	-	x	-	-	-	-	-	-	-
Clapp (1914a)	-	-	-	-	-	-	-	-	x
Clapp (1914b)	-	-	-	-	x	-	-	-	-
Clapp and Cooke (1917)	-	-	x	x	-	-	-	-	-
Fahlstrom (1982)	-	-	-	x	-	-	-	-	-
Grieve (1974)	-	-	-	-	x	-	-	-	-
Hanson (1976)	-	-	-	x	x	-	-	-	-
Hudson (1974)	-	x	-	-	x	-	-	-	-
Kachelmeyer (1978)	-	x	x	-	-	-	-	-	-
Massey et al. (1988, 1989)	-	-	-	x	-	x	-	-	-
McClellan (1927)	x	x	-	-	-	-	-	-	-
Muller (1983)	-	x	x	x	x	-	-	-	-
Muller and Jeletzky (1970)	-	x	x	x	x	x	x	x	x
Packard (1972)	-	-	-	-	-	-	-	-	x
Rinne (1973)	-	-	-	-	-	-	-	-	x
Simmons (1973)	-	-	-	x	-	-	-	-	x
Stickney (1976)	-	-	-	-	x	-	-	-	-
Sturdavant (1975)	-	-	-	-	x	-	-	-	-
Sutherland Brown and Yorath (1985)	-	-	-	-	-	-	-	x	-
Sutherland Brown et al. (1986)	-	-	-	-	-	x	x	x	-
Vance (1977)	x	x	-	-	-	-	-	-	-
Ward (1978a)	x	x	-	-	-	-	-	-	-

NTS 92	F/2	F/6	F/7	F/9	F/10	F/11	F/13	F/14
Allmaras (1978)	-	-	x	-	x	-	-	-
Bickford (1986)	x	x	x	x	x	x	x	x
Fiske (1977)	-	-	x	-	x	-	-	-
MacKenzie (1922)	-	-	x	-	x	x	-	-
Massey et al. (1988, 1989)	x	-	x	-	-	-	-	-
Muller and Atchison (1971)	-	-	x	-	x	x	-	x
Muller and Jeletzky (1970)	x	x	x	x	x	x	x	x
Richards (1975)	-	-	-	-	-	-	-	x
Richardson (1873)	-	-	x	-	x	-	-	-
Sutherland Brown et al. (1986)	x	-	x	-	-	-	-	-

Localities referred to in the main text are identified by number on the location map in the pocket (Figure A.1) according to the following list.

Alberni Valley	19
Alberni Summit	22
Active Pass	104
Annette Inlet	197
Ash River	18
Bryden Bay	127
Beaufort Range	17
Bloedel Creek	11
Bennett Bay	109
Boatswain Bank	129
BP borehole 1	46
BP borehole 2	45
BP borehole 3	44
BP borehole 4	21
BP borehole 5	40
BP borehole 6	42
BP borehole 7	9
BP borehole 8	43
BP borehole 9	39
BP borehole 10	34
Brackman Island	94
Beaver Point	92
Booth Bay	87
Chuckanut Basin	122
Cowichan Valley	140
Cowichan Lake	142
Coal Island	125
Coal Point	131
Cape Keppel	128
Campbell Lake	4
Comox Lake	8
Cottam Point	52
Cowichan River	140, 135
Cowichan Bay	133
Chemainus River	138
Cusheon Creek	91
Chemainus	143
Cedar	70
Coffin Point	77
Campbell Bay	108
Cumberland	9
Craig Bay	51
Chrome Island	33
Central Nanaimo Basin site:	ca. 88, 89, 100
Central Comox Basin site:	ca. 16, 25, 29
Deep Cove	131
Dodds Narrows	68
Descanso Bay	62
Deep Bay	23
Denman Island	15
De Courcy Island	72
Englishman R. Falls	47
Englishman River	48
Extension	73
Ellen Bay	98
Eleanor Point	93
Fulford Harbour	90
Ford Cove	32
French Creek	41
False Narrows	66
Fraser Delta	123
Georgia Strait	55
Galiano Island	102
Gabriola Island	65
Goudge Island	126
Harmac well	69
Hornby Island	27
Haslam Creek	75
Hatch Point	130
Hamley Point	124
Jack Point	61
Johns Island	120
Langley Lake	12
Little Mountain	49
Lantzville	56
Ladysmith	76
Long Harbour	88
Le Boeuf Bay	64
Little Sucia Island	115
Lambert Channel	24
Lasqueti Island	38
Mayne Island	104
Maple Bay	134
Mount Prevost	138
Mount Washington	6
Mount Tzuhalem	144
Millstream River	57
Mount Galiano	102
Miners Bay	104
Mount Benson	58
Mount Maxwell	89
Montague Harbour	100
Manning Point	26
Mount Geoffrey	27
Madrona Point	51
Moresby Island	96
Mesachie Lake	141
Marie Canyon	140

Appendix B. Locality descriptions

Benson Formation

San Juan Islands

The easternmost exposures of the Benson Formation are in the San Juan Islands. On Orcas Island, Ward (1978a) reports 30 m of interbedded conglomerate and carbonaceous, coarse grained sandstone, which can be assigned to the Benson Formation. The Benson Formation may comprise Gull Rock, and Flattop Island. McClellan (1927) describes the beds on Gull Rock as coarse conglomerate interbedded with sandstone, and those on Flattop Island to consist of ca. 10 m of thin bedded shale and shaly sandstone, overlain by ca. 75 m of coarse conglomerate.

The Benson Formation is very thick in the Stuart Island area. The Cactus Islands are comprised of massive to cross-bedded sandstone and conglomerate (200 m), and thin bedded shale and sandstone (12 m), according to McClellan (1927). On Johns and Ripple islands, it is represented by over 472 m of thick bedded conglomerate and sandstone, with shale interbeds (McClellan, 1927), which clearly underlie Haslam Formation exposed to the northwest. The section on southeastern Johns and Ripple islands comprises thick bedded, poorly sorted conglomerate, and medium to coarse grained sandstone, with fine grained sandstone and siltstone interbeds. The conglomerate contains pebble to boulder size, well rounded clasts, which include granodiorite, intermediate volcanic rock, sandstone, siltstone, chert, and argillite. Sandstone lenses are common in the conglomerate. The sandstone has abundant shale rip-up clasts, floating cobbles, and rare coal debris. At the western end of Johns Island, thick bedded, pebbly, and medium to coarse grained sandstone is interbedded with and overlain by thin to medium bedded, fine grained sandstone and siltstone. This interval is probably transitional between the Benson and Haslam formations.

Moresby Island

The Benson Formation crops out on northern Moresby Island. Between Pelorus and Parkin points, on the northeastern shore, are excellent exposures of the Tzuhalem member, resting unconformably on basement, and overlain by the Saanich member. The Tzuhalem member consists of, from base up, 1.5 m of greenish grey, fine grained sandstone, containing abundant angular cobbles of basement schist; overlain by ca. 5 m of coarse sedimentary breccia, consisting mostly of angular cobbles and boulders of schist, greenstone, rock quartz, and intermediate to mafic volcanic rocks. The breccia is clast supported and has a sparse, granule sandstone matrix. It is inversely graded, in part. The overlying Saanich member consists of about 10 m of amalgamated, massive, medium grained sandstone beds, with coarse grained to granule sandstone interbeds with some cobble lags. Trough cross-bedding is common. The sandstone contains rare, large, cyclindrical burrows, small pelecypod and brachiopod shells, and coal debris.

The unconformity is also well-exposed between Parkin and Reynard Pts., where thick bedded, granule to coarse grained sandstone, with abundant floating pebbles and cobbles overlie basement. The contact is erosional, with at least 0.5 m of relief visible. Overlying these beds are medium to thick bedded, massive to planar laminated, medium to coarse grained sandstone, with cobble and pebble sandstone interbeds. Planar cross-bedding is developed locally. Clapp (1912a) collected Trigonia cf. T. evansana from these beds. Canoe Rock, off the northwestern coast, consists of medium bedded, massive and planar laminated, medium grained sandstone.

Portland Island

The Benson Formation crops out on eastern Portland Island, and on the adjacent small islands: Brackman Island, Hood Island, Chads Island, Tortoise Islets, and Pellow Islets. Brackman Island consists of thick bedded, fine to medium grained sandstone, overlying very fine grained sandstone and siltstone, which is assigned to the Saanich member. The finer grained unit is bioturbated, carbonaceous, and contains thin coal lamina. The coarser grained unit locally scours into the underlying unit, in channels up to 10 m wide by 4 m deep. Herringbone cross-bedding, and large to small-scale, planar cross-bedding is developed, smaller-scale beds having high-angle foresets.

On Tortoise Islets, the Saanich member consists of medium to thick bedded, medium grained sandstone, with medium interbeds of pebbly sandstone. Planar lamination and hummocky cross-stratification is observed; bidirectional foreset beds are developed locally (Plate 3a). One sequence is, from base up: herringbone cross-bedded sandstone, planar laminated sandstone, and massive (bioturbated?) fine grained sandstone. Rare shell fragments are present in the pebbly sandstone.

On Portland Island at Princess Bay, the Saanich member consists of medium to thick bedded, planar laminated, fine grained sandstone, with medium interbeds of coarse grained sandstone, displaying bidirectional, planar crossbeds. Overlying these beds, are thick bedded, massive, coarse grained sandstone, and bioturbated, fine grained sandstone. The coarse grained beds are planar cross-bedded locally.

The Saanich member on eastern Portland Island comprises: a) thick bedded, planar laminated to massive, medium to coarse grained sandstone, with rare pebbly sandstone lenses; b) mottled and burrowed, very fine grained sandstone; and c) planar laminated, fine grained, carbonaceous sandstone. Large ?Ostrea shells are present locally. Northeasternmost Portland Island is composed of thin bedded, grey, fine grained sandstone and siltstone, with medium interbeds of massive, medium grained sandstone. These beds may be transitional between the Saanich member and Haslam Formation.

The Saanich member on the Pellow Islets consists of thick bedded, crudely planar laminated, fine to medium grained sandstone, with coarse grained sandstone interbeds. The finer grained beds are well burrowed locally, and contain abundant carbonaceous debris. The coarser grained beds contain rare, medium-scale crossbeds.

Russell Island

The basal unconformity is exposed on southeastern Russell Island, where a coarse, sedimentary breccia of angular, boulder size clasts, overlies basement schist. The breccia is overlain by interbedded angular pebble conglomerate, and coarse grained, greenish grey sandstone. This lower section is assigned to the Tzuhalem member. The overlying Saanich member consists of medium to thick bedded, medium grained sandstone. Planar cross-bedding is developed locally. On northern Russell Island, the Saanich member consists of medium to thick bedded, medium grained sandstone, with common rounded floating clasts, and very coarse grained to granule sandstone lenses. At the western end of the island, the member consists of medium to thick bedded, massive to planar laminated, medium grained sandstone. Vertical and horizontal burrows occur, including Planolites. Rare pelecypod shells are present, some of which may be trigoniids.

Sidney Island

The southernmost exposures of the Benson Formation are on Sidney Island. Exposures are limited to the islet west of the radio tower on the northwestern side of the island, and to the eastern coast on strike with Hamley Point. The formation overlies granodiorite, but the contact is not exposed. At Hamley Point the formation consists of well-indurated, fine to medium grained sandstone and siltstone, with minor conglomerate and shale. The section begins in very thick bedded, fine grained sandstone with lenses of pebbly sandstone and conglomerate, which is assigned to the Tzuhalem member. The conglomerate is supported by a medium grained sandstone matrix, with abundant shell debris. Clasts are very well rounded, but are poorly sorted, with pebble to large cobble sizes represented. They include argillite, green, white, and red chert, rock quartz, granodiorite, and intermediate volcanic rock. The fine grained sandstone is planar laminated to planar cross-bedded, and contains abundant floating cobbles. Overlying these beds is a ca. 10 m section of thin bedded, fine grained sandstone and siltstone. This section and succeeding beds are assigned to the Saanich member. The fine grained sandstone is massive or planar laminated, and contains rare floating cobbles. Basal contacts are sharp, but irregular. Burrows are common in the siltstone and the sandstone. Overall, the section crudely grades upward. Overlying the thin bedded section is thick bedded, concretionary, medium grained sandstone, with medium interbeds of siltstone. The sandstone is planar laminated, with planar cross-bedding developed locally. Shale rip-up clasts are concentrated in the basal part of some sandstone beds. The siltstone is bioturbated, and contains shell coquinas and rare carbonaceous material. Sandstone dikes, soft sediment deformation, and calcite veins are common.

The author collected Pterotrigonia klamathonia and a variety of indistinct gastropods and bivalves (Haggart, 1988b) from Hamley Point Previously, Jeletzky (1977, as cited by Popenoe et al., 1987) collected the following fossils from the same locality: Gyrodes (gyrodes) dowelli, Natica conradiana vacculae n. subsp., and Pterotrigonia klamathonia.

Mandarte and Halibut islands consist of thick to medium bedded, fine to medium grained sandstone, with thin interbeds of siltstone and very fine grained sandstone. Medium lenses of cobble conglomerate are present locally. The sandstone is planar laminated or massive. Low-angle planar crossbeds are locally developed. Trigoniid bivalves and indistinct burrows are present. These beds are assigned to the Saanich member.

Forrest Island and adjacent islets are composed of the Saanich member. The southern end of the island consists of medium to thick bedded, coarse grained sandstone, and carbonaceous siltstone and shale. The sandstone is planar laminated, massive, or planar cross-bedded. The fine grained beds contain much coal debris, including coalified rooted stumps up to 0.3 x 0.6 m in profile. Ophiomorpha and ?Paleophycus are locally abundant in some layers (Plate 3b). Contacts are gradational between the fine and coarse grained beds. On the northern side of the island, the Saanich member comprises thin bedded to massive, fine grained sandstone, siltstone, and shale, with thin to thick interbeds and lenses of coarse grained sandstone. The shale contains large, irregular, discontinuous concretionary beds and concretions. Coaly debris is common. Robust pelecypod shells occur in the sandstone.

The Saanich member forms the Little Group Islands to the northwest. It consists of: a) thick bedded, medium to coarse grained sandstone, exhibiting planar lamination and low-angle planar cross-bedding; and b) thin bedded, planar laminated, medium to fine grained sandstone and siltstone, with thick lenses and interbeds of coarse grained sandstone; rare trough crossbeds are developed. In both facies, coal debris is common.

Coal Island

Coal Island consists of a structurally thickened succession of the lower Nanaimo Group, composed mostly of the Saanich member. Haslam Formation may underlie the lowland from Little Bay to the bay northeast of Kamai Point. The Saanich member on the southwestern part of the island consists of thick to medium bedded, medium grained sandstone, interbedded with fine grained sandstone, siltstone, and shale sections. The coarser grained beds are massive or planar laminated, and locally exhibit small-scale trough crossbeds, and large, low-angle, planar cross beds (set height of 1 m, foreset length up to 5 m). The finer grained beds contain coal debris, including coalified stumps (Plate 4a).

At Fir Cone Point at the northwestern end of the island, the Saanich member consists of thin to medium bedded, fine to medium grained sandstone, with interbeds of shale, siltstone and very fine grained sandstone. Contacts are sharp, even, and continuous. The sandstone is typically planar laminated. Low-angle planar crossbeds, ripple cross-lamination, and fluid escape structure, are developed locally. Floating pebble to boulder size clasts are common.

Exposures on southeastern Coal Island are extensive. Two sections (Sections 273 and 351) were measured from Kamai to Charmer Pts. which serve to illustrate the lithology and stratification sequences developed in the member. However, the sections are not continuous, because the member is locally structurally deformed, and the total measured thickness may be much greater than the actual thickness of the member.

Three facies are recognized in the lower? Coal Island section: a) thick to medium bedded, planar laminated, medium grained to coarse grained sandstone, with thin sandstone interbeds, locally displaying large scale planar cross-bedding; b) thin bedded to laminated or massive shale and siltstone, with rare coal debris; and c) fine to very fine grained sandstone, laminated siltstone, and carbonaceous shale, with coal seams (up to 2 m thick), and abundant coal debris and burrows. Section 273 consists of alternations of facies "a" and "b" in the lower part, and "b" and "c" in the upper part. The overlying section 351 consists of alternations of: a) medium to very thick bedded, massive to crudely planar laminated, medium to coarse grained sandstone, with large to medium-scale planar and trough crossbeds; b) medium bedded, planar laminated, medium grained sandstone, with shale rip-up clasts, load casts, and concretions; and c) thin bedded, laminated or massive, fine grained sandstone and siltstone, with medium interlenses of coarse grained sandstone, and coal debris, coalified stumps, and calcite veins.

A microfossil sample from Killer Whale Point yielded a solitary, poorly preserved foraminifer, indicating possible marine conditions (Cameron, 1988a). A sample from 348 m in the measured sections had no marine indicators present (Cameron, 1988a).

The Saanich member forms Fernie and Goudge islands, west of Coal Island. The southern end of Fernie Island consists of thick bedded, coarse grained sandstone with common coal spars. Trough and planar cross-bedding is well developed. Southern Goudge Island comprises thick bedded, medium to coarse grained sandstone, overlying thin bedded to massive shale. The coarse grained beds are crudely planar laminated, and display planar cross-bedding, rare asymmetrical ripple marks, and coal debris. The fine grained beds contain abundant coal litter, and coal seams up to 3 cm thick. Northeastern Goudge Island consists of thin bedded shale and siltstone, with thick to medium interbeds and lenses of fine to medium grained sandstone. Rare coal debris is present. The author collected the following Turonian-Coniacian macrofossil assemblage from these beds: _Pterotrigonia evansana_, _Pterotrigonia cf. P. klamathonia_, _Acila (Truncacila) cf. A. (T.) demessa_, _Glycymeris sp._, and numerous indeterminate bivalves, gastropods, and inoceramids (Haggart, 1988a).

Piers Island

The stratigraphic succession on Piers Island is structurally disturbed. Piers Island lies in the direct footwall of the Tzuhalem Fault, as recognized by: a) elevated vitrinite reflectance levels with respect to the beds on northern Saanich Peninsula, which is interpreted to be caused by tectonic loading (Chapter 5); and b) the locally intensely deformed nature of the beds, which is interpreted to be a result of footwall collapse due to the propagating Tzuhalem Fault (Chapter 2). As such, the stratigraphic succession is undoubtedly thrust repeated; hence, it is not continuous in any profile. The stratigraphic pin points are: 1) Haslam Formation is recognized at Indian Point and Harvey Point (based on lithology and the occurrence of identical fossil suites), and at Wilhem Point (based on lithology); 2) Haslam Formation is overlain by the Extension Formation conglomerate and pebbly sandstone, as clearly exposed between Wilhem and Schmidt points and on Clive Island; and 3) Haslam Formation at Harvey Point overlies a shell bearing coarse grained unit which is assigned to the Saanich member. Thus, several thrust faults must be present, which, from northeast to southwest, place the Haslam Formation and underlying Saanich member over a repeated Extension Formation and underlying Haslam Formation succession.

The Saanich member on eastern Piers Island, consists of thick bedded, planar laminated, coarse grained sandstone, interbedded with fine grained sandstone, siltstone, and massive, concretionary shale. Inoceramid fragments, the pelecypod _Crassatella conradiana_, and indeterminate venerid bivalves occur in these beds (Haggart, 1988a). The beds forming Quadros Point on Knapp Island may also be the Saanich member. They consist of thick to thin bedded, massive or laminated, siltstone and shale, with medium grained sandstone dykes and lenses. Rare coal debris, poorly preserved shells, and floating cobbles are present. Bedding is irregular or indistinct.

Saanich Peninsula

The Benson Formation crops out widely on northern Saanich Peninsula from Tsehum Harbour to Moses Point and south to Towner Bay, forming prominences at Cloake and Horth Hills. The formation is thrust repeated, so that it appears to be a very thick succession. The outcrop area comprises at least 4 to 6 horses. Unfortunately, no complete, stratigraphically continuous section is available in the area. The formation is dominantly sandstone, which, according to Kachelmeyer (1978), is immature lithic arenite.

The basal contact of the Benson Formation is exposed at Armstrong Point, where basement volcanic rock is overlain by poorly sorted, polymictic, cobble conglomerate, and granule sandstone, with abundant shale rip-up clasts and concretions, overlain by thin bedded siltstone, and planar laminated, medium grained sandstone. Coal debris occurs in the sandstone. This lower section is about 8 m thick. Overlying the basal section are 15+ m of thin bedded siltstone and fine grained sandstone. Large-scale slump scars are developed in these beds.

At Thumb Point, to the west, the basal section is about 13 m thick, consisting of 3 m of poorly sorted, pebble to cobble size conglomerate, with angular clasts up to 0.5 m in diameter, overlain by 10 m of thick bedded, coarse grained sandstone, with siltstone interbeds. The overlying fine grained section consists of ca. 20 m of medium bedded, fine grained sandstone and shaly siltstone, with sharp even, and continuous contacts.

The Saanich member is exposed at several points along the northern side of Tsehum Harbour. Two sections were measured from Blue Heron Basin to Bryden Bay (Sections 283, 293). The Blue Heron Basin section consists of thick to medium bedded, massive to planar laminated, medium to coarse grained sandstone, with recessive interbeds of laminated siltstone and fine grained sandstone, bearing abundant coal debris and thin seams. Minor cross-bedding is developed in some of the sandstone units. Coarse grained sandstone lenses are common in some of the fine grained beds. Concentrations of coalified branches occur in the basal part of some of the thick sandstone beds.

The Bryden Bay section comprises alternating: a) thick to medium bedded, massive or crudely planar laminated, medium to coarse grained sandstone, with trough and planar cross-bedding locally developed; and b) thin bedded, massive or planar laminated, very fine to fine grained sandstone, siltstone, and shale, with abundant coalified stumps, roots, and spars. Also present in facies "b" are fine grained sandstone or siltstone concretions, and lenses of fine to coarse grained sandstone exhibiting trough and ripple cross-lamination. Richardson (1872) noted inoceramid fragments occurring in patches at Bryden Bay, probably in facies "b".

Overlying the beds at Bryden Bay is a sequence of medium to thick bedded, coarse to fine grained sandstone, typically planar laminated, with thin to medium interbeds of very fine grained sandstone, with abundant coaly debris. Contacts are generally sharp, and even. Symmetrical ripple marks, and unidirectional and bidirectional planar cross-bedding (with set height about 0.15 m) are developed locally.

A section was measured through the Saanich member along the last 1 km of the Patricia Bay highway, ending up in the Haslam Formation at Swartz Bay ferry terminal. The total section measured is 645 m, of which ca. 330 m is the Saanich member, but at least two thrust faults are inferred to be present, based on vitrinite reflectance data. The Saanich member in section 350 consists of alternations of: a) thick to very thick bedded, massive to planar laminated, medium to coarse grained sandstone, with thin to medium interbeds of fine grained sandstone, bearing coal debris; and b) thin to medium bedded, planar laminated, fine grained sandstone, siltstone, and shale, with coal debris. Contacts are sharp and even. The coarse grained beds display rare large loadcasts and flame structures, and oscillation ripple marks. Channels with relief up to 2 m are noted in these beds. The fine grained beds contain well preserved fossil leaves, and near the top of the Saanich member, some small indistinct pelecypod shells.

East of Horth Hill, there are several isolated exposures of the Saanich member. These outcrops consist of medium to thick bedded, coarse grained sandstone, with fine grained sandstone, siltstone, and shale interbeds. Asymmetrical ripple marks and small pelecypod shells occur locally. West of Horth Hill, the Saanich member comprises thick bedded, massive, coarse to medium grained sandstone; medium to thick bedded, planar laminated, medium to fine grained sandstone; and thin to medium bedded, carbonaceous silty shale, siltstone, and fine grained sandstone, with thin coal seams. Asymmetrical ripple marks and planar cross-bedding is locally developed.

North of Cloake Hill and along the coast of the northern Saanich Peninsula, are good exposures of the upper Saanich member underlying the Haslam Formation. These beds consist of thick to medium bedded, fine to medium grained sandstone, interbedded with thin bedded, fine grained sandstone and siltstone. Stratification is massive, planar laminated, or convolute laminated. Contacts are sharp, even, and continuous. The author collected <u>Acila</u> <u>?sp.</u> and <u>Inoceramus</u> <u>cf.</u> <u>I.</u> <u>lobatus</u> from beds 0.6 km north of Cloake Hill (Haggart, 1988a). Clapp (1912a) collected <u>Tellina</u> <u>sp.</u>

and _Inoceramus_ _cf._ _barabini_ from the northwestern shore of the Saanich Peninsula.

Clapp (1913) records the log of a borehole drilled into the Benson Formation just west of Cloake Hill. The formation penetrated is described as interbedded, very coarse grained sandstone, sandstone, and carbonaceous shale, 331 m thick (apparent thickness). For beds dipping 46^{O} to the northeast, and a vertical borehole, actual thickness would be about 230 m. The bottom of the formation was not reached.

To the west, the Saanich member forms shoreline outcrop around Moses Point and Deep Cove. The member consists of medium to thick bedded, medium to coarse grained sandstone, interbedded with thin to thick bedded, fine grained sandstone, siltstone, and shale. Coal spars are common. The coarser grained beds are typically massive, or may be crudely planar laminated.

To the south, the Saanich member crops out from Deep Cove to Towner Bay, although the beds are not continuous, as they occupy four separate fault blocks. At Towner Bay, the Saanich member consists of thin to medium bedded, planar laminated, fine grained sandstone, siltstone, and shale (Plate 2b). The beds are tightly folded and overthrust by an overturned succession of basement granodiorite, conglomerate, pebbly sandstone, and planar laminated fine grained sandstone and siltstone.

On the western side of the point west of Towner Bay, basal Benson Formation is tightly folded and faulted, such that the complete stratigraphic succession is obscured. The Tzuhalem member is about 30 m thick. The basal unconformity is exposed, with relief up to 0.5 m. Overlying the basement are medium bedded, pebbly sandstone and medium grained sandstone with conglomerate lenses, featuring planar lamination and low-angle, bidirectional planar cross-lamination. Clasts consist of siltstone, argillite, red and green chert, rock quartz, porphyritic volcanic rocks, and intrusive and metamorphic rocks; calcareous concretions are common. This lower section is about 15 m thick. It is overlain by at least 6 m of poorly sorted, cobble conglomerate, with a coarse grained to granule sandstone matrix. Sandstone lenses with abundant shale rip-up clasts are common. Overlying? and folded with the conglomerate beds are 10 to 20 m of chaotic, massive, coarse to medium grained sandstone, with pebbly sandstone lenses and large floating cobbles. Apparently overlying these beds, and forming the southern side of the next bay to the north is a section consisting of thick bedded, planar laminated, coarse to medium grained sandstone, and thin bedded, planar laminated, fine grained sandstone and siltstone, featuring small-scale flame structures and load casts.

North of the next bay, section 333 was measured, comprising about 200 m of the Saanich member. The section consists of alternating: a) thick bedded, coarse grained sandstone, exhibiting planar lamination or planar and trough cross-bedding (sets about 0.5 m thick), and common coal spars and Ophiomorpha burrows; and b) thin bedded, planar laminated, fine grained sandstone, siltstone, and shale, with rare, thin interbeds of coarse grained sandstone. Sandstone channels (3 m deep by 10 m wide) with distinct lateral pinch-outs into fine grained beds are present. Asymmetrical ripple marks, load casts, and coal debris are common. The Saanich member is also exposed on Coal Point, where it consists of the same facies as described above.

Cowichan Valley

Across Saanich Inlet, the Benson Formation crops out at Hatch Point and extends along the southern Cowichan Valley to Cowichan Lake. At Hatch Point, the Saanich member is well developed, comprising about 500 m of thick bedded, medium to coarse grained sandstone; medium to thin bedded, fine to coarse grained sandstone; and thin bedded, fine grained sandstone and siltstone. The sandstone is typically planar laminated, although some large-scale, trough cross-bedding is developed in some of the thicker beds. Some sandstone units are lenses or pods, with undulating contacts and rare ripple marks. Kachelmeyer (1978) notes the occurrence of Planolites in Hatch Point exposures.

The Benson Formation crops out in several creek cuts along southern Cowichan Valley. At Kelvin Creek, the Saanich member comprises thick bedded, medium to coarse grained sandstone, with thin to medium interbeds of fine grained sandstone and siltstone, bearing coal debris. Outcrops near Glenora Creek and south of Marie Canyon are noted by Bickford (1986).

The Benson Formation crops out in several areas along the southern side of Cowichan Lake. At Mesachie Lake, approximately 10 m of poorly organized and poorly sorted greenish-grey conglomerate and sandstone overlie green Karmutsen volcanics. These beds are assigned to the Tzuhalem member. Clasts are pebble to boulder size and are mostly composed of the basement lithology. Numerous bivalve shells are present in the greenish sandstone matrix, some with very thick shells, others disposed as thin coquinas within the sandstone interbeds. At roadcuts northwest of Millar Creek, the Saanich member comprises thick bedded, massive to planar laminated, fine to medium grained sandstone and siltstone, with minor coal debris and ?seams. At the western end of Cowichan Lake, near Nitinat, the Saanich member consists of thick bedded, massive, fine to medium grained, carbonaceous sandstone, with shale rip-up clasts and rare pelecypods.

The Benson Formation crops out in several strips parallel to faults, at Redbed Creek, Meade Creek, and on the upper reaches of the Chemainus River. At Meade Creek, the Tzuhalem member is exposed, comprising well indurated, polymictic pebble conglomerate and pebbly sandstone.

In the eastern part of the Cowichan Valley, the Benson Formation lies mostly beneath the surface. However, the Saanich member is exposed beneath the Haslam Formation, upstream from the Duncan pumphouse on the Cowichan River. The member consists of thick bedded, planar laminated, medium grained, carbonaceous sandstone. These beds are inferred to be thrust over Haslam Formation which lies further upstream. The Benson Formation crops out on Solly and Chipman Creeks north of the Chemainus River, and in Copper Canyon in the immediate footwall of the Fulford Fault (Massey et al., 1988; Clapp and Cooke, 1917; Bickford, 1986).

Extensive outcrops of the Benson Formation occur in the Mount Tzuhalem area. The upper Saanich member crops out along the roads southeast of Quamichan Lake, comprising medium to thick bedded, massive to planar laminated, fine grained sandstone. Hummocky cross-stratification is well developed locally. Some carbonaceous units and indistinct burrows are present. The Saanich member also is exposed on the dip slope of Mount Tzuhalem, where it consists of medium to thin bedded, massive to planar laminated, carbonaceous, fine grained sandstone. Indistinct pelecypod and ammonite fragments occur locally.

The same member is exposed along both sides of Birds Eye Cove. Exposures on the western side consist of thick bedded, massive, fine to medium grained sandstone, with thin to medium interbeds of pebble conglomerate. The pebbles mostly consist of chert, argillite, and metamorphic rock. Trough cross-bedding is locally developed. On Chisholm Island, the Saanich member consists of medium bedded, planar laminated and planar and trough cross-bedded, fine to medium grained sandstone, with floating pebbles of metamorphic and igneous rocks. ?Skolithos is developed in the sandstone. Along the eastern side of Birds Eye Cove, a long section of the Saanich member is exposed, comprising medium to thick bedded, planar laminated, medium to coarse grained sandstone, with interbeds and lenses of pebble conglomerate and granule sandstone, and fine grained, burrowed sandstone. The conglomerate is poorly sorted, and consists of subangular, mostly metamorphic rock clasts, in a chaotic matrix. Several clasts protrude up into succeeding sandstone layers. Rare, poorly preserved gastropod shells occur in these beds. At Paddy Mile Stone Point, the Saanich member consists of medium bedded, fine grained sandstone, interbedded with very coarse grained to granule sandstone. Contacts are continuous, but irregular. Rare coal debris occurs in the finer grained beds.

The cliffs above Genoa Bay, on Mount Tzuhalem, expose 120+ m of very thick bedded pebble to boulder conglomerate interbedded with medium to coarse grained, lithic sandstone, which is assigned to the Tzuhalem member. The conglomerate is well indurated, poorly sorted, generally matrix supported, the matrix commonly being a greenish-grey to yellowish-grey grit. The lower part is poorly sorted containing angular boulder size clasts, whereas the upper part shows fair sorting and is composed of more varied, rounded pebbles of chert, vein-quartz, meta-andesite, granodiorite, and other metamorphic and granitic clasts (Clapp and Cooke, 1917). Clapp (1912a) reports Trigonia tryoniana occurring in the Benson Formation on Mount Tzuhalem. Boulder conglomerates are well exposed south of Octopus Point, along the western shore of Sansum Narrows (Plate 2a). The boulders are up to 0.5 m in diameter, and include granodiorite, gabbro, and chert, in a granule sandstone matrix.

Saltspring Island

The Benson Formation crops out in a continuous belt across Saltspring Island, from Maxwell Creek to Yeo Point, and forms isolated outcrops between Yeo Point and Eleanor Point, and west of Lake Maxwell. A small patch of Nanaimo Group sandstone reported to occur at an elevation of ca. 427 m on Mount Tuam (Clapp, 1913, p. 95) may also be assigned to the Benson Formation. In the main outcrop belt, the Benson Formation is extremely variable in thickness, ranging from less than 100 m to almost 400 m. Hanson (1976) divided the formation into a basal conglomerate member which corresponds to the Tzuhalem member, a middle mudstone member and an upper sandstone member which correspond to the Saanich member. The Benson Formation sandstone on Saltspring Island is arkosic arenite or wacke (Hanson, 1976).

The thickest exposures of the Benson Formation are at Mount Maxwell (Plate 2a), where it fills a paleo-valley, 1.2 km wide, with several hundred metres relief (Hanson, 1976). The Tzuhalem member forms Baynes Peak, and is described by Hanson as being typically very thick bedded, broadly lenticular conglomerate, with thin interlenses of sandstone and pebbly sandstone, about 180 m thick. Clasts consist of granodiorite, greenstone, diorite, schist, phyllite, rock quartz, aplite, chert, argillite, quartzite, and sandstone (Hanson, 1976). At the top of the cliff at Baynes Peak, the conglomerate is well stratified, poorly sorted, with pebble to cobble size clasts, and contains graded coarse grained sandstone interbeds. At the western edge of the outcrop belt, on the southwestern side of Maxwell Creek, Hanson (1976) describes the ocurrence of atypical pebble to cobble conglomerate containing abundant, abraded Ostrea sp., Lima sp., Pecten sp., echinoid, and barnacle fragments. On Maxwell Park road, southwest of Roberts Lake, the Saanich member consists of thick bedded, massive to crudely planar laminated, medium to coarse grained or pebbly sandstone, with minor conglomerate and mudstone interbeds. Planar cross-bedding is locally developed. Hanson (1976) notes conglomerate filled channels in these beds. Hanson also reports that below the sandstone dominated beds in the Mount Maxwell area, there are carbonaceous siltstone and sandy mudstone beds.

South of Blackburn Lake, the Saanich member consists of thick to medium bedded, medium to very coarse grained sandstone, with pebbly sandstone lenses, and thin interbeds of medium to coarse grained sandstone, with abundant shale rip-up clasts, and rare coal debris. Pebbles are rounded, and include rock quartz and felsic volcanic rock. Planar cross-bedding is common, with sets about 10-15 cm thick.

In Peter Arnell Park, the Saanich member consists of planar laminated, fine to very fine grained sandstone, containing abraded pelecypod fragments and *Planolites* (Hanson, 1976).

East of the Cusheon Creek delta, the Benson Formation consists of rusty weathering, carbonaceous, shaly siltstone and fine grained sandstone, and coarse grained to granule sandstone, with abundant floating, angular clasts and rounded pebbles. Pelecypods and ammonites are present at the top of the section, which are described under Haslam Formation. About 0.8 km west of Yeo Point, Usher (1952) collected *Didymoceras (B.) elongatum*.

The beds at Yeo Point are medium bedded sandstone and cobble to boulder conglomerate (Hanson, 1976). Common clasts in the conglomerate are granodiorite, rock quartz, and fine grained felsic igneous rocks. Mollusc shells are present in the sandstone, and basement blocks up to 6 m in diameter occur in the basal conglomerate. The unconformity has relief of 3+ m.

At Beaver Point, about 1 m of poorly sorted, pebble to boulder conglomerate with a granule sandstone matrix, overlies the basement rock. Overlying the conglomerate is thin to medium bedded, fine to coarse grained sandstone, with rare floating pebbles and pebbly lenses, and interbeds of pebbly sandstone and conglomerate. Thin and thick shelled pelecypods, and indistinct burrows occur in the sandstone. Planar cross-bedding is developed locally. Hanson (1976) notes shallow channels occurring in these beds. On the eastern shore of the bay southwest of Beaver Point, the basal unconformity is exposed again, with large boulders and angular blocks of basement rock entrained in a disorganized pebbly sandstone matrix. Succeeding beds consist of thick bedded, planar laminated sandstone, and pebble to cobble conglomerate.

Exposed on the shoreline, north of Eleanor Point, is about 10 m of massive to thin bedded, bioturbated, fine grained sandstone, with rare floating cobbles. Coalified branches, small concretions, burrows, and pelecypod shells are common. Hanson (1976) collected *Trigonia sp.*, *Modiolus sp.*, *Teredo*, *Rhynchonella sp.*, and a nautiloid cephalopod from these beds. Hanson also reports *Planolites*, ?*Asterosoma* or ?*Teichichnus*, ?*Helminthoida*, and ?*Phycosiphon* in these beds.

Chemainus Valley

The Benson Formation crops out at several localities around Chemainus. A partly exposed outcrop belt extends from the Chemainus River to Sansum Narrows, and at least 3 fault-repeated strips of the Benson Formation occur in the central part of the Chemainus River valley south of Chemainus. Most of the formation is represented by the Saanich member sandstone, which ranges from lithic arenite to arkosic wacke (Fahlstrom, 1981). Along the shoreline between Sherard and Grave points, the Benson Formation comprises thick bedded, massive, fine to medium grained sandstone, and minor granule sandstone, overlying basement. Southwest of Crofton, the formation consists of medium to thick bedded, fine grained sandstone, with shale rip-up clasts.

About 0.7 km north of the Halalt Indian Reserve, the Saanich member consists of medium bedded, very fine grained sandstone, bearing large inoceramids and indistinct gastropods and pelecypods, including *Inoceramus ex. gr. I. ezoensis* (Haggart, 1988a). Immediately west of Fuller Lake, ?uppermost Saanich member consists of thick bedded, planar laminated, fine grained sandstone and silty shale. Fahlstrom (1981) noted shallow channels in these beds. Foraminifers recovered from this locality are suggestive of paleo-water depths of 20-50 m (Cameron, 1988a).

The Benson Formation is exposed along the coast, northwest of Chemainus. It consists of several hundred metres of thick to medium bedded, medium to coarse grained sandstone, with minor pebble conglomerate, bearing pelecypod, brachiopod fragments, including inoceramids. These beds are in contact with basement along the Chemainus to Saltair road. Macrofossils in the basal beds include *Rhynchonella suciensis*, and *Lysis suciensis* (Haggart, 1988a; Fahlstrom, 1981).

West of Saltair, the Saanich member is partly exposed, comprising thick to medium bedded, fossiliferous, fine to medium grained sandstone, and thin bedded shale. The author collected *Inoceramus cf. I. ezoensis*, *Glyptoxoceras sp.*, and *Didymoceras (B.) elongatum* from these beds (Haggart, 1988a). A microfossil sample from a basal shale, yielded a very low diversity foraminiferal assemblage, probably representative of paleo-water depths of 100-200 m (Cameron, 1988a).

Nanaimo Area

The Benson Formation is widely exposed in the Nanaimo area. The Tzuhalem member consists of: a) poorly sorted, pebble to boulder conglomerate, composed of subangular to well rounded clasts of green meta-andesites of the Karmutsen Formation in a matrix of greenish volcanic detritus; or b) polymictic, pebble conglomerate, with clasts of Karmutsen volcanics, and metasediments and gabbro derived from the Sicker Group (Clapp, 1914a). Arkosic sandstone interbeds are common. The conglomerate member commonly grades upward into the Saanich member, which underlies Haslam Formation shales, or Haslam Formation rests directly on the Tzuhalem member. Between Nanaimo and Ladysmith, the Benson Formation is not exposed, but has been penetrated in a few deep boreholes (Muller and Atchison, 1971). The formation has apparent thicknesses of 116+ m in the BP Yellow Point well, and 87 m in the BP Harmac well.

The Benson Formation is exposed in Haslam Creek canyon, where it consists of pebble conglomerate, interbedded with arkosic sandstone - Tzuhalem member, grading up into interbedded arkosic sandstone and shaly sandstone - Saanich member (Clapp, 1914a). The conglomerate is composed of subrounded to rounded clasts of metamorphic and volcanic rocks. Muller and Jeletzky (1970) described the section to comprise ca. 165 m of conglomerate, with minor sandstone, siltstone, and shale interbeds near the top; overlain by ca. 70 m of interbedded sandstone, siltstone, and shale; overlain by ca. 65 m of sandstone. Naumanni subzone fossils occur in the upper sandstone of the formation on Haslam Creek (Muller and Jeletzky, 1970). Pterotrigonia evansana is reported in these beds by Crickmay and Pocock (1963).

The Benson Formation crops out discontinuously from Haslam Creek to Wolf Creek, to the northwest. At Elkhorn Creek, the formation consists of, in part, angular cobble conglomerate, overlain by fine grained sandstone and shaly siltstone. Usher (1952) collected Epigoniceras epigonum, Didymoceras (B.) elongatum, Pachydiscus elkhornensis, P. buckhami, and Hauericeras gardeni from the lower part of the section on Elkhorn Creek. Below this locality, on the Nanaimo River, Usher (1952) recovered D. (B.) elongatum from beds assigned to the Benson Formation.

The Benson Formation occurs in isolated exposures in the Wolf Mountain area. Bickford (1986) describes the formation to consist of very coarse to coarse grained sandstone, with floating, rounded greenstone pebbles, and cobble to boulder conglomerate, in a coarse grained sandstone matrix.

Between Nanaimo and Wellington, the Benson Formation was penetrated in several boreholes. Muller and Atchison (1971) show that the formation comprises up to 90 m of conglomerate and sandstone, but also is locally absent. The section on Benson Creek consists of ca. 30 m of interbedded sandstone, siltstone, and shale, overlying 90+ m of sandstone, which rests on Karmutsen Formation (Muller and Jeletzky, 1970). The section contains both Naumanni and Haradai subzone index fossils. As such, the Benson Formation at this locality is contemporaneous with Haslam Formation at other localities in the basin. Inoceramus naumanni occurs in the Benson Formation on the northwestern side of Benson Creek. The upper part of the Saanich member, as exposed on McGarrigal Creek, consists of thin to medium bedded, massive, very fine grained sandstone and siltstone bearing inoceramids.

The Benson Formation underlies a broad area around Boomerang Lake. According to Bickford (1986), the formation comprises thin bedded, planar laminated, fine to very fine grained sandstone, siltstone, and mudstone, and very thick bedded, cobble conglomerate with a coarse grained sandstone matrix.

The Benson Formation crops out on the northern shore of Departure Bay. Just north of Departure Creek mouth, the formation consists of medium to coarse grained sandstone, pebbly sandstone, and pebble conglomerate. Clasts are subangular to subrounded, and include green, grey, and red chert, and rock quartz. At Horswell Bluff, the formation comprises interbedded fossiliferous, calcareous sandstone, brown bioclastic limestone, and boulder conglomerate. The sandstone contains shell coquinas, and large, floating boulders of basement rock. The boulders in the conglomerate are cemented by coquinas of pelecypod and brachiopod shells, and muddy granule sandstone. The limestone is composed of hexagonal tabulate coral, bryozoa, and shells of Inoceramus (Richardson, 1872). Crickmay and Pocock (1963) report the occurrence of Spondylus sp. and Pterotrigonia evansana at this locality.

On the southern shore of the head of Nanoose Harbour, the Benson Formation consists of thin to medium bedded, fossiliferous sandstone, overlying basement metasiltstone. The sandstone contains large inoceramids and thin coquinas of shell hash, including Inoceramus cf. I. chicoensis, oyster fragments, a ?baculitid ammonite, brachiopod fragments, and small bryozoan fragments (Haggart, 1988b).

Haslam Formation

Nanaimo Area

The northernmost exposures of the Haslam Formation are at Lantzville, northwest of Nanaimo. The formation consists of thin bedded or massive mudstone and concretionary siltstone, which underlies the East Wellington Member of the Extension Formation at Blunden Point. The Haslam Formation extends in low sea bluffs for about 1 km west of Blunden Point. Usher (1952) reports *Inoceramus cf. schmidti* and *Epigoniceras epigonum* in this section.

South of Lantzville, the Haslam Formation occupies the lowlands around Wellington. Although outcrop generally is limited to creek cuts, abundant old borehole data show that it underlies much of the area (see Muller and Atchison, 1972). The section on Benson (Brannan) Creek comprises ca. 65 m of interbedded concretionary shale, siltstone, and sandstone, overlain by ca. 50 m of shale and siltstone (Muller and Jeletzky, 1970). These beds are in contact with the Saanich member of the Benson Formation. Usher (1952) reports finding the following ammonites in the Haslam Formation on Benson Creek, upstream of the confluence with Flynnfall Creek: *Epigoniceras epigonum*, *Hauericeras gardeni*, *Canadoceras newberryanum*, *Pachydiscus haradai*, and *Pseudoschloenbachia brannani n.sp.*. According to Muller and Jeletzky (1970), the basal ca. 30 m of the Haslam Formation on Benson Creek is within the Haradai subzone of the Elongatum Zone. Usher (1952) reports concretions in this section, which contain numerous inoceramids, including *Inoceramus schmidti* and *I. elegans*.

From Wellington to Departure Bay, the Haslam Formation subcrops over a broad area. Borehole data show that the formation is chiefly shale, and ranges from ca. 20 m to 80 m in thickness (Muller and Atchison, 1971). In boreholes 24 and 27 (Muller and Atchison, 1971), the Haslam Formation overlies a very thin Benson Formation or basement itself, attesting to the onlapping and overlapping nature of the formation, and the presence of paleotopography in the basin. The Haslam Formation must be less than 40 m thick along the northern shore of Departure Bay, where it lies between the Extension Formation on Brandon and Jesse islands and Inskip Rock (Clapp, 1914a), and a thin Benson Formation on basement forming the northern shore.

From Nanaimo to Extension, there are few outcrops of the Haslam Formation, however, its presence is verified by borehole data. Few boreholes penetrated the entire Haslam Formation, as the top of the Haslam Formation signified the base of the productive coal measures for the coal miners. Borehole W-38, located about 0.5 km south of the Nanaimo waterworks, penetrated over 150 m of Haslam Formation; in borehole W-42, near Starks, the Haslam Formation is ca. 190 m thick (Bickford, 1986).

Southwest of Extension, on the Nanaimo River, a gently dipping succession of the Haslam shale overlies the Benson Formation. The section is estimated to be greater than 250 m thick. Ward (1978a) reports the occurrence of Didymoceras (B.) elongatum, Inoceramus orientalis, I. naumanni, and Glyptoxoceras subcompressum in the lower part of the section; I. schmidti, Canadoceras multisulcatus, and C. yokayami in the upper part. Usher (1952) also collected Pachydiscus haradai, Phylloceras sp. indet., Epigoniceras epigonum and D. (B.) elongatum from this section.

The Haslam Formation is exposed at a new roadcut at Boulder Creek on the Nanaimo Lakes highway. Here the formation consists of massive, fossiliferous shale, with abundant concretions. The author collected Glyptoxoceras subcompressum, Epigoniceras epigonum, Inoceramus cf. chicoensis, and Sphenoceramus cf. S. elegans from these beds, indicating the lower part of the Schmidti Zone (Haggart, 1988a, b). However, Inoceramus naumanni, and I. n. sp. aff. I. orientalis are also present at this locality (Jeletzky, 1983), indicating the Naumanni subzone of the Elongatum Zone. A sample from this locality yielded a high diversity foraminiferal assemblage indicative of paleo-water depths close to 200 m, and a low energy, somewhat oxygen deficient environment (Cameron, 1988b).

On the southern side of Nanaimo River, on Elkhorn Creek, opposite the locality described above, the Haslam Formation consists of fossiliferous, concretionary, grey shaly siltstone and very fine grained sandstone. The author collected Sphenoceramus orientalis, S. schmidti, Inoceramus ex. gr. I. ezoensis, and Glyptoxoceras subcompressum from the formation, which are indicative of the Schmidti Zone (Haggart, 1988a). Usher (1952) collected numerous Elongatum Zone fossils from Elkhorn Creek. The upper part of the section yielded Hauericeras gardeni, Pachydiscus buckhami n.sp., P. elkhornensis n.sp., P. haradai, and D. (B.) elongatum, which are indicative of the Haradai subzone. This part of the section may overlap with the section from which the author collected fossils from.

On the next creek to the east, which is also named Elkhorn Creek on most topographic maps, a section is present which is very much like uppermost Saanich member or lowermost Haslam Formation in the Stocking Creek area, northwest of Chemainus. The section consists of grey siltstone and fine grained sandstone, containing very large inoceramids (35 x 26 cm) and ammonites.

Southeast of the Elkhorn Creek area, the Haslam Formation underlies a broad, lowland area, between Mount Hayes, McKay Peak, and upper Haslam Creek. Outcrop is restricted to creek and road cuts. The formation comprises thick bedded, massive siltstone and shale, wtih rare fine grained sandstone interbeds (Clapp, 1912b, 1914a). Muller and Jeletzky (1970, p. 17) show that the section on Haslam Creek comprises about 200 m of concretionary shale and siltstone, with minor interbedded sandstone.

Usher (1952) collected numerous ammonites from the Haslam Formation on Haslam Creek west of Mount Hayes. The lower beds yielded Hauericeras gardeni, Epigoniceras epigonum, Canadoceras (P.) newberryanum, and D. (B.) elongatum. The upper beds, around the confluence of the northern fork and the southern fork, yielded H. gardeni, D. (B.) elongatum, and Pachydiscus haradai. Muller and Jeletzky (1970) measured 122 m of Haslam Formation on Haslam Creek which is assigned to the Elongatum Zone. The lower 30 m is Naumanni subzone; the next 92 m is Haradai subzone. Overlying these beds is an isolated section of ca. 50 m of Haslam Formation, bearing fossils indicative of the Schmidti Zone, including Inoceramus schmidti, I. orientalis, and Pachydiscus (Canadoceras) cf. yokoyami (Muller and Jeletzky, 1970).

To the east, complete sections of the Haslam Formation were penetrated in the Harmac and Yellowpoint wells, with apparent thicknesses of 68 and 133 m, respectively. Twombley (1987) notes that the Haslam Formation in the Yellow Point well is rich in dinocysts.

Chemainus Area

The Haslam Formation is considered to subcrop over much of the low coastal plain area around Saltair and Chemainus. The formation crops out at several locations near Chemainus, the best exposures afforded by the valley incised by the Chemainus River, and the wavecut terrace at Chemainus. Bird Rock and the wavecut terrace north of the hospital in Chemainus consist of over 50 m of thin bedded, very fine grained sandstone and siltstone, with medium interbeds and lenses of fine grained sandstone (Section 2). According to Fahlstrom (1981), the Haslam Formation sandstone in the Chemainus area is arkosic wacke to arenite. Stratification is mainly planar and convolute lamination; contacts generally are sharp, continuous, and even to slightly irregular. Ellipsoidal concretions up to 0.3 m in diameter and concretionary lenses are common. Burrows are common on top surfaces of bedding planes. The author collected Baculites sp. cf. B. bailyi and ?Pachydiscus neevesi from this locality (Haggart, 1988a). Foraminifers recovered from a sample from this locality are indicative of paleo-water depth close to 200 m (Cameron, 1988b).

The Haslam Formation crops out fairly continuously on the lower Chemainus River, from 7.5 to 1 km upstream of the Trans-Canada Highway bridge. The formation is comprised of massive, dark grey, concretionary siltstone and shale, with thin to medium interbeds of planar laminated, fine grained sandstone. Coaly debris and concretionary bands and layers are common. Burrows, pelecypods, brachiopods, and ammonites occur locally. One locality, 3.2 km upstream of the bridge, on the northern bank, yielded Didymoceras (B.) elongatum, and Sphenoceramus cf. S. orientalis (Haggart, 1988a). Four microfossil samples were collected from the lower Chemainus

River section, which yielded high diversity foraminiferal assemblages. Two of the assemblages are indicative of paleo-water depths close to 200 m; the other two indicate paleo-water depths of 200-300 m, for one, and 200-600 m with some downslope transport, for the other (Cameron, 1988a).

The Haslam Formation also crops out on the lower Chemainus River, upstream from the Crofton-Chemainus highway bridge, where it consists of thick to medium bedded, grey, fine grained sandstone, interbedded with thin to medium bedded, planar laminated, very fine to fine grained sandstone, siltstone, and shale. Contacts are generally undulatory, but sharp.

Cowichan Valley

In the Cowichan Valley, the Haslam Formation subcrops over a very broad region, with good outcrops typically only at road and river cuts. In the Maple Bay area, the Haslam Formation is well exposed on the beach, and on the northern slopes of Mount Tzuhalem, especially in the new housing developments. Section 40 was measured on the Maple Bay beach, encompassing over 200 m of: a) thick bedded, massive, concretionary, fossiliferous shale, with rare, medium interbeds of fine grained sandstone; b) laminated, silty, grey shale; and c) thin to medium bedded siltstone, shale, and fine grained sandstone, featuring Bouma T_{BCD} sequences. Six samples from this section yielded foraminifers. Three samples, from the basal 100 m of section, indicate paleo-water depths close to 200 m (Cameron, 1988a). Three samples, from the upper 100-250 m in the section, indicate paleo-water depths of 200-400 m (Cameron, 1988a). The deeper water indicators correspond to the part of the section with graded beds (Plate 5b); whereas, the lower, massive part of the section corresponds to the shallower water indicators. At about 50 m in the section, the author collected <u>Didymoceras</u> <u>(B.)</u> <u>elongatum</u>, <u>Inoceramus</u> <u>(Sphenoceramus?)</u> <u>ex.</u> <u>gr.</u> <u>naumanni</u>, and <u>Glyptoxoceras</u> <u>sp.</u> <u>cf.</u> <u>G.</u> <u>subcompressum</u> (Haggart, 1988a). At 100 m in the section, the author recovered ?<u>Ryugasella</u> <u>sp.</u> (Haggart, 1988a). In a roadcut ca. 80 m above the beach, fossiliferous Haslam Formation is well exposed, which approximately corresponds to that part of the beach section between 100 and 150 m. <u>D.</u> <u>(B.)</u> <u>elongatum</u>, <u>Sphenoceramus</u> <u>cf.</u> <u>S.</u> <u>elegans</u>, <u>Glyptoxoceras</u> <u>subcompressum</u>, and <u>Inoceramus</u> <u>cf.</u> <u>I.</u> <u>ezoensis</u>, were collected from these beds (Haggart, 1988a). A microfossil sample from this outcrop yielded foraminifers indicative of paleo-water depths of 200-600 m (Cameron, 1988a).

Elsewhere in the Maple Bay area, several isolated outcrops of the Haslam Formation occur, mostly consisting of massive to crudely flat bedded shale (Plate 5a), and very fine grained sandstone, locally cross-laminated. At the fault contact with Sicker Group by the Brigantine Pub in Maple Bay, a weathered and leached foraminiferal assemblage was recovered, which probably represents paleo-water depths of 100-200 m (Cameron, 1988b).

The Haslam Formation crops out at several localities in the Richards Creek area, west of Maple Bay. It consists of massive or planar laminated siltstone, shale, and minor fine grained sandstone. The formation is fossiliferous, bearing a variety of ammonites, pelecypods, and gastropods. Just east of the Mays and Herd Roads intersection with the road to Maple Bay, the author collected Eupachydiscus haradai and Sphenoceramus cf. S. orientalis from the Haslam Formation (Haggart, 1988a). North of Maple Bay Road, another collection from the Haslam Formation yielded Sphenoceramus schmidti, S. elegans, and S. sachalinensis (Haggart, 1988a). Foraminifers from this locality, are probably representative of paleo-water depths of 150-400 m (Cameron, 1988a).

The Haslam Formation underlies the slopes of Mount Prevost and the adjacent summit to the west; however, only isolated outcrops occur at most localities, hence no complete section is available. Seismic data indicate that the Haslam Formation may be over 1000 m thick in this area, in large part due to tectonic thickening (Chapter 2). The Haslam Formation in the Mount Prevost area comprises: a) finely laminated shale and siltstone, with rare thin to medium interbeds of fine grained sandstone; and b) homogeneous shale. Contacts are sharp, even, and continuous in the thin bedded sections. Sedimentary features observed include small scour and fill structure, load casts, graded beds, cross-lamination, and concretions. The formation is locally abundantly fossiliferous. At a locality 2 km north of Mount Prevost, the following collection was made: Gaudryceras striatum, Baculites cf. B. bailyi, and Sphenoceramus ex. gr. S. schmidti (Haggart, 1988a). Four microfossil samples from Mount Prevost yielded foraminifers. Two from the northeastern flank of the mountain yielded assemblages indicative of paleo-water depths of 200-600 m. The other two, from the eastern base of the mountain, are indicative of paleo-water depths of 100-200 m (Cameron, 1988a).

In the upper Chemainus River area, the Haslam Formation crops out between Chipman Creek and the logging camp gate, downstream at Copper Canyon, and south of the river. The formation consists of thick bedded, massive shale and siltstone, and interbedded shale and very fine to medium grained sandstone. The latter facies occurs in the uppermost part of the section, as exposed on Chipman Creek, and appears to coarsen and thicken upward to basal Extension Formation, as described under the section on the Extension Formation. The alternating shale and sandstone sequence features Bouma T_{ABCD}, T_{BCD}, and T_{CD} sequences, planar lamination, ripple cross-lamination, convolute lamination, load casts, tool marks, and prod marks. A highly diverse assemblage of foraminifers was retrieved from a sample of the Haslam shale taken near the logging camp gate, which indicate paleo-water depths of 200-600 m. A sample from

Chipman Creek yielded a meagre assemblage of foraminifers suggestive of in 150-300 m paleo-water depth, with a moderate amount of downslope transport (Cameron, 1988a).

The Haslam Formation crops out along the Cowichan Lake highway, near Hillcrest and Paldi. The formation consists of thickly bedded, massive, fossiliferous shale. Near Hillcrest, the author collected Sphenoceramus orientalis ambiguus, and Glyptoxoceras subcompressum (Haggart, 1988a). Near Paldi, in an old road ballast pit just off the highway, the author collected: Didymoceras (B.) elongatum, S. orientalis f.t., S. orientalis ambiguus, Inoceramus cf. I. japonicus, and G. subcompressum (Haggart, 1988a). Foraminifers from this locality are of very high diversity, and indicative of paleo-water depths close to 200 m (Cameron, 1988a).

Southwest of Paldi, the Haslam Formation crops out along the Cowichan River at Skutz Falls and in Marie Canyon. The formation is comprised of: a) laminated siltstone and shale, with thin calcareous bands; and b) thin to thick bedded, medium to fine grained sandstone, interbedded with siltstone and shale. Contacts are sharp, even, and continuous. Over 275 m of section was measured downstream of the railway bridge (Section 21). Sedimentary features include oscillation ripple marks, flute casts, small-scale trough cross-lamination, concretions, dewatering pipes, and Bouma T_{BCD} sequences. Burrows, inoceramids, and other pelecypods are present, including: Sphenoceramus cf. S. orientalis, Inoceramus sp., Anomia sp. (Haggart, 1988a), and Paleophycus. Ward (1978a) collected Baculites bailyi, Canadoceras yokoyami, C. multisulcatus, and I. schmidti from the same beds. Ward suggests that the Haslam Formation is greater than 500 m thick in this area.

Five samples from Marie Canyon yielded foraminiferal assemblages. The stratigraphically lowest? assemblage, is suggestive of paleo-water depths of about 80-100 m (Cameron, 1988a). The other four assemblages (all from section 21) are indicative of paleo-water depths of 100-200 m (Cameron, 1988a).

The Haslam Formation crops out on Cowichan River, at a few places below Marie Canyon. Northwest of Deerholme, the formation comprises thick bedded, finely laminated shale and siltstone. A highly diverse assemblage of foraminifers was retrieved from this locality, which is indicative of paleo-water depths close to 200 m, in a low energy, partly oxygen deficient environment (Cameron, 1988b).

Below the pump house at Duncan is a thin bedded, concretionary siltstone, and massive, very fine grained sandstone sequence, which overlies the Saanich member of the Benson Formation. This section is assigned to the Haslam Formation based on correlation to the Haslam Formation on strike near Hillcrest. Below the pumphouse section, at the first bridge over the river, the Haslam Formation is exposed again, consisting of siltstone with fossiliferous concretions bearing anomiid bivalves and Baculites sp. (Haggart, 1988a).

The Haslam Formation subcrops in a number of elongate, footwall strips in the Cowichan Lake area. The lithology is much the same as in the Cowichan River valley to the east: massive, concretionary shale and siltstone, and thin bedded, very fine grained sandstone, siltstone, and shale. The Haslam Formation in the footwall of the Meade Creek fault consists of massive, black shale, which contains ?Glyptoxoceras sp. and pelecypods (Haggart, 1988a). Two samples yielded highly diverse foraminiferal assemblages from the Meade Creek exposures. One indicates paleo-water depths of 180-300 m; the other indicates paleo-water depths of 200-600 m (Cameron, 1988a). Ward and Stanley (1982) report Inoceramus naumanni and Polyptocheras vancouverense in the Haslam Formation immediately north of Cowichan Lake.

As already noted, the Haslam Formation underlies a large part of the Cowichan valley, but is mostly covered by drift, except on some creek and river cuts. The valley itself is segmented by several thrust faults which repeat lower Nanaimo Group at least three times. The most southwesterly subcrop belt of the Haslam Formation parallels Koksilah Ridge, extending from Cowichan Lake to Boatswain Bank. Recessive outcrops of the Haslam Formation at Boatswain Bank, southwest of Cowichan Bay, consist of thin bedded, concretionary shale and siltstone.

Saltspring Island

The Haslam Formation occupies three outcrop belts on Saltspring Island. The northern belt extends from the mouth of Maxwell Creek, south of Booth Bay, to the Cusheon Creek delta, on Captain Passage. The central belt extends from Burgoyne Bay to Fulford Harbour. The southern belt is of limited extent, occupying a narrow strip along southern Saltspring Island, at Cape Keppel. At the mouth of Maxwell Creek, the Haslam Formation consists of massive, concretionary shale and laminated siltstone. The section is in fault contact with the overlying Extension Formation at the northern end of the beach. The author collected Didymoceras (B.) elongatum and Inoceramus cf. chicoensis from this section (Haggart, 1988b). Hanson (1976) notes that the Haslam Formation angularly overlies Sicker Group in the bed of Maxwell Creek. The surface is irregular, with up to 2 m of relief, which is filled by pebble to boulder conglomerate.

To the southeast, the Haslam Formation underlies Maxwell Creek valley, below Mount Erskine and Mount Belcher. The Haslam Formation is 182 m thick south of Mount Erskine, according to Hanson (1976). Hanson describes the basal beds of the Haslam Formation here, to consist of sandy and silty mudstone with concretions, small clay-filled burrows, and rare inoceramids and uncoiled ammonites.

In a road ballast pit, just east of Roberts Lake, the Haslam Formation consists of massive, grey, fossiliferous shale. The author collected Didymoceras (B.) elongatum, Glyptoxoceras subcompressum, and Sphenoceramus sp. from this locality (Haggart, 1988a, b). A very high diversity foraminiferal assemblage was recovered from these beds, which is indicative of paleo-water depths close to 200 m, in a low energy, low turbidity, slightly oxygen deficient environment (Cameron, 1988a).

To the southeast, the Haslam Formation underlies the Blackburn Lake - Cusheon Lake area, and continues along the Cusheon Creek valley to Captain Passage. The Haslam Formation at the Cusheon Creek delta is ca. 205 m thick (Hanson, 1976). It largely consists of massive, concretionary shale. The uppermost beds are finely laminated, with regular concretionary siltstone layers, about 1/m. The upper contact with the Extension Formation is faulted. The formation overlies pebbly sandstone and siltstone of the Benson Formation. At the lower contact, the author collected Didymoceras (B.) elongatum, Glyptoxoceras subcompressum (Haggart, 1988a), and indistinct pelecypods. On the southeastern side of the delta, the author collected D. (B.) elongatum, Pachydiscus neevesi, and Sphenoceramus cf. S. orientalis (Haggart, 1988a). On the beach at Cusheon Creek delta, Ward (1978a) collected D. (B.) elongatum, Eupachydiscus haradai, Inoceramus orientalis, and G. subcompressum. Hanson (1976) notes Thalassinoides, indistinct ammonites, and crustacean remains, occurring in the Haslam Formation at Cusheon Creek.

The central belt of the Haslam Formation occupies the lowland between Burgoyne Bay and Fulford Harbour, and crops out along the southwestern shore of Fulford Harbour. The valley is covered by drift; however, a deep shaft penetrated the Haslam Formation beneath the drift, near the head of the harbour (Clapp and Cooke, 1917). On the southwestern shore of the harbour, west of Russell Island, the Haslam Formation consists of massive, concretionary, fossiliferous shale. Coalified branches and numerous calcite veins are present. The author collected Sphenoceramus orientalis f.t. and Hauericeras cf. H. gardeni from these beds (Haggart, 1988a). Two foraminiferal assemblages also were recovered from the Haslam Formation at this locality. One indicates paleo-water depths of 200-600 m, with oxygen deficient conditions; the other is a high diversity assemblage which indicates paleo-water depths of 300-400 m, with some downslope transport, and slightly oxygen deficient conditions (Cameron, 1988a). Below the massive shale beds, ca. 1.1 km north of the Isabella Island beacon, is a thin sequence of rusty, concretionary siltstone, which apparently overlies basement, although the contact may be faulted.

The southern belt exposures of the Haslam Formation at Cape Keppel, are limited to the shoreline area between a point 0.4 km east of Cape Keppel, and a point 1.9 km northwest of Cape Keppel. The Haslam Formation is in the footwall of the Tzuhalem Fault at this locality. The formation consists of massive, grey shale, with thin to medium interbeds of planar laminated, fine to medium grained sandstone. Hanson (1976) considers the Haslam Formation at Cape Keppel to be at least 60 m thick. Hanson notes rare? Thalassinoides on top surfaces of some of the sandstone interbeds. Two samples from the Haslam Formation at Cape Keppel yielded foraminifers. A moderately diverse assemblage in one sample is indicative of paleo-water depths of 200-400 m, in a low energy environment with some downslope transport; the other sample resulted in a very sparse recovery of foraminifers suggestive of a shelf environment (Cameron, 1988b).

Saanich Peninsula

On northern Saanich Peninsula, the Haslam Formation is exposed along the shoreline, north of Cloake Hill, and in the Swartz Bay area. At the former locality, the Haslam Formation comprises massive, grey, concretionary silty shale, with rare siltstone partings, overlain by thin to medium bedded, grey, silty shale and fine grained sandstone exhibiting Bouma T_{CD} sequences. Some of the top surfaces of the sandstone beds feature numerous trace fossils, including Thalassinoides, Ancorichnus and ?Taenidium. Sandstone from this section is immature arkosic wacke (Kachelmeyer, 1978).

At Swartz Bay, a good section of lower Haslam Formation is partly exposed, which overlies upper Benson Formation (Section 350). The Haslam Formation comprises medium to thick bedded, fine grained sandstone, siltstone, and shale, alternating with thin bedded siltstone and shale, and rare, thick bedded, coarse grained sandstone. The sandstone beds are massive or planar laminated, and contain rare dewatering structure and coal debris. A sample from this section yielded meagre foraminiferal assemblage suggestive of paleo-water depths of 200-400 m, with some downslope transport indicated (Cameron, 1988b). Higher up in the succession, immediately west of the ferry terminal, Ward (1978a) collected: Didymoceras (B.) elongatum, Eupachydiscus perplicatum, Glyptoxoceras subcompressum, Baculites bailyi, Polyptychoceras vancouverensis, and Inoceramus orientalis.

Piers Island

On Piers Island, the Haslam Formation crops out on the southwestern shore, around Indian Point and Patrol Island; on the northern shore between Harry and Harvey points; and, on the southeastern shore around Wilhem Point. The Indian Point exposures consists of concretionary, thin bedded, shale and fine grained sandstone, featuring up to 6 Bouma T_{CDE} sequences/m. The contact with the overlying Extension Formation is strongly deformed. Ward (1978a) collected

Didymoceras (B.) elongatum, Baculites bailyi, Glyptoxoceras subcompressum, and Inoceramus orientalis from these beds.

A repeated section of the Haslam Formation occurs between Harry and Harvey points on northern Piers Island. Here the formation comprises thin bedded, fine grained sandstone, siltstone, and mudstone, featuring Bouma T_{BCD} and T_{CD} sequences. Contacts are even, sharp, and continuous. The section thins and fines upward into a massive shale. At Harvey Point, Ward (1976a) collected the same species of fossils as those found near Indian Point, plus Ryugasella ryugesensis. Clapp (1912a) recovered Inoceramus cf. I. barabini and I. sagensis from beds at Harry Point. A low diversity foraminiferal assemblage was recovered from the Haslam Formation at Harry Point, which is probably representative of paleo-water depths of 200-400 m, in a relatively high energy environment (Cameron, 1988b).

Around Wilhem Point, the Haslam Formation consists of thin bedded, fine grained sandstone and shale, featuring Bouma T_{CDE} and T_{DE} sequences (Plate 4b). The contact with the overlying Extension Formation is discussed in the following section on the Extension Formation. A fairly diverse foraminiferal assemblage was recovered from the Haslam Formation at Wilhem Point, which indicates paleo-water depths of 200-600 m, with some downslope transport (Cameron, 1988b).

To the east, the Haslam Formation crops out on southern Knapp Island and Pym Island. It comprises thin bedded, fine grained sandstone, siltstone, and shale, featuring Bouma T_{CDE} and T_{DE} sequences, up to 10 sequences/m. On Pym Island, Ward (1978a) collected Didymoceras (B.) elongatum, Glyptoxoceras subcompressum, Baculites bailyi, Inoceramus orientalis, and I. naumanni. Ward measured 423 m of Haslam Formation on Pym Island.

To the southeast, the Haslam Formation probably underlies the narrow valley between Lewis Bay and the bay north of Kamai Point on Coal Island. The formation consists of recessive, thin bedded shale, with rare, thick, medium to coarse grained sandstone interbeds. It is also possible that these beds are Saanich member.

Domville Island

The Haslam Formation crops out along the western shoreline of Domville Island. The formation comprises ca. 150 m of thin bedded, concretionary, planar laminated fine grained sandstone, siltstone, and shale (Plate 6a), which underlies the Extension Formation conglomerate. The contact is described in the succeeding section on the Extension Formation. Bouma T_{CDE} and T_{CD} sequences are common. Contacts are sharp, even, and continuous. A sample from near the top of the Haslam Formation yielded foraminifers indicative of paleo-water depths of 200-600 m, with some downslope transport (Cameron, 1988b).

San Juan Islands

The Haslam Formation is partly exposed on Stuart, Satellite, and Johns Island, where it consists of thin to medium bedded, fine grained sandstone, siltstone, and shale, featuring Bouma T_{BCD} and T_{BD} sequences. Shale rip-up clasts are common in the sandstone beds. Rare concretions and trace fossils occur, including Taenidium and ?Helminthoida. Soft sediment deformation is developed locally. Contrary to Ward's (1978a) interpretation, the author considers the coarse grained beds on Johns Island to be assigned more appropriately to the Benson Formation rather than the Haslam Formation.

The Haslam Formation forms shoreline exposures on northern Orcas Island, south of Freeman Island, east of Point Doughty, and at Terrill Beach. The formation consists of thin to medium bedded shale, siltstone, and fine grained sandstone, with lenses of coarse grained sandstone, bearing abundant shale rip-up clasts. Coal spars are common. Ward (1978a) estimates the Haslam Formation to be over 300 m thick on Orcas Island. Didymoceras (B.) elongatum, Glyptoxoceras subcompressum and Inoceramus orientalis have been collected from the Haslam Formation on Orcas Island (Ward, 1976b, 1978a).

Extension Formation

San Juan Islands

The Extension Formation outcrops on several of the San Juan Islands. Coarse conglomerate, with minor sandstone and shale forming Barnes, Clark, and The Sisters islands (McClellan, 1927) is considered by Ward (1978a) to be the Extension Formation, although Ward and Stanley (1982) suggest that some of the beds are the Haslam Formation. McClellan notes that the conglomerate is composed of pebbles of andesite, granodiorite, chert, argillite, sandstone, and various other country rock lithologies, in a matrix of arkosic sandstone. The ammonite _Pseudoschloenbachia cf. P. umbulazi_ is present in fine grained beds associated with the Extension Formation conglomerate on Barnes Island (Ward, 1978a).

The Extension Formation on Orcas Island comprises thick bedded, massive, coarse grained sandstone and poorly sorted, polymictic, cobble conglomerate, with sandstone lenses. Also assigned to the Extension Formation is minor lignitic shale rich in fossil leaf impressions, noted by McClellan (1927). The base of the Extension Formation is clearly erosional into the underlying Haslam Formation The conglomerate is composed predominantly of granodiorite, grey and red chert, sandstone, intermediate volcanic rock, and basic plutonic rock. Ward (1978a) states that the Extension Formation on Orcas Island is locally fossiliferous, and McClellan reports _Ostrea sp._ in these beds.

On Waldron Island, the Extension Formation is well exposed along the southeastern shore, where it consists of thick bedded, massive, medium to coarse grained sandstone; poorly sorted, pebble to boulder conglomerate; and some fine grained sandstone interbeds. Thick shelled pelecypods are locally abundant. Clasts up to 1.5 m in diameter are noted. Pacht (1980) reports that the general range in clast size diameter is 5-20 cm, and rare herringbone cross-stratification is developed in the sandstone. Coal debris is locally common. Ward (1978a) divides the formation into upper and lower conglomerate members with an intermediate sandstone member containing numerous shallow water bivalves and gastropods.

Bare Island and Skipjack Island, north of Waldron Island, are comprised of the Extension Formation. According to McClellan (1927), the formation consists of alternating beds of conglomerate and sandstone, locally cross-bedded. The section on Skipjack Island is greater than 150 m thick. _Ostrea_ is present on Bare Island, and a diverse fossil assemblage is present on Skipjack Island (McClellan, 1927) as previously noted. McClellan states that the assemblage is especially characterized by the pelecypods _Perna excavata_, _Trigonia evansana_, _Glycimeris suciensis n. sp._, and the gastropod _Cinula obliqua_. Ward (1978a) collected _Inoceramus schmidti_? on Skipjack island.

The Extension Formation on Stuart, Satellite, and Gossip islands, is widely exposed and forms three prominent ridges on the limbs of the Reid Harbour syncline and Stuart Island anticline. It consists of thick bedded, poorly sorted conglomerate, pebbly sandstone, and coarse grained to granule sandstone. The conglomerate is generally matrix-supported, and disorganized or inversely graded. Clasts range from pebble to cobble size, and include argillite, felsic volcanic rock, granodiorite, rock quartz, green chert, and basalt. Shale rip-up clasts are locally abundant in the sandstone. Both lower and upper contacts with the Haslam and Pender formations appear to be gradational. The formation is of variable thickness, from 250 m to greater than 500 m; however, some of the beds may be repeated by faulting. McClellan (1927) reports a thickness of about 460 m.

Domville Island

West of Stuart Island, the Extension Formation outcrops in the Gooch and Domville islands area. On Rum Island, the formation comprises poorly sorted, pebble to cobble conglomerate with coarse grained sandstone interbeds. The conglomerate is matrix supported, polymictic, and locally graded. Clasts are commonly imbricated, subrounded to well rounded, and include sandstone, argillite, felsic volcanic rock, chert, and granodiorite. Sandstone interbeds are planar to cross-laminated. Up section, the formation consists of thick bedded, planar to cross-laminated, coarse grained sandstone, interbedded with recessive, finer grained beds. Rare coal debris is present.

The conglomerate and sandstone beds continue to the west, forming most of Gooch Island. Based on map interpretation, the formation is about 300 m thick on Gooch Island. On Rubly Island, the Extension Formation comprises thick bedded, cobble conglomerate, and massive, coarse grained sandstone bearing medium interbeds of conglomerate. The sandstone is locally cross-bedded, and contains floating cobbles. Dominant clasts in the conglomerate are felsic volcanics, chert, and argillite.

On Domville Island, the contact with the underlying Haslam Formation is well exposed, with cobble to boulder conglomerate sharply and erosionally overlying thin bedded siltstone and shale. The upper part of the Extension Formation on Domville Island is sandy also, consisting of thick bedded, coarse grained sandstone, featuring large, low-angle, planar crossbeds, and some smaller, high-angle foreset beds. Floating cobbles and pebbly lenses are common in the sandstone. Upper Extension Formation probably forms the small islet north of Greig Island. The Extension Formation on Domville Island is estimated to be ca. 175 m thick.

Piers Island

To the northwest, the formation is submarine, reappearing on Knapp, Clive, Piers, and Arbutus islands. Lower Nanaimo Group on these islands is structurally deformed: at least 3 thrust faults are inferred to be present, and several sections are strongly disrupted (Chapter 2). The sharp contact between the Extension and Haslam formations is clearly exposed near Schmidt Point on southeastern Piers Island, and on Clive Island. At Schmidt Point, the Extension Formation consists of thick bedded, poorly sorted, pebble to boulder conglomerate, with a granule sandstone matrix, interbedded with recessive intervals of thin bedded to massive, concretionary shale. Clasts are subangular and include sandstone, conglomerate, argillite, rock quartz, green and grey chert, basalt, andesite, and metasedimentary rock. The conglomerate is matrix supported. Up section, conglomerate is replaced by pebbly, medium grained sandstone, with minor conglomerate interbeds. Recessive intervals in this part of the section consist of thin bedded, fine grained sandstone and siltstone, which are commonly laterally replaced by massive, fine grained sandstone with coal pods. Conglomerate locally infills irregular channels up to 2 m deep by 10 m wide (Kachelmeyer, 1978). The basal contact is clearly erosional into the underlying thin bedded, concretionary, very fine grained sandstone, siltstone, and shale of the Haslam Formation. This erosional basal contact is also present on Clive Island. On Clive Island, the Extension Formation consists of thick bedded conglomerate with medium interbeds of pebbly sandstone; contacts are generally diffuse. Large coalified logs are present.

The conglomeratic beds continue to the southeast onto Knapp Island. The section here, comprises about 100 m of thick bedded, medium to coarse grained sandstone, pebbly sandstone, and poorly sorted, polymictic, pebble to cobble conglomerate. The sandy, pelecypod shell-bearing beds overlying the conglomeratic unit is Saanich member of the Benson Formation, because they underlie and are, in part, interbedded with the Haslam Formation on northern Piers Island. Thus, between the conglomerate unit and the sandy beds, there is an inferred bedding plane thrust which places upper Benson Formation over lower Extension Formation. Alternatively, the sandy beds may be upper Extension Formation, and the thrust lies higher up in the transitional interval.

