GEOPHYSICAL CONSTRAINTS ON THE STRATIGRAPHY, STRUCTURE AND TECTONIC EVOLUTION OF THE LATE DEVONIAN/ CARBONIFEROUS MONCTON SUBBASIN, NEW BRUNSWICK

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by

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ABSTRACT

A synthesis of public domain seismic reflection, gravity, magnetic, borehole and map data reveals that the Moncton Subbasin evolved as series of linked half-grabens which formed by oblique extension beginning in Late Devonian time. Transpressional wrench faulting resulted in deformation, localized uplift and erosion in the Early Carboniferous (end of Tournaisian); episodes of strike-slip faulting punctuated a broad sag-style subsidence in the Late Carboniferous. Quantitative estimates of net extension and subsidence rates have been derived by balancing interpreted seismic cross-sections and making seismic-unit thickness and map measurements; these suggest that north-south oblique extension on the order of 10 km accommodated subsidence along the Caledonia-Clover Hill Fault zone in the Late Devonian and Tournaisian. The subsidence rate averaged at least 120 mm/10^3 yr and was greatest during the late Tournaisian.

The distribution of Avalon zone basement units beneath the Carboniferous cover is inferred from an analysis of gravity and magnetic data in concert with borehole and map observations. The Brookville terrane is interpreted to lie tectonically emplaced over the younger Caledonia terrane, and to extend beneath Carboniferous cover as far north as the Northumberland Strait.

Seismic stratigraphic analysis of the terrestrial sediments of the Horton Group in the Elgin/Portage Vale area

reveals alluvial fan and fan-delta seismic stratigraphic units in a previously undescribed Late Devonian/Tournaisian depocentre. The Albert Formation oil shale member coincides with a maximum flooding surface and is mappable seismically in the thick lacustrine succession. Seismic isopachs of progressively younger Lower Carboniferous sequences migrate to the southwest in a manner consistent with the oblique extension model of basin evolution.

Taken as a whole, these observations suggest the pull-apart model of the Maritimes Basin should be re-evaluated. The early, extensional phase of basin evolution is consistent with the gravitational collapse of the Acadian orogen.

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1.0 Introduction

1.1 Purpose and Scope

The Moncton Subbasin, in southern New Brunswick, has been of considerable economic importance to Atlantic Canada. Beginning in 1849 with the discovery of Albertite, a solid bitumen mined for use in Boston gas plants, the subbasin has yielded oil, gas and oil shales, salt, potash, gypsum, limestone and minor base metals. Yet despite the volume of exploration activity in the last century, little is known about structural aspects of the subbasin and its tectonic evolution. This is due in part to poor exposure and multiple episodes of fault motion during the Carboniferous, and in part to the lack of attention focused on these problems in recent years.

Two viewpoints, long perceived as opposing, on the structural evolution of the subbasin have been published. Gussow (1953), presented a comprehensive review of oil exploration data, favouring a thrust-belt model of Carboniferous deformation. This was later disputed by Webb (1963, 1969) who favoured a wrench tectonic regime in the Carboniferous. The debate continues today with arguments for (e.g. Grierson et al., 1987; Martel, 1987; Leger, 1986) and against (e.g. Poll, 1970; McCutcheon and Robinson, 1987) Carboniferous wrench tectonics as a dominant control on basin formation and evolution.

The Moncton Subbasin is unique among the Carboniferous deposits bordering and underlying the Gulf of St. Lawrence for several reasons.

1. It contains the best drilled succession of Lower Carboniferous sediments in the region, since it hosts the only Carboniferous oil and gas field in the region at Stoney Creek, now shut in.

2. It is covered by a regional grid of recent reflection seismic and other geophysical data.

3. It is dissected by some of the main faults in the Maritime Carboniferous system. Understanding the timing and kinematics of these would contribute greatly to our understanding of Carboniferous tectonics in the northern Appalachian region as a whole.

The goal of this thesis is to understand the tectonic evolution of the Moncton Subbasin in Late Devonian and Early Carboniferous time. This period of Carboniferous basin history is poorly understood in the region and bears upon future work in the related fields of: (i) resource exploration in the Carboniferous of Eastern Canada; (ii) late Devonian and Carboniferous tectonic history of the northern Appalachians; (iii) plate reconstructions of the Late Palaeozoic; and (iv) the kinematics of within-orogen basin subsidence. This goal has been achieved by a systematic analysis of the available geophysical data - seismic reflection, gravity and aeromagnetics - in the light of published geological mapping and drilling results.

The data presented in this thesis are available in the public domain through the New Brunswick Department of Natural Resources in Fredericton. The aeromagnetic and gravity data have been previously published in other forms (Geological Survey of Canada - GSC - Aeromagnetic Map series; Chandra et al. 1982). The seismic data presented in this thesis were released by the New Brunswick Department of Natural Resources in 1989.

The technical scope of this research has included the analysis of reflection seismic profiles and geophysical well-log data, the processing and analysis of the potential field data, and a geological field trip to the area. The seismic data have been analyzed in light of the map, well and potential-field data resulting in contributions to the solution of four main problems:

1. The correlation of pre-Carboniferous basement terranes and their structure beneath the basin;
2. Understanding basin stratigraphy;
3. Late Devonian and early Carboniferous tectonic events and structural styles associated with basin formation and Early Carboniferous deformation; and
4. Late and post-Carboniferous tectonic events which for the purposes of this thesis are considered a tectonic overprint - partially obscuring the Late Devonian/Early

Carboniferous rock record of primary interest.

1.2 Study Area

The Moncton Subbasin is an erosional remnant of Late-Devonian and Carboniferous sedimentary rocks exposed in the area south and west of Moncton, New Brunswick. The central part of the basin is a broad valley drained by the Kennebecasis and Petitcodiac rivers (Figure 1-1) bounded to the northwest by Carboniferous ridges of the Kingston Uplift and to the south by the mountains of the Caledonia Uplift, a pre-Carboniferous basement prominence which lines the north side of the Bay of Fundy. Carboniferous rocks of the Kingston uplift are usually included in the Moncton Subbasin, and its northern boundary is considered to be the Belleisle Fault Gussow (1953), which extends northeastward from Belleisle Bay to the coast south of Buctouche.

The basin south of Moncton consists mainly of low relief, rolling topography covered partly by forest and partly by farmland some of which has been reclaimed by secondary forest cover due to depopulation. Relief greater than 100 m is rare. In the southwestern end of the subbasin, between Sussex and Salt Springs, there is a more immature topography with average elevations about 100 m and maximum elevation 350 m along upturned bedding ridges of erosion-resistant sandstone and conglomerate. In the Caledonia Uplift elevations commonly exceed 300 m and locally exceed 400 m, particularly in the area north and east of Fundy National Park.

In most parts of the subbasin not drilled for exploration purposes, published geological maps are based upon outcrop evidence afforded by the streams and rivers draining the highland areas exposing the Carboniferous section in widely-spaced transects across the basin margin. Good exposures of fault surfaces are particularly rare (Poll, 1970).

1.3 Previous Geophysical Studies

The comprehensive review of Gussow (1953) constitutes the only other published attempt to integrate geological and geophysical data in the Moncton Subbasin for the purpose of basin analysis. That study was a compilation of geological and geophysical work done by the Shell Oil Company in the area during the 1940's and included a comprehensive description of the stratigraphy, geological mapping results, and thirteen cross-sections based on vintage seismic reflection data. Gravity and seismic refraction results from selected areas in the basin were also presented. Gussow (1953) described the basin architecture and recognized two major periods of deformation in the Carboniferous rocks, associated with movement along four northeast-trending "master faults" in the area. In 1958, a regional aeromagnetic survey was conducted by the federal government. Bhattacharyya and Raychaudhuri (1967) published a regional analysis of these data which included the Moncton Subbasin and confirmed the extension of the northeast magnetic trends of the subbasin under the Gulf of St. Lawrence. A more detailed aeromagnetic grid was collected over the Caledonia mountain area in 1971, which was subsequently analyzed by Tijirian (1974) and Gupta (1975) whose work traces trends in the pre-Carboniferous basement rock south of the thesis area. Allan Spector and Associates Limited (Spector 1979; 1980), under contract to the New Brunswick Department of Natural Resources, reassessed the 1958 aeromagnetic data for depth to basement and inferred lithology based upon intensity of magnetization of basement rock units. The depth to magnetic basement map of Spector (1979; 1980), made without the benefit of seismic corroboration, is incorporated into the discussion of basement structure found in Chapter 3. Chandra et al. (1982) compiled the Bouguer gravity data from the provincial Department of Natural Resources, the federal Earth Physics Branch (E.M.& R.), the University of New Brunswick, and the private sector. The resulting digital data set was published in a series of 1:50,000 Bouguer anomaly maps. No further analysis of these data has been published except 2-dimensional models of several salt anomalies (Chandra et al., 1982), again without benefit of seismic constraints.

The first documented seismic study is the work of Gussow (1953), who reports the interpretation of more than 160 km of reflection data collected by Shell Oil in 1948 and 1949. The Shell data are no longer available (Three-D Geoconsultants Limited, 1989), but interpreted sections of 13 of those lines are presented in Gussow's report.

This thesis utilizes the only recent regional seismic data set collected in the Moncton area. This consists of some 1900 km of Vibroseis reflection data collected by Chevron Canada Resources between 1981 and 1984, released by the New Brunswick Department of Natural Resources in January 1989. Figure 1-2 shows the seismic reflection coverage of this 4 year program. Grierson et al. (1987) refer to the data in an expanded abstract in which they present arguments for the evolution of the Maritimes basin in a wrench tectonic regime. Martel (1987) presents three of the seismic lines in the part of the Cumberland Subbasin east of Moncton which Williams (1974) calls the Sackville Subbasin. Martel's interpretation of these data, which image sediments equivalent in age to those of the Moncton Subbasin in a fault bounded graben with a buried central arch, requires three stages of extension or transtension and two stages of compression or transpression. These coincide with Gussow's (1953) episodes of thrusting, within the Carboniferous, which Martel incorporates into a wrench tectonic model for the area. In a recent unpublished thesis, St. Peter (1992) has interpreted several of the seismic lines along the southeast margin of the Moncton

Subbasin to support his geological study of facies distributions in the Albert Formation.

This thesis is structured around four main themes to which the geophysical data analysis contributes. In Chapter 2, a brief summary of the published literature is presented describing the geological setting for this study. In Chapter 3, the first theme is addressed: the pre-Carboniferous basement and how geophysics can be used to elucidate its structure and the distribution of terranes beneath the Carboniferous cover. In Chapter 4, seismic contributions to the understanding of basin stratigraphy are discussed. It will be shown that seismic stratigraphy is applicable even though most of the section is non-marine in origin, and hence not subject to sea level control. By correlating unconformities in the subsurface and applying principles of seismic stratigraphy certain Lower Carboniferous lithofacies can be mapped seismically in the Elgin area and the paleoenvironments of the Albert Formation in that area can be reconstructed. Inferences can be drawn about the timing and relative rates of subsidence and sediment supply in the early stages of basin formation. In Chapter 5, the Early Carboniferous tectonic evolution of the subbasin is discussed. This is best illustrated by the southern basin margin, along which good seismic control is available, and in which area the structural style of initial basin subsidence and a subsequent transpressional inversion event are imaged. Late Carboniferous and younger tectonic events are difficult to distinguish from earlier events and locally obscure the older events as discussed in Chapter 6. Finally, in Chapter 7, the geophysical results are summarized and a synthesis of the kinematics of subbasin evolution is presented in the context of Carboniferous basin development elsewhere in the Maritimes and the late Palaeozoic plate setting of Eastern Canada.

2.0 Geologic Framework

"...*In entering, therefore, on the Carboniferous system, we go.. back in the history of the Earth to a time when the rocks that formed the shore of the red sandstone sea were themselves being deposited in the form of sediment, in waters which washed the sides of the Cobequid Hills and the other old Metamorphic ranges*" (Dawson, 1868 p.128)

2.1 Introduction

The Upper Paleozoic sediments, on which this work is focused, were deposited among the metamorphic ranges created by the Devonian mountain-building events of the Acadian orogeny, during the final assembly of Pangea and before the great continent broke up along rift valleys heralding the opening of the Atlantic. Geologists of Dawson's time did not recognize the possibility of preservation of sediments without marine conditions (Bell, 1944): hence his reference to the "red sandstone sea" of the Triassic.