On western Piers Island, the contact of the Extension and Haslam formations is disrupted. The basal units are poorly sorted, pebble to cobble conglomerate, and medium grained sandstone. Up section, the beds are finer-grained, consisting of thick bedded, medium grained sandstone, with fine grained sandstone interbeds; stratification is planar laminated or massive. The sandstone is locally carbonaceous. Shell debris is not observed in these beds.

Arbutus Island, to the west of Piers Island, consists of coarse grained sandstone and poorly sorted cobble conglomerate assigned to the Extension Formation.

Cape Keppel

To the northwest, the Extension Formation underlies Satellite Channel and Saanich Inlet. In the footwall of the Tzuhalem Fault at Cape Keppel, thick bedded, coarse grained sandstone and pebbly sandstone overlie the Haslam Formation, and are assigned accordingly to the Extension Formation. The sandstone contains some planar laminated, fine grained sandstone and siltstone interbeds, abundant floating pebbles of argillite, rock quartz, chert, felsic volcanic rock, and coal debris. On the western side of Cape Keppel, the Extension Formation is represented by polymictic, coarse conglomerate, composed of clasts of chert, felsic volcanic rock, and metasedimentary rock, in a coarse grained sandstone matrix. Hanson (1976) estimates that the Extension Formation at Cape Keppel is ca. 60 m thick.

Cowichan Valley

In the Cowichan Valley area, coarse grained beds overlying the Haslam Formation are assigned either to the Extension Formation or Protection Formation; however, the two formations cannot be distinguished in the field solely based on lithology - both may be conglomeratic. Separation of the the formations in the field can only be made with reference to stratigraphic position, ie. by recognizing the position of the unit with respect to the Haslam or Pender formations.

The Extension Formation forms a large subcrop belt from Cherry Point (southeast of Cowichan Bay) to the Cowichan River. There are few good outcrops in this belt, so its areal extent is mostly inferred. Nevertheless, the apparent simplicity of the structure allows the inferred areal extent of the formation to be made with some confidence. Outcrops at Cherry Point are of planar laminated, medium grained sandstone. However, some large blocks of polymictic, boulder conglomerate occur in float along the beach which may be sourced locally from coarser-grained Extension Formation.

Southeast of Cowichan Station, the Extension Formation consists of thick bedded, medium to coarse grained sandstone, and poorly sorted, pebble to cobble conglomerate. The conglomerate is matrix supported, and contains sandstone lenses. Contacts are irregular and locally erosional. Clasts are well rounded, and include argillite, volcanic rock, white quartz, granodiorite, shale, sandstone, and chert. Conglomerate is crudely flat bedded. The Extension Formation also outcrops on the CN rail line southwest of Deerholme, and on Holt Creek to the west (Bickford, 1986).

The Extension Formation outcrops in the upper Chemainus River and Mount Prevost areas. In the Chemainus River canyon downstream of Chipman Creek, the Extension Formation gradationally overlies the Haslam Formation. The transitional interval consists of thin to medium bedded, fine to medium grained sandstone, siltstone, and shale, which thickens and coarsens upward into massive pebble conglomerate. Contacts are discontinuous. The main body of the formation comprises polymictic pebble conglomerate, and medium to thick bedded, coarse to fine grained, massive sandstone, with shale interbeds. Thin coal seams are present, and assymetrical ripple marks and planar cross-bedding are locally developed. Channels up to 10 m wide and 1.5 m deep are present. A sample from this locality yielded a few foraminifers suggestive of inner shelf to marginal marine paleo-water depths of less than 30 m (Cameron, 1988a), which may have been transported into deeper water.

Conglomeratic beds underlying the Pender Formation outcrop south of the Chemainus River and in the Mount Prevost area. These Extension Formation beds appear to shale out from the upper Chemainus River area to Mount Prevost, such that the Extension Formation at Mount Prevost consists of a few medium beds of pebbly sandstone, pebble conglomerate, and medium grained sandstone, interbedded with shale.

Pender Islands

Some of the best exposures of the Extension Formation occur on South Pender Island between May, Gowlland, and Tilly points. The section is very thick, and obviously repeated by thrust faults. At Tilly Point, the lower part of the formation consists of ca. 20 m of massive sandstone and planar to cross-laminated siltstone, overlain by ca. 38 m of thin bedded to massive shale featuring Bouma T_{BCDE} and T_{CDE} sequences (Pacht, 1980). Pacht assigned theses beds to the "Comox" (ie. Benson) and Haslam formations, but the author prefers to include them in the Extension Formation (as did Hudson (1974)), or in an Extension/Haslam transitional interval. The rest of the section at Tilly Point comprises thick bedded, grey sandstone, pebbly sandstone, and greenish grey to reddish brown, cobble to boulder conglomerate. The lower part of the section is poorly stratified compared to the upper part. The conglomerate is either disorganized, planar cross-bedded, or flat bedded, with inverse grading developed locally. The sandstone in the section is lithic arenite according to Hudson (1974).

At Gowlland Point, the formation comprises thick to very thick bedded, poorly sorted, pebble to boulder conglomerate, with a distinct reddish brown, muddy, coarse grained sandstone matrix (Plate 6b). Hudson (1974) showed that the reddish colour of the matrix is due to pervasive hematite staining. Clasts are well rounded, and include granodiorite, metamorphic rocks, red and green chert, and sandstone. This section is crudely flat bedded or cross-bedded, with numerous scours and cross-bedded sandstone lenses present. Pacht (1980) measured the Extension Formation to be 560+ m thick from near Tilly Point to Gowlland Point, but there are probably several thrust faults present which thicken the sequence.

The entire southwestern coast of North Pender Island, from Wallace Point to Thieves Bay, is comprised of the Extension Formation. Prominent seacliffs are formed by the Extension Formation at Oaks Bluff. The formation is at least 400 m thick, based on map interpretation, barring any structural repeats. In Peter Cove, near Wallace Point, the upper part of the Extension Formation is exposed, comprising thick bedded, poorly sorted cobble conglomerate, with medium interbeds of planar laminated, coarse grained sandstone with floating pebbles. The conglomerate is clast supported, polymictic, and disorganized, with subrounded pebble to boulder size clasts. Planar cross-bedding is developed locally in the sandstone.

Hudson (1974) describes the accessible parts of the section at Oaks Bluff to consist of thick bedded conglomerate, with thin to medium interbeds of mudstone and sandstone. The sandstone is medium to very coarse grained. The conglomerate is poorly sorted, with subangular to subrounded, pebble to boulder size clasts of rock quartz, chert, sandstone, andesite, basalt, granite, diorite, greenstone, and metamorphic rocks, in a medium to very coarse grained sandstone matrix. Contacts are scoured, undulatory, or gradational.

In the Beddis Rock-Thieves Bay area, upper Extension Formation consists of thick bedded pebbly sandstone, fine to very coarse grained sandstone, and poorly sorted, polymictic cobble conglomerate. The sandstone is massive or planar laminated, and features dewatering pipes, small concretions, shale rip-up clasts, and granule sandstone and rare conglomerate lenses. Contacts are loaded, scoured, or gradational. Coal debris is common. Planar crossbeds with high-angle foresets are locally developed. Overall, the formation is gradational into the overlying Pender Formation. The transitional interval features coquinas consisting of pelecypods, gastropods, and brachiopods. Hudson (1974) examined an upper Extension Formation sandstone from this locality, and determined that it is lithic arenite.

Saltspring Island

Northwest of Thieves Bay, the Extension Formation underlies Swanson Channel, and outcrops on the Channel Islands. The southwestern island consists of thick bedded, planar laminated or massive, medium grained sandstone, with shale rip-up clasts and floating granules. Planar cross-bedding and erosional contacts are developed locally. On the northeastern island, the Extension Formation comprises poorly sorted, polymictic pebble to boulder conglomerate, and massive to planar laminated, coarse grained sandstone with shale rip-up clasts. Small scour channels are evident.

On Saltspring Island, the Extension Formation outcrops from the Cusheon Creek delta to the mouth of Maxwell Creek, forming prominences at Mount Belcher and Mount Erskine. The formation shows a distinct westward thickening. At Cusheon Creek, the lower part of the formation consists of coarse grained sandstone, and polymictic, pebble to cobble conglomerate with sandstone lenses. The sandstone lenses are locally planar cross-bedded, and contain numerous floating clasts. Crude grading is observed in the conglomerate. The contact with the underlying Haslam Formation is angularly discordant, and is a fault contact. It is possible that the especially thin section of Extension Formation at Cusheon Creek is due, in part, to fault cut-out. The upper part of the formation at Cusheon Creek consists of massive to planar laminated, medium grained sandstone and siltstone, with numerous shale rip-up clasts. Pacht (1980) observed Bouma T_{ABDE} and T_{BDE} sequences in these beds. Hanson (1976) reports the occurrence of a pelecypod aff. Lima sp. in the lower section, and Ward (1978a) recovered Inoceramus elegans from sandstone in the upper section. Pacht (1980) measured the Extension Formation to be ca. 70 m thick at Cusheon Creek, whereas Hanson (1976) measured it to be 55 m thick.

The Extension Formation in the Blackburn Lake-Cusheon Lake area consists of thick bedded, massive, polymictic, pebble to cobble conglomerate, with minor planar laminated, fine grained sandstone interbeds. The conglomerate is clast supported, and has a coarse grained sandstone matrix. Coal debris is common. Clasts include rock quartz, chert, argillite, and granitic and felsic volcanic rocks. Clasts are generally rounded.

Hanson (1976) divided the Extension Formation into lower conglomerate, middle heterogeneous, and upper conglomerate members. The lower member consists of very thick bedded, laterally extensive, pebble to cobble conglomerate, with minor very coarse to medium grained sandstone. The sandstone is locally pebbly, discontinous, and forms channels up to 0.5 m deep, and 3.0 m wide. The middle member comprises well stratified sandstone and conglomerate, with minor siltstone and mudstone. The sandstone is very fine to very coarse grained to pebbly, and is commonly trough to planar cross-bedded. The lower part is conglomeratic, with numerous lenticular pebble to conglomerate beds. Channels up to 2.0 m deep and 15.0 m wide are noted, with mudstone drapes and coalified lag deposits. Other features noted by Hanson (1976) are normal grading, pebble imbrication, flute and groove casts, and thick shelled pelecypods including Glycimerus. The upper member is very thick bedded, polymictic conglomerate, with clasts ranging from pebbles to boulders up to 1.8 m in diameter. Large mudstone rip-up clasts are present. Thick sandstone lenses occur, consisting of fine to coarse grained sandstone, locally pebbly and planar laminated. Thick bedded sandstone with ripple marks occurs at the top of the member. Channeling and scour and fill structure are common in this unit. Hanson (1976) estimates the Extension Formation on Mount Erskine to be greater than 395 m thick.

On the western side of the island, the Extension Formation forms a headland north of Maxwell Creek. The contact with the underlying Haslam Formation is faulted, but little section appears to be missing. Lowermost Extension Formation consists of thick bedded, massive, medium grained sandstone; medium to thin bedded, carbonaceous siltstone and fine grained sandstone, with thin, sheared coal seams; and thin bedded, concretionary siltstone and shale. This lower section is overlain by a sandstone dominant unit comprised of thin to thick bedded, typically planar laminated, fine to coarse grained sandstone, with pebble conglomerate and laminated siltstone interbeds. One sandstone bed contains a coquina of thin-shelled brachiopods, gastropods, pelecypods, and rare inoceramids, including <u>Cucullaea</u> <u>truncata</u>, <u>Arctica</u> <u>sp.</u>, and the ammonite <u>Pseudoschloenbachia</u>? (Haggart, 1988a). The sandstone unit is overlain by thick bedded, massive, poorly sorted, polymictic, cobble conglomerate, which is clast supported, with a coarse grained to granule sandstone matrix. Clasts range from small pebble to boulder size. The upper contact of the Extension Formation conglomerate with Pender Formation mudstone occurs over a ca. 30 m interval, 0.8 km north of Maxwell Creek (Hanson, 1976).

A small outcrop of the Extension Formation overlies the Haslam Formation on the western shore of Fulford Harbour opposite Jackson Rock. The formation consists of polymictic, poorly sorted, pebble conglomerate, with interbeds and lenses of coarse grained sandstone. The conglomerate is clast supported and imbricated. Clasts are composed of rock quartz, argillite, chert, sandstone, carbonace, and various volcanic and metamorphic rocks.

Chemainus area

The Extension Formation outcrops at Bare Point and in the Mainguy Island area, near Chemainus. At Bare Point, the formation consists of thick bedded, polymictic, pebble to cobble conglomerate, and medium to coarse grained sandstone. The conglomerate is clast supported, with mean clast size diameter about 4 cm. Clasts are subangular to subrounded, and include grey, green, and red chert, sandstone, granitoid rocks, and gneiss. Cross-bedded, coarse grained sandstone commonly fills scour channels. Fahlstrom (1981) reports channels up to 4 m wide by 1 m deep in this unit. In the Mainguy Island area, the Extension Formation grades from pebbly conglomerate to pebbly sandstone, through coarse grained to fine grained sandstone (Fahlstrom, 1981). Thin section analysis by Fahlstrom shows that the Extension Formation sandstone is lithic arenite to wacke.

Nanaimo area

The Extension Formation forms a ridge extending from near Ladysmith to Haslam Creek. A transverse fault offsets the formation just east of Haslam Creek. From Haslam Creek to Nanaimo, the Extension Formation outcrops widely, although it is moderately faulted and folded, and no completely exposed sections are available. Nevertheless, there are numerous old coal exploration borehole and mine records which can be referred to for stratigraphic control. On Haslam Creek, a good section of lower Extension Formation is exposed, comprising thick bedded conglomerate and sandstone (ca. 20 m thick), overlying a sandstone and carbonaceous shale section (ca. 40 m thick), which overlies the Haslam Formation. The conglomerate is clast supported, with clast size ranging from pebbles to cobbles. Large-scale, planar cross-bedding, graded beds, channels, and scours are common. The underlying shaly section comprises about 10 fining upward sequences, from coarse grained sandstone to shale. Contacts are even, although some channeling is evident. The shales are carbonaceous and contain much coaly debris. The shaly section is equivalent to the East Wellington Member, whereas the conglomeratic beds are Millstream member. The Wellington seam, which should directly underlie the conglomeratic beds in this area, is either not developed or very recessive.

East of Cassidy, the Extension Formation was penetrated in the Harmac and Yellow Point wells, with apparent thicknesses of 109 m and 131 m respectively. In the Yellow Point well, a short core in the Extension Formation comprised pebble conglomerate, with chert, rock quartz, and volcanic rock fragments (Twombley, 1987).

Near the railbed west of Cassidy, lower Extension Formation is well exposed, consisting of thick bedded, polymictic conglomerate and sandstone. The conglomerate contains pebble to cobble size clasts in a granule to coarse grained sandstone matrix. Clasts are subangular and include black to grey chert, felsic and intermediate volcanic rocks, argillite, rock quartz, and some rare, but distinct, red chert. Sandstone lenses are present in the conglomerate. Borehole control shows that the Extension Formation in this area includes minor shale and sandstone interbeds, and is up to 200 m thick (Muller and Atchison, 1971).

In the Timberland Lake area, lower Extension Formation conglomerate is much the same as described above, according to Bickford (1986). Bickford notes trough cross-bedding, and channels up to 3 m deep and 30 m wide in the conglomerate. The conglomerate directly overlies the Wellington seam, which is generally less than 1 m thick in this area (Muller and Atchison, 1971). East Wellington

Member in the area is comprised of thick to thin bedded, very fine to medium grained sandstone and siltstone, locally containing coalfied roots (Bickford, 1986).

Between Extension and southern Nanaimo, the Extension Formation forms broad, gentle dip slopes, mostly comprised of pebble conglomerate. The conglomerate is thick bedded, and contains minor sandstone and siltstone interbeds. Clasts are subrounded to well rounded, and predominated by dark chert, rock quartz, plutonic rocks, and greenstone, with minor coal debris. The matrix is typically rusty, coarse grained sandstone. The thickness of the unit is generally less than 150 m in this area, based on borehole data. The Northfield member is up to 15 m thick in this area, based on boreholes W-38 and W-26 (Bickford, 1986). These beds are partly exposed south of the waterworks on Chase River, where they consist of thin bedded, carbonaceous shale and coal. The East Wellington Member is also partly exposed, consisting of planar laminated to massive, fine to medium grained sandstone. The East Wellington Member is 20 m thick in borehole W-26 (Bickford, 1986).

The bulk of the exposure in the western Nanaimo area is of Millstream member conglomerate. The member in this area consists of thick to very thick bedded, pebble conglomerate, pebbly sandstone, and granule to coarse grained sandstone. However, subsurface control (Muller and Atchison, 1971, p. 8) shows that the member also contains several shale layers. Bickford (1986) notes that shell fossils have been observed in boreholes in upper Extension Formation in this area. The member is on the order of 100 m thick, and the Northfield and East Wellington members are up to 20 m and 30 m thick respectively, based on the borehole data.

The Extension Formation outcrops between western Nanaimo and Wellington. Again, Millstream member forms the broadest exposure, occupying the trough of a gently east-plunging, open syncline. The member comprises thick bedded, massive, pebble conglomerate and medium grained to granule sandstone. Bickford (1986) reports large channels up to 2 m deep and 40 m wide, and common medium to thick lenses of sandstone within the conglomerate. Borehole data show that the lower part of the member is dominated by shale and sandstone, and that the entire member is up to 130 m thick (Muller and Atchison, 1971, p. 8). The same borehole data show that Northfield and East Wellington members are well developed, and up to 30 m and 15 m thick, respectively.

East Wellington Member is well exposed at the southern end of the industrial park between Long Lake and Brannen Lake, where it comprises thick to medium bedded, typically massive, granule to coarse grained sandstone, and fine to medium grained carbonaceous sandstone, with pebbly sandstone lenses. Burrows and coal debris are common, and rare pelecypod shells are present. Planar and trough cross-bedding is evident. Contacts are discontinous.

The Extension Formation also outcrops south of Mount Benson, on Wolf Mountain where it comprises: a) thick bedded, massive, pebble conglomerate; b) very fine to coarse grained sandstone; and c) minor carbonaceous shale and coal (Bickford, 1986). The conglomerate contains clasts of volcanic and metamorphic rocks, rock quartz, and minor red chert, in a coarse grained sandstone matrix. Both planar and trough cross-bedding are observed. Bickford and Kenyon (1988) show that the Wellington No. 1 and No. 2 seams are present, as well as a coal seam within the Millstream member known as the Millstream Jacks seam.

The most northerly Extension Formation outcrop is at Blunden Point in Lantzville. The Extension Formation is considered to underlie the area from Blunden Point to the small headland east of Icarus Point. Blunden Point consists of East Wellington Member, comprising planar cross-bedded and planar laminated, medium grained sandstone and siltstone, with abundant burrows, including Phycodes, and coquinas of gastropods and pelecypods. Muller and Jeletzky (1970) state that these beds form the uppermost part of the Schmidti Zone, but do not declare which diagnostic forms are present. The member is gradationally underlain by the Haslam Formation. East of Blunden Point, the Extension Formation consists of medium bedded pebble conglomerate, pebbly sandstone, and medium grained to granule sandstone. Planar lamination and planar cross-bedding are locally developed. There is abundant coal float from the coal seam mined here, which is probably Wellington seam equivalent (Muller and Atchison, 1971).

Pender Formation

San Juan Islands

On southern Waldron Island, the Pender Formation is represented by ca. 100 m of fine grained sandstone and siltstone overlying the Extension Formation conglomerate (Ward, 1978a). These outcrops are richly fossiliferous. McClellan (1927) collected 33 macrofossil species, which include Baculites chicoensis, Schluteria selwynianum, Neophylloceras ramosum, and Inoceramus vancouverensis. Ward (1978a) collected I. vancouverensis, Canadoceras newberryanum and B. chicoensis in siltstone, 80 m above the Extension Formation, on southeastern Waldron Island.

On Stuart Island, the Pender Formation is preserved in a northwest-southeast trending syncline in the Reid Harbour area. It comprises thin bedded, fine grained sandstone, siltstone, shale, and medium to thick bedded, fine to medium grained sandstone with shale rip-up clasts, and granule lenses and layers. Stratification in the coarser, thicker units is massive of planar lamination. Contacts are sharp, even, and continuous. Planolites, Thalassinoides, and vertical to oblique sand-filled burrows are locally abundant. Rare coal debris is present. The formation is transitional from underlying Extension Formation over about 75 m of section. Ward (1978a) reports Baculites chicoensis and Canadoceras newberryanum in the Pender Formation on Stuart Island.

West of Stuart Island, the Pender Formation may lie between Comet and Brethour islands in the north, and Domville and Gooch islands in the south. On northern Gooch Island, the beds are finer-grained than on the southern side, and are probably part of the transition sequence from the Extension to Pender formations They are composed of thin bedded, siltstone and shale, with medium, coarse grained sandstone interbeds.

Pender Islands Area

On Saturna Island, the fine grained section below 793 m in the Saturna No. 1 well, may be the Pender Formation. Six samples taken from this interval yielded foraminifers of variable abundance and diversity and of late Santonian to early Campanian age (McGugan, 1981).

The Pender Formation on South Pender Island extends from Egeria Bay to the Canned Cod Bay area, occupying a narrow valley which includes Greenburn Lake. Accurate thickness estimates of the Pender Formation in this area are not possible because the section is faulted. On the eastern side of the island, the contact of the Pender Formation with the overlying Protection Formation is diffuse, due to numerous sandstone interbeds. The author's preference is to assign to the Pender Formation all of the beds from the first recess in the shoreline north of Gowland Point to the northern side of Canned Cod Bay. This section is described by Pacht (1980) as thin bedded shale and siltstone, with numerous massive to planar laminated sandstone interbeds and lenses. Bouma T_{ABCDE}, T_{BCDE}, T_{CDE}, T_{ABE}, and T_{BCE} sequences are prevalent. Ward (1978a) recovered *Inoceramus vancouverensis*, *Canadoceras newberryanum*, and *Baculites chicoensis* from this interval.

In the roadcut above Egeria Bay, upper Pender Formation is conformably overlain by the Protection Formation. Here, the Pender Formation consists of thin bedded shale and fine grained sandstone. A weathered and leached microfauna recovered from these beds probably represents paleo-water depths of 200-600 m, with some downslope transport (Cameron, 1988a).

On North Pender Island, the Pender Formation crops out fairly continuously from Thieves Bay to the cove south of Arbutus Point. Hudson (1974) measured a section at the latter locality, which includes the entire Pender Formation. The formation is 194 m thick, and consists of thin to medium bedded mudstone, siltstone, and sandstone. The sandstone is very fine to medium grained, and is planar laminated to cross-laminated. The mudstone is concretionary, and locally contains rare pelecypod fragments including inoceramids. Usher (1952) reports finding *Pachydiscus newberryanus* in these beds.

The Pender Formation is locally exposed to the northwest, in the valley occupied by Pender Lake. In this area, the formation comprises fossiliferous and concretionary, massive to thin bedded grey shale and siltstone. *Inoceramus subundatus* and *I. vancouverensis* were collected from this area (Haggart, 1988a). Foraminifers recovered from the Pender Formation 400 m southeast of Pender Lake, probably represent paleo-water depths of 200-600 m, with some downslope transport (Cameron, 1988a). Another Pender Formation sample, taken about 800 m further southeast, yielded a microfauna indicative of paleo-water depths of 400-600 m, with downslope transport evident (Cameron, 1988b).

On northwestern North Pender Island, the Pender Formation comprises massive, grey, fossiliferous, concretionary siltstone and mudstone. This area is Ward's (1978a) type area for the Pender Formation. The Pender Formation is in contact with graded conglomerate and pebbly sandstone of the Extension Formation at Boat Nook. The contact is transitional with lenses of coarse grained sandstone and conglomerate interspersed in basal Pender Formation. A sample from the Pender Formation at Boat Nook yielded foraminifers probably representative of paleowater depths close to 200 m, with some downslope transport and oxygen deficiency indicated (Cameron, 1988b). Usher (1952) collected *Pachydiscus newberryanus* from this locality, and Hudson (1974) reports *Inoceramus sp.* from the area.

To the northwest, at the point west of Thieves Bay, the same contact is exposed: coarse clastic beds grade into thin bedded siltstone and mudstone over a short interval. Pachydiscus newberranus was collected from two locations in basal Pender Formation in this outcrop area (Usher, 1952).

At the northern end of the head of Thieves Bay, thin bedded, concretionary Pender Formation mudstone is overlain by basal Protection Formation sandstone. Pacht (1980) measured the Pender Formation to be 147 m thick at Thieves Bay. A fairly diverse microfauna indicative of paleo-water depths of 200-600 m, was recovered from the Pender Formation at this locality (Cameron, 1988a).

Saltspring Island

To the northwest, the Pender Formation underlies Swanson Channel, coming onshore Saltspring Island, just north of Cusheon Creek. At this locality, the Pender Formation comprises thin bedded, fine grained sandstone and grey shale, with rare, thicker, medium grained sandstone interbeds. Bouma T_{BCD}, T_{CDE}, and T_{BD} sequences are well developed, up to 10 sequences/m. Contacts are sharp, even, and continuous. Ward (1978a) collected Inoceramus ex. gr. subundatus, Baculites sp. indet. and Pseudoxybeloceras (Cyphoceras) sp. from this outcrop. Hanson (1976) reports burrows and Inoceramus sp. from this section. The Pender Formation at Cusheon Creek is 322 m thick according to Hanson.

To the northwest, the Pender Formation occupies the valley area north of the ridge formed by the Extension Formation, all the way to the St. Mary Lake fault. The formation is left laterally offset on the fault and forms the lower part of the northern slope of Mount Erskine, and the shoreline south of Booth Bay. The Pender Formation is apparently repeated on the Ganges fault, the hanging wall section forming part of the northern shore of Booth Bay.

The formation on the northern shore of Booth Bay consists of thin bedded siltstone and shale, with fine grained sandstone interbeds, overlain sharply by thick bedded Protection Formation sandstone. Inoceramid fragments, coaly debris, and concretions occur in the Pender Formation. Hanson (1976) reports Inoceramus sp., burrows, and rare load and flute casts in these beds. A sample from this locality yielded a high diversity microfauna indicative of paleo-water depths of 600-1200 m, with significant downslope transport of shallower water indices (Cameron, 1988a).

Cowichan Valley

The Pender Formation is reported to outcrop near the curling club in northwestern Duncan by Bickford (1986), and probably subcrops in much of the lower Cowichan River area, but is not exposed due to surficial sediment cover. South of the Cowichan River, it is also inferred to subcrop near

Keating Lake, and in a broad belt from Cowichan Station to Satellite Channel (Bickford, 1986).

The Pender Formation crops out in the Mount Prevost and upper Chemainus River areas. In the Mount Prevost area, the formation consists of massive to finely laminated, grey shale, which overlies variably coarse grained Extension Formation. In the upper Chemainus River area, by far the best exposure is a steep shale slope on the northern side of Chemainus River canyon, below Chipman Creek. The section is 150+ m thick, consisting of massive to thin bedded, grey shale and siltstone, with rare resistant siltstone and fine grained sandstone interbeds. The contact with the underlying Extension Formation is sharp and even, but visibly discordant (Plate 7b). Basal Pender Formation is disposed as large-scale, low-angle, planar crossbeds which downlap on a flat, uniform, top surface of the Extension Formation. Three samples from the shale slope yielded foraminifers (Cameron, 1988a) - the lowest sample resulted in a low diversity microfauna, probably representative of 100-150 m paleo-water depths; the middle and upper samples yielded microfaunas indicative of paleo-water depths of 150-200 m.

On the southern side of Chemainus River, the Pender Formation is moderately deformed. Outcrops consist of thin bedded to massive siltstone and shale, with very fine grained sandstone interbeds. Bouma T_{CDE} sequences and load casts are locally developed. Bickford (1986) reports inoceramids and burrows in these beds. A sample from this area yielded a fairly high diversity microfauna indicative of paleo-water depths close to 200 m, with some oxygen deficiency indicated (Cameron, 1988b).

In the Chemainus area, the Pender Formation is recessive, and not exposed, occupying the strip between the Protection Formation on Shoal Islands, and the Extension Formation between Bare Point and Mainguy Island.

Nanaimo Area

Between Ladysmith and Nanaimo, the Pender Formation crops out at several localities. In the south, these outcrops are generally isolated due to the recessive nature of the formation; outcrop continuity is greater in the north, where the formation is coarser-grained. The formation occupies a narrow valley northeast of the ridge formed by the Extension Formation, striking from Ladysmith to Haslam Creek. It is present in Timberland Lake area (Bickford, 1986), and is exposed on the Nanaimo River, northwest of Cassidy. From there, it forms a more or less continuous outcrop belt to Nanaimo and northern Newcastle Island.

The Pender Formation was penetrated in the subsurface in the Harmac and Yellow Point wells, east of the outcrop belt. Apparent thicknesses are 189 m in the Harmac well, and 217 m in the Yellow Point well. The Douglas coal zone is present in both wells.

The upper part of the Newcastle Member is exposed east of Beck Lake, and on Highway 1, south of Chase River (Section 90), where it consists of thin bedded shale, siltstone, and planar laminated, fine grained sandstone, with rare concretions and ferruginous banding. The Douglas coal seam is in this section, but it is not exposed due to its highly recessive nature, and historical mining activities.

Basal Newcastle Member, including the Newcastle seam, is exposed in Chase River. The section comprises: a) medium to thick bedded, typically planar laminated, fine to medium grained sandstone, with pebble lenses and abundant coal debris; b) thick bedded, pebble to cobble conglomerate; and c) thin to thick bedded coal seams. Large conglomerate channels with large-scale planar crossbeds (lateral accretion surfaces) are evident. Smaller-scale basal scouring is also developed. Large _Inoceramus_ _sp._ is locally present in the roof of the Newcastle seam.

In southern Nanaimo, basal Newcastle Member is also exposed, comprising thick bedded, pebble conglomerate and granule sandstone, bearing abundant pelecypod shells concentrated in layers, and coal debris. Large burrows and large _Inoceramus_ _sp._ is reported in this section by Bickford (1986). The underlying Cranberry Member also is locally exposed in this area, consisting of planar laminated, coarse grained sandstone and pebble conglomerate. Scour and fill structures and planar cross-bedding are locally developed. However, much of the member is recessive and probably is fine grained.

In Nanaimo, there are several good sections of lower Newcastle Member exposed; upper beds are not exposed. From base up, a typical lower Newcastle Member succession is: a) Newcastle coal seam comprised of coal and mudstone (1.3+ m); b) thin to medium bedded fine grained sandstone, with minor carbonaceous mudstone, siltstone and granule lenses (0.6 m); c) planar cross-laminated, fine grained sandstone, with some large concretions, pelecypod shells, and coal spars (3.0 m); d) slightly recessive massive sandstone (4.0 m); and e) thick bedded, massive, pebble conglomerate, with coarse grained sandstone matrix (5.0+ m). Locally, basal Newcastle Member is repeated by southwest-directed thrusting as exposed in the parking lot near city hall, where the roof succession and part of the Newcastle seam is thrust over the roof succession (Plate 19).

The underlying uppermost Cranberry Member consists of thin to medium bedded mudstone, siltstone, and very fine grained sandstone, with abundant coalified plant fragments and ferruginous concretions (Bickford, 1986).

The Pender Formation is well exposed on northern Newcastle Island. Newcastle Member consists of thin bedded, shaly siltstone, and fine grained sandstone, with abundant coal debris; coal; and medium to thick bedded, fine to coarse grained sandstone, with abundant coal debris and concretions. Trough and planar cross-bedding is developed in some sandstone units. The Douglas Seam is located on the island from immediately south of Shaft Point to the small bay west of McKay Point, and the Newcastle Seam intersected the surface just north of Shaft Point, and between Nares and McKay points (Clapp, 1912b). The underlying Cranberry Member consists of: a) medium to thick bedded, massive to graded, cobble to pebble conglomerate; b) massive to planar laminated, pebbly sandstone with well rounded pebbles; and c) recessive, thin bedded, shale and siltstone. Channels up to 10 m deep are developed locally in the conglomerate. Sandstone units are trough and planar cross-laminated locally. Bickford (1986) recognized scattered, large burrows in some of the sandstone units.

Usher (1952) reports the occurrence of 7 pelecypod and 5 gastropod species from the roof of the Douglas seam at Nanaimo. Bickford (1986) notes that the "Douglas Grit" which lies between the Newcastle and Douglas seams is shell-bearing, including inoceramids.

Protection Formation

Nanaimo Area

The Protection Formation crops out on Newcastle and Protection islands, adjacent to Nanaimo Harbour, and forms a continuous outcrop belt from Nanaimo to Ladysmith Harbour. From Cassidy to Ladysmith, the outcrop belt is narrow due to the high dip of the formation. The Protection Formation crops out on Round Island, near Dodds Narrows, near the crest of the Stuart Channel anticline. Also, an isolated outcrop is reported on the hill immediately east of Timberland Lake, west of Brenton (Bickford, 1986).

On Newcastle Island, the Protection Formation comprises thick bedded, fine to medium grained, white sandstone, interbedded with thin, shaly siltstone and fine grained sandstone. The coarser grained beds are trough and planar cross-stratified or planar laminated; finer grained beds are planar laminated. Crossbed sets are generally about 1 m thick, and have assymptotic toesets. Herringbone cross-bedding is locally developed. Bickford (1986) reports large burrows in the Protection Formation on southwestern Newcastle Island. In general, the basal part of the Protection Formation is coarser-grained than upper parts. Near McKay Point, the formation is in sharp contact with underlying, thin bedded, fine grained beds of the Newcastle Member. At the southern end of the island, the formation is estimated to be 75-100 m thick.

The Protection Formation is widely exposed on Protection Island. At the southern end of the island, about 125 m of the Protection Formation was penetrated in an old coal exploration borehole - W-22 (Bickford, 1986). Usher (1952) reports _Inoceramus sp._ occurring in upper Protection

Formation on Protection Island. Control on the Protection Formation along the Nanaimo waterfront and under the Nanaimo River mudflats is provided again by old borehole data compiled by Bickford (1986). The formation comprises thick bedded sandstone interbedded with fine grained sandstone, siltstone, and rare shale. About 500 m north of Nanaimo Town Indian Reserve 1, the formation is 140 m thick (Borehole W10), and in the middle of the mudflats, it is about 210 m thick (Borehole W-43).

At Petroglyph Park, basal Protection Formation consists of thick bedded, planar laminated, fine grained sandstone, overlying poorly sorted pebble conglomerate and pebbly sandstone. East of Chase River, the formation comprises medium to thick bedded, fine to coarse grained sandstone, carbonaceous mudstone, and coal (Bickford, 1986).

Section 90 was measured in basal Protection Formation at a Highway 1 roadcut, south of Chase River. The section comprises thick bedded, coarse to medium grained sandstone, pebbly sandstone, pebble conglomerate, and planar laminated, fine grained sandstone, overlying thin bedded, concretionary siltstone and silty shale of the Newcastle Member. Stratification in the coarse grained beds is planar lamination or trough and planar cross-lamination. The conglomerate is matrix supported and poorly sorted. Abundant coal debris is locally present, including cobble size pieces of coalified wood. Contacts are sharp but irregular.

Along the highway north of Cedar, the Protection Formation is well exposed, consisting of thick to thin bedded, fine to medium grained sandstone, with thin siltstone and mudstone interbeds. Coal seams up to 0.5 m thick are present. The fine grained sandstone is locally trough cross-laminated; medium grained sandstone beds are commonly planar laminated. At the eastern end of the outcrop, there is a transition to thin bedded, silty shale of the Cedar District Formation.

The Protection Formation is exposed on Round Island and the islet off its southern coast. On the islet, the formation comprises medium bedded, planar laminated, medium to fine grained sandstone. The fine grained sandstone has a regular, thin planar parting. Horizontal burrows are noted on bedding plane tops. The same lithofacies is present on the western side of Round Island. In addition, overlying these beds, are planar laminated, fine grained sandstone and siltstone with discontinuous coal seams up to 8 cm thick. Scoured into the fine grained beds is a 4 m deep channel, filled with laminated, very fine grained sandstone at the base, with large shale rip-up clasts, sandstone dykes, coal spars, and disrupted coarse grained sandstone lenses featuring solution pipes. These beds pass up into tabular, planar cross-bedded, coarse grained sandstone, well exposed on the eastern side of the island.

Between South Wellington and Cassidy, there are numerous isolated exposures of the Protection Formation which consist of: crudely planar laminated, fine to medium grained sandstone; and thick to medium bedded, planar cross-bedded, medium grained sandstone and pebble conglomerate. Crossbed sets are up to 1.5 m thick; these are clearly channel-fill deposits. Coal debris and spars are common. Contacts are irregular and commonly gradational.

Complete sections of the Protection Formation were penetrated in both the Harmac and Yellow Point wells. The formation is 187 m thick in the Harmac well, and 201 m thick in the Yellow Point well; thicknesses are uncorrected for inclination of beds.

At Transfer Beach, in Ladysmith Harbour, upper Protection Formation is exposed (Section 76) comprising ca. 60 m of thick bedded, fine to medium grained sandstone, with thin interbeds of very fine grained sandstone, siltstone, and rare mudstone. Contacts are generally sharp, even and continuous; some small scour and fill structures are present. Stratification in the coarser grained beds is massive or planar lamination; planar cross-bedding is locally developed. The thick beds are commonly capped by thin bedded, siltstone and mudstone. Shale rip-up clasts and load casts are present. Top surfaces of sandstone beds are locally burrowed. Fine grained beds are planar to convolute laminated, and locally feature soft sediment deformation, flame structures, and load casts. Many of the beds in the section are graded. The section is overlain by the Cedar District Formation with a transitional interval of about 10 m. These beds consist of thin bedded, fine grained sandstone and siltstone, with rare medium grained sandstone interbeds. Bouma T_{ABC}, T_{AD}, T_{BCD}, and T_{CD} sequences are present. Contacts are sharp, even, and continuous. T_C units are convolute laminated or trough cross-laminated.

Chemainus Area

Southeast of Ladysmith, the formation underlies Stuart Channel, coming onshore as a narrow chain of islets in the Shoal Islands. The Protection Formation in the Shoal Islands consists of medium to thick bedded, planar laminated, fine to medium grained sandstone. Planar and trough cross-lamination is locally developed. Fahlstrom (1981) noted the occurrence of a thin shell bed, convolute bedding, and well preserved, symmetrical ripple marks in these beds. Her thin section analysis of two Protection Formation samples shows that it is arkosic arenite.

Cow'chan Valley

To the west, in the Cowichan Valley area, a coarse grained formation, assigned to the Protection Formation, overlies presumed Pender Formation. However, because the formation is generally coarser-grained than the Protection Formation elsewhere in the Nanaimo Basin, and as no complete section is available in the Cowichan Valley which includes this formation, the correlation is provisional.

In upper Chemainus River area, the Protection Formation comprises medium to thick bedded, pebbly sandstone and pebble to cobble conglomerate, intercalated with medium to thin bedded, fine grained sandstone, siltstone, and shale. Pebbly lenses are present in the fine grained beds. The conglomerate is supported by a coarse grained sandstone matrix, and is rusty weathering and polymictic. Clasts are subangular to subrounded, composed dominantly of chert, rock quartz, argillite, sandstone, coal, gabbro, and gneiss. Rare, indistinct shell molds occur in the conglomerate (Bickford, 1986). A sample of silty shale from these beds yielded a sparse microfauna, probably representing paleo-water depths of 20-50 m (Cameron, 1988b).

The high cliffs at the top of Mount Prevost are composed of Protection Formation equivalent (Plate 7a). The formation comprises 150+ m of thick bedded, well indurated, pebble to cobble conglomerate, pebbly sandstone, and fine to coarse grained sandstone (see Section 30). The conglomerate is poorly sorted and generally clast supported. Clasts are subangular to subrounded, composed of rock quartz, chert, granodiorite, volcanic rock, and sedimentary rock. Contacts are irregular, discontinous, and sharp to diffuse. Stratification is massive or normally graded; planar cross-bedding is developed locally. Graded sandstone beds are common, from granule to fine grained size. Planar laminated sandstone, some channels, and rare coal seams are also evident.

The Protection Formation? is poorly exposed in the footwall of the Tzuhalem Fault at the head of Cowichan Bay. The formation comprises medium to thick bedded, massive to planar laminated, carbonaceous, fine to medium grained sandstone, interbedded with very fine grained sandstone and siltstone. Clapp and Cooke (1917) report the occurrence of the pelecypod Axinea veatchii in these beds. This unit has been mapped previously as the Cedar District Formation? by Muller and Jeletzky (1970). Given the poor exposure due to thick Quaternary sediment cover, lithostratigraphic correlation of this unit is impossible. Nevertheless, it does appear to overlie the Haslam Formation exposed on the Cowichan River in southwestern Duncan, and thus is probably the Extension or Protection Formation equivalent.

Saltspring Island

The Protection Formation forms the point south of Vesuvius Bay on Saltspring Island, and strikes to the southeast parallel to Booth Inlet. There it is offset by the St. Mary Lake transverse fault. To the east, the formation is repeated by a thrust fault, the hanging wall section extending from the golf course area to the town of Ganges and Grace Islet, and the footwall section striking from south of eastern Booth Inlet to the northern point, north of Cusheon Creek.

The Protection Formation in Vesuvius Bay area comprises medium to thick bedded, medium to coarse grained sandstone, with abundant floating clasts and granule layers; planar and convolute laminated, and ripple cross-laminated, fine grained sandstone; and, thin bedded siltstone and mudstone. Planar cross-bedding is locally developed. According to Hanson (1976), the formation has abundant sole markings (load casts, groove casts, flute casts), burrows, fragmented pelecypod shells, including inoceramids, and is 60-90 m thick; it has a transitional contact with the overlying Cedar District Formation. Clapp and Cooke (1917) report the occurrence of <u>Inoceramus</u> <u>sagensis</u> in a stone quarry in the Protection Formation on the northern shore of Booth Bay.

On eastern Saltspring Island, exposures of the Protection Formation are few. In Ganges, at Grace Point, the formation consists of thick bedded, massive, medium grained sandstone, with thin to medium bedded, silty shale. Minor channel scours and load casts are present. Hanson (1976) describes a basal contact with the Pender Formation to be transitional over ca. 6 m at Grace Point. In the Ganges area, Hanson notes sole marks, tubular burrows, and prod casts in the Protection Formation.

The southern footwall body of the Protection Formation, according to Hanson (1976), comprises about 30 m of very thick to thin bedded, fine to coarse grained sandstone, with mudstone interbeds, overlain by an undetermined thickness of pebbly sandstone, and conglomerate intercalated with mudstone. The basal beds are exposed at the northern end of the public beach north of Cusheon Creek. Overall, the lower Nanaimo Group is obviously tightly folded and faulted in the area, and is poorly exposed, so the Protection Formation thickness cannot be determined. Based on map interpretation, the formation may be several hundred metres thick.

Pender Islands

The Protection Formation passes offshore Saltspring Island, presumably underlies Swanson Channel, and crops out again on North Pender Island form Mouat Point to Bedwell Harbour. In Mouat Point area, the formation comprises thick bedded, massive to planar laminated, medium to very coarse grained sandstone, with abundant floating pebbles and shale rip-up clasts, and thin interbeds of siltstone and shale. Pacht (1980) measured a section in the Protection Formation at Mouat Point, calculating a total thickness of 544 m. Pacht noted some conglomerate beds in the section, as well as dish structure, rare crossbeds, inverse grading, and channels in the coarse grained beds. In the fine grained beds, he noted Bouma T_{ABCDE}, T_{BCDE}, and T_{CDE} sequences, ripple cross-laminated siltstone, and rare coal debris.

The formation thins to ca. 150-200 m to the southeast, forming a continuous ridge, striking into Bedwell Harbour, which consists of thick bedded, massive to planar laminated, coarse grained sandstone, with thin mudstone interbeds. Hudson (1974) noted load, groove, and flute casts on basal bedding surfaces in this unit. The sharp contact with underlying thin bedded, fine grained beds of the Pender Formation is exposed just southeast of Pender Lake, and, according to Hudson (1974), near Arbutus Point, on Bedwell Harbour to the southeast. Hudson's thin section analysis shows that the sandstone is arkosic wacke.

On South Pender Island, the Protection Formation crops out from Richardson Bluff to Higgs Point, comprising thick bedded, medium to coarse grained sandstone, with abundant shale rip-up clasts and coal debris. On the roadcut above Egeria Bay, the formation overlies thin bedded shale and fine grained sandstone of the Pender Formation, with a slightly gradational, planar contact. Based on map interpretation, the Protection Formation is about 200 m thick here.

The sandstone formation on northern Waldron Island has been assigned to the Protection Formation by Ward (1978a). McClellan (1927) describes the formation to consist of buff sandstone and minor conglomerate, bearing large thick shelled Ostrea and Trigonia evansana.

Brethour Island Area

Between northern Saanich Peninsula and Stuart Island, the Protection Formation crops out on Comet, Brethour, Reay, and probably Imrie islands. The assignment of these beds to the Protection Formation is based only on the fact that they overlie probable Extension Formation cropping out on Domville Island. On Reay Island, the formation comprises medium bedded, medium to coarse grained sandstone, with thin siltstone and fine grained sandstone interbeds. Climbing ripples and abundant coalified stumps and roots occur. Several coarsening upward sequences are present.

On Brethour Island, the basal section consists of medium bedded, coarse grained sandstone, interbedded with thin bedded, medium to fine grained sandstone and siltstone, up to 50 beds/m. The fine grained beds are planar or wavy laminated, and display planar and ripple cross-lamination locally. The upper section features 15-20 m thick coarsening upward sequences comprised of: thin bedded mudstone and siltstone with abundant coal debris; grading to medium cross-beds of medium grained sandstone; overlain by medium bedded, massive, coarse grained sandstone.

On eastern Comet Island, the formation is comprised of medium bedded, coarse grained sandstone, and thin bedded mudstone and siltstone. The coarse grained beds are planar laminated or planar cross-bedded. Load casts, flame structures, ripple marks, small burrows, and coal spars are present.

Cedar District Formation

Cedar Area

The northernmost exposures of the Cedar District Formation occur in the Cedar vicinity, along the shoreline south of Dodds Narrows, along lower Nanaimo River, in the lowland east of Cassidy, and in Ladysmith Harbour area. The formation in this region comprises massive, olive grey silty mudstone; thin bedded silty mudstone, siltstone, and fine-grained sandstone; and, contains rare interbeds of massive, thick bedded, coarse grained sandstones. The fine grained beds are commonly planar laminated, and contain numerous calcareous concretions and concretionary layers. Minor sandstone dykes locally are associated with the coarse grained sandstones. Both lower and upper contacts of the formation are transitional. In the Harmac well, which spudded in the Cedar District Formation, the transition from the Cedar District Formation to the Protection Formation occurs over 14 m, and is comprised of interbedded sandstone and shale. In the Yellow Point well, the base of the Cedar District Formation is transitional over 75 m, consisting of 25 m of interbedded sandstone and shale, overlain by 50 m of dominantly sandstone. The upper contact of the formation is sharp and even at Dodds Narrows. Uppermost Cedar District is well exposed on southwestern Mudge Island, comprising thin bedded, planar laminated, silty mudstone and very fine grained sandstone, interbedded with thick, medium- to coarse grained sandstone beds; overlain by thin bedded siltstone and mudstone with medium sandstone interbeds. The thick sandstones are typically massive, have loaded bases, abundant mudstone rip-up clasts, and well developed dish structure. Some of the thinner sandstone beds are intensely burrowed, and are convolute laminated. Thick bedded De Courcy sandstone overlies this interval and also laterally replaces it to the northwest.

Macrofossils are scarce in the Cedar District Formation in this region. Ward (1978a) recovered Baculites inornatus, Neophylloceras ramosum, and Canadoceras newberryanum from the upper part of the Dodds Narrows section. Rinne (1973) found a mold of an indistinct ammonite in the Cedar District Formation. However, microfossils are abundant. Sliter (1973) recovered diverse foraminifers in 68 samples from Dodds Narrows, which he interpreted to represent paleo-water depths of 800-1000 m, with much down-slope transport indicated. A high diversity microfauna was recovered from one sample from the Dodds Narrows section, which represents upper slope paleo-water depths of 200-600 m, in a fairly high energy environment, with strong indications of down-slope transport (Cameron, 1988b). A sample from southwestern Mudge Island, only yielded 4 shallow water foraminifers (Cameron, 1988b), which may have been transported down-slope. A very pyritic residue in the latter sample indicates an oxygen deficienct paleo-environment (Cameron, 1988b). A flyschoid microfauna, with some indications of down-slope transport, representative of paleo-water depths of 200-600 m, was recovered from a sample of the Cedar District Formation near the town of Cedar.

Upper Cedar District Formation along the eastern side of Ladysmith Harbour consists of finely laminated siltstone and mudstone; and a thick bedded, well indurated, reddish weathering, medium grained sandstone and mudstone unit, probably equivalent to the Woods Island sandstone cropping out to the southeast. Contacts are generally even, and continuous. The bases of the sandstone units are sharp, and locally loaded, and burrows are common. On the western side of the harbour, at the Trans-Canada Highway, outcrops of lower Cedar District Formation consist of thick bedded, light grey sandstone and thin bedded, laminated siltstone and mudstone. Coal debris and Inoceramus ezoensis (Haggart, 1988a) are present in the sandstone. This sandstone unit is probably in the same stratigraphic position as the thick sandstone unit at the base of the Cedar District Formation penetrated by the Yellow Point well.

To the southeast, the Cedar District Formation is poorly exposed, mostly underlying Ladysmith Harbour. The basal contact with the Protection Formation may be exposed at Transfer Beach (Section 76) as previously discussed under the Protection Formation. Resistant sandstone units within the formation do outcrop on the Woods, Dunsmuir, and Bute islands. These consist of thick bedded, coarse grained sandstone, interbedded with thin to medium bedded, siltstone, mudstone, and fine grained sandstone. The coarse grained sandstone exhibits basal scouring, mudstone rip-up clasts, and is commonly flat bedded. The fine grained beds contain rare coal debris, and are planar laminated or convolute laminated. A sparse recovery of foraminifers from a sample taken on Dunsmuir Island, is suggestive of ?mid-shelf water depths (Cameron, 1988b) but may be deeper if affected by down-slope transport. Upper Cedar District Formation is also exposed along the coast from Sharpe Point to Evening Cove. At Sharpe Point, the formation comprises thick bedded, medium grained, locally carbonaceous, flat bedded sandstone, with granule layers, interbedded with convolute to planar laminated fine grained sandstone and siltstone; contacts are even and continuous. At Evening Cove, exposures consist of medium to thick bedded sandstone with thin siltstone interbeds, overlying planar and convolute laminated thin bedded siltstone and fine grained sandstone displaying Bouma T_{BCD} and T_{CD} sequences.

Shoal Islands

The Cedar District Formation southeast of Ladysmith Harbour underlies Stuart Channel coming ashore on the Shoal Islands, where it is probably greater than 500 m thick. At the northwestern end of this archipelago, the formation consists of thin bedded siltstone, bearing inoceramids, including Inoceramus ex. gr. I. ezoensis (Haggart, 1988a). Foraminifers recovered from a sample from this locality are suggestive of paleo-water depths of 100 to 200 m (Cameron, 1988b).

At the southeastern end of the Shoal Islands, the Cedar District Formation is broadly exposed, comprising thin bedded, very fine grained sandstone, siltstone, shaly siltstone, and shale, with some fine grained sandstone interbeds (Section 46). Contacts are sharp, even, and very continuous (Plate 8a). The beds are generally planar or convolute laminated. Bouma T_{BCD}, T_{CD}, and rare T_{DE} sequences are developed, T_C layers showing convolute or ripple cross-lamination. Thin calcareous bands (locally iron-stained), calcareous concretions and concretionary beds are common. Load casts and flame structures are common, scoured bases are not. Several fine grained sandstone lenses and pods are present in the lower half of the exposed section. The Cedar District Formation sandstone here is arkosic arenite (Fahlstrom, 1981). The author collected Inoceramus sp. in the middle of the section (Haggart, 1988a). Indistinct grazing trails and burrows are exposed on top surfaces of the sandstone units; overall, bioturbation is prevalent. Fahlstrom (1981) reported ?Thalassinoides occurring in the Cedar District Formation in the Shoal Islands area.

At the northern end of the southeastern Shoal Island, the author collected Canadoceras cf. C. newberryanum (Haggart, 1988a). Foraminifers recovered in a sample from this area, are indicative of paleo-water depths of 50 to 150 m (Cameron, 1988b). Two samples taken from the southern end of the island, in the measured section, yielded a sparse microfauna also suggestive of middle to outer shelf paleo-water depths of 30 to 150 m (Cameron, 1988b).

Thetis Island

The Cedar District Formation crops out in the Thetis Island area, in the lowlands between Moore and Burchill Hills, and forms the shoreline around Telegraph Harbour and Clam Bay. In general, the formation is poorly exposed on Thetis and Kuper islands. The best exposures are of the upper part of the formation which consists of medium to thick bedded, coarse to medium grained, massive sandstone, and thin bedded, typically convolute laminated, fine grained sandstone and siltstone; mudstone is rare. Normal grading and soft-sediment-deformation are common. Lower Cedar District Formation is considered to be finer-grained, by virtue of its recessive nature. Simmons (1973) noted isolated burrows in the formation, as well as some Bouma T_{CD} sequences. His thin section analyis shows that Cedar District sandstone is immature arkosic arenite in the area.

Saltspring Island

On Saltspring Island, the Cedar District Formation forms northern and southern outcrop belts. Lower Cedar District Formation is poorly exposed and obviously fine grained. Upper Cedar District Formation is variably coarse grained, and closely related to the overlying De Courcy Formation displaying possible interfingering relationships of various units (see Hanson, 1976, p. 110). The formation at Vesuvius Bay is ca. 330 m thick. On the eastern side of the island, structural complications and only partial exposure preclude accurate thickness estimates; Hanson suggests that the formation is greater than 450 m thick.

The northern belt xtends from northwestern Saltspring Island to just northwest of Walker Hook, forming much of the northeastern shoreline. It comprises thin bedded, grey mudstone, siltstone, and fine grained sandstone, with rare, medium grained sandstone beds and calcareous concretionary layers. Some mudstone intervals are massive; whereas, up to 15 coarse/fine grained sequences/m may be developed locally. Bouma T_{CD} sequences are common. The sandstone units locally are planar laminated or finely ripple cross-laminated. Indistinct burrows and sparse coal debris are present. Foraminifers recovered in two samples from the northern outcrop belt yielded an essentially flyschoid microfauna, indicating paleo-water depths of 200-600 m, and a high energy environment (Cameron, 1988a).

In the Southey Point area, upper Cedar District Formation is quite sandy, as recognized by Pacht (1980), and includes a thick, dominantly sandstone unit, known as the Southey Point member. At Southey Point, it comprises thick bedded, medium to coarse grained sandstone, with thin, carbonaceous, fine grained sandstone interbeds. The fine grained sections are up to 4 m thick. Convolute and planar lamination, and locally abundant horizontal burrows are developed. The coarse grained beds are massive or planar laminated. Basal load casts, and mudstone rip-up clasts are common. Hanson (1976) reports well developed dish structure in these beds. To the west, on the shoreline opposite Grappler Rock, the member is thinner-bedded, comprising medium bedded, coarse grained sandstone, interbedded with fine grained sandstone. Abundant coal spars and large mudstone rip-up clasts occur. Trace fossils present include Thalassinoides, Planolites, and ?Taenidium. Hanson (1976) reported the occurrence in this area of a 5 cm thick coal seam, which is obviously detrital.

The southern outcrop belt of the Cedar District Formation extends from Vesuvius Bay to Ganges Harbour. In the west, the formation comprises thin bedded shale and mudstone, interbedded with sandstone interbeds up to 2 m thick. Contacts are sharp, even, and continuous. Sedimentary structures include slumping, contorted beds, fluid escape pipes, sandstone dikes, groove and tool marks, concretions, and large mudstone rip-up clasts in the sandstones. Trace fossils include indistinct burrows and Planolites. Rare coal debris is present, but the beds are low in organic content. Clapp and Cooke (1917) record the occurrence of Inoceramus vancouverensis in the Vesuvius Bay section.

In the east, at Ganges Harbour, the formation crops out extensively, the better exposures being upper Cedar District Formation along the northern shore. This upper part consists of thin bedded, recessive, fine grained sandstone, siltstone, and mudstone, interbedded with medium to thick bedded, fine to coarse grained sandstone. Contacts are sharp, even, and continuous. The sandstone contains mudstone rip-up clasts, rare basal granule layers, coal debris, solution pipes, and exhibits asymmetrical ripple marks. Graded and massive bedding, and planar to convolute lamination are observed. Bouma T_{ABCD}, T_{BCD}, and T_{CD} sequences are prevalent, up to 20 sequences/m. The contact with the overlying De Courcy Formation is sharp, even, and well exposed near Welbury Bay, and on Third Sister Island.

Foraminifers recovered from two samples taken near Welbury Point indicate paleo-water depths of 300 m, with considerable down-slope transport and oxygen deficiency (Cameron, 1988a).

Additional sedimentary structures observed in the Cedar District Formation by Hanson (1976) on Saltspring Island include load casts, ball-and-pillow structure, and rare flute casts. Hanson (1976) also reports Inoceramus, Baculites, and the trace fossils Helminthoida and Thalassinoides.

Prevost Island

To the southeast, the Cedar District Formation underlies Ganges Harbour, and Swanson and Trincomali channels. The formation comes onshore on northeastern Prevost Island, where it consists of thin bedded, fine grained sandstone and siltstone, with up to 30 alternations/m. Contacts are sharp, even, and continuous. Some shallow scouring is evident at the bases of some of the sandstone units. Foraminifers recovered from a sample taken opposite Hawkins Island are indicative of a flysch environment, in upper slope paleo-water depths of 200-600 m (Cameron, 1988a). Ward (1978a) reports Baculites rex in upper Cedar District Formation on Prevost Island.

Hawkins Island itself consists of thick bedded, massive, medium grained to granule sandstone with abundant shale rip-up clasts and sparse coaly debris. Contacts are locally irregular. Pelecypods are present in the sandstone, including Inoceramus subundatus and Inoceramus sp. aff. I. vancouverensis (Haggart, 1988a). Along strike to the southeast, these beds may be continuous with beds forming Portlock Point, northeast of Richardson Bay, on Prevost Island. The latter beds consist of thick bedded, polymictic, moderately well sorted, pebble conglomerate, and massive sandstone. Conglomerate clasts are subangular, and are supported by a matrix of coarse grained sandstone. Whether or not these beds are considered as a distinct coarse grained member of the Cedar District Formation requires further study; however, they clearly are part of the Cedar District-De Courcy Formation transition interval.

Pender Islands

The Cedar District Formation crops out on North Pender Island between Shingle Bay, Port Browning, and Bedwell Harbour, in the south, and also forms shoreline outcrop along Navy Channel, in the north. The Navy Channel exposures consist of planar laminated, fine grained sandstone, siltstone, and massive, grey mudstone. Hudson (1974) considered these beds to be the Northumberland Formation, but based on profiles of Mayne and North Pender Island, the author considers them to be the Cedar District Formation, as did Muller and Jeletzky (1970). Hudson (1974) describes the contact with the overlying De Courcy Formation at Colson Cove to be sharp and undulatory, at the top of a general thickening upward sequence. However, as Hudson notes, the De Courcy/Cedar District formations transition consists of 3 to 4 fine grained units interbedded with coarse grained units, over about 200 m of section. Hudson (1974) analysed a thin section of Cedar District sandstone from Colson Cove area, and classified it as arkosic wacke. In excess of 300 m of the Cedar District Formation is present along Navy Channel.

Usher (1952) collected Phylloceras sp. indet. from the Cedar District Formation north of Hope Bay. A sample taken near Davidson Bay, although weathered and leached, yielded foraminifers probably representative of paleo-water depths of 200-600 m (Cameron, 1988a).

The Cedar District Formation in the southern outcrop belt is tightly folded and faulted such that accurate thickness estimates are precluded, and stratigraphic position within the Cedar District and De Courcy formations is locally obscured. The unit is of considerable thicknesss, possibly up to 600 m, but may be tectonically thickened (Chapter 2). The upper contact with the De Courcy Formation is transitional over ca. 200 m, with several De Courcy sandstone tongues? interfingering with upper Cedar District Formation.

At the head of Bedwell Harbour, the formation comprises thin bedded, shales and siltstones, with medium, fine grained sandstone interbeds. Bouma T_{BCD}, T_{DE}, and T_C sequences are common. The sandstone units interbedded with upper Cedar District Formation consist of medium to thick bedded, fine to medium grained sandstone, with some finer grained interbeds. Contacts are sharp, even, and continuous, although scoured bases are developed locally. Floating cobbles are common. The bases of the sandstone units display abundant bottom marks, including tool and prod marks, and groove casts.

Foraminifers recovered from upper Cedar District Formation near Prior Centennial Park, represent paleo-water depths of 200-400 m, with some down-slope transport indicated (Cameron, 1988a). A sample in lower Cedar District Formation taken near Pender Lake, yielded a flyschoid microfauna indicative of paleo-water depths of 200-600 m (Cameron, 1988b).

Hudson (1974) reports pelecypod shells, including inoceramids, and horizontal trace fossils in the Cedar District Formation on North Pender Island; some of these occurrences may actually be in Pender Formation. Thin section analysis of Cedar District sandstone at Bedwell Harbour shows it to be arkosic arenite.

The formation crops out at Razor Point, where it consists of thin bedded, grey shale and siltstone, and medium bedded sandstone. Contacts are sharp, even, and continuous. The sandstone interbeds are massive or planar laminated, and some exhibit ripple marks. Up the section, the Cedar District Formation becomes increasingly sandy. Baculites rex and Anapachydiscus nelchinensis occurs in these beds (Ward, 1976a, 1978a). Elsewhere on North Pender Island, Hoplitoplacenticeras cf. plasticum was collected near the base of the Cedar District Formation, according to Muller and Jeletzky (1970).

The Cedar District Formation on South Pender Island is exposed along the northern coast at Mortimer Spit,; in Little Bay area; and underlies Camp Bay and its associated valley. At the western end of the Camp Bay valley, the formation is either laterally replaced by the De Courcy Formation or is faulted out.

Ward (1978a) reports the occurrence of Baculites rex and B. occidentalis in the beds near Mortimer Spit. In the Little Bay area, upper Cedar District Formation interfingers with the De Courcy Formation, consisting of several thick sections of thin bedded mudstone and fine grained sandstone, with intervening thick bedded, coarse grained sandstone sections. The thin bedded sections exhibit Bouma T_{BCD} and T_{CD} sequences, up to 15 sequences/m. The coarse grained sections consist of massive to crudely flat bedded, thick, coarse grained sandstone, interbedded with medium, fine grained sandstone interbeds. Sandstone dykes and crude dish structures are developed.

Two samples of the Cedar District Formation yielded foraminifers. One sample from between Hermit and Spalding Hills yielded weathered, leached, and pyritized forms, probably indicative of paleo-water depths of ?30-100 m, with oxygen deficiency (Cameron, 1988a). The other sample, taken from shoreline outcrop near Little Bay, revealed a sparse microfauna suggestive of paleo-water depths of 150 to 400 m (Cameron, 1988b). From the same beds, Ward (1978a) collected Metaplacenticeras cf. pacificum and Inoceramus vancouverensis. Ward (1976a) reports Pachydiscus neevesi, Pseudoxybeloceras lineatum, and Neophylloceras lambertense in other Cedar District Formation outcrops on South Pender Island.

Mayne Island

Upper Cedar District Formation is exposed along the southern coast of Mayne Island at Navy Channel where it clearly underlies the De Courcy Formation. At Dinner Bay it consists of thin bedded, planar laminated and planar cross-bedded, fine grained sandstone and siltstone, interbedded with medium to thick beds of coarse grained sandstone and a 4 m thick pebble conglomerate bed. Opposite Conconi Reef, there are good exposures of deformed Cedar District Formation consisting of thin bedded sandstone and mudstone. A sample taken from this section produced a very high diversity microfauna, indicating paleo-water depths of 200-600 m, with much down-slope transport of shallower water elements evident (Cameron, 1988a).

Between Dinner Bay and Navy Channel, within the Cedar District Formation, is a conglomerate and coarse grained sandstone unit, ca. 210 m thick, that has previously been described as Extension-Protection Formation (Muller and Jeletzky, 1970; Stickney, 1976; and Muller, 1983), and as the De Courcy Formation (Pacht, 1980). Based on cross-sections from North Pender to Mayne Island, it appears unlikely that the "Extension-Protection Formation" should be exposed in the northeastern limb of the Navy Channel anticline, given the known thickness of the Cedar District Formation in this area. Furthermore, conglomerate occurs in upper Cedar District Formation on Prevost, Saturna, and Little Sucia islands, in a similar stratigraphic position to the coarse grained beds described above.

Stickney (1976) describes the coarse grained member as consisting of thick to very thick bedded, coarse grained sandstone and poorly sorted pebble conglomerate, with minor mudstone. The mudstone commonly infills channels with a maximum 2 by 4 m profile. The conglomerate contains pebble to boulder size clasts, dominated by quartzite, granitic rocks, and basalt, with minor amounts of andesite and metamorphic rock. Rounding is good. The conglomerate is variably clast or matrix supported. Stickney recognizes pebble imbrication, numerous channel scours, current lineation, and groove marks on the soles of channel-fills. The sandstone exhibits scour channels, planar lamination, normal grading, loading features, and mudstone rip-up clasts. His thin section analysis reveals that the sandstone is arkosic wacke to arenite.

Stickney (1976) reports the occurrence of trace fossils _Helminthoida_? and _Thalassinoides_, the ammonite _Baculites_, and a gastropod ?_Nerinea_. Other sedimentary features noted in the Cedar District Formation on Mayne Island by Stickney include graded beds, calcareous interbeds, and small concretions. Thin section analysis shows that Cedar District sandstone is arkosic wacke (Stickney, 1976).

Saturna Island

On Saturna Island, upper Cedar District Formation underlies the central valley from Lyall Harbour to Narvaez Bay, and occupies the region between Saturna Beach and Bruce Bight along the southern coast. In this belt, upper Cedar District Formation is about 110 m thick. Elsewhere on Saturna Island, the entire Cedar District Formation ranges between 300 and 450 m in thickness.

At Trueworthy Bight, the upper part of the lower Cedar District Formation comprises grey shale interbedded with thin to medium bedded, planar laminated, fine grained sandstone. The section is sharply overlain by thick bedded, coarse grained sandstone. This sequence is part of the Cedar District-De Courcy Formation transition interval. Inocerami fragments are common in the fine grained section, including Inoceramus ex. gr. I balticus (Haggart, 1988a). Foraminifers recovered from a sample from this location are representative of paleo-water depths of about 200-600 m, with a fair amount of down-slope transport, and a relatively low energy environment (Cameron, 1988b).

Along the southern shore, east of Trueworthy Bight, the Cedar District Formation is well exposed, consisting of thin bedded shale and siltstone, interbedded with medium to thin bedded, fine to medium grained sandstone. Bouma T_{CD} and T_{BD} sequences are evident. Rusty concretions and large burrows are present. Pacht (1980) reports inoceramids, other bivalves, and rare Diplocraterion in these beds. Contacts are sharp, even, and continuous. A meagre microfauna recovered from the Cedar District Formation, 1.5 km west of Murder Point, indicates paleo-water depths of ca. 150-300 m (Cameron, 1988b).

Underlying the fine grained strata, near Murder Point, there is a poorly sorted, quartz rich, pebble conglomerate, overlain by 4 to 5 m of white weathering, planar laminated, coarse grained sandstone. Pacht (1980) reports that inoceramids occur in this sandstone. The sandstone units are planar cross bedded and ripple cross-laminated. Clasts in the conglomerate range from large boulder to small pebble size, and consist of rock quartz, sandstone, argillite, concretionary limestone, and a minor amount of metamorphic rock. This unit is most likely an interbed within the Cedar District Formation rather than the Protection Formation, as a similar interbed within the Cedar District Formation is known from Little Sucia Island.

Ward (1978a) reported Baculites rex in the Cedar District Formation near Murder Point. Usher (1952) collected Schluteria selwyniana in the Cedar District Formation about 600 m west of Murder Point, and Phylloceras sp. indet., from just east of Murder Point. Sturdavant (1975) notes inoceramids in the Cedar District Formation on Saturna Island. His thin section analysis of a Cedar District sandstone at Murder Point, shows it is lithic wacke.

Upper Cedar District Formation at Narvaez Bay comprises thin bedded shale, siltstone, and fine grained sandstone, interbedded with thick bedded, coarse grained sandstone. Bouma T_{CD} and T_{BD} sequences are evident in the finer grained sections, up to 5 sequences/m. Rare coal debris is present.

The Cedar District Formation at Lyall Harbour is poorly exposed, but control in this area is provided by the Saturna No. 1 well. Bell (1958) reports 638 m of the Cedar District Formation was penetrated, comprising dark grey, silty shale, with very occasional, thin, wispy siltstone beds, and thin, rare, calcareous siltstone and fine grained sandstone interbeds; inoceramid, pelecypod, and brachiopod shells are abundant. McGugan (1981) recovered foraminifers in 111 samples from the Cedar District Formation in the well. McGugan considers these faunas to represent a neritic, normal salinity sea environment, but also acknowledges co-occurrence of deep water elements (?outer neritic to upper slope), and suggests that the distribution of foraminiferal taxa may be the result of intermittent transport and mixing; i.e. down-slope transport.

Sucia Islands

The Cedar District Formation crops out on Little Sucia Island, comprising thick bedded, massive, greeenish-tan, fine grained sandstone, siltstone, and sandy mudstone. The exposed thickness of the formation is about 250 m (McClellan, 1927). The section is very fossiliferous and contains small coal spars and clasts, and thin conglomerate and coquina lenses. An interbed of poorly sorted, polymictic, pebble conglomerate is present at the southern tip of the island. The unit is medium to thick bedded, and well indurated. Common clasts are white quartz, grey chert, gneiss, and green volcanics.

The Little Sucia Island locality has yielded abundant and diverse macrofossils to a number of collectors. The author collected Ostrea sp., Cucullaea sp., and Inoceramus subundatus (Haggart, 1988b). Ward (1978a) reports 3 collections from the section, one below the conglomerate interbed, one 50 m above the conglomerate, and another ca. 200 m above the conglomerate. From all three, Ward collected Baculites inornatus, Inoceramus vancouverensis, and Canadoceras newberryanum. In addition, at the upper two sites, Ward collected Hoplitoplacenticeras vancouverensis. Ward also reports B. occidentalis in these beds. Usher (1952) reports the occurrence of H. vancouverensis, Pachydiscus neevesi, P. sp. cf. P. jacquoti, Schluteria selwyniana, and Diplomoceras? sp.. Muller and Jeletzky (1970) report, in addition to those ammonites found by Usher (1952): Patagiosites aff. P. arbucklensis and Pachydiscus (annapachydiscus) aff. wittekindi. Popenoe et al. (1987) report Gyrodes (sohlella) canadensis in the Cedar District Formation on Little Sucia Island.

The ammonites collected on Sucia Island include Vancouverense Zone index fossils, such as H. vancouverensis, and B. inornatus. However, at least three of the ammonites are Suciaensis Zone index fossils (Muller and Jeletzky, 1970): Pachydiscus suciaensis, P. ootacodensis, and Diplomoceras notabile (McClellan, 1927, p. 133). Furthermore, one of the ammonites present - Pachydiscus multisulcatus (McClellan, 1927, p. 133) - is an index fossil for the Schmidti Zone according to Muller and Jeletzky (1970) and Ward (1978a). Furthermore, Incceramus schmidti and I. elegans are reported to occur on Little Sucia Island (Muller and Jeletzky, 1970). The data at hand suggest that either the Cedar District Formation on Sucia Island is long ranging from at least upper Schmidti Zone, through Vancouverense and Pacificum Zones, to basal Suciaensis Zone, or some of the ammonites have longer local ranges than previously recognized. Given the richly fossiliferous and mostly fine grained nature of the beds, it is conceivable that the section is condensed.

The Cedar District Formation is apparently not present in the southwestern part of the Nanaimo Basin due to post-depositional erosion. Reports of the Cedar District Formation equivalent (Duncan Formation) in the Cowichan Valley area, by Clapp and Cooke (1917), have not been verified by the author. Usher (1952) reports the occurrence on James Island of Pachydiscus neevesi, a Vancouverense Zone index fossil according to Muller and Jeletzky (1970). However, the author has collected P. neevesi from Haslam Formation at Cusheon Creek, Saltspring Island (Haggart, 1988a), so the ammonite is longer ranging than it was previously thought to be. A Haslam Formation source on James Island is more probable than a Cedar District Formation source, based on occurrence of only lower Nanaimo Group in the area. Nevertheless, no outcrops of Nanaimo Group are known to exist on James Island, thereby casting some doubt about the accuracy of the location of the source of the fossil. James Island is covered by a thick mantle of Quaternary sediment.

De Courcy Formation

Cedar Area

The most northern exposures of the De Courcy Formation are in the Harmac area, southeast of Nanaimo. At Jack Point, the formation comprises thick bedded, medium to coarse grained sandstone, interbedded with fine grained sandstone, siltstone, and mudstone interbeds. The coarse grained beds contain some gritty sandstone, large shale rip-up clasts, sheet structure, rare concretions, and floating pebbles. Planar lamination is common. The finer grained beds are mostly recessive and thin bedded.

At the industrial park near Duke Point, a good section in lower De Courcy Formation is exposed (Section 100), comprising very thick bedded, medium to very coarse grained sandstone, interbedded with rare, thin, fine grained sandstone, siltstone, and mudstone units. The sandstone is generally massive, although, locally, crude planar lamination and large-scale planar cross bedding is developed. Concretions up to 3 m in diameter are present in the coarse grained sandstone; otherwise it is a very uniform lithology. Large-scale wedging of some of the thick beds is observed. Indistinct amalgamated channels are present in the upper part of the section. The finer grained beds are from 0.03 to 3.0 m thick, and are planar to convolute laminated. Trough cross-lamination, indistinct ?flute casts, and rare burrows, are locally developed. Detrital coal layers up to 1 cm thick, and abundant coal debris, are common in the fine grained sections. The De Courcy Formation is estimated to be 300 m thick in the Harmac area, based on map interpretation.

At Dodds Narrows, the contact with the underlying Cedar District Formation is sharp, and very even. The De Courcy Formation here consists of thick bedded, medium to coarse grained sandstone, with dish and sheet structure developed.

The formation is exposed more or less continuously on the northeastern limb of the Stuart Channel anticline, from Mudge Island in the north, to Pylades Island in the south. On the eastern side of Mudge Island, uppermost De Courcy Formation consists of medium bedded, planar laminated, very coarse grained sandstone. Underlying these beds, on Link Island, the De Courcy Formation comprises thick bedded, medium grained sandstone, interbedded with planar laminated, fine to medium grained sandstone. Trough cross-lamination is developed locally in the finer grained beds. Underlying these beds, at the southern end of Link Island, is medium to thick bedded, medium to coarse grained sandstone. The sandstone is flat bedded or massive.

Along the eastern coast of De Courcy Island and at Pirates Cove, the formation comprises medium to thick bedded, typically planar laminated, coarse to very coarse grained sandstone, with few finer grained interbeds. In a cove on the southeastern side of De Courcy Island, the following section is exposed over a few metres (from top down): massive, very coarse grained sandstone with dish and sheet structure; ripple cross-laminated, very fine to fine grained sandstone; trough and planar cross-laminated, coarse grained sandstone; planar laminated, medium grained sandstone; grey siltstone; and massive, very coarse grained sandstone.

On Whaleboat Island and the eastern side of Pylades Island, the De Courcy Formation consists of medium to thick bedded, medium to coarse grained sandstone. Bedding is massive or crudely planar laminated. On the southwestern side of De Courcy Island, lower De Courcy Formation consists of medium bedded, coarse grained sandstone, interbedded with thin bedded, fine grained sandstone. The fine grained sandstone units are planar laminated, and about 0.3 m thick.

The coarse grained sandstone contains shale rip-up clasts and sparse carbonaceous debris, including some leaf imprints.

Lower De Courcy Formation is well exposed along the western coast of De Courcy Island, comprising, in the main, very thick to medium bedded, planar laminated to massive medium grained sandstone, with shaly siltstone interbeds (Plate 8b). A sample of a fine grained bed from this locality did not produce any foraminifers or any conclusive marine indicators (Cameron, 1988b). The De Courcy Formation is estimated to be ca. 375 m thick on De Courcy Island.

South of Dodds Narrows, the De Courcy Formation is exposed along the eastern coast of Vancouver Island, for a distance of some 17 km. Its northern contact with the Cedar District Formation intersects the shoreline about 1.3 km north of Reynolds Point. The formation between Boat Harbour and the contact comprises medium to thick bedded, massive, coarse grained sandstone, with abundant floating chert pebbles and shale rip-up clasts, interbedded with a few thin bedded mudstone units. At Flewett Point, the formation consists of coarse to very coarse grained, planar laminated sandstone, with shale rip-up clasts, interbedded with convolute, planar, and trough cross-laminated, fine grained sandstone and siltstone. Some coaly debris is present in carbonaceous siltstone.

From Flewett Point to Yellow Point, the De Courcy Formation is much the same as described above: thick bedded, massive, medium to coarse grained sandstone, interbedded with thin to medium bedded, fine grained sandstone, siltstone, and mudstone. Contacts are generally sharp, planar, and continuous. Coaly debris and minor cross-stratification occurs in some of the finer grained beds. Floating pebbles, shale rip-up clasts, rare planar cross-bedding, and concretions occur in the coarser grained beds. A sample taken on the shoreline near Priest Lake yielded one fish tooth and one shallow water foraminifer (Cameron, 1988b). Rinne (1973) found indistinct shell debris in a concretion in the De Courcy sandstone in this area. The shoreline of Kuleet Bay consists of the De Courcy Formation as described by Rinne (1973, p. 20). Elsewhere in the eastern Vancouver Island outcrop belt of the De Courcy Formation, Rinne noted numerous channels up to 7.5 m thick by 15 m wide. His thin section analysis of 16 samples of the De Courcy sandstone, show that it is all arkosic wacke. In the BP Yellow Point well, 161 m of the De Courcy Formation was penetrated.

The De Courcy Formation forms a prominent bluff called the Woodley Range east of Ladysmith Harbour. The formation here comprises massive, thick bedded, medium to coarse grained and pebbly sandstone, interbedded with thin, siltstone and mudstone beds. Rare coaly debris, burrows, and horizontal traces occur in the sandstone. Some of the mudstones are carbonaceous, and bear plant imprints. Rinne

(1973) estimated the thickness of the De Courcy Formation in the Woodley Range to be ca. 410 m.

Lower De Courcy Formation is well exposed between Evening Cove and Coffin Point at the southern end of the Woodley Range (Section 104). The formation consists of four typical facies: 1) thick bedded, medium to very coarse grained sandstone, massive to crudely planar laminated, capped by thin, fine grained sandstone, siltstone, or mudstone; 2) thick, graded, coarse to fine grained sandstone and siltstone, with sharp bases, load casts, flame structures, and large shale rip-up clasts, arranged in Bouma T_{ABCD} sequences, with T_C layers showing convolute, wispy, and ripple cross-lamination; 3) thin bedded, fine grained sandstone, siltstone, and mudstone units, arranged either as couplets of sandstone, siltstone or mudstone, or as Bouma T_{BCD} sequences; and 4) thick bedded, coarse grained, granule, to pebbly sandstone, showing planar lamination, trough cross-bedding, or scour and fill structure, with common basal pebbly sandstone lags.