The "metamorphic ranges" make up the Appalachian/Caledonide Orogen - a Palaeozoic mountain belt stretching from the southern U.S. to Newfoundland. Since the Atlantic ocean, as we know it, did not exist at that time, the mountain belt continues in neighbouring lands to the east including Britain and Scandanavia. The Maritimes sedimentary basin (Figure 2-1) lies within the orogen, where it takes a bend to the east which Williams and Hatcher (1982) refer to as the "St. Lawrence promontory". Not only were the sediments deposited in intermontane valleys among the ranges near the bend, but in late Devonian and Carboniferous time that part of the orogen foundered and was flooded by the sea. A great accumulation of sediment, eroded in Carboniferous time from the Palaeozoic ranges, now lies under the Gulf of St. Lawrence and there is evidence to suggest that Late Carboniferous and Permian sediments were once deposited over an even wider area surrounding the present Gulf.

Late Carboniferous orogeny profoundly affected both southern Appalachians and central Europe where the events are usually referred to as the Alleghenian and Variscan orogenies respectively. Extensive faulting and isolated igneous activity are recorded in the Maritimes Basin at that time, but little or no metamorphism is evident, and basin subsidence, locally episodic, continued into the Permian.

In the following sections the geologic literature on the Moncton Subbasin is summarized beginning with a brief overview of the Appalachian orogen and Maritimes Basin. This is followed by a summary of the Moncton Subbasin stratigraphy prefaced with a comment on some problems with the stratigraphic nomenclature which place the seismic stratigraphic observations of Chapter 4 in perspective.

2.2 The Maritimes Sedimentary Basin

Upper Palaeozoic rocks of the Moncton Subbasin form part of a much larger Upper Palaeozoic sedimentary basin-fill which blankets the Appalachian terranes over an area of more than 400,000 sq km. The present day erosional limit of Upper Palaeozoic sediments is shown in Figure 2-1.

The Maritimes Basin comprises all sedimentary rocks of late Middle Devonian to Early Permian age in the central and southern portions of the Gulf of St. Lawrence, including those on land in Prince Edward Island and Newfoundland, Nova Scotia, New Brunswick and the Gaspé Peninsula of Quebec (Howie and Barss, 1974). The sediments are dominantly non-marine in origin. Although their limits are poorly constrained, Carboniferous sediments are also known from isolated borehole and offshore seismic reflection data to lie under the Mesozoic sediments of the Bay of Fundy, the northeast coast of Newfoundland and the southern Grand Banks (Bell and Howie, 1990). Much more of Atlantic Canada was once covered. Grist et al. (1992) suggest, based on fission track analysis of apatite grains from Nova Scotia, Newfoundland and Gulf of St. Lawrence boreholes, that up to 4 km of Permian and Upper Carboniferous sediments have been eroded.

The Moncton Subbasin, or Moncton Basin (Wright, 1922; Gussow, 1953), is a fault-bounded sediment wedge. More than 3000 square kilometres of Late Devonian and Carboniferous sedimentary rocks are exposed north of the Caledonia mountains and south of the Belleisle Fault in southern New Brunswick. It is one of several "subbasins" identified by Kelly (1967) as making up the southern margin of the Maritimes Sedimentary Basin. The pattern of subbasins, and in fact the definition of Moncton Subbasin cited above, will be shown to mainly reflect the control of late- and post-Carboniferous faulting in the erosional pattern of the Carboniferous rocks and not necessarily the locations of individual depocentres.

2.3 Stratigraphy

2.3.1 Lithostratigraphy vs. Chronostratigraphy

Maritimes Basin stratigraphy suffers from a historical tangling of rock-stratigraphic and time-stratigraphic terms. For the purposes of this study it is important to have a chronological framework for stratigraphic correlation. Without one, no progress can be made in determining the absolute timing of tectonic events in the subbasin or in correlating these events with those elsewhere in the Maritimes and Europe. Many attempts have been made to revise the stratigraphic nomenclature (e.g. Kelly, 1967; Carter and Pickerel, 1985; Ryan et al., 1991), most aimed at systematizing the lithostratigraphy. In this section I briefly outline the problems with, and evolution of, stratigraphic nomenclature as it relates to the unit descriptions of this chapter and the goals and methods of Chapter 4.

Geologists describe and correlate rocks on the basis of properties which can include lithology, magnetic polarity, fossil content, geochemistry or age. But not all properties will give rise to the same correlations within a given rock body. The most important types of stratigraphic subdivision are:

1.) lithostratigraphic: based on observable lithologic features;
2.) biostratigraphic: based on fossil content; and
3.) chronostratigraphic: based on age, which may be determined by fossil content, radiogenic or other means.

In general, lithostratigraphic units are diachronous, that is, they do not everywhere represent the same range of geologic time. But some events, such as volcanic ash falls, give rise to widespread deposition of a given type over a short time span, and hence are rock units that can also serve as time markers.

The roots of modern stratigraphic nomenclature lie in early work of the GSC by Bell (1927,1944) for the Maritimes Basin and Wright (1922) for the Moncton area. Bell proposed a regional stratigraphic subdivision for the Carboniferous consisting of six units. These were, in ascending order, the Horton, Windsor, Canso, Riversdale, Cumberland and Pictou

Series. Bell's series were biostratigraphic subdivisions based on the vertical distribution of plant species (Bell, 1927), but in a later paper (Bell, 1944) they were redefined as groups, a term normally reserved for lithostratigraphic units. Bell believed (Ryan et al., 1991) his groups were separated by unconformities or disconformities of regional time significance. Wright (1922), working in the Moncton Subbasin, also subdivided the Carboniferous rocks into a number of series, similarly defined on the basis of fossils and unconformities.

The goal of the early GSC work was then to erect a chronostratigraphy, for as Bell (1944) states:

> *"The lithological succession varies so decidedly from place to place that it cannot generally be used for age correlation. The vertical succession of plant species, on the other hand, remains generally constant regardless of age or geographic location and permits the establishment of a standard scale of ages or time zones. Without such a scale there is serious danger of giving a time value to certain lithological features, and making these features a basis for subdivision and correlation"*

Unfortunately the choice of unconformities as bounding surfaces for the classifications of Wright and Bell was more suited to a lithostratigraphic subdivision than a chronostratigraphic one, since unconformities can change in age from place to place even though all rocks above are, except in extraordinary circumstances, younger than all rocks below (Miall, 1990). Bell's (1944) group correlations were impractical to apply where contacts are conformable or where no fossils are preserved to indicate a time break. The groups were subsequently mapped by others as *de facto* lithostratigraphic units which were soon proven to have diachronous boundaries (Kelly, 1967) with the result that Bell's group names are now treated as lithostratigraphic units while efforts continue to define their ages from place to place.

Figure 2-2 is a chronostratigraphic chart which integrates the published stratigraphic data. It is based on the lithostratigraphy of the Moncton Subbasin as summarized by Gussow (1953) which has been modified, at least locally, by several authors including Greiner (1962), McCutcheon (1981), Carr (1968), McLeod (1979), Anderle et al. (1979) and St. Peter (1989a, 1989b, 1992).

Some key observations should be made concerning the chronostratigraphic chart of Figure 2-2:

1. The Memramcook Formation is now recognized, on the basis of miospores (Carr, 1968), to be included in the Upper Devonian. Thus it is no longer accurate to refer to Moncton Subbasin sediments collectively as "Carboniferous".

2. The Moncton and Hopewell groups, both defined by

Norman (1941) on the basis of lithology, continuity and stratigraphic position, contain major unconformities and are inconsistent with Bell's group boundaries which are defined on age. Use of the Moncton Group as a formal stratigraphic unit is abandoned following the recommendation of St. Peter (1992).

3. The Windsor Group has been defined in southern New Brunswick as a strictly lithostratigraphic unit by McCutcheon (1981) and its deposition spans only part of the Windsorian stage (Kelly, 1967).

4. The significance of the Cumberlandian strata not being represented is unclear. No Westphalian "B" fossils have been found in the area; however, no unconformity has been observed either and it is possible that the apparent missing section is due to inadequate sampling and/or spore preservation in the poorly exposed redbeds.

From his text, it is clear that Gussow considered Bell's Groups to be time-stratigraphic units rather than rock units contrary to our present day understanding of the "group" as a lithostratigraphic unit comprising one or more formations.

The chronostratigraphic chart (Figure 2-2) is drawn to scale in time and represents diagrammatically the chronological sequence of deposition and erosion. By necessity this chronostratigraphic column is interpretive, so few spore dates being available in the red-bed units. Together with the geological compilation map of St. Peter (1989a,b) (shown in modified form in Plate 2-1) it provides a geological framework in which to interpret the seismic data. In Chapter 4, seismic data will be used to construct a more detailed chronostratigraphy for the Elgin area.

2.3.2 Pre-Carboniferous Basement Complex

Precambrian metavolcanics, metasediments and igneous intrusive rocks of the Avalon Composite Terrane (Keppie, 1985) and its Lower Palaeozoic cover sequences outcrop to the south and west of the Moncton Subbasin and occur as isolated inliers in some fault zones and on the Kingston and Westmoreland Uplifts. A dioritic intrusion of pre-Carboniferous age is exposed 15 km east of Moncton at Calhoun (Plate 2-1) and intrusive rocks are intersected at shallow depths in wells north of Sackville (Martel, 1987) and west of Moncton (St. Peter, 1987b) along a buried basement ridge commonly referred to as the Westmoreland Uplift (Martel, 1987). Isolated basement inliers are associated with the Jordan Mountain, Indian Mountain and Cloverhill faults (Figure 2-1).

Avalon zone rocks of southern New Brunswick have recently been subdivided into terranes (Barr and White, 1991a) in the light of new stratigraphic and radiometric dating results.

In view of the rapidly changing ideas on the Precambrian rocks of southern New Brunswick, and the distinctive geophysical signatures of some basement units, the extent and nature of Avalon zone rocks under the Carboniferous cover is discussed in further detail in Chapter 3.

2.3.3 Memramcook Formation

The Memramcook Formation (Norman, 1941) is the lowermost stratigraphic unit in the Moncton Subbasin. It is dated as Late Devonian (Haquebard, 1972; Carr, 1968; Barss et al. 1979) based on miospores, although no Memramcook fossil or spore dates are available from the southern part of the subbasin. The formation consists of red fanglomerates near the southeast basin margin, grading upwards and away from the faults into conglomeratic sandstone and brownish-red sandstone with mudstone beds. Unit thickness in the type area exceeds 900 m. In the field, the Memramcook Formation is unfossiliferous and lithologically indistinct from several of the overlying formations so it is correlated on the basis of continuity and its stratigraphic position in relationship to the Albert Formation (Gussow, 1953). The Memramcook Formation was deposited in piedmont alluvial fans and associated braided fluvial environments (Carter and Pickerel, 1985) and is described in detail by Popper (1965).

2.3.4 Albert Formation

The Albert Formation gradationally overlies, and is in part laterally equivalent to the Memramcook Formation (McLeod and Ruitenberg, 1978). Due to its economic significance as a producer of the solid bitumen Albertite, oil and gas, and oil shales, it has been extensively studied (e.g. Norman, 1932; Gussow, 1953; Greiner, 1962; Macauley and Ball, 1982; Smith and Gibling, 1987; Foley, 1989; Chowdhury et al., 1991; Chowdhury and Noble, 1992; St. Peter, 1992). The Albert comprises a wide range of lithologies which suggest sedimentation in and around a large lake (Greiner, 1974) which eventually became filled with sediment and was succeeded at least locally by a playa lake in which evaporites (Gautreau member) accumulated. Albert lithologies include grey sandstones, siltstones and shales, thinly laminated grey bituminous shale with interbeds of siltstone and argillaceous limestone, grey fanglomerates similar in lithology, but generally not in colour to the underlying Memramcook Formation, and evaporites. Traditionally (e.g. Gussow, 1953) the contacts of the Albert Formation with the underlying Memramcook, and overlying Weldon Formation, have been defined on the basis of colour: the Albert comprising predominantly grey, as opposed to red, sediments. St. Peter (1992) has redefined the Albert formation more rigorously as a lithostratigraphic unit. He defines the Albert as a unit comprising all Horton Group lacustrine deposits including those which can be demonstrated to be lateral facies equivalents of lake deposits. He further defines the boundary with the underlying Memramcook Formation as the level at which distal facies silts and sands of the upper Memramcook fine into dominant shale and mudstone regardless of colour. Spatial relationships among the Albert Formation lithotypes have been discussed by Greiner (1962), Smith and Gibling (1987), Carter and Pickerel (1985), and St. Peter (1992), and are summarized schematically in Figure 2-2. The age of the Albert Formation is Tournaisian (Utting, 1987). A previously reported (Greiner, 1974) Late Devonian age based on crossopterygian fish from the basal Albert is now considered suspect as spore dates from the same locality, confirm an early Tournaisian age (St. Peter, 1992). The Albert Formation locally exceeds 1700 m in thickness (Gussow, 1953).