Upper De Courcy Formation, which overlies the section described above, is exposed on Coffin Island. Here the formation is comprised of thick bedded, granule to coarse grained sandstone, interbedded with thin, fine grained sandstone and siltstone. Normal and reverse grading, and planar and convolute lamination are developed. Other sedimentary features observed are shale rip-up clasts, flame structures, load casts, and soft sediment deformation. Pebbly sandstone layers are present at the bases of some of the sandstone units.

Thetis Island

To the east, the De Courcy Formation crops out on Thetis Island in both limbs of a faulted, northwest-plunging anticline. Its thickness is greater than 205 m, based on map interpretation. Good outcrops are present at Pilkey Point on northeastern Thetis Island, which consist of thick bedded, coarse grained sandstone and rare pebble conglomerate, with fine grained sandstone interbeds up to 1 m thick. Simmons (1973) notes occasional boulder size clasts in channel-fill conglomerate in this area. His pebble counting reveals that common constituents of conglomerate clasts are chert, vein quartz, quartzite, granitic and other igneous rocks, and foliated metamorphic rocks. The coarse grained beds are massive, or crudely planar laminated, with rare floating pebbles and coal clasts; the fine grained beds are locally convolute laminated and carbonaceous. Simmons (1973) notes the occurrence of isolated burrows in the formation. Offshore, these beds form Ragged Islets, and probably Miami Islet as well. Further north, the De Courcy Formation probably forms Danger Reefs.

West of Pilkey Point, at least the upper part of the De Courcy Formation is considered to outcrop in the middle of

North Cove. This is contrary to the interpretation of Simmons (1973) who mapped the outcrop as the Northumberland Formation. The present view is based primarily on reconciliation of the thickness of the Galiano, Northumberland, De Courcy formations succession on southwestern Thetis Island, with the thickness of the succession exposed in the North Cove area. In North Cove, the De Courcy Formation consists of medium bedded, coarse grained sandstone, interbedded with fine grained sandstone and siltstone.

The De Courcy Formation outcrops on Thetis Island extend from Pilkey Point to Clam Bay, and from North Cove to Foster Point. The De Courcy Formation forms prominent Moore Hill and Burchell Hill. On Kuper Island, the formation is exposed at Donckele Point, in the western limb of the Thetis Island anticline. The De Courcy Formation on Kuper Island and at Foster Point is medium to fine grained, planar laminated, and contains rare mudstone rip-up clasts, and calcareous concretions (Simmons, 1973). Simmons also notes planar cross-laminated sandstone, and scour and fill channel features. His analysis of 3 sandstone samples, indicates that the De Courcy Formation sandstone is arkosic wacke.

Escape Reef and North Reef may also be the De Courcy Formation. The North Reef beds consist of thick to medium bedded, coarse to medium grained sandstone. Bouma T_{ABC} sequences of massive, to planar laminated, to convolute laminated sandstone are featured. The eastern limb outcrop belt continues off the southeastern coast of Thetis Island, forming Leech Island, Centre Reef, and other reefs around Penelakut Spit. To the southeast, the De Courcy Formation forms the islands from Norway Island to Wallace Island, over 9 km of on strike exposure.

Secretary Island Area

The De Courcy Formation on Norway Island consists of medium bedded, coarse grained sandstone, with interbeds of massive to thin bedded, grey shale and fine grained sandstone. A few thick beds of massive, coarse grained sandstone are present. Sheet structure is common in the coarse grained beds. Rare coal debris is present in the fine grained units.

Underlying the beds on Norway Island, on the islet west of Mowgli Island, the De Courcy Formation comprises thick bedded, medium to coarse grained sandstone, with common sheet structure, overlying a finer grained section of medium to thin bedded, shaly siltstone and medium grained sandstone. The fine grained units are locally convolute laminated, and show well developed dewatering structures.

At the southern end of the Secretary Islands, the De Courcy Formation comprises thick to medium bedded, medium to coarse grained sandstone, interbedded with thick sections of thin bedded, grey shale with rare fine grained sandstone interbeds. Concretions are common in the fine grained beds.

Small pebble conglomerate lenses occur in the sandstone sections.

The De Courcy Formation on Wallace Island comprises medium to thick bedded, very coarse to coarse grained sandstone, interbedded with shaly siltstone and fine grained sandstone. Contacts are sharp, even, and continuous. Some fining upward sections occur. The thick beds are massive or planar laminated, and feature crude dish structure, sheet structure, and rare shale rip up clasts and coal debris. Some scouring is observed at the bases of the thick sandstone units. The fine grained beds are bioturbated, featuring Teichichnus, and are locally carbonaceous. Formation thickness on Wallace Island is 450+ m, based on map interpretation.

Saltspring Island

The De Courcy Formation crops out in two belts on Saltspring Island. The northern belt extends from Stonecutters Bay to the northern shore of St. Mary Lake, and then to Walker Hook. The southern belt extends from Dock Point to the southeast to a point south of St. Mary Lake, and then is sinistrally offset on a transverse fault, to the southeastern shore of St. Mary Lake, and continues to Welbury Point on eastern Saltspring Island.

Hanson (1976) divided the De Courcy Formation into 4 members termed De Courcy tongues, which are interbedded with upper Cedar District and lower Northumberland formations. The writer, however, takes a different approach to naming these various sandstone bodies, as previously described in the Cedar District section. If Cedar District and De Courcy formations merely relate to fine grained and coarse grained lithofacies respectively, then their recognition in an interbedded fine and coarse grained succession has little stratigraphic significance. Furthermore, it is the authors bias that if a member cannot be demonstrated to be a tongue of the main body of a formation, then it should be considered to be an isolated member of the enclosing formation.

The De Courcy Formation crops out in Stonecutters Bay area where it clearly underlies The northumberland Formation and overlies the Cedar District Formation. This section comprises Hanson's (1976) De Courcy Tongues 3 and 4, and the Northumberland Tongue 1. The formation correlates to beds at Walker Hook. According to Hanson (1976), the De Courcy Formation is 78 m thick. The Southey Point member in the underlying Cedar District Formation was considered to be a lower tongue of the De Courcy Formation by Hanson. For reasons already discussed, it is more appropriately placed in the Cedar District Formation. Nevertheless, in this part of the Nanaimo Group, it is apparent from the lithostratigraphic complexity, that the Cedar District and De Courcy formations are intimately related, an observation that has significance in any interpretation of their depositional history.

The De Courcy Formation at Stonecutters Bay is described by Hanson (1976) to consist of, from bottom to top: 1) 19 m of very thick bedded, generally massive sandstone and minor pebbly sandstone, interbedded with medium to thin beds of fine to very fine grained sandstone; 2) 23 m of poorly exposed, thin bedded sandstone, siltstone, and mudstone; and 3) 37 m of very thick bedded, medium to coarse grained sandstone, with rare, thin mudstone and siltstone partings, and concretions up to 1.5 m in diameter.

At Walker Hook, the De Courcy Formation is well exposed, consisting of thick to medium bedded, coarse grained sandstone, with medium to thin, fine grained sandstone interbeds. The coarse grained sandstone is massive to planar laminated. Rare tool marks are preserved on bottom surfaces of the sandstone. Locally the sandstones are carbonaceous. The fine grained sandstone is locally rusty weathering, and features small-scale planar cross-lamination, indistinct burrows, flame structures, and soft sediment deformation. The base of the De Courcy Formation is transitional over 10-15 m into underlying Cedar District Formation at the northern tip of Walker Hook.

In the southern outcrop belt, the sandstone dominant unit forming Dock Point is the De Courcy Formation This formation correlates to the section at Foster Point on Thetis Island, and correlates to the section at Welbury Point on eastern Saltspring Island. It clearly overlies the Cedar District Formation occupying Vesuvius Bay, and underlies the Northumberland Formation occupying Duck Bay. The De Courcy Formation comprises Hanson's (1976) De Courcy Tongues 3 and 4, and Northumberland Tongue 1. Hanson's De Courcy Tongue 1, which forms the point south of Vesuvius Bay is considered to be the Protection Formation (Clapp and Cooke, 1917).

The De Courcy Formation at Dock Point consists of thick bedded, typically massive, medium to very coarse grained sandstone, with thin, fine grained sandstone and siltstone interbeds. Floating chert, argillite, and mudstone rip-up clasts are present in the very coarse grained sandstone. Indistinct burrows are locally exhibited on medium grained sandstone beds. Additional features observed in this section by Hanson (1976) include frondescent marks, groove casts, thin lenses and channels of fine pebble conglomerate, and vertical burrows and <u>Planolites</u>. Hanson's analysis of several De Courcy sandstone units on Saltspring Island, shows that they are arkosic arenite or wacke.

The De Courcy Formation crops out south of Bullocks Lake and along the road to the Long Harbour ferry terminal. It comprises medium to thick bedded coarse grained sandstone, with fine grained sandstone and siltstone interbeds. Mudstone rip-up clasts are locally present in the thick sandstone; stratification is massive or crudely planar. At Welbury Point, the section is much the same:

thick bedded, medium to coarse grained sandstone, crudely planar laminated or massive, with abundant mudstone rip-up clasts, and thin bedded, planar laminated fine grained sandstone. The contact with the underlying Cedar District Formation is very sharp, as previously described in the Cedar District Formation section. A sample of lower De Courcy Formation siltstone from 0.6 km northwest of Welbury Bay, yielded a leached, low diversity microfauna, probably representative of paleo-water depths of 100 to 150 m (Cameron, 1988a).

The De Courcy Formation is exposed in the core of an overturned syncline in Ganges Harbour, forming the shoreline north of Ganges, Chain Islands, First and Second Sister islands, and part of Third Sister Island. The contact with underlying Cedar District Formation on Third Sister Island is sharp, with thick bedded, poorly sorted, coarse grained sandstone resting on thin bedded, fine grained sandstone. The coarse grained sandstone is massive to planar laminated, and contains abundant floating granule size clasts. Fine grained beds exhibit Bouma T_{CD} and T_{BD} sequences up to 15 cm thick.

On First Sister Island, the De Courcy Formation comprises thick bedded, medium to coarse grained, massive sandstone, with thin to medium siltstone interbeds. Coarse grained beds exhibit solution pipes. Fine grained beds feature irregular contacts, contorted beds, coarse grained sandstone injection? pods, and rare ripple marks. Bouma T_{ABC} units up to 2 m thick are common. On the Deadman Islands, the De Courcy Formation consists of very thick bedded, coarse grained sandstone, interbedded with thick sections of medium, coarse grained sandstone and siltstone. Small scour channels with granule to small pebble lags are present.

On the shore north of Ganges, thick, coarse grained De Courcy sandstone overlies medium, graded beds composed of fine grained sandstone, siltstone, and mudstone. Bouma T_{BCD} sequences are common, up to 4 sequences/m. Contacts are regular, even, and continuous. Solution pipes are present. This fine grained section is uppermost Cedar District Formation.

Prevost Island Area

The De Courcy Formation crops out on the Acland Islands adjacent to southern Prevost Island. The section is greater than 100 m thick, and consists of thick to very thick bedded, massive to planar laminated, coarse to very coarse grained sandstone. Planar cross-bedding is locally well developed, in sets about 0.3 m thick. Pebbly sandstone layers and shale rip-up clasts are common.

On northeastern Prevost Island, the De Courcy Formation crops out in a broad belt from Peile Point to the headland between Diver and Richardson Bays. The formation is estimated to be ca. 425 m thick, based on map interpretation. At Peile Point the formation consists of thick bedded, massive to planar laminated, coarse grained sandstone, interbedded with rare fine grained sandstone and siltstone. Burrows are evident on top surfaces of some of the fine grained beds. Bouma T_{ABC} sequences, scoured bases, and planar crossbeds, are locally developed. Rare large coal clasts occur in the section.

Grieve (1974) subdivided the De Courcy Formation on Prevost Island into 7 units, the basal two of which are placed in the Cedar District Formation by the writer. Grieve's upper 5 units are: 1) interbedded sandstone and conglomerate; 2) overlain by mudstone and mudstone with interbedded sandstone; 3) sandstone; 4) turbidites; and 5) sandstone with interbedded mudstone.

Pender Islands

The De Courcy Formation on North Pender Island crops out in two belts. The northern belt extends from Stanley and Willy points to the Welcome Cove area, and continues along the eastern coast to Bald Cove. The southern belt stretches from Shingle Bay, and the headland between Shingle and Ella Bay to Port Browning, Shark Cove, and Bedwell Harbour. Tight folding and faulting has repeated the De Courcy beds in the southern belt.

The northern belt consists of thick bedded, coarse grained sandstone, pebbly sandstone, and matrix supported pebble conglomerate, intercalated with thin bedded, shaly siltstone, mudstone, and fine grained sandstone. Normal grading and crude planar lamination is observed. Sandstone units commonly have loaded bases, shale rip-up clasts, sheet structure, sandstone dykes, and are locally coaly. A sample of De Courcy siltstone from near Willey Point yielded a very sparse microfauna, suggestive of a shelf environment (Cameron, 1988a).

Hudson (1974) interpreted the northern belt outcrop as "Geoffrey Formation" (ie. Galiano Formation). Sedimentary features in this belt noted by Hudson include groove, flute, and load casts. His thin section analysis of the De Courcy Formation sandstone on North and South Pender Islands classifies it as arkosic wacke.

In the southern belt, northeast of Cramer Hill, the De Courcy Formation comprises thick bedded, coarse grained sandstone, pebbly sandstone, pebble conglomerate, and fine grained sandstone interbeds. The conglomerate has well rounded pebbles, and is matrix supported. Small pebble lenses and floating pebbles occur in the sandstone. Hudson (1974) noted load casts on sandstone units in this area.

In the Lively Peak area, the De Courcy Formation consists of medium to thick bedded, fine to coarse grained sandstone, and poorly sorted pebbly sandstone, interbedded with thin bedded, grey siltstone and fine grained sandstone. The sandstone is locally coaly. Hudson (1974) reports the occurrence of much poorly sorted, pebble conglomerate in this area. Clasts are subrounded to rounded, and include andesite, rock quartz, rhyolite, greenstone, schist, phyllite, sandstone, and mudstone (Hudson, 1974).

The De Courcy Formation crops out at Brackett Cove and on the shoreline between Pollard Cove and Razor Point on Port Browning. In this area the formation comprises thick bedded, massive to planar laminated, coarse to medium grained sandstone, and minor pebble conglomerate, with thin bedded, fine grained sandstone and siltstone interbeds. The coarse grained sandstone contains shale rip-up clasts. The conglomerate is poorly sorted and disorganized. Dominant clasts are chert, sandstone, concretionary limestone, and argillite. Fine grained sections show Bouma T_{ABCD} and T_{AB} sequences up to 10 sequences/m.

At Shark Cove, the De Courcy Formation comprises thick bedded, massive, coarse grained sandstone and pebble conglomerate, interbedded with planar laminated, medium to fine grained sandstone. The sandstone is well-indurated. Fine grained beds feature load casts, flame structures, climbing ripples, planar cross-lamination, and shale rip-up clasts. The conglomerate is polymictic, poorly sorted, clast supported, and generally massive or crudely graded.

Lower De Courcy Formation on Bedwell Harbour comprises thick bedded, medium to coarse grained sandstone, interbedded with chaotic, fine grained sandstone, and mottled coarse grained sandstone with abundant shale rip-up clasts. These coarse grained beds are intercalated with recessive sections of medium to thin bedded, massive to planar laminated fine grained sandstone, silty shale, and siltstone.

The De Courcy Formation on South Pender Island is a continuation of the southern outcrop belt on North Pender Island. Mount Norman and Spalding Hill are formed by the De Courcy Formation. Lower De Courcy Formation at Beaumont Provincial Park on Bedwell Harbour is comprised mainly of thick bedded, massive, medium grained sandstone and rare granule sandstone, with medium, fine grained sandstone interbeds. The tops of some of the thick sandstone units are planar or convolute laminated. Shale rip-up clasts are common in the basal parts of the sandstone units. Rare coaly debris and shale rip-up clasts occur in some fine grained units. Intercalated in the coarse grained beds are thicker, fine grained sections composed of thin bedded, fine grained sandstone and siltstone, with sharp, even, and continuous contacts, exhibiting Bouma T_{BCD} or T_{CD} sequences.

The De Courcy/Cedar District transition beds in the Little Bay area have been discussed in the preceding passage on the Cedar District Formation. The northern coast of South Pender Island consists mostly of thick bedded, massive, coarse grained sandstone and pebble to cobble conglomerate. Minor conglomerate filled channels are evident locally. The conglomerate is polymictic, clast supported, and poorly sorted. Dominant clasts are chert, mudstone, argillite, and rock quartz.

Galiano Island

The De Courcy Formation is exposed on Galiano Island between Phillimore and Collinson points, and on a chain of islands in Trincomali Channel: Ballingall Islets, Wise Island, Sphinx Island, Parker Island, and Julia Island. On the small islet south of Wise Island, the De Courcy Formation comprises very thick bedded, poorly sorted, pebble to large cobble conglomerate, overlain by medium bedded, medium grained sandstone. The contact is gradational over about 10 cm. The conglomerate is matrix to clast supported, about 10 m thick, contains sandstone lenses, and the matrix is coarse grained to granule sandstone. Constituent clasts are white quartz, granodiorite, sandstone, argillite, concretionary limestone, and various volcanic and metamorphic rocks. The base of the conglomerate is erosional into an underlying large sandstone lense. Below this is more thick bedded conglomerate and coarse grained sandstone.

On Parker Island, the De Courcy Formation is about 310 m thick at its maximum, based on map interpretation. Carter (1976) considered these beds to be a "Geoffrey" (i.e. Galiano) Formation tongue, but the writer agrees with previous correlations (Muller and Jeletzky, 1970; Clapp, 1914b). Carter describes the formation on Parker Island as thick bedded conglomerate, sandstone, and minor mudstone. Contacts are sharp, and even or undulatory. Thin section analysis shows that the sandstone is arkosic wacke (Carter, 1976).

Mayne Island

The De Courcy Formation forms Enterprise Reef and crops out from Crane Point to St. John Point on Mayne Island, forming prominences such as Deacon and Heck Hills. The formation is estimated to be greater than 220 m thick. In Deacon Hill area, the formation consists of thick bedded, massive to planar laminated, coarse grained sandstone, interbedded with planar laminated, fine grained sandstone and siltstone. Pebbly sandstone lenses, shale rip-up clasts, and rare coal debris are present in some of the coarse grained units.

Upper De Courcy Formation is exposed south of Horton Bay, where it is transitional to the Northumberland Formation underlying the bay. It comprises thick to medium bedded, massive, coarse to medium grained sandstone, interbedded with thin to medium mudstone interbeds. Contacts are sharp, even, and continuous.

The section from St. John Point to Robson Channel comprises both coarse grained and fine grained lithofacies. The coarse grained lithofacies consists of thick bedded, coarse grained sandstone with pebbly sandstone layers, with thin, typically convolute laminated siltstone interbeds. The fine grained lithofacies consists of thin bedded siltstone and fine grained sandstone. _Pachydiscus_ _sp._ was recovered from lower De Courcy Formation at this locality by Stickney (1976). The author collected a sample from approximately the same location which yielded a weathered and leached microfauna suggestive of paleo-water depths of 100-200 m (Cameron, 1988a).

Additional sedimentary features in the De Courcy Formation noted by Stickney (1976) included normal grading, scattered burrows, flame structures, groove, prod, flute, and load casts, climbing ripples, and small trough cross-lamination. His thin section analysis classifies the sandstone as arkosic wacke. Stickney also reports limited occurrences of conglomerate in the De Courcy Formation. Clasts consist of chert, quartzite, granitic rocks, plus minor basalt, andesite, metamorphic rock, and sandstone.

Saturna Island

To the southeast, the De Courcy Formation probably forms Lizard Island (Stickney, 1976), and is continuous with the section cropping out between Digby and Mikuni points on Saturna Island. The De Courcy Formation extends below Mount David and Mount Elford, above Lyall Harbour, all the way to eastern Saturna Island, cropping out between Fiddlers Cove and Narvaez Bay. The formation consists of thick to medium bedded, massive to planar laminated, coarse to medium grained sandstone, intercalated with thin bedded mudstone, siltstone, and fine grained sandstone. Thin section analysis by Sturdavant (1975) shows that the lower coarse grained sandstone member is lithic wacke. Sturdavant measured a section encompassing the De Courcy Formation from Digby to Mikuni points. The section can be divided into a basal coarse grained member (45+ m), a middle fine grained member forming Veruna Bay (205 m), and an upper coarse grained member (41 m). The lower member includes minor pebble conglomerate. The middle member is only partly exposed, and features Bouma T_{BCDE}, T_{CDE}, and T_{DE} sequences, concretionary limestone layers, and vertical and horizontal burrows. The upper member includes pebbly sandstone and lenses. To the east, the coarse grained members thicken at the expense of the middle member, such that in the eastern outcrop belt, the middle member is absent. A sample from the intermediate recessive member exposed in a roadcut above Lyall Harbour, yielded a microfauna probably indicative of paleo-water depths of 200-300 m, with oxygen deficiency evident (Cameron, 1988b).

Between Narvaez Bay and Fiddlers Cove, the De Courcy Formation forms prominent cliffs along the shore. Here the formation comprises thick bedded, massive, coarse grained sandstone, intercalated with medium to thick sections of thin bedded, fine grained sandstone and siltstone. Contacts are sharp, even, and continuous.

The De Courcy Formation forms most of the exposed beds on Saturna Island south of the central valley between Lyall

Harbour and Narvaez Bay. The southern faces of Mount Fisher and Mount Warburton Pike are formed by the De Courcy Formation. High sea cliffs of the De Courcy Formation are present at Elliott Bluff, and Monarch Head. Below the main body of the De Courcy Formation between Breezy Bay and Bruce Bight are transition beds between Cedar District and De Courcy formations comprised of a lower coarse grained sandstone member, and an upper fine grained member (previously described under the Cedar District Formation), both ca. 110 m thick. The coarse grained unit consists of thick bedded, massive to planar laminated, coarse grained sandstone, with medium, fine grained to medium grained sandstone interbeds. Coal debris is locally present. Contacts are sharp, continuous, and even to undulatory.

At Trueworthy Bight, as mentioned previously, the underlying beds contain Inoceramus ex. gr. I. balticus (Haggart, 1988a), and foraminifers indicative of upper slope paleo-water depths of 200-600 m. Sturdavant (1975) found Inoceramus sp. in the coarse grained sandstone member itself, in the cliffs above Trueworthy Bight. The coarse grained sandstone member continues offshore from Taylor Point, forming Java Islets. Thin section analysis by Sturdavant (1975) shows that the member is composed of arkosic wacke.

The main body of the De Courcy Formation is well exposed in the Monarch Head area, comprising thick bedded, massive, coarse grained sandstone, interbedded with recessive section of thin to medium bedded, coarse to fine grained sandstone and siltstone (Plate 9b). The coarse grained beds contain abundant floating granules and pebbles. The fine grained sections are commonly graded, and feature rare coal debris (including detrital seams), sandstone dykes, and planar to convolute lamination. Extensive horizontal burrows are noted in the De Courcy Formation in this area by Sturdavant (1975).

On the other side of the island, at Elliott Bluff, the De Courcy Formation is comprised of very thick bedded, massive, fine to coarse grained sandstone, with rare, medium siltstone interbeds. Contacts are sharp, even, and continuous.

Sturdavant (1975) reports conglomerate channels on Brown Ridge, up to 3 m deep by 61 m wide, which are scoured into underlying sandstone. Conglomerate clasts are dominated by chert, limestone, basalt, quartzite, and greenstone; minor constituents are granite, granodiorite, gneiss, rhyolite, schist, phyllite, gabbro, mudstone, and carbonized wood.

Sucia Islands

The De Courcy Formation on Sucia Islands overlies approximately 250 m of the Cedar District Formation. The formation comprises 4 coarse grained members separated by intervening recessive intervals covered by water, which may be fine grained in nature. The section from Fossil Bay to the top of the fourth coarse grained member in Echo Bay is ca. 750 m thick, based on map interpretation; McClellan (1927) suggests almost 900 m for the same section.

The basal coarse grained member comprises cross-bedded, coarse grained sandstone containing abundant pebble and cobble layers, and poorly sorted, disorganized conglomerate lenses. The sandstone is thick bedded and poorly indurated. Clasts are composed of granitic, volcanic and sedimentary rock. Large-scale planar cross-bedding is well developed: individual sets are 2 to 3 m thick and 30 to 40 m long. Foresets commonly have assymptotic toe sets. The second coarse grained member, forming Johnson Point, consists of planar cross-bedded sandstone interbedded with pebbly sandstone and conglomerate beds. Crossbed sets are thinner here, about 0.5 m thick. The third coarse grained member, forming the adjacent islet to the north, comprises thick bedded, planar cross-bedded, medium grained sandstone and pebbly sandstone with pebble conglomerate lenses. Coal spars and floating pebbles are common. Carbonaceous debris commonly defines foreset laminae. Cross-bedded pebble conglomerate beds up to 6 m thick are present. The fourth coarse grained member, exposed on the next islet to the north, comprises planar and trough cross-bedded sandstone, conglomerate, and pebbly sandstone, as described above. Coal debris and carbonaceous foreset laminae are common. Numerous, discrete thin to thick conglomerate lenses and beds are present.

Pacht (1980) measured a section in the De Courcy Formation, from Lawson Bluff to Echo Bay, which is ca. 350 m thick, and corresponds to the lower two coarse grained members described above. The section comprises: medium to thick bedded, planar and trough cross-bedded sandstone; flat bedded sandstone with disorganized conglomerate lenses; medium to thick bedded conglomerate and pebbly sandstone. Crossbed sets are up to 1 m thick. Rare herringbone cross-bedding and coalified wood fragments are noted.

Northumberland Formation

Gabriola Island

On Gabriola Island, the Northumberland Formation forms shoreline exposures southeast of Lock Bay on the northeastern side of the island, and on the southwestern side of the island at False Narrows. In the northeast, the formation consists of thin bedded mudstone, siltstone, and fine grained sandstone, containing numerous concretions and concretionary layers. The sandstone is commonly extensively burrowed. Large inoceramid fragments and rare coalified branches are present. Sandstone dykes are also present in this section.

The section at False Narrows (Section 168) comprises thin bedded, grey, recessive mudstone, with very fine grained sandstone interbeds, and, in the upper part, contains some thick bedded, coarse grained sandstone units. Contacts are sharp, planar, and continuous. The mudstone is variably silty, and contain numerous inoceramid and ammonite shells, and concretions which may be cored by fossil ammonites. Several thick, medium to coarse grained sandstone dykes and sills cut through the mudstone (Plate 10a). The fine grained sandstone and siltstone interbeds are planar laminated and intensively burrowed; their tops are commonly convolute laminated. Some basal load casts are present. Packard (1972) noted planar and trough cross-lamination in a few of these beds. The thick bedded, coarse grained units are generally massive, featuring dish and sheet structure, and dewatering pipes (Plate 10b). These beds are locally crudely planar laminated, and are commonly capped by thin fine grained sandstone beds with shale rip-up clasts. Basal contacts are sharp. The entire section at False Narrows is estimated to be ca. 250 m thick.

Usher (1952) describes Pachydiscus suciaensis and Pachydiscus ootacodensis from the Northumberland Formation at False Narrows. Large ammonite fragments and inocerami are reported to occur at Lock Bay and False Narrows sections by Packard (1972); the author observed these fossils plus extensive trace fossils and a few brachiopods at these localities.

At False Narrows, the Northumberland Formation yielded a highly diverse microfauna, indicating paleo-water depths of 600-1200 m, with a fair amount of down-slope transport, and some oxygen deficiency (Cameron, 1988b). A second sample from this locality indicates upper slope or deeper paleo-water depths of 200-600 m (Cameron, 1988b). At the northern end of the False Narrows outcrops, in upper Northumberland Formation, Cameron (1988b) recovered a microfauna indicating paleo-water depths of 200-300 m, with some down-slope transport.

Valdes Island

Southeast of Gabriola Island, the Northumberland Formation underlies Pylades Channel, coming onshore Valdes Island in the Blackberry Point-Shingle Point area. Usher (1952) reports fossiliferous Northumberland Formation from this area. Muller and Jeletzky (1970) map this outcrop as the Mayne formation (their "Spray" Formation), but the Galiano formation, which can be traced across Gabriola Passage and down the northwestern coast of Valdes Island, clearly overlies these beds. Mapping by the author indicates that the Mayne formation must outcrop at higher elevations, on the northeastern side of Mexicana Hill.

Galiano Island

To the southeast, the Northumberland Formation underlies the northeastern side of Trincomali Channel, emerging on Parker and southern Galiano islands. On Parker Island, the Northumberland Formation comprises mostly thin bedded, grey, muddy siltstone and very fine grained sandstone, with rare units up to 3 m thick of medium bedded, fine to coarse grained sandstone. Trace fossils such as Thalassinoides are prevalent in the very fine grained sandstone. Coarse grained units have abundant mudstone rip-up clasts, and are massive or locally graded; fine grained sandstone is usually planar laminated. The formation is only ca. 100 m thick at this locality.

The formation is exposed at Payne Bay, Galiano Island (Carter, 1976) and continues to the southeast below Sutil Mountain and Mount Galiano. At Active Pass, the Northumberland Formation is dextrally offset by a transverse fault, coming onshore Mayne Island at Village Bay. It then forms an outcrop belt from Village Bay to Horton Bay, Mayne Island, from Curlew and Samuel islands to Winter Cove, and then down Saturna Island to Fiddlers Cove, in the southeast.

Mayne Island

The section at Village Bay, Mayne Island, is ca. 200 m thick, based on map interpretation. It consists of thin bedded, fine grained sandstone and silty mudstone. The sandstone beds are up to 0.6 m thick, but the average thickness is about 0.06 m. Numerous feeding traces and burrows such as Thalassinoides and Planolites are developed on bedding plane tops. Small brachiopod shells and concretions up to 0.5 m in diameter are present. Bouma T_{BCD} and T_{BC} sequences are evident.

At Village Bay, a very high diversity microfauna was recovered from the Northumberland Formation, representing paleo-water depths of 600-1200 m, with evidence of much down-slope transportation Cameron (1988a). McGugan (1979) has reported an abundant and diverse microfauna in 16 samples of the Northumberland Formation from Village Bay, but interpreted a relatively shallow, shelf paleo-environment for them.

Stickney (1976) described crushed inocerami shells, scaphopods?, poorly preserved straight ammonites, and common trace fossils such as Thalassinoides and Helminthoida?, from the Mayne Island area. His thin section examination of the Northumberland Formation sandstone on Mayne Island shows that it is arkosic wacke.

Microfauna in the Northumberland Formation between Mount Parke and Horton Bay, Mayne Island, indicate paleo-water depths of 150-200 m, and some down-slope transportation (Cameron, 1988b). The formation on Curlew Island, to the southeast, also contains a microfauna indicative of approximately 200-400 m paleo-water depths (Cameron, 1988a).

On Curlew Island, the Northumberland Formation comprises thin bedded mudstone, siltstone, and fine grained sandstone, with rare interbeds of medium grained sandstone. Contacts are sharp, planar, and continuous. Bouma T_{ABCD} and T_{CD} sequences are evident. Encased in the fine grained beds is a tongue of the Galiano formation consisting of thick bedded, medium grained sandstone, less than 50 m thick. Individual sandstone units are up to 2 m thick and are planar laminated. Pacht (1980) estimates that the Northumberland Formation is 350 m thick at Horton Bay.

Samuel Island

On Samuel Island the Northumberland Formation increases in thickness to over 350 m. The section on Samuel Island, however, is only partly exposed. On the northwestern side of Irish Cove, the contact of a Galiano formation tongue with the overlying upper Northumberland Formation is exposed. The Northumberland Formation comprises thin bedded, fine grained sandstone, siltstone, and mudstone, with about 10 coarse/fine grained sequences/m. Up section, some thicker, medium grained sandstone beds up to 0.4 m occur, featuring planar lamination, ripple cross-lamination, and extensively burrowed fine grained sandstone tops. The thick sandstone is intercalated with thick mudstone units.

On southwestern Samuel Island, a fairly diverse microfauna in the Northumberland Formation indicates 200-600 m paleo-water depths (Cameron, 1988b). At Winter Cove, Saturna Island, the foraminifers also indicate paleo-water depths of 200-600 m (Cameron, 1988b). At these two localities, Cameron interprets oxygen deficiency on the sea-floor based on the occurrence of Chilostomella.

Saturna Island

On Saturna Island, upper Northumberland Formation is laterally replaced by the Galiano formation sandstone, however, the lower part of the formation continues along the southwestern sides of Mount David and Mount Elford to

Fiddlers Cove. At Winter Cove the formation is over 350 m thick, compared to less than 100 m at Fiddlers Cove. The Northumberland Formation also crops out at high elevations on southwestern Saturna Island. At Winter Cove, the Northumberland Formation consists of thin bedded to massive shale and siltstone, with rare fine grained sandstone interbeds. Rusty weathering concretions and layers are abundant. Sturdavant (1975) observed Bouma T_{BCDE}, T_{CDE}, and T_{DE} sequences in the formation on Saturna Island, as well as *Thalassinoides*, the pelecypod *Mytilus*, an indistinct ammonite, and coaly debris. Ward (1976a) collected *Pachydiscus suciaensis* from this locality.

North Pender Island

Exposures of the Northumberland Formation on North Pender Island form the coast line north of Razor Point, and the formation occupies the valley from Bald Cone to Grimmer Bay. A second outcrop band extends from just north of Razor Point, to Brackett Cove and then to the western shore just south of Ella Bay. The beds here are steeply dipping or overturned; inland, the precise location of the unit is uncertain. The formation consists of thin bedded, grey mudstone, siltstone, and fine grained sandstone. The sandstone is planar laminated and commonly extensively burrowed. Convolute and ripple cross-lamination are common; contacts are sharp, planar, and continuous. Hudson (1974) notes rare groove, load, and flute casts on basal bedding surfaces. Hudson also describes the occurrence of inocerami and abundant horizontal trace fossils on North Pender Island.

A fairly diverse microfauna in the Northumberland shale, approximately 1 km northeast of the head of Otter Bay on North Pender Island, indicates paleo-water depths of 200-600 m, with considerable down-slope transport (Cameron, 1988a).

Prevost Island

On Prevost Island, the Northumberland Formation underlies the lowland from Diver Bay to James Bay, and probably lies just off the southwestern coast of the island on the other side of the Long Harbour syncline. At James Bay, the formation consists of thin bedded silty mudstone and siltstone. Contacts are very even, continous, and sharp. Faint colour lamination is observed in the mudstone. Grieve (1974) divided the Northumberland Formation on Prevost Island into 3 units: a basal turbidite unit; a middle mudstone unit, with interbedded sandstone; and, an upper, uniform mudstone unit. At James Bay, foraminifers recovered from lower Northumberland Formation indicate paleo-water depths of 200-600 m, and oxygen deficiency well marked by a very pyritic residue (Cameron, 1988a).

Saltspring Island

The northeastern limb outcrop on Prevost Island passes offshore under Trincomali Channel, coming onshore Saltspring Island, opposite Atkins Reef. The southwestern limb outcrop comes onshore at Welbury Bay, Saltspring Island. On Saltspring Island, the two bands of outcrop in opposite limbs of the Long Harbour syncline strike northwest to St. Mary Lake, are sinistrally offset by a transverse fault at St. Mary Lake, and then continue to the northwestern shore, at Duck Bay and opposite Idol Island.

The Northumberland Formation on Saltspring Island is locally fossiliferous. Usher (1952) describes Pachydiscus suciaensis from the Northumberland Formation, opposite Atkins Reef on northeastern Saltspring Island. Hanson (1976) reports large Inoceramus, crushed immature Baculites, echinoids, scaphopods, and abundant trace fossils including Helminthoida and Tomaculum problematicum, in the Northumberland Formation on Saltspring Island. At Welbury Bay, Hanson reports the occurrence of a planispiral ammonite over 0.6 m in diameter.

The upper contact with the overlying Galiano formation is sharp or transitional over a short interval. Just west of the ferry terminal at Long Harbour, uppermost Northumberland Formation consists of thin bedded, shaly planar laminated siltstone and fine grained sandstone, with about 30 coarse/fine grained sequences/m. The siltstone contains rare coal debris. Contacts are sharp, including the formation boundary with the Galiano formation, which is also well exposed. In this upper part of the Northumberland Formation, Hanson (1976) notes poorly sorted, coarse grained sandstone lenses, and abundant coal debris, including coalified wood with Teredo borings. A low diversity microfauna recovered from the Northumberland Formation at this outcrop, indicates 100-200 m paleo-water depths, with somewhat oxygen deficient conditions (Cameron, 1988a).

At northeastern St. Mary Lake, the Northumberland Formation consists of thin bedded, brown weathering, mudstone, planar laminated siltstone, and fine grained sandstone. Ferruginous bands are present, some of which are rich in organic matter. There are generally about 10 coarse/fine grained sequences/m. The fine grained sandstone displays fine cross-lamination, and is commonly bioturbated and non-graded. Contacts are very even and continuous.

Foraminifers from northeastern St. Mary Lake (Section 251, Appendix B), Saltspring Island, represent 200 to 600 m paleo-water depths (Cameron, 1988a). Cameron interprets much down slope transport of megaspores and other shallower water indicators, and oxygen deficient conditions. A sample from the southern end of St. Mary Lake, although badly weathered and leached, suggests shallower paleo-water depths of 80 to 150 m.

On northwestern Saltspring Island, the formation consists mostly of thin bedded siltstone, silty mudstone, and minor sandstone. Rare fine grained sandstone dykes are locally present. The contact with the overlying Galiano formation is exposed near Duck Bay, where thick bedded, coarse grained sandstone overlies recessive, thin bedded silty mudstone and planar laminated fine grained sandstone, with a transition interval of about 7 m.

Thetis Island

The southwestern limb outcrop of the Northumberland Formation passes offshore under Stuart Channel. The Northumberland Formation in the northeastern limb continues across southwestern Kuper and Thetis islands, although it is only very locally exposed. At Foster Point, Thetis Island, the Northumberland Formation consists of thin bedded, grey siltstone and mudstone, overlying a medium to coarse grained, massive sandstone unit, which is thick bedded, and intercalated with thin bedded, fine grained sandstone. Contacts are locally undulatory. Another sandstone unit crops out in mid-channel between Foster Point and Hudson Island, consisting of thick bedded, coarse grained sandstone, with rare mudstone rip-up clasts, interbedded with fine grained sandstone. The beds between the coarse grained sandstone dominated units, which are covered by water, are probably the thin bedded facies described above.

At Foster Point, Thetis Island, Cameron (1988a) recovered well preserved agglutinated foraminifers indicating paleo-water depths of 200 to 600 m.

Simmons (1973), describes sharp, planar, conformable contacts of the Northumberland Formation with Galiano formation, which are exposed at North Cove, Thetis Island, and at Active Point, Kuper Island. Simmons notes planar laminated and graded beds in upper Northumberland Formation, as well as load casts, rare groove casts, convolute lamination, mudstone rip-up clasts, and flame structures. According to his thin section examination, the Northumberland Formation sandstone is arkosic wacke. Usher noted fossiliferous Northumberland Formation on Thetis Island, but no macrofossils were observed by the author. Simmons (1973) reports the occurrence of worm burrows in the formation.

Galiano formation

Gabriola Island

The Galiano formation occurs on the southwestern and northeastern sides of Gabriola Island, and forms high cliffs along the western part of the island. It consists of coarse grained sandstone and conglomerate, with a minor fine grained component. The formation is estimated to be about 150 m thick. At Descanso Bay, 72 m of section were measured (Section 156) consisting of medium to thick beds of coarse grained to very coarse grained sandstone and minor pebble conglomerate. Rare planar laminated siltstone partings occur. The sandstone shows planar and trough cross-bedding at the base, with abundant shale rip-up clasts, floating granules, pebbles, and cobbles. Pebble lenses and large concretions are common. Contacts are locally irregular, showing loaded bases. Convolute lamination regularly occurs at the tops of beds. The conglomerate is poorly sorted, polymictic, matrix supported, and mostly in pebble size grade with rare floating cobbles.

The conglomerate facies is well exposed on southern Gabriola Island. The roadcut near Percy Anchorage (Section 170) shows thick bedded, pebble to cobble conglomerate overlying alternations of thick beds of medium grained sandstone and thin beds of fine grained sandstone and siltstone. The conglomerate is massive, or graded from cobble to pebble size, to pebbly sandstone. Clasts are poorly sorted, but well rounded. Graded sets of cobble through pebble conglomerate, to flat bedded, pebbly sandstone are also exposed along strike to the east. On the northern shore of Gabriola Passage, massive cobble conglomerate forms a steep bluff overlying medium to thick bedded sandstone interbedded with thin, fine grained sandstone and siltstone. Cladichnus is developed in some of the siltstone beds.

The Galiano formation on northeastern Galiano Island consists of thick bedded sandstone of variable grain size containing numerous pebbly sandstone lenses, but also includes some fine grained sandstone and planar laminated mudstone alternations. Solution pipes, soft sediment deformation features, and calcareous concretions occur in the Galiano formation at LeBoeuf Bay. The contact with the overlying Mayne formation is sharp, but conformable. Packard (1972) records three pebble counts in conglomerate channels of the Galiano formation, observing, in descending order of abundance: quartzite, various volcanic and granitic rocks, chert, sandstone, and foliated metamorphic rocks. The writer noted greater abundances of chert, rock quartz, and argillite pebbles in the Galiano formation. Thin sections of the Galiano formation sandstone examined by Packard (1972) reveals that it is arkosic wacke.

Valdes Island

To the southeast, the Galiano formation forms the shoreline along northwestern Valdes Island, where it is comprised of thick, massive, white-weathering coarse grained sandstone, interbedded with thin, fine grained sandstone and siltstone. These strata are remarkably continuous along strike (Plate 11b). Excellent dish and sheet structures are observed in the thick beds, and some large-scale, low-angle, planar cross bedding occurs. The Galiano formation probably forms the cliff at Mexicana Hill, based on cross-sections. The unit is faulted south of the hill, reappearing on Reid and Hall islands.

Trincomali Channel

Thick bedded, pebble conglomerate, pebbly sandstone, and massive, coarse grained sandstone of the Galiano formation outcrop on Reid and Hall islands. The conglomerate is stratified internally, the sandier zones clearly defining bedding. Clasts are moderately sorted and rounded, dominant lithologies being argillite, rock quartz, red and green chert, concretionary limestone, sandstone, metamorphic rock, and various volcanic rocks. To the southeast, the Galiano formation underlies much of eastern Trincomali Channel.

From Charles Island to Mayne Island, distinguishing the unit from the underlying coarse grained De Courcy Formation is difficult due to rapid thickness variation in the intervening Northumberland shale, and the fact that the De Courcy Formation is in part conglomeratic in the area. Several lithostratigraphic correlations are possible (Clapp, 1914b; Muller and Jeletzky, 1970; Carter, 1976; Muller, 1983). The writer prefers to interpret beds on Charles Island, on Gray Peninsula of Parker Island, and which form prominent outcrops from Winstanley Point to Sutil Mountain and Galiano Mountain on Galiano Island, to be the Galiano formation. These beds do not continue along the northern shore of Georgeson Bay, rather, they are offset by a transverse fault trending from Salamanca Point on northeastern Galiano Island to Enterprise Reef off Mayne Island, and thus are continuous with beds at Helen Point, Mayne Island. Beds on Wise and Parker islands, and along the southern shore of Galiano Island to Collinson Point are considered to be the De Courcy Formation, with a thin Northumberland Formation intervening below the Galiano formation outcrops.

Galiano Island

In the Galiano Island area the formation thickens rapidly southwards, from 75-100 m on Charles Island and Gray Peninsula, Parker Island, to over 350 m at Mount Galiano. On Charles Island and Gray Peninsula, the unit consists of thick bedded, massive, medium grained sandstone, interbedded with medium beds of planar laminated, fine grained sandstone and mottled grey siltstone.

On Galiano Island, Carter (1976) described the Galiano formation (his middle member of the "Geoffrey" Formation) to consist mostly of conglomerate and lenticular sandstone beds. The conglomerate has well rounded, poorly sorted clasts, predominated by chert, quartzite, and granitic rock, but also contains metamorphic and volcanic rock fragments. Clasts are generally cobble size with rare boulders. Contacts are planar, undulatory, or scoured, and generally sharp. Carter (1976, p. 43) notes pebble conglomerate channels occurring on Mount Galiano, which are 9 to 30 m wide and 3 to 14 m deep; the channel fill is massive and non-imbricated. In fact, most of the conglomerate comprising the section is massive or only crudely graded. In the upper part of the formation, Carter notes increasing stratification in the conglomerate, and grading of conglomerate to sandstone over short transition intervals. From Winstanley Point to the shoreline below Mount Galiano on Active Pass, Carter observed increasing maximum clast size in the Galiano formation. His thin section examinations show that the Galiano formation sandstone is immature arkosic wacke.

Mayne Island

From Helen Point, Mayne Island, to East Point, on Saturna Island, the Galiano formation forms a fairly continous outcrop belt, with prominences at Mount Parke, Mayne Island, and at Mount David and Mount Elford, on Saturna Island. Between Mount David and Mount Parke, the Northumberland Formation thickens at the expense of the Galiano formation which reaches a minimum on southeastern Samuel Island.

The Galiano formation on Mayne and Samuel Island is described by Stickney (1976) to comprise thick channel conglomerate and associated sandstone, interbedded with sandstone and minor mudstone. The sandstone is chiefly arkosic wacke, as determined from thin sections (Stickney, 1976). From Helen Point to central Mayne Island, Stickney notes increasing thickness of conglomerate units; to the east, the conglomerate diminishes, and eventually the Galiano formation consists only of sandstone in the Samuel Island area. The formation is much thinner here, and is associated with a much thickened Northumberland Formation. The sandstone is thick bedded, and coarse grained, in general, but locally may be planar laminated or trough cross-stratified. Some grading is developed. Mudstone rip-up clasts, burrows, and pebble lenses occur. Channel fill sandstone with basal groove marks and current lineation is observed by Stickney (1976). The conglomerate is poorly sorted, generally from cobble to boulder size, the largest clasts being 1 x 3 m; overall, clast size decreases to the east. The clasts are dominated by granitic rock, quartzite, chert, and volcanic rock. Imbrication is common. The interbedded mudstone shows grading, lamination, trough cross-lamination, Bouma T_{CD} sequences, and abundant burrows and traces such as _Thalassinoides_.

Saturna Island

On Saturna Island, the Galiano formation thickens rapidly towards the central part of the northern side of the island, reaching a maximum thickness of 450-550 m, then gradually thins towards East Point. Northwest of Mount David, in the Winter Harbour area, the formation consists of two distinct sandstone units with intervening Northumberland shale, each less than 100 m thick. The lower one is clearly a coarsening and thickening upward unit from thin bedded, fine grained sandstone and mudstone, to thick bedded, massive, coarse grained sandstone. Contacts are sharp, planar, and continuous. Rare inoceramids are present at the base of the first thick sandstone, and coal debris is present in the fine grained beds. The upper unit is in the same facies, but the thick sandstone is locally planar laminated and contains abundant shale rip-up clasts, and the fine grained sandstone is commonly convolute laminated.

Most of the Galiano formation on Saturna Island is sandstone, with minor mudstone and siltstone interbeds; conglomerate is rare. Sturdavant (1975) described matrix supported conglomerate filling a 1 x 4 m channel on the south side of Mount Elford. The formation also becomes coarser-grained at East Point, where thick bedded coarse grained sandstone is intermixed with poorly sorted polymictic pebble conglomerate with large floating cobbles and boulders of shale, sandstone, cemented siltstone, and spheroidal and irregularly shaped small concretions. The sandstone is interspersed with numerous discrete pebble conglomerate lenses. Large channels are present which are locally filled with pebble to cobble, poorly sorted, matrix supported conglomerate.

On the southern side of East Point, underlying the conglomeratic beds, is thick bedded, coarse grained sandstone, interbedded with thin to medium beds of fine to medium grained sandstone. The fine grained beds are planar laminated, and locally display climbing ripples, planar cross-lamination, and contain rare coal debris. The coarser grained beds are generally massive, but become planar laminated near their tops, and are locally crudely graded. Basal load casts, sheet structures, floating pebbles, and medium-scale planar crossbeds occur. One of the beds contains a 1.5 x 4 m rip-up clast of thin bedded sandstone. Contacts are generally sharp, planar, and conformable; however, distinct large-scale, low-angle truncation surfaces do exist. Calcite veins are common throughout the East Point exposures. The Galiano formation crops out at the top of Mount Fisher (Sturdavant, 1975), and, based on cross-sections, probably crops out on the northern flank of Mount Warburton Pike, although its areal extent has not firmly been established. Thin section analysis of the Galiano formation sandstone by Sturdavant (1975) shows that it is immature arkosic wacke and arenite.

The Galiano formation probably crops out on Patos Island to the east of Saturna Island. McClellan (1927) estimates that about 440 m of cross-bedded sandstone and conglomerate comprise Patos Island. The Galiano or Gabriola Formation may also outcrop on Matia Island, where McClellan (1927) estimates that there are 616+ m of cross-bedded arkosic sandstone, conglomerate, and shale.

North Pender Island

On North Pender Island, the Galiano formation is up to 400 m thick, and is also dominated by thick bedded, massive to planar laminated, coarse grained sandstone, with minor fine grained interbeds, and conglomerate. Contacts are generally sharp and planar. Sedimentary structures noted in the formation by Hudson (1974) include groove, load, and flute casts; graded tops of some the sandstone beds; medium-scale, planar and trough cross-lamination; and convolute lamination. Horizontal burrows, and Zoophycus? trace fossils are also reported. Thin sections of the Galiano formation sandstone examined by Hudson (1974) show that it is arkosic wacke. Hudson described thick bedded pebble conglomerate in the Galiano formation at James Point and Dent Hill. Clasts are well rounded, tightly packed, and consist mainly of chert, quartzite, andesite, basalt, and granitic rock.

Prevost Island

Some of the best exposures of the Galiano formation are present on southwestern Prevost Island. The lower part of the formation crops out from Point Liddell to Secret Island, and is repeated between Selby Point and Red Islets on the northeastern limb of the Long Harbour syncline. The upper part surrounds Annette Inlet and Ellen Bay. Lower Galiano formation consists of thick bedded, cobble conglomerate and coarse grained sandstone intercalated with sections of thick to medium bedded, coarse to fine grained sandstone and siltstone exhibiting Bouma T_{ABCD} sequences. The sandstone units in the coarser grained sections show undulatory, often scoured bases, are locally graded, and convolute laminated, and contain abundant shale rip-up clasts. The conglomerate has well rounded, large cobble size clasts of granitic and volcanic composition, as well as sedimentary clasts of sandstone, limestone, mudstone, and argillite. The conglomerate is clast supported, and generally unstratified. Both sandstone and conglomerate infills numerous large channels.

The upper part of the formation, between Annette Inlet and Glenthorne Passage, and at Annette Point, is comprised of much the same facies as described above, except that the conglomerate is slightly coarser-grained, containing pebble through boulder size clasts. This conglomerate is clast supported, with an unstratified, coarse grained sandstone matrix. Contacts are sharp, but boulders of the underlying conglomerate commonly protrude into the overlying sandstone (Plate 11a).

Saltspring Island

The conglomerate dominant beds of the Galiano formation continue across Captain Passage to Saltspring Island.

Exposures along the northeastern shore of Welbury Bay consist of large cobble to boulder, polymictic conglomerate, interbedded with coarse grained sandstone and pebble conglomerate. Clasts are predominantly of granodiorite, porphyritic volcanic rock, argillite and sandstone. Bedding is massive; contacts are sharp and planar. Small pebble filled channels occur in the sandstone.

Upper Galiano formation consists of thick bedded, coarse grained sandstone with lenses of pebble conglomerate, and locally abundant mudstone rip-up clasts. At Nose Point, Hanson (1976) notes small channels infilled with pebble conglomerate, and a large 30 x 3 m channel infilled by pebbly sandstone and conglomerate.

Lower Galiano formation is exposed west of the Long Harbour ferry terminal. The contact with the underlying Northumberland Formation is remarkably sharp. This part of the unit consists of thick bedded, massive, coarse grained sandstone with minor fine grained interbeds. Tool marks, and very large flute marks (troughs up to 1.5 m) are featured at the bases of some of the sandstone beds. Sedimentary features noted by Hanson (1976) include crude lamination, mudstone rip-ups, and large calcareous spherical concretions. He also found Inoceramus shells in a silty mudstone interbed (Hanson, 1976, p. 142).

The basal contact of the Galiano formation is also well exposed to the northwest, above St. Mary Lake. A short section measured over the interval (Section 251) shows that the contact is transitional over 11 m. This contact is transitional over 7 m on Sunset Drive above Duck Bay on northwestern Saltspring Island.

Hanson's (1976) detailed studies of the Galiano formation on Saltspring Island reveal: a) a northwestward decrease in bed thickness and maximum clast size in the conglomerate unit (his middle member); b) a northwestward decrease in the total amount of conglomerate; and c) increasing mudstone intercalations to the northwest in the upper and lower thirds of the formation. The Galiano formation sandstone is classified as arkosic to lithic arenite and wacke (Hanson, 1976, p. 195). The Galiano formation is up to about 400 m thick on Saltspring Island.

Thetis Island Area

To the northwest, across Houstoun Passage, the Galiano formation crops out on Tent Island, where it consists of thick bedded, coarse grained sandstone, massive to planar laminated, with a few pebbly sandstone lenses and beds. Large shale rip-up clasts and floating pebbles occur, some of which contain coal debris.

On the western shore of Kuper Island, the Galiano formation consists of thick bedded, medium to coarse grained sandstone and pebble conglomerate, interbedded with planar laminated, fine grained sandstone. Mudstone rip-up clasts are abundant. The pebble conglomerate beds are generally less than 0.5 m thick, have irregular channeled bases, and are discontinuous. They are poorly sorted (small pebbles to large cobbles); some of the large clasts protrude into overlying sandstone.

On Scott, Dayman, and Hudson islands, the formation is comprised of thick bedded, medium to coarse grained sandstone, interbedded with medium beds of planar laminated, fine to medium grained sandstone. Spherical concretions occur, up to 0.5 m in diameter. Contacts are sharp, planar, and continuous. On western Hudson Island, Simmons (1973) reports pebble conglomerate.

The Galiano formation on southwestern Thetis Island consists of thick bedded, coarse grained sandstone, massive to crudely planar laminated, with matrix supported pebble conglomerate lenses. The conglomerate clasts are dominated by rock quartz, gray chert, and various volcanic rocks. On northwestern Thetis Island, the formation consists of medium bedded, coarse grained sandstone, and thin bedded, carbonaceous, fine grained sandstone. Simmons (1973) reports over 30 m of thick bedded, pebble conglomerate at Fraser Point. Clasts are well rounded. Planar cross bedding is noted in the conglomerate. Thin section analysis of the Galiano formation sandstone by Simmons (1973) shows that it is immature arkosic arenite.

Mayne formation

Saturna Island

The southernmost outcrops of the Mayne formation are on the northern shore of Saturna Island, where the basal contact with the Galiano formation is exposed. The formation is described by Sturdavant (1975) to consist of interbedded planar laminated mudstone and very fine grained sandstone. The contact is described as gradational, with the amount of mudstone increasing upwards at the expense of sandstone from the underlying unit. Bouma T_{BCD}, T_{CD}, and T_{DE} sequences are also noted, and the trace fossil <u>Thalassinoides</u> was observed. Thin section examination of a sandstone from the Mayne formation was examined by Sturdavant (1975) and classified as an arkosic arenite. In the borehole on northern Tumbo Island described by Blakemore (1910), about 30 m of the Mayne formation was penetrated below a depth of 245 m, consisting of shale and fine grained sandstone, with thin coal seams.

Mayne Island

Mayne Island is the type area for the Mayne formation comprising large outcrop areas at Miners and Bennett Bays. At Bennett Bay the unit consists of thin bedded, fine grained sandstone and dark grey mudstone with up to 10 sandstone/mudstone sequences/m. The sandstone is commonly planar or convolute laminated. A diverse suite of trace fossils commonly is observed on bedding plane tops of the sandstone units, including Thalassinoides, Paleophycus, Scolicia (Plate 12a), Ancorichnus, Taenidium?, Helminthopsis?, and Cladichnus?. Rare ammonites (see above), inocerami fragments, and coalified branches are also present.

At Miners Bay, the Mayne formation has the same aspect as at Bennett Bay. The contact with the overlying Gabriola Formation is better exposed and clearly transitional. This section features abundant large inoceramid shells and rusty weathering concretions (probably pyrite rich). Trace fossils present are Ancorichnus, Scolicia, and Thalassinoides?. Stickney (1976) describes Bouma T_{ABCD}, T_{BCD}, and T_{BC} sequences in these sections, and the occurrence of ?Zoophycus. His thin section analysis of the Mayne formation sandstone reveals that it is arkosic wacke and arenite.

Foraminifers recovered from the Miners Bay section, indicate paleo-water depths of 200-600 m (Cameron, 1988a). The microfauna recovered from the section at Bennett Bay represent paleo-water depths of 400-600 m, and much down-slope transportation. In both of these samples, very pyritic residues indicate oxygen deficient conditions (Cameron, 1988a).

Galiano Island

The Mayne formation at Montague Harbour consists of thin bedded, fine grained sandstone, siltstone, and planar laminated, medium grained sandstone; and thick beds of massive siltstone and mudstone, with thin mudstone interbeds. Abundant but poorly preserved burrows are present in the sandstone. Thicker sandstone locally displays irregular bases, and trough cross-lamination at their tops. Carter (1976) noted pyrite nodules, clastic dykes, Bouma sequences, and Thalassinoides in the Mayne formation, and his thin section analyses show that the Mayne formation sandstone is arkosic wacke and arenite.

North Pender Island

The Mayne formation is exposed at the head of Otter Bay, Mayne Island. Hudson (1974) describes the formation as thin bedded, planar laminated mudstone interbedded with thin to thick bedded sandstone and planar laminated siltstone. Hudson recognized Bouma T_{BC} and T_{CD} sequences, pyrite-marcasite nodules and bands, and fine grained sandstone rip-up clasts in the succession. The sandstone is arkosic wacke according to Hudson's (1974) thin section analysis.

Saltspring Island

The Mayne formation underlies Long Harbour and crops out locally along its peripheries on Saltspring Island. The section here is siltier than equivalents on the outer Gulf Islands, comprised of thin bedded planar laminated siltstone and shale with minor fine grained sandstone. There are up to 10-15 beds per meter. Bedding contacts are sharp and regular. Burrows and calcareous worm tubes (Haggart, 1988a) are prevalent. Small ripple marks are present at the tops of some of the sandstones. Numerous soft sediment deformation features are present, such as large-scale slumps. Hanson (1976) reported that the upper part of the unit is mudstone rich and bioturbated.

Foraminifers from Saltspring Island exposures represent paleo-water depths of 100-200 m (Cameron, 1988b). Microfossils previously collected from basal Mayne formation on Saltspring Island by Hanson (1976) consisted mostly of land derived spores and pollen, with few marine dinoflagellates represented.

Gabriola Island

On Gabriola Island, the best exposures of the Mayne formation are at Descanso and Leboeuf Bays. At Descanso Bay, the section (Section 156) comprises 110 m of thin bedded mudstone and siltstone interbedded with thin to medium beds of fine to medium grained sandstone. The siltstone is commonly planar laminated and the sandstone is commonly trough or ripple cross-laminated. The bases of some of the sandstone units scour into underlying beds with shale rip-up clasts along the small channel margins. Limonitic bands are present. Contacts in general are sharp and regular. Bioturbation is noted in the siltstone, and Cladichnus is present. Small pelecypod shells are locally present. The top of the section contains fewer coarser grained alternations, and is conformably overlain by the Gabriola Formation with a sharp contact.

At Leboeuf Bay (Sections 166 and 167) the Mayne formation is comprised of ca. 100 m of thin bedded shaly siltstone and shale, interbedded with thin to medium, fine grained sandstone. Bouma T_{ABCD}, T_{BCD} and T_{CD} sequences occur, with well developed convolute laminated and disrupted layers (Plate 12b). Large flame structures and load casts adorn some of the sandstone bases. Iron stained concretionary nodules of marcasite (Packard, 1972) and coal debris are present in the middle of the unit. Also in the middle, is a massive, thick sandstone bed which crudely grades from medium grained sandstone to a well burrowed siltstone at the top. Dish structure is crudely developed, and numerous sandstone dykes and sills are associated with this bed. The contact with the overlying Gabriola Formation is sharp, as at Descanso Bay.

Deep water conditions are indicated by the microfauna recovered from the Descanso Bay section: 600-800 m paleo-water depth and much down-slope transport is indicated (Cameron, 1988b). Out of four samples at Leboeuf Bay, Cameron (1988b) recovered one fairly diverse microfauna indicating 200-300 m paleo-water depth, and oxygen deficient conditions. The other samples yielded shallower water faunas, indicating considerable down-slope transport.

Gabriola Formation

Tumbo Island

In the Tumbo Island area, the Gabriola Formation is partly exposed, consisting of, in ascending order, ca. 100 m of cross-bedded, medium to coarse grained sandstone; a covered, recessive interval ca. 120 m thick; ca. 90 m of cross-bedded sandstone with floating cobbles and pebble conglomerate interbeds; and ca. 80 m of cobble conglomerate. The contact with the underlying Mayne formation is not exposed, but was penetrated in a shallow coal exploration borehole located on Tumbo Island (Blakemore, 1910). The base of the exposure is close to the base of the Gabriola Formation. Thin sections of Gabriola sandstone from Tumbo Island examined by Sturdavant (1975) indicate that it is immature, arkosic and lithic arenite.

The basal sandstone is comprised of amalgamated, thick planar sets, typically 4 m thick by 10 m long, with rare fine to medium grained sandstone interbeds containing small coal debris. The set boundaries are typically low-angle truncation surfaces, others are remarkably flat erosion surfaces. Some trough cross-bedding is evident as well. The recessive interval is probably a fine grained unit. The upper sandstone displays planar sets, some of which are much larger than those of the basal sandstone (Plate 13a). One set is over 60 m long by 7 m high. The conglomerate unit is polymictic, poorly sorted, and generally matrix supported. The matrix is a tan, coarse grained sandstone. Clasts are well rounded to subangular, and of pebble to cobble size. Common constituents are sandstone, siltstone or silty tuff (typically of a distinctive pink colour), mudstone, greenstone, rhyolite, basalt and andesite, jasperoid and green chert; granodiorite and granite. The clasts are imbricated to the southeast. The matrix is generally disorganized, although some crude size grade alternation is evident. The unit is very thick bedded (up to 8 m) and massive. The upper part contains rare coarse grained sandstone lenses (3 m wide by 0.5 m thick). The borehole described by Blakemore (1910) penetrated 245 m of the Gabriola Formation, consisting of interbedded sandstone, conglomerate, and shale, with abundant thin coal stringers.

The Gabriola Formation crops out on Anniversary Island, east of Samuel Island, where it consists of thick bedded, massive or planar laminated, coarse grained to granule sandstone. Lenses of pebble conglomerate are common. Medium interbeds of fine grained sandstone with abundant shale rip-up clasts are present. The tops of some of the thicker beds show convolute lamination. Only ca. 50 m of section is exposed at this locality. Thin section examination reported by Stickney (1976) shows that the sandstone is an immature arkosic arenite.

Mayne Island

The Gabriola Formation crops out on Mayne Island, on Georgeson Island, and on a string of small islets to the southeast. The contact with the underlying Mayne formation at Miners Bay is transitional, consisting of several thick bedded sandstones interbedded with thin bedded, planar laminated mudstone and fine grained sandstone. In general, the lower beds consist of ca. 50-100 m of thick bedded, medium grained sandstone. They are either massive or crudely flat bedded. Overlying the sandstone, at Campbell Bay and beneath Hall Hill is silty shale (Usher, 1952) ca. 75 m thick. The remainder of exposed Gabriola Formation is dominated by sandstone. At Edith Point about 110 m of thick bedded coarse grained sandstone is exposed. Beds are massive, flat bedded, or cross-bedded with large low-angle planar foresets. Some of the thick beds are capped by planar laminated, fine grained sandstone. Convoluted flat bedding is locally observed. Pebble conglomerate lenses and load casts are present at the bases of some of the beds. Coal detritus and shale rip-up clasts are also present. These beds continue to David Cove where additional features observed are rare indistinct horizontal trace fossils on bedding tops, and some mudstone interbeds.

At Maude Bay, the Gabriola Formation is well exposed, consisting of: medium to thick beds of sandstone and mudstone which display sequences of crudely flat bedded, medium grained sandstone; convolute laminated, rippled, or trough cross-laminated, fine grained sandstone and siltstone; and mudstone (Bouma T_{BCD}); or massive coarse grained sandstone beds with fine grained sandstone or siltstone caps (Bouma T_{BD}). The latter beds have well developed load casts and flame structures at their bases, and contain numerous shale rip-up clasts. Vertical sand-filled burrows - Teichichnus - are present in some of the finer grained beds. Overlying these beds are planar cross-bedded sandstone, locally infilling scours up to 0.5 m deep; massive sandstone with rare shale rip-up clasts and crude dish structure; plus rare mudstone containing abundant sand-filled burrows. The section is overlain by thick bedded, very coarse grained to granule sandstone exhibiting good dish structure.

The top of exposed Gabriola Formation at Georgina Point consists of thick bedded massive coarse grained sandstone, interbedded with recessive siltstone and fine grained sandstone. About 250 m of section is exposed from Maude Bay to Georgina Point. Stickney (1976) notes the occurrence of conglomerate in the Gabriola Formation on Hall Hill, but confirms that the bulk of the unit is sandstone; in thin section examination he classifies the sandstone as arkosic wacke and arenite.

Galiano Island

The Gabriola Formation forms most of Galiano Island, with the thickest section - over 1150 m - exposed on the southeastern shore from Mary Anne Point to Salamanca Point. Muller (1983), Carter (1976), and Muller and Jeletzky (1970) consider the fine grained units in the Sturdies Bay vicinity to be the shale dominant horizon underlying Gabriola Formation, i.e. the Mayne formation (their "Spray" Formation). This is untenable given: a) the orientation of the beds which is the same as the beds on the other side of Active Pass; b) the known position of the Mayne formation on Mayne Island; and c) the obvious lack of any significant fault transverse to the strike of the beds, i.e. down the northeastern section of Active Pass, given the unfaulted contact between the Galiano and Northumberland formations on Mayne Island. The author considers the beds exposed north of Mary Anne Point to be the Gabriola Formation. Clapp (1914b) also correlated this section to the Gabriola Formation on Mayne Island, across Active Pass.

The southeastern shore section, in the lower part, consists of thick bedded, coarse grained sandstone, generally massive but with crude planar lamination and flat bedding developed locally. Pebble conglomerate lenses, floating pebbles and shale rip-up clasts are present. The middle and upper beds consist of alternating, interbedded, thick, coarse grained sandstone as described above and thin, fine grained sandstone and siltstone, but also include several dominantly fine grained intervals, such as at Sturdies Bay. Contacts are generally sharp and planar. Cross-lamination locally occurs in the fine grained sandstone. Sandstone dykes are locally developed. Carter (1976) reported minor occurrences of micrite in the upper section, as well as load casts, flame structures, and groove marks on the bases of some of the coarse grained sandstone beds, and burrows on some of the bedding plane tops. Carter (1976, p. 96) also noted the occurrence of asymmetrical ripple marks and heavy mineral lamination in some of the more fine grained beds.

The Gabriola Formation is in contact with the underlying Mayne formation in the Montague Harbour vicinity. Carter (1976) describes the contact as sharp but conformable, with groove marks and load structures. Lower Gabriola Formation in this area consists of cliff forming, very thick bedded, coarse grained to pebbly sandstone. Bedding is flat or massive. One section consists of, in ascending order: 2 m of planar laminated, fine grained sandstone with rare coal debris, convoluted at the top; 0.6

m of crudely graded, coarse to medium grained, trough cross-bedded sandstone with loaded base; 2 m pebbly sandstone with an erosional base (up to 0.2 m relief); overlain by many metres of massive, coarse grained sandstone. The pebbles in the sandstone are well sorted, subangular, and composed mostly of chert (green, red, and grey), rock quartz, and argillite.

To the northwest, the Gabriola Formation is exposed along the length of Galiano Island, forming prominent cuestas in the more resistant strata. At North Galiano the formation is composed of thick bedded, coarse grained sandstone, typically massive, interbedded with medium to thin bedded, coarse grained sandstone and planar laminated, fine grained sandstone. Coarse grained beds are locally gritty, with abundant shale rip-up clasts. Planar tabular cross-bedding and loaded bases are present in some of the thicker units. Thickening and coarsening upward sequences are observed, with thin bedded, fine grained sandstone at the base, to thick bedded, massive, coarse grained sandstone beds at the top.

At Dionisio Point, the same facies are developed with additional features being trough cross-lamination and rare coaly debris in some of the fine grained interbeds, and pebbly sandstone layers in the coarse grained units. Thin sections of Gabriola sandstone examined by Carter (1976) show that the formation ranges from arkosic wacke to arenite.

The Gabriola Formation extends across Porlier Pass to Valdes Island, where it forms much of the outcrop on the Island. Mexicana Hill and the shoreline outcrop north of Shingle Point Indian Reserve, however, is made up of older units (the Northumberland and Galiano formations) contrary to Muller and Jeletzky (1970) who place these rocks in the Gabriola Formation. The base of the Gabriola Formation crosses Gabriola Passage on the western side of Cordero Point to the eastern side of Degnen Bay on Gabriola Island. The Gabriola Formation is widely exposed on Gabriola Island, especially on the northern and southeastern coasts.

Gabriola Island

At the southeastern end of the island, the unit, in general, is composed of medium to thick bedded, coarse grained to granule sandstone, interbedded with planar laminated, fine grained sandstone. Several recessive intervals may be underlain by mudstone. Near Hoggan Lake on the southwestern side of the island, a short section in the Gabriola Formation consists of, in ascending order: 4 m of massive, coarse grained sandstone, thin parting of shaly siltstone; 0.5 m of coarse grained sandstone; 0.2 m of shaly siltstone; 4 m of massive coarse grained sandstone; thin carbonaceous siltstone with leaf imprints; 1 m coarse grained sandstone; thin shale parting; 2 m of massive coarse grained sandstone with pebble conglomerate lenses at its base. At Descanso Bay, the knife-edge contact of the Gabriola Formation with underlying Mayne formation is well-exposed.

The best exposures of the Gabriola Formation on Gabriola Island are from just east of Orlebar Point to Tinson Point on the northern shore (Section 167). Almost 350 m of section is exposed, in sharp but conformable contact with the underlying Mayne formation. Overall, the section is composed of thick bedded, massive, coarse grained sandstone, interbedded with medium to thin beds of medium to fine g[illegible] sandstone and siltstone, intercalated with short sections of thin bedded mudstone, siltstone and very fine grained sandstone. These latter units feature Bouma T_{BCD} and T_{CD} units. The coarse grained beds dominate, however, with individual beds reaching 5 to 8 m in thickness. Although most of the beds are massive sandstone plus fine grained sandstone couplets, some graded sandstone is noted, especially in the upper part of the section where full Bouma T_{ABCD}, T_{BCD}, and T_{CD} sets are developed (Plate 13b). Contacts are general sharp and planar to slightly undulating with some scouring and loading observed, and bedding is flat, although some large low-angle planar cross-bedding is noted. Large spherical calcareous concretions (up to 1.5 m in diameter), shale rip-up clasts, and floating pebbles, are common in the thicker sandstone. Convolute and planar lamination, ripple marks, and trough cross-lamination is locally developed in the interbedded fine grained units. Dish structure is especially well developed in some beds. Coaly debris is present in some of the finer grained units, especially in the upper half of the section where thin detrital coal seams occur. Some bedding plane tops in this upper part reveal feeding traces and burrows in abundance; notable forms are *Thalassinoides* and *Granularia*?. Thin section analysis of the Gabriola Formation sandstone by Packard (1972) reveals that it is arkosic wacke.

Comox Formation

Cottam Point

The type exposure of the Cottam Point member and the basal unconformity are at Cottam Point, east of Parksville. There the member consists of a poorly sorted, clast supported, boulder conglomerate, composed of angular to subangular clasts of metasedimentary rocks, in a greenish-grey gritty sandstone matrix (Plate 14b). Relief of up to 2 m is visible on the unconformity. The stratigraphic separation on the thrust fault between the Cottam Point member conglomerate and Parksville member sandstone (bearing Schmidti Zone index fossils) at Cottam Point is uncertain. It is possible that fault separation is small, and the conglomerate and the sandstone are of similar age. Support for this notion is based on comparison of beds at Northwest Bay to the section exposed on southern Lasqueti Island. The sections look similar, and both contain <u>Pterotrigonia</u> <u>evansana</u>, but the conglomerate is associated with the sandstone on Lasqueti Island. Alternatively, stratigraphic separation on the fault is much larger, and the conglomerate is much older than the sandstone. The sandstone formation on northern Lasqueti Island, in the Scottie Bay area is either a young part of the Nanaimo Group or an equivalent of the Burrard Formation (in Whatcom Basin) based on the occurrence of uppermost Cretaceous to Lower Tertiary pollen (Muller and Carson, 1969). The sandstone is glauconitic and about 100 m thick (Bickford, 1986).

Englishman River Area

At Englishman River Falls, the basal conglomerate member consists of poorly sorted cobble to boulder conglomerate resting on basalts of Karmutsen Formation. There the clasts are subrounded to well rounded, composed of basement rock. Some very large blocks of basement occur, possibly 3 to 4 m in diameter. Thick shelled pelecypod fragments are common in the coarse grained sandstone matrix. Stratification in the unit is poor. Muller and Jeletzky (1970) estimate its thickness to be in excess of 120 m at that locality.

On the northwestern wall of Englishman River canyon, 2.5 km southwest of the falls, the Comox Formation sandstone contains <u>Inoceramus</u> <u>ex.</u> <u>gr.</u> <u>I .</u> <u>chicoensis</u>, and several other pelecypods (Jeletzky, 1983).

The Comox Formation crops out over large parts of the Moriarty Lake, Dash Creek, and Fourth Lake areas, where it is intruded by numerous Catface Formation sills (Bickford, 1986). In the upper reaches of South Englishman River, the formation consists of thin to medium bedded, very fine to coarse grained sandstone, with occasional floating pebbles and pebbly lenses, scattered worm burrows, and rare pelecypod shells (Bickford, 1986).

North of Bell Creek, about 4 km southeast of Fourth Lake, the Comox Formation comprises thick bedded, poorly sorted conglomerate, with carbonaceous sandstone interbeds. The sandstone is concretionary, and contains abundant coal debris, plant imprints, and mollusc shells. The conglomerate is well indurated, clast supported, and contains pebble to cobble size clasts of argillite and variably metamorphosed green volcanic rocks. West of Fourth Lake, the Comox Formation consists of up to 55 m of boulder to cobble conglomerate (C.J. Yorath, personal communication, 1988).

Borehole BP#1 penetrated over 225 m of Comox sandstone and conglomerate, intruded by a 55 m sill. Borehole BP#2 penetrated about 16 m of Comox sandstone and conglomerate with a few minor sills, resting on granodiorite, and BP#3 intersected about 145 m of sandstone overlying 47 m of conglomerate, overlying granodiorite. Borehole BP#8 penetrated only 7 m of Comox Formation sandstone and conglomerate between the Trent River Formation shale and the Karmutsen Formation. In borehole BP#6 a thick section of the Comox Formation was encountered below the Trent River Formation at a depth of 334 m, comprising 191 m of sandstone with two thin sills, overlying 21 m of conglomerate.

Little Qualicum River Area

The Comox Formation is thin at Little Qualicum Falls, consisting of fossiliferous granitic clast conglomerate and carbonaceous fine grained sandstone unconformably overlying granodiorite basement (C.J. Yorath, personal communication, 1988). Between the Little Qualicum River area and Deep Bay, the Comox Formation generally is not exposed; however, it has been intersected in boreholes on the coastal plain. In borehole BP#5, about 30 m of Comox Formation sandstone was penetrated below 300 m. The Comox Formation is 56 m thick, below 351 m in borehole BP#7. In borehole BP#11, the Comox Formation sandstone was encountered between 548 and 622 m, overlying either the Trent River or Comox Formation shale between 622 and 656 m.

Central Area

The main body of the Comox Formation crops out between Deep Bay and Oyster River. Based on borehole data (Muller and Atchison, 1971), the formation is up to 250 m thick in the Tsable River area, and up to 270 m thick in the Cumberland area. According to MacKenzie (1922) the formation is dominantly composed of thick bedded, fine to medium grained sandstone, with subordinate coal, carbonaceous shale, and locally developed basal sedimentary breccia and conglomerate. There are lenses of pebble conglomerate, and thick cobble to boulder conglomerate layers, within the formation (Usher, 1952).

The basal conglomerate is best described as a texturally heterogeneous basal breccia. Bickford and Kenyon (1988, p. 448) describe the member as consisting of up to 300 m of coarse conglomerate interlensed with sandstone, siltstone, and vari-coloured shale, with rare coal seams. The basal conglomerate is exposed at Wilfred Creek, where it consists of subangular clasts dominated by volcanic rock with subordinate granitic and metasedimentary rocks, in a fine grained sandstone matrix (Muller and Jeletzky, 1970).

The Cumberland member is best developed in the central area of the Comox Basin, where it comprises the main productive coal measures, up to 150 m thick. The coals are typically associated with marine strata. MacKenzie (1922) notes the occurrence of pelecypods in the roof of a seam mined at Cumberland. Usher (1952) reports that the pelecypods are thick shelled, littoral species, and records the occurrence of an ammonite shell in a similar position. Rare shell debris occurs in concretions associated with the coal measures at Hamilton Lake, and thin shelled pelecypods and brachiopods occur in siltstone overlying the No. 1 seam at Quinsam. A sample of the siltstone contained ostracods, a few megaspores, and gastropods, suggestive of a marginal marine environment (Cameron, 1988b).

Detailed correlation of the coal measures in the Cumberland area is presented by Muller and Atchison (1971, p. 12 and 14). There is marked relief on the unconformity, and distribution of the coal measures is, to a large degree, controlled by paleotopography (Muller and Atchison, 1971; MacKenzie, 1922).

The Dunsmuir member is also well developed in the central area of the Comox Basin, where it typically consists of thick bedded, medium grained sandstone, with minor coal, shale, and intraformational conglomerate. MacKenzie (1922) describes a channel fill conglomerate occurring in upper Comox Formation which varies from 18 to 183 m in thickness, and locally replaces productive measures. This conglomerate body is exposed on Tsable River, and at a roadcut located about 1 km northwest of the Tsable River mine. The succession at the roadcut consists of dark grey shale, overlain by 2 m of grey cobble to pebble sandstone, overlain by 1.5 m of thin bedded shale, overlain by 5 m of thick bedded pebble to cobble conglomerate, pebbly sandstone, and massive sandstone. A microfossil sample from the basal shale yielded a foraminiferal assemblage indicative of paleo-water depths of 50 to 150 m, in a fairly high energy environment, with a large amount of down-slope transport (Cameron, 1988b).