2.3.5 Weldon and Hillsborough Formations

The Weldon and Hillsborough formations were originally assigned to the "Moncton Group" (Norman, 1941), a controversial alluvial redbed unit which overlies the Albert Formation and locally attains thicknesses greater than 1800 m. In the Hillsborough area, the Weldon and Hillsborough formations are recognizable and separated by an angular unconformity (Gussow, 1953). The lower unit, the Weldon, is conformable with the underlying Albert of Tournaisian age, and the upper unit, the Hillsborough, is conformable with the Mid Visean limestones of the Windsor Group. The unconformity within the Moncton is also observed at Urney (McCutcheon, 1978) and appears widespread in the seismic data presented in Chapters 4 and 5 of this thesis. Gussow (1953) notes that the Hillsborough Formation is generally coarser than the Weldon, consisting of fluvial channel and alluvial conglomerates with minor sandstone and calcrete, while the Weldon Formation comprises predominantly interchannel, overbank and floodplain deposits (Carter and Pickerel, 1985). The most common lithologies are red and locally grey mudstone, shale and siltstone with minor sandstone and conglomerate, gypcrete and calcrete.

Attempts to correlate the Hillsborough and Weldon Formations throughout the subbasin on the basis of lithology have led to conflicting map patterns (compare e.g. Gussow, 1953, Figure 5; McLeod, 1979, Plate 1; St. Peter, 1989a; St. Peter, 1992, Plate 2) and a myriad of interpretations of the Moncton "Group's" single distinctive lithological marker, the Boyd Creek Tuff (St. Peter, 1989a). That marker, an undated ash bed, is potentially useful as an event marker in dating Moncton rocks in the eastern end of the map area, but its stratigraphic position is uncertain. Gussow attributes it to the basal Hillsborough since it varies in thickness as if deposited on an eroded Weldon surface; St. Peter (1992) attributes it to the Weldon since it seems to be deformed as the Weldon is; and McLeod (1978) claims, based on mapping and borehole data, that the tuff unit actually cuts across the Weldon-Hillsborough boundary.

Throughout much of the Moncton Subbasin, the Weldon and Hillsborough Formations are not recognizable by field mapping. In Plate 2-1 rocks at the equivalent stratigraphic level are assigned to an undivided "Moncton Group" in areas where there is no compelling stratigraphic evidence to assign them to either formation.

In this thesis the Memramcook, Albert and Weldon formations are assigned to the Horton Group (after Gussow, 1953; Greiner, 1962; McCutcheon, 1978; and St. Peter, 1992) and the Moncton Group is abandoned as a formal stratigraphic unit. This classification is consistent with the seismic observations to be presented in Chapter 4.

Figure 2-2, the chronostratigraphic chart, shows the most likely spatial relationship between the "Moncton Group" lithofacies. Recommendations to revise the Moncton's rank to formation status (Kelly, *in* Poole et al., 1970; and Carter and Pickerel, 1985) apparently underestimate the subbasin-wide nature of the angular unconformity between the Weldon and Hillsborough formations. A thorough description of "Moncton Group" rocks was presented by Schroder (1963) but a satisfactory resolution of its stratigraphy awaits the determination of a significant number of spore dates and improved borehole data.

2.3.6 Windsor Group

The Windsor Group overlies the Hillsborough formation and overlaps onto basement at the Horton basin margins. Basal algal laminite limestones of the Macumber Formation or, locally, algal mounds of the Gays River Formation are overlain by evaporites which grade upward into fine grained clastics. Only the lowest one, and locally two, of the five Windsor Group subzones defined by Bell (1929) in Nova Scotia are present in New Brunswick (McCutcheon, 1981). Thus some of the redbeds stratigraphically above the Windsor, assigned to the Hopewell Group, and below the Windsor, assigned to the Hillsborough Formation, were deposited coevally with Windsor Group rocks described in Nova Scotia by Bell (1929). Thus rocks of the Hillsborough formation, Windsor Group, and lower Hopewell Group are all "Windsorian" in age (Kelly, 1967) as shown in Figure 2-2. A comprehensive summary of Windsor Group rocks in New Brunswick has been published by McCutcheon (1981) who attributes their deposition to a marine incursion with evaporite deposition occurring in deep water in a restricted hypersaline sea.

Visean volcanism has been reported in several parts of the Maritimes Sedimentary Basin (Fyffe and Barr, 1988), and it has been noted that a tuff unit occurs in the "Moncton Group" at Boyd Creek. The only evidence for Windsorian volcanism in the Moncton Subbasin is cited by Roulston and Waugh (1983).

They interpret the diverse and widespread borate mineral assemblage found in the Upper Halite Member of the Cassidy Lake Formation in both the Plumsweep and Salt Springs areas as the result of volcanism which added boron thus modifying the brine geochemistry at the time of Windsor Group evaporite deposition.

2.3.7 Hopewell Group

The Hopewell Group was the name given by Norman (1932) to the "various assemblages laid down after the interruption in Windsor time and before the commencement of the deposition of the characteristic Boss Point beds". As such its dominantly conglomeratic redbed sediments may range in age from Mid-Visean to earliest Westphalian (Poll, 1970). Throughout most of the Moncton Subbasin the Hopewell Group cannot be subdivided (Gussow, 1953) and it consists of a generally conglomeratic redbed sequence lithologically indistinguishable from the Moncton Formation. It too is devoid of fossils and is recognized on the basis of its relationship to the Windsor Group. In the Cumberland Subbasin, including the exposures at Hopewell Cape and the Maringouin Peninsula at the extreme east end of the map in Plate 2-1, the Hopewell can be divided into formations; the lower Maringouin and Shepody formations are conformable with the underlying Windsor Group and separated by an angular unconformity from the upper, generally coarser, Enragé Formation, which is conformable with the overlying Boss Point strata. The Windsor/Hopewell contact is not observed in outcrop (Gussow, 1953) and in boreholes it is in some places a gradational contact and others apparently disconformable (McCutcheon, 1981) or unconformable (McLeod, 1979). The Hopewell Group contains an angular unconformity, but there is some debate as to its extent. Some authors believe a profound angular unconformity is present throughout the subbasin (eg. Gussow, 1953; McCutcheon, 1981; St. Peter, 1992). But Anderle et al. (1979) describe an apparently conformable succession of Hopewell sediments between the Windsor and Boss Point in the Marchbank syncline which they subdivide into mappable formations again with a general coarsening upward trend, and it is possible that the angular unconformity is restricted to areas near the major fault zones. Leger (1969) attributes Hopewell Group deposition to non-marine fluviatile conditions in an alluvial fan environment. The lowermost, fine grained sediments are distal water-lain deposits; the sandier Shepody Formation and its equivalents are fluvial deposits eventually overstepped by the coarser Enragé Formations. The fining upward trend within the Enragé Formation is interpreted by Leger (1969) to indicate the end of an episode of Namurian tectonic activity and a reduction in relief of the source area by continued erosion in the arid to semi-arid climate of the time.

2.3.8 Boss Point Formation

Distinctive sediments of the Boss Point Formation disconformably overlie the Hopewell Group (Gussow, 1953; Poll, 1970) and have been assigned to the Petitcodiac Group by Norman (1941), the Riversdale Group by Gussow (1953) and a revised Cumberland Group by Ryan et al. (1991). They consist of grey-buff quartzose sandstones with minor shales, silts and coal stringers, and a characteristic basal conglomerate with abundant well-rounded quartz pebbles. The base, dated by miospores, is time transgressive, ranging in age from Namurian B to earliest Westphalian (McLeod, 1979). Boss Point sediments, which are more texturally mature than any others in the Carboniferous succession, were deposited in a fluvial environment over a broader basinal area than the Hopewell Group and had a more distant source, which paleocurrent data suggest was to the south (Poll, 1970).

2.3.9 Pictou Group

Nearly flat-lying rocks of the Pictou Group are believed to overlie the Boss Point Formation disconformably, Bell's (1927) Cumberland Series being unrepresented in the fossil record of the Moncton Subbasin. It is possible that the Cumberland's absence is a sampling problem since outcrops are few and unfossiliferous (C. St. Peter, 1992, pers. comm.). The Pictou consists of mostly flat-lying sequences of grey conglomerate and sandstone with alternating finer grained redbeds (Poll, 1970). Pictou Group sediments have been described and subdivided into formations by Gussow (1953) and Carr (1968) but Poll (1970) recognized that correlations based on lithology were tenuous due to the repetitive and laterally variable nature of the fluvial deposits. He subdivided the Pictou into three cyclothems each grading from conglomerates at the base to dominant siltstones at the top. Each cyclothem shows a corresponding upward colour change from red to grey with coal beds occurring locally near the red-grey transition. The ages of the four cyclothems are Early Westphalian "C", Late Westphalian "C" and Westphalian "D" to Stephanian (Poll, 1970) respectively, although beds as young as Permian are exposed north of the study area on Prince Edward Island and may once have covered the study area. Pictou sediments were deposited in fluvio-lacustrine and paludal (marsh) environments under less arid climatic conditions than the lower Carboniferous rocks in the succession. More recently, from extensive drilling in the shallow Carboniferous section, Ball et al. (1981) suggests Poll's (1970) cyclothem model may itself be too simple to describe the borehole observations.

2.4 Structure

2.4.1 Introduction

The Moncton Subbasin has undergone a complex faulting history involving at least three main tectonic episodes. In Chapters 5 and 6 these will be discussed in detail as revealed in the geophysical data. A brief review is presented here. Three main northeast-southwest trending fault zones transect the Moncton Subbasin as shown in Plate 2-1. These are the Belleisle, the Kennebecasis-Berry Mills, and the Clover Hill-Caledonia fault zones. These, together with the Harvey-Hopewell fault zone at the extreme southeastern corner of the map area, comprise the four "master faults" of Gussow (1953), which have controlled Late Palaeozoic sedimentation and deformation in southeastern New Brunswick. These three fault systems have all undergone multiple episodes of movement before and during the Carboniferous, but the actual fault planes are seldom exposed "permitting a certain degree of freedom in the interpretation of the sense of fault movement" (Poll, 1970 p.52).

2.4.2 Fault Zones

The Kingston uplift, a highland comprising mainly deformed lower Carboniferous rocks, is bounded by the Belleisle and Kennebecasis-Berry Mills faults. Two contrasting interpretations of these fault systems have been published (Gussow, 1953; Webb, 1963) as shown in Figure 2-3. Gussow (1953) considered the Belleisle and Kennebecasis-Berry Mills, (which he called Peekaboo-Petitcodiac-Berry Mills) "master faults" to be southeast verging thrusts active mainly during the Namurian (pre-Enragé Formation). As shown in Figure 2-3(a) his cross-section across Indian Mountain, the Lutes Mountain Fault is interpreted as a steep thrust fault with a vertical displacement that exceeds 2.4 km. The Berry Mills Fault is considered to be a low angle, southeast-verging thrust with a throw of 5 or 6 km in the central part of the Kingston Uplift. A contrasting theory of Moncton Subbasin structure was proposed by Webb (1963), who while acknowledging that some late thrusting may have taken place, considered the Belleisle and Kennebecasis-Berry Mills faults to be dextral strike-slip faults active before Windsor Group deposition (Figure 2-3[b]). This hypothesis was based mainly on the relationships of fold axes to fault trends. Webb (1963) notes that fold axes seen in the pre-Windsor rocks are consistent with an east-west principal axis of compression and dextral motion on the faults.