The conglomerate bodies occurring in upper Comox Formation and lowermost Trent River Formation have been considered by Muller and Jeletzky (1970) and Bickford and Kenyon (1988, Fig. 4-3-2) to be younger than the Comox Formation. None of the channel deposits have been dated, so it is just as likely that they are only slightly younger Comox Formation, as shown by MacKenzie (1922, p. 394-395).

The Comox Formation occurs at high elevations in Forbidden Plateau-Mount Washington area where it is locally intruded by Eocene Catface sills and dykes. The formation consists of variably hornfelsed conglomerate and sandstone.

Campbell River Area

The Comox Formation in northern Comox Basin is disposed in two main belts separated by a basement uplift extending from the Mount Washington area to Campbell Lake. Based on borehole data, the formation is up to 315 m thick in the Campbell River area (Muller and Atchison, 1971). Based on exposures on Oyster River, the formation may be greater than 650 m thick in that area (Muller and Jeletzky, 1970). Overall, there is little biostratigraphic control on the succession, and it is poorly exposed. The thick section exposed on Oyster River contains Naumanni subzone fossils, including _Bostryochoceras sp. aff. B. otsukai_, and includes over 125 m of basal conglomerate (Muller and Jeletzky, 1970). Bickford and Kenyon (1988) state that in this region, the Dunsmuir member is thicker, finer-grained, and contains some thicker coal seams, such as occur at Quinsam.

Alberni Valley Area

The Comox Formation is widely distributed in the Alberni valley area, where it comprises up to 300 m of sandstone with subordinate conglomerate. A more or less continuous outcrop belt extends from Bainbridge (north of Port Alberni) to Alberni Summit, and up Cameron River valley, below Mount Arrowsmith. Between Bainbridge and Bostock on the E&N railway, the Comox Formation consists of thick bedded, medium grained to granule sandstone, with carbonaceous siltstone interbeds. Coal debris and large branch and log imprints are common. Trough cross-bedding is locally developed. The contact with the overlying Trent River Formation is exposed, with the Comox Formation grading from thick bedded, medium grained sandstone, through 5 m of fine grained sandstone, overlain by 3 m of siltstone with small trough crossbeds, to massive, grey, concretionary shale and siltstone. At Cherry Creek, to the southeast, the formation is coarser-grained, comprising poorly sorted, pebble to cobble conglomerate, with a disorganized fine to medium grained sandstone matrix. Clasts are well rounded.

In the Alberni Summit-Cameron River area, the formation comprises three facies: a) thick bedded, massive, poorly sorted, cobble to boulder conglomerate, with a coarse grained to granule sandstone chloritic or rusty weathering matrix, composed of angular to subrounded clasts of argillite, shale, green and red chert, rock quartz, metasiltstone, schist, felsic volcanic rocks, and rare coalified branches; b) thick to medium bedded, pebbly sandstone, and fine to medium grained sandstone with pebble lenses, locally planar cross-bedded; and c) thin to medium bedded, locally laminated carbonaceous siltstone and mudstone, with pebble lenses, rare fossil leaf imprints, coalified branches and thin coal seams. A microfossil sample of the siltstone facies, taken just west of the sharp bend in Highway 4 on the western side of Alberni Summit, yielded a few poorly preserved foraminifers, indicative of a marginal marine paleoenvironment (Cameron, 1988b).

To the south, the Comox Formation forms an outlier at Patlicant Mountain, where it consists of ca. 95 m of pebble conglomerate overlain by 40 m of shelly and pebbly sandstone (C.J. Yorath, personal communication, 1988). In southern Alberni valley at Bainbridge Lake, the formation comprises thick bedded, angular boulder conglomerate, and fine grained sandstone bearing pelecypods and ammonites, resting unconformably on weathered basement (C.J. Yorath, personal communication, 1988). Northwest of Bainbridge Lake by 3.5 km, almost 300 m of the Comox Formation was penetrated, which is intruded by numerous sills. It comprises pebble to cobble conglomerate and very fine to coarse grained sandstone overlain by carbonaceous and coaly mudstone and fine to medium grained bioturbated sandstone (C.J. Yorath, personal communication, 1988).

In Port Alberni, isolated exposures of the Comox Formation consist of carbonaceous siltstone and shale, and thick bedded, medium to coarse grained sandstone with abundant coalified log and branch imprints and thin coal seams. A sample of the shale collected from the Comox Formation 0.6 km north of Katharine Point in Port Alberni, yielded no foraminifers, but some indeterminate shell debris, suggestive of marginal marine conditions (Cameron, 1988b).

From Port Alberni to Ash River, the Comox Formation is poorly exposed, in part because it is overstepped by the Trent River Formation. A few small outliers of polymictic, poorly sorted pebble to boulder conglomerate exist on the western side of the valley at McCoy Lake, Sproat River, and Robertson Creek. A large outlier of the Comox Formation forms the top of Thunder Mountain (Plate 1a), comprised of thick bedded, pebble to cobble conglomerate, and massive, medium to very coarse grained sandstone. The conglomerate consists of well rounded to angular clasts of argillite, grey and green chert, sandstone, siltstone, basalt and other volcanic rocks, with rare coal debris. Bickford (1986) reports inoceramid fragments in some of the siltstone clasts. The conglomerate is locally planar cross-bedded. The sandstone contains rare, large floating clasts of sandstone, siltstone, and mudstone. Muller and Jeletzky (1970) place these beds in their "Extension-Protection" Formation as they contain clasts of "older" Nanaimo Group; however, these clasts may have been derived from only slightly older Comox Formation.

The Comox Formation is widely distributed north of Ash River in the Alberni valley. In the main, it consists of medium to thick bedded, medium to coarse grained sandstone, and thin bedded, fine grained sandstone, siltstone, and carbonaceous mudstone with abundant coaly plant litter. The coarser grained sandstone is planar cross-bedded locally. Bickford (1986) reports the occurrence of large burrows in the sandstone.

A good section in upper Comox Formation is present on Lanterman Creek. According to Bickford (1986), the section consists of: a) thin to medium bedded, very fine grained sandstone, siltstone, and mudstone, with occasional medium to coarse grained sandstone layers, lenses of rippled, very fine grained sandstone, rare shell debris, and scattered burrows; b) very fine grained sandstone with pebble conglomerate lenses; and c) massive pebble conglomerate composed of greenstone and granodiorite clasts.

The Comox Formation crops out on the northeastern side of Alberni valley, 3 km northeast of Elsie Lake, where it comprises: a) medium to coarse grained sandstone, bearing pelecypods and gastropods; b) pebble conglomerate, with subrounded pebbles; and 3) coal (C.J. Yorath, personal communication, 1988). About 10 km to the southeast, along the valley wall, similar beds are exposed, comprising thick bedded, medium to coarse grained sandstone, interbedded with carbonaceous and locally concretionary siltstone, mudstone, and coal, and angular pebble to cobble conglomerate.

Trent River Formation

Englishman River Area

The Trent River Formation crops out discontinuously along 6 km of Englishman River below the falls. It comprises thin bedded, concretionary siltstone and mudstone, which is abundantly fossiliferous locally. At the first bend in the river below the lower falls, the author collected Eupachydiscus haradai, Hypophylloceras (N.) sp., Sphenoceramus orientalis, S. schmidti, Glyptoxoceras ?sp., Inoceramus sp., and Cymatoceras suciaensis (Haggart, 1988a). Ward (1978a) had previously collected Canadoceras yokoyami, C. multisulcatus, and I. schmidti from this locality. Scott (1974) collected foraminifers from the Trent River Formation in this area, which indicate an age for the formation of near the Santonian-Campanian boundary. A microfossil sample collected from the Trent River Formation about 4.5 km downstream of the locality referred to above, yielded foraminifers suggestive of paleo-water depths of 100 to 150 m (Cameron, 1988b).

About 5 km west of Englishman River falls, borehole BP#8 penetrated 198 m of Trent River Formation which is intruded by a sill. Roughly 3.5 km to the northwest, borehole BP#6 intersected 314 m of Trent River Formation These thicknesses are uncorrected for bedding dip.

The Trent River Formation crops out in several outliers south of the main part of the Comox Basin, at Labour Day Lake, and north of Moriarty Lake. The formation is intruded locally by the Catface Formation as clearly indicated in shallow boreholes (eg. BP#2) and surface mapping (Bickford, 1986). Scott (1974) collected "shallow" water foraminifers from the Trent River Formation in Moriarty Lake area.

Little Qualicum River Area

The Trent River Formation at Little Qualicum falls consists of thin bedded, fossiliferous shales and siltstone, overlying basement with a veneer of the Comox Formation. Ward (1978a) collected Didymoceras (B.) elongatum, Glyptoxoceras subcompressum, and Inoceramus orientalis from these beds. Muller and Jeletzky (1970) note that the Trent River Formation exposed on Qualicum and Little Qualicum River contains Naumanni Subzone fauna.

Between Little Qualicum River and Deep Bay, due to deep drift cover, control on distribution of the Trent River Formation is afforded only by coal exploration boreholes. Borehole BP#5, located 1.8 km northeast of Little Qualicum falls, penetrated 216 m of Trent River Formation overlying the Comox Formation. Borehole BP#9b, located 3.6 km north of Little Qualicum falls, intersected 300 m of the Trent River Formation. Borehole BP#7, located near Spider Lake, penetrated 133 m of Trent River Formation shale above the Comox Formation. Borehole BP#11, located 2.5 km west of the fish hatchery on Qualicum River, penetrated 430 m of Trent River Formation overlying the Comox Formation. Borehole BP#10, located near Bowser, penetrated over 522 m of the Trent River Formation shale. Inoceramus naumanni was collected from core from this borehole.

Deep Bay Area

From the Deep Bay area to the northwest, there are several river cuts which expose the Trent River Formation. In addition, numerous shallow boreholes have penetrated the formation in this area (Muller and Atchison, 1971), so its distribution is well constrained.

On the Ship Peninsula, the middle part of the Trent River Formation is exposed, comprising thin to medium bedded, fine grained sandstone, siltstone, and silty shale (Plate 16a). The sandstone is massive or planar laminated, and calcareous layers are common. Soft sediment deformation features are present, and a variety of horizontal and vertical trace fossils are featured on bedding plane tops. A microfossil sample from this locality yielded foraminifers suggestive of paleo-water depths of 50 to 100 m (Cameron, 1988b).

The Trent River Formation on Tsable River has yielded several ammonites. In the basal section are Eupachydiscus perplicatum and Hauericeras gardeni, and higher up in the formation are H. gardeni, Phylloceras sp., Didymoceras (B.) elongatum, and Glyptoxoceras ?subcompressum (Usher, 1952). Foraminifers collected by McGugan (1964) and Langhus (1968) from the Trent River Formation on lower Tsable River, are interpreted by Scott (1974) to range from Santonian to early Campanian in age. Scott believes that the foraminiferal assemblage is indicative of relatively "deep" paleo-water depth.

Trent River

A thick, more or less continuous, section through the Trent River Formation is exposed on Trent River. The lower section comprises thin bedded or massive, concretionary siltstone and mudstone, with abundant sandstone dykes, overlying the Comox Formation sandstone. Ammonites and pelecypods are locally abundant, including: Baculites chicoensis, Inoceramus orientalis, Glyptoxoceras subcompressum, Didymoceras (B.) elongatum, Inoceramus naumanni, Hauericeras gardeni, Eupachydiscus perplicatum, Polyptychoceras vancouverensis, Baculites bailyi, and Epigoniceras epigonum (Usher, 1952; Muller and Jeletzky, 1970; Ward, 1978a). Usher also collected H. gardeni on lower Bloedel Creek.

Overlying these beds is an intraformational conglomeratic unit (Muller and Jeletzky, 1970) assigned to the Tsable member. Overlying beds consist of homogeneous mudstone and siltstone, which contain: a) in the lower part, a Chicoense Zone faunal assemblage - Inoceramus vancouverensis, Canadoceras newberryanum, Baculites chicoensis, and Submortoniceras chicoense (Ward, 1978a); and b) in the upper part, a Vancouverense Zone faunal assemblage - Hoplitoplacenticeras sp., I. subundatus, I. vancouverensis, C. newberryanum, Pseudoschloenbachia cf. P. umbulazi, Pseudoxybeloceras cf. P. lineatum, and Ryugasella cf. R. ryugasensis (Ward, 1978a; Muller and Jeletzky, 1970). In the lower part of Trent River, south of Royston, the formation consists of thin bedded or massive, silty mudstone, with rare sandstone interbeds and local shell debris (Bickford, 1986). Based on borehole data, the Trent River Formation in the Royston area is greater than 350 m thick (Muller and Atchison, 1971).

Foraminifers have been collected from the formation on Trent River by McGugan (1964), Sliter (1973), and Scott (1974). Scott (1974) places the Trent River Formation below the Tsable member in the Santonian, and the overlying beds in the Campanian. Sliter (1973), based on 51 samples through the basal 216 m of the Trent River Formation also recognized the Santonian/Campanian boundary, but placed it at a lower level than did Scott (1974). Sliter interprets outer shelf to upper slope paleo-water depth of about 200 m for the foraminiferal assemblage from the lower 130 m of section, and slope paleo-water depths of 800-1000 m for the upper part of his section, indicating a significant deepening during deposition.

Courtenay Area

Silty shale of the Trent River Formation crops out on the Browns and Puntledge rivers west of Courtenay, and was penetrated in numerous boreholes in drift covered areas (Muller and Atchison, 1971). Numerous ammonites and pelecypods have been collected from these exposures. Lower Trent River Formation on Browns River contains a Naumanni Subzone faunal assemblage which includes *Schluteria selwyniana*, *Baculites chicoensis*, *Baculites bailyi*, *Glyptoxoceras subcompressum*, *Didymoceras (B.) elongatum*, *Inoceramus naumanni*, *Hauericeras gardeni*, *Eupachydiscus perplicatum*, *Polyptychoceras vancouverensis*, *Phylloceras sp.* and *Neophylloceras sp.* (Usher, 1952; Ward, 1978a). McGugan (1964) collected ?Santonian to Campanian foraminifers from the Trent River Formation on Browns River. The Trent River Formation on Puntledge River contains both Naumanni and Haradai Subzone faunal elements including all but the last three species found on Browns River, as noted above, and, in addition, *Eupachydiscus haradai*, *Pachydiscus binodatus*, and *P. buckhami* (Usher, 1952; Muller and Jeletzky, 1970; Ward, 1978a). A plesiosaur has been discovered recently in the Trent River Formation on Puntledge River (pers. comm. Dr. R. Ludwigsen, Denman Island).

In the Forbidden Plateau-Mount Washington area, Muller and Jeletzky (1970) report the occurrence of ca. 30 m of locally fossiliferous, variably hornfelsed, marine shale, which is assigned to the Trent River Formation. At Mount Washington, the formation consists of massive, carbonaceous, shaly siltstone.

Campbell River Area

To the north, the Trent River Formation is poorly exposed, and borehole control on distribution of the formation is sparse (Muller and Atchison, 1971). According to Muller and Jeletzky (1970, p.12), the Trent River Formation (their Haslam Formation) is absent in the Oyster River area. The first exposed beds overlying the Comox Formation on Oyster River are thin to thick bedded, poorly indurated, fine to medium grained concretionary sandstone, featuring large-scale, planar cross-bedding, robust pelecypods, and burrows (Bickford, 1986). As the intervening beds are not exposed, it is unclear whether or not the upper unit described above is a continuation of the Comox Formation or a sandy member of the Trent River Formation.

Texada Island

Small outliers of Nanaimo Group occur on Texada Island, in the Gillies Bay-Mouat Creek area, on the shoreline west-southwest of Mount Davies, and on lower Cook Creek. The Cook Creek exposures consist of poorly sorted boulder conglomerate and pebbly sandstone which contains a coquina bearing Schmidti Zone index fossils (Muller and Jeletzky, 1970). The Trent River Formation on Mouat Creek consists of massive, poorly indurated mudstone. A microfossil sample from here yielded foraminifers which are probably representative of upper slope paleo-water depths of 200-300 m, with some down-slope transport indicated (Cameron, 1988b). *Baculites occidentalis*, *B. chicoensis*, and abundant *Inoceramus vancouverensis* are present in the shale (Ward, 1978a; Muller and Jeletzky, 1970).

Denman Island

Upper Trent River Formation forms the western side of Denman Island, where it conformably underlies the Denman Formation. A maximum of about 300 m of section is exposed. On northern Denman Island, the Trent River Formation consists of massive mudstone and siltstone. A microfossil sample from this locality yielded foraminifers indicative of paleo-water depths of 150-400 m, with a strong oxygen deficiency (Cameron, 1988b). Sliter (1973) recovered foraminifers from the top 52 m of the Trent River Formation, at this locality, which he interprets to be indicative of slope paleo-water depths of 800-1000 m. McGugan (1964) collected upper Campanian foraminifers from western Denman Island.

Uppermost Trent River Formation shale which directly underlies the Denman Formation, east of the community of Denman Island, yielded foraminifers indicative of in paleo-water depths of 200-600 m, with a large amount of downslope transport (Cameron, 1988b). The contact is described under the section on Denman Formation.

On the shoreline, at the same latitude, a 15 m thick intraformational coarse grained unit is developed, comprising medium to thick bedded, pebble conglomerate and coarse grained sandstone, interbedded with fossiliferous mudstone and siltstone (Allmaras, 1978). Allmaras notes the occurrence of pelecypods, gastropods, inoceramids, ammonites, horizontal burrows, and *Zoophycus*. Fossils collected from these beds include *Metaplacenticeras cf. M. Pacificum*, *Inoceramus vancouverensis*, *I. subundatus*, *Baculites chicoensis*, and *Schluteria selwyniana* (Muller and Jeletzky, 1970; Usher, 1952). In the overlying fine grained beds, Allmaras (1978) observed Bouma $T_{(A)BCDE}$, $T_{(A)BCE}$, and T_{ABE} sequences, concretions, concretionary layers, thick shelled mulluscs, fragmented ammonites and inoceramids, and numerous sandstone dykes. A variety of trace fossils were observed by Allmaras, including ?*Planolites*, *Taenidium*, *Chondrites*, *Teichichnus*, *Scolicia*, and *Zoophycus*. The Trent River Formation sandstone examined by Allmaras (1978) is lithic wacke and arkosic to lithic arenite.

On southwestern Denman Island, the Trent River Formation also encompasses a coarse grained member, comprised of: a) shale with thick sandstone lenses containing floating pebbles, carbonaceous debris, and pelecypod shells; b) medium to thick bedded, pebble conglomerate and planar laminated, coarse grained sandstone, interbedded with thick shale units; and c) thick bedded, fine to medium grained sandstone, interbedded with siltstone and shale (Allmaras, 1978). Allmaras notes that within the conglomerate there are coal lenses, gastropods, inoceramids, and other pelecypods. The shale encompassing the coarse grained member is massive, concretionary, and contains thin limonitic bands and numerous sandstone dykes and injection pods. It is at least 400 m thick in this area, based on drillhole data (Usher, 1952). A microfossil sample taken from Repulse Point yielded foraminifers indicative of paleo-water depths of 800-1200 m, with evidence of down-slope transportation of terrestrial material (Cameron, 1988b).

The coarse grained beds occurring in upper Trent River Formation on Denman Island are informally referred to by the author as the Baynes Sound member. Due to the large stratigraphic separation between these beds from those beds assigned to the Tsable member as described below, it is inappropriate to include them in the Tsable member.

Alberni Valley

The Trent River Formation underlies large areas of the Alberni Valley, from China Creek in the southeast, to Lanterman Creek area in the northwest. The formation is also present at Patlicant Mountain where it is intruded by an Eocene sill. At the southern end of Alberni Valley, near China Creek, the Trent River Formation comprises thick bedded, massive shale, partly rusty weathering. A microfossil sample from this locality yielded a very high diversity foraminiferal assemblage, indicative of paleo-water depths of 200-300 m (Cameron, 1988b). Borehole BP#4, located 3.5 km northwest of Bainbridge Lake, intersected 27 m of Trent River Formation shale overlying the Comox Formation sandstone. The same contact is located at the surface in southeastern Port Alberni.

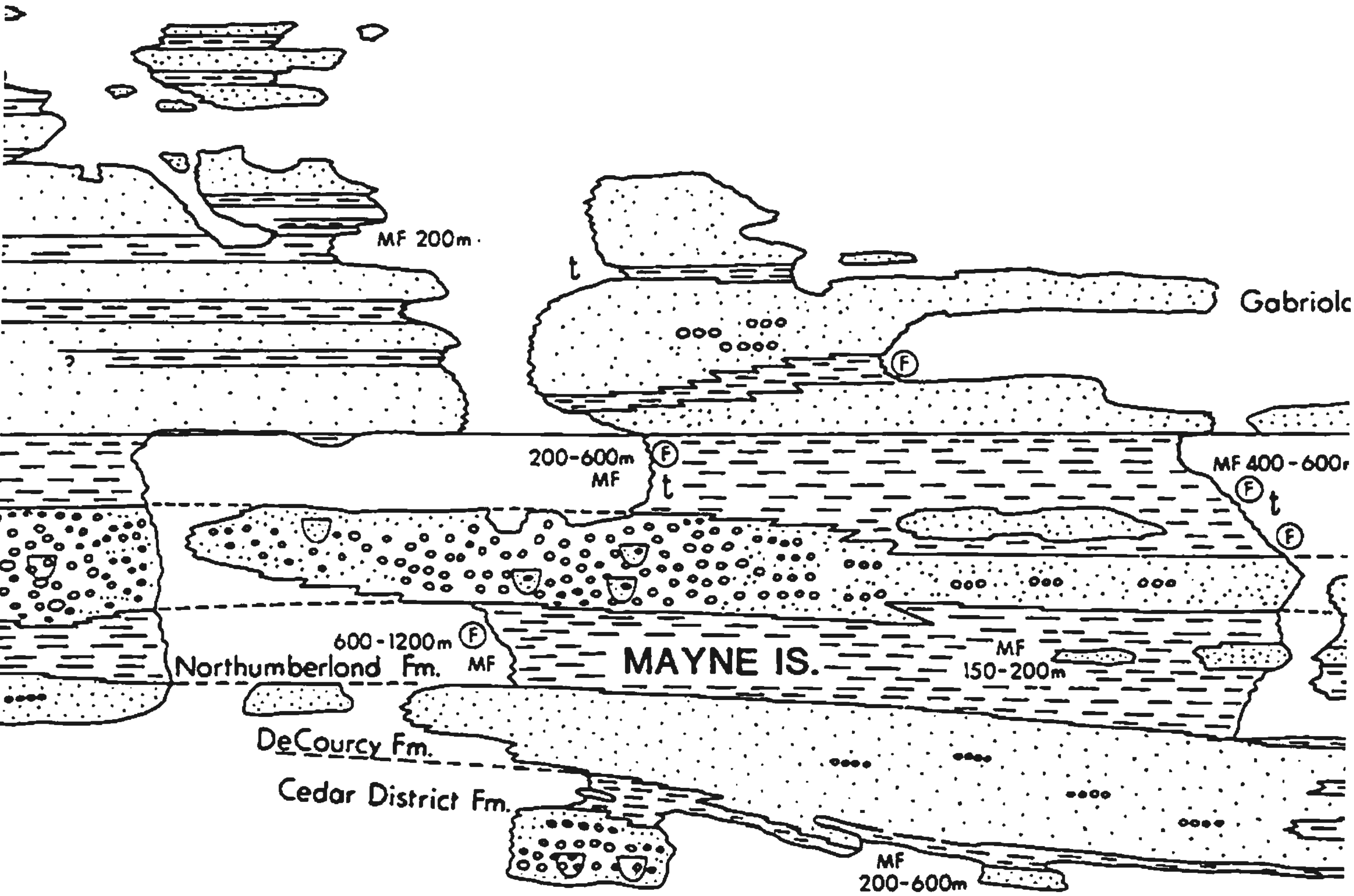
The most extensive outcrops of the Trent River Formation in Alberni valley, are in the Rogers Creek area, northeast of Port Alberni. In Rogers Creek the formation consists of thin bedded or massive, silty shale and siltstone. Foraminifers recovered from Rogers Creek are indicative of paleo-water depths of 200-600 m, with a moderate amount of down-slope transport (Cameron, 1988b).

On Highway 4, below Alberni Summit on the western side, the formation consists of massive silty shale or laminated shale with thin interbeds of very fine grained sandstone and siltstone. Foraminifers recovered from this locality are suggestive of paleo-water depths of 100-200 m, with evidence of oxygen deficiency and a firm substrate (Cameron, 1988b).

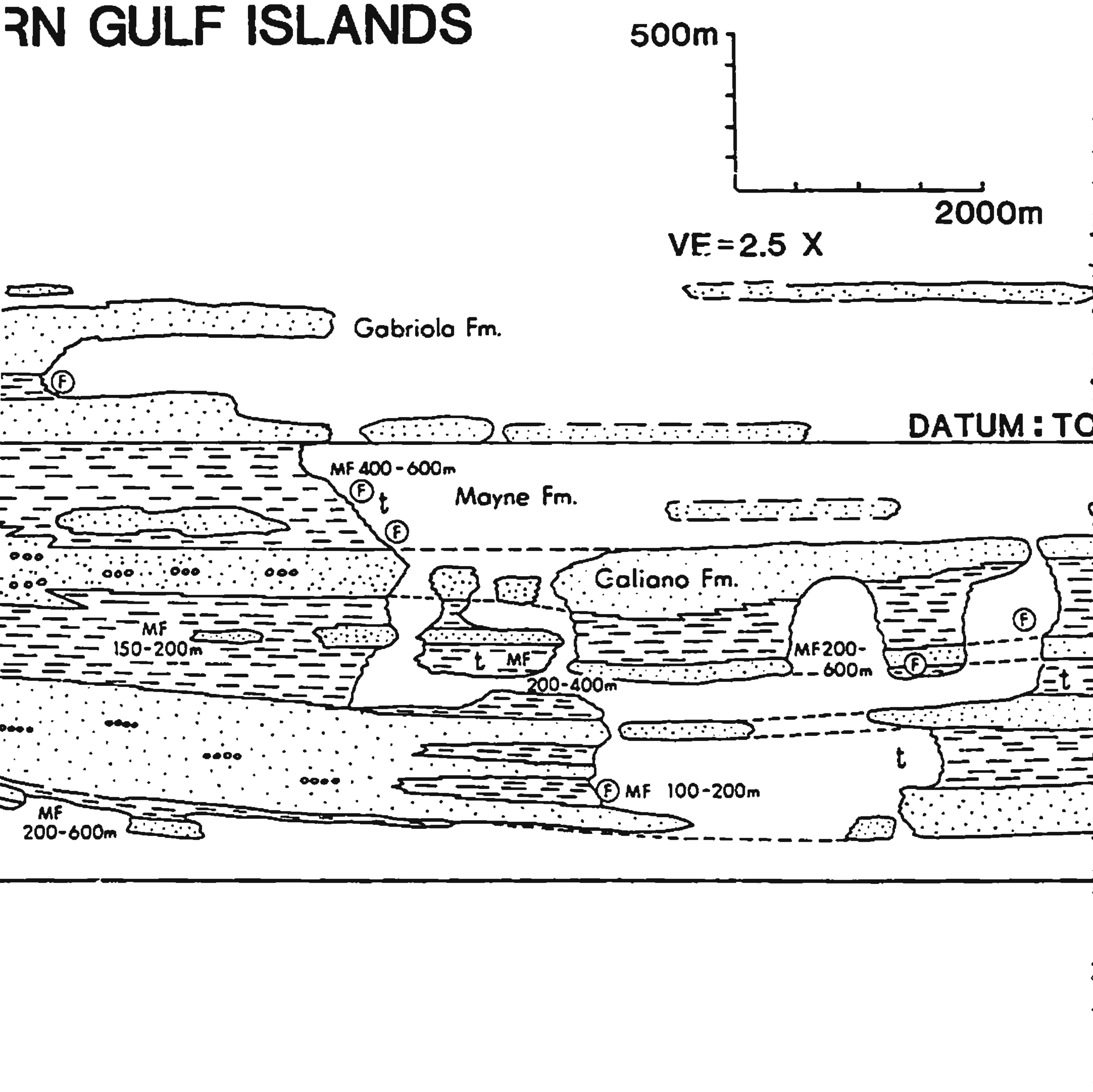
The Trent River Formation is poorly exposed in the remainder of the Alberni valley lying to the northwest. At

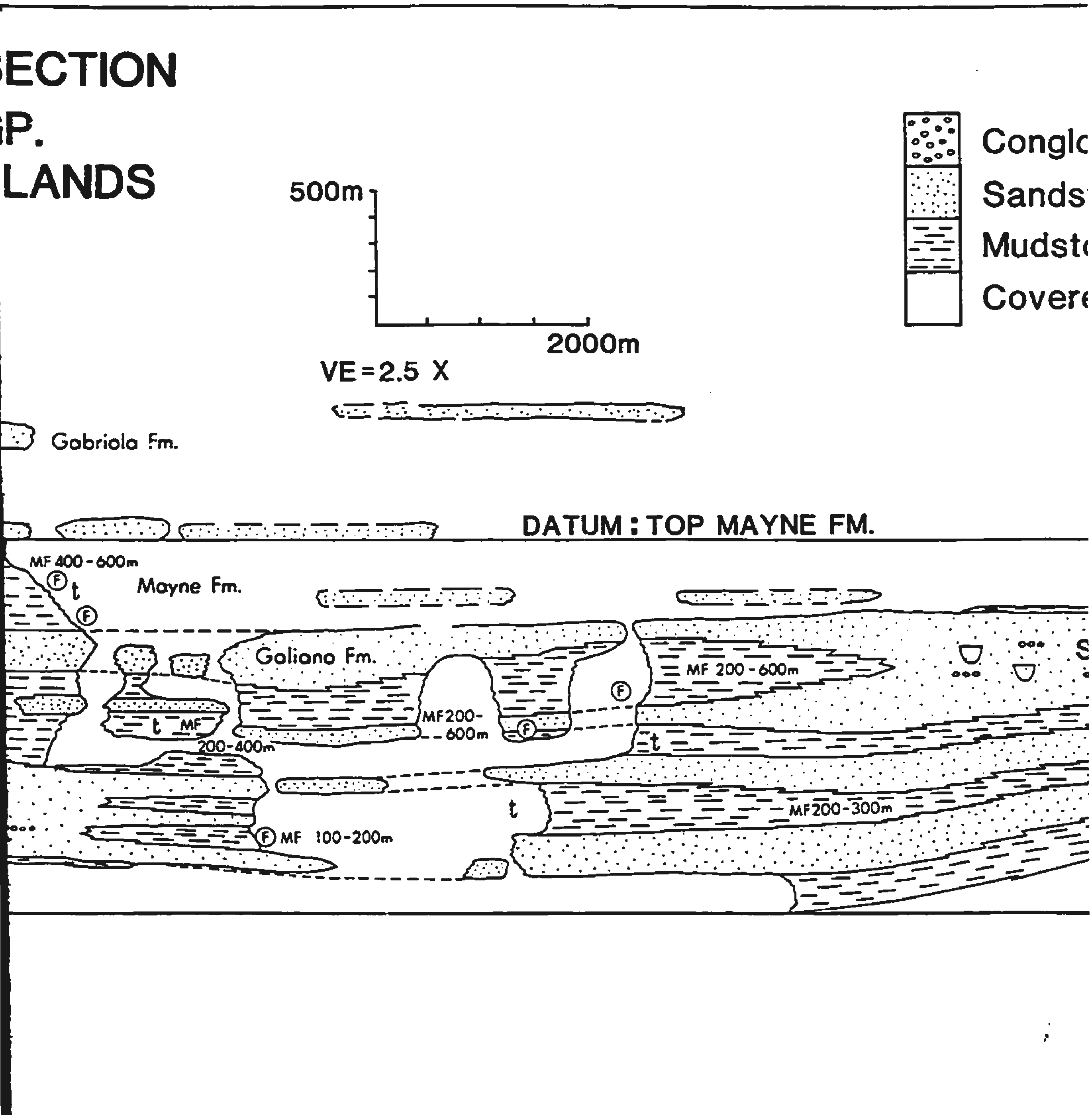
Figure 3.4

STRATIGRAPHIC CROSS-SECTIO
UPPER NANAIMO GP.
SOUTHEASTERN GULF ISLANDS

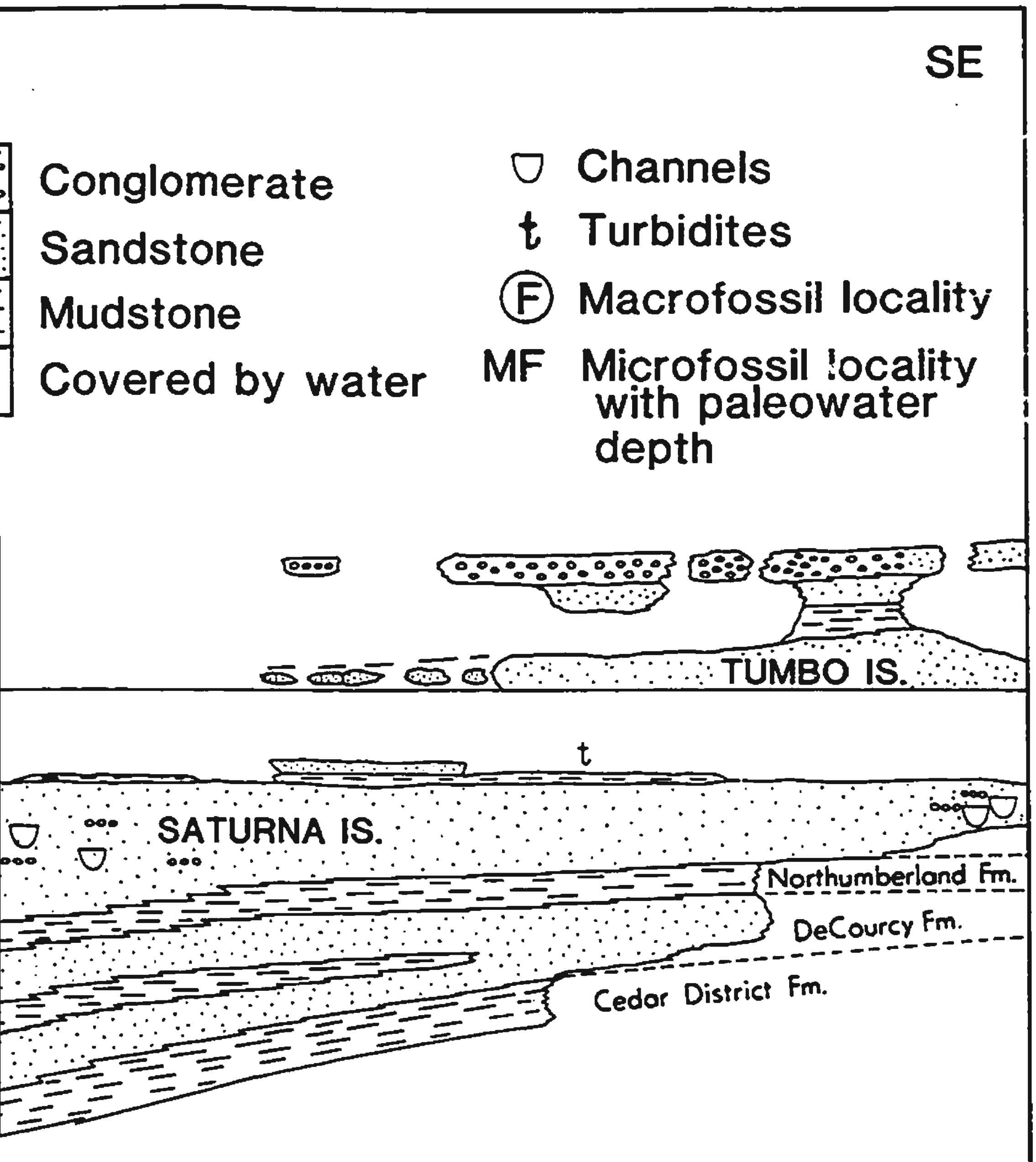


; CROSS-SECTION
NANAIMO GP.
RN GULF ISLANDS

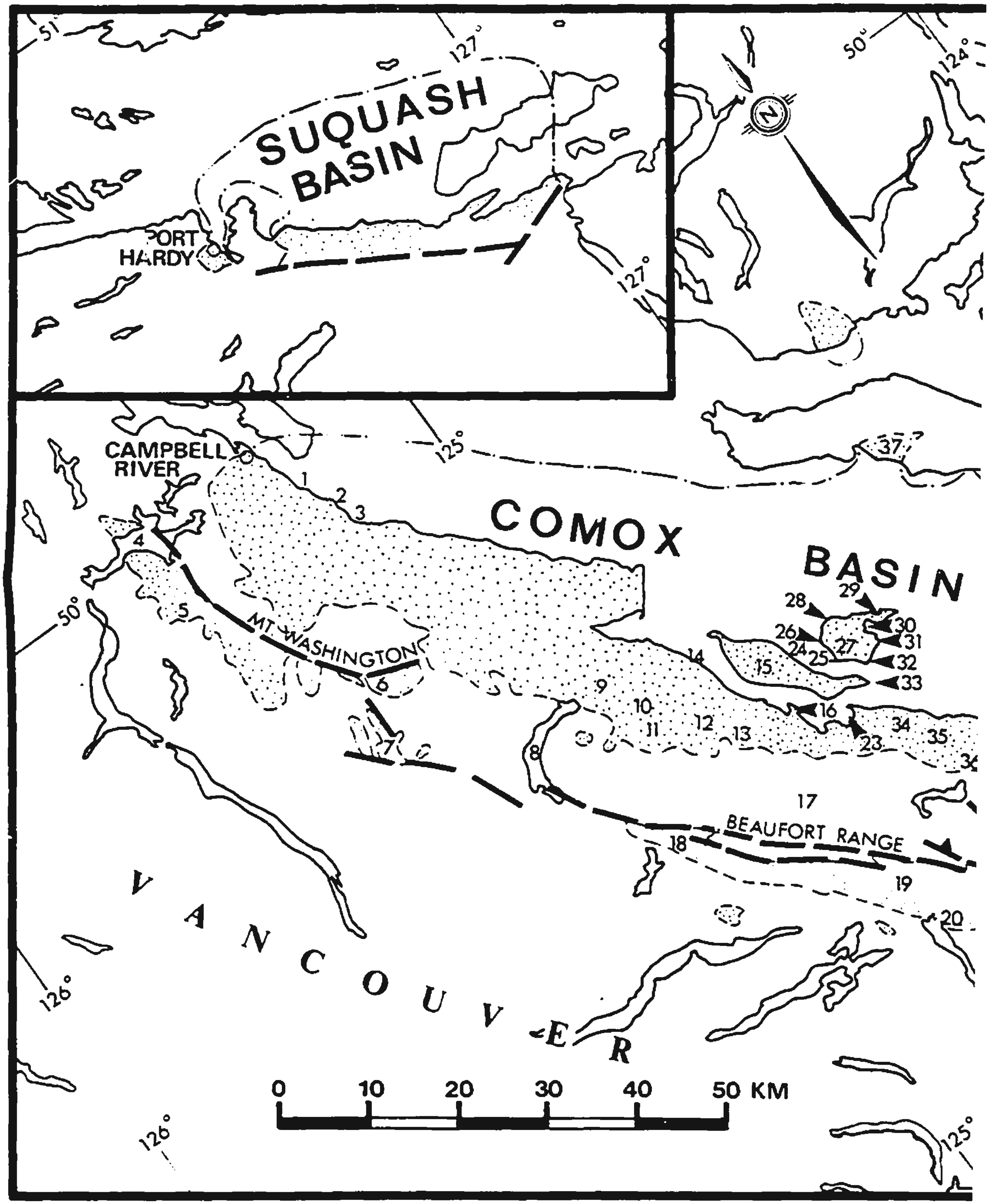




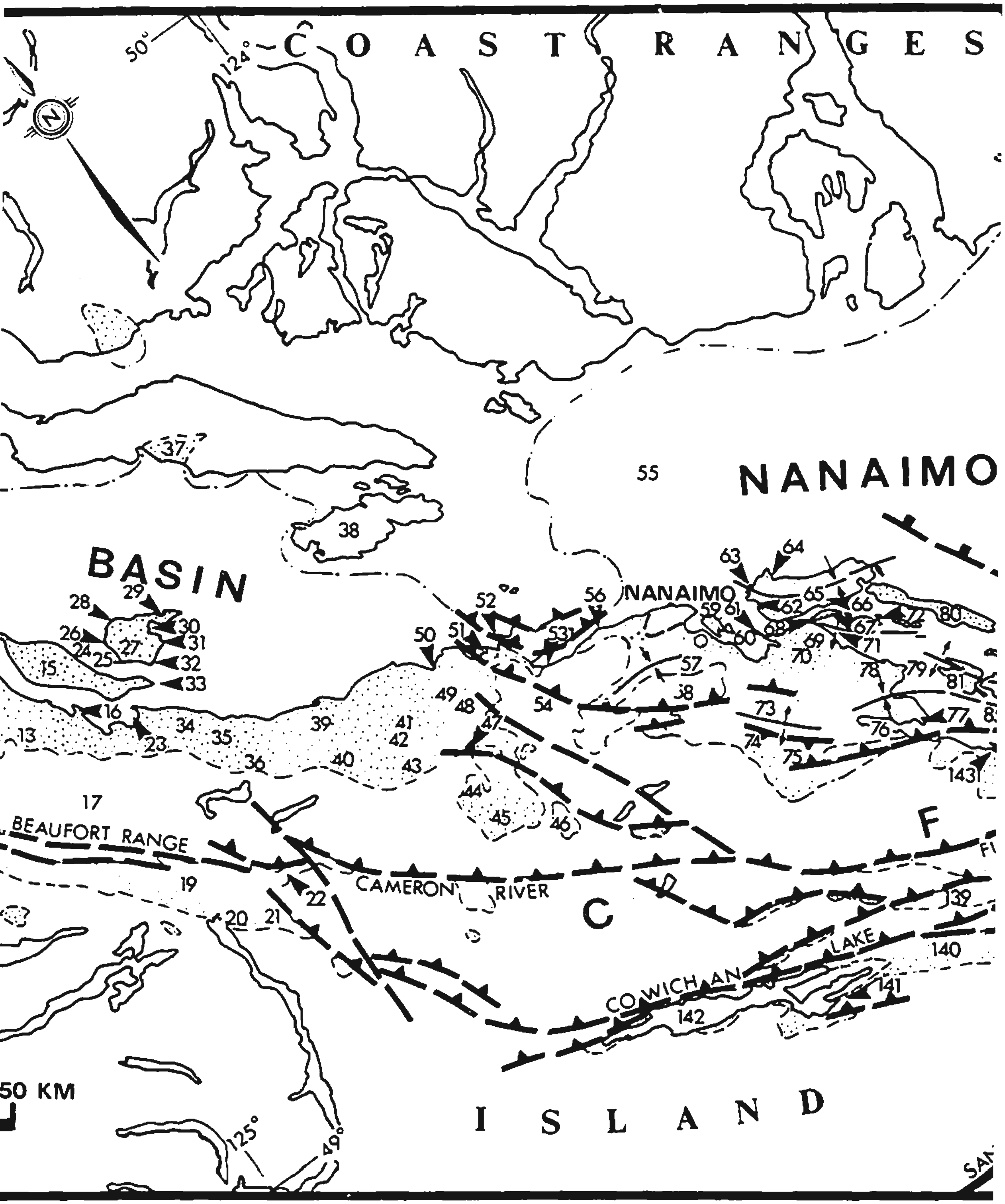
ECTION
P.
LANDS
500m
2000m
VE=2.5 X
Congl
Sands
Mudst
Cover
Gabriola Fm.
DATUM : TOP MAYNE FM.
MF 400-600m
Mayne Fm.
Galiano Fm.
MF 200-600m
MF200-600m
MF 200-400m
MF200-300m
MF 100-200m



Author : T.D.J. ENGLAND , 1989
F-512/1



SUQUASH BASIN
PORT HARDY
CAMPBELL RIVER
COMOX BASIN
MT. WASHINGTON
BEAUFORT RANGE
VANCOUVER
0 10 20 30 40 50 KM
51°
50°
127°
126°
125°
124°



COAST RANGES
50°
124°
NANAIMO
BASIN
NANAIMO
BEAUFORT RANGE
CAMERON RIVER
C
F
COWICHAN LAKE
50 KM
ISLAND
125°
49°

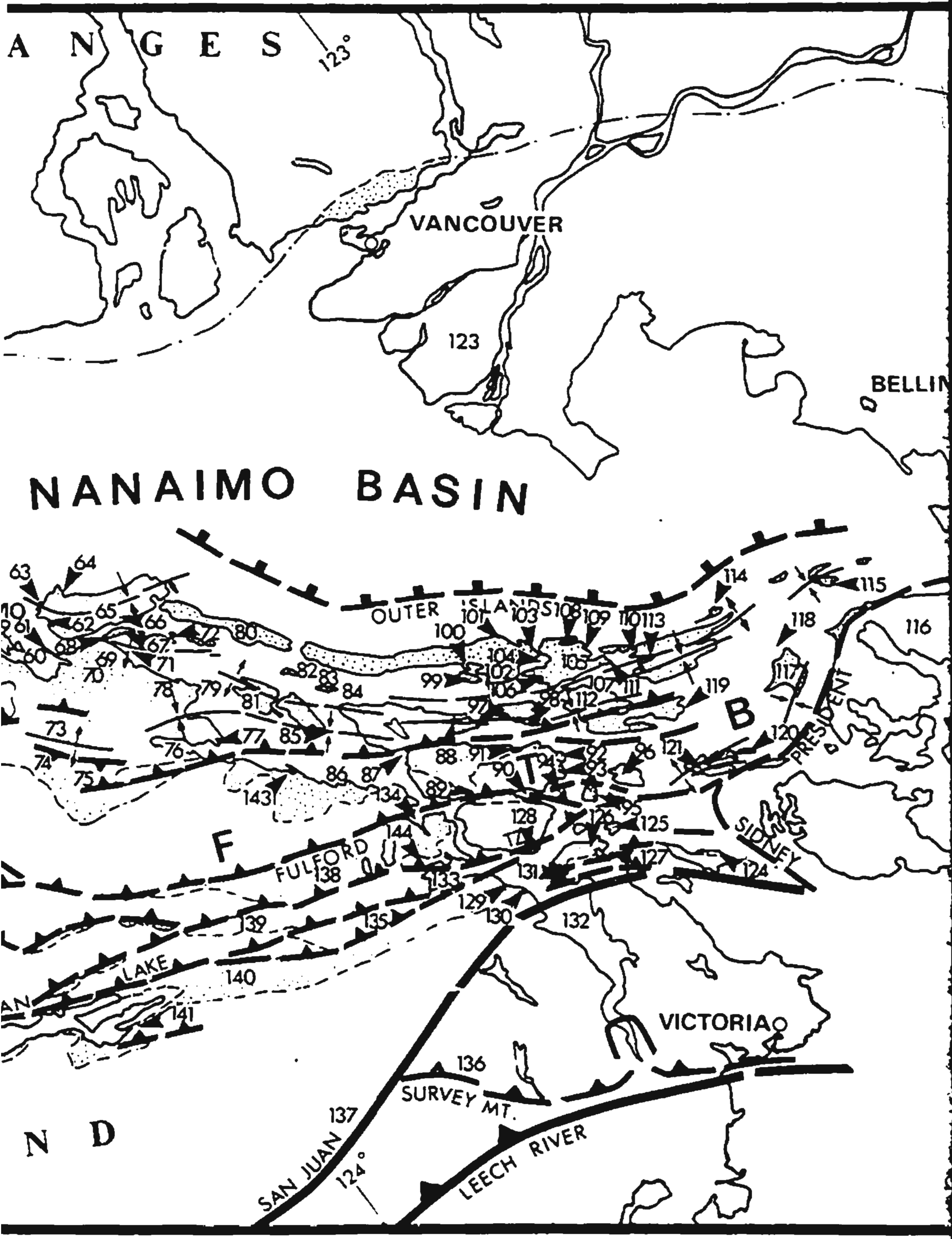
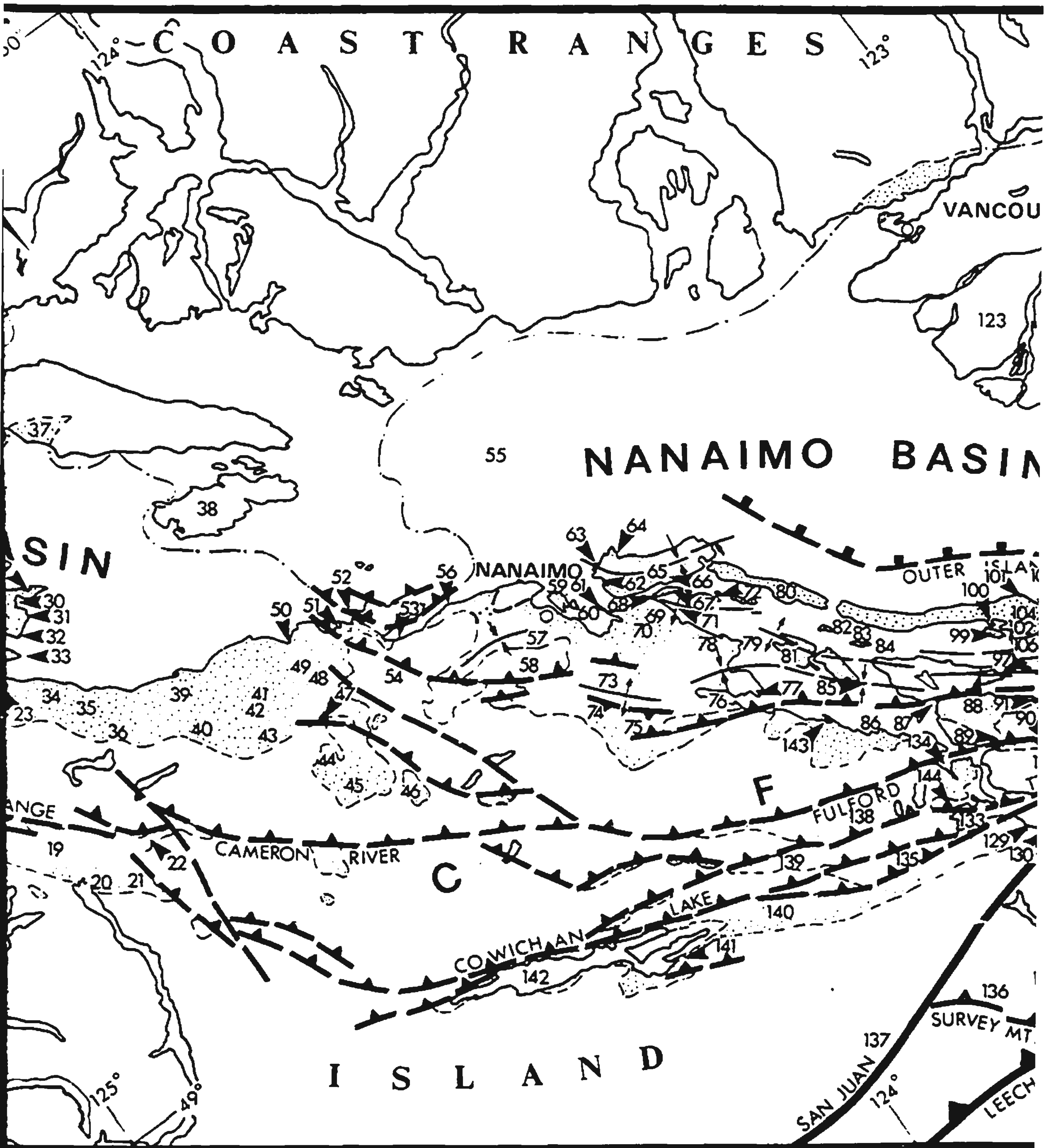


Figure A.1 Location guide.



COAST RANGES
124°
123°
VANCOU
123
NANAIMO BASIN
55
37
38
SIN
NANAIMO
OUTER ISLA
CAMERON RIVER
C
F
FULFORD
COWICHAN LAKE
ISLAND
SAN JUAN
SURVEY MT.
LEECH
125°
49°
124°
ANGE
19
20
21
22
136
137
138
139
140
141
142
143
144

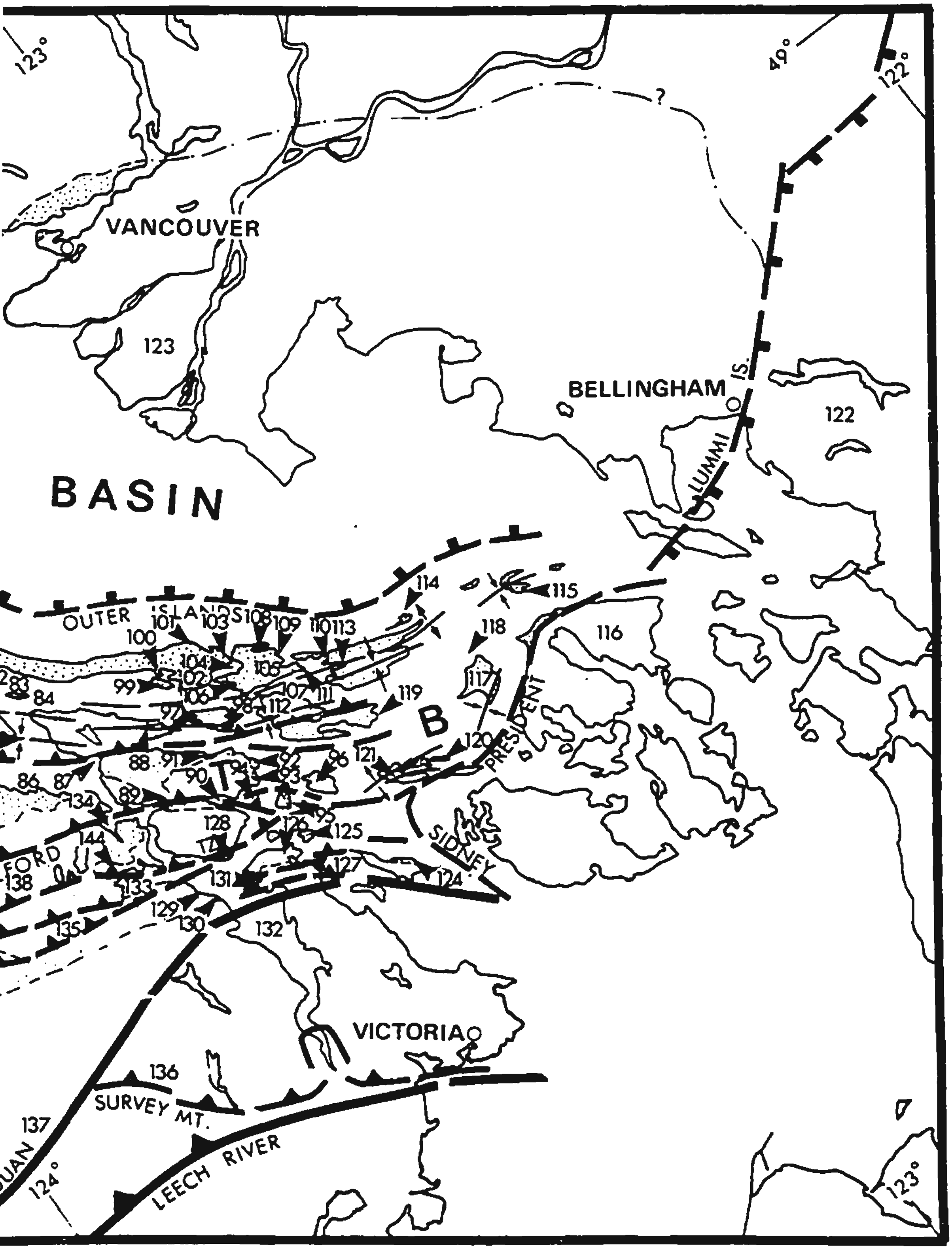


Figure A.1 Location guide. See Appendix A.

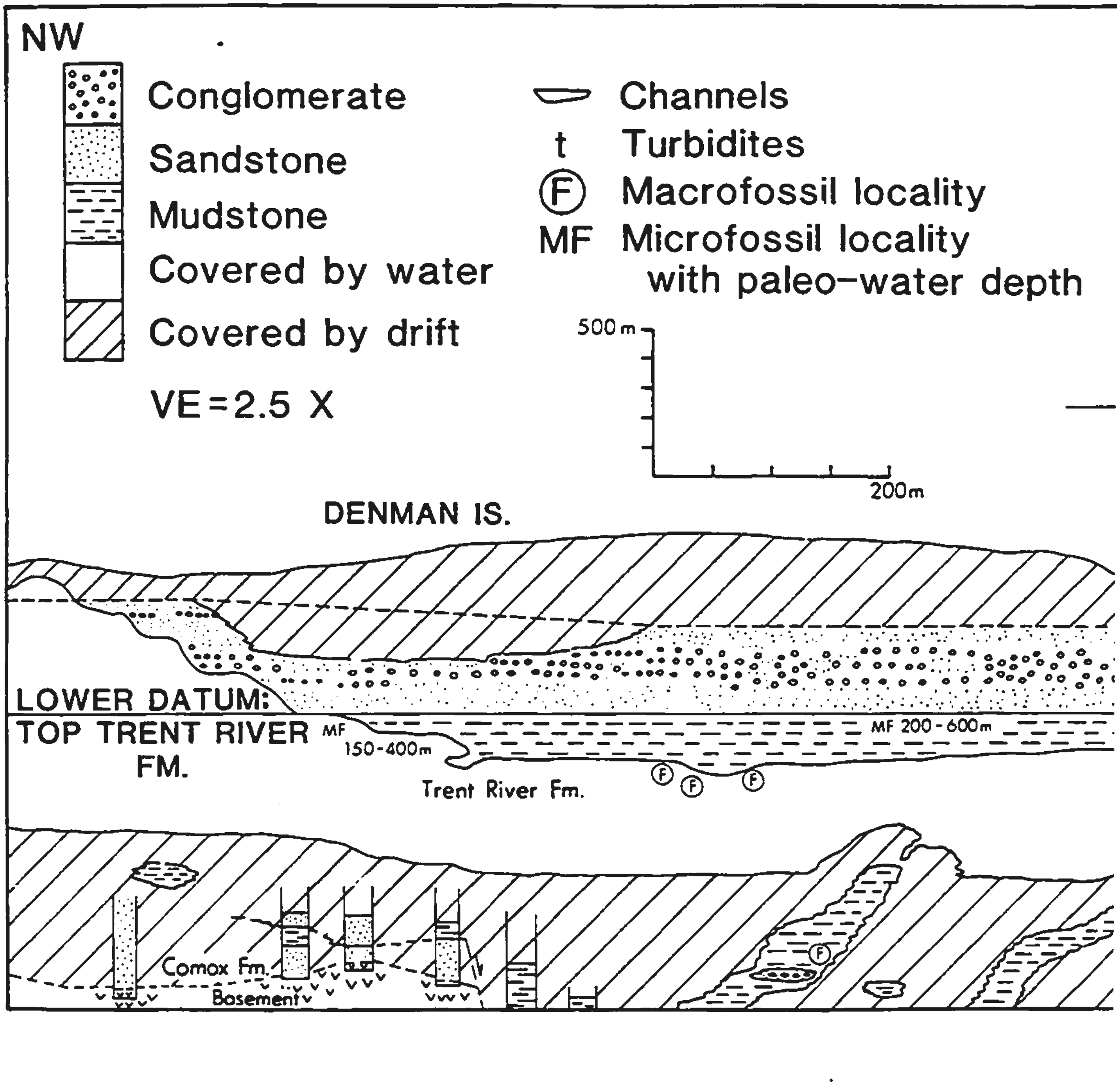
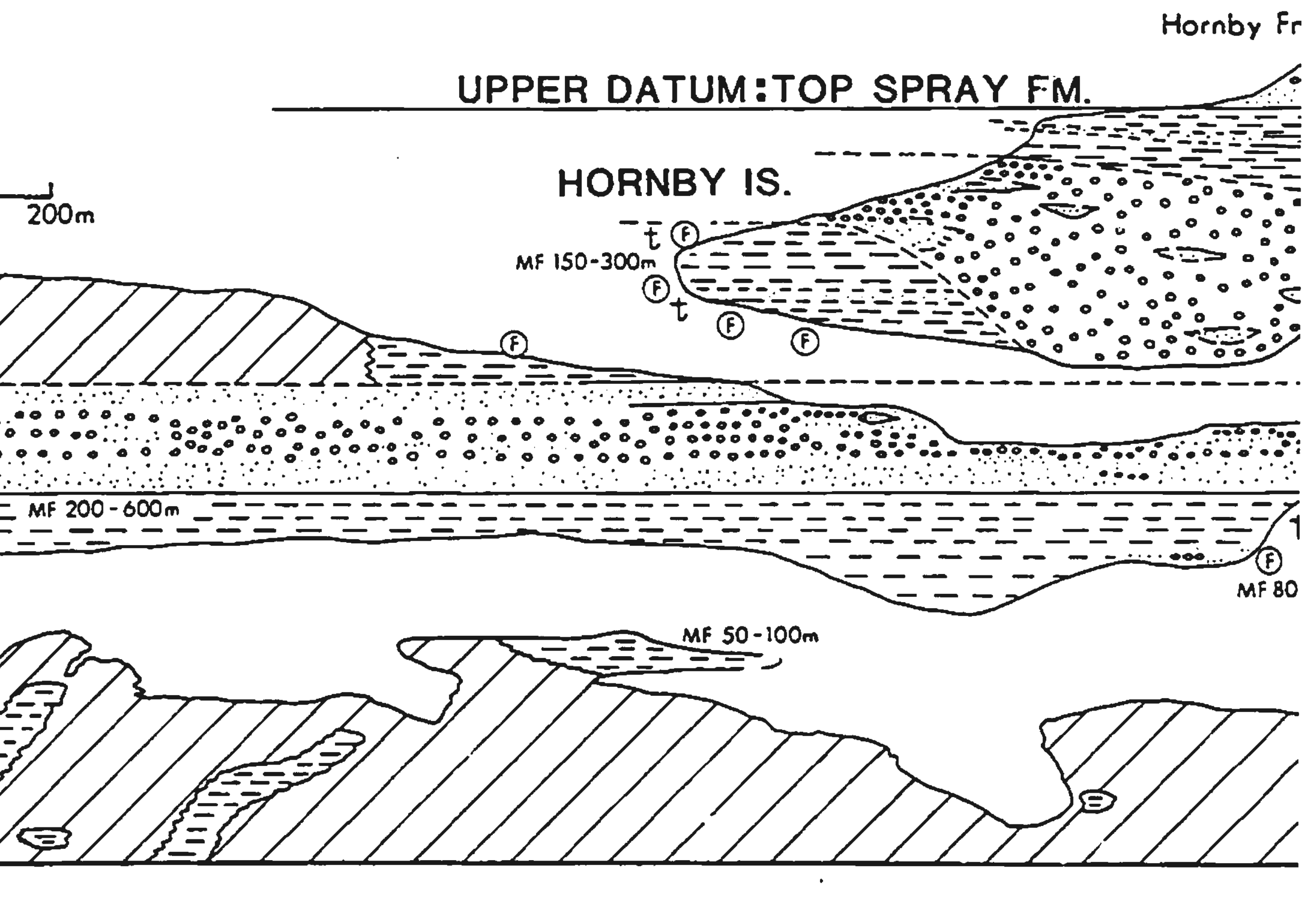
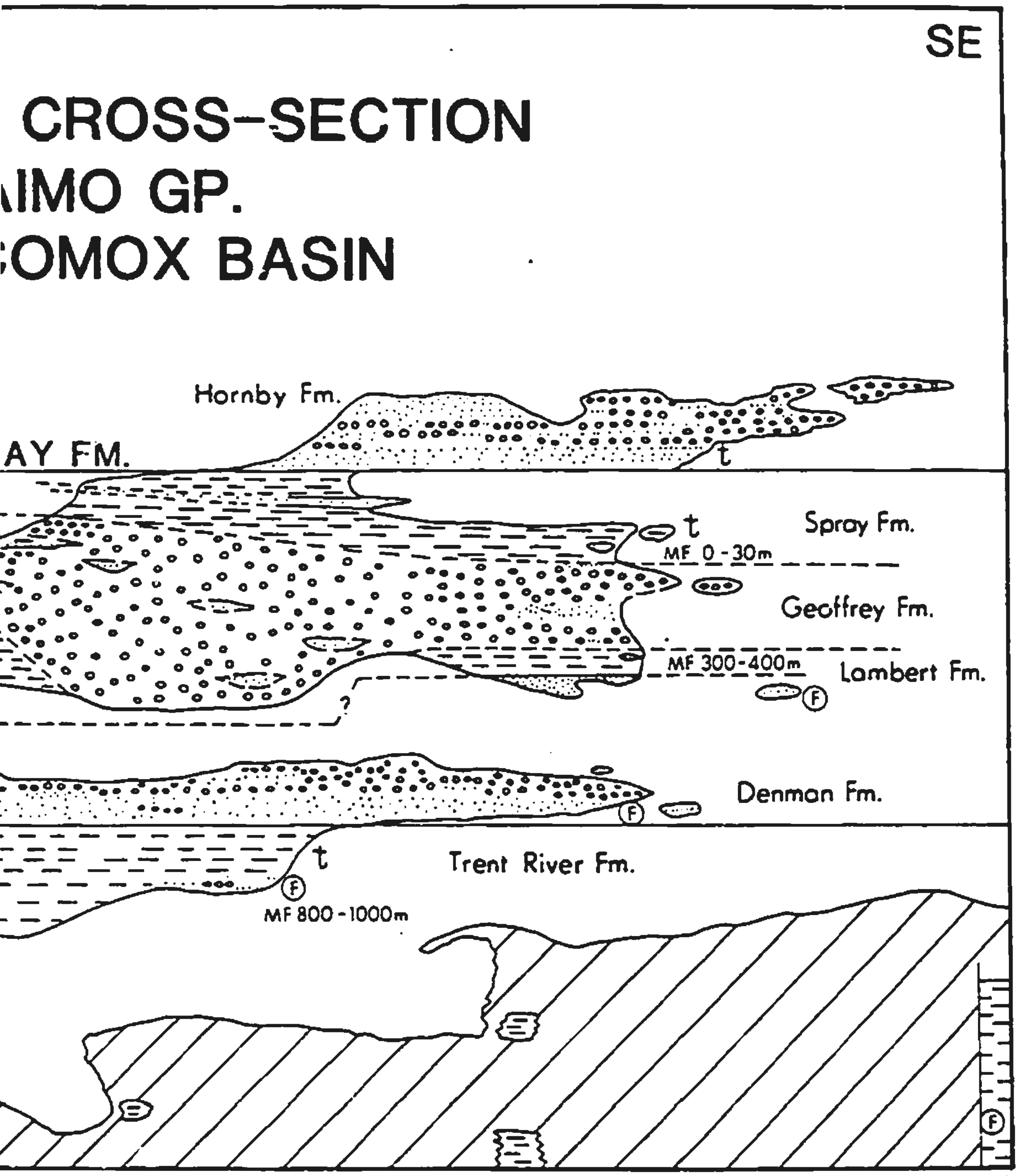

NW
Conglomerate
Sandstone
Mudstone
Covered by water
Covered by drift
VE=2.5 X
Channels
t Turbidites
F Macrofossil locality
MF Microfossil locality with paleo-water depth
500m
200m
DENMAN IS.
LOWER DATUM: TOP TRENT RIVER FM.
MF 150-400m
MF 200-600m
Trent River Fm.
Comox Fm.
Basement

Figure 3.3

STRATIGRAPHIC CROSS-SE
NANAIMO GP.
CENTRAL COMOX BAS

locality
ocality
-water depth





Author : T.D.J. ENGLAND , 1989

F-512

FORMATION	ZONE INDEX FOSSILS		SU	SU	SU							SU				P	V							C	C
	LOCALITY	ZONES PRESENT AT LOCALITY	P.SUCIAENSIS	P. INDRA	P.OCTACODE	N.HORNBYE.	P.FORBESIA.	A.COOPERI	N.RAMOSUM	GAUDRYCERA	H.OBSTRICTU	D.NOTABILE	N.LAMBERT.	B.OCCIDENT.	G.DENMANEN	M.PACIFICUM	H.OPLITOPLAC	I.SUBUNDATUS	I.VANCOUVER	C.NEWBERRY.	P.UMBULAZI	S.SELWYNIAN	R.PYUGASEN.	B.CHICOENSIS	S.CHICOENSE
LAMBERT	HORNBY IS (C)	SU	1	1	1								1	1											
LAMBERT	HORNBY IS (B)	SU	1	1	1	1	1	1	1		1			1											
LAMBERT	HORNBY IS (A)	SU	1	1	1			1	1	1		1		1											
LAMBERT	DENMAN IS (E)	SU?													1										
D.	NORRIS ROCK	SU?													1										
O.	SHELTER PT	SU, V?	10?	10	10	6														6					
TRENT RIVER	DENMAN IS (W)	P														5		5	5			1			
TRENT RIVER	TRENT RIVER(C)	V													5		6	5	6	5,6	5		5		
TRENT RIVER	TRENT RIVER(B)	C																	6	6				6	6
TRENT RIVER	TEXADA IS.	C,S												5										6	
TRENT RIVER	LASQUETI IS	S?																							
TRENT RIVER	CRAIG BAY	S													1										
TRENT RIVER	NORTHWESTBAY	S																							
TRENT RIVER	COTTAM PT	S																							
TRENT RIVER	RATHTREVOR	S?																							
TRENT RIVER	ENGLISHMAN R	S, E2																							
TRENT RIVER	L QUALICUM R	E																							
TRENT RIVER	BOWSER (BP10)	E1																							
TRENT RIVER	TSABLE R (B)	E																							
TRENT RIVER	TSABLE R (A)	E1																							
TRENT RIVER	BLOEDEL CK	E																							
TRENT RIVER	TRENT RIVER (A)	E1																					6		
TRENT RIVER	PUNTLEDGE R(B)	E1,E2																				1	6		
TRENT RIVER	PUNTLEDGE R(A)	E																							
TRENT RIVER	BROWNS R (B)	E1																				1			
TRENT RIVER	BROWNS R (A)	E1																							
COM	OYSTER RIVER	E																							
COM	ENGLISHMAN R	E																							

Table 3.3 Occurrence of macrofossils in the Comox Basi
4= author (Haggart, 1988a,b) 5= Muller & Je
6= Ward (1976a,b; 1978a,b) & Ward & Stanley
10= Richards (1975)

		a	V							C	C	S	S	S					E2	E	E1		E1	E1				
	G.DENMANENI	M.PACIFICUM	H.OPLITOPJAC	I.SUBUNDATUS	I.VANCOUVER	C.NEWBERRY.	P.UMBULAZI	S.SELWYNIANI	R.PYUGASENI.	B.CHICOENSIS	S.CHICOENSI	I.SCHMIDTI	P.MULTISULC	C.YOKOYAMI	P.EVANSANA	I.ELEGANS	I.ORIENTALIS	G.SUBCOMP.	E.HARADAI	D.ELONGATU.	I.NAUMANNI	H.GARDENI	E.PERPLICAT	P.VANCOUV.	B BAILYI	E EPIGONUM	B.OTSUKAI	I.CHICOENS.
	1																											
	1																											
						6									10													
		5		5	5			1																				
	5		6	5	6	5.6	5		5																			
					6	6				6	6																	
5										6		5.6																
															9													
	1											4	1															
													1		9													
												5	6	6														
																4												
												4.6	6	6			4	4'	4									
																	6	6		6								
																					5							
																		1		1		1						
																						1	1					
																						1						
									6								5.6	6		1.6	6	1	5.6	5.6	6	1	6	
								1	6								5.6	6	6	1.6	6	1	1		6		6	
																		1		1		1						
								1									6	6		6	6	1	1.6		6			
																						1		1				
																					5						5	
																												5

ls in the Comox Basin. 1= Usher (1952)
a,b) 5= Muller & Jeletzky (1970) & Jeletzky (1983)
b) & Ward & Stanley (1982) 9= Crickmay & Pocock (1963)

PENDER	PENDER LAKE	C?													4	4																																
	ARBUTUS PT	C?																	1																													
	GOWLLAND PT	[illegible]													6				6	6																												
	STUART IS.	C																	6	6																												
	WALDRON IS.	[illegible]													6		3	3	6	3,6																												
EXTENS.	BARNES IS.	S?																							6																							
	MAXWELL CK	S?																							4																							
	SKIPJACK IS	C, S?																		3						6?																			3			
	CUSHEON CK.	S																												6																		
HASLAM	LANTZVILLE	S																										1																					
	NANAIMO R.(B)	S																					6				6		6																				
	ELKHORN CK.(B)	S																										4									4					4		4							
	HASLAM CK.(B)	S																										5		5												5									
	MT. PREVOST	S																										4						4																	
	MARIE CANYON	S																					6				6		6				6							4									
	BENTON CK.	S,E2																	1					5		1			1	1	1				1													
	CHEMAINUS	S?,E?																			4												4																
	ORCAS IS.	E																																6	6					6									
	PIERS IS.	E																							7									6	6	6					6			7						
	FULFORD H.	E																														4																	
	FALDI	E																									4								4	4					4									
	ROBERTS LAKE	E2																				4									6			4,6	4,6					4,6									
	RICHARDS CK	E2																												4		4	4									4									
	CHEMAINUS R.	E																																4						4									
	HASLAM CK(A)	E2																														1	1		1															
	ELKHORN CK(A)	E2																														1	1		1															
	NANAIMO R.(A)	E1,E2																														1			1,6	6	1			6	6									
	BOULDER CK.	E1																													4					4	4			5	5	4								
	COWICHAN LK.	E1																																		4			6	6										
	MAPLE BAY	E1																													4				4	4				4			4							
	PYM ISLAND	E1																															6	6	6				6	6									
	SWARTZ BAY	E1																															6	6	6		6	6		6									
BENSON	NANOOSE H.	E																																							4								
	BENSON CK	E?																																						5									
	DEPARTURE BAY	E?																																												9			
	HASLAM CK.	E																																												9			
	STOCKING CK.	E																																4	4							4							
	CHEMAINUS	E?																																								4							
	YEO POINT	E																																1															
	SAANICH PEN	E1																																									7	4					
	MT. TZUHALEM	K?																																											7				
	MORESBY IS.	K?																																												7			
	GOUDGE IS.	K?																																												4	4		
	HAMLEY PT.	K																																													8	4,8	8

Table 3.2 Occurrence of macrofossils in the Nanaimo Basin. See the reverse side for the key to the numbers.

Formation	Zone index fossils		SU	SU						P	F	V	V																											E1	E1	E1					E1			K	K	K
	Locality	Zones present at locality																																											N. CONRADIA
North Mayne G. Formation	CAMPBELL BAY	SU	1																																											
	MINERS BAY	SU		2																																										
	BENNETT BAY	[illegible]	1	1																																										
	DESCANSO BAY	SU?				4																																								
	FALSE NARROWS	SU	1				1																																							
	ATKINS REEF	SU	1																																											
	WINTER COVE	SU	6																																											
Cedar District	MORTIMER SPIT	P							6	6																																				
	RAZOR POINT	P								6																																				
	TRUEWORTHY B.	P?						4																																						
	MURDER PT.	P								6								1																														
	S. PENDER IS.	P									56				6						6																											
	DODDS NARROWS	V												6			6		6																													
	LADYSMITH	V?																																							4							
	SHOAL IS.	V?																	4																						4							
	VESUVIUS BAY	V?													7																																	
	HAWKINS IS.	V?													4	4																																
	N. PENDER IS.	V											5																																			
	HOPE BAY	C?																		1																												
	SUCIA IS	SU,CVS	3		3		3		6			16		6	6	4		1	1		1	3				5			5																3			
Prot.	BOOTH BAY	C?																					7																									
	WALDRON IS	C?																																											3			
Pender	CUSHEON CK.	C														6																																
	THIEVES BAY	C?																	1																													
	PENDER LAKE	C?													4	4																																
	ARBUTUS PT	C?																	1																													
	GOWLLAND PT	C													6				6	6																												
	STUART IS.	C																	6	6																												
	WALDRON IS.	C													6		3	3	6	36																												
Extens.	BARNES IS.	S?																						6																								
	MAXWELL CK	S?																						4																								
	SKIPJACK IS	C, S?																		3						6?																			3			
	CUSHEON CK.	S																											6																			
	LANTZVILLE	S																								1																						
	NANAIMO R. (B)	S																				6				6		6																				

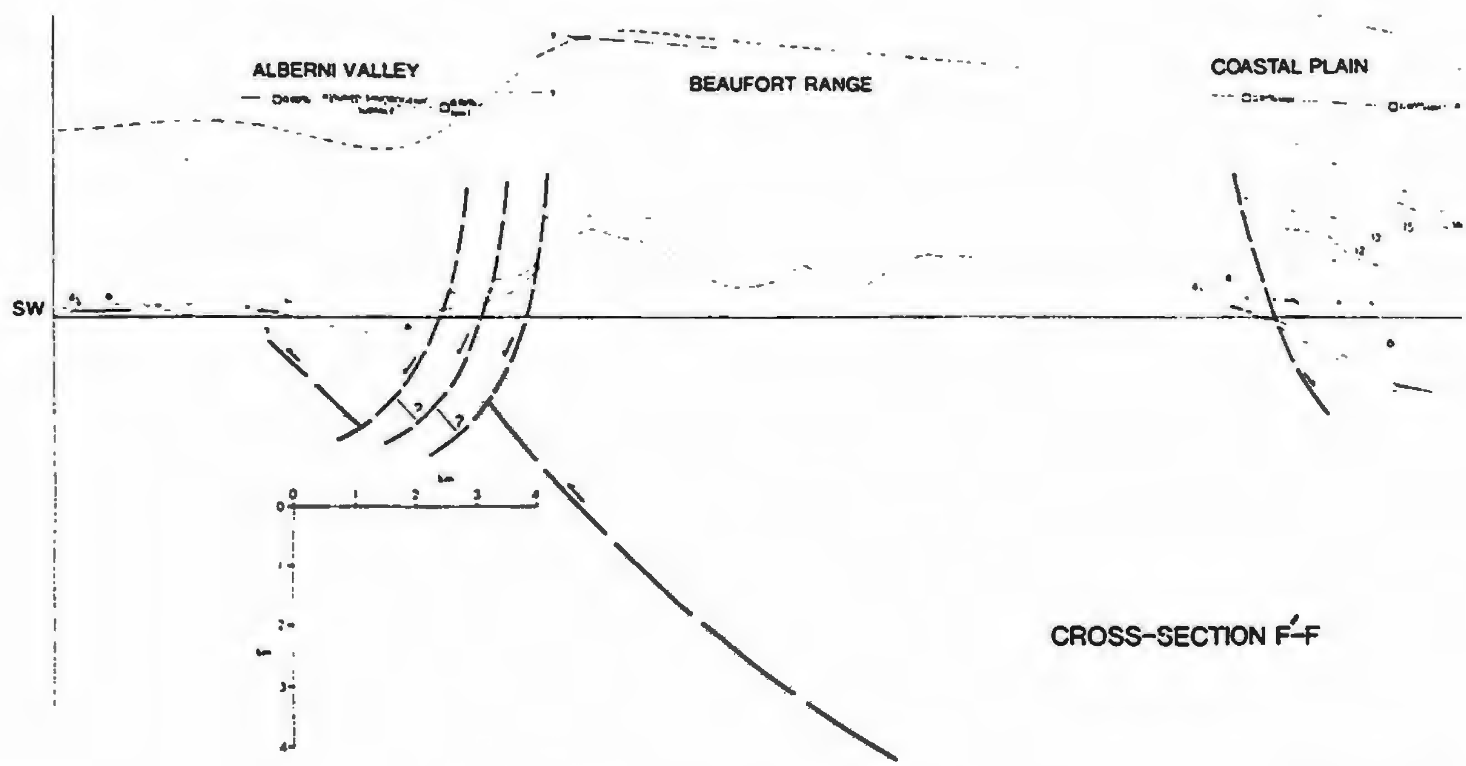

ALBERNI VALLEY
BEAUFORT RANGE
COASTAL PLAIN
SW
CROSS-SECTION F′-F

Figure 2

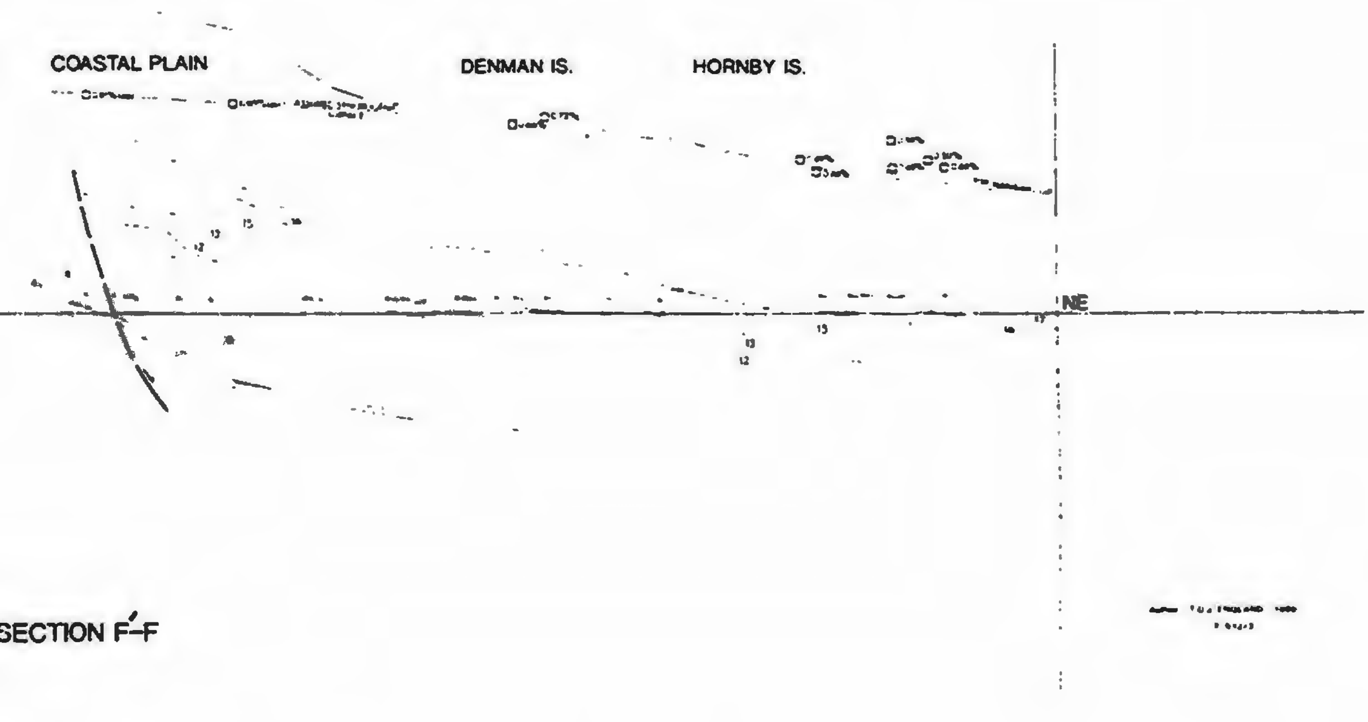
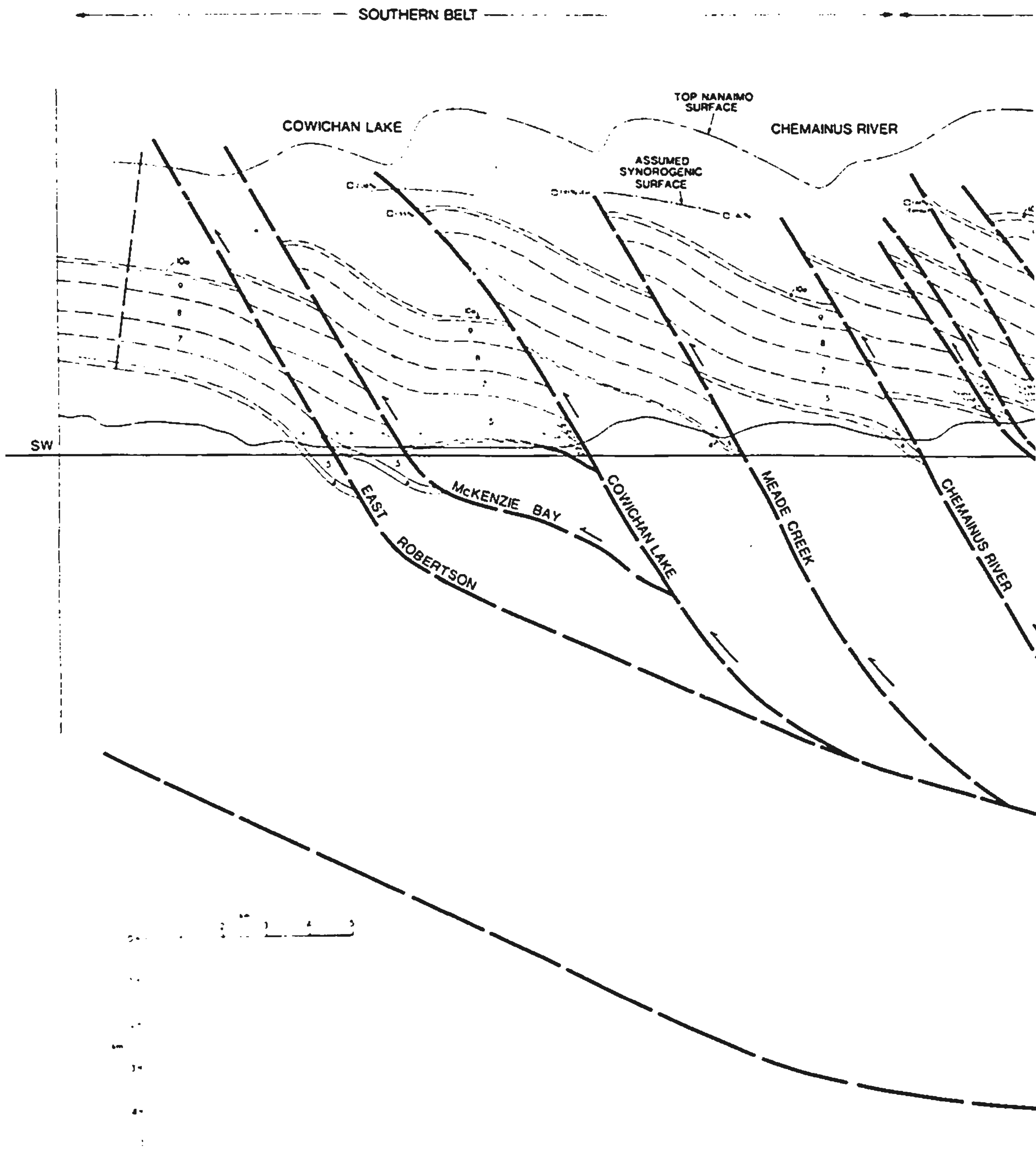
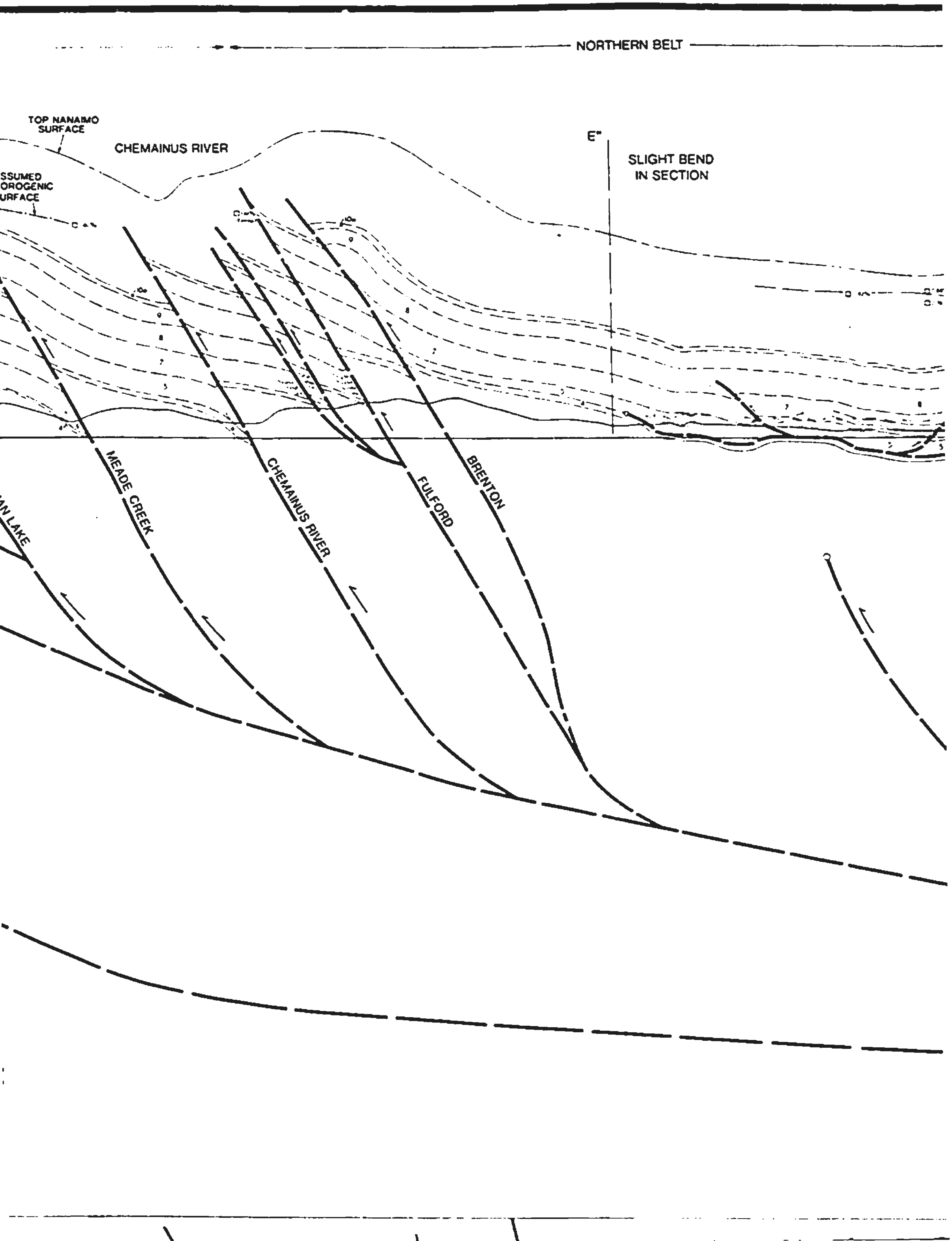


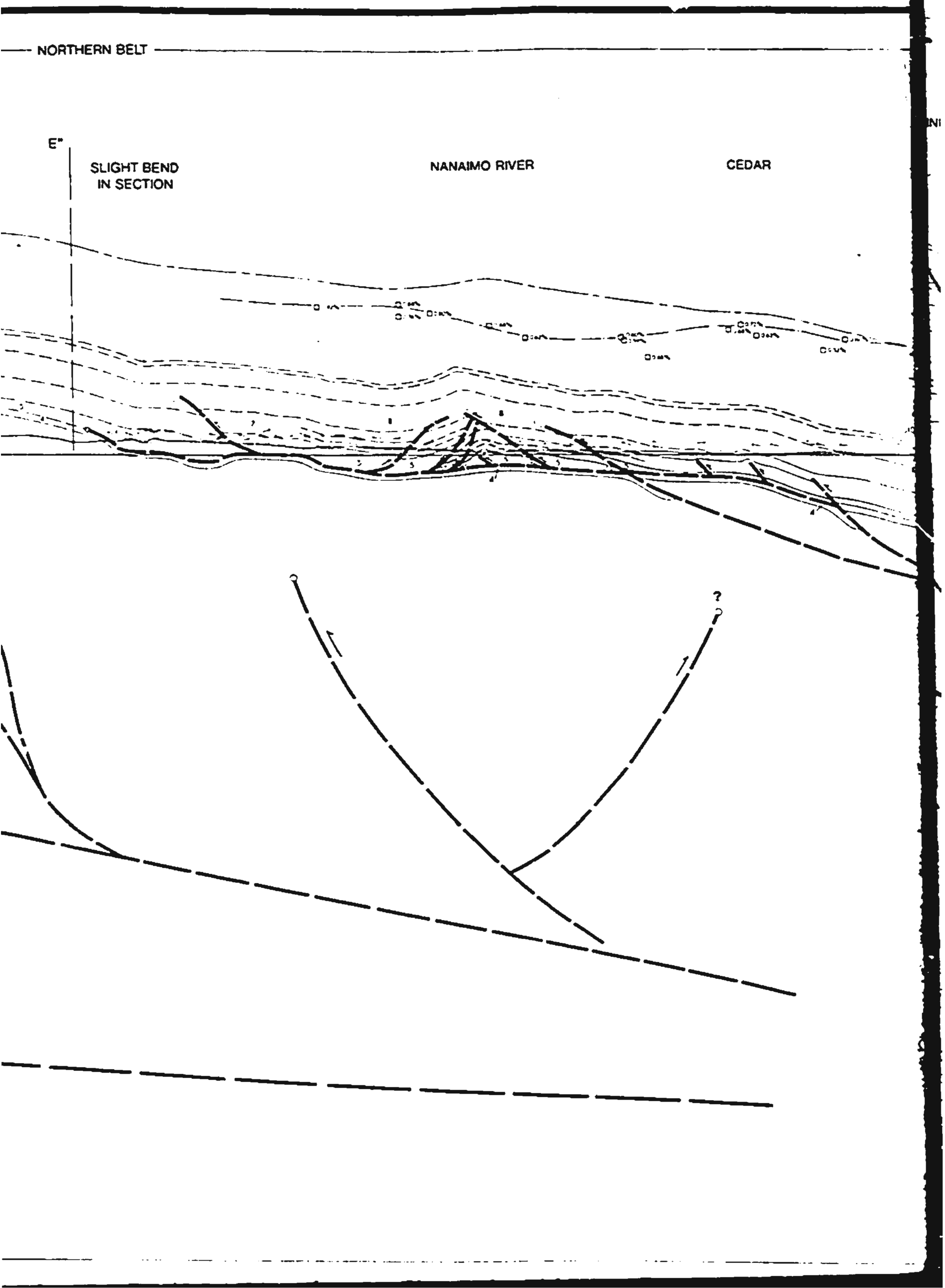
Figure 2.20 Structure section F'-F from the Alberni Valley to Hornby Island. The assumed synorogenic surface is based on %Ro values for outcrops which correspond to positions directly below the open squares (see text for discussion).



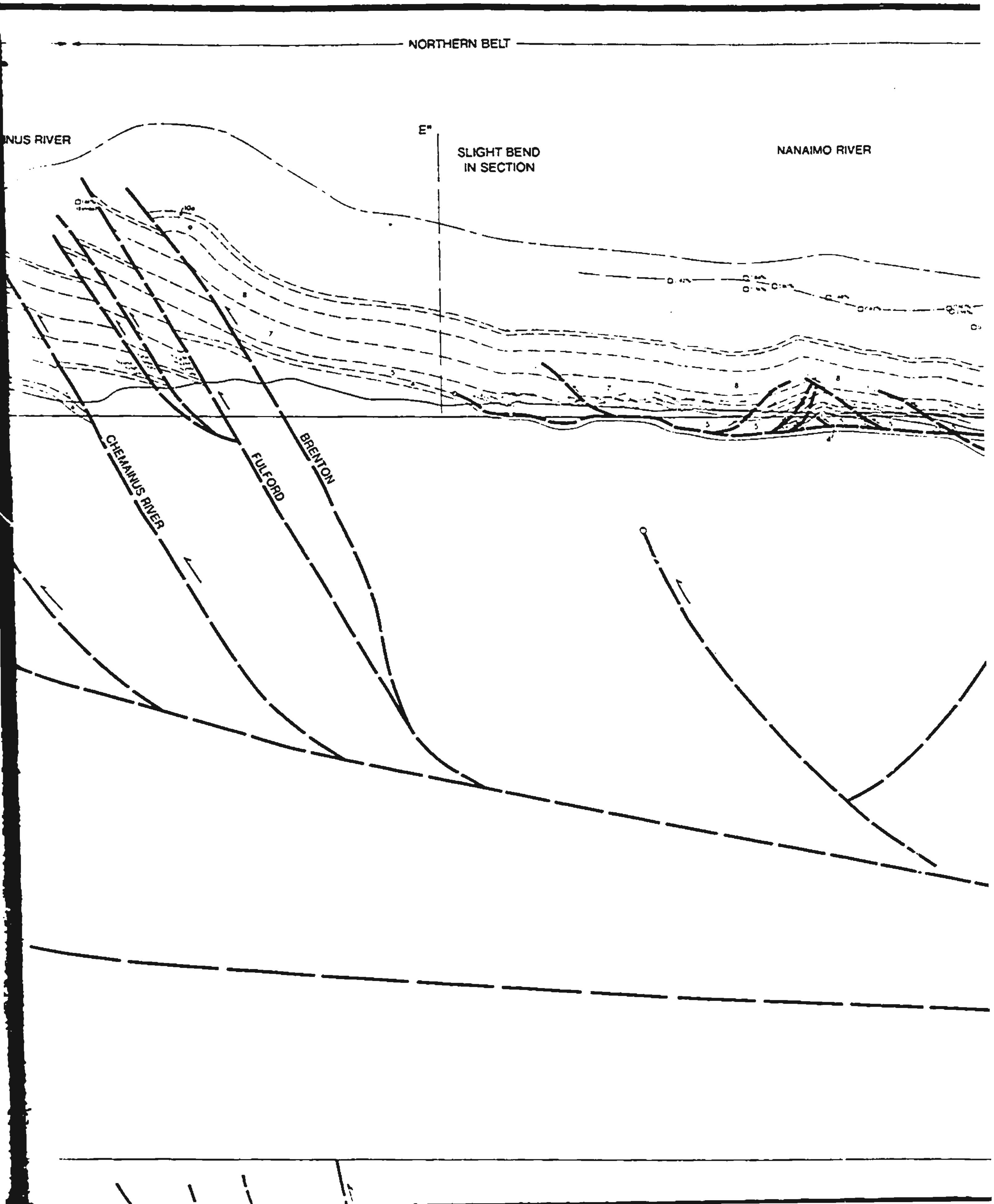
STRUCTURE SECTION E–E



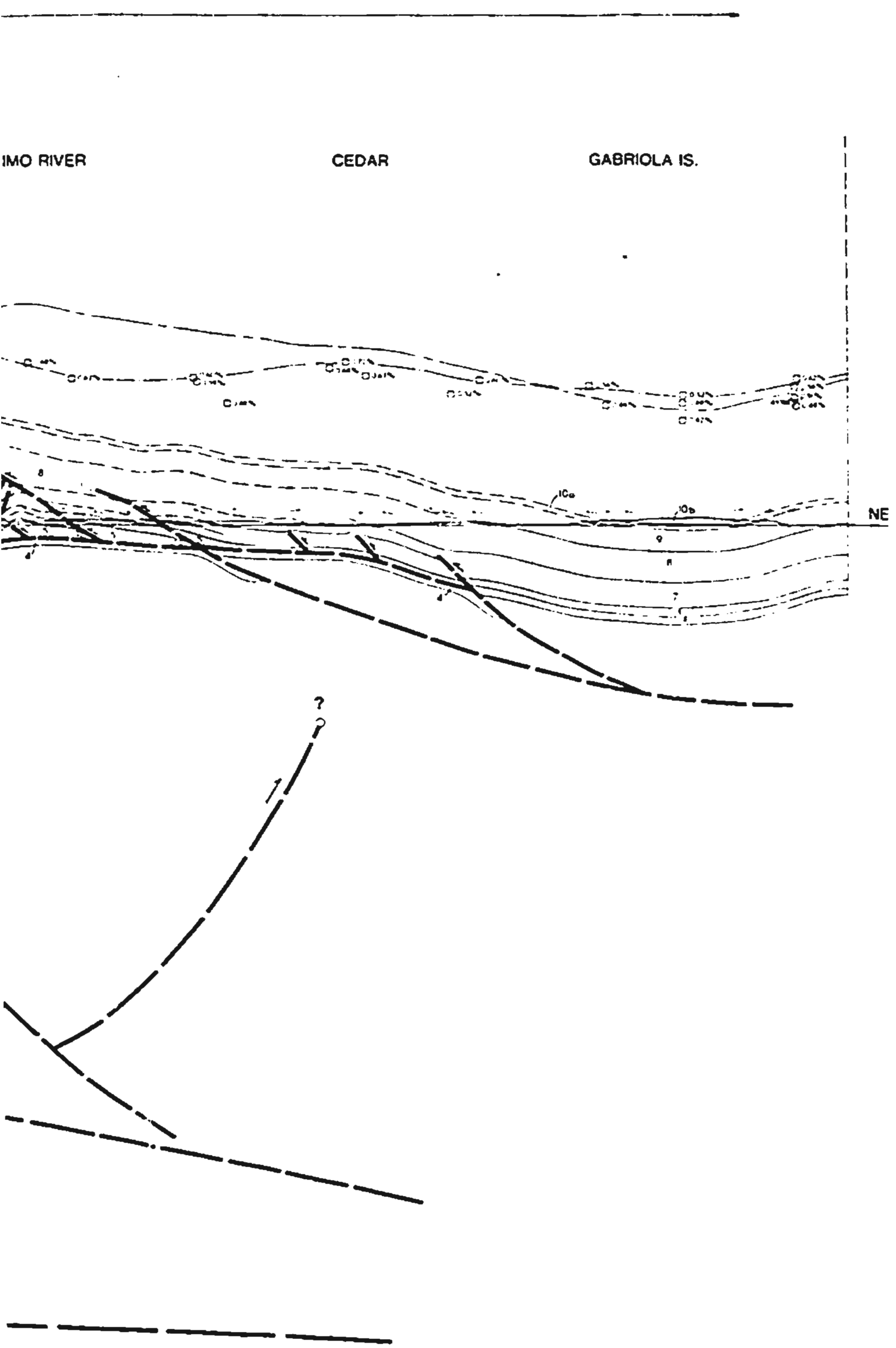
NORTHERN BELT
TOP NANAIMO SURFACE
CHEMAINUS RIVER
SSUMED
OROGENIC
URFACE
E"
SLIGHT BEND
IN SECTION
AN LAKE
MEADE CREEK
CHEMAINUS RIVER
FULFORD
BRENTON



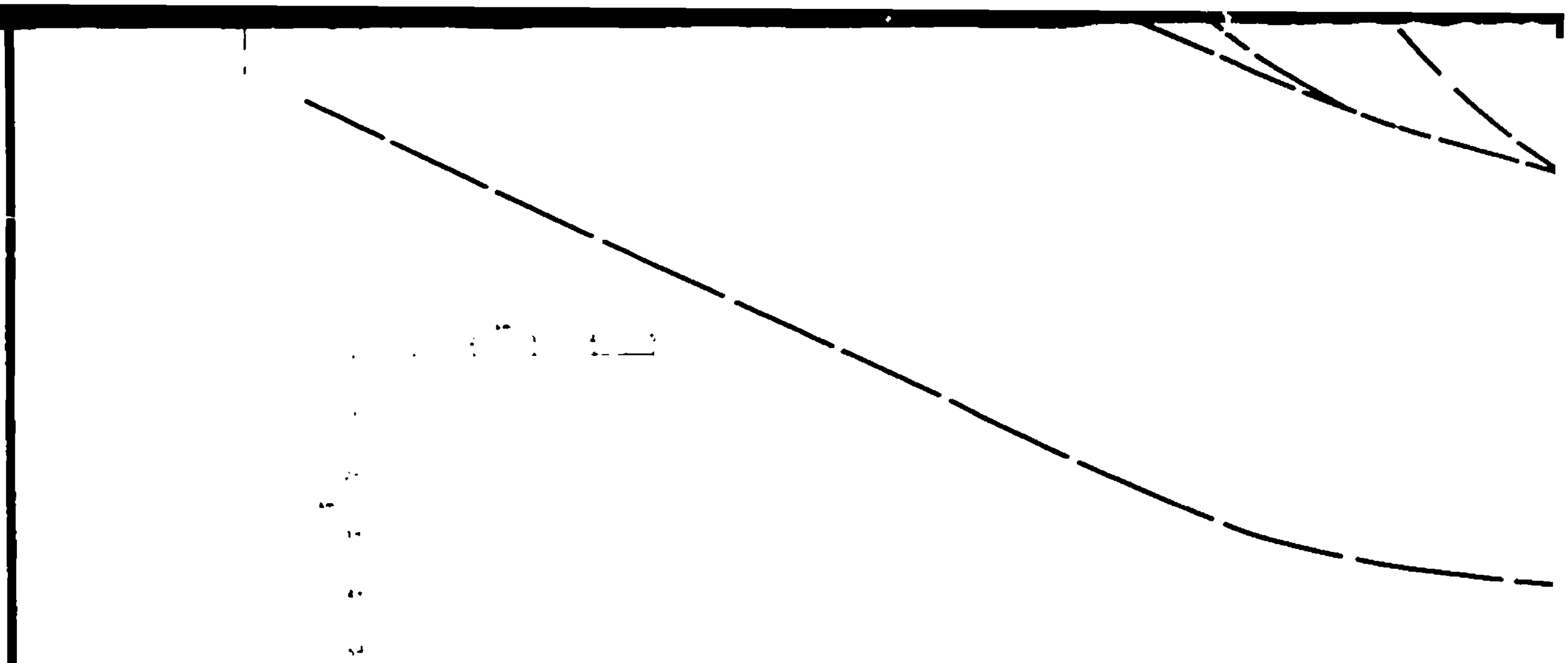
NORTHERN BELT
E"
SLIGHT BEND IN SECTION
NANAIMO RIVER
CEDAR
?



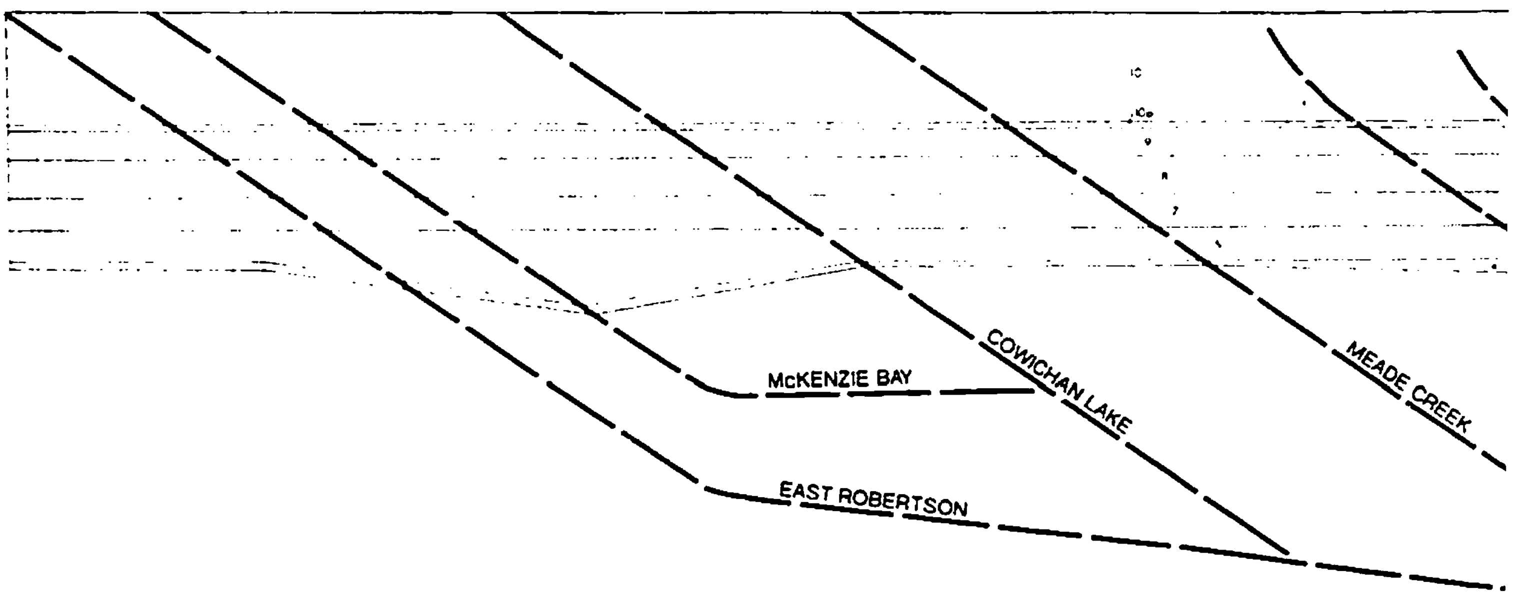
NORTHERN BELT
NUS RIVER
E"
SLIGHT BEND
IN SECTION
NANAIMO RIVER
CHEMAINUS RIVER
FULFORD
BRENTON



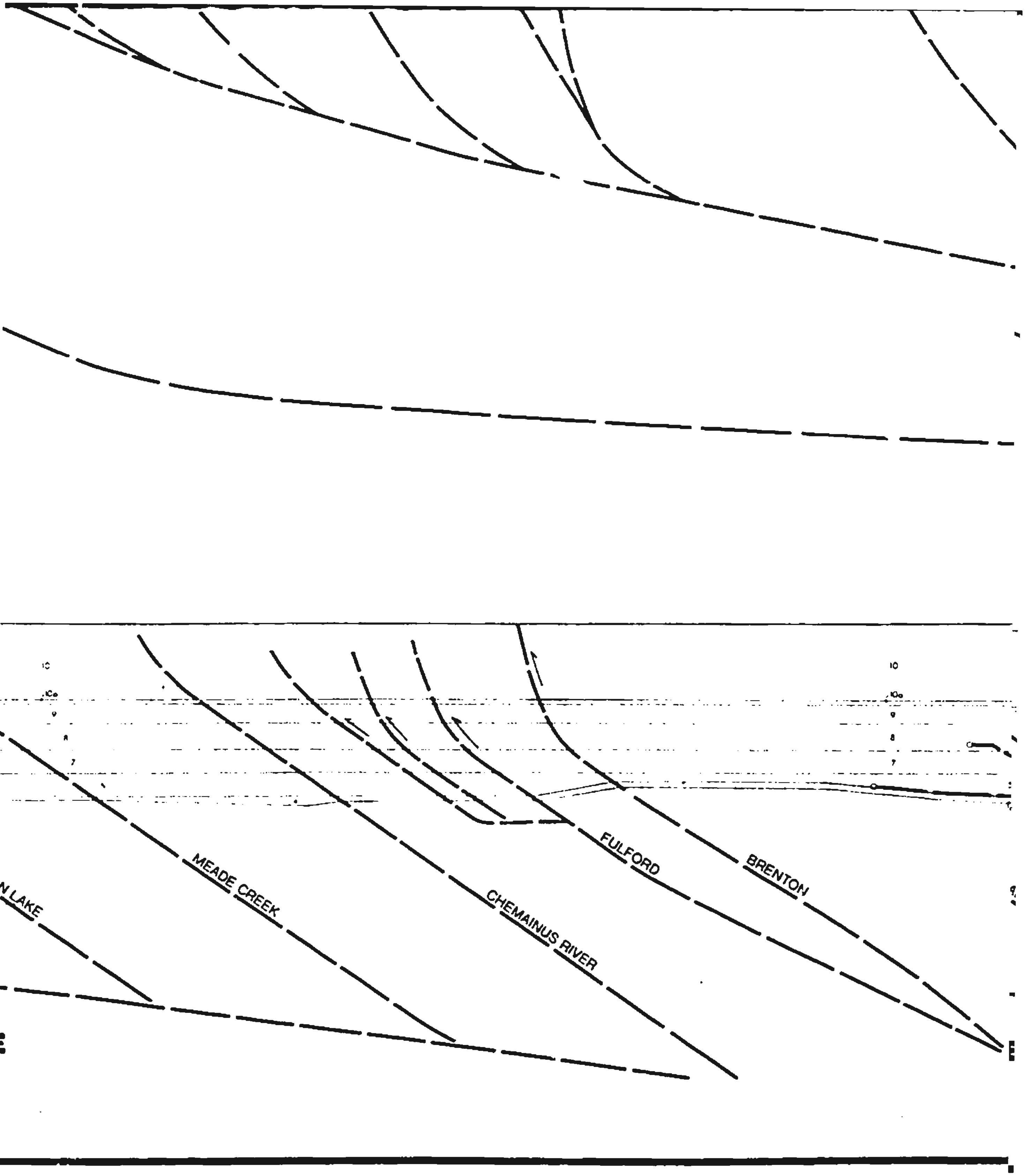
IMO RIVER
CEDAR
GABRIOLA IS.
NE



STRUCTURE SECTION E-E



RESTORED STATE SECTION E'–E


N LAKE
MEADE CREEK
CHEMAINUS RIVER
FULFORD
BRENTON

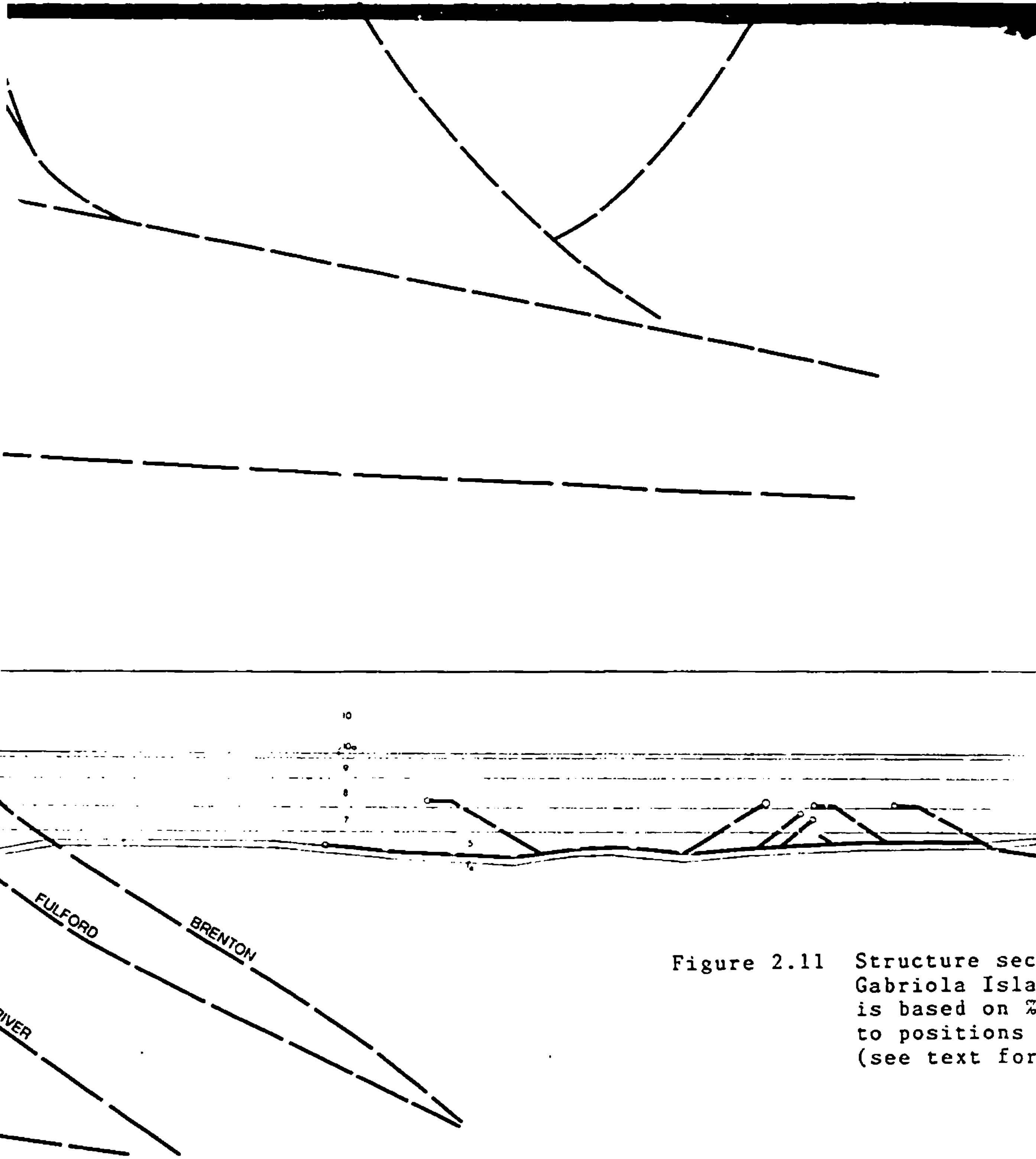
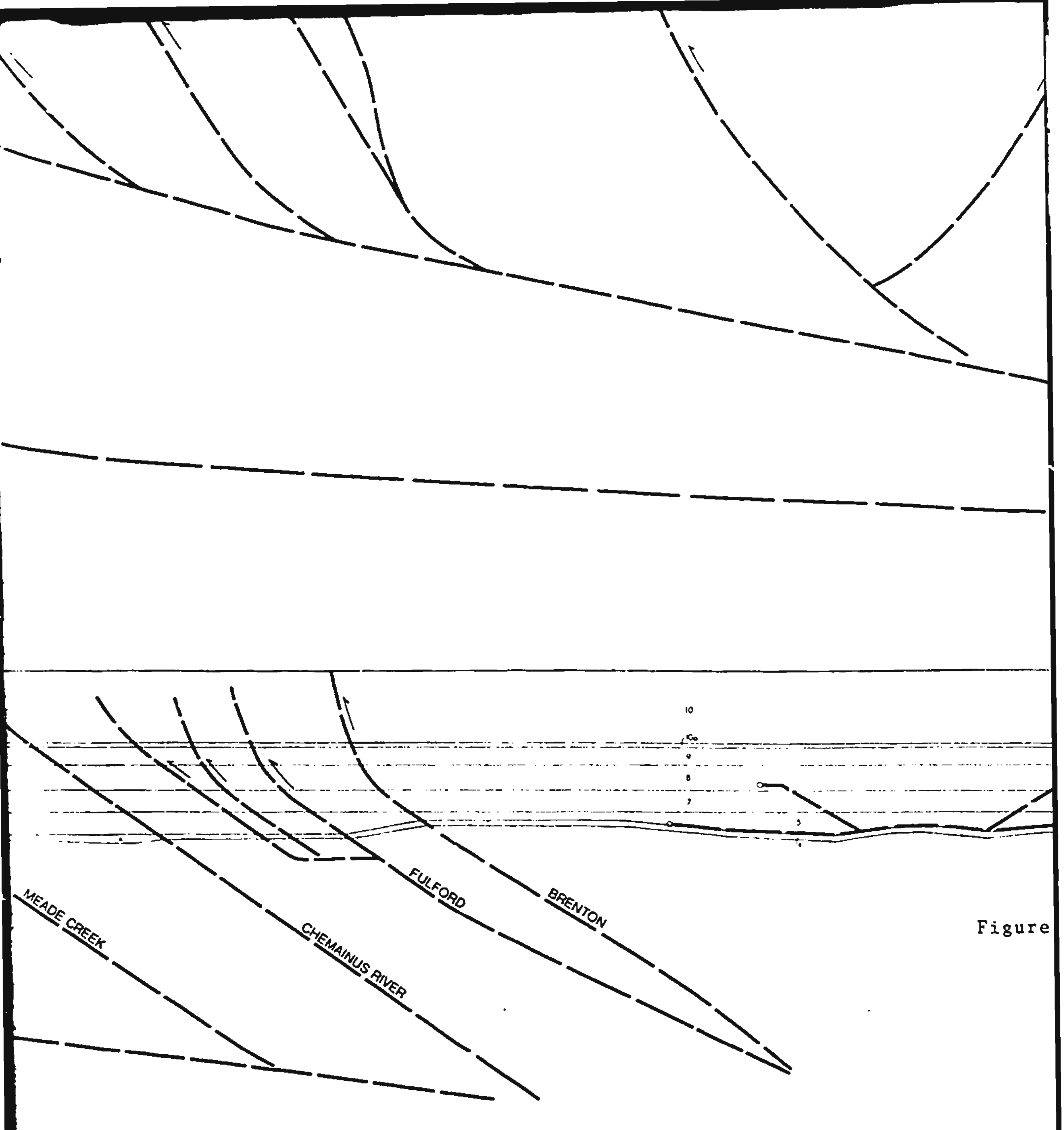


Figure 2.11 Structure sec
Gabriola Isla
is based on %
to positions
(see text for



Figure

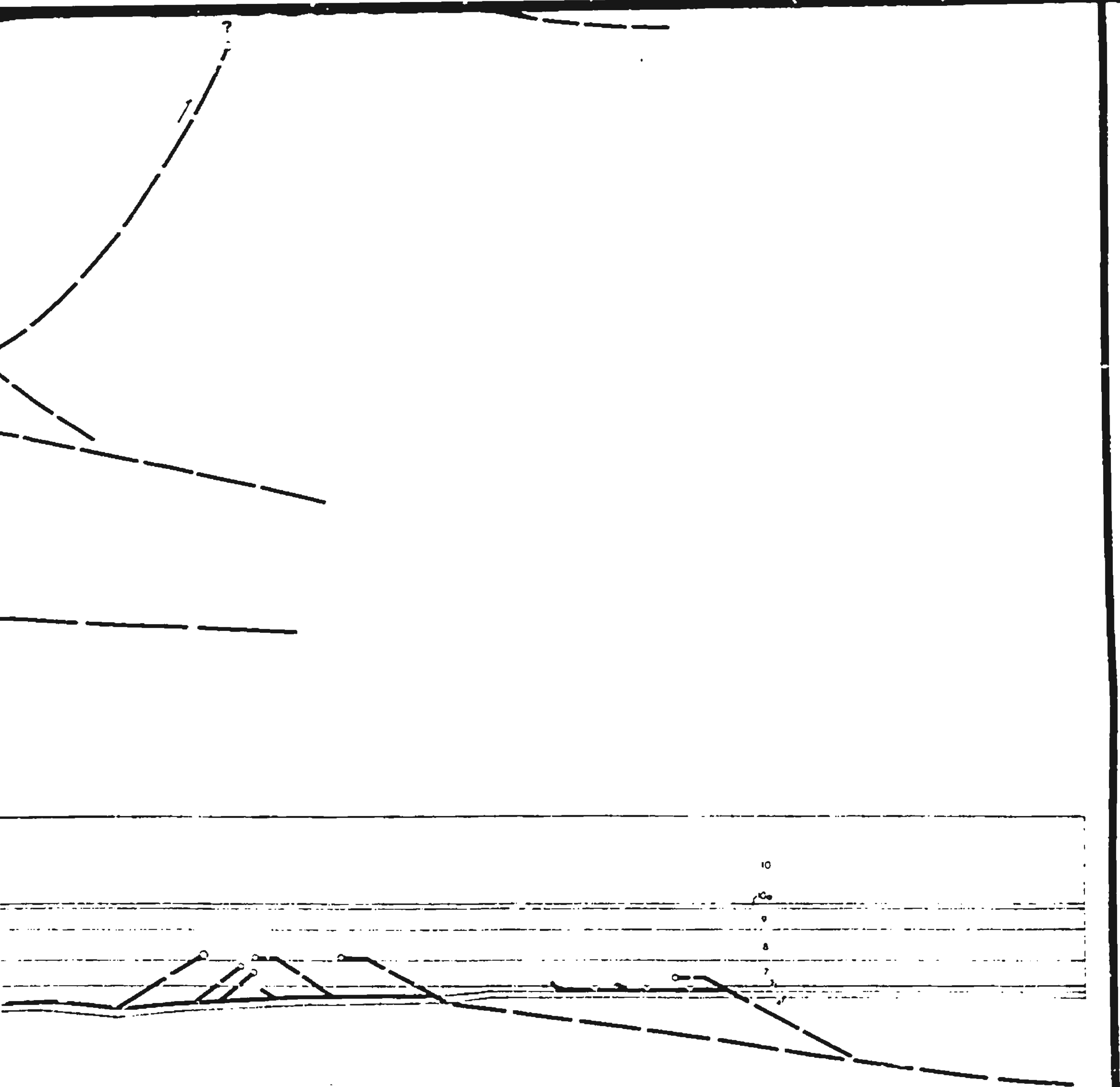
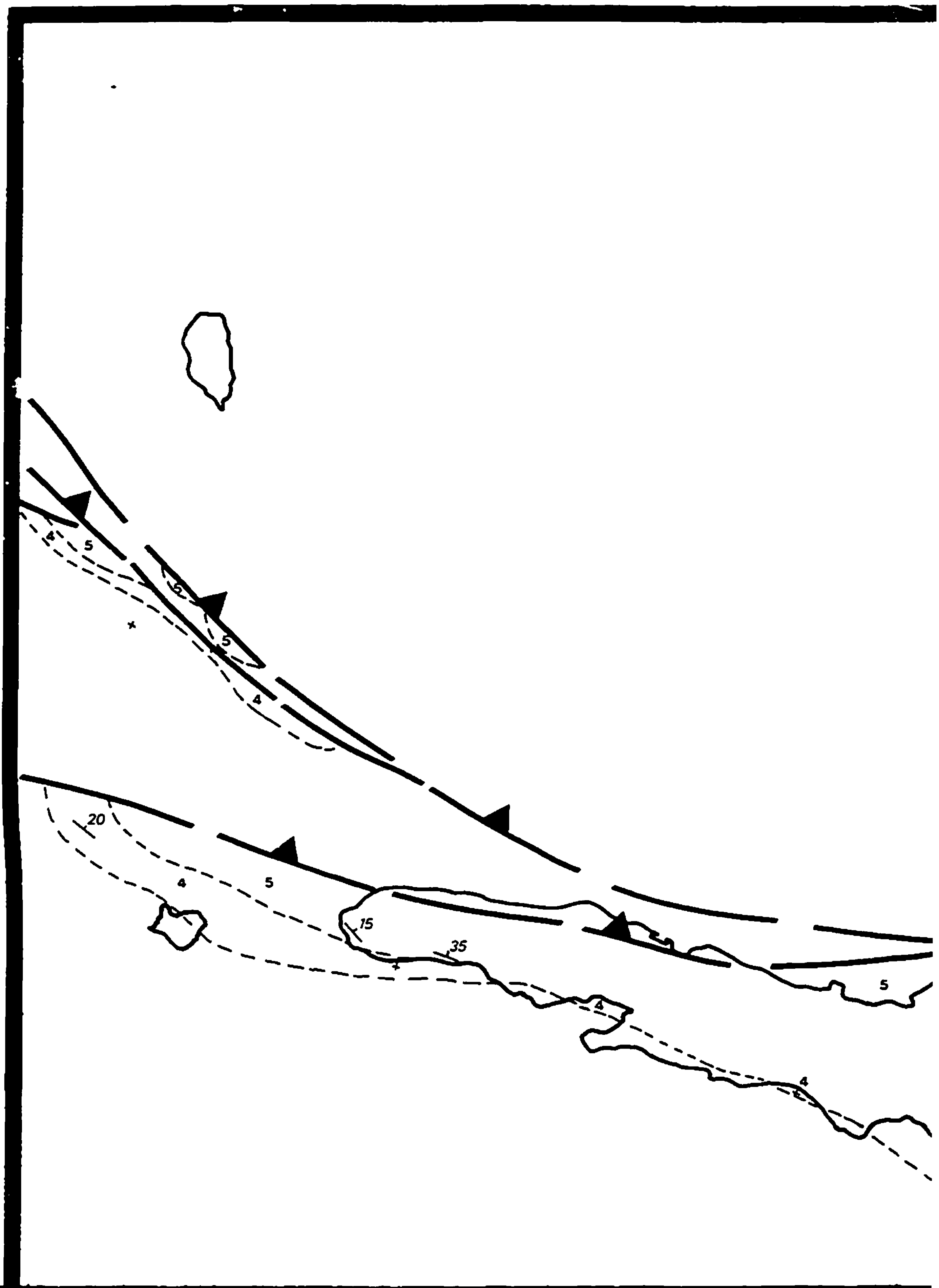
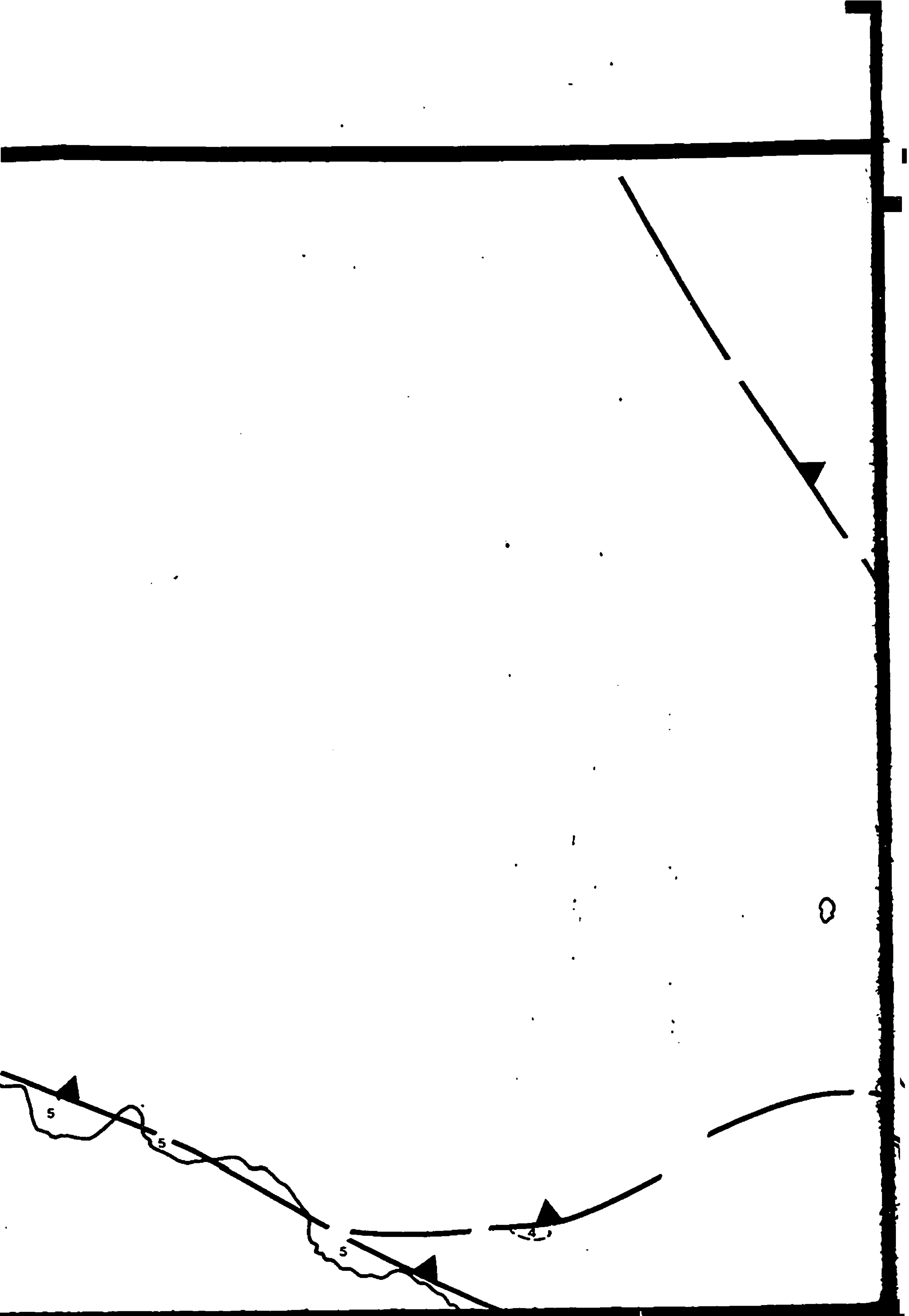


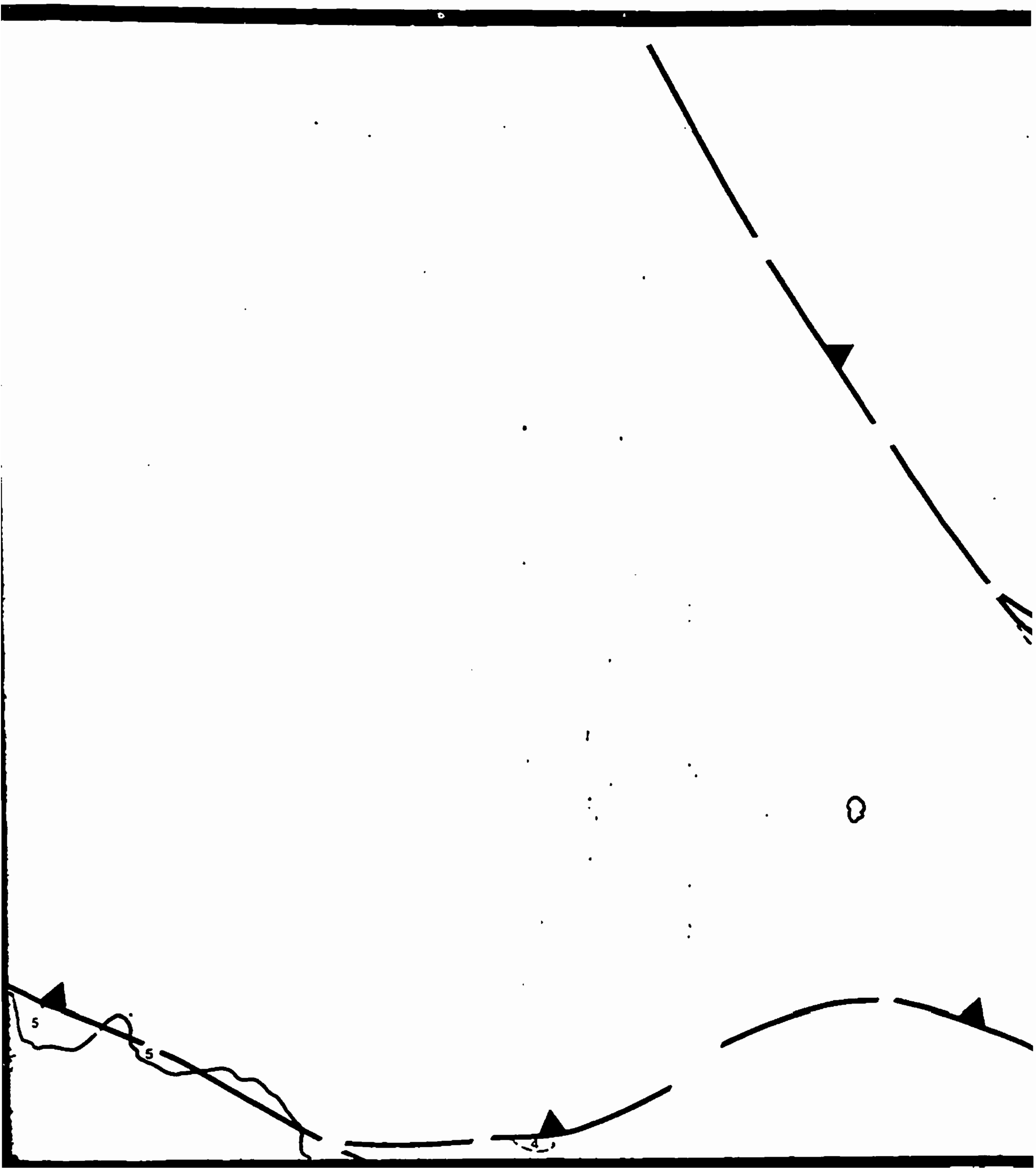
Figure 2.11 Structure section E'-E from Cowichan Lake to Gabriola Island. The assumed synorogenic surface is based on %Ro values for outcrops which correspond to positions directly below the open squares (see text for discussion).



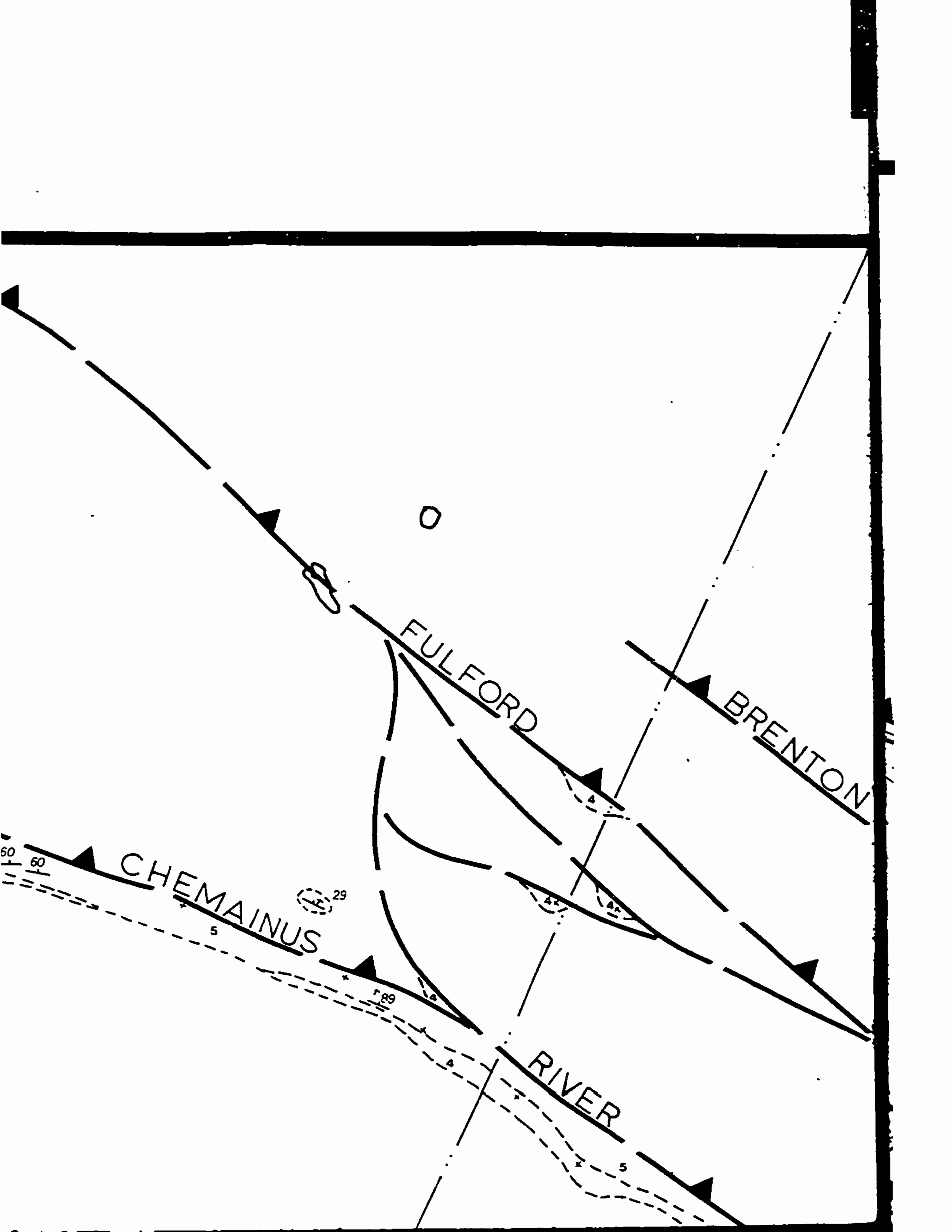
4
5
5
5
4
20
4
5
15
35
5
4
4

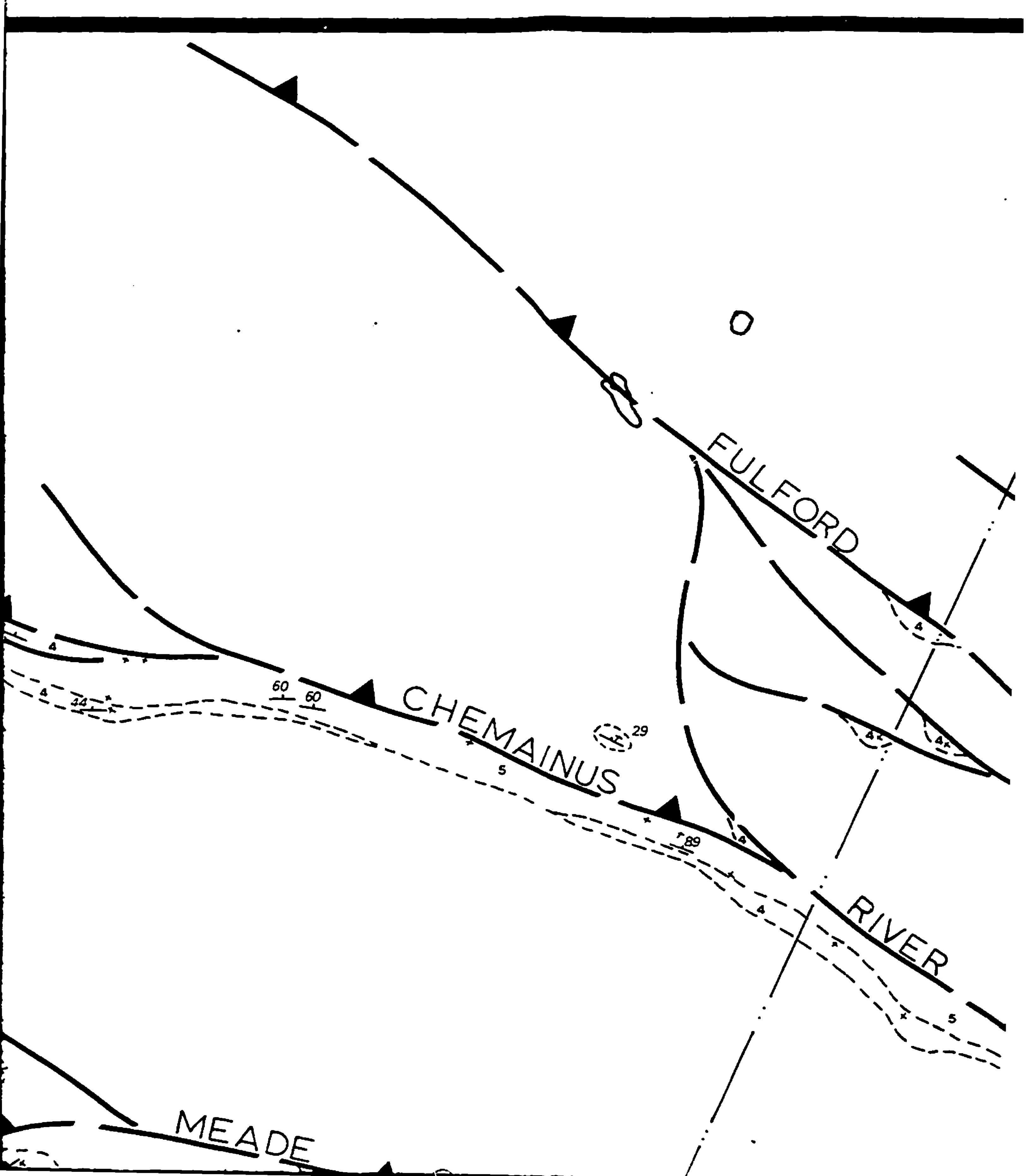

5
5
5
5
4
4

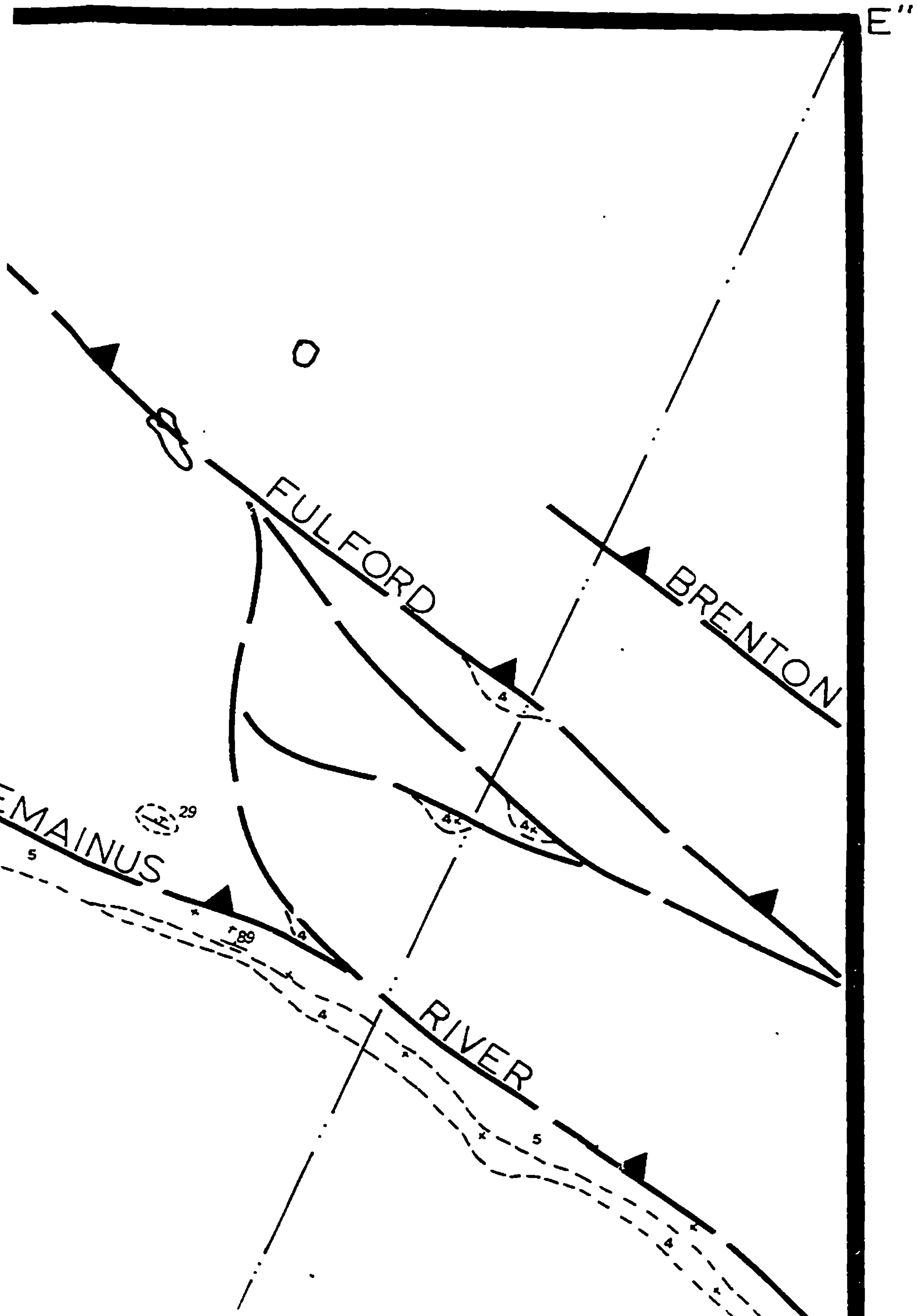

5
5
5
4


5
5

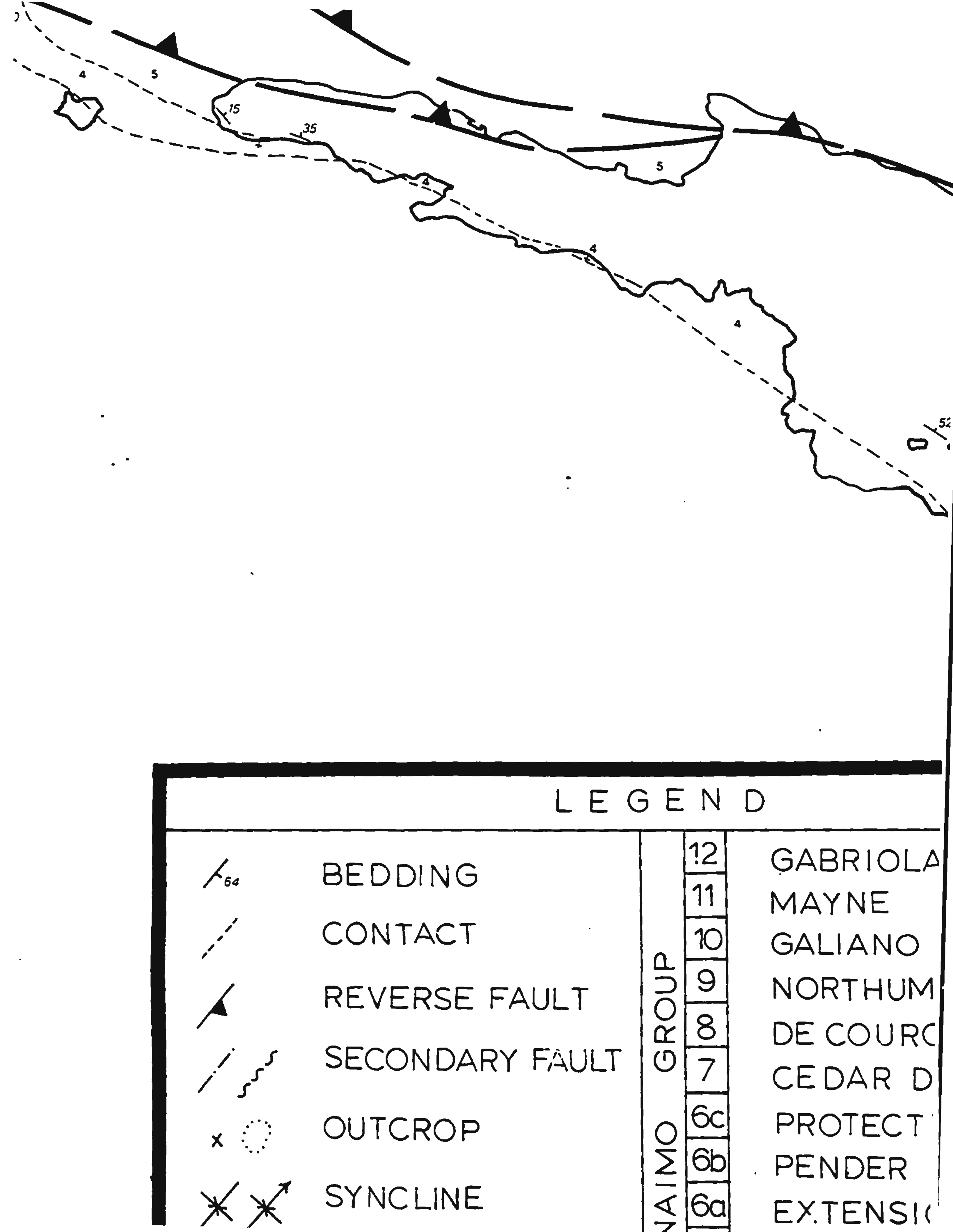
CHEMAINUS
30
4
4
44
60
60
5
29
89

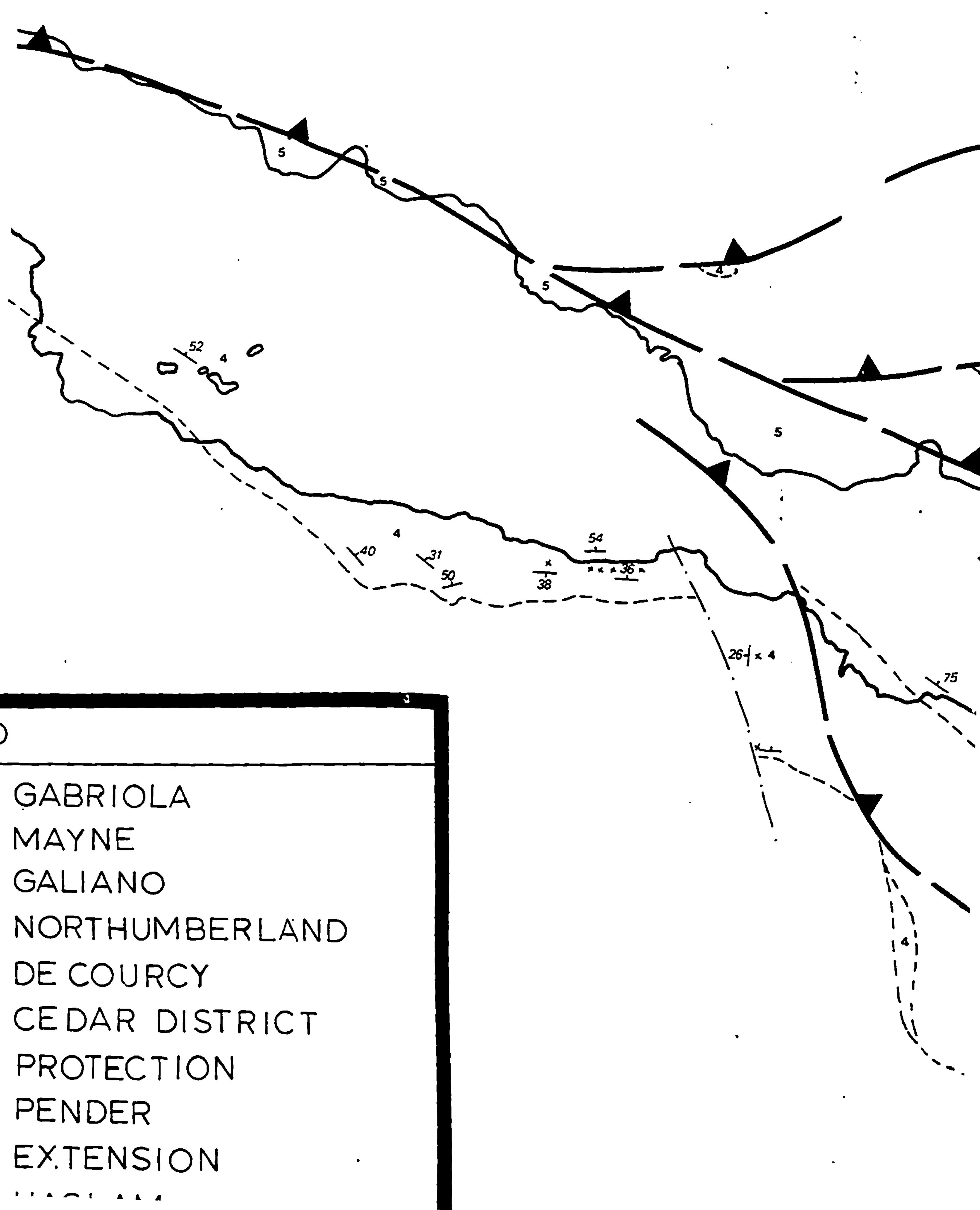

FULFORD
BRENTON
CHEMAINUS
RIVER
60
60
29
5
89
5

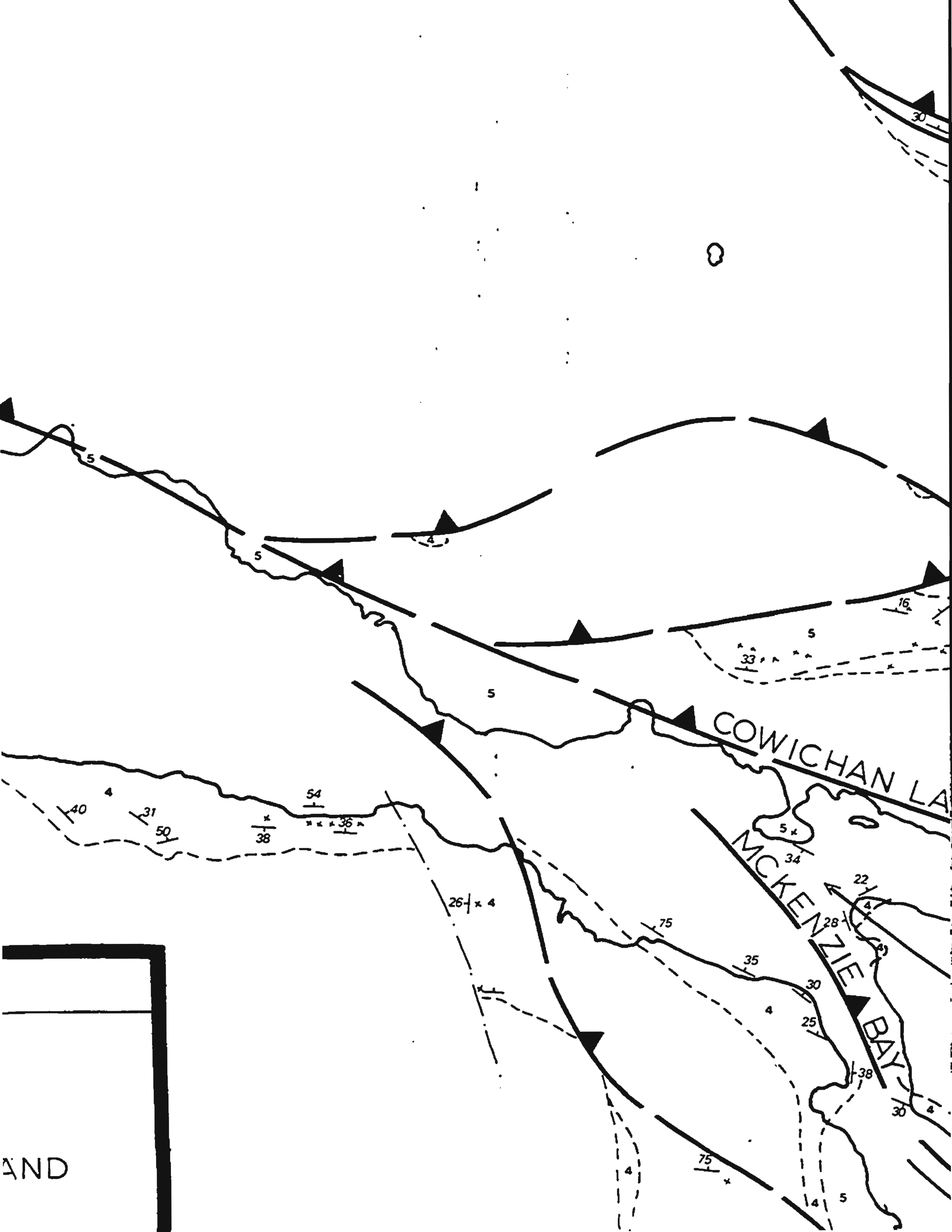

FULFORD
CHEMAINUS
RIVER
MEADE
60
60
44
29
89
5



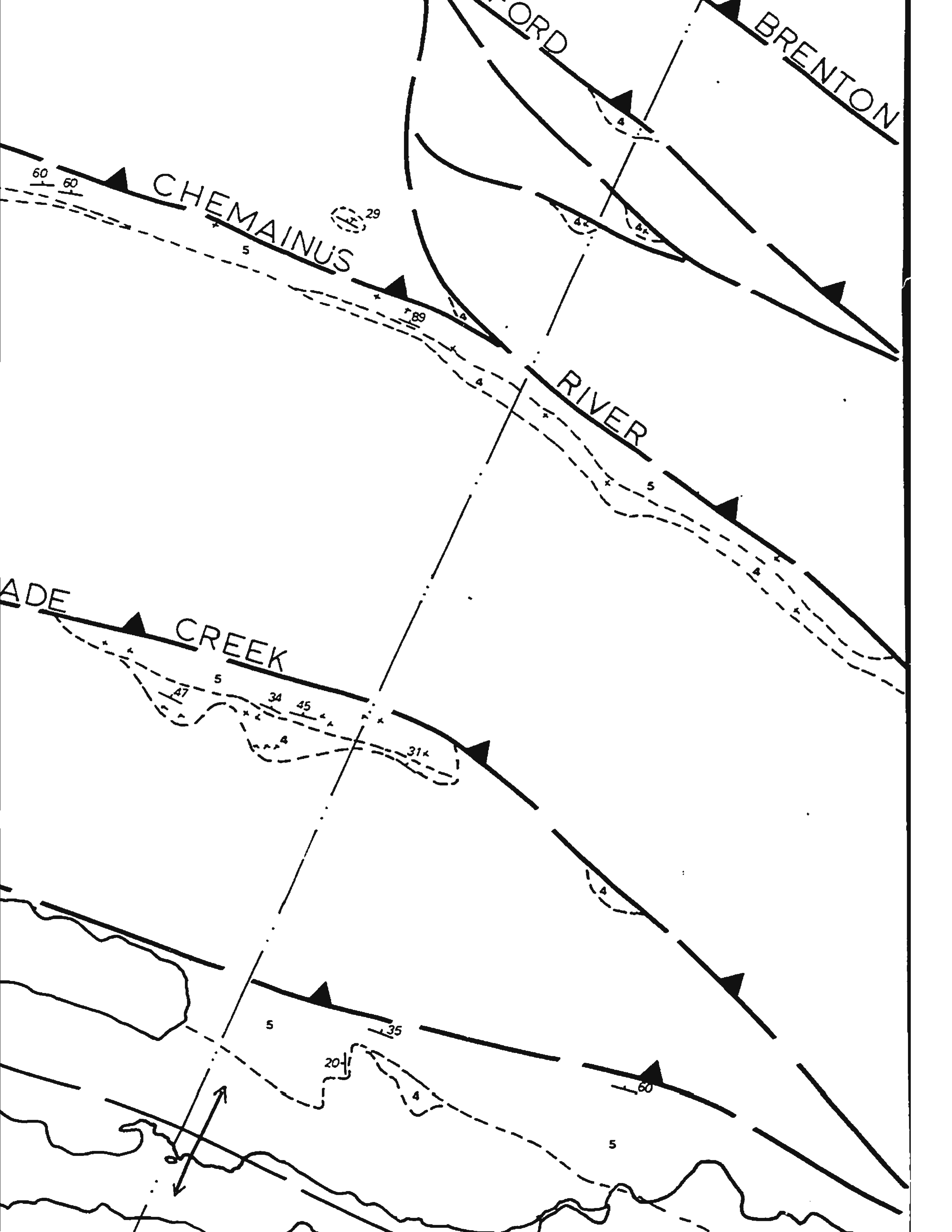
E''
FULFORD
BRENTON
EMAINUS
RIVER
29
89


4
5
15
35
5
4
4
4
52
LEGEND
64
BEDDING
CONTACT
REVERSE FAULT
SECONDARY FAULT
OUTCROP
SYNCLINE
NAIMO GROUP
12 GABRIOLA
11 MAYNE
10 GALIANO
9 NORTHUM
8 DE COUR
7 CEDAR D
6c PROTECT
6b PENDER
6a EX.TENSI