Subsequently published studies of these fault zones have done little to resolve the two fault models. Leger (1986) has made microstructural measurements at two locations in the Belleisle Fault and cites evidence of ductile dextral Acadian (Mid-Devonian) or older movement but he is unable to resolve the Carboniferous stress pattern recorded in the younger brittle fractures. Garnett and Brown (1973) interpret the latest movement on the Belleisle Fault in the Seven Mile Lake area as brittle high-angle reverse faulting with the southeast side up. This is consistent with McCutcheon and Robinson's (1987) contention that the Belleisle Fault has not undergone significant Carboniferous strike-slip displacement. But their argument is based on a cross-cutting fault at Oak Bay, south of the study area, which they believe is pre-Carboniferous but which Williams and Hy (1990) interpret as a Triassic feature associated with the opening of the Atlantic Ocean. Dissimilar Cambrian rocks are observed north and south of the fault indicating that major, probably strike-slip, movement has occurred prior to the Acadian Orogeny (Ruitenberg and McCutcheon, 1982). But later movement has not left much net lateral displacement as evidenced by the similarity of the Silurian Long Reach Formation across the fault, and the lack of significant displacement on a Silurian or Early Devonian granitic pluton northeast of Loch Alva (Ruitenberg and McCutcheon, 1982). Meanwhile, the 64 km of dextral offset attributed to the Belleisle Fault in the Carboniferous by Webb (1969) has become an integral component of the prevailing theory of Maritimes Basin evolution as a pull-apart basin (Bradley, 1982).

The Kennebecasis Fault exhibits shallowly-plunging slickensides (Leger, 1986) and brittle fractures suggestive of a maximum compressive stress oriented *ca*. 110°. Its latest movement then, was likely brittle dextral strike-slip.

The Clover Hill-Caledonia Fault zone has had multiple movement episodes in the Carboniferous. Late Devonian and Early Carboniferous movement gave rise to Horton Group fanglomerates preserved near the fault (Carter and Pickerel, 1985). Gussow (1953) interprets the Caledonia, Prosser Mountain and Hillsborough faults as an *en echelon* series of thrust sheets more or less paralleling the northern flank of the Caledonia Massif. Thrusting is described as southeast-directed in the Clover Hill, Caledonia and Hillsborough faults. Northwest directed thrusting is assigned to the subsidiary Pollett River and Prosser Mountain faults with the latter placing basement rocks over Hillsborough Formation conglomerate. Webb (1969) attributes 13 km of right lateral strike slip to the Prosser Mountain Fault on the tenuous basis of displaced map-pattern of basement/cover contact. Anderle et al. (1979) consider the Clover Hill Fault near the Marchbank syncline a high-angle southeast directed thrust with latest movement in late Pennsylvanian to early Permian while Roberts and Williams (1993), believe some of the displacement may be as late as Triassic. Leger (1986) notes that shallowly plunging slickensides are observed in the Caledonia fault zone indicating that latest movement was probably strike-slip but his microstructural measurements failed to establish the nature of Early Carboniferous fault movement.

2.4.3 Folding

Two major folding events affect rocks of the Moncton Subbasin: The first, which separates the folded Weldon Formation, and the relatively undeformed Hillsborough Formation, will be referred to here as the "Moncton Episode" (Figure 2-2). The second event, during Hopewell Group deposition, is also a period of locally intense folding and thrusting. This later "Hopewell Episode" locally affects Horton Group rocks and in some areas is difficult to distinguish from the earlier, Moncton, deformation event. Horton Group rocks are deformed by east-northeasterly trending, gently plunging close folds in the Dorchester-Hillsborough area. Ruitenberg and McCutcheon (1982) believed that broad north-northeasterly ones constitute the final phase of the Moncton episode. Another set of open folds, trending northeast-southwest parallel to the main fault systems, affects both Horton and Windsor Group rocks. Webb (1963), using published maps, isolated structural features affecting Moncton and older rocks from those affecting younger formations. His view that, in general, the folds in Moncton and older rocks (Webb, 1963, Figure 11) had more northerly-trending axes, oblique to the major faults. This he interpreted as evidence for dextral strike-slip deformation during the Moncton episode and it remains the most compelling evidence for strike slip motion of the faults which Gussow (1953) considered to be thrusts.

There is also a third episode of folding and faulting after deposition of the Boss Point Formation in Westphalian B time (Poll, 1970 p. 49). Open northeast-trending folds are observed in the Upper Carboniferous sediments which Gussow (1953) attributes to salt migration in the subsurface. The seismic analysis of Chapters 5 and 6 substantiates this but the possibility of late or post-Carboniferous folding being associated with the faulting is likely. Late (post Boss Point) movement is suggested for all three major fault zones (Poll, 1970) and has recently been cited for the Indian Mountain Fault (St. Peter, 1992) and the Clover Hill Fault (Roberts and Williams, 1993).

2.4.4 Summary

There are two main periods of Carboniferous deformation evident in the Moncton Subbasin. The first followed deposition of the Horton Group, causing folding and faulting of the Memramcook, Albert and Weldon Formations and is therefore late Tournaisian or early Visean in age. The second major period of deformation occurred during Hopewell Group deposition before deposition of the Enragé Formation and is therefore Late Visean to Namurian in age. Gussow (1953) believed that most thrusting on the master fault systems occurred during the Namurian episode but Webb (1963, 1969) contends that most deformation was due to the dextral strike slip motion during the Moncton (Tournaisian?) event with possibly minor thrusting in the Namurian. An episode of late- or post-Carboniferous brittle faulting and minor folding is superimposed on earlier events and is reflected in the today's erosional outcrop pattern.

Triassic rocks lie in the hanging wall of the Harvey-Hopewell Fault on the Bay of Fundy coast reminding us that the possibility of Mesozoic structures associated with the opening of the Atlantic being superimposed on Carboniferous ones should not be ignored.

3.0 Basement Terranes beneath the Moncton Subbasin: A Structural Framework for Carboniferous Sedimentation

3.1 Introduction

A first step in understanding the processes of basin evolution is to understand the physiographic and geologic setting in which the sediments accumulated. Basement topography localizes sediment deposition, determines the spatial distribution of lithofacies, and where preexisting faults are reactivated, basement structural elements partially control the subsidence, sedimentation and subsequent patterns of deformation.

Sediment thickness maps of Eastern Canada have been published by the Geological Survey of Canada (Howie and Barss, 1974; GSC, 1977). Figure 3-1, based on the most recent of these, shows depth (referenced to sea level) to basement in the study area. This map was compiled primarily from sparse borehole data augmented by potential field data. One goal of this thesis is to improve upon this map where recent geophysical data permit. Figure 3-1 provides a useful reference point to begin this discussion, since the Moncton Subbasin and its neighbours the Cumberland Subbasin and New Brunswick Platform are clearly shown along with the intervening basement "Uplifts".

In this chapter I will attempt to define the present disposition of basement units beneath the Late-Devonian/Carboniferous basin. The shape of the basin, location of its Horton Group depocentres and the relationship of these to the main fault zones will be estimated using geophysical data. In the section which follows the basement units exposed in the areas surrounding the Moncton Subbasin are discussed with a view to anticipating their geophysical signature. Then in section 3.3 borehole constraints on the interpretation are summarized. Magnetic, gravity and seismic data are introduced in section 3.4 and the processing of these data is discussed. In section 3.5 the data are analyzed, geophysical trends are identified and the geophysical response related as far as possible to observed geological structure. Finally in section 3.5 the logical implications of the data sets, considered together, are explored. Maps of buried basement terranes and the distribution of thickest Late Palaeozoic sediments are presented.

3.2 Background: Basement Rocks of the Surrounding Area and their Physical Properties

3.2.1 Introduction

Early Palaeozoic and older rocks of the Avalon Zone (Williams, 1979) or Avalon Composite Terrane (Keppie, 1985) underlie the Moncton Subbasin and adjacent areas of southern New Brunswick. According to the definitions of both authors only Precambrian rocks sealed by a Cambrian cover sequence bearing a distinctive Acado-Baltic fauna can be considered

"Avalon" and the Avalon Composite Terrane is believed to have been assembled by Early Palaeozoic time (Keppie, 1985).

Despite being well exposed in the area around Saint John, immediately southeast of the study area, the structural complexity and uncertain stratigraphic relationships among Avalon units have allowed much dissension among geologists. Not all are agreed on either its time of assembly, the extent of rocks which should be called "Avalon", or the location of their western boundary, which is obscured by sedimentary cover (Williams, 1979; Keppie, 1985; Fyffe et al., 1991; Brown and Helmstaedt, 1970; Haworth and LeFort, 1979).

A recent revision of Avalon stratigraphy (Barr and White, 1989, 1991a; Barr et al., 1990; White and Barr, 1991) is adopted in the following discussion. Although not yet universally accepted, the reclassification of the southern Avalon Composite Terrane into separate terranes, based on fieldwork which was motivated by recent results in geochemistry and radiometric dating in the region, provides a useful framework for basement rock classification for the purposes of this study.

Rocks traditionally called Avalon can be subdivided into four belts (Barr and White, 1991a). From east to west these are the Caledonia terrane, the Brookville Terrane, the Kingston Belt and the Ragged Falls-Long Reach Belt, also known as the New River Belt (Johnson and McLeod, 1994), (Figure 3-

2). Several lower and middle Palaeozoic sedimentary units lie on, or in faulted contact with, the Avalon rocks. The oldest is the Saint John Group, a Cambrian-Ordovician sedimentary succession with a distinctive non-North American fauna. The other sedimentary units include the Cookson and Annidale groups (St. Croix Terrane of Fyffe and Fricker, 1987), which lie to the west in faulted contact with the other avalon units, and two younger Palaeozoic sedimentary units, the Mascarene and Fredericton cover sequences, which overlie the Precambrian terranes locally. Since any of the above units could locally underlie the Carboniferous sediments of the Moncton Subbasin, each is discussed briefly in the following section with a view to understanding its relative stratigraphic position and anticipated geophysical signature.

3.2.2 Caledonia Terrane

The Caledonia Terrane (Figure 3-2) makes up the Caledonia massif and is described in detail by Barr and White (1988, 1989, 1991a, 1991b). It is mainly composed of metavolcanic and metasedimentary rocks of the Caledonia Highlands previously correlated with the Coldbrook Group of the Saint John area (Ruitenberg et al., 1979) and associated plutonic rocks. It is overlain by Cambrian sediments of the St. John Group which contain an Acado-Baltic fauna. Based on field mapping, U-Pb (zircon) dating and geochemical studies, Barr and White (1988) have divided the volcanic and sedimentary rocks into two distinct sequences. The older package (Broad River Group of McLeod et al., 1994; sequence "A" of Barr and White, 1988), dominates the eastern half of the Caledonia Massif (Figure 3-2). This unit is late Precambrian (Hadrynian) in age and contains intermediate to felsic tuffaceous volcanic rocks, flows and volcanogenic sediments. The tuffs yield dates of 600 to 630 Ma, and their chemistry suggests they were deposited in a volcanic arc on continental crust as a result of an Andean-type subduction event (Barr and White, 1991a). These rocks are complexly faulted and folded and metamorphosed to greenschist facies.

A younger sequence (Coldbrook Group of McLeod et al., 1994; sequence "B" of Barr and White, 1988) interpreted to overlie sequence "A" unconformably, is less deformed and metamorphosed. Sequence "B" is Precambrian to Early Cambrian in age and consists of a lower unit of intermediate to felsic volcanics with minor tuffaceous rocks and a basal package of metasediments. This lower unit is ca. 548 Ma or older based on U-Pb (zircon) dates from a rhyolite flow (Bevier, 1988) and was deposited subaereally in a volcanic arc, perhaps due to an extensional event in an intra-arc setting (Barr and White, 1988). The sediments are fluvio-lacustrine in origin and siltstones are interlaminated with volcanic flows that may have been deposited in an inter-volcanic lake. The upper unit of the Coldbrook Group is dominated by basalt and rhyolite flows interfingered with and overlain by a redbed sequence, the upper conglomeratic unit of which has been previously assigned to the basal Saint John Group (Barr and White, 1991a; Tanoli and Pickerel, 1990). There is no significant time break between deposition of the upper and lower units of the Coldbrook Group. Both are 560 - 550 Ma in age.