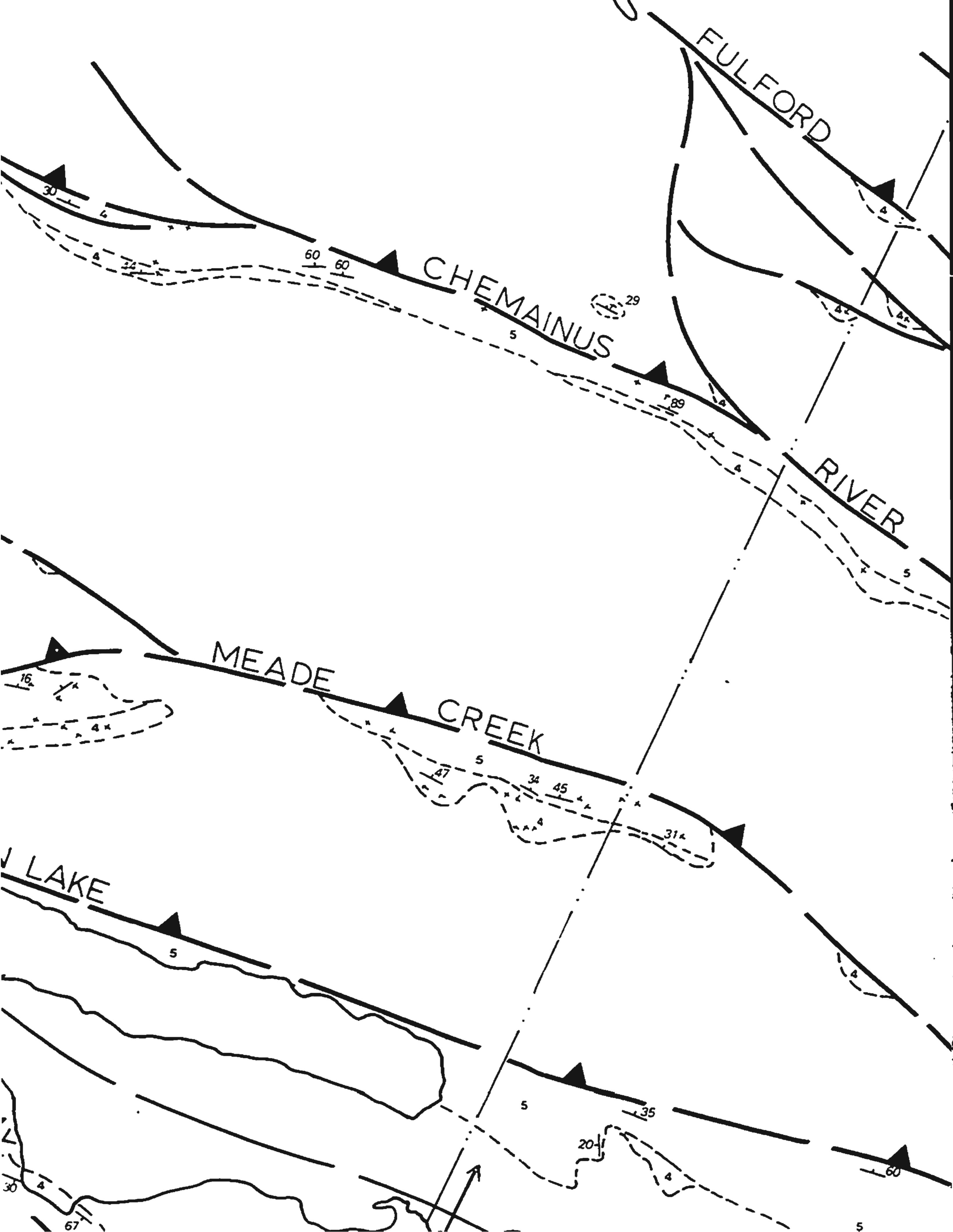

5
5
5
4
5
5
52
4
4
40
31
50
54
38
36
26
4
75
4
GABRIOLA
MAYNE
GALIANO
NORTHUMBERLAND
DE COURCY
CEDAR DISTRICT
PROTECTION
PENDER
EXTENSION

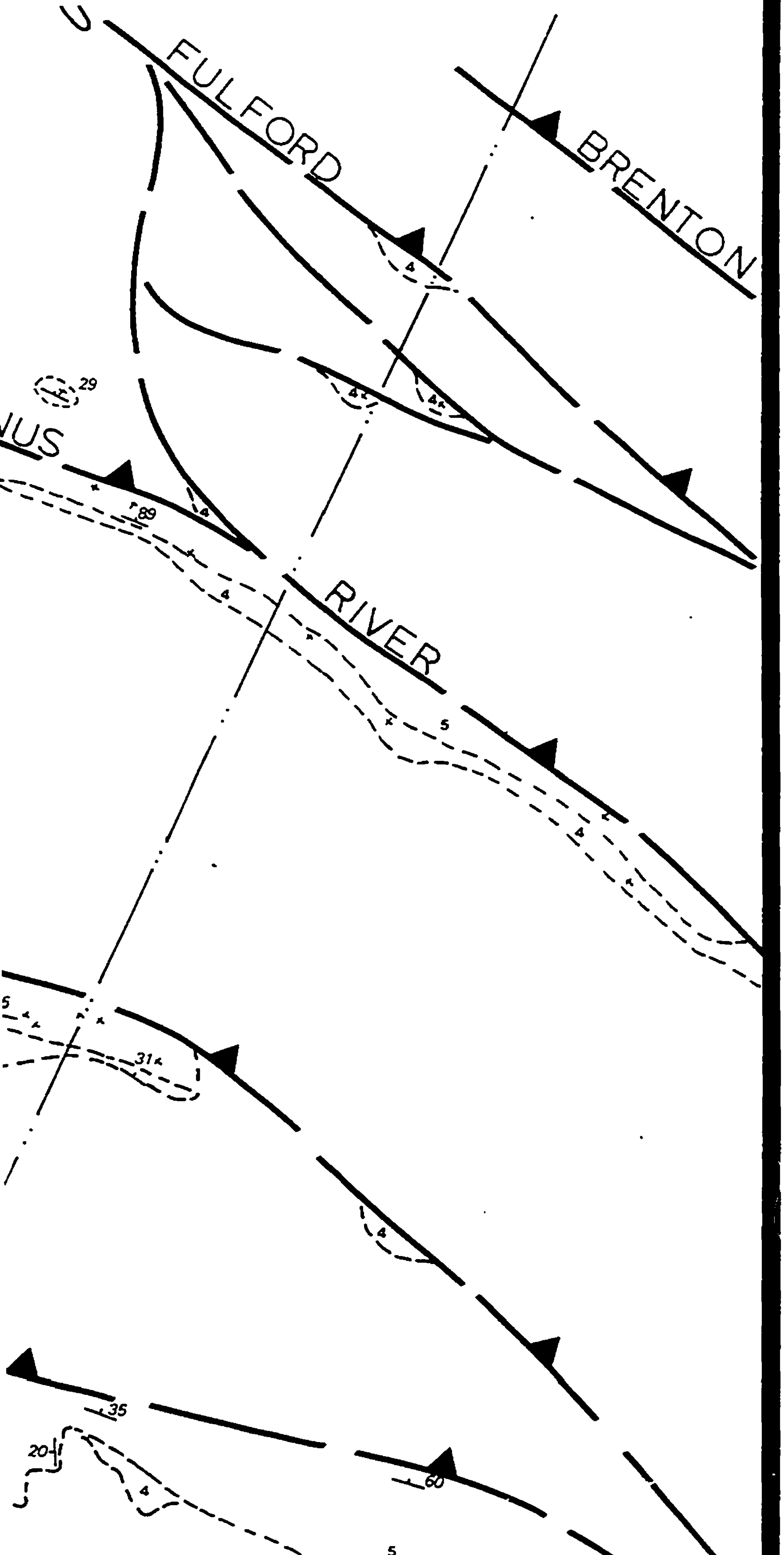

COWICHAN LA
MCKENZIE BAY
AND

CHEMAINUS
MEADE CREEK
COWICHAN LAKE
MCKENZIE BAY



ORD
BRENTON
CHEMAINUS
RIVER
ADE
CREEK
60
60
29
5
4
89
5
47
34
45
31
35
20
60


FULFORD
CHEMAINUS
RIVER
MEADE
CREEK
LAKE
30
4
60
60
29
5
89
16
47
34
45
31
35
20
60
67

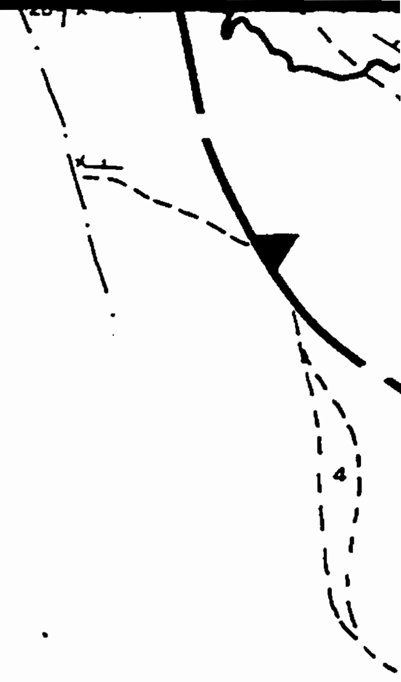

FULFORD
BRENTON
RIVER
29
89
31
35
20
60

LEGEND

	BEDDING
	CONTACT
	REVERSE FAULT
	SECONDARY FAULT
	OUTCROP
	SYNCLINE
	ANTICLINE
	CROSS-SECTION LINE
	BOREHOLE

NANAIMO GROUP	12	GABRIOLA
	11	MAYNE
	10	GALIANO
	9	NORTHUMB
	8	DE COURCY
	7	CEDAR DIS
	6c	PROTECTIC
	6b	PENDER
	6a	EXTENSIO
	5	HASLAM
	4	BENSON
	3	ISLAND IN
	2	VANCOUVE
	1	SICKER GR

	G/4	
C/16	B/13	B/14
	B/12	B/11



GABRIOLA
MAYNE
GALIANO
NORTHUMBERLAND
DE COURCY
CEDAR DISTRICT
PROTECTION
PENDER
EXTENSION
HASLAM
BENSON
ISLAND INTRUSIONS
VANCOUVER + BONANZA GPS.
SICKER GROUP

FIGURE A2 COWICHAN LAKE

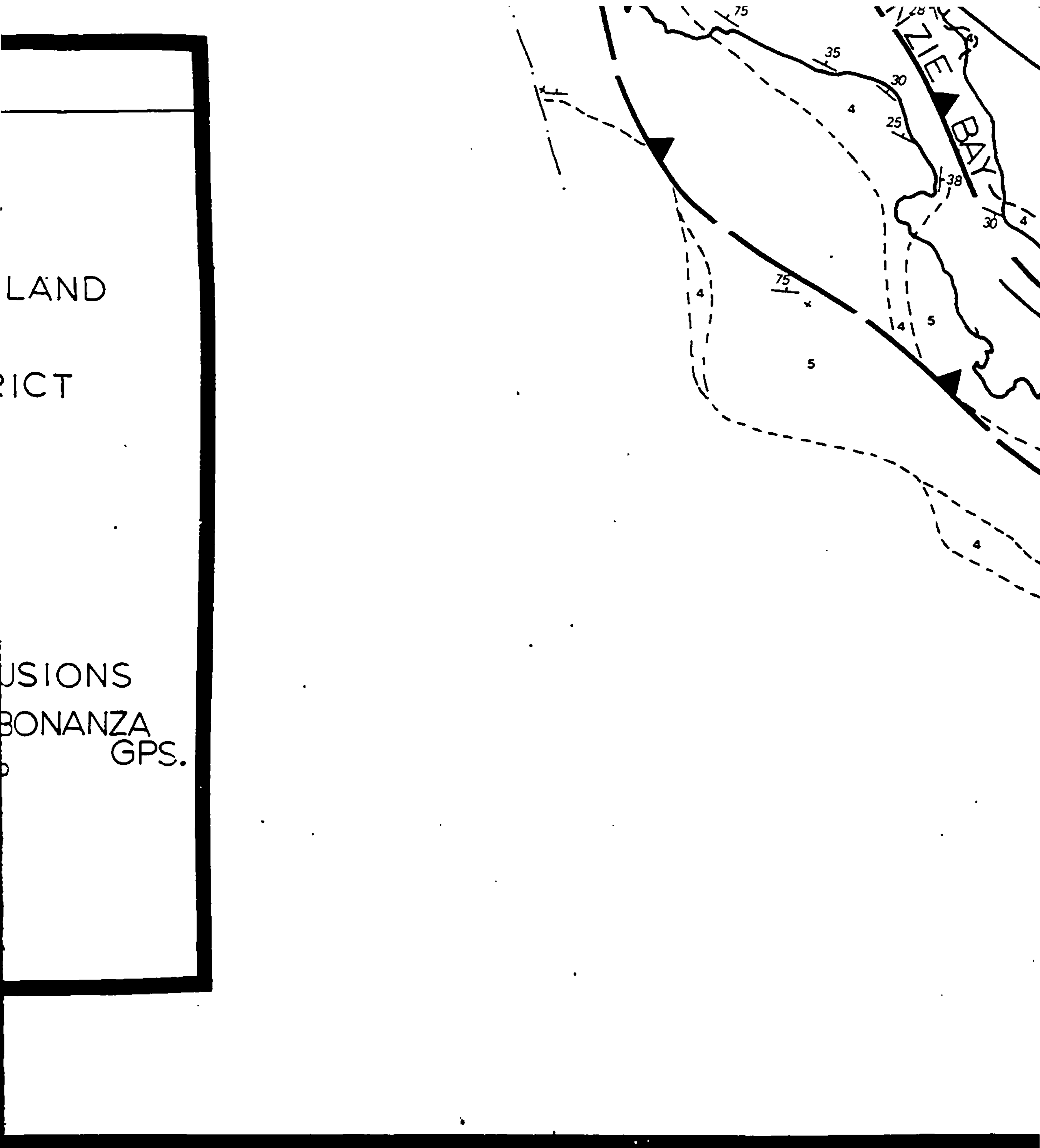
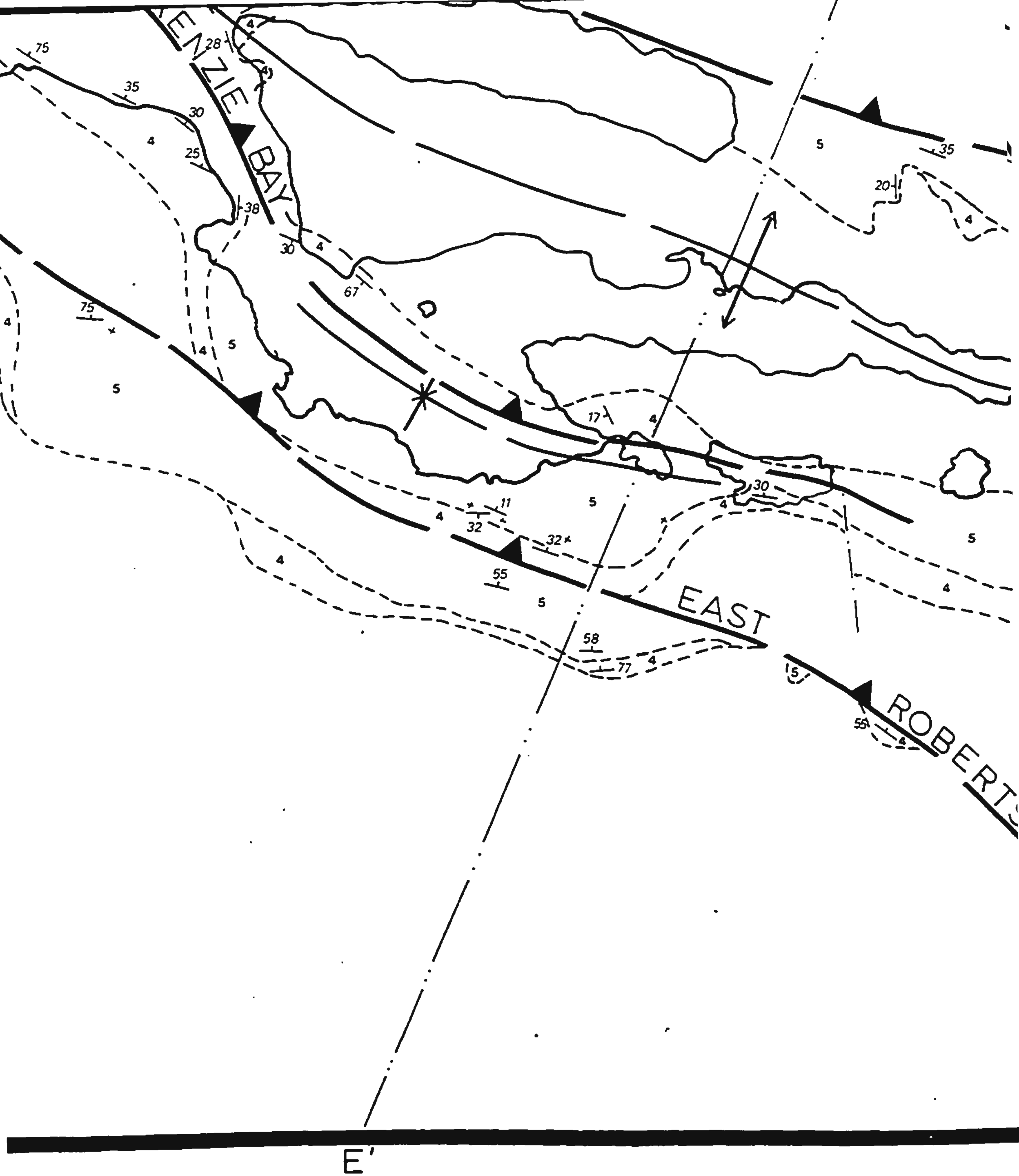
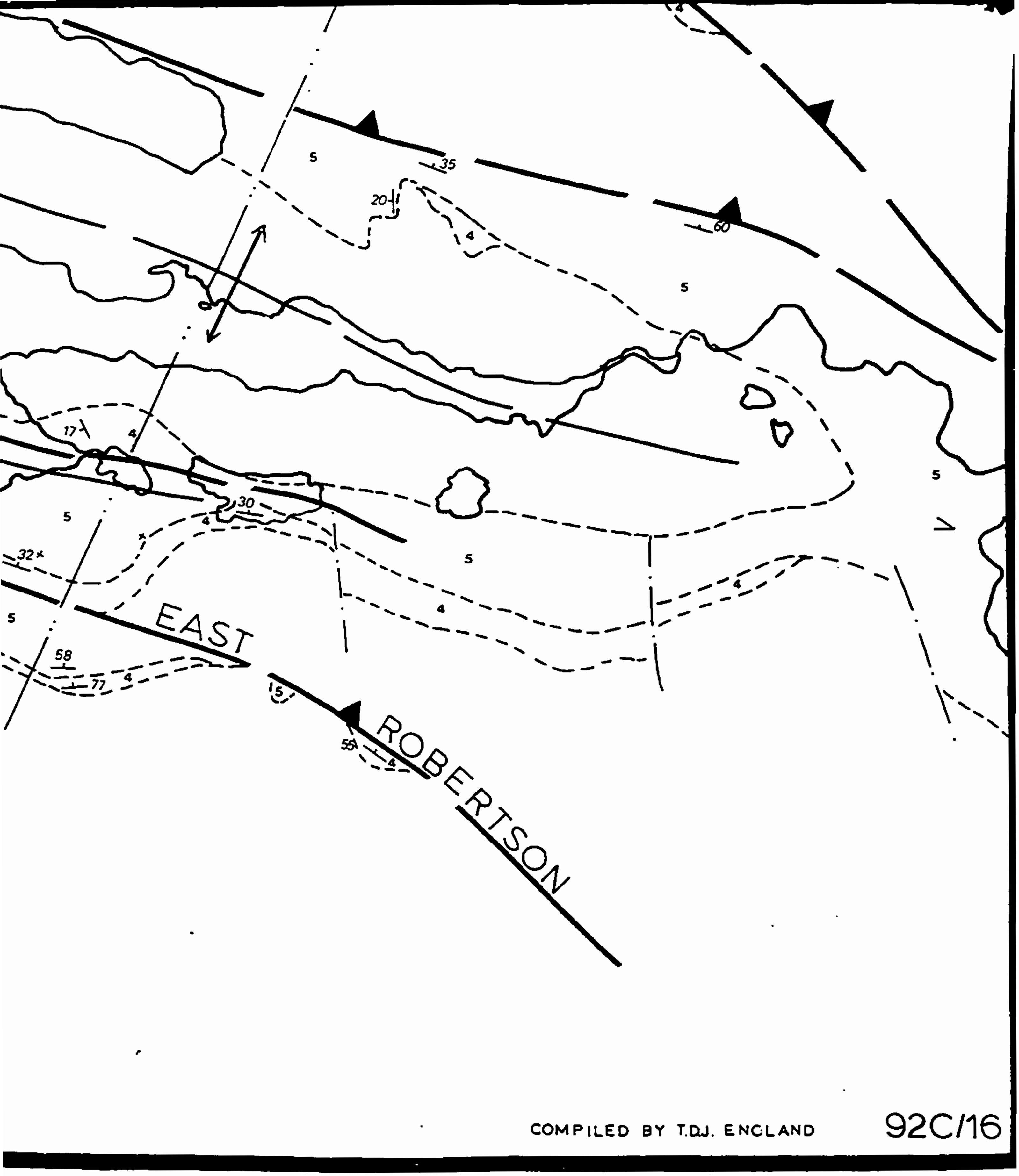


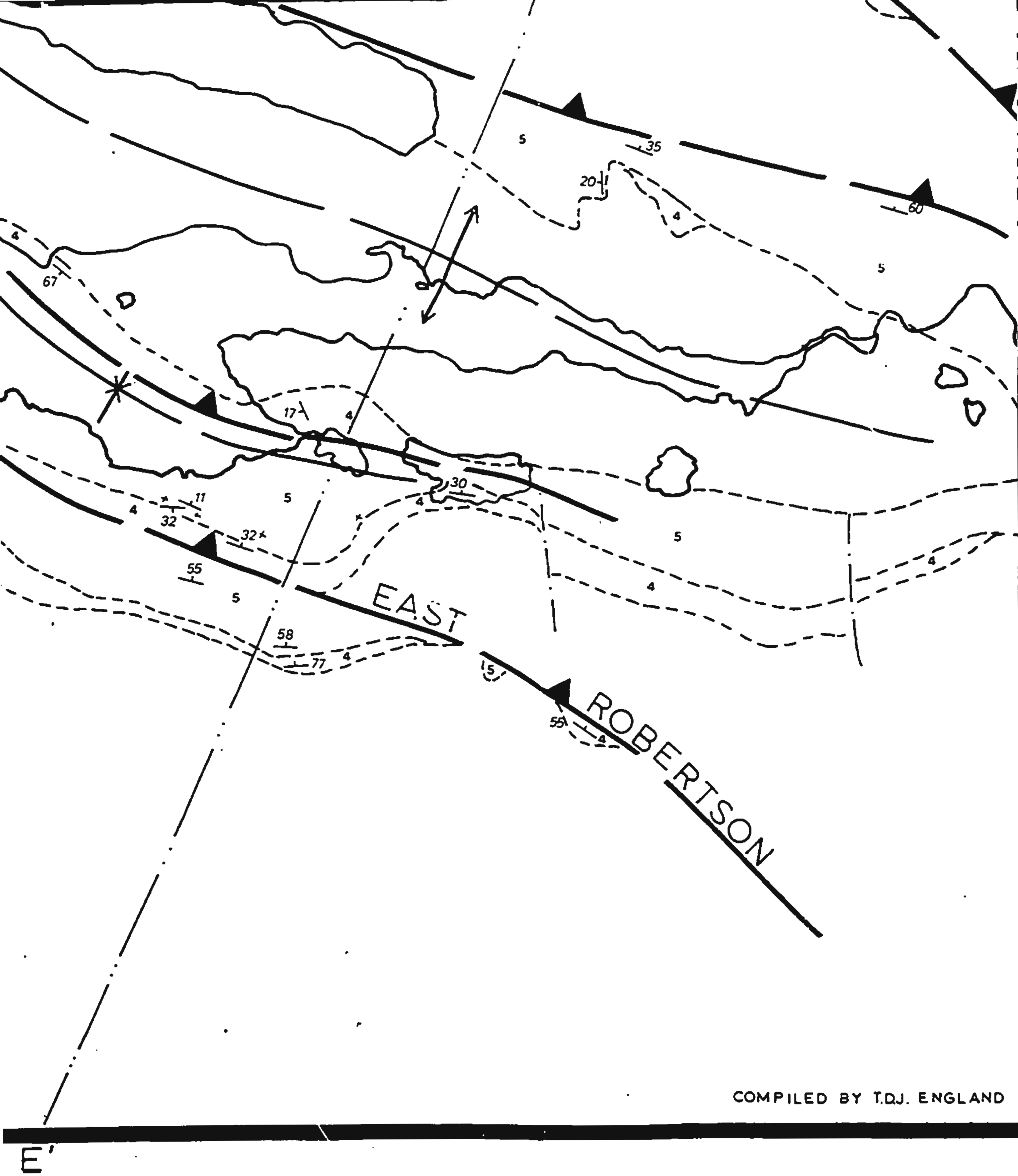
FIGURE A.2 COWICHAN LAKE

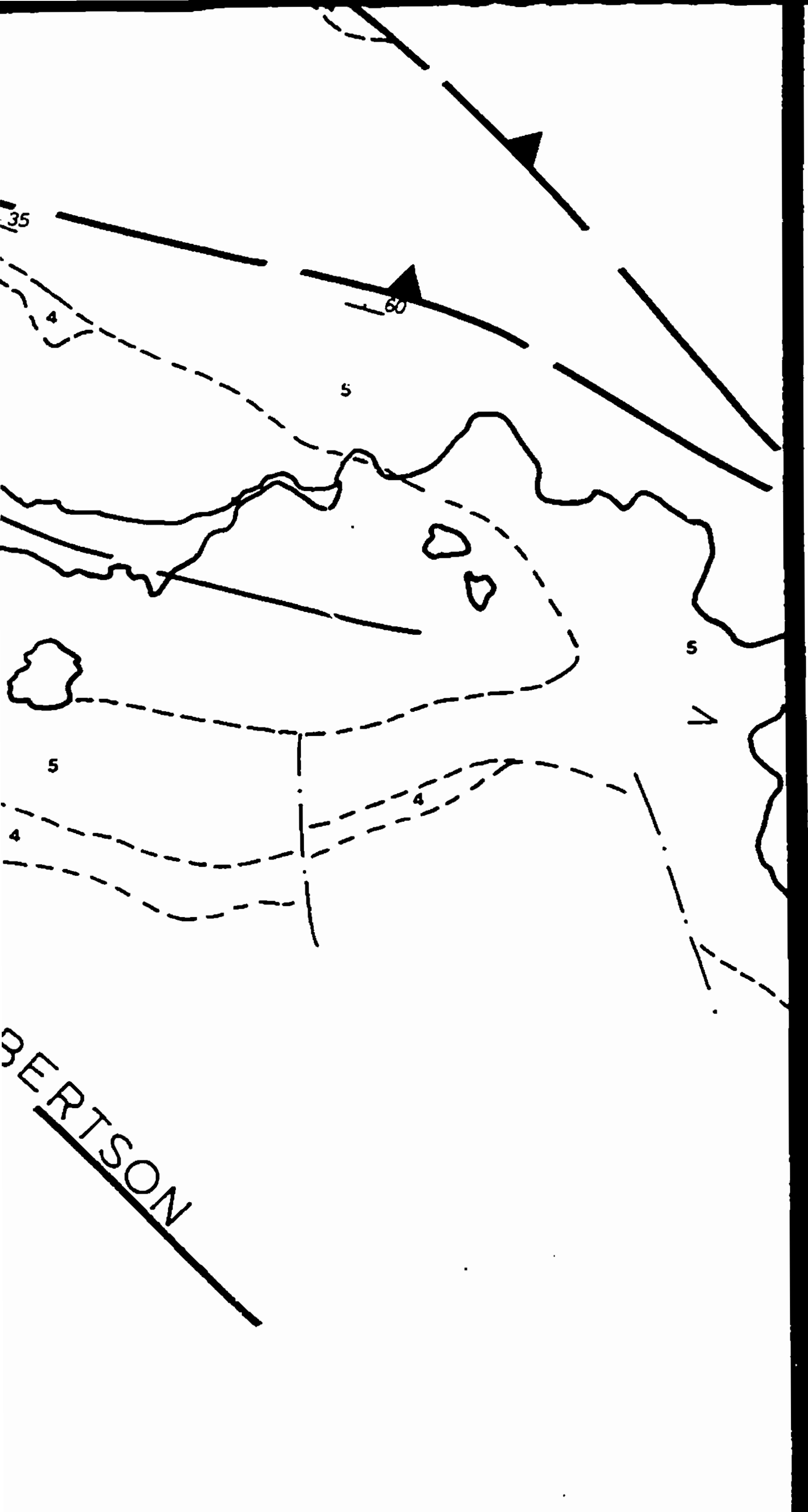


ENZIE BAY
EAST
ROBERTS
E'



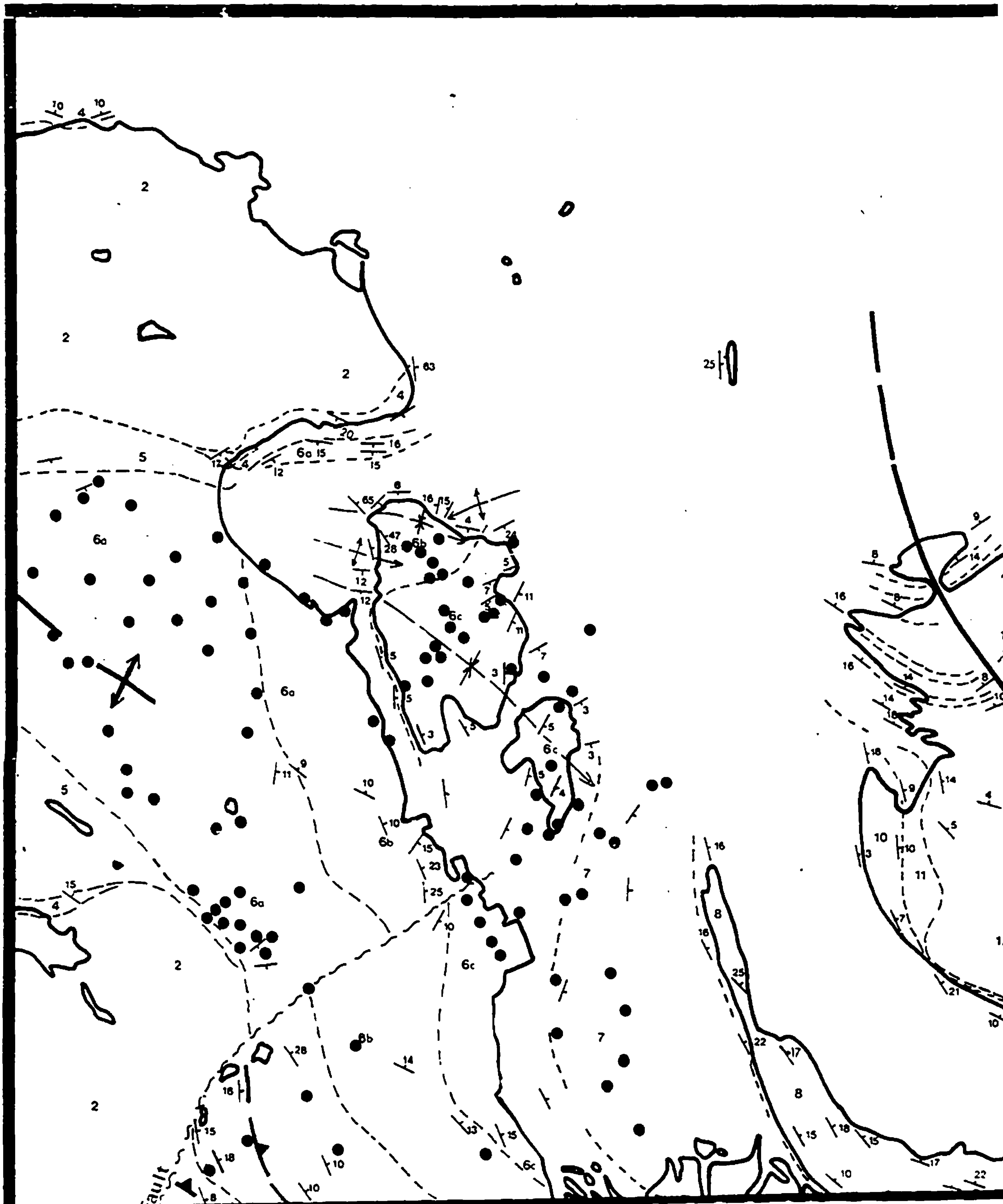
EAST ROBERTSON
COMPILED BY T.D.J. ENGLAND
92C/16


EAST ROBERTSON
COMPILED BY T.DJ. ENGLAND
E'

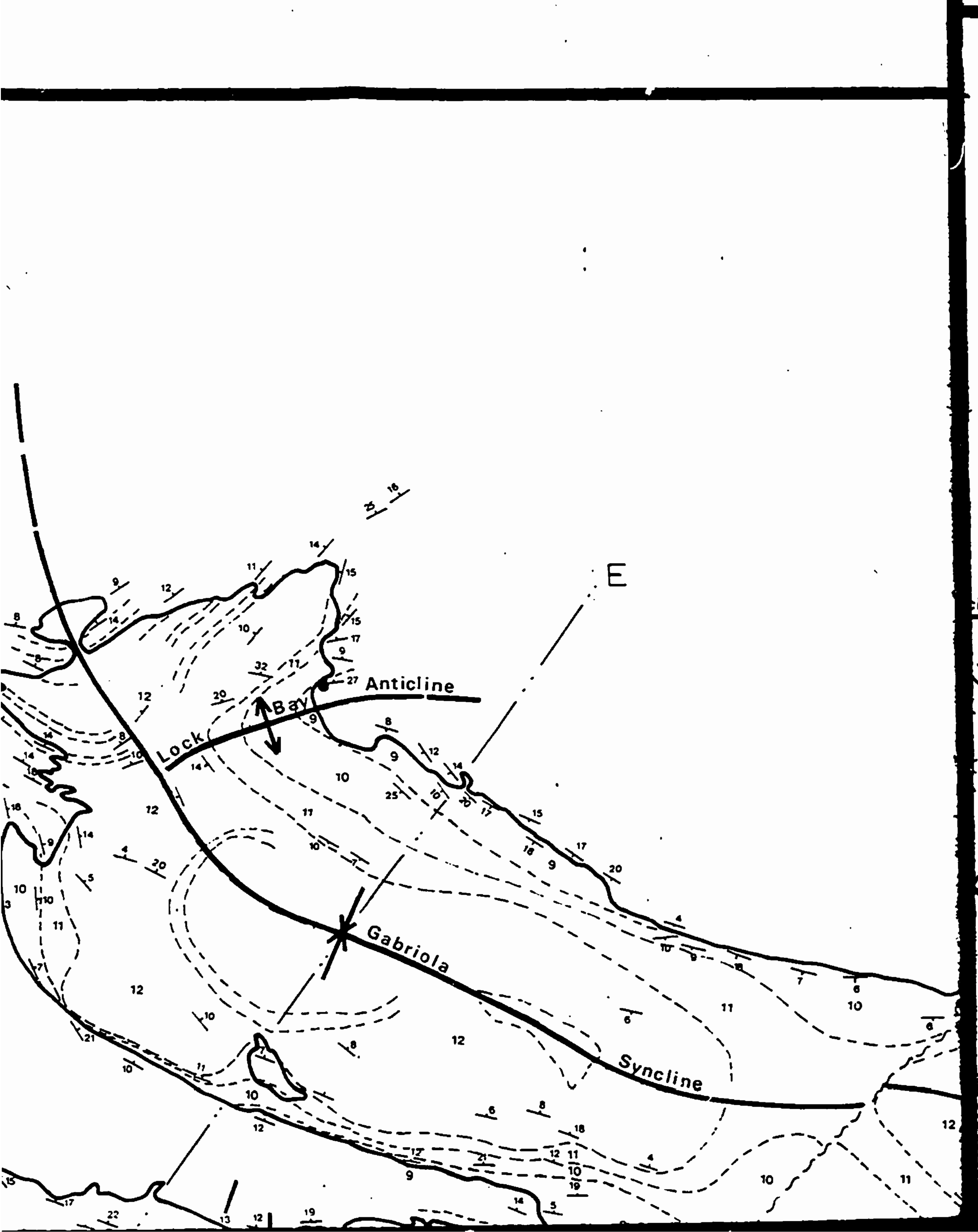


COMPILED BY T.D.J. ENGLAND

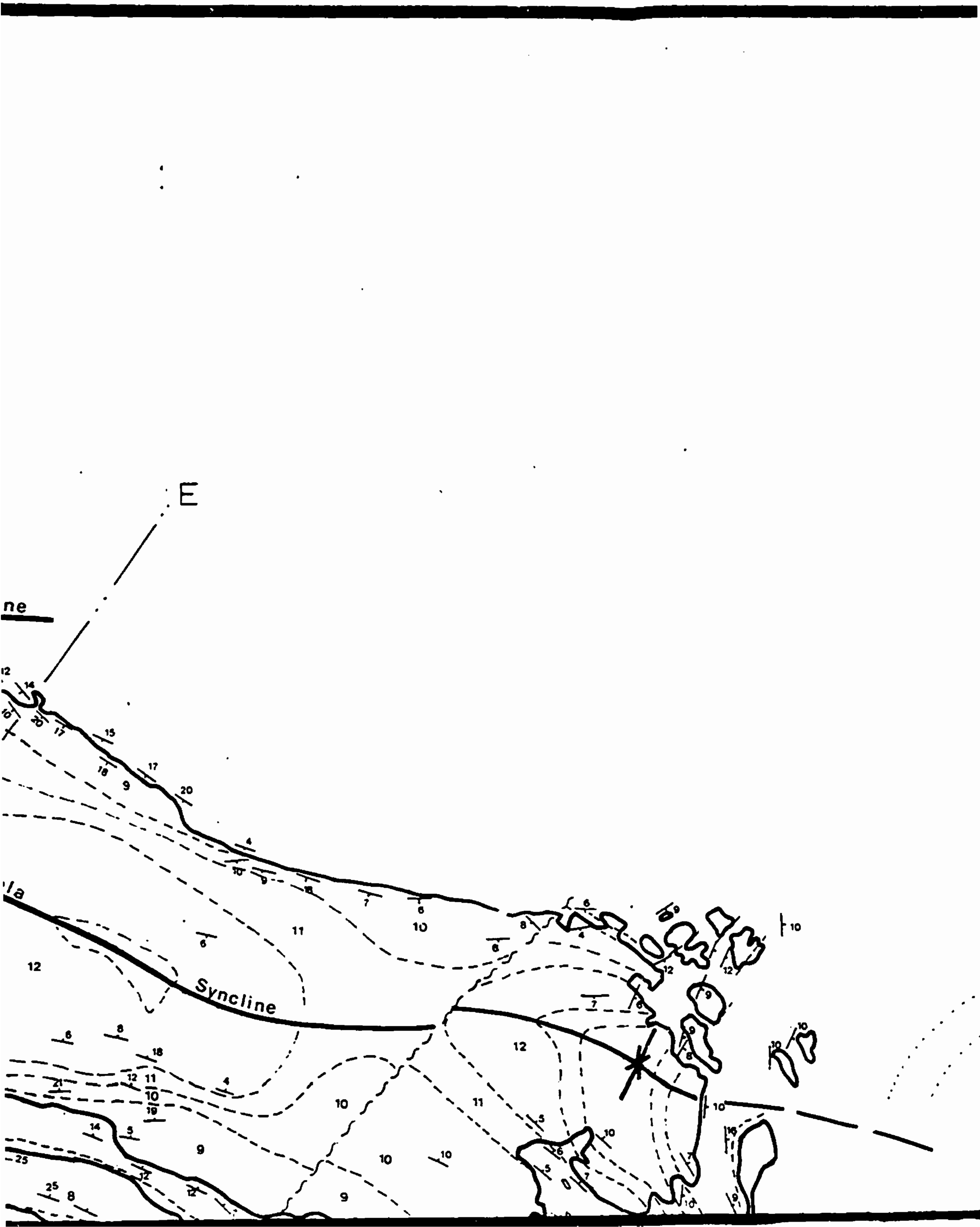
92C/16

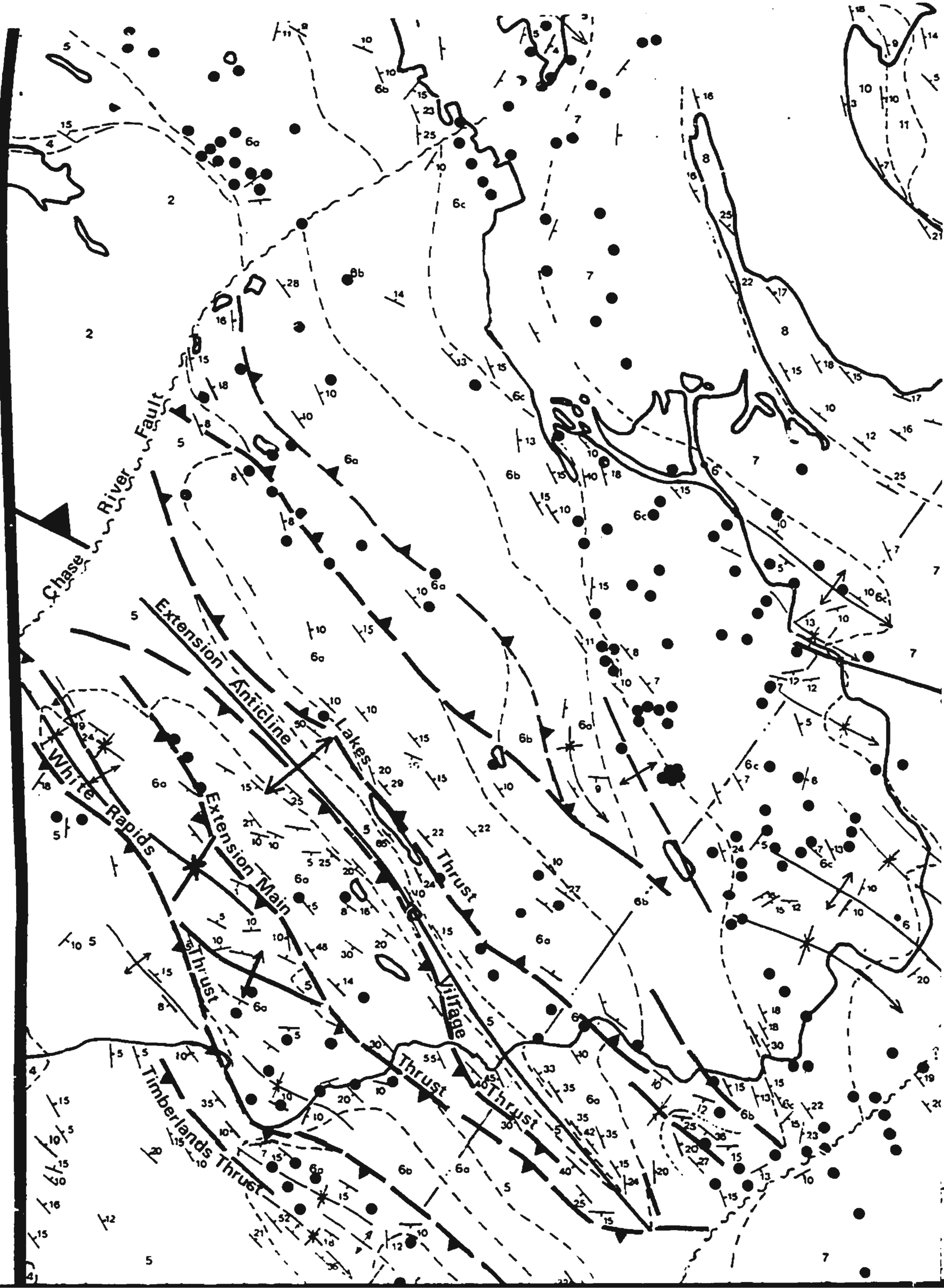


2
5
6a
6b
6c
7
8
10
11



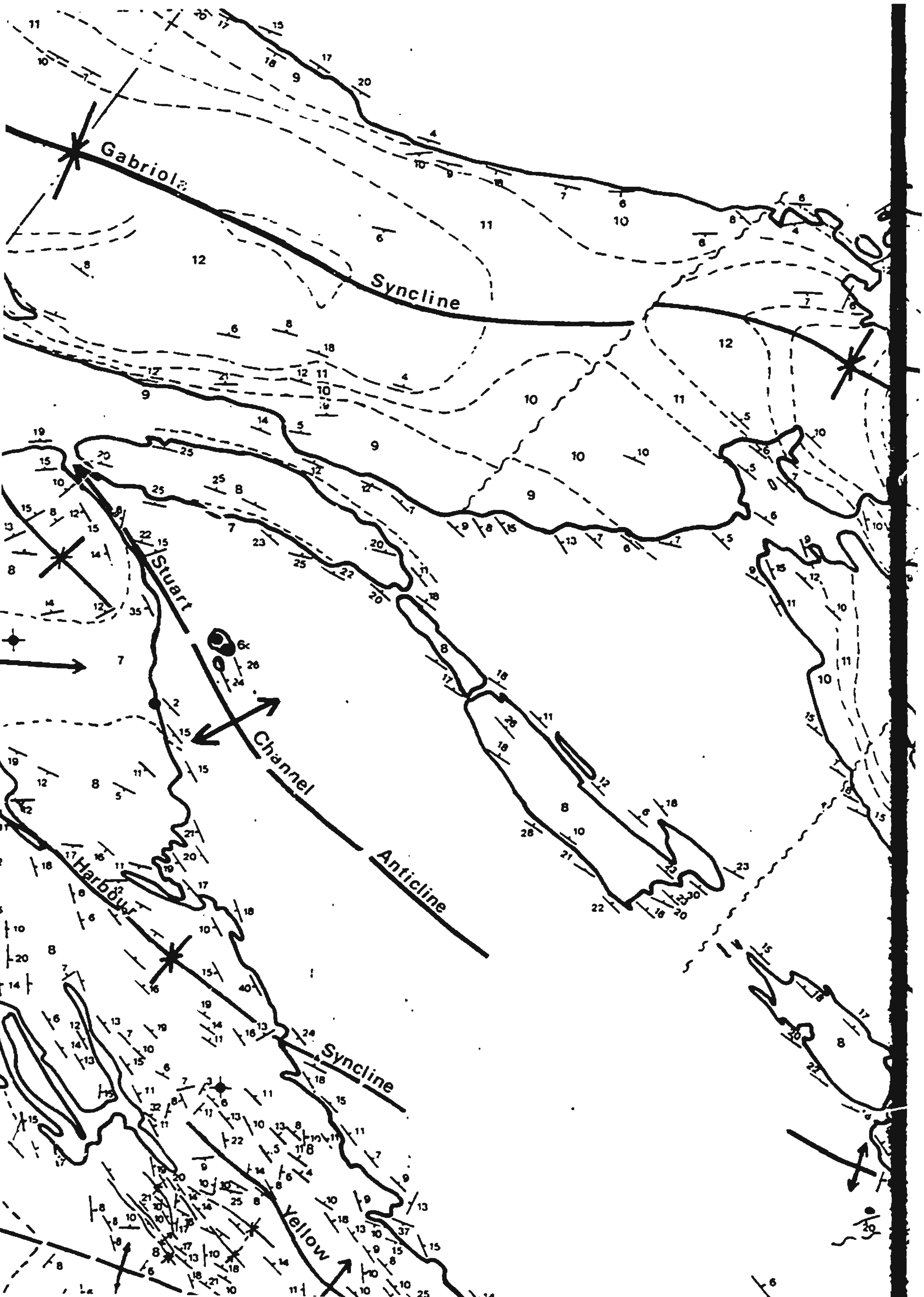
E
Lock Bay Anticline
Gabriola Syncline

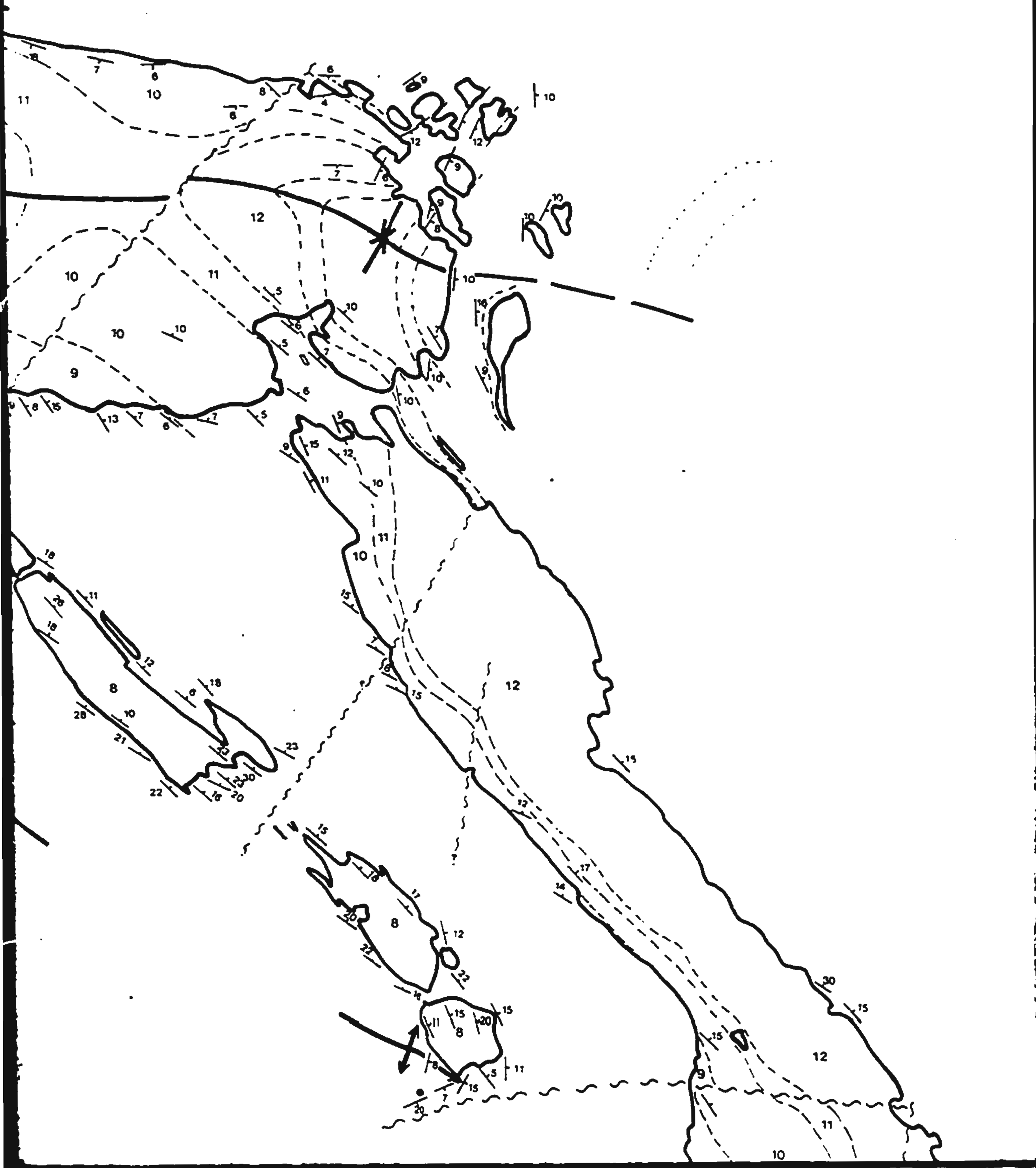

E
ne
Syncline

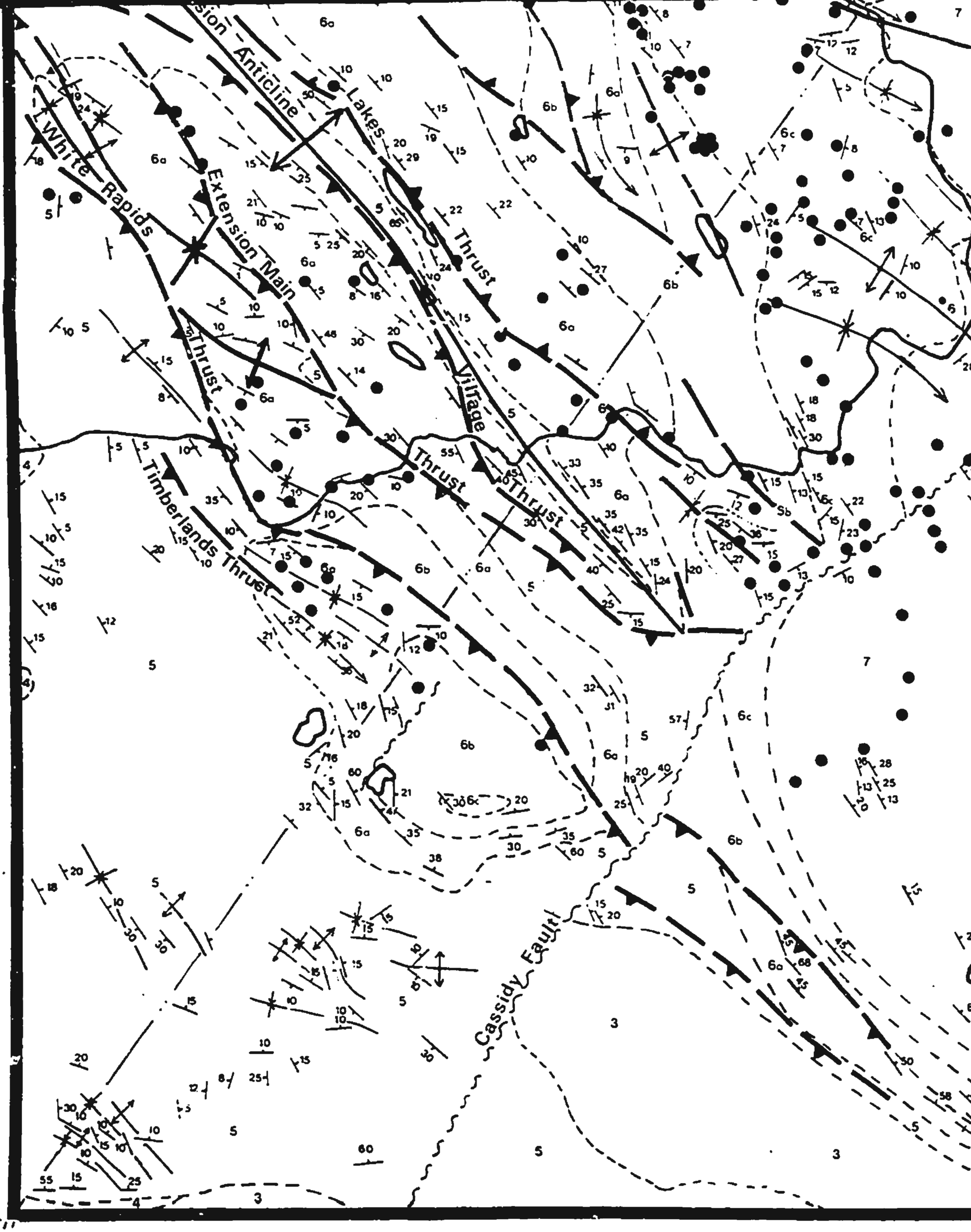


Chase River Fault
Extension Anticline
Lakes
White Rapids
Extension Main
Thrust
Village
Thrust
Thrust
Thrust
Timberlands Thrust


Gabriola
Stuart Channel
Boat Harbour


Gabriola Syncline
Stuart Channel Anticline
Harbour Syncline
Yellow




Anticline
Lakes
White Rapids
Extension Main
Thrust
Thrust
Village
Thrust
Thrust
Timberlands Thrust
Cassidy Fault

E''

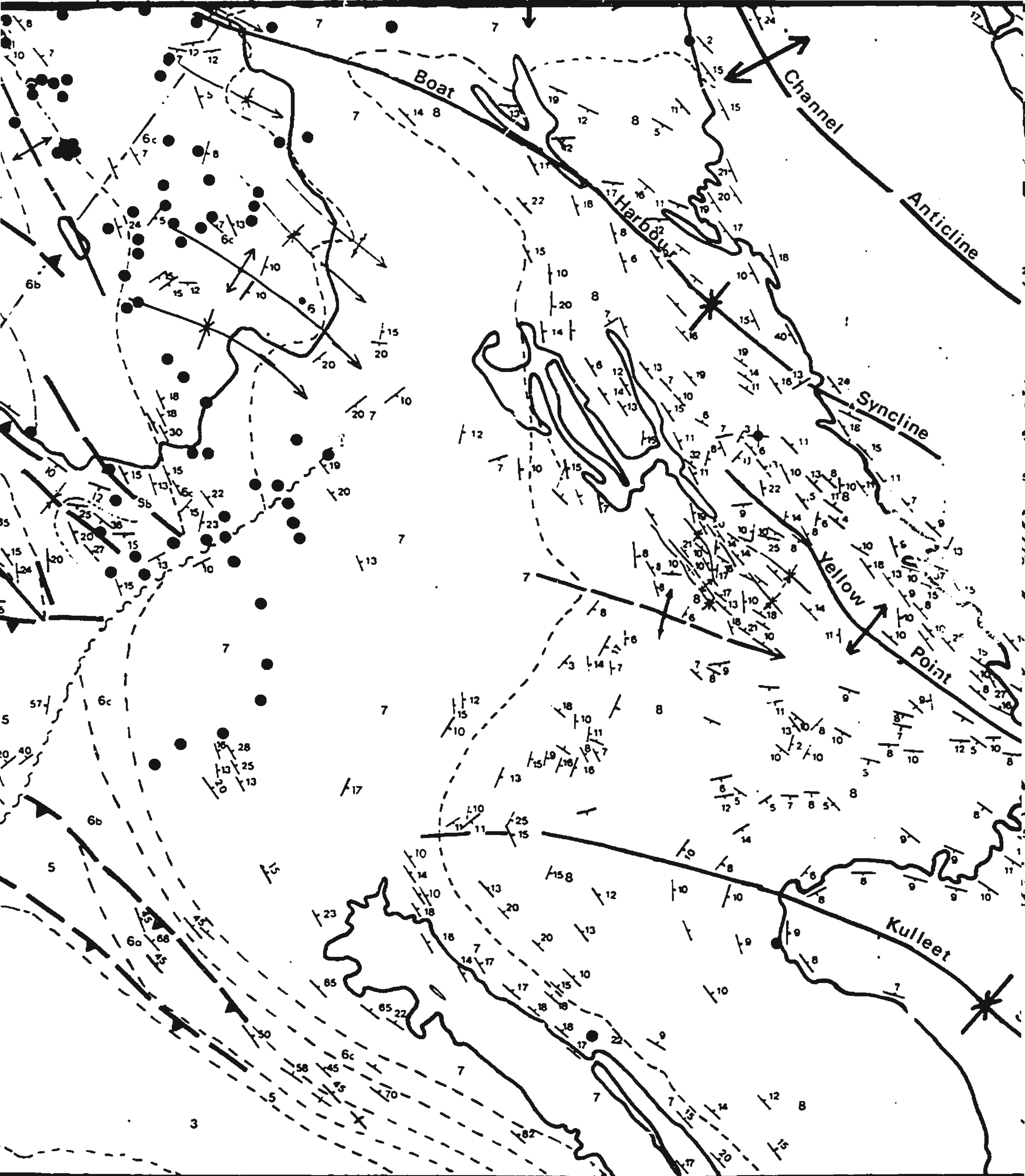


FIGURE A.3 NAI

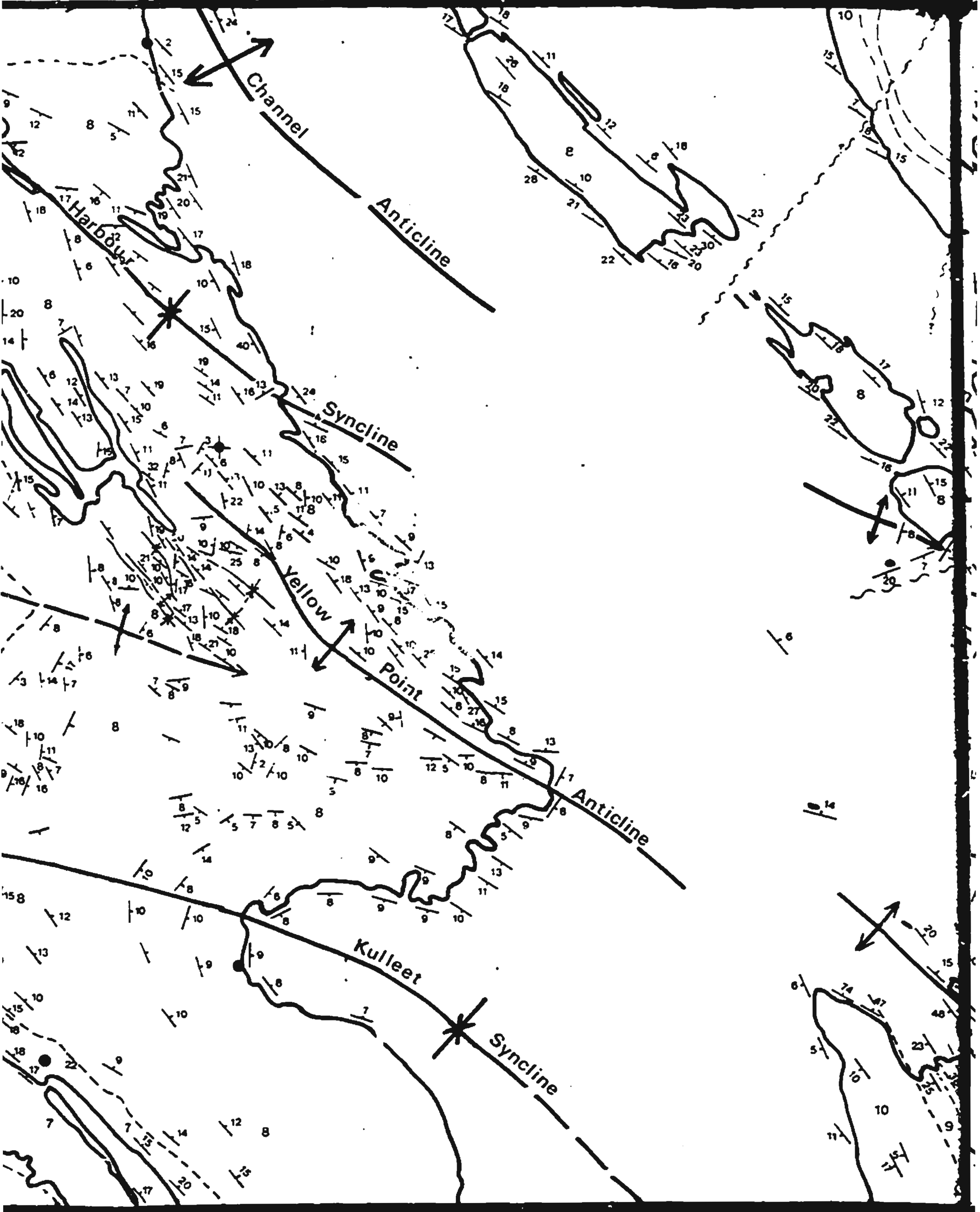
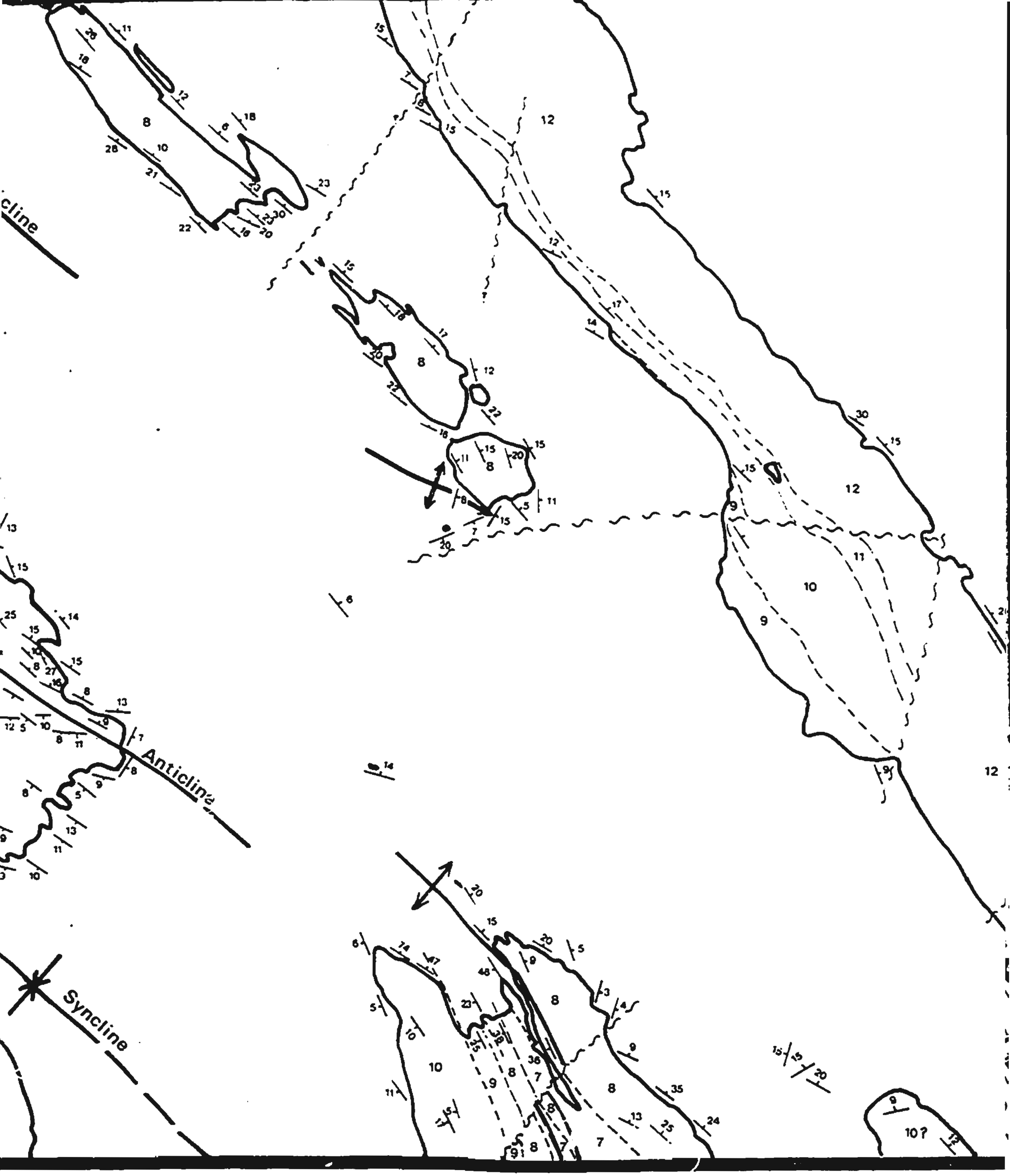
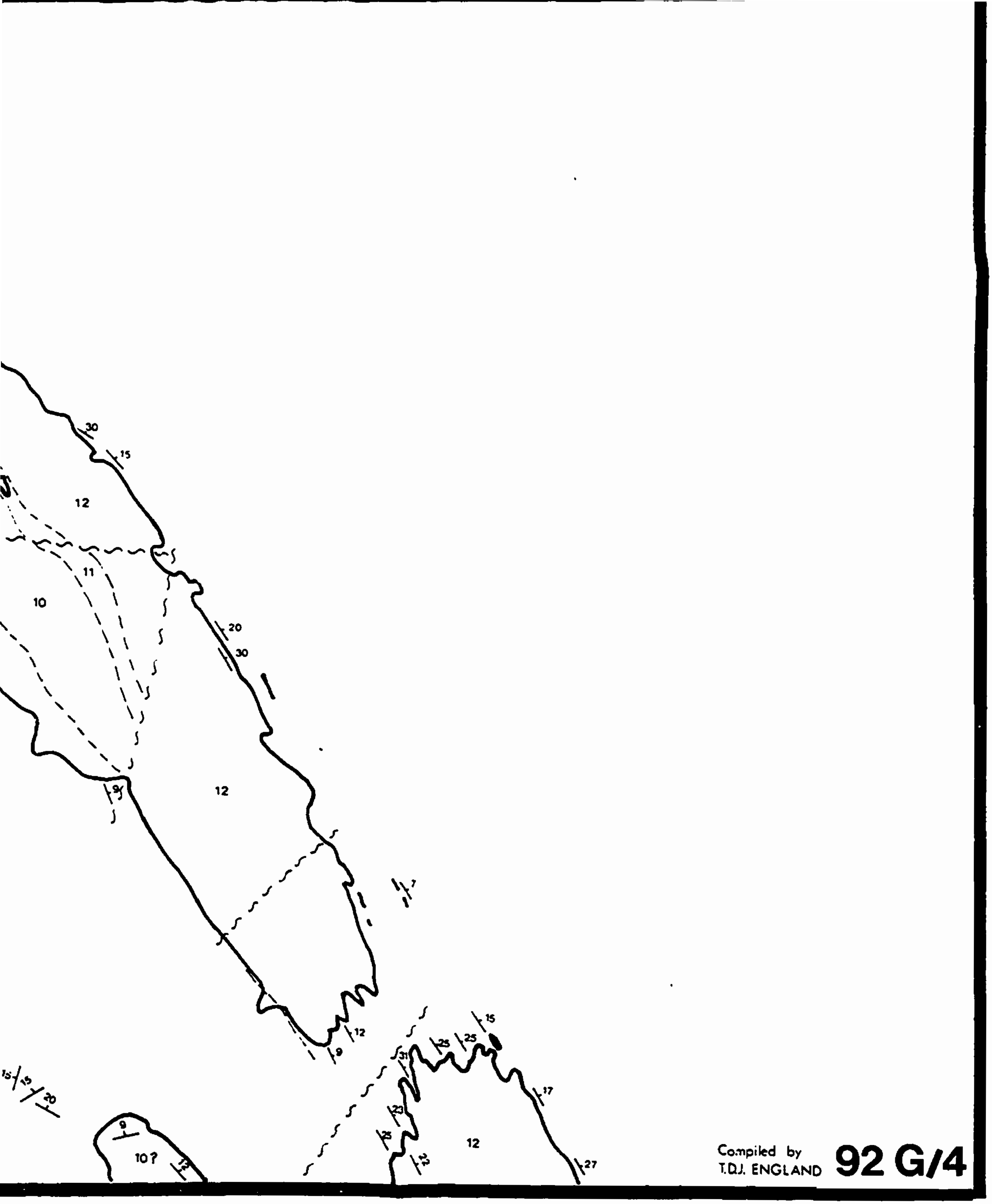