Plutonic rocks in the Caledonia terrane fall into three main categories, which are mapped separately in Figure 3-2a:

1. Bimodal granite and diorite/gabbro intrusions with ages ca. 550 Ma; and
2. Granodioritic plutons with ages ca. 615-625 Ma.; and
3. Gabbroic intrusions, with ages ca. 550 Ma; the most distinct geophysically.

3.2.3 Brookville Terrane

The Brookville Terrane (Figure 3-2) (Barr and White, 1991a) comprises the Brookville Gneiss (Currie et al., 1981) Green Head Group (Hayes and Howell, 1937) and associated plutonic units previously assigned to the Golden Grove intrusive suite (Wardle, 1978). Until recently, it was believed the Brookville Gneiss was stratigraphically overlain by the marbles and other metasedimentary rocks of the Green Head Group, and that together they represented basement to the volcanic and sedimentary rocks of the Caledonia massif (e.g.

Keppie, 1985; Nance, 1986). But recent U-Pb dating work shows that this cannot be so because at 605 Ma (Bevier et al. 1990; Dallmeyer et al. 1990) the igneous protolith for the orthogneiss in the Brookville "basement" is significantly younger than the 1000 Ma (Hofmann, 1974) Green Head "cover".

The Brookville terrane is in faulted contact with the Kingston Belt to the north and the Caledonia terrane to the south and has been intruded by undeformed plutonic rocks ranging in composition from granitic to gabbroic. Some of the less deformed Brookville plutons yield U-Pb (zircon) ages of ca. 540 Ma (White et al., 1990b; Bevier et al., 1991) that are similar in age to the younger bimodal plutons in the Coldbrook Group of the Caledonia terrane, but Brookville terrane plutons are distinct compositionally (Dallmeyer and Nance, 1990). Gabbro and quartz diorite plutons are represented in the map area of Figure 3-2.

The Saint John Group, which locally overlies the Caledonia terrane, is in faulted contact with the Brookville terrane so the Brookville cannot be unequivocally classified as Avalon following the definition of Keppie (1985).

3.2.4 Kingston Belt/Ragged Falls - Long Reach Belt

The Kingston Belt (Fyffe et al., 1991) lies north of the Brookville terrane and is bounded by the southern extension of the Kennebecasis Fault and in part straddles the Belleisle

Fault. Its distinctive feature is a bimodal sheeted dyke swarm (Kingston complex of Currie, 1984) with associated plutonic units. The dyke swarm is 3 to 6 km wide with an outcrop strike length of more than 100 km. The metamorphic grade decreases from southwest to northeast (Eby and Curry, 1993; Nance and Dallmeyer, 1993) and the trend of individual dykes in the swarm changes from northerly to northeasterly. Shear zones bound the Kingston complex and deformation has been in part contemporaneous with dyke emplacement (Ruitenberg and McCutcheon, 1982). Rast and Dickson (1982) believed the swarm was late Precambrian in age and marked the opening of Iapetus with some component of transtensional shearing, but more recently the dykes have been dated as Silurian (Doig et al., 1990).

Volcanic and metasedimentary rocks outcropping on the Kingston Peninsula adjacent to the dyke swarm were once correlated with the Coldbrook Group (e.g. Fyffe et al. 1991) but are mapped separately by McLeod et al. (1994) as the (possibly Silurian) Bayswater Volcanics (Figure 3-2).

Volcanic and metasedimentary rocks north of the Kingston complex are generally more mafic and are shown as the Ragged Falls - Long Reach Belt (R.F.- L.R. of Figure 3-2) consisting of late Precambrian igneous units overlain by Cambrian sedimentary and volcanic rocks bearing an Acado-Baltic Fauna (see Brown's Flat Beds below) and Middle to Late Ordovician volcano-sedimentary rocks bearing a North American fauna (Johnson and McLeod, 1994).

3.2.5 Saint John Group

The Saint John Group is the Cambro-Ordovician sedimentary cover bearing the distinctive Atlantic realm fauna that defines the Avalon Composite terrane. As shown in Figure 3-2, the St. John Group outcrops in isolated fault blocks in the Caledonia terrane near the southwest corner of Figure 3-2 and sediments of similar age outcrop along the North side of Belleisle Bay. It has been described and subdivided into formations by Tanoli and Pickerel (1990), and consists of a succession of clastic sediments which range from red and grey terrestrial deposits at the base to black carbonaceous shales at the top recording a transgression of the sea and deposition in the progressively deepening waters of the Iapetus ocean.

Even though St. John Group equivalent rocks are found as far west as the Belleisle Fault, they occur in faulted contact with the Kingston Complex, St. Croix and Brookville terranes making it difficult to prove a genetic link with any terrane other than Caledonia. Rocks previously assigned to the St. John Group, but lying outside the Caledonia terrane, have been informally named the Brown's Flat Beds (Johnson and McLeod, 1994).

A schematic chronostratigraphic chart summarizing the time and space relationships among the St. John Group and other pre-Carboniferous cover sequences discussed below is presented in Figure 3-3.

3.2.6 St. Croix Terrane

There is some dispute as to whether rocks north of the Belleisle Fault belong to the Avalon zone or not. Fyffe et al. (1991) attribute rocks of the Cookson Group south of the study area, and the Annidale Group (units O_s, O_{vs} in Figure 3-2) at the western edge of the study area to the St. Croix terrane, an Ordovician tectonostratigraphic package that can be traced along the western margin of the Avalon terrane from Maine to Northumberland Strait. The St. Croix terrane is subdivided into two belts, the Annidale belt which outcrops in the southwestern edge of the map area in Figure 3-2, and the Rolling Dam Belt further west (Fyffe et al., 1991). The Annidale belt (Annidale Group of McLeod et al., 1992), dated as Early Ordovician, is an intensely sheared and faulted volcanic-sedimentary sequence. The succession is steeply dipping and consists of thick beds of mafic flows, pillow lavas, breccias and tuffaceous rocks locally interlayered with thin- to medium-bedded siltstone and sandstone. Some felsic volcanics are also present, as is minor carbonaceous slate. Farther south along strike, the Rolling Dam Belt consists of

Lower to Middle Ordovician sediments with minor volcan cs. Recent developments in field mapping and palaeontology of the Cookson Group have inverted its previously presumed stratigraphy (Fyffe and Riva, 1990).

It has been suggested that the St. Croix terrane represents an Ordovician sedimentary apron derived from the Avalon terrane, a model supported by Ludman (1986,87), Bevier (1987) and Thomas and Willis (1989) but the Avalon-St. Croix boundary is tectonic and the genetic link has been challenged on stratigraphic grounds and by the Nd-Sm isotope work (Fyffe, et al. 1991). McLeod et al. (1992) believe Annidale Group volcanics formed near the southeastern margin of Iapetus.

3.2.7 Fredericton Cover Sequence

Rocks of the Fredericton cover sequence outcrop immediately west of the map area of Figure 3-2 and thus may underlie Carboniferous sediments in the study area. The unit consists mainly of Late Silurian turbidites which McKerrow and Ziegler (1971) believed marked the site of a former Silurian ocean. Devonian and Lower Carboniferous felsic intrusions occur along the southern margin of the Fredericton belt (Ruitenberg et al., 1977) and four phases of deformation are evident in the sediments. The Fredericton-Norumbega Fault bisects the Fredericton belt and is believed by some to represent the western boundary of the Avalon zone in New

Brunswick (Keppie, 1985).

3.2.8 Mascarene Cover Sequence

The youngest of the units which locally constitute basement to the Moncton Subbasin sediments is the Mascarene Cover sequence (Fyffe and Fricker, 1987) or Coastal Volcanic belt of Maine (Ludman, 1991). The Mascarene obscures the Avalon-St. Croix boundary and can be divided into five distinct fault-bounded belts (McLeod et al., 1990), one of which, the Nerepis belt, extends into the southwestern corner of the map area (Figure 3-2) outcropping along the north side of the Belleisle Fault.

The Nerepis belt consists of fault slivers of grey to green sandstone, siltstone, slate and minor conglomerate successions characterized by a distinctive quartzose sandstone. Only this sedimentary succession is shown in the map of Figure 3-2, but farther west, off the map edge, a conformable succession of volcanic rocks, including mafic flows, breccias and tuffaceous rocks, conformably underlies felsic flows and clastic sediments like those exposed in the map area. The volcanic rocks of the Nerepis belt are bimodal subalkaline rhyolites and tholeitic basalts (McCutcheon and Ruitenberg, 1987). Geochemical signatures of the felsic rocks of the upper formation suggest they formed in a rifting environment.

3.2.9 Late Devonian and Carboniferous Igneous Activity

Both intrusive and extrusive igneous rocks once believed to be Carboniferous, but now considered mostly Late Devonian (McLeod et al., 1994) are present in southern New Brunswick. It is possible that the correlatives of these rocks occur in the subsurface of the Moncton Subbasin and it is therefore important to anticipate their geophysical signature.

Two of these units, named the Fairfield Volcanics by McLeod et al. (1994), are represented in the map area of Figure 3-2. The Fairfield volcanics which are Late Devonian in age, and are hence Memramcook Formation equivalents (ca. 367 Ma; McLeod et al., 1994), outcrop 5 and 15 km west of St. Martins in the southwestern corner of Figure 3-2(A). Rhyolite flows and tuffs outcrop there with minor red siltstone (Barr and White, 1991a). Three other units outcropping near the study area are: volcanic rocks of the Piskahegan Group, and Perry Formation, and intrusive rocks of the St. George Batholith.

The Perry Formation is a conglomeratic alluvial sequence localized in two separate basins in the Mascarene belt near the Canada - U.S. border and outcropping in both New Brunswick and Maine. Two distinct basalt members have been mapped in the alluvial sequence, and total formation thickness locally exceeds 1100 m. Plant fossils indicate a Late Devonian age.

Thus the Perry Formation is time equivalent to the Memramcook Formation.

The Piskahegan Group, which consists of felsic and mafic volcanics with interbedded redbeds, is exposed in the Mt. Pleasant area along the northern edge of the St. Croix terrane and in isolated outcrop and in boreholes of the New Brunswick Platform. The volcanics were thought to be Viséan (Williams et al., 1985) since they are overlain by the Windsor Group, but are now believed to be Late Devonian (L. Fyffe, pers. comm.).

The St. George batholith, which outcrops over an area of some 1200 km^2, intrudes the Kingston, Mascarene and St. Croix belts southwest of the map area. The batholith has yielded dates ranging from Early Silurian (Utopia Granite; 430 Ma) to Late Devonian (Mount Douglas granite; 367 Ma) (McLeod et al., 1994). The geophysical signature of the St. George Batholith has recently been discussed by Thomas and Willis (1989).

3.2.10 Rock Properties

In order to constrain any interpretation of the gravity data it is necessary to obtain representative densities of the rock units in the area. Density values for rock samples collected in the Caledonia massif (Gupta and Burke, 1977) and in Avalon zone rocks southwest of the subbasin (Thomas and Willis, 1989) have been published and are presented in Table

3-2.

Magnetic susceptibility measurements have also been published for the Caledonia Highlands area (Gupta and Burke, 1977) and the area south and west of the Moncton Subbasin (McGrath, 1970). These data were collected using *in situ* susceptibility meters and have been classed by lithology.

The values in Table 3-2 show the expected relationship, that basic rocks are generally magnetic, and felsic and sedimentary rocks are less so. But both McGrath (1970) and Gupta and Burke (1977) report a wide range of susceptibility values for all basement rock types sampled. While published average susceptibility values are not available for the other basement terranes McGrath (1970) notes that all rock types sampled in the area showed wide ranges of susceptibility values. Most interestingly some of the younger granites i.e. parts of the Pokiak Batholith west of Fredericton, and parts of the St. George Batholith south of the study area (Late Devonian) are highly magnetic, showing k values of up to 2675. McGrath attributes this to an adamellite (monzo-granite) intrusion, an alkali-feldspar-rich granitic rock which locally contains a high proportion of magnetite.