FIGURE A.3 NANAIMO

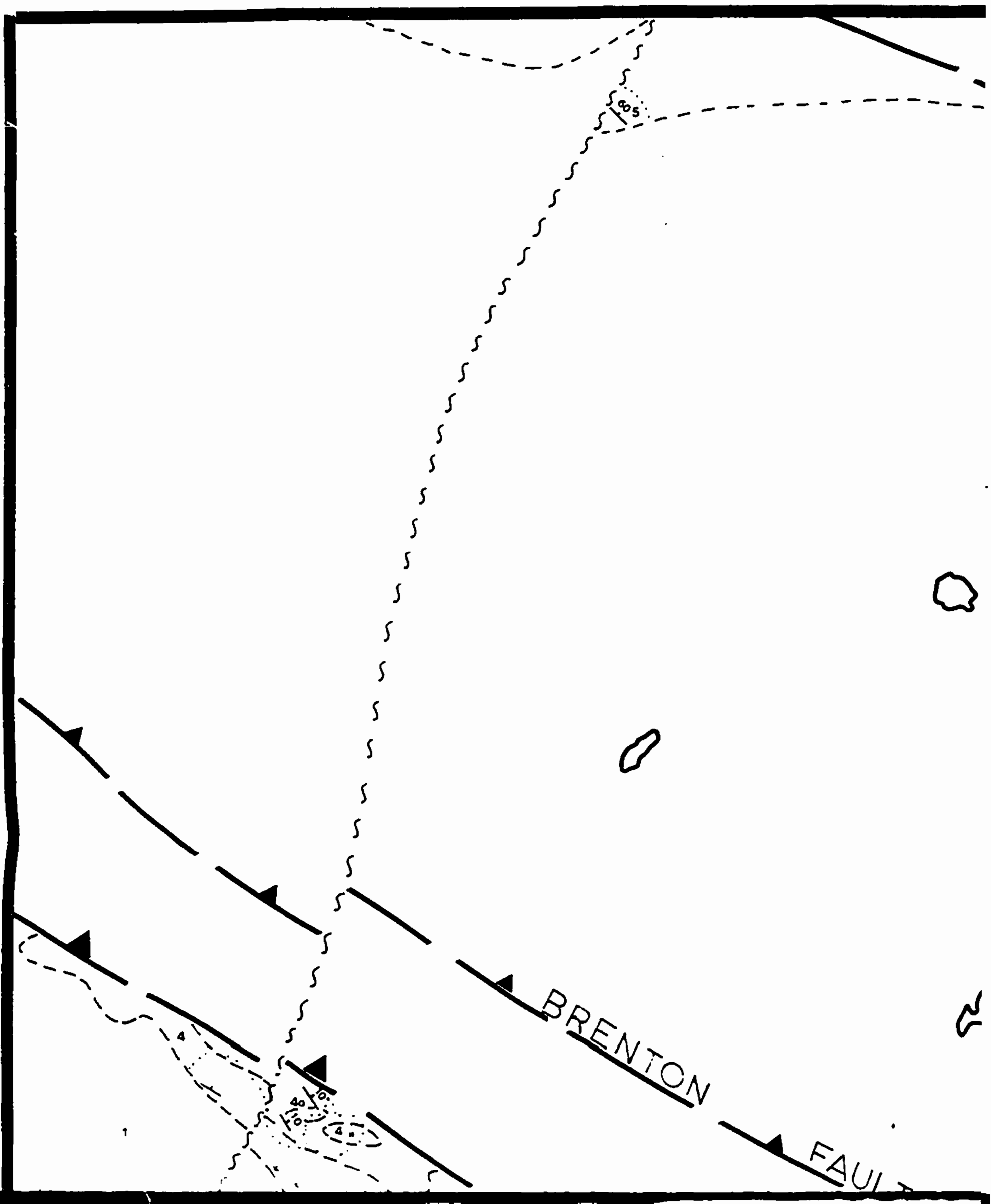


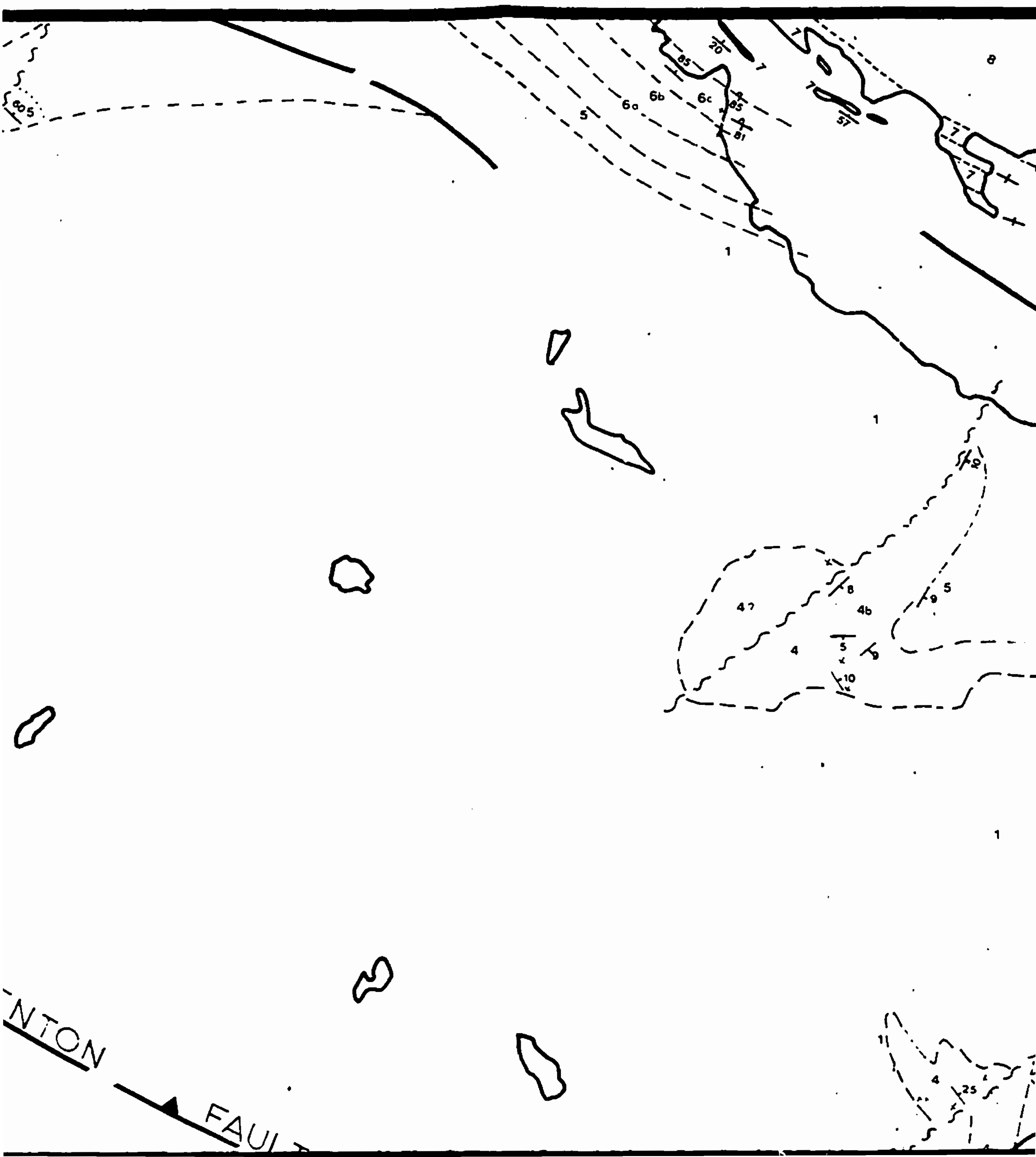
NANAIMO



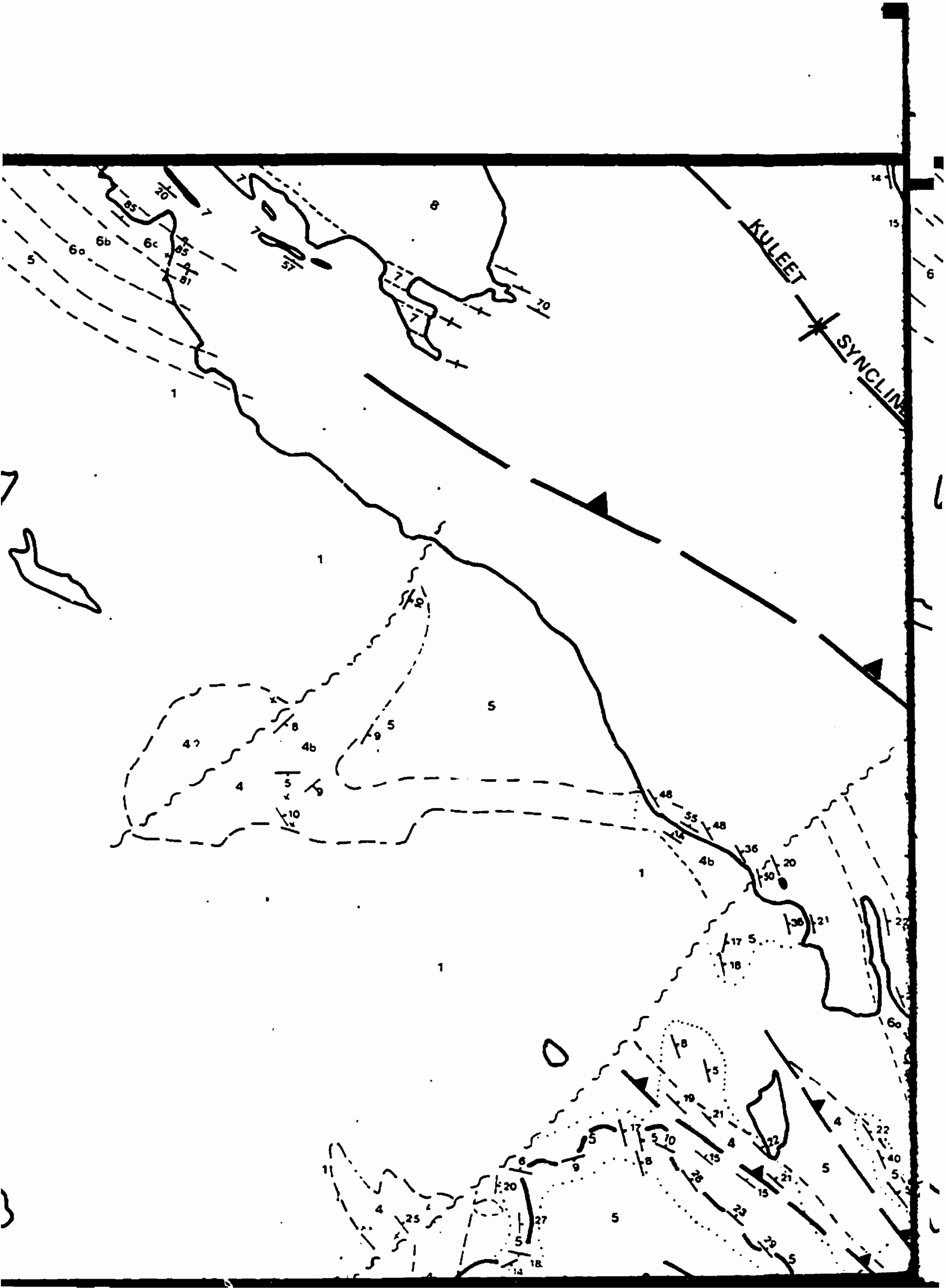
Compiled by
T.D.J. ENGLAND

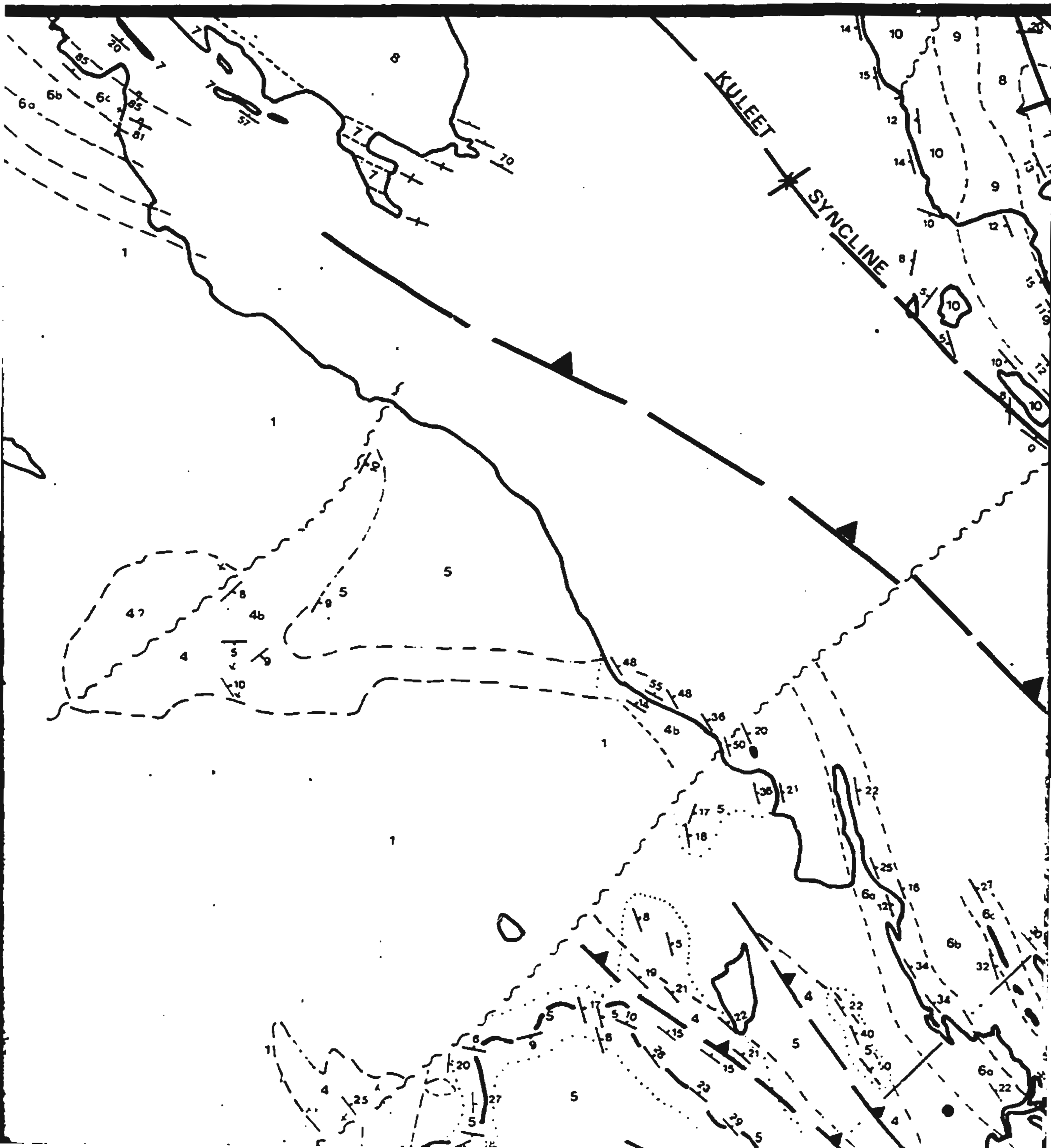
92 G/4

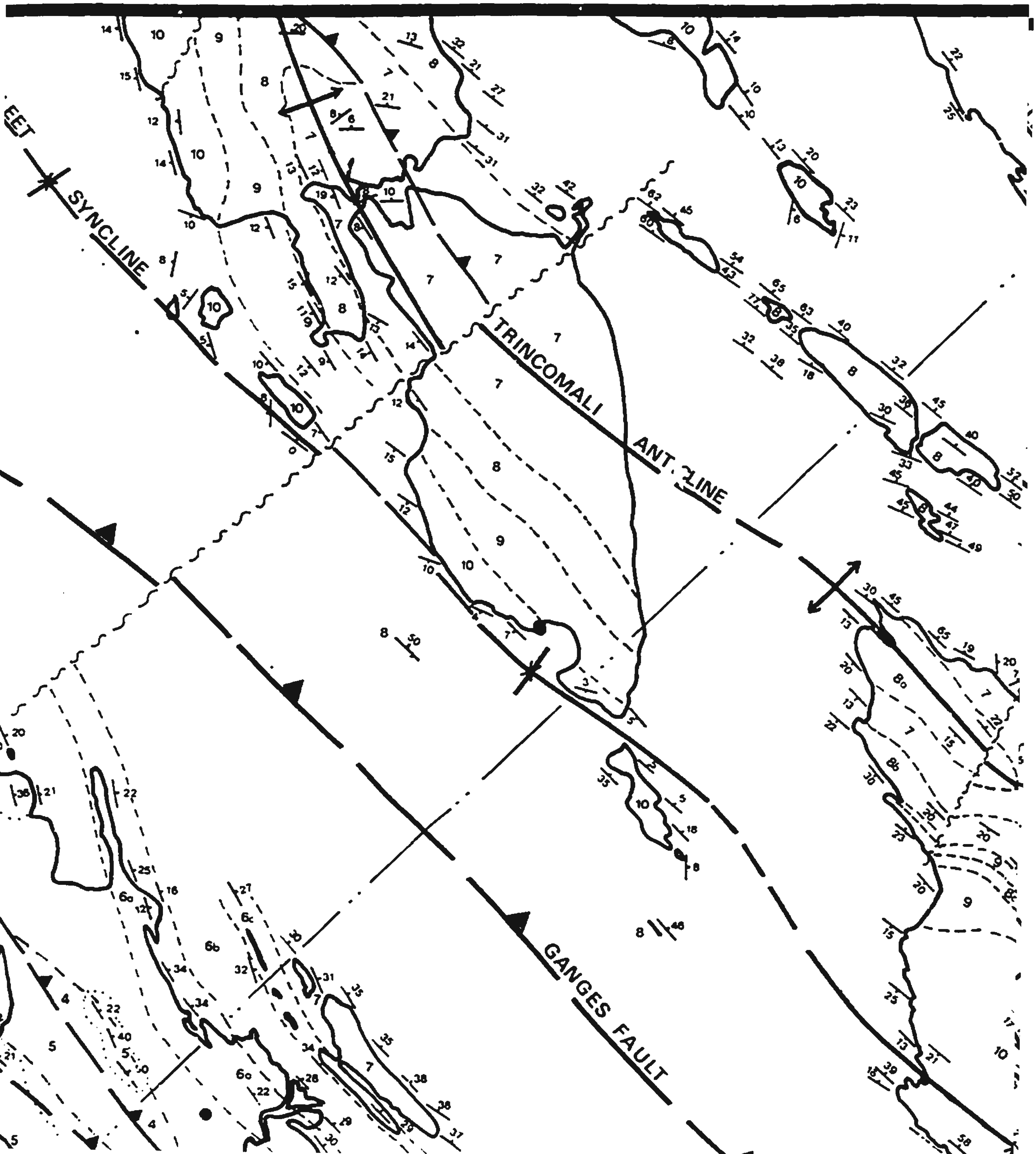

BRENTON
FAUL



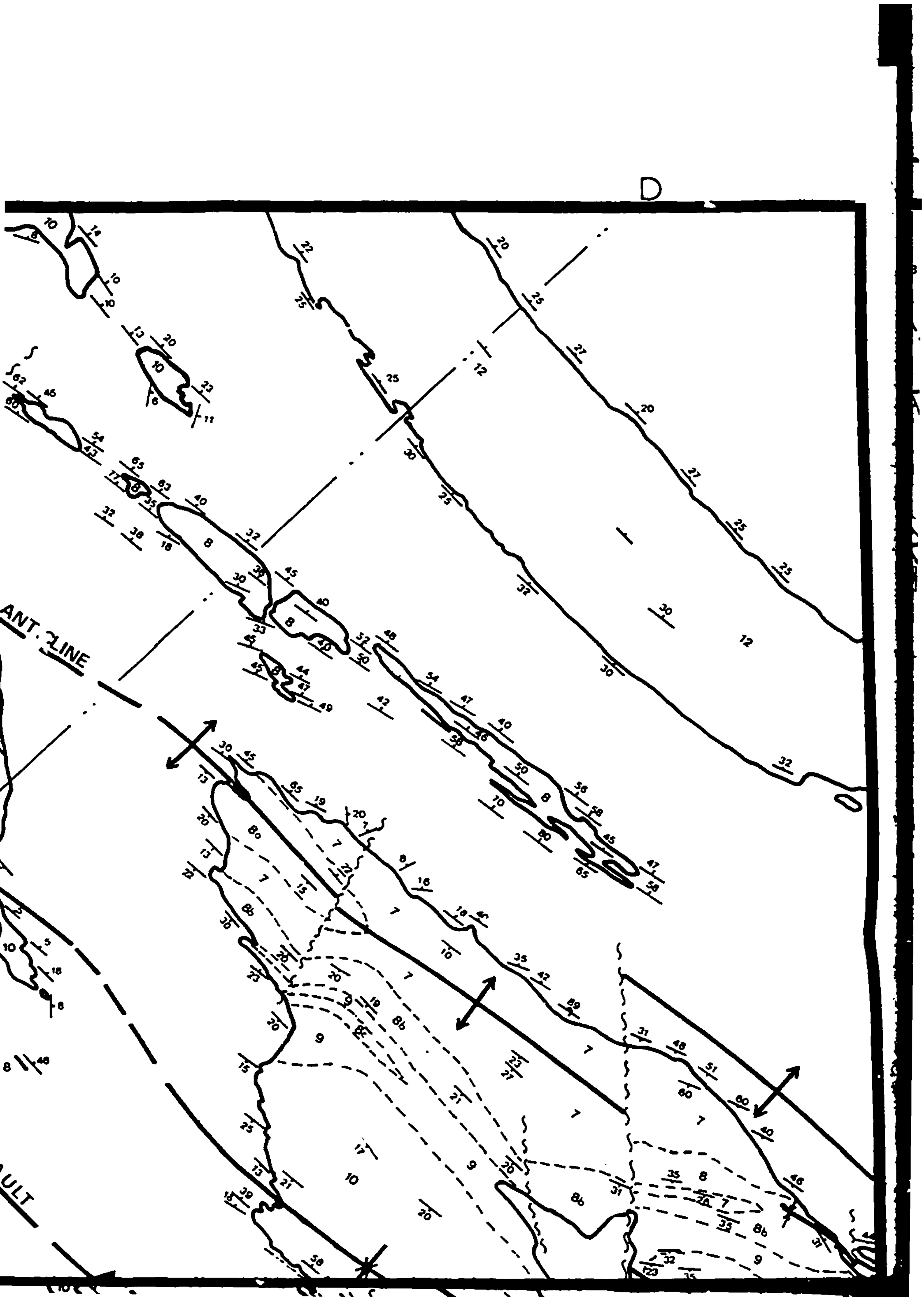
8
6a
6b
6c
5
1
1
4b
4
5
1
NTON
FAUL

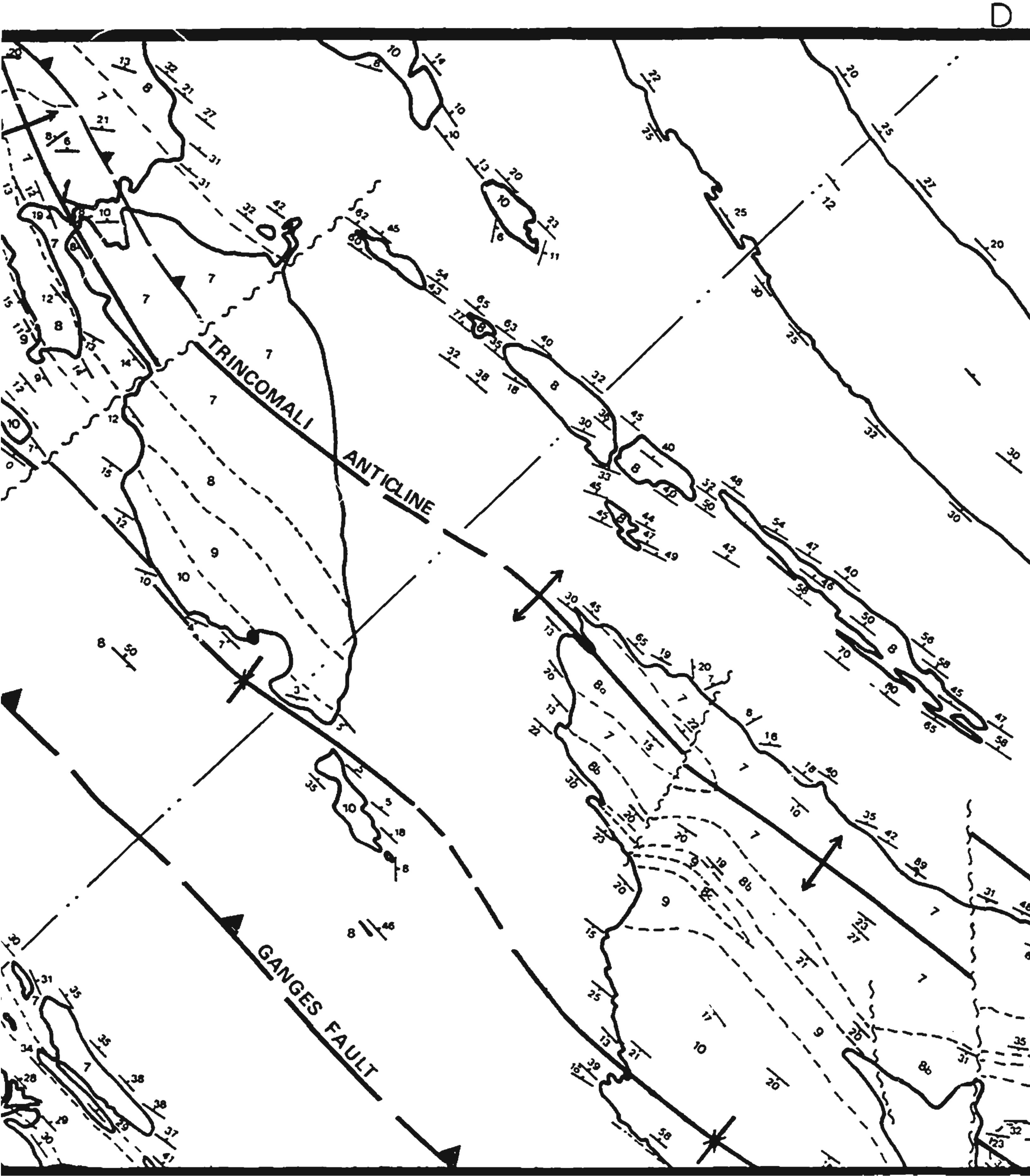

KULEET SYNCLINE

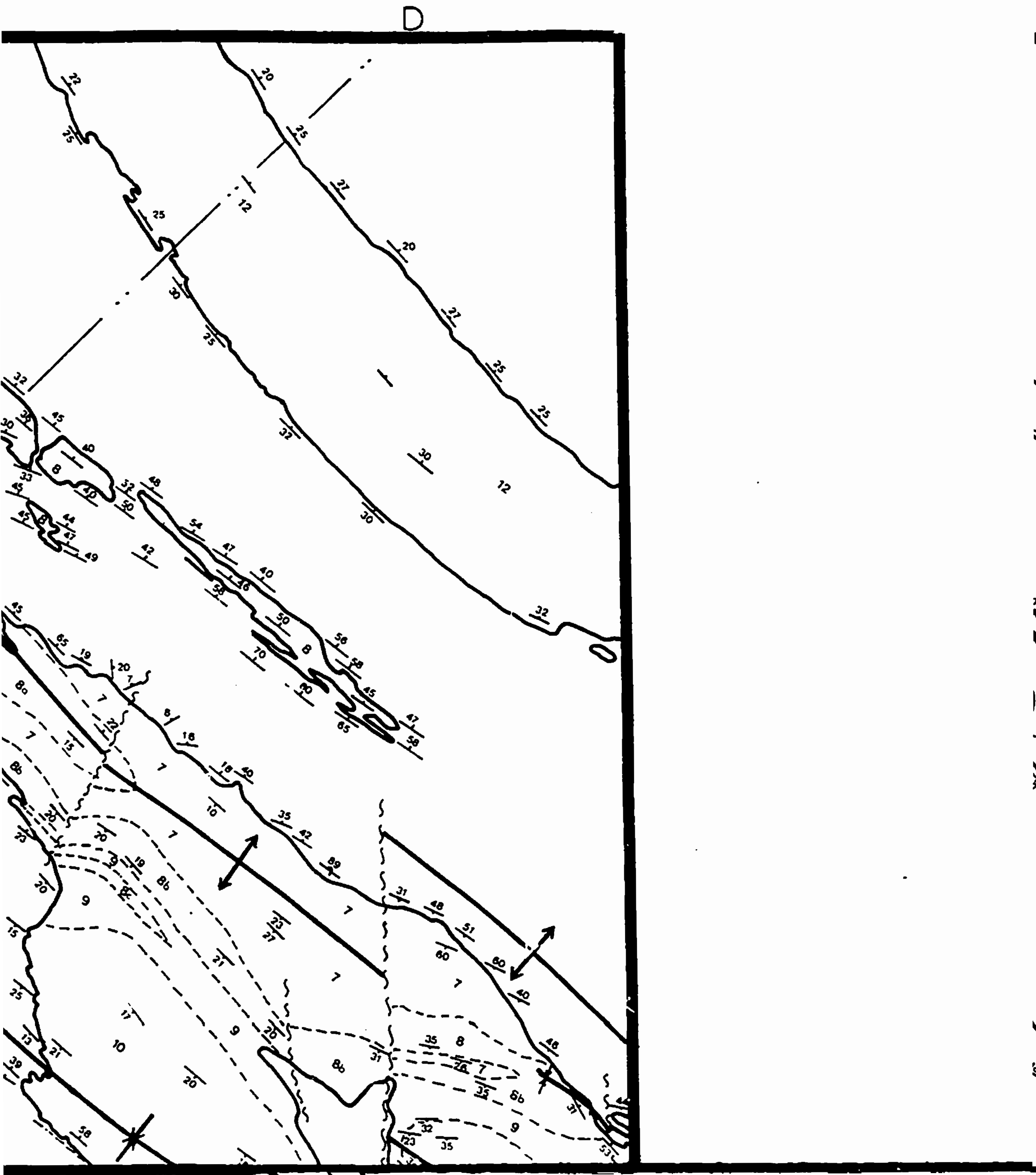

KULEET
SYNCLINE



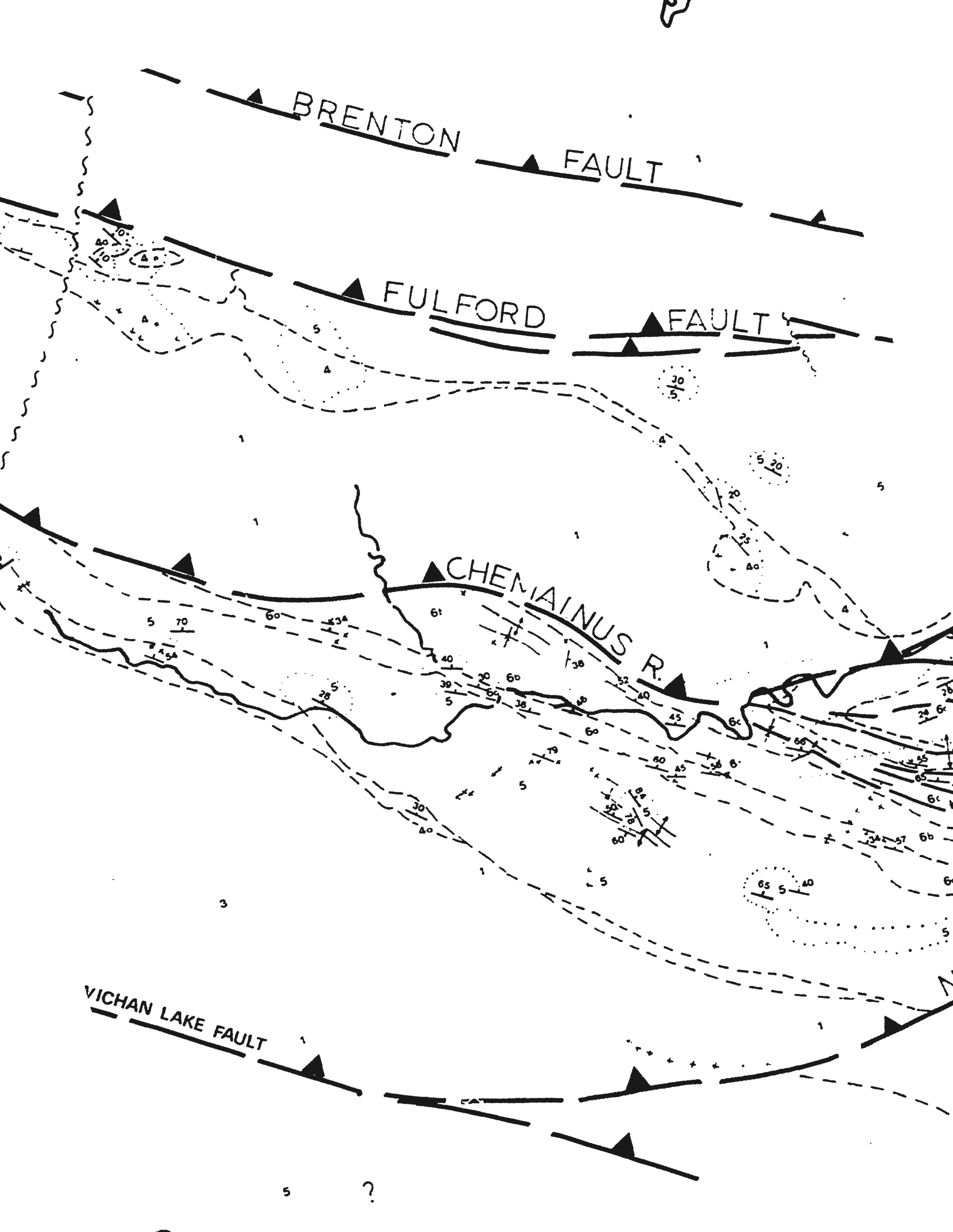
SYNCLINE
TRINCOMALI
GANGES FAULT


D
ANT. CLINE
ULT

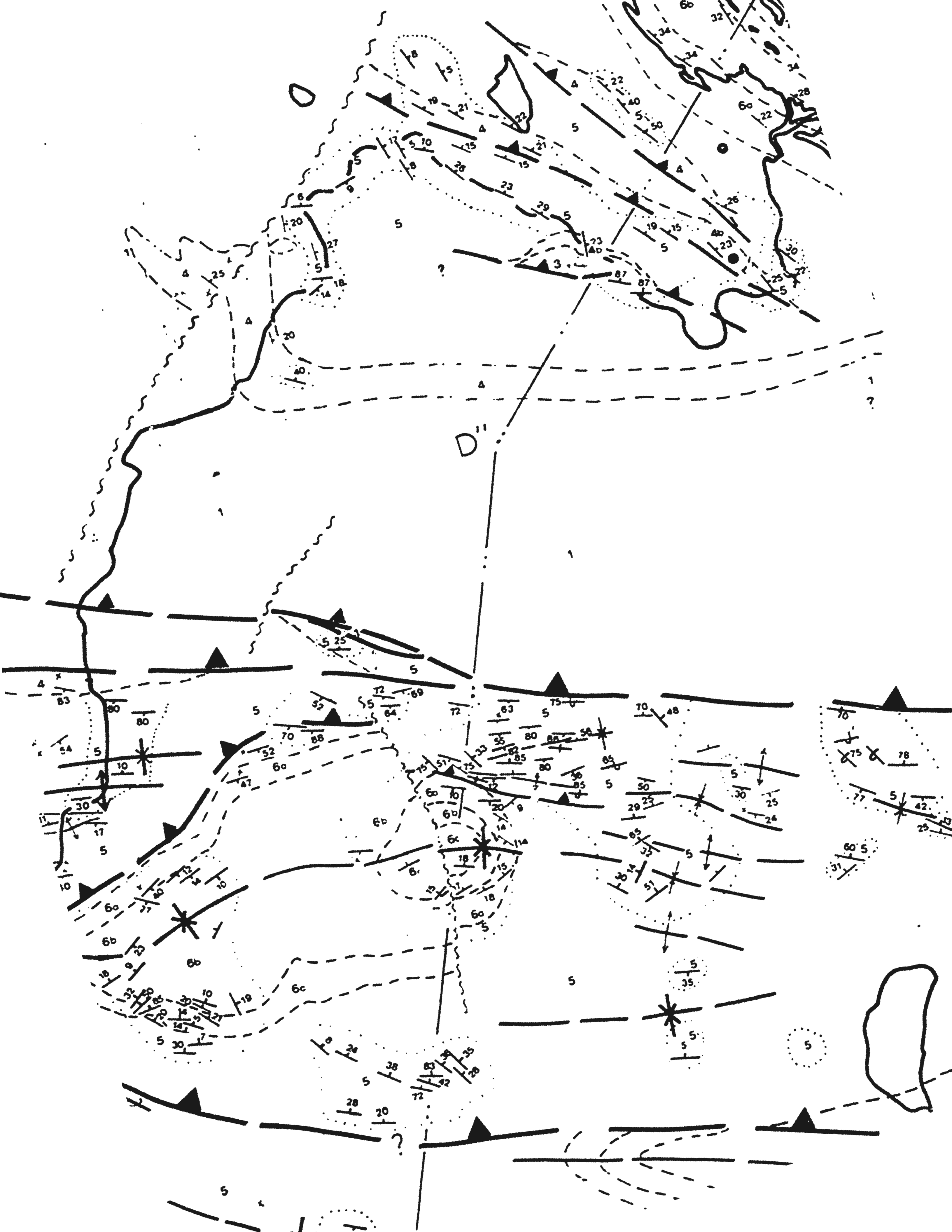

D
TRINCOMALI ANTICLINE
GANGES FAULT

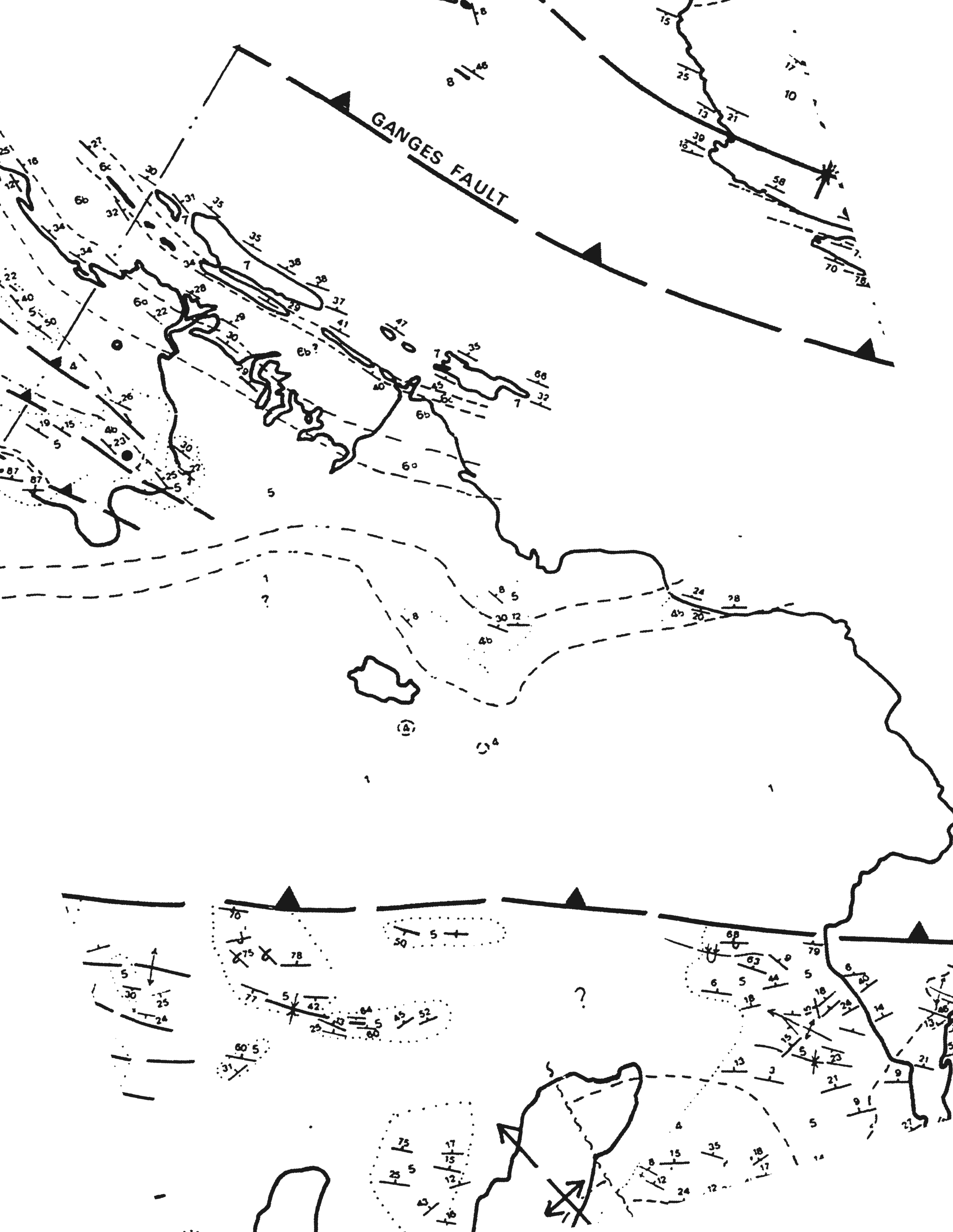


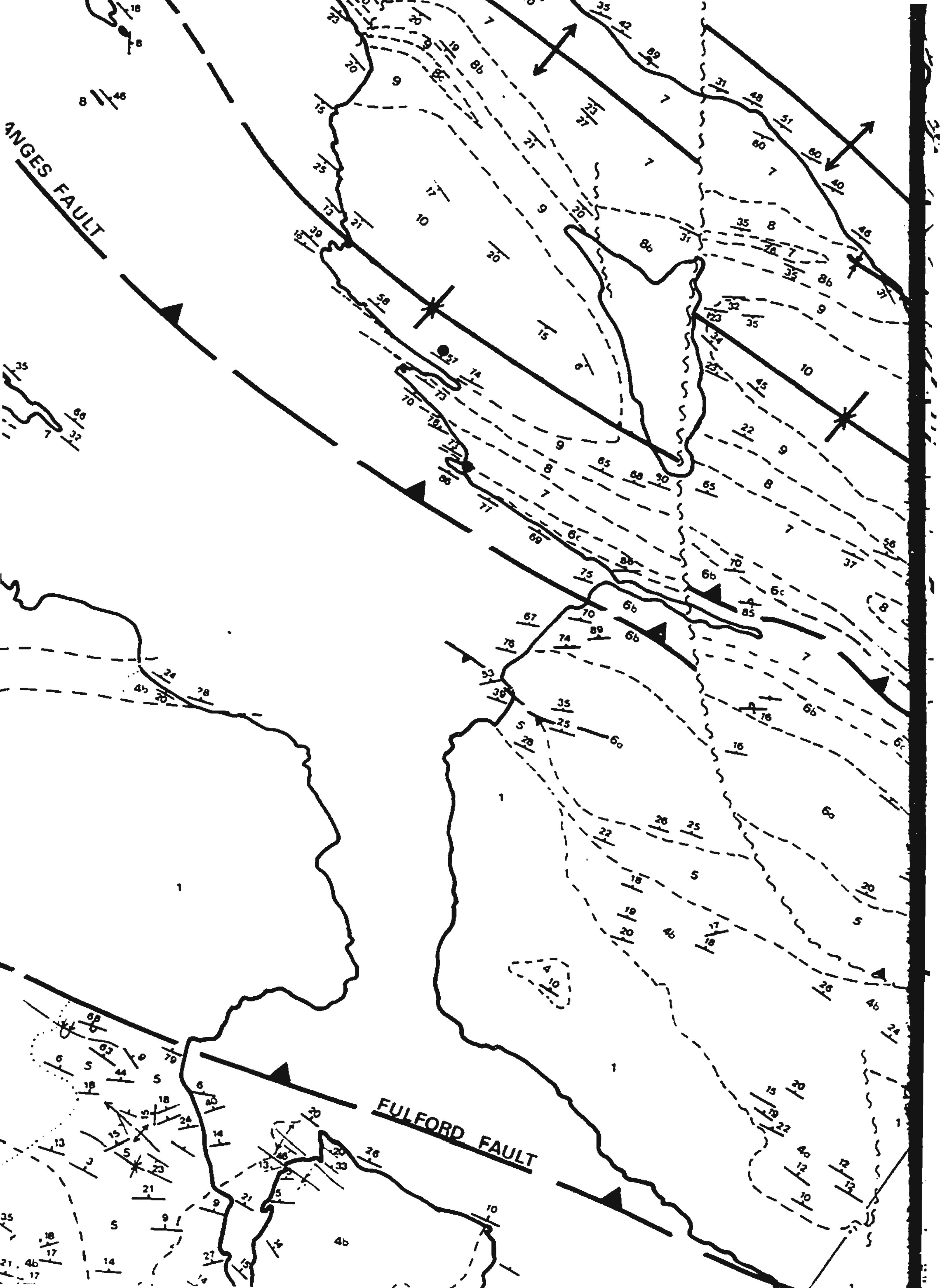
D

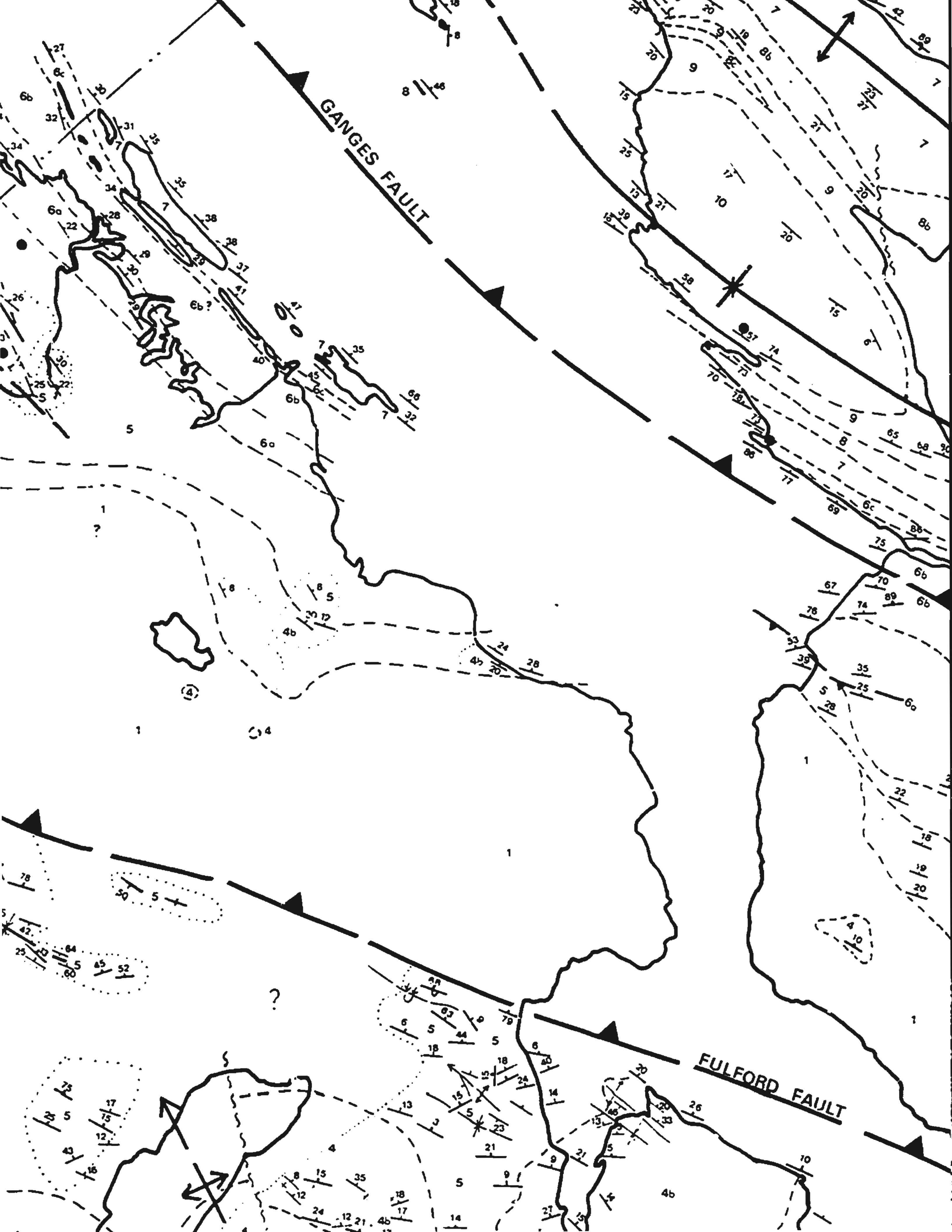

BRENTON FAULT
FULFORD FAULT
CHEMAINUS R.
VICHAN LAKE FAULT

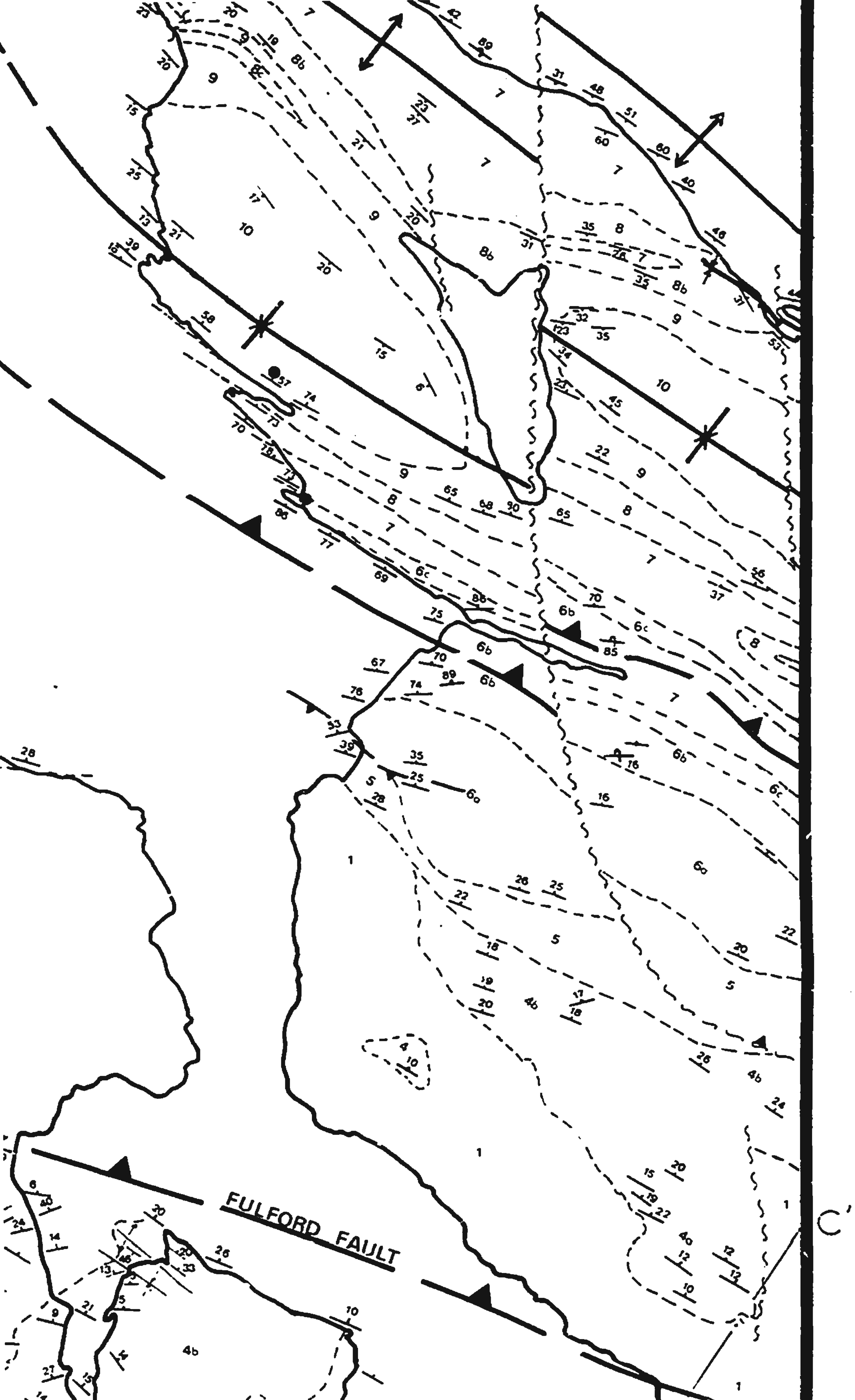

D''
NORTH

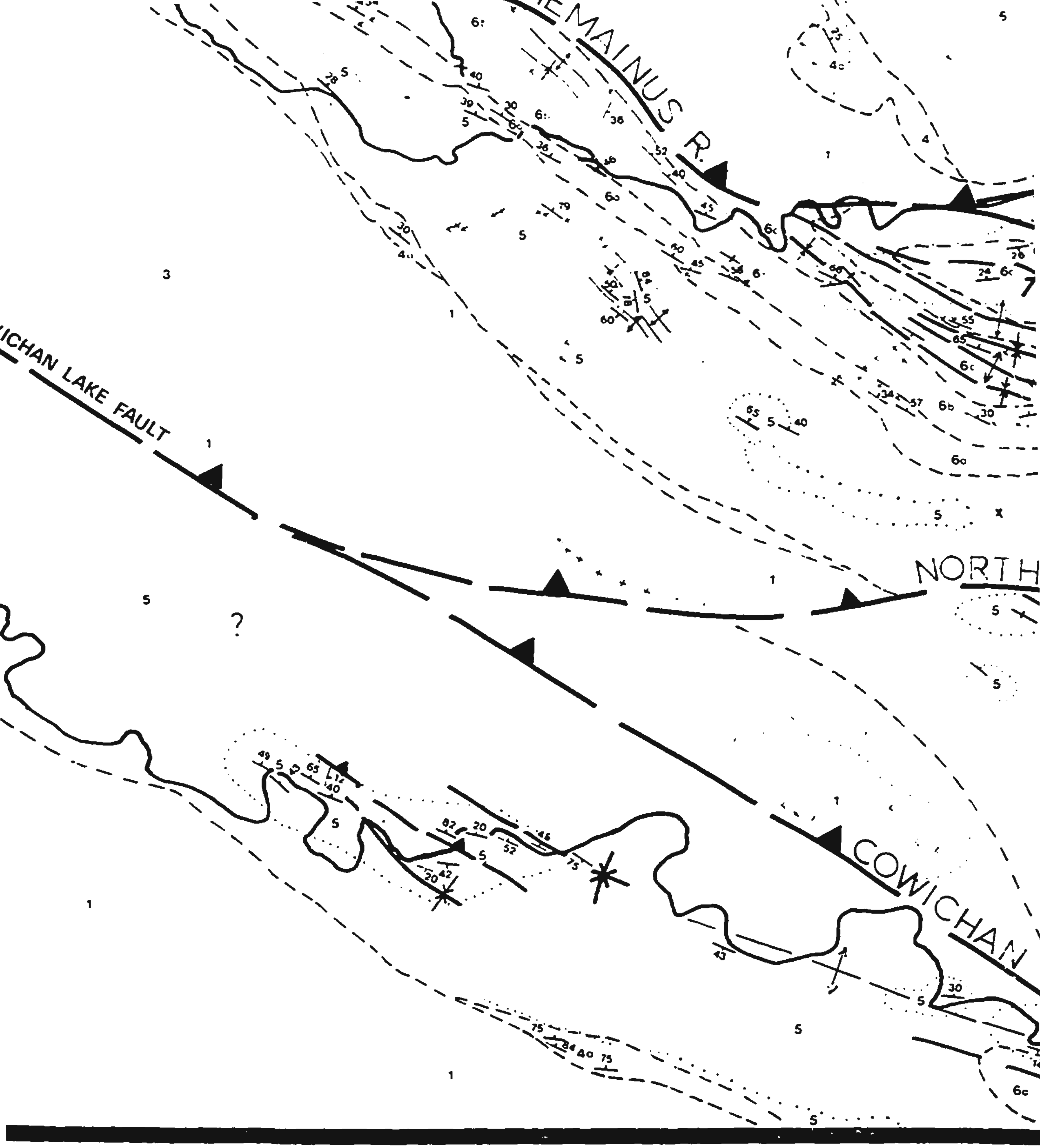

D''


GANGES FAULT


ANGES FAULT
FULFORD FAULT


GANGES FAULT
FULFORD FAULT


FULFORD FAULT
C''



EMAINUS R.
ICHAN LAKE FAULT
NORTH
COWICHAN

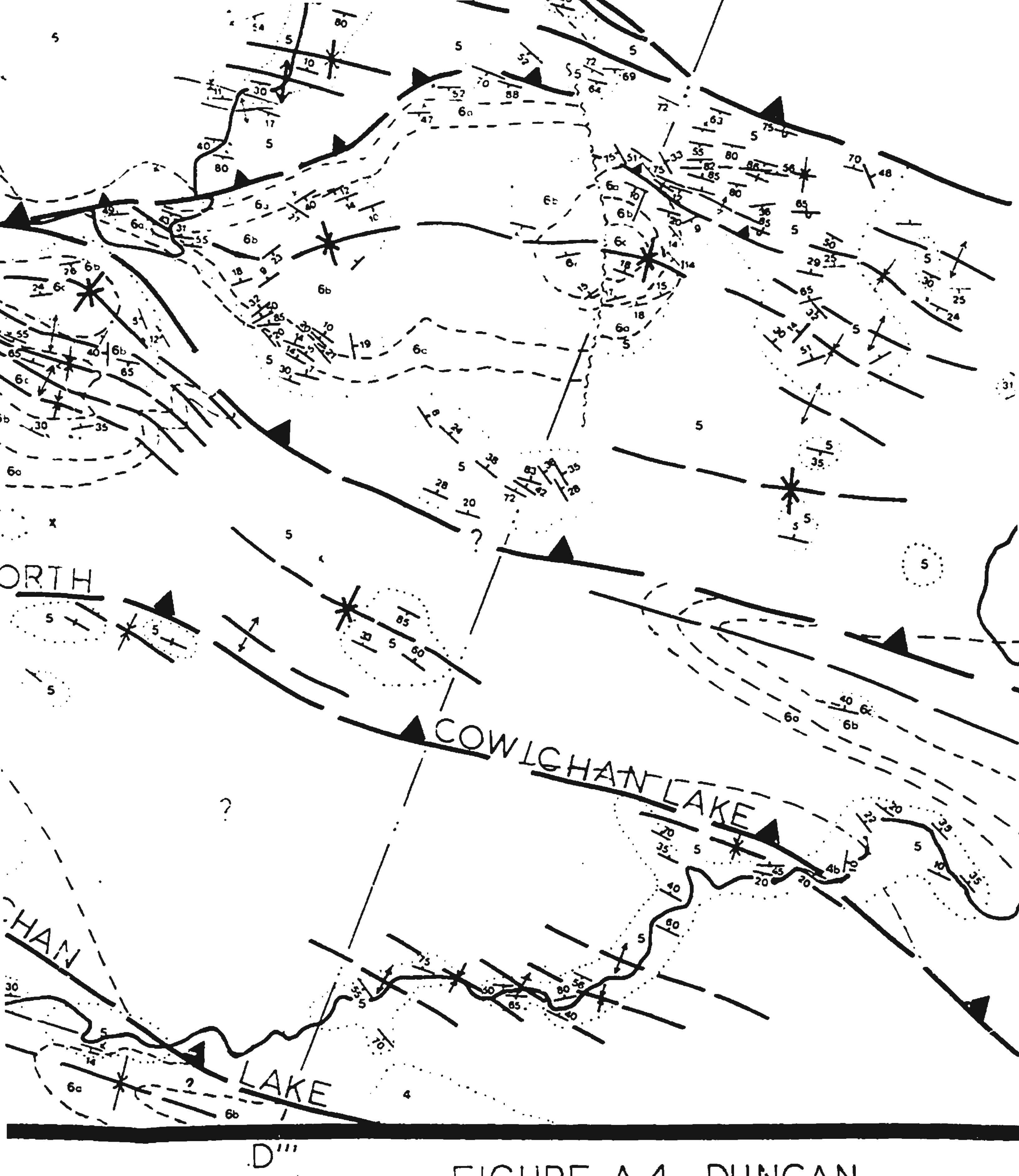


FIGURE A.4 DUNCAN

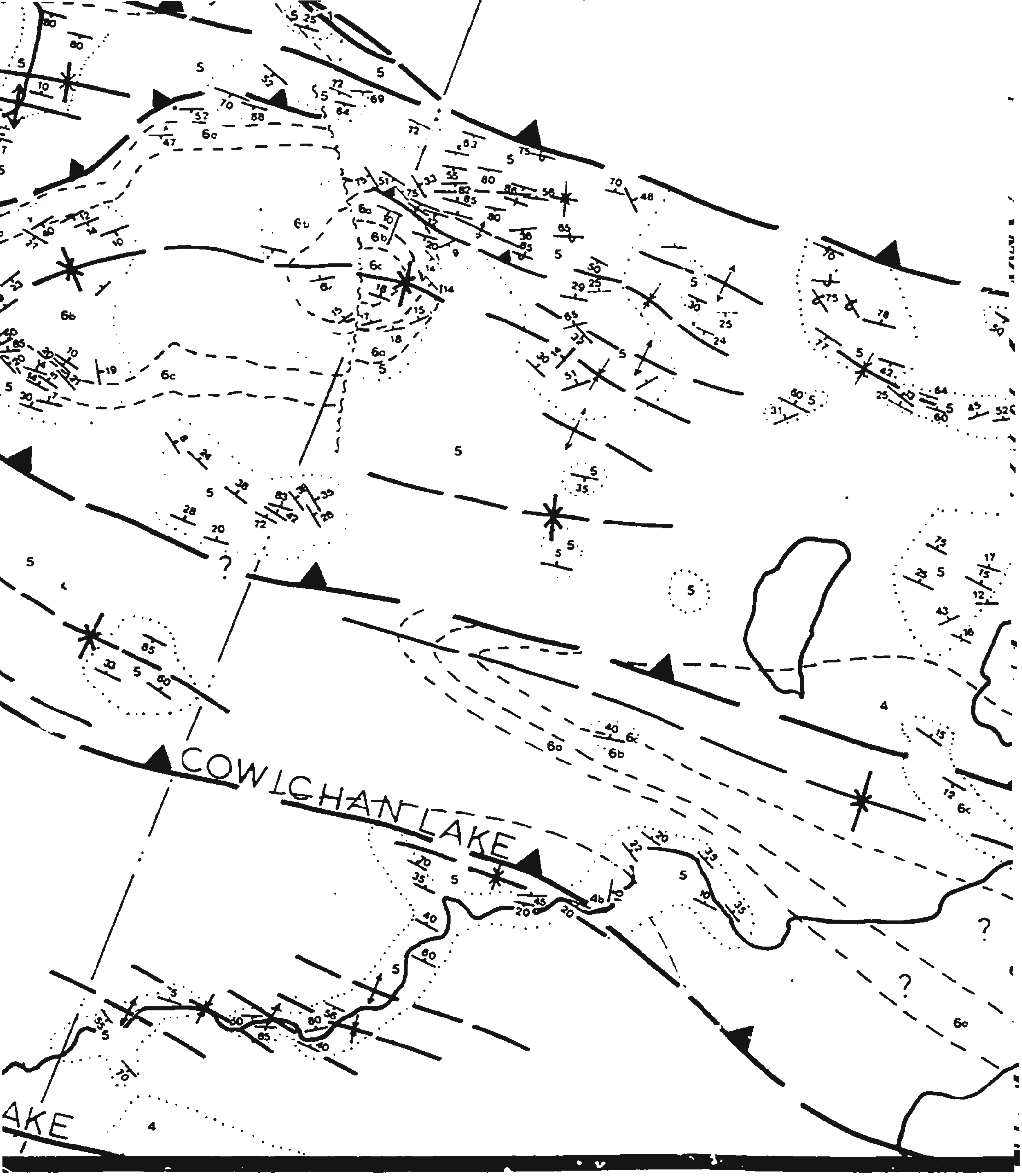
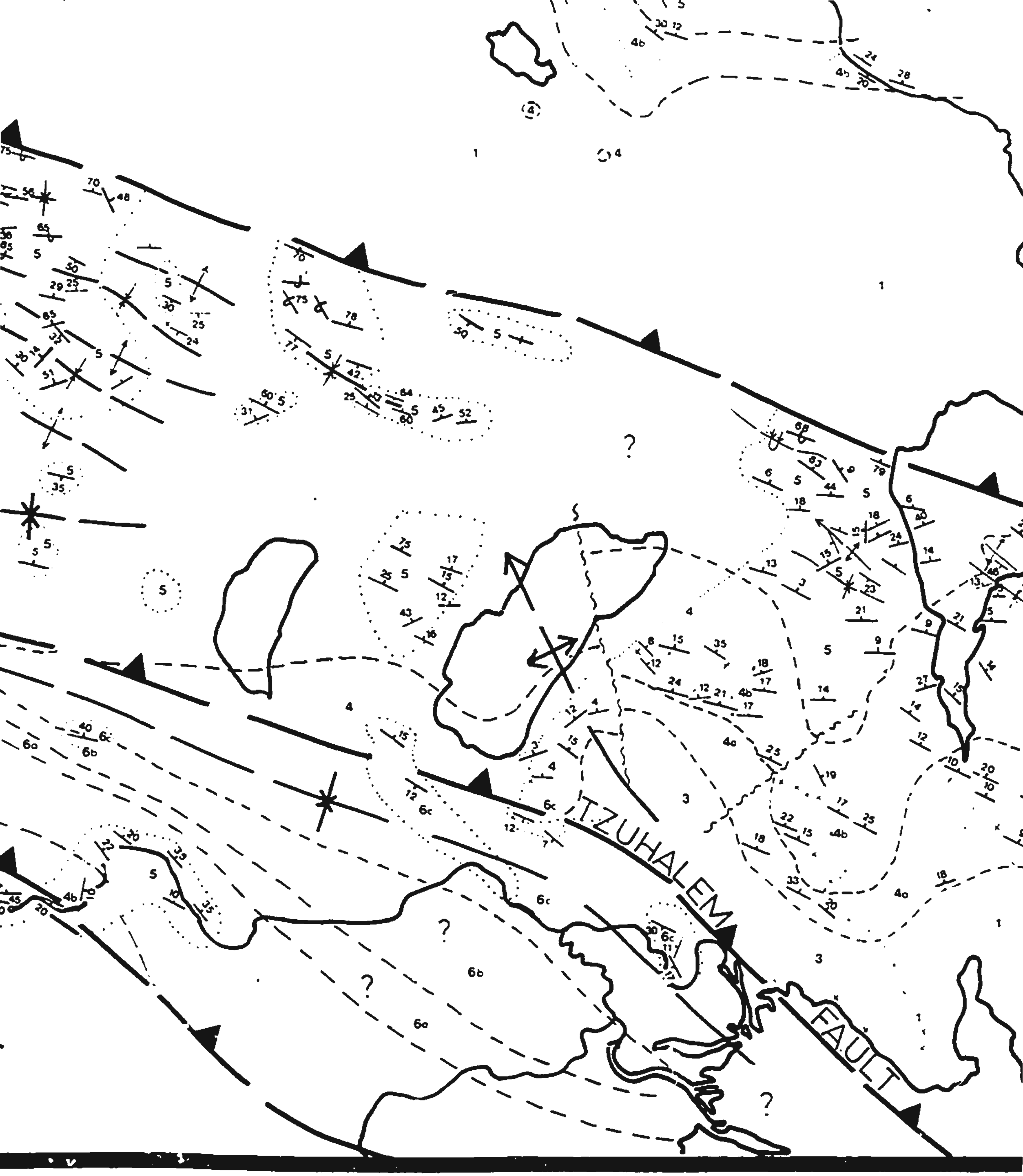
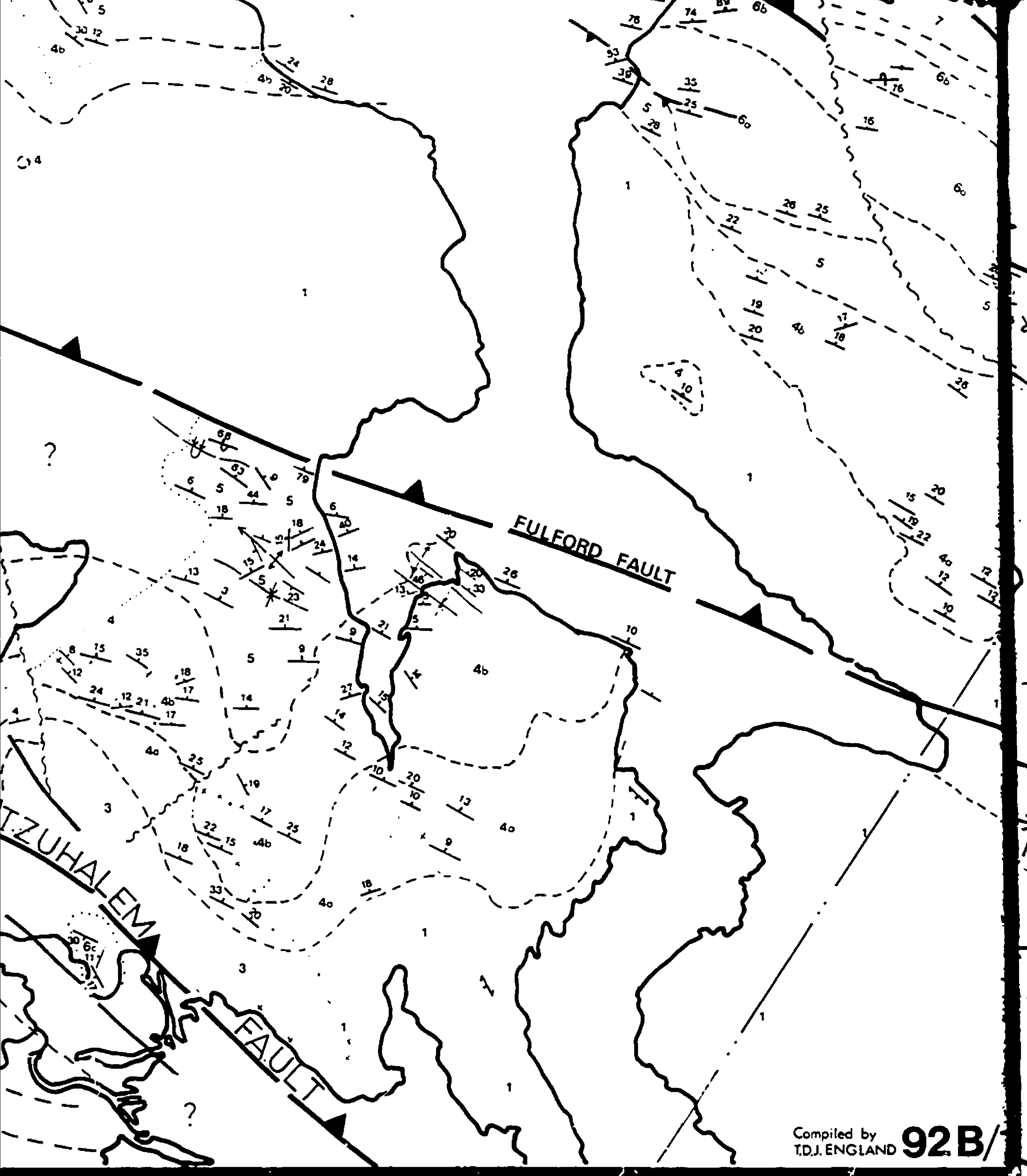


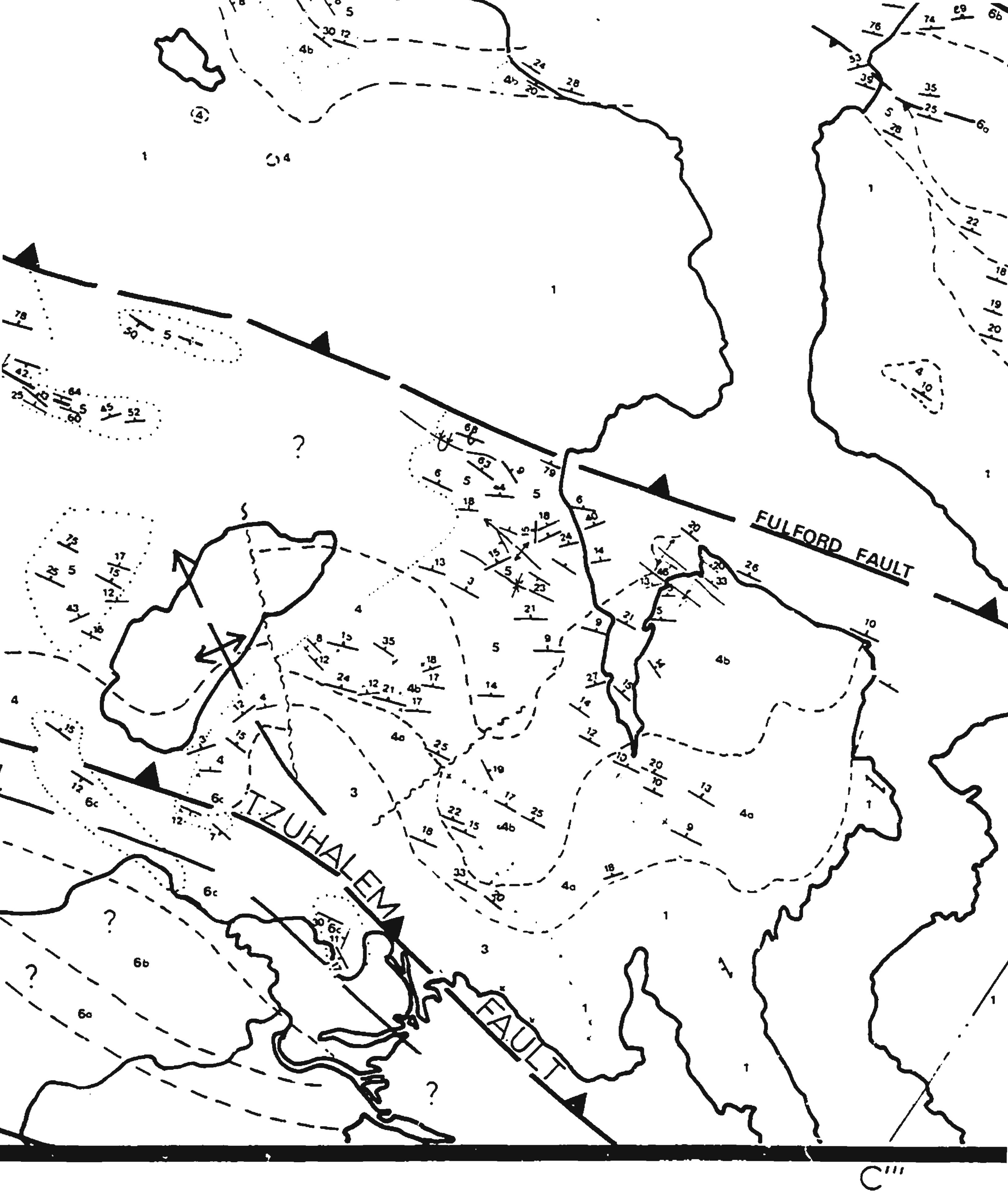
FIGURE A.4 DUNCAN



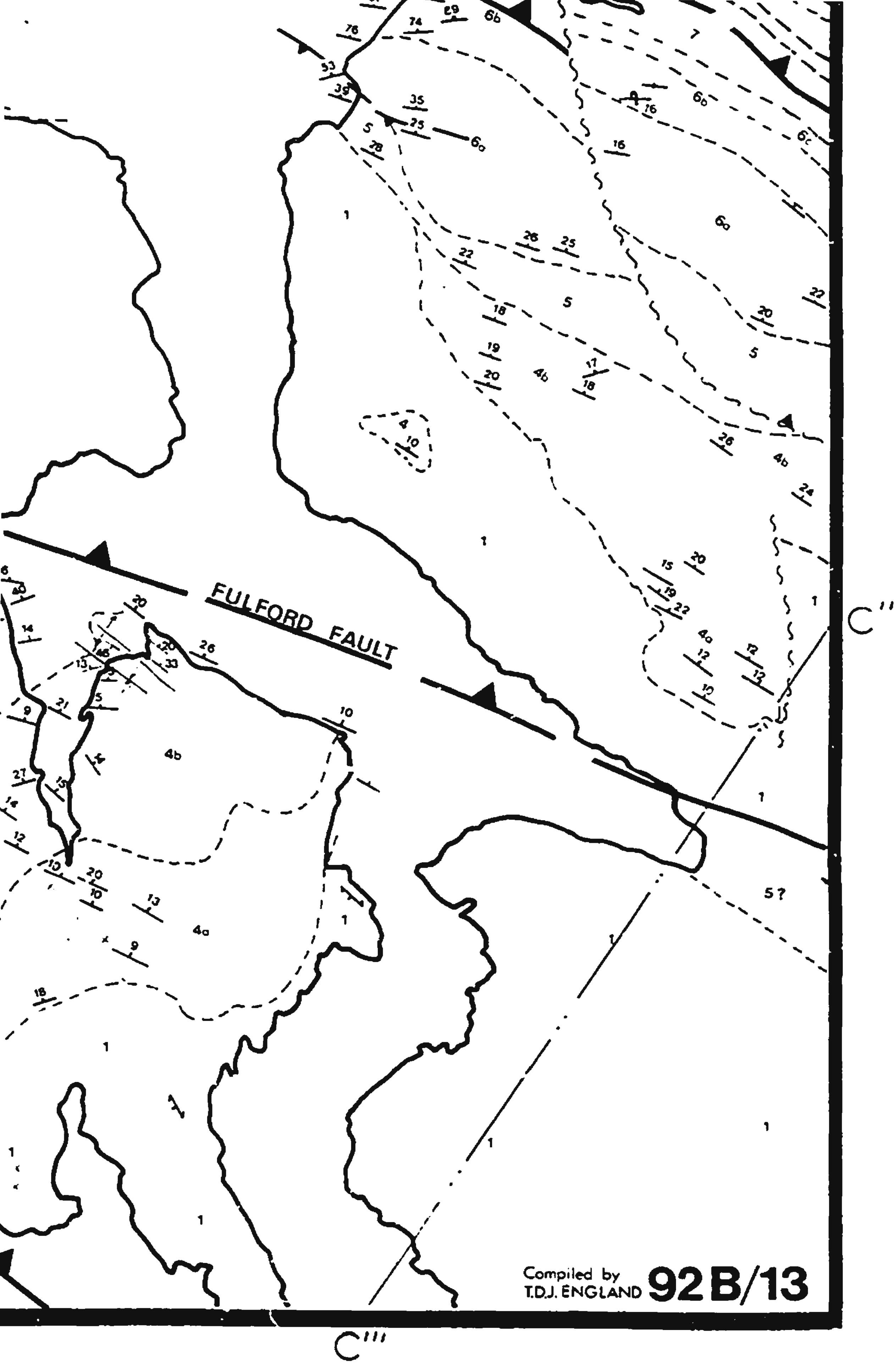
NCAN

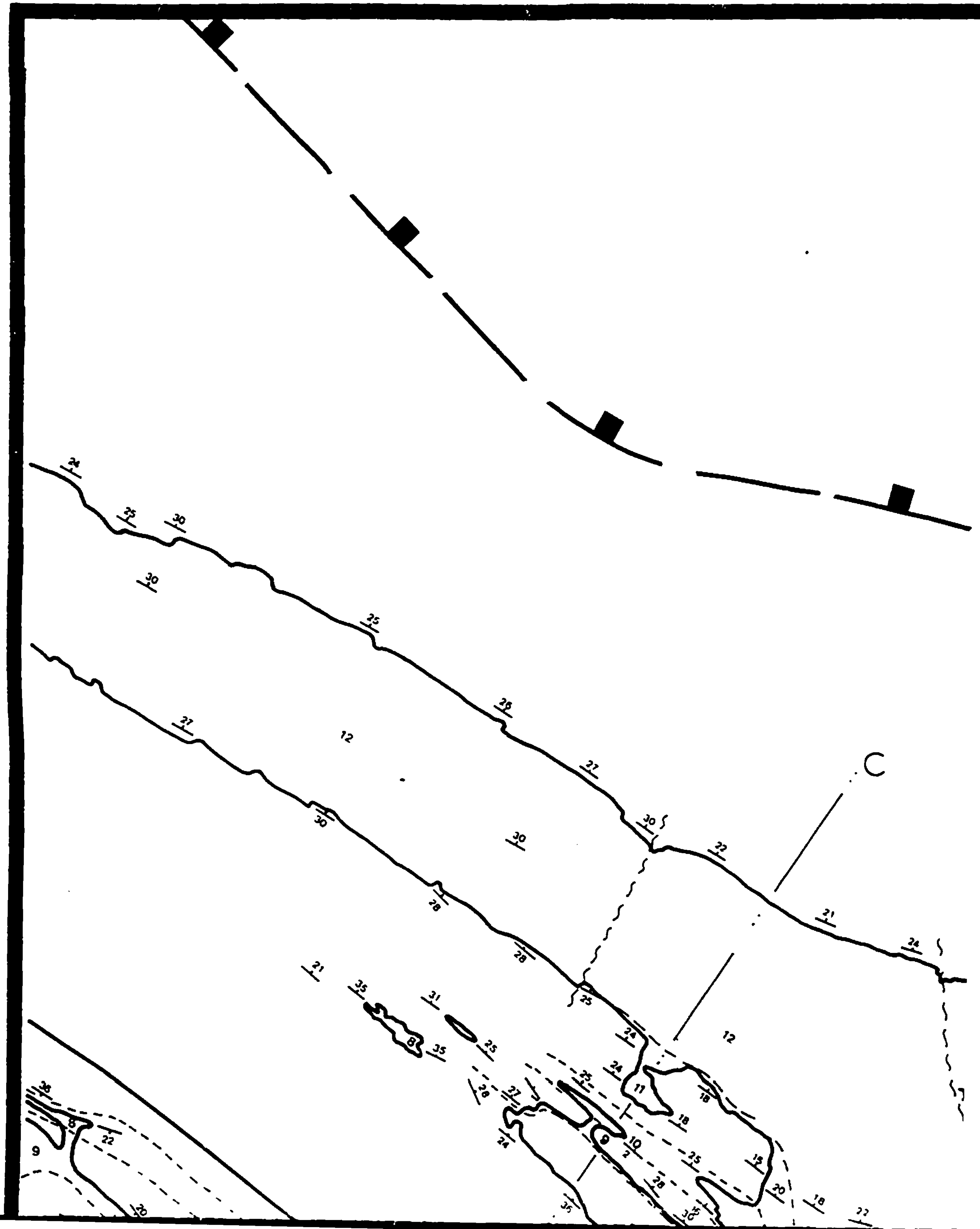


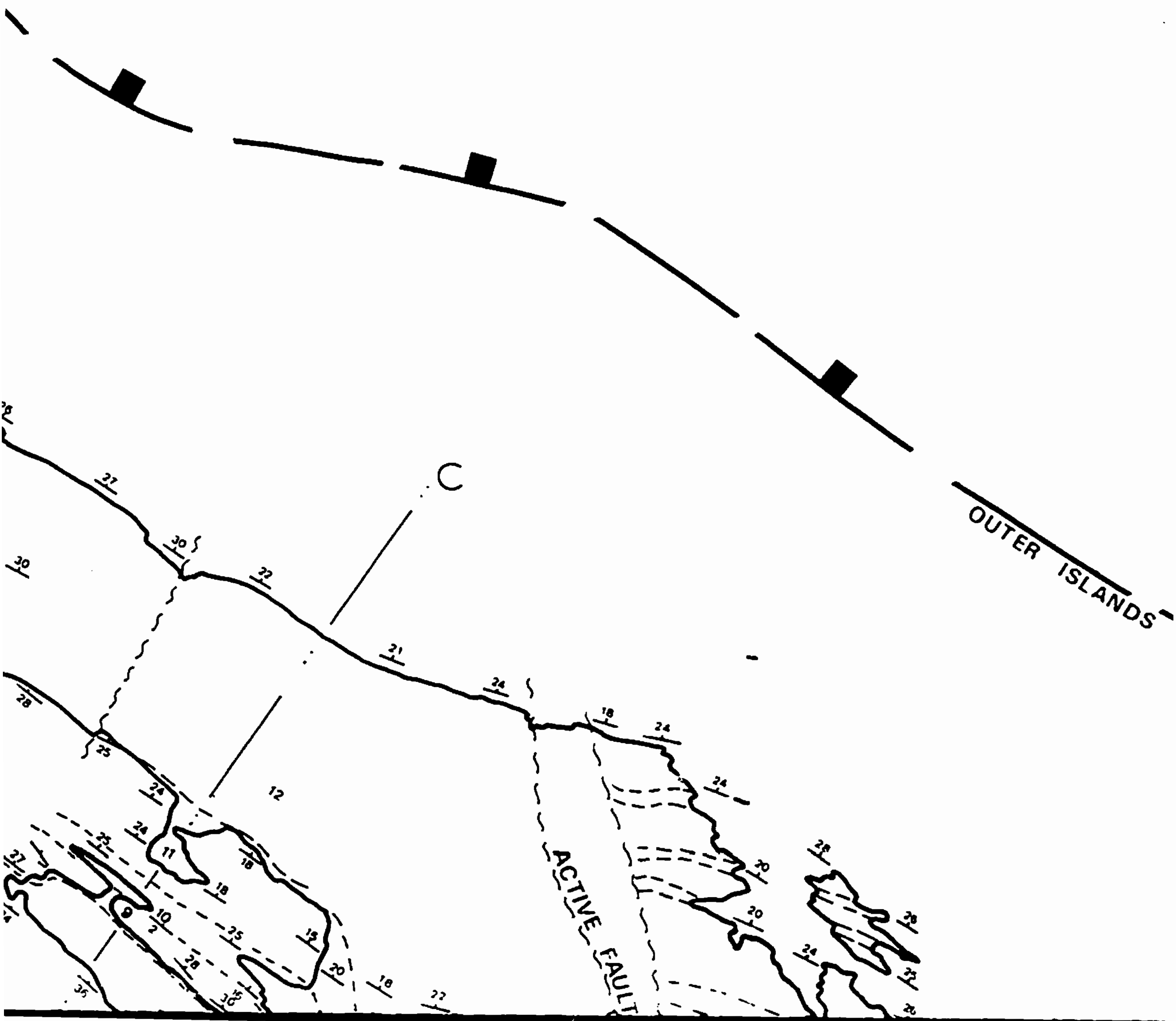
C'''

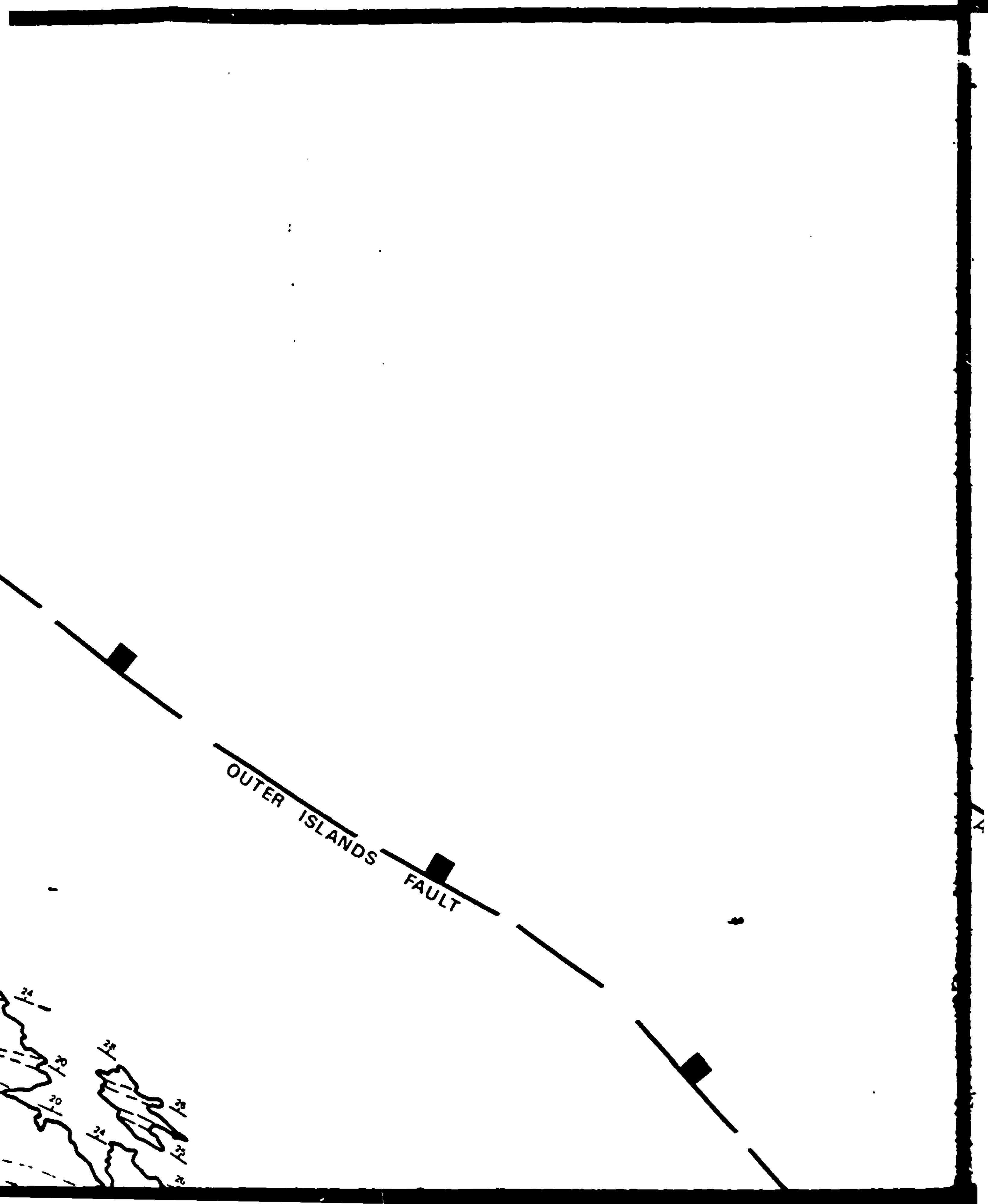


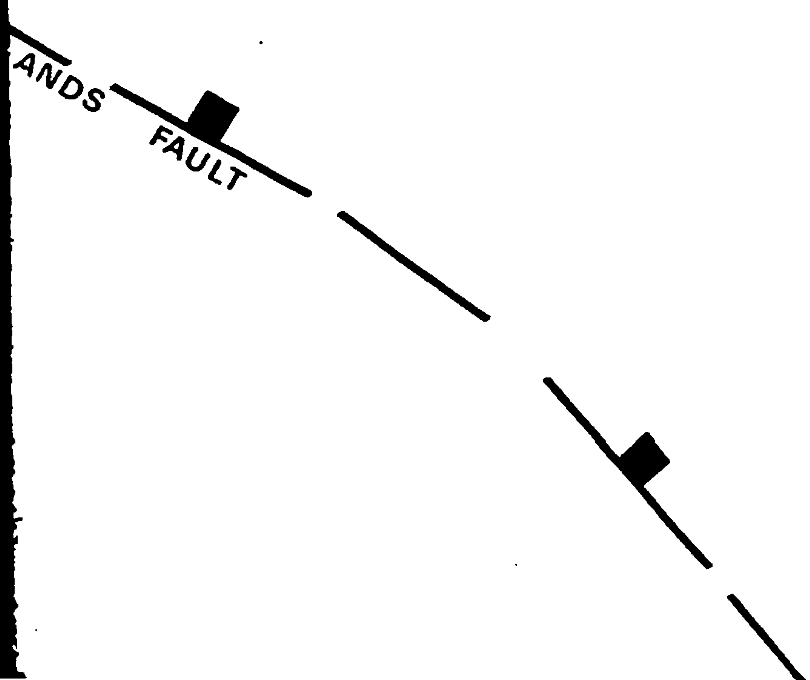
FULFORD FAULT
TZUHALEM FAULT
C'''

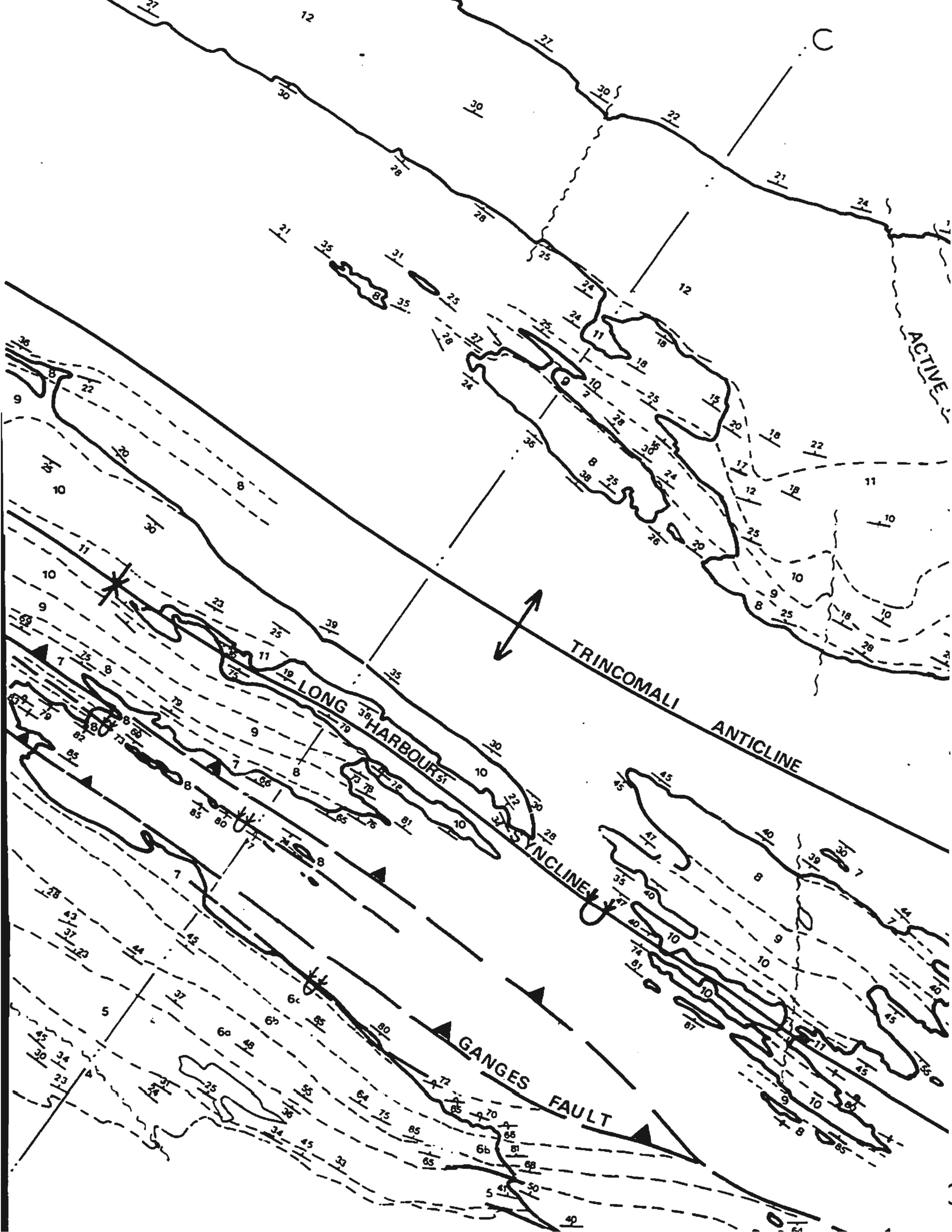

FULFORD FAULT
C''
C'''
Compiled by
T.D.J. ENGLAND
92B/13

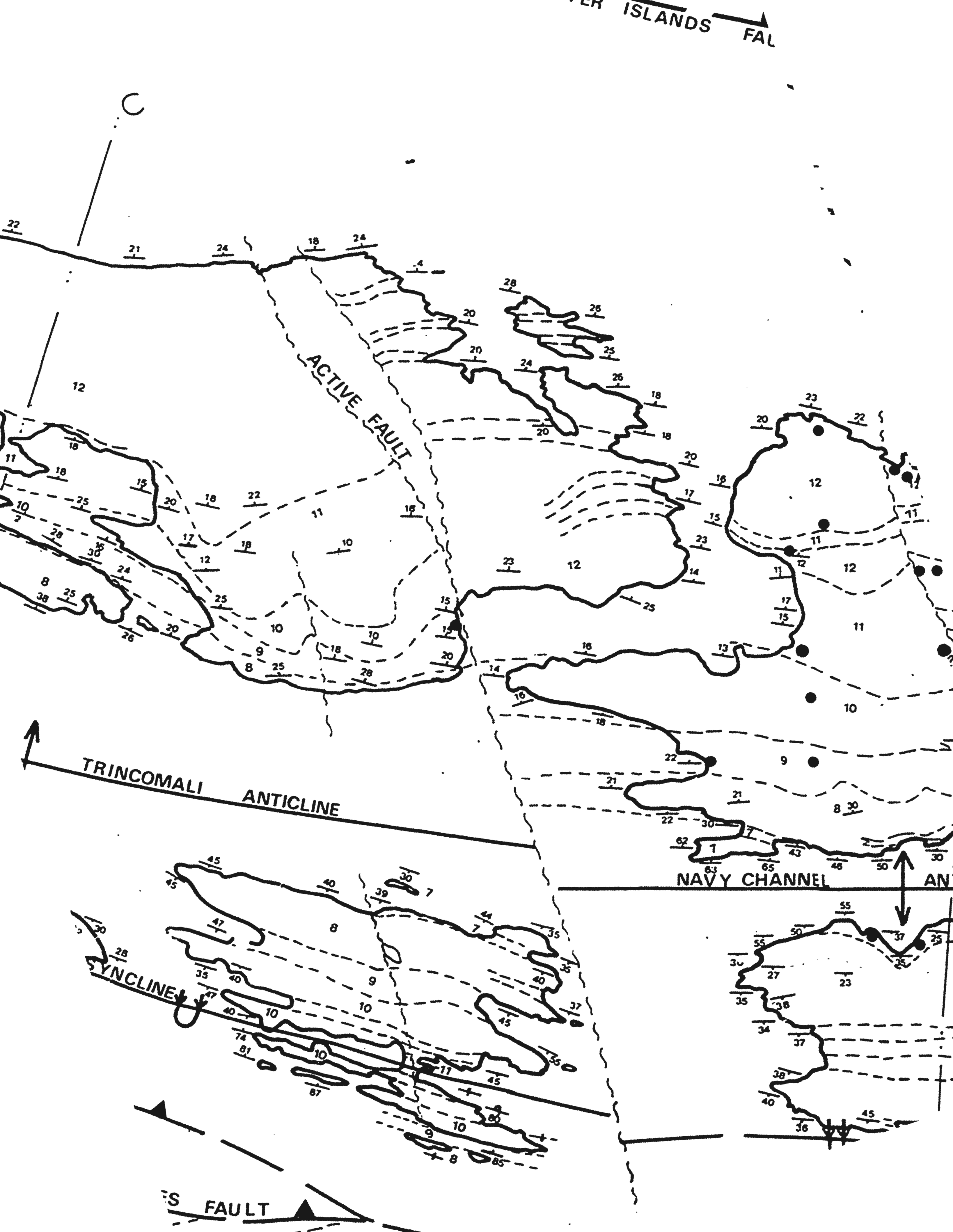

C
12
12

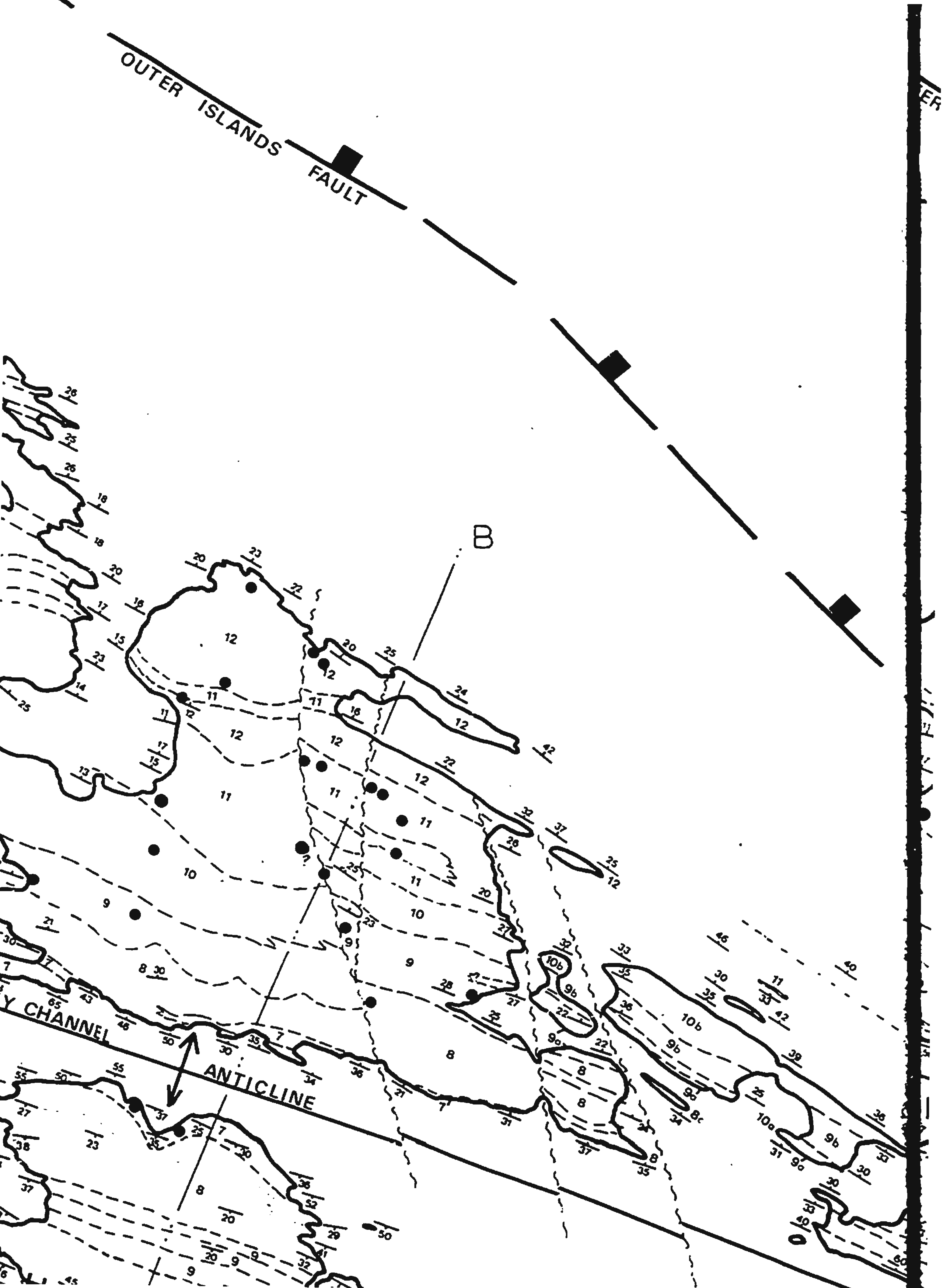

C
OUTER ISLANDS
ACTIVE FAULT
12


OUTER ISLANDS FAULT

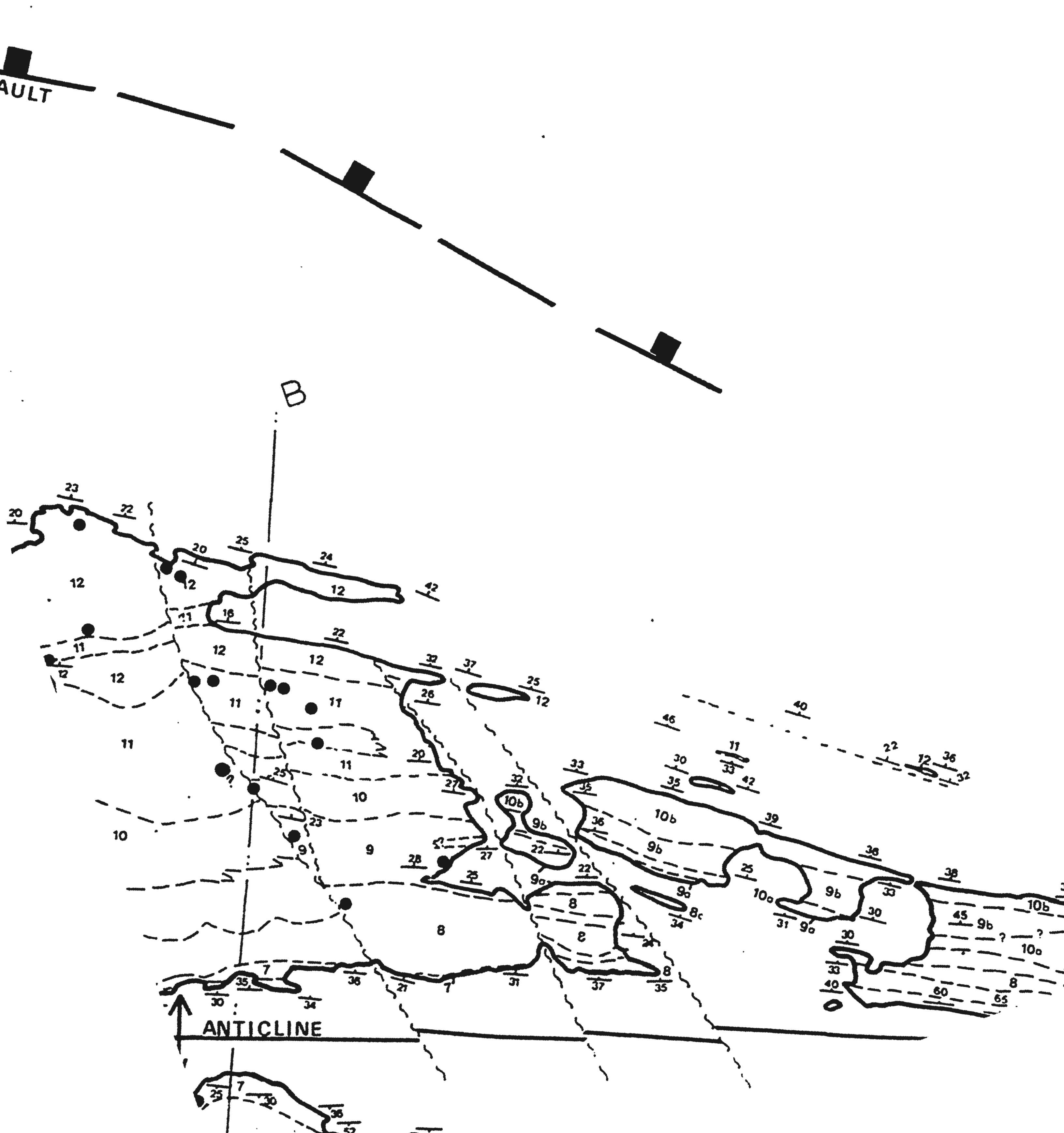

ANDS
FAULT

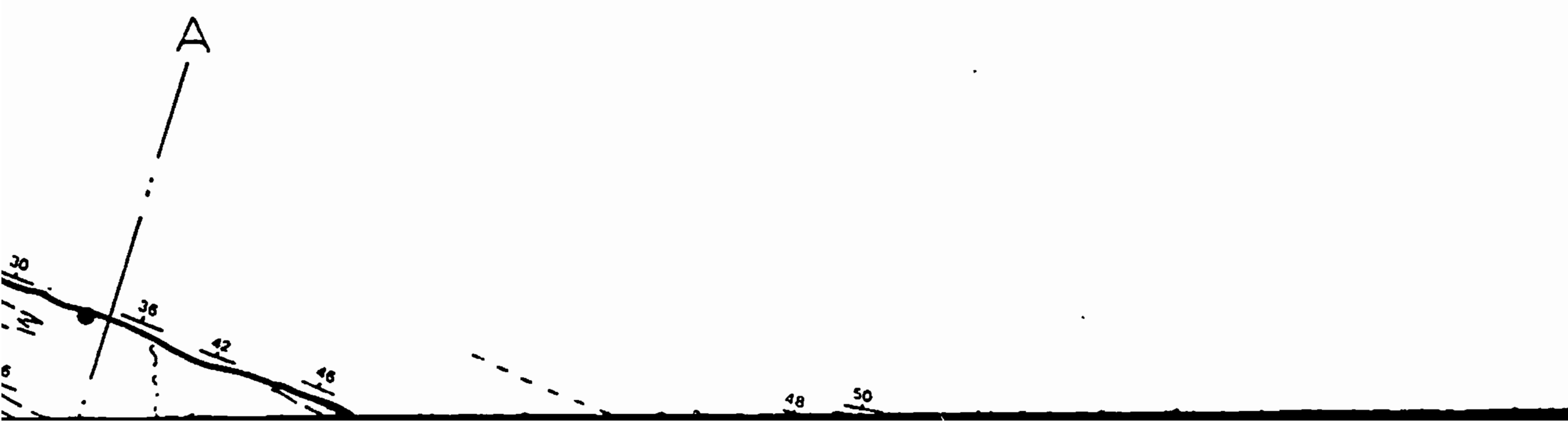

C
ACTIVE
TRINCOMALI ANTICLINE
LONG HARBOUR SYNCLINE
GANGES FAULT

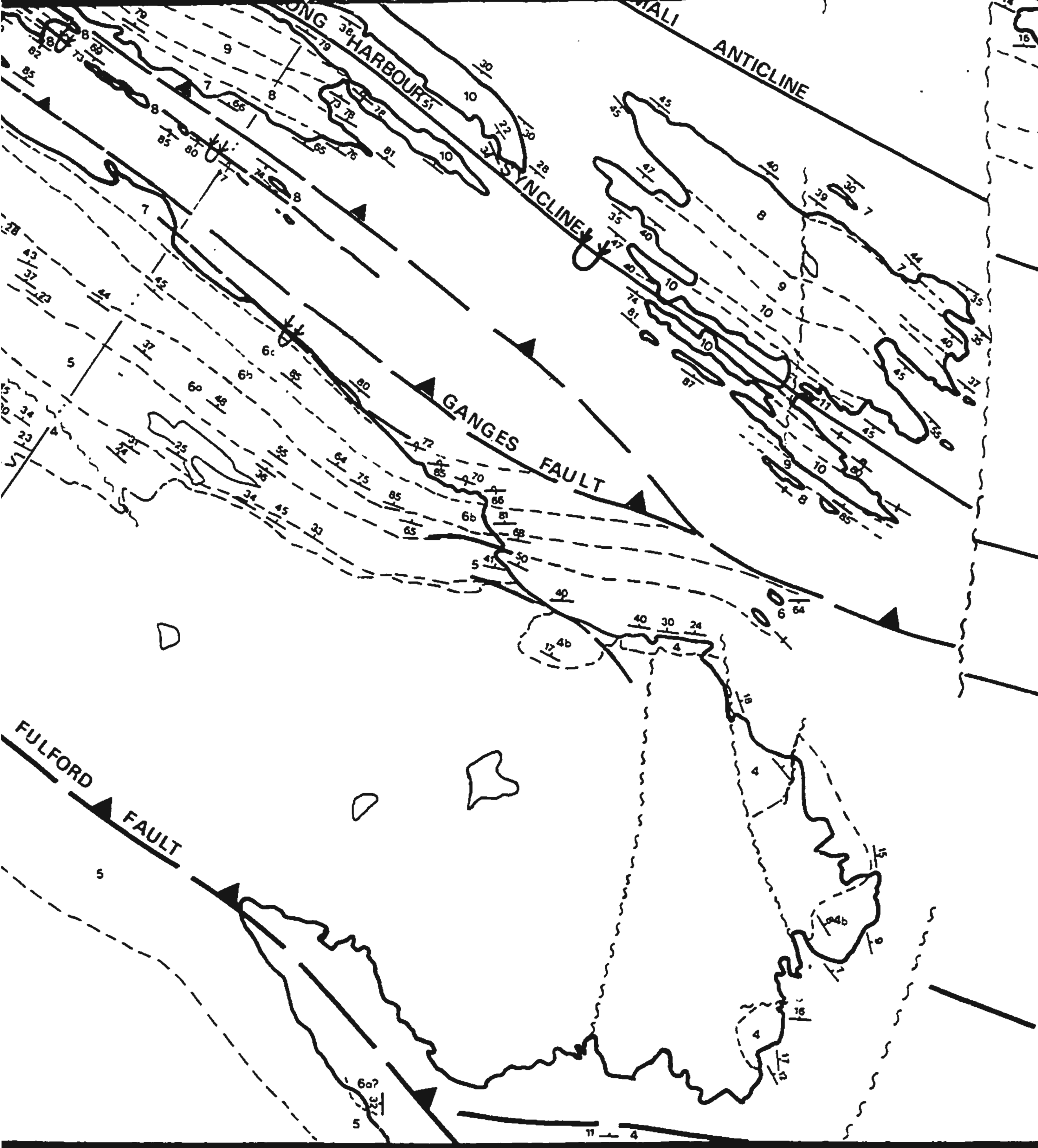

ISLANDS FAU
ACTIVE FAULT
TRINCOMALI ANTICLINE
NAVY CHANNEL ANT
SYNCLINE
S FAULT



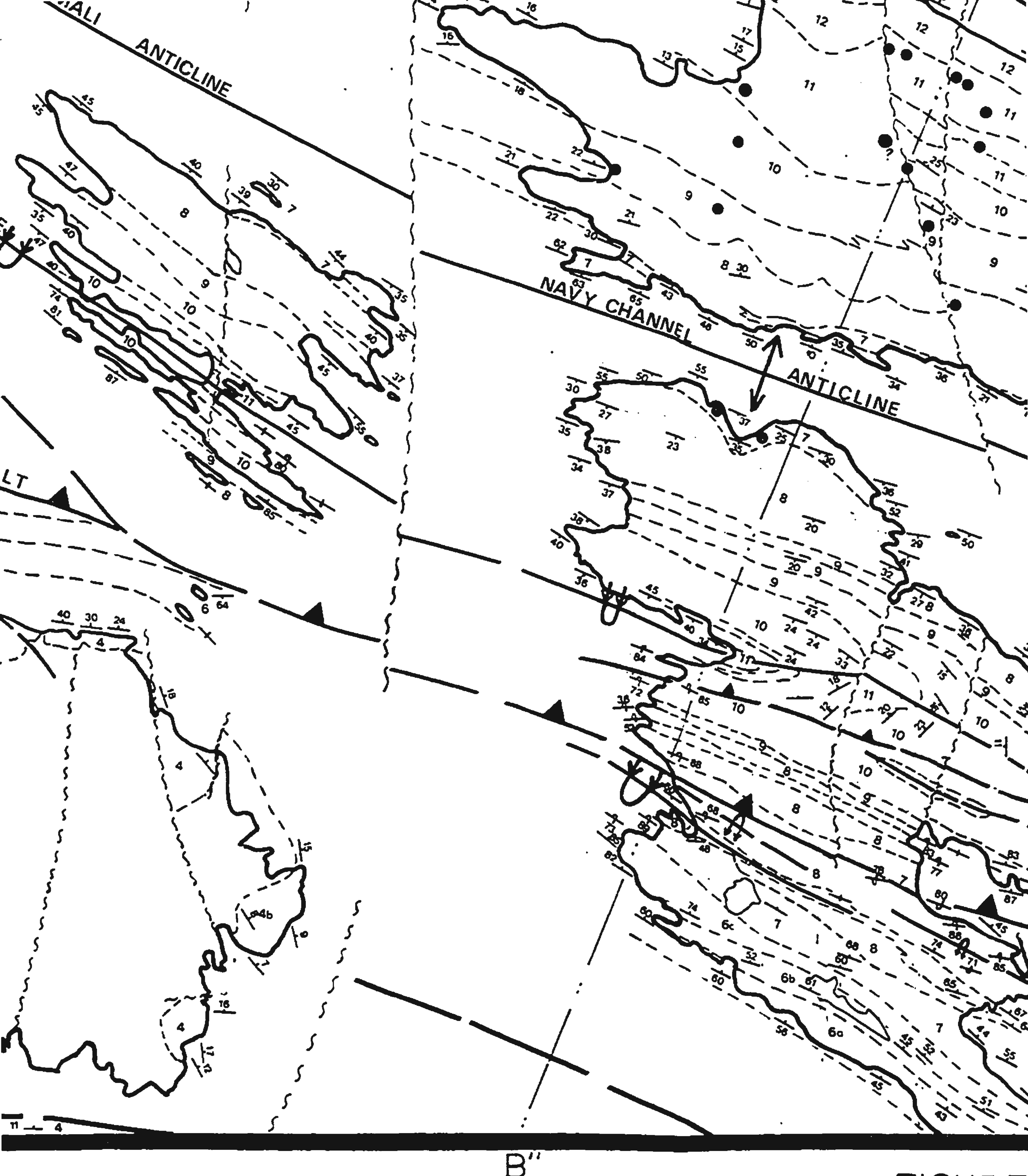
OUTER ISLANDS FAULT
B
Y CHANNEL ANTICLINE


AULT
B
ANTICLINE


A
30
36
42
46
48
50
6



HARBOUR
SYNCLINE
ANTICLINE
GANGES FAULT
FULFORD FAULT



FIGURE

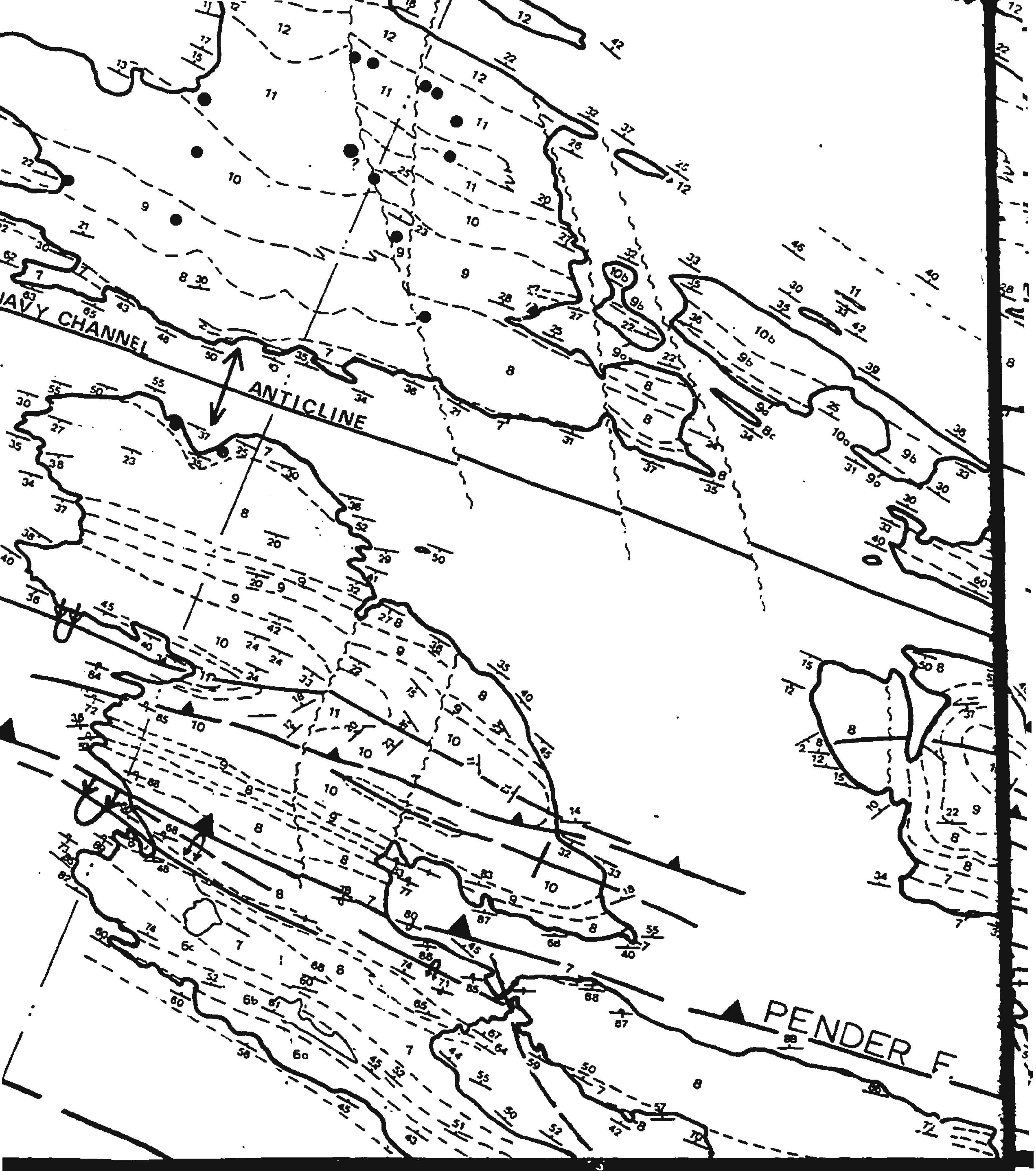
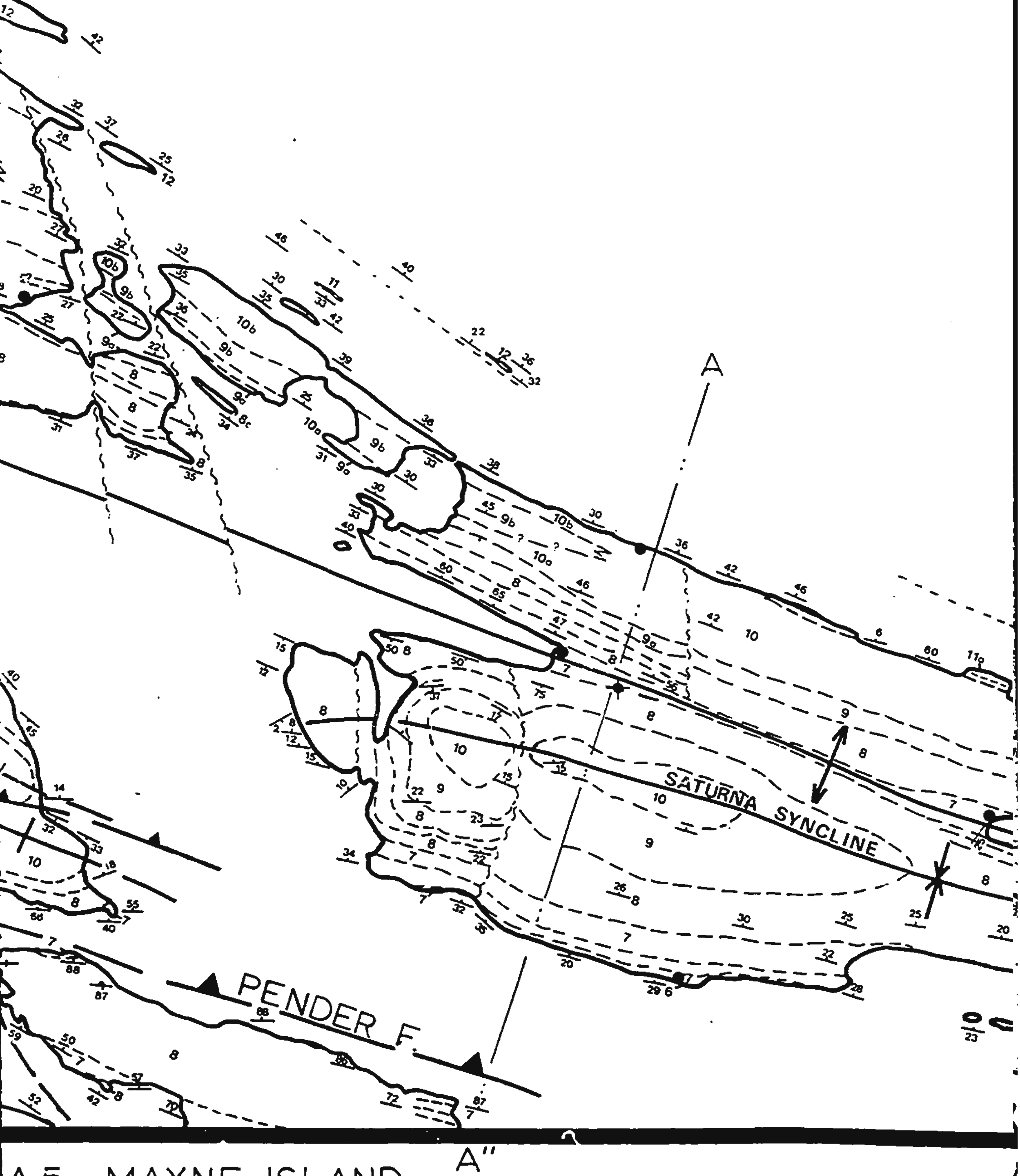
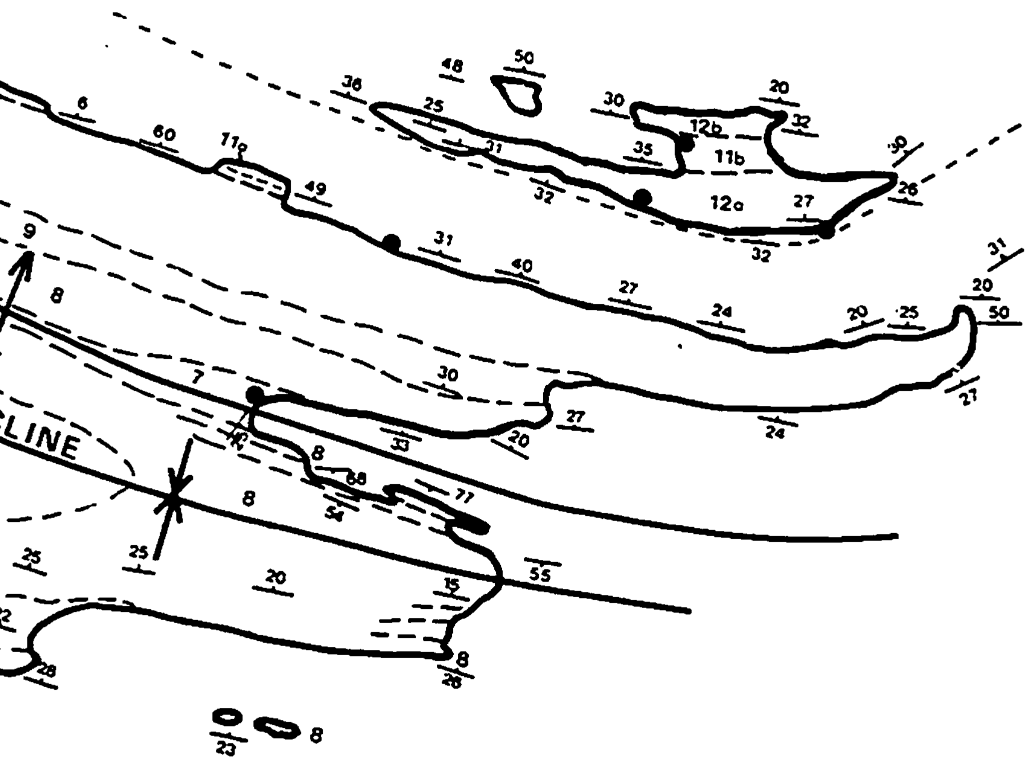


FIGURE A.5 MAYNE ISLAND

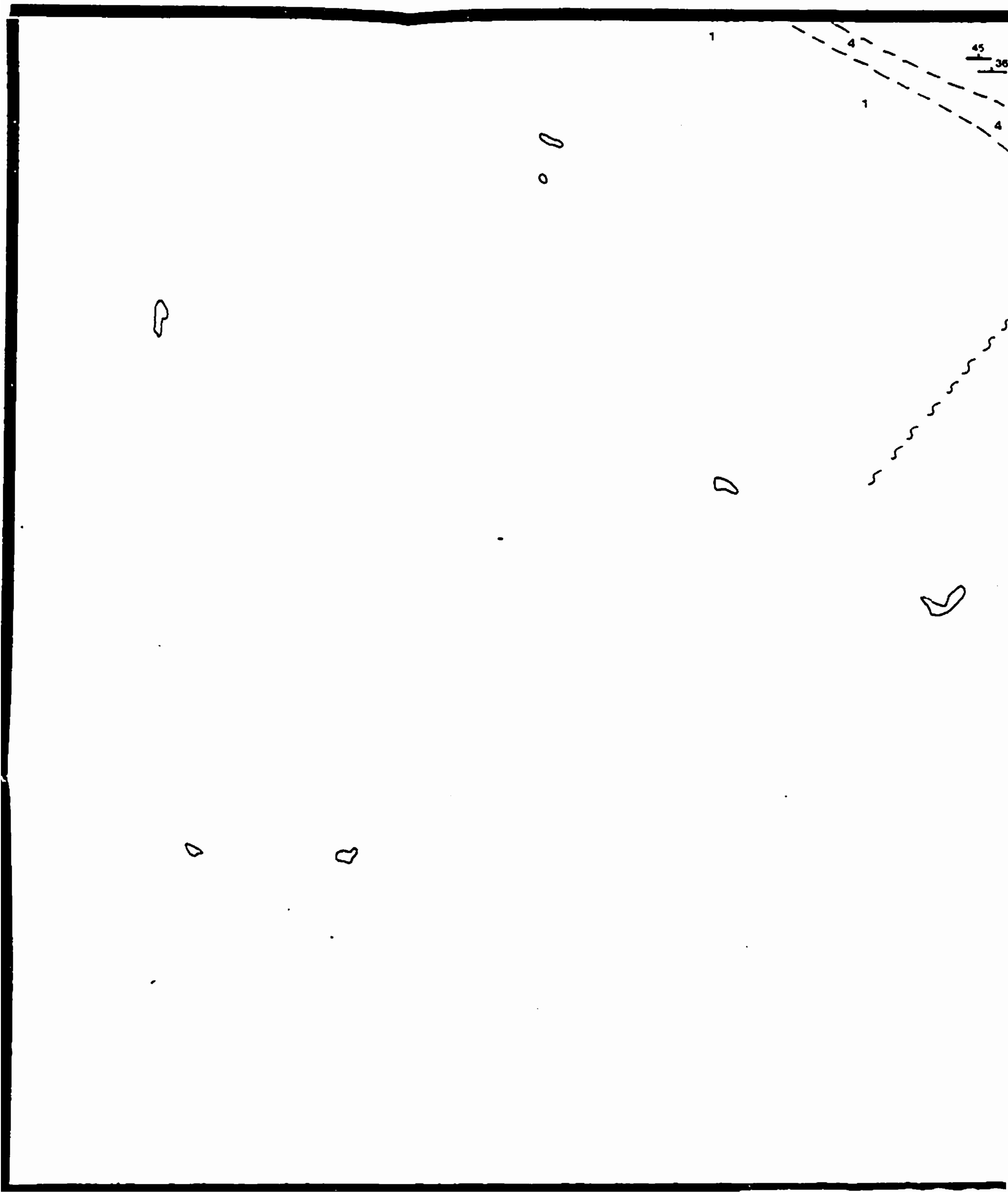


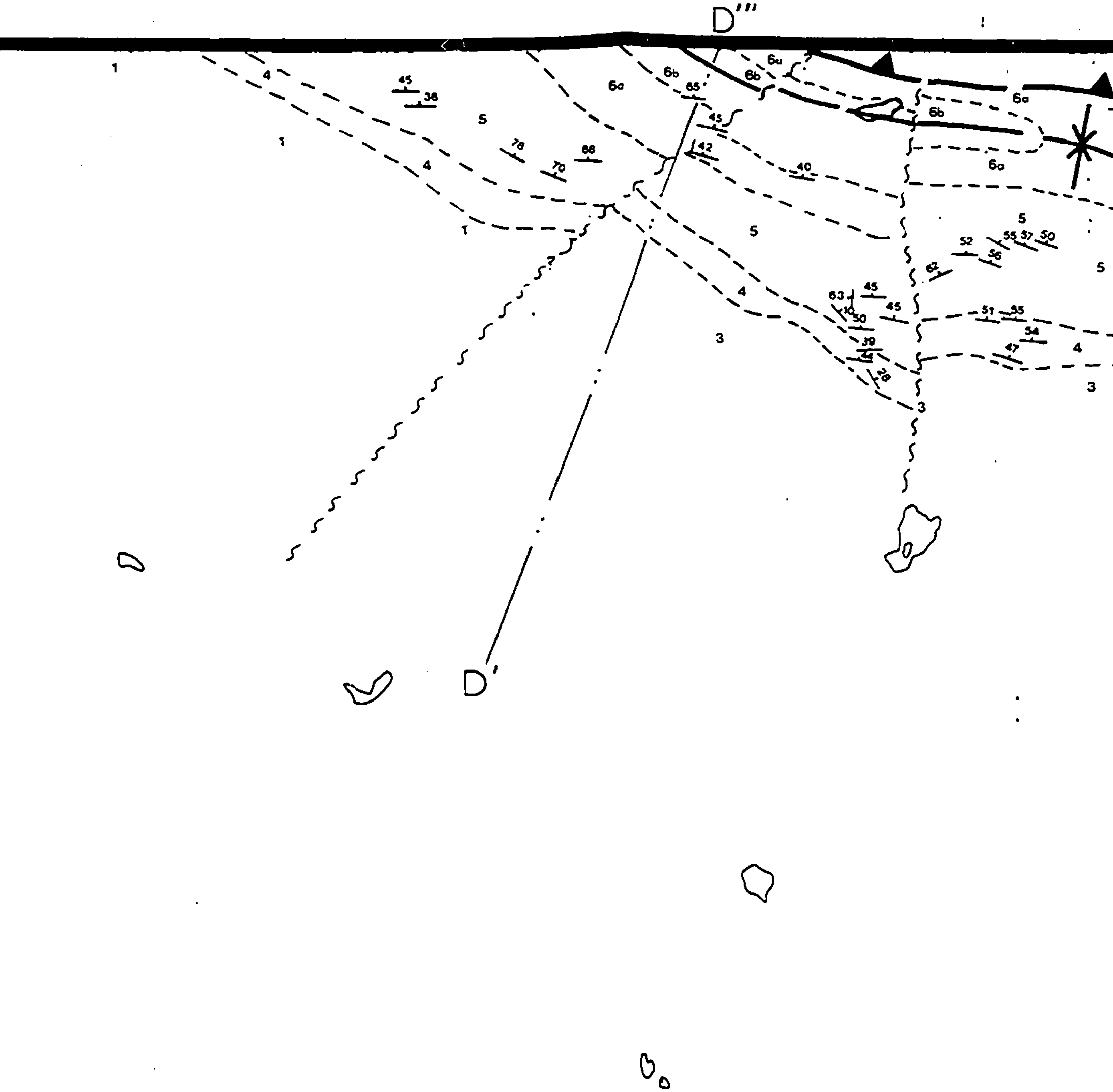
A.5 MAYNE ISLAND



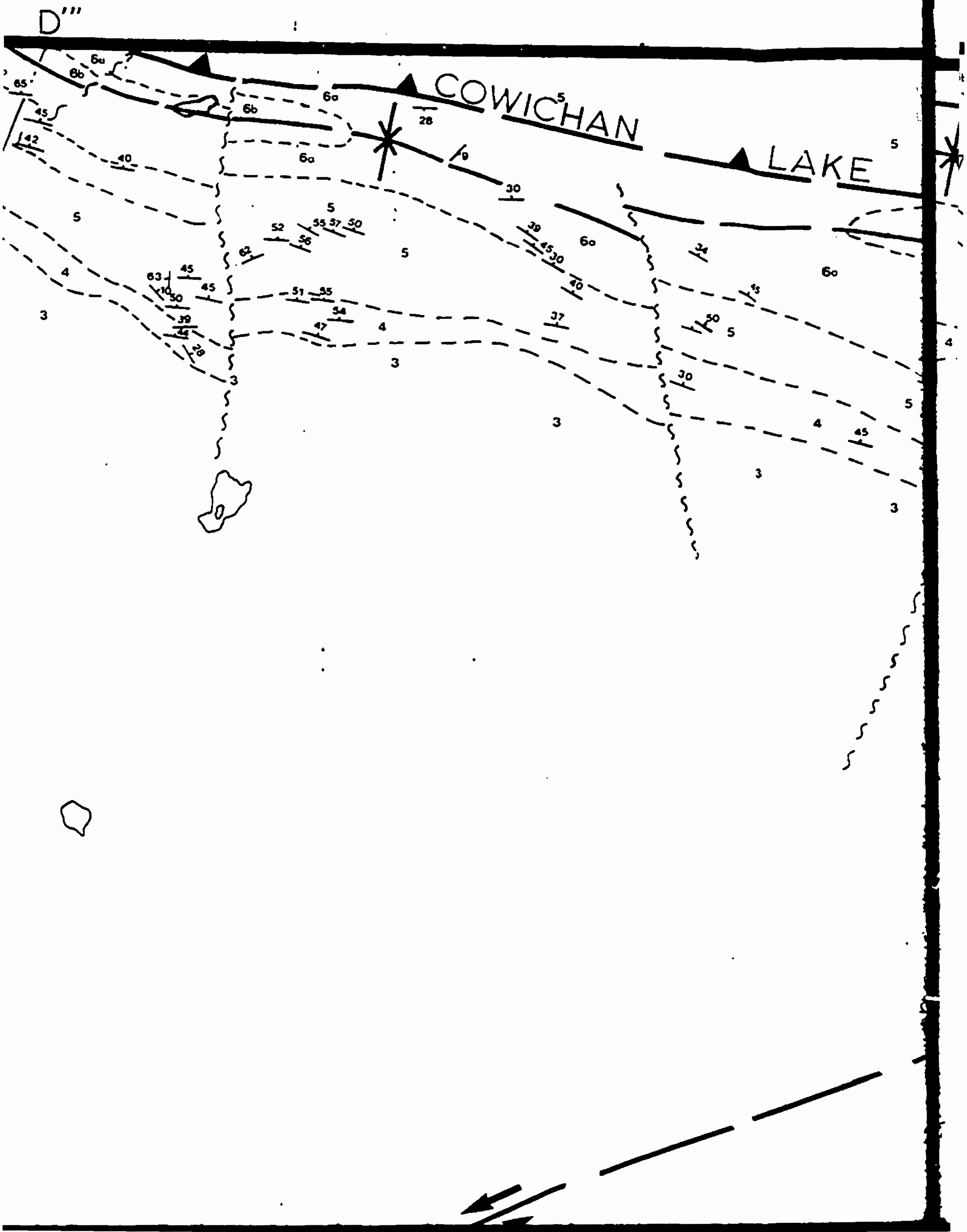
Compiled by T.D.J. ENGLAND

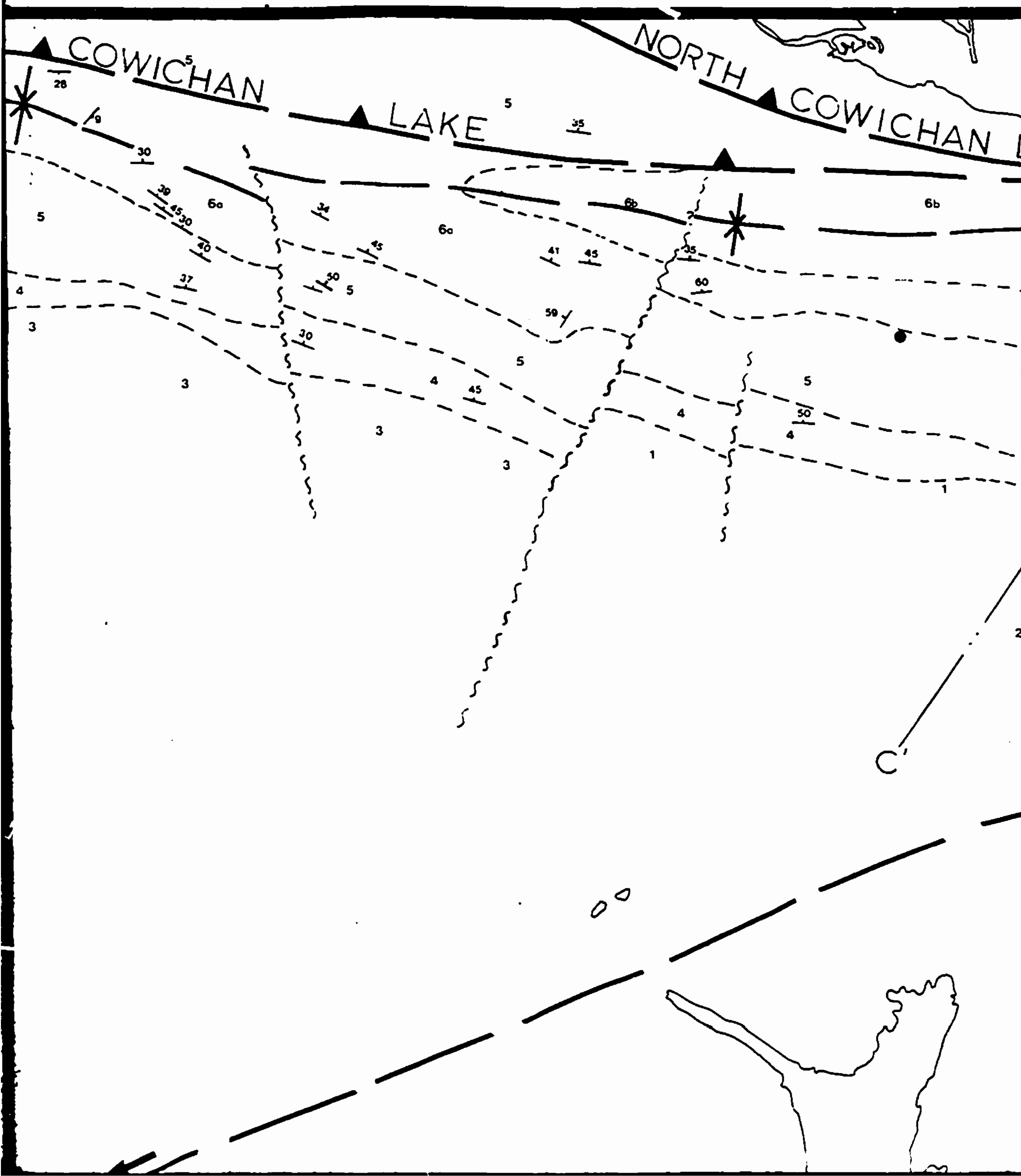
92 B/14

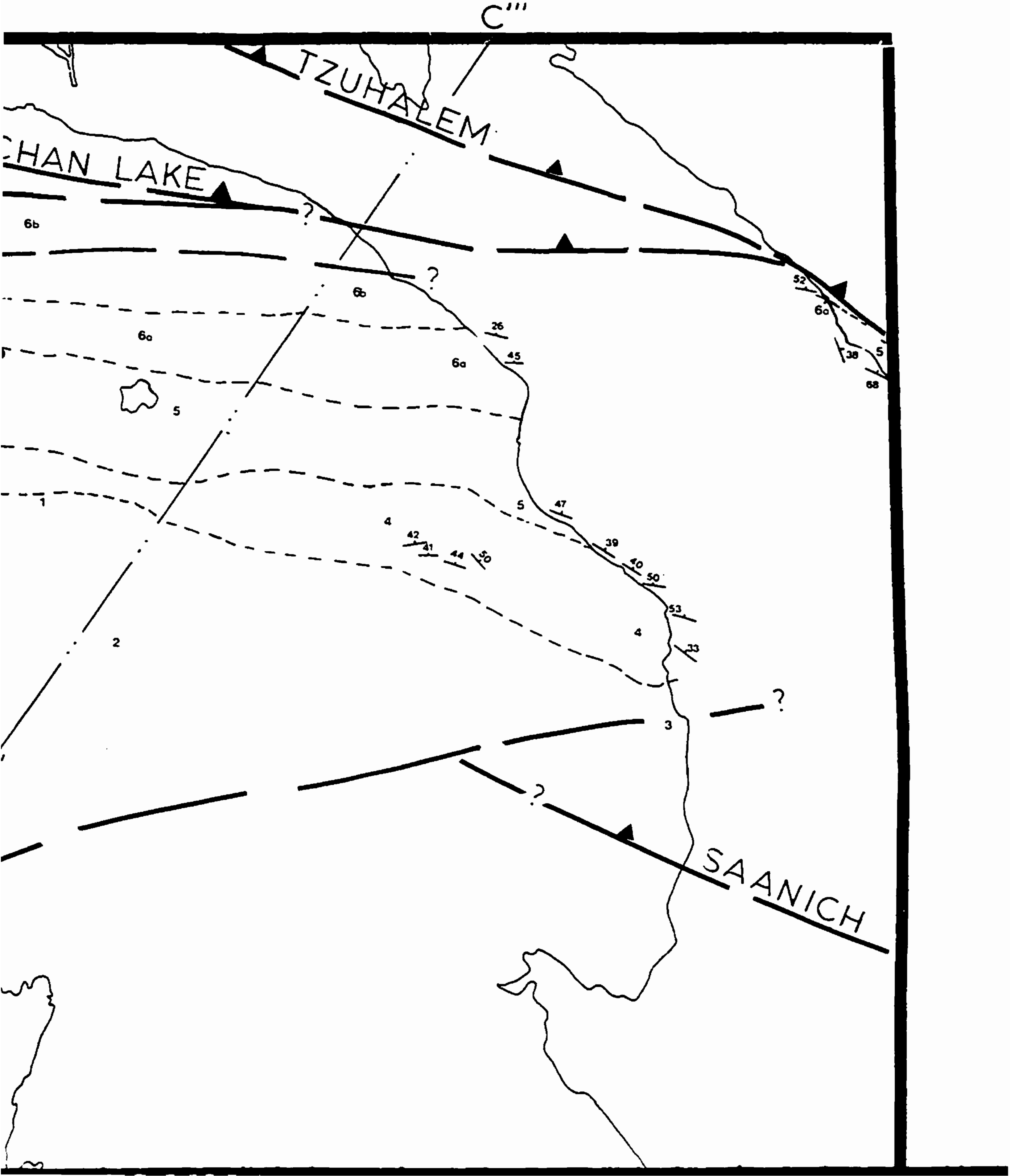

1
4
45
36
1
4



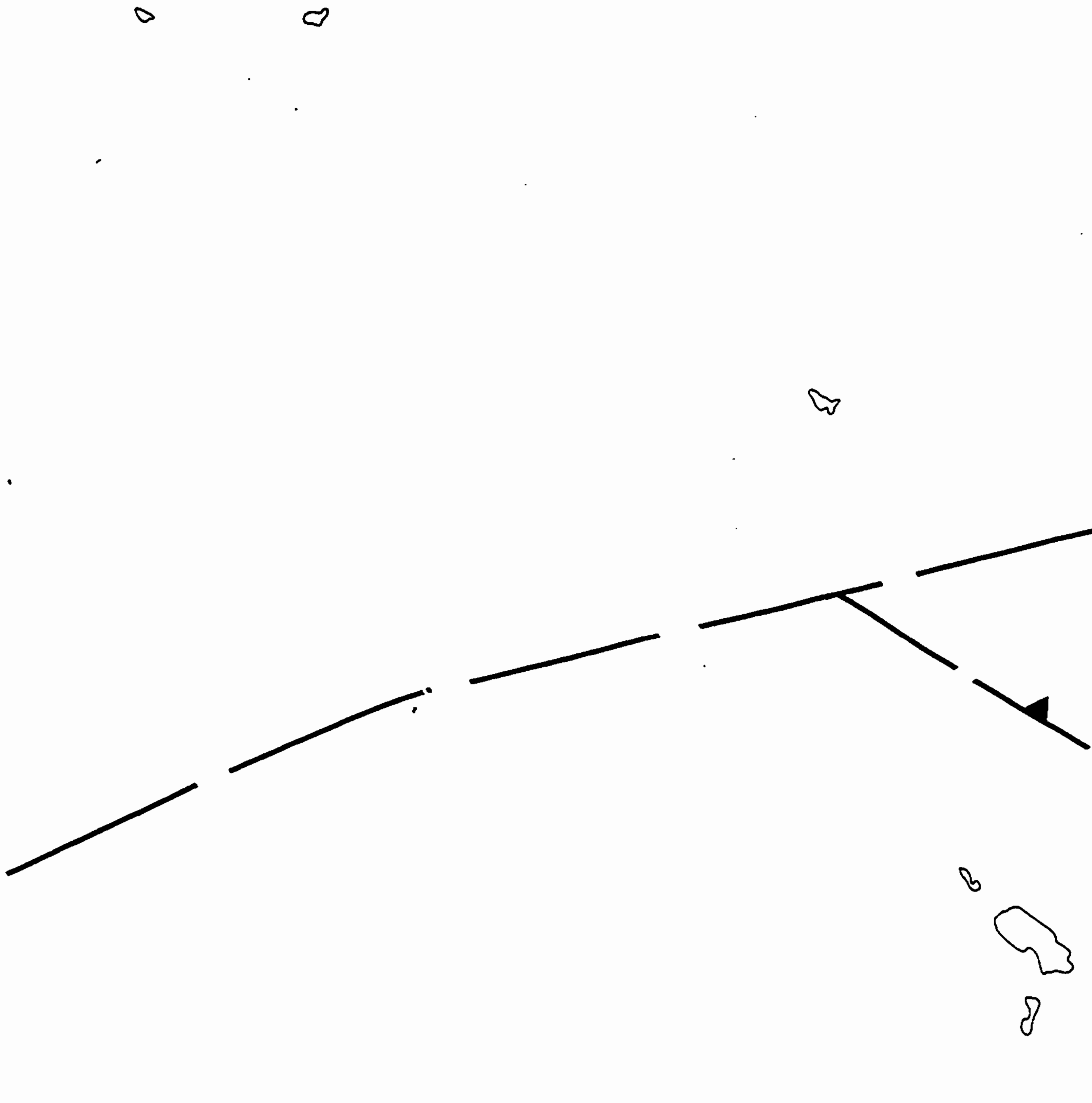
D'''
D'
1
4
5
6a
6b
3

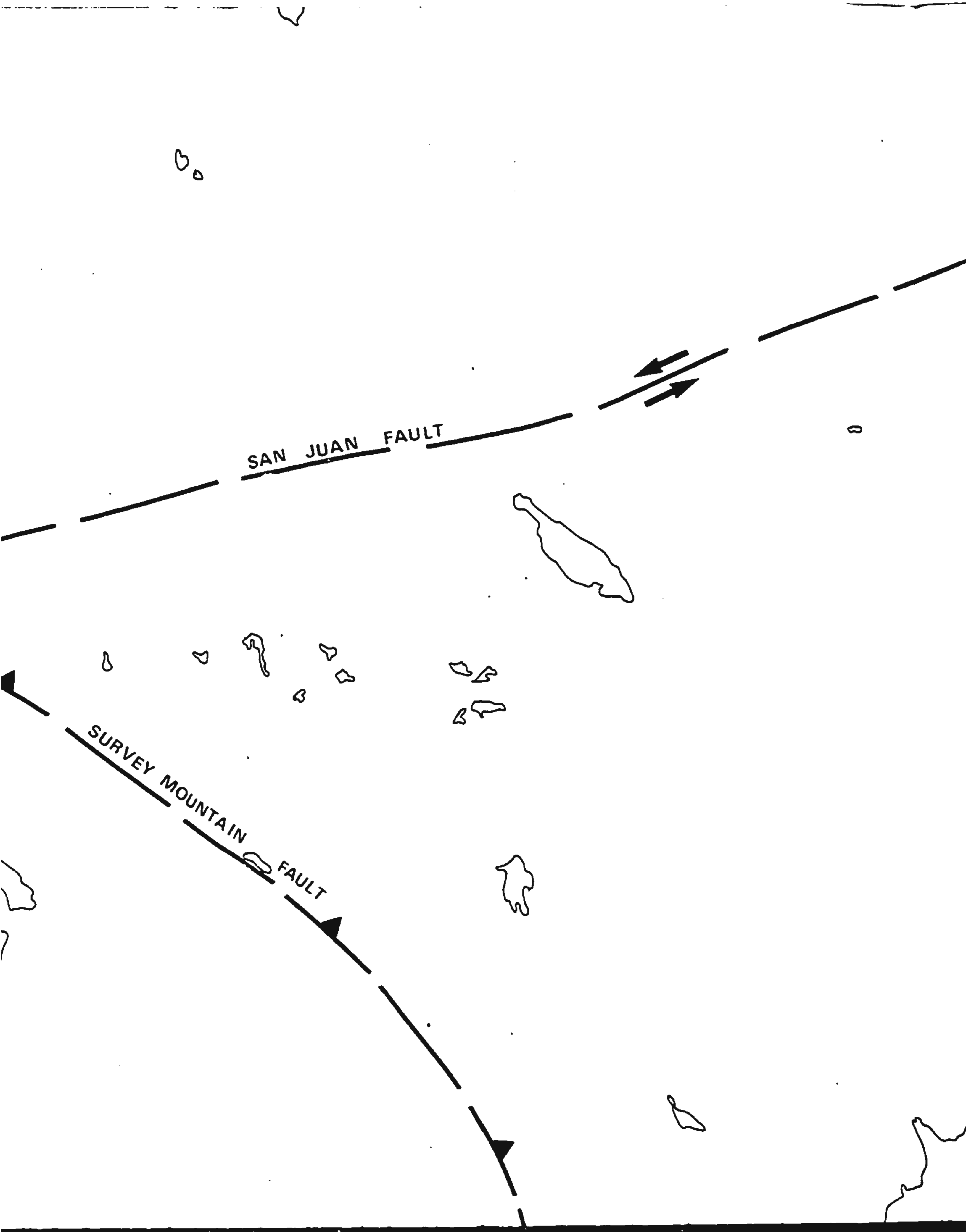

D'''
COWICHAN LAKE


COWICHAN LAKE
NORTH COWICHAN
6a
6b
5
4
3
1
C'

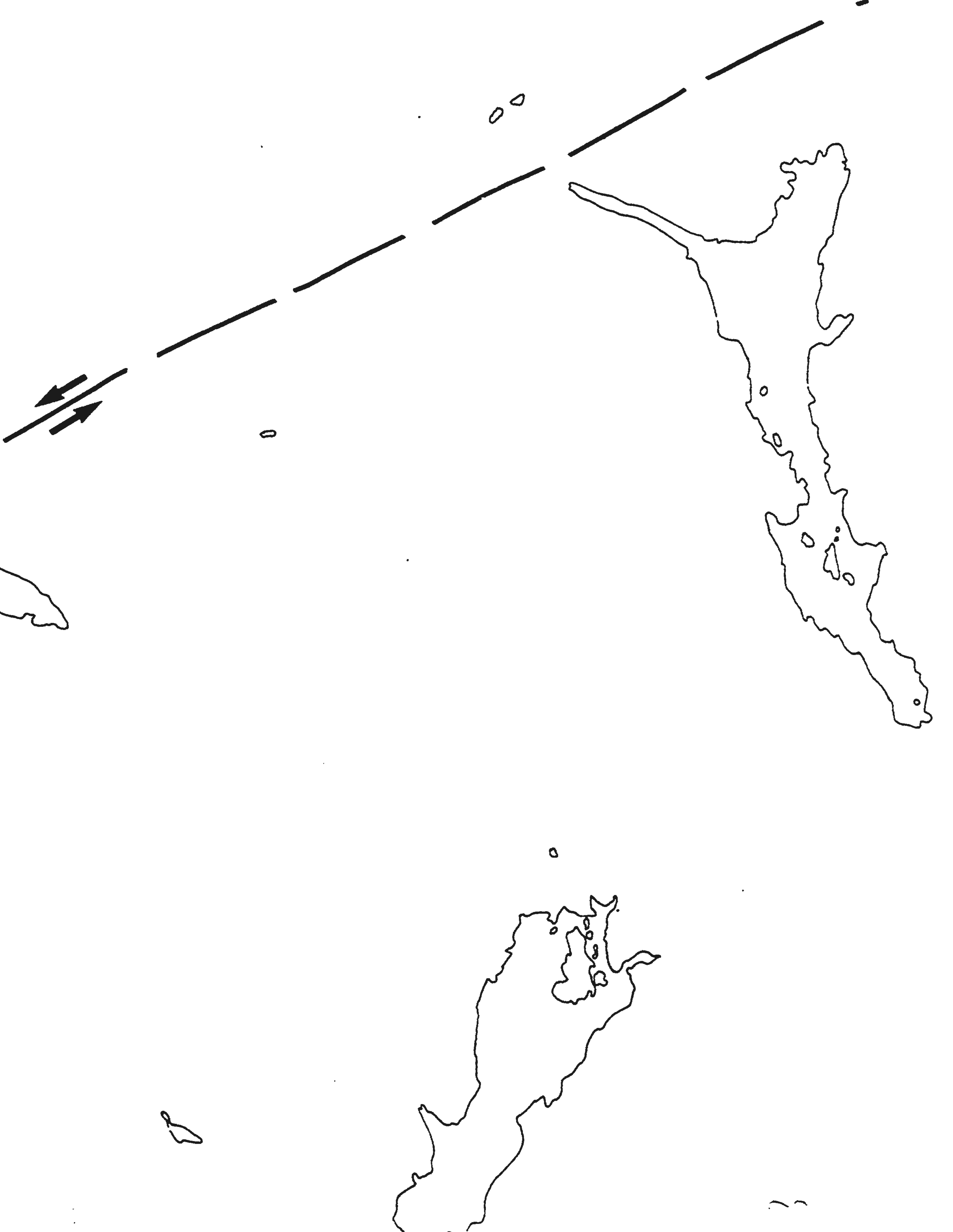


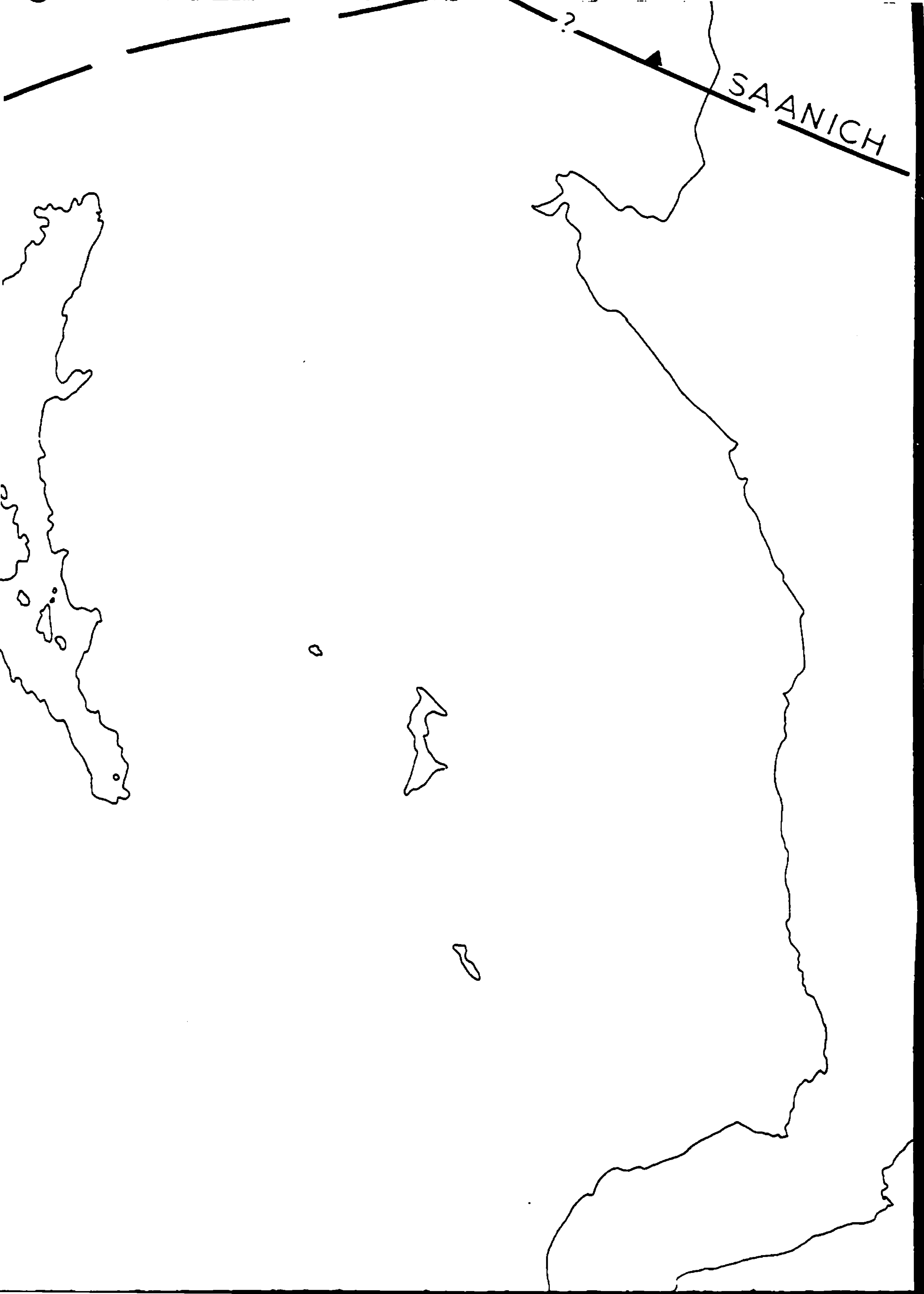
C'''
TZUHALEM
CHAN LAKE
SAANICH
6b
6a
5
4
3
2
1
?





SAN JUAN FAULT
SURVEY MOUNTAIN FAULT




SAANICH