Table 3-1
Summary of Published Rock Densities southern N.B.

MAP UNIT (LITHOLOGY) (Fig. 3-2)		NUMBER OF SAMPLES	DENSITY RANGE (g/cm^3)	DENSITY MEAN±S.D. (g/cm^3)	SOURCE
CALEDONIA TERRANE					
Pre-Cambrian:					
	Silicic Flows	40	2.61-2.76	2.67±0.05	(KBS77)
	Mafic flows	57	2.70-2.92	2.80±0.07	(KBS77)
ε	Sediments	59	2.54-2.70	2.61±0.04	(KBS77)
DC	Sediments (Dev.-Early Carb.)	91	2.59-2.80	2.70±0.04	(KBS77)
C	Sediments (Late Carb.)	40	2.53-2.67	2.64±0.03	(KBS77)
T_R	Sediments	18	2.42-2.58	2.49±0.04	(KBS77)
Intrusives:					
	Granite	39	2.59-2.77	2.64±0.04	(KBS77)
	Granodiorite	15	2.70-2.79	2.77±0.02	(KBS77)
Mafic Intrusives:					
	Gabbro	19	2.83-3.02	2.94±0.05	(KBS77)
BROOKVILLE TERRANE					
H_{GH}	Dolomite	48	2.78-2.86	2.83±0.02	(KBS77)
	Intrusives(mainly silicic, some intermediate)	10	2.62-2.79	2.69±0.06	(TW89)
KINGSTON BELT					
S_K	(granites(9),mafic intrusives(2),and (1) intermed. volc.	11	2.57-3.05	2.69±0.15	(TW89)
MASCARENE COVER SEQUENCE					
S	(Mixed volcanics (6), gabbros(3) and sediments(3)	12	2.62-2.98	2.82±0.10	(TW89)
ST. CROIX TERRANE					
O_{VS}	(sediments and volcanics)	31	2.67-3.04	2.77±0.06	(TW89)
FREDERICTON COVER SEQUENCE					
	(Mainly sediments, few volcanics)	28	2.59-2.95	2.70±0.09	(TW89)
INTRUSIVES					
	(Late Devonian granite-St. George Batholith)	114	2.57-2.74	2.60±0.03	(TW89)
OTHER					
	(Late Devonian Mount Pleasant volcanics)	41	2.47-2.76	2.59±0.07	(TW89)

Data sources: KBS77 = Gupta and Burke (1977)
TW88 = Thomas and Willis (1989)

Table 3-2
Summary of published rock magnetic properties

(Source: Gupta and Burke, 1977)

ROCK TYPE	NO. SITES	NO. READINGS	k-RANGE (cgs units)	k-AVG. (cgs units)
CALEDONIA TERRANE				
Granite	6	62	10-180	51
Diorite	3	30	2005-5122	3758
Gabbro	5	70	2360-5731	4082
Gneiss	3	28	12-317	64
Chlorite schist	2	24	17-80	52
Chlorite schist	2	20	16-2388	1245
Rhyolite	6	74	16-77	33
Diabase	2	19	44-50	46
Andesite	3	25	422-1267	884
Basalt	3	29	612-4138	2020
Carboniferous sandstone	2	20	13-28	20

3.3 Borehole Data

Figure 3-2 shows 26 boreholes which intersect pre-Carboniferous basement in the area bordering the Moncton Subbasin and drilling results are tabulated in Table 3-1. Boreholes 8 to 16 in the area between Moncton and Port Elgin, along with the basement outcrop at Calhoun, indicate the Westmoreland uplift (Gussow, 1953) a granitic basement high which is usually considered the northern boundary of the Moncton Subbasin. Rocks encountered in these holes are probably Brookville terrane intrusives. It is notable that holes 8 to 11, drilled on a magnetic anomaly 10 km south of

Moncton, intersected a gabbro body. Cambrian (ca. 550 Ma) gabbros are found in the Caledonia Terrane (Figure 3-2) but no Brookville terrane gabbros have yet been dated. Several holes west of the Belleisle Fault (e.g. nos. 1,4,5,6,20,21,23,24) intersect St. Croix terrane rocks. Boreholes at Coal Branch (nos. 2 and 3) intersect a granitic pluton which is probably Devonian or Early Carboniferous in age since it is relatively undeformed and unmetamorphosed (St. Peter and Fyffe, 1990). Greenhead marble of the Brookville terrane was intersected at depth in a well at Middlesex (no. 18) and is also found in a small inlier along the western margin of the Caledonia terrane near Elgin. The Irving/Chevron Smithtown hole (no. 26) was spudded in a Brookville terrane pluton and penetrated a thick (Upper Carboniferous) Hopewell Group section, confirming that the southeastern margin of the Brookville terrane is thrust over Carboniferous sediments along the Clover Hill Fault.

Table 3-3 Boreholes intersecting basement, Moncton Subbasin and surrounding area

REFERENCE MAP[1]	CAT[2]	COMPANY	WELL NAME	TOTAL DEPTH (m)	BASEMENT LITHOLOGY	PROSPECT TYPE
1	473	D'Arcy	Buctouche 1	742.4	Graphitic Slate (St. Croix)	Oil and gas
2	472	D'Arcy	Coal Branch 1	757.6	Fresh granite (Dev-Carb?)	Oil and gas
3	471	Maritime Oilfields	Canaan Station 30	375.0	" "	Oil and gas
4	439	Province of N.B.	239	44.2	Phyllite (St. Croix)	Coal
5	438	Province of N.B.	222	122.3	Phyllite (St. Croix)	Coal
6	437	Province of N.B.	221	116.2	Slate and phyllite(St. Croix)	Coal
7	435	Province of N.B.	220	66.2	Granodiorite	Coal
8	423	Killarney Oil and Gas	T-4	182.9	Gabbro at 118 m	Titanium
9	422	Killarney Oil and Gas	T-3	160.1	Gabbro and pegmatite	Titanium
10	421	Killarney Oil and Gas	T-2	310.4	Mainly gabbro (120.4 m)	Titanium
11	420	Killarney Oil and Gas	T-1	304.9	Mainly Gabbro (120 m)	Titanium
12	407	N.B.G.O.	Lower Coverdale 92	231.1	Granite and schist	Oil and gas
13	406	N.B.G.O.	Mud Creek 52	873.5	Granite and schist	Oil and gas
14	402	Imperial/N.B.G.O.	Port Elgin 1	927.1	Granite	Oil and gas
15	401	Shell/N.B.O.	Westmoreland 1	314.0	Granite	Oil and gas
16	399	D'Arcy	Cape Bald 2	767.1	Granite at 392 m	Oil and gas
17	398	D'Arcy	Cape Bald 1	350.6	Granite at 295 m	Oil and gas
18	146	Irving/Chevron	Middlesex 1	1835.0	Marble (Brookville)	Oil and gas
19	109	Province of N.B.	238	72.0	Slate	Coal
20	106	Province of N.B.	279	113.1	Phyllite	Coal
21	105	Province of N.B.	278	115.8	Slate and intermed. volc.	Coal
22	103	Province of N.B.	261	122.3	Qtz. and diorite	Coal
23	102	Province of N.B.	260	177.7	Phyllite and slate	Coal
24	101	Province of N.B.	240	122.3	Phyllite and slate	Coal
25	53	Province of N.B.	292	122.0	Qtz.-mica schist	Coal
26	37	Irving/Chevron	Smithtown 1	949.0	Granite (over Hopewell)	Oil and Gas

notes:

[1] Borehole reference number, Figure 3-2

[2] Borehole reference number, St. Peter, 1987b

3.4 Geophysical Data

3.4.1 Introduction

The first potential field measurements in the Moncton Subbasin area were undertaken by the Dominion Observatory (Miller, 1940; 1946). Based on Miller's work, and to supplement the sparse coverage of Shell's seismic data, Gussow (1953) recognized the need to supplement Shell's regional seismic lines in the subbasin with gravity data to delineate basement uplifts and prospective salt structures beneath the Upper Carboniferous cover. Two parts of the basin were surveyed and maps presented (Gussow, 1953, figures 13 and 14) covering the area from Turtle Creek north to the Northumberland Strait and east to the Nova Scotia border and the area of the Anagance Axis (Plate 2-1) from Sussex to Petitcodiac. Gussow interpreted a gravity high in the Moncton - Shediac area to be the geophysical expression of the Westmoreland uplift and lows at Dorchester and Gautreau Village (Plate 2-1) as salt structures. The elongate low along the Anagance structure he interpreted as a salt feature, perhaps localized by a linear fault zone. The first regional gravity survey was published in 1953 (Garland, 1953) and has formed a basis for GSC maps in the Maritimes.

The gravity field of the western Caledonia Highlands has been discussed by Burke (1976) based on data collected by the University of New Brunswick. He reported that Bouguer gravity highs and lows were well correlated with mafic and felsic units, respectively, as mapped by Ruitenberg et al. (1979). Gravity data proved useful in determining the location of faults and delineating the extents of basic intrusions in the Caledonia terrane. Additional gravity surveys have been carried out since then by government and industry, spurred largely by the potential for commercial potash deposits associated with Carboniferous salt structures. Such data have been compiled and standardized by the New Brunswick Department of Natural Resources (Chandra et al., 1982). These data, of which 1063 data points fall in the map area of Figure 3-2, are analyzed in the following section.

Aeromagnetic data were collected by the Geological Survey of Canada covering the Moncton Subbasin and New Brunswick Platform (GSC, 1960). These consisted of total field measurements made with a fluxgate magnetometer. Flight line spacing for the survey was 0.8 km for north-south lines and 13.0 km for east-west cross lines. All lines were flown at 0.305 km altitude. These data were obtained (GSC, 1990) in gridded digital format for analysis in the following section.

The first attempt at a quantitative interpretation of these data was that of Bhattacharyya and Raychaudhuri (1967) who used a 3.2 km grid to digitize published maps of a region, encompassing all of eastern New Brunswick, northern Nova Scotia, Prince Edward Island and the adjacent Gulf of St.

Lawrence. Using a variety of computer processing techniques they were able to separate out anomalies having spatial wavelengths greater than 8, 16 and 25 km. They calculated a second vertical derivative map, and employed a least squares method to determine the intensity and direction of polarization. They also estimated depth to the top and base of the causative magnetic bodies. The result of this study was the distinction of a series of northeast-southwest trending lineaments defining the extent of fault-bounded "magnetic units" in the basement beneath the Carboniferous cover and under the Gulf. The wide sample spacing (3.2 km) of that study did not adequately define many anomalies in the original maps, which were based upon data collected on a much finer line spacing. As a result, a consultant was contracted by the New Brunswick Department of Natural Resources to reanalyse the magnetic data (Spector, 1979). In that study, depths to magnetic bodies were calculated, using a prism method, from the widths of anomalies on the original aeromagnetic chart recordings. The depths to magnetic basement were plotted and contoured for an area that includes most of the Moncton Subbasin (Figure 3-4). Note that there is a marked difference between the depth to basement maps of Figures 3-1 and 3-4. Figure 3-1 is contoured in kilometres while Figure 3-4 is contoured in kilofeet. Both are referenced to sea level and take borehole and potential field data into account, but no account of the methodology accompanies the GSC map (GSC, 1977). In general the magnetic basement map (Figure 3-4) portrays a more complex and shallow structure in the central subbasin than Figure 3-1, suggesting that there may be magnetic material in the basin fill. More importantly the difference between Figures 3-1 and 3-4 underlines a first order problem: the geometry of the Moncton subbasin is unknown. Spector (1979) plotted the dips of prisms whose characteristic curves best fit the anomalies and interpreted faults. They also inferred basement lithologies based on observed magnetic field strength. Good correlation was found to exist between the "magnetic" faults and mapped faults along the margins of the Moncton Subbasin: notably, the Belleisle, Ward Creek, Clover Hill, Smith Creek, and Berry Mills faults (Spector, 1979).

3.4.2 Aeromagnetic Data

The aeromagnetic data used here were obtained in gridded format (GSC, 1990) and analyzed using the GEOSOFT software package. First the data were regridded at 812 m grid spacing and displayed as a colour total field map. A smoothed contour map was generated at a scale of 1:250,000 (Plate 3-1, in Map pocket). To investigate trends in the data, a residual anomaly map (Figure 3-5) was generated by filtering the map in the Fourier domain to remove long wavelength variations in the field, and calculating the residual field's first and second vertical derivative (Figures 3-6 and 3-7). Derivative filters tend to enhance shallow features and sharpen the edges of anomalies (Telford et al., 1990). Features such as faults which juxtapose units of differing thickness or magnetic properties are accentuated as linear map features since the second derivative is maximum at the peaks and troughs of magnetic anomalies. Zero-crossings of the second derivative are the points of inflection on the anomaly flanks. Large amplitudes on the second vertical derivative are generally associated with shallow anomalies.

3.4.3 Gravity Data

To determine the relationship between the gravity field and the basement geology, a long wavelength regional trend was removed from the data. All processing was done using the GEOSOFT software package and consisted of the following steps:

1. Select and edit for unreasonable values all Bouguer gravity data from the Chandra et al. (1982) data set between latitudes 45° 15'N and 46° 30'N, and longitudes 64°00' W and 66°00' W.

2. Interpolate the Bouguer gravity values to an 812 m square grid. This produced a grid of size 192x173.

3. Fit a least squares plane to the edge points of the grid and subtract this from the data. This is necessary to

ensure the Fourier transform is not dominated by low frequencies.

4. Pad the two dimensional data set with zeros to make it square, in this case 252x252 grid points.

5. Fill holes in the grid by linear interpolation to ensure there are no discontinuities in the data being Fourier transformed.

6. Perform a two-dimensional Fast Fourier Transform on the data.

7. Apply a half-Gaussian bell-shaped low-pass filter to the Fourier domain data which passes almost all signal above a certain spatial wavelength given by the standard deviation of the Gaussian function. A cutoff wavelength of 200 km was chosen after some experimentation as discussed below.

8. The data passed by this filter is the regional field data, that rejected is the residual field.

9. Perform an inverse Fourier Transform on the residual field data.

10. Correct the data for the planar trend removed in step 3 above.

11. Mask the residual gravity data with the original data. This step trims the residual data to the dimensions of the original data and discards any data that have been interpolated in areas where there were gaps in the original data.

The selection of a cutoff criterion for spatial wavelengths which are considered "regional" was determined subjectively by examining the regional field maps generated for a range of cutoff values. Since long wavelength anomalies can either come from deep point sources or shallow broad sources, such as, for example, a sedimentary basin filled with material less dense than the surrounding basement, a long wavelength filter can remove desired gravity effects of important broad shallow features observed in the seismic data. Whereas the largest shallow feature observed in the seismic data is the post-Windsor basin about 20 km across, and because it is a primary goal to investigate basement, it is crucial to retain anomalies of spatial wavelength on the order of 40 km. This ensures that no information on basin shape is lost and preserves the contribution of changes in basement lithology to the potential fields. Tests showed that spacial wavelength filters with low cutoffs of 50, 100 and 150 km all removed significant amounts of the 40 km wavelength signal, which is in this case at least partially due to near surface long wavelength geological effects. A conservative 200 km wavelength filter was therefore chosen. The resulting residual field is shown in Figure 3-8, the residual Bouguer anomaly map. First (Figure 3-9) and second (Figure 3-10) vertical derivative maps were also prepared from the residual Bouguer anomaly data. Note that the mottled appearance of the second derivative maps (Figures 3-10,3-7) is an artifact of the processing which reflects the relatively coarse grid spacing of the sampled data. Significance is given to trends in the second-derivative map rather than individual point values. A contour map of the Bouguer anomaly showing the gravity station locations was prepared at a scale of 1:250,000 (Plate 3-2).

3.4.4 Seismic Data

Detailed analysis of a subset of the Chevron/Irving seismic data shown in Figure 1-3 will be the subject of Chapters 4 and 5 of this thesis. But two results, resulting from an initial, cursory analysis of the entire Chevron/Irving data set, bear upon the objectives of this chapter and therefore will be presented here with the potential field data.

Plate 3-3(a) is an example of a seismic reflection profile from the Chevron/Irving data set. Two observations are readily made. First, in the upper 1 second or so there is a relatively undeformed, layered sedimentary succession, the Late Palaeozoic sediments. Second, at depth beneath the sedimentary basin, in the lower left-hand quadrant of the Plate, there is a thick zone of high amplitude seismic response. One cannot determine from one processed record whether that response is reflected energy from a basement rock unit, reverberatory noise, or an artifact of the coherency enhancement and migration processing the data has undergone. If it is of geologic origin, it should correlate from line to line in a geologically reasonable map pattern.

Density and seismic velocities of the lower Horton Group rocks are comparable to those of the pre-Carboniferous basement from which they are derived and little or no seismic energy is reflected from the sediment-basement interface, a fact that will be shown in chapter 5. Despite the generally poor reflectivity contrast between Horton and basement rocks, many of the seismic lines in the subbasin exhibit the same high amplitude sequence of reflections within the basement, itself underlying a wedge of virtually reflection-free material. These I will refer to informally as the "Reflective basement facies" and "Transparent basement facies" respectively. Plate 3-3(b) shows an interpreted example of the "Reflective basement facies". In this case the top of the "Transparent basement facies" rocks has been traced seismically from the nearby Middlesex well (Borehole #18, Figure 3-2). The criteria used for distinguishing between Horton Group and transparent basement is discussed in detail in Chapter 5.

As a first stage of the seismic analysis all lines in the Irving/Chevron data set were inspected to determine:

a) whether the top of reflective basement could be identified and correlated from line-to line; and

b) whether relatively undeformed Horton Group sediments are imaged in the data. Such sediments are recognized in the seismic data by the presence of a layered succession beneath the basal Windsor/Hillsborough unconformity. Horton Group rocks imaged in this way are commonly tilted and may exhibit some faulting.

The results of these two exercises are presented in Figures 3-11 and 3-12. The first is a time structure map of the top of reflective basement, the second, a map showing where readily identifiable Horton Group sediments lie in the subsurface. It is important to note a point that will be made more rigorously in Chapter 4. Not all Horton Group sediments are readily identifiable in the seismic data. So Figure 3-12 represents a conservative estimate of the extent of Horton basins in the subsurface.

The fact that the structure of the reflective basement facies can be mapped over the eastern part of the map area (Figure 3-11) suggests it is indeed of geological origin and not an artifact of the seismic processing. In the following discussion I attempt to determine the significance of the reflective basement in tracing the extent and structure of basement terranes beneath the subbasin.

Contours in Figure 3-11 represent seismic 2-way time in seconds. Since the average velocity of Carboniferous sediments intersected in boreholes is 4.2 km/s (as will be discussed in chapter 4.2.3), one second on the map of Figure 3-11 represents approximately 2.1 km !· ·ch.

3.5 Analysis

3.5.1 Relationship of the Magnetic Total Field Anomalies to Mapped Surface Geology

Anomalies in the residual magnetic total field map of Figure 3-5 exhibit a general southwest-northeast trend which reflects the predominant structural trend. First and second derivative maps of the total field (Figures 3-6, 3-7) further accentuate the fault trends. In the Bay of Fundy, an arcuate belt of magnetic anomalies trends northeast-southwest and bends eastward into the dual east-trending maxima which represent the Cobequid Highlands of Nova Scotia. These are likely associated with Triassic basaltic magmatism in the Fundy rift (Ballard and Uchupi, 1975). Jansa et al. (1993) interpret similar anomalies east of Nova Scotia as Mesozoic dykes, associated with the opening of the Atlantic. A broad deepening low extends northeastward from the Bay of Fundy; this represents the accumulated sediments of the Moncton Subbasin's neighbour, the Cumberland Subbasin (Figure 3-1), and within the Bay of Fundy itself, the Triassic basin superimposed on it (Ballard and Uchupi, 1975). A broad and internally complex magnetic high (anomalies M1 to M8 of Figure 3-5) coincides with the Caledonia terrane which has been discussed in detail by Gupta (1975). Its most prominent features are, from west to east: a broad low (M1 of Figure 3-5) associated with Triassic and Carboniferous sediments and felsic tuffaceous rocks of the Coldbrook Group south and west of St. Martin's. North of that low, along the northern edge of the Caledonia Massif, broad magnetic highs (M2) are associated with the Upham Mountain and southernmost tip of the Bonnell Brook plutons which are described as a syenogranites (Barr and White, 1988) of the younger Precambrian bimodal granite suite along the northern edge of the Caledonia terrane. Both anomalies are considerably broader than the mapped surface extents of the plutons. A narrow magnetic high trending north-northeast (M3) extends from about 4 km north of Salmon River to Mechanic Settlement where it culminates in an anomaly which corresponds to the Mechanic Settlement gabbroic pluton (M4). The anomaly extends beyond the mapped extent of the pluton some 6 km under the Moncton Subbasin, apparently unaffected by the Clover Hill Fault.

The extensive Point Wolf River pluton has areas with two distinct magnetic signatures. Its southern half, in which granite dominantly outcrops, is characterized by a rhomboidal magnetic low (M5) as if bound by parallel sets of northwest- and east-trending faults. By contrast, its northern half, in which the rocks are petrologically heterogeneous but generally more mafic, is indistinguishable magnetically (M6) from the remainder of the eastern Caledonia highlands, which have a generally high magnetic anomaly that extends over the lower pre-Carboniferous metasediments and metavolcanics of the eastern Caledonia highlands. Two striking features of the northeastern end of the Caledonia massif are that the granodiorite plutons and the mapped gabbroic stock (below anomaly M7) generate a broad magnetic high as if the Kent Hills granodiorite and Caledonia Road suite were part of a continuous magnetic unit at depth. The other is that in the area east of the Harvey Hopewell Fault (Plate 2-1), the magnetic signature of the Caledonia terrane rocks dies away gradually to the northeast. Furthermore, the Harvey Hopewell Fault (M8), which seems to extend straight northeast to Dorchester from Harvey, rather than bending to the east as Webb (1963) and St. Peter (1989a) (Plate 2-1) indicate, cuts the Caledonia terrane abruptly.

Two positive anomalies (M9A,9B) near Sackville are separated by a linear trough. These anomalies do not coincide with any mapped or drilled basement feature, and they are linked to the Caledonia terrane anomaly west of the Harvey Hopewell Fault by a saddle-shaped zone of moderately high total field values stretching southwest across Shepody Bay.

The area south and east of Moncton is characterised by isolated peaks on an east-west trending saddle of moderate total field values. Two isolated peaks in the magnetic field occur south of Moncton (M10). The southernmost of these anomalies near Stoney Creek has been drilled (see borehole 8-11 in Figure 3-2) and gabbroic rocks were intersected. Both anomalies are about the same size as, and lie in a north-south linear trend with, the Caledonia Mountain stock, a gabbroic intrusion of unknown age which intrudes the granodiorite pluton about 6 km west of Albert Mines (Barr and White, 1991a). North of Moncton a magnetic low opens and deepens to the northeast into the Northumberland Strait.

The Moncton Subbasin itself is marked by two distinct magnetic lows. A northern one (L1 of Figure 3-5) centred 5 km east of Turtle Creek, which if defined by its 160 nT contour, stretches from Pollett River in the west to Memramcook in the east, and is bounded to the north and south by the Westmoreland and Caledonia "uplifts". The northern basin is linked by a narrow trough to a smaller one centred 4 km north of Goshen. The second, and most extensive, magnetic low (L2 of Figure 3-5) covers a rhomboidal area of some 400 square kilometres south of Sussex, bounded to the west by the Belleisle Fault and to the east by the Caledonia massif.

Narrow magnetic troughs corresponding to the fault-bounded wedges of Carboniferous sediments south of the Clover Hill and Kennebecasis faults bound the Brookville terrane anomaly (M11) and extend southwestward from the Sussex low. Both the intrusive rocks of the Brookville terrane north of the Clover Hill Fault (M11) and the Kingston Belt (M12) north of the Kennebecasis Fault, form long narrow northeast-trending magnetic highs bounded by steep gradients and are abruptly truncated by east-west trends at their northern tips. North of Bloomfield Station, the Clover Hill Fault has no magnetic signature.

The Kingston Uplift is marked by a trend of three elongate magnetic highs on the south side of the Belleisle Fault. In the south, the first (M12) coincides with the exposed Kingston complex and associated volcanics of the Kingston Peninsula, the second (M13) coincides roughly with the mapped extent (Plate 2-1) of the Jordan Mountain inlier but extends farther to the northeast beneath Cornhill and Intervale. The third and largest of the Kingston Uplift anomalies (M14 of Figure 3-5) lies north of Indian Mountain, midway between Shediac and Canaan Station. There are no boreholes or outcrops to indicate the nature of the source, but Spector (1979) estimate its depth at *ca.* 1000 m.

The Belleisle Fault is marked by a distinctive narrow magnetic trough extending from Belleisle Bay in a straight line northeast more than sixty kilometres to a point about 5 km west of Havelock. From there it is marked only by the gradient between the magnetic highs of the Kingston Uplift and the broad low of the New Brunswick Platform to the west. The location of the Belleisle Fault, specifically whether it continues straight to the Northumberland coast or bends to the east along the northern edge of the Shediac anomaly is a matter of recent debate (St. Peter and Fyffe, 1990; Durling and Marillier, 1990) since it has not been observed in the northern half of the map area, being generally believed to be sealed by Boss Point and younger strata poorly exposed in that area.

North of the Belleisle Fault two distinct highs are present, one (M15) marking a Silurian or Devonian intrusion in the Mascarene belt, and the other (M16), of unknown origin generating an elongate anomaly on the north side of the Belleisle Fault about 10 km north of Jordan Mountain.

3.5.2 Relationship of the Bouguer Gravity Map to Surface Geology

Like the aeromagnetic data, the gravity field is dominated by northeast striking features diverging slightly to the north, with generally higher values near the Bay of Fundy and lower ones on the New Brunswick Platform. Positive gravity anomalies are associated with the Cobequid Highlands in Nova Scotia (anomaly G1 of Figure 3-8) and the Caledonia Terrane in New Brunswick (G2 of Figure 3-8). Since the Caledonia highlands are sampled only by the 4 km data spacing of the GSC data, set it is impossible to correlate anomalies with individual units except in a general sense. The highest gravity values are found in the Mechanic Settlement (G2) area in a broad maximum which coincides with the magnetic anomaly over the gabbroic intrusion and also extends north under the Moncton Subbasin. A trough of relatively low Bouguer anomaly values (G3) bisects the Caledonia Massif along a line cutting southeast from Sussex to the Bay of Fundy coast.

The most prominent gravity low on the map is a broad trough (G4) extending north from the Bay of Fundy underlying both Shepody Bay and Cumberland Subbasin and trending northeast to Port Elgin. Its minimum value occurs in a northwest trending trough between Sackville and Amherst, and roughly coincides with the axis of deposition of the Carboniferous Cumberland Subbasin (Figure 3-1).

There is no basin-wide gravity low characterizing the Moncton Subbasin itself. A broad gravity high (G5) bounded roughly by the Pollett and Little Rivers bridges the anomalies due to the Caledonia (G2) and Westmoreland (G9) uplifts in the middle of the subbasin. Again the signature of the basin can be subdivided into three distinct parts interpreted here as Horton Group depocentres: one (G6) extending eastward from Little River to the Hillsborough area where it opens up to join the Sackville gravity low; a second low (G7) north of Goshen; and a third (G8) extending southwest from Sussex to Bloomfield Station. The Sussex and Goshen gravity lows are joined by a linear trough extending from ca. 3 km east of

Penobsquis to Sussex, a salt-cored anticline which is a prolific potash producer (Roulston and Waugh, 1983).

The Moncton area sits on a broad gravity high (G9), which broadens and becomes more intense near the Northumberland Coast just south of Shediac, and tapers to the south. The Kingston Uplift is marked by a series of poorly sampled (possibly continuous) gravity highs (G10) over the Kingston complex, another (G11) at Jordan Mountain, which although most intense at Jordan Mountain seems to connect with a string of anomalies (G11-G13) extending from Sussex to Lutes Mountain.

Well defined positive gravity anomalies possibly linked to the Shediac anomaly come onshore at Buctouche (G14) and Cocagne (G15) and trend southwest from the Northumberland coast for some 20 to 30 km. The Belleisle Fault again seems to be well defined at its southern end by the potential field data, separating a gravity high over the Mascarene and St. Croix terrane outcrops from a trough of Carboniferous sediments to the south, but its continuation to the northeast past Indian Mountain (G12) is unclear. West of the Belleisle Fault, gravity values are generally very low, despite the fact that the St. Croix terrane is near the surface in several wells in the area. Anomaly G17 roughly 30 km in diameter, situated north of the Canaan River, coincides with outcrops and borehole penetration of St. Croix metasediments near the surface. G18, near Coal Branch, may be continuous with the

Buctouche anomaly (G15) which has been drilled at Buctouche as St. Croix metasediments (St. Peter and Fyffe, 1990). Neither the Canaan River, Coal Branch nor Buctouche anomaly has a corresponding magnetic anomaly.

3.5.3 Trend Analysis

First and second derivative maps for both the gravity and aeromagnetic data were calculated from the residual data presented in the previous section. The goal of derivative processing was to highlight trends in the data, specifically fault trends. Because faults or other geologic contacts juxtapose geologic units of contrasting magnetic properties or densities, the gradient of the induced field is steepest over a vertical contact. Two criteria were used for identifying faults in the potential field data: continuity of extreme gradient zone in map view; and recognizable offset or termination of potential field anomalies.

The loci of points giving extreme values on the potential field derivative maps were traced to generate a geophysical trend map Figure 3-13.

The potential field trends identified fall into 4 sets:

1. NE-SW (40 - 55°): e.g. the southern ends of the Belleisle and Kennebecasis faults - Belleisle and Kennebecasis Bays;
2. ENE-WSW (60 - 80°): e.g. Lutes Mountain Fault along

the North River;

3. E-W (85 - 95°): e.g. the northern boundary of the Mechanic Settlement Pluton and western extension of the Gordon Falls Fault ("A" in Figure 3-13); and

4. N-S (0 - 15°): e.g. the western boundary of Point Wolf River pluton and axis of the Saint John Group sedimentary rocks "B" and "C" in Figure 3-13 respectively).

Some observations can be made from the geophysical trend map which bear on the distribution of faults and basement contacts in the subsurface.

1. NE-SW fault trends in the southern half of the map area (Figure 3-13) generally give way to ENE-WSW trends in the North.

2. E-W trending faults, inferred from the potential field data, are virtually unreported in the Carboniferous of southern New Brunswick, but they are common on the other side of the Bay of Fundy, in the Cumberland Subbasin. An example of this fault class is the Minas Geofracture, which is reported to have undergone as much as 165 km dextral movement in the late Carboniferous and another 75 km sinistral movement in the Mesozoic (Keppie, 1985).

3. If the four dominant trends are listed according to their lateral continuity, the ENE-WSW trend is the most laterally continuous and the N-S trend, the least. The N-S trend being

both the least continuous (i.e. cut by younger structures) and confined to the Caledonia basement block (i.e. sealed by Carboniferous cover) is almost certainly a pre-Carboniferous feature. If any of the lineaments represent through-going wrench faults as Webb (1963) has proposed, then the most recent fault movement may be represented by the most laterally continuous (i.e. NE-SW) trend pattern.

4. The map pattern of Kingston Uplift faults as mapped by St. Peter (1989b; Plate 2-1), which is distinct from that of Gussow (1953) or Fyffe et al. (1982), is not entirely consistent with the potential field trends.

3.5.4 Analysis of the Reflective Basement Map

The time-structure map of Figure 3-11 shows several distinct, fault bounded units existing in the subsurface. The first question one must pose is: What geologic contact are we observing at the top of "reflective basement"?

The top of reflective basement is not the base of Horton Group. It is clearly within the basement unit. The depth to reflective basement everywhere exceeds the depth to magnetic basement (Figure 3-4) estimated by Spector (1980) and, although none of the basement-intersecting boreholes falls in an area where the reflective basement is mappable, reflective basement is found at a depth of 1.7 s (3 km) not far from borehole 13 southeast of Moncton in which pre-Carboniferous basement was penetrated at a depth of less than 230 m. Martel (1987) speculated that an early Carboniferous volcanic sequence, like the Fissett Brook Formation of Cape Breton Island, may explain the strong "basal reflectors" he observed in the Sackville Subbasin northeast of Moncton. No Late Devonian or Early Carboniferous volcanic rocks are known in the Moncton Subbasin from either outcrop or borehole, although the Perry and Piskahegan formations and Fairfield Volcanics (McLeod et al., 1994) provide a regional precedent. In this section I will investigate which if any, of the observed basement units discussed in section 3.2 could reasonably be responsible for such a strong upper reflection and subparallel internal seismic layering.

The reflection coefficient, R, or fraction of a seismic wave's amplitude which is reflected at normal incidence from an abrupt geologic contact is given by

$$R = (\rho_2 v_2 - \rho_1 v_1) \;/\; (\rho_2 v_2 + \rho_1 v_1) \qquad (3.1)$$

where ρ_1 *and* ρ_2 are the rock densities above and below the interface; and v_1, v_2 are the compressional wave velocities above and below the interface respectively.

Significant changes in both velocity and density are common at lithologic boundaries in sedimentary rock due both to the variation in lithology of the matrix and, more importantly, variations in porosity, but crystalline rocks, on the other hand, have almost no porosity. Velocities in basement rock typically vary between approximately 4.0 and 5.5 km/s near the surface and increase to values 25-50% greater at a depth of 1-2 km as the microcracks dominating their elastic properties close under lithostatic pressure and reflectivity becomes dominated by density changes. But even though some geologic contacts in the basement approximate planar boundaries between two homogeneous media, it is unlikely that we will achieve a very strong first-order reflection within the basement.

Nelson (1984) notes that it is often characteristic of well indurated Precambrian sediments, metamorphic or some igneous rocks, to observe interlayering of rock types of alternating high and low densities and possibly velocities. If the seismic frequencies are "tuned" to the layering, relatively high amplitude reflections. This phenomenon has been discussed by Smithson et al. (1977) who take as an example the seismic response of an interlayered metavolcanic and metasedimentary succession. The Broad River and lower Coldbrook groups of the Caledonia terrane, and layered mafic intrusions, such as the Mechanic Settlement Pluton, have properties similar to the example discussed by Smithson et al. (1977).

The preceding line of reasoning nominates the Caledonia terrane as "reflective basement". In Figure 3-11, the contours in the area nearest the Caledonia uplift project to the surface with approximately the same structural trend as the Broad River sequence of interbedded metavolcanics and metasediments. This is another argument for a Caledonia Terrane which extends west beneath the subbasin as a source of reflectors for the reflective basement facies.

The overlying, seismically transparent unit (TBF of Plate 2-1(b) has been drilled in borehole 12. At that location TBF is granite and Barr (S.M. Barr, 1992, pers. comm.) correlates granites in the nearby Calhoun area with the Brookville terrane. Basement intersections of Green Head marble at Middlesex (borehole 19 of Figure 3-2) and isolated outcrop of the same unit at the edge of the Caledonia uplift near Elgin (C. St. Peter, 1991, pers. comm.) suggest that the central Moncton Subbasin may be underlain by Brookville terrane rocks which are non-reflective and which overlie a Caledonia metasedimentary/volcanic package which is highly reflective, along a gently northwest-dipping contact beneath the central subbasin.

3.6 Synthesis

3.6.1 General

The goal of this synthesis is to bring together the geological and geophysical results both to generate a subcrop map of basement terranes beneath the Moncton Subbasin and to characterize the basement structure on a basin scale, locating the Horton Group depocentres, fault scarps and so on.

The ambiguity of potential field data is well known. The amplitude of the anomaly increases both with decreasing sediment thickness and with increasing density and magnetic susceptibility of the basement. This fact, coupled with the general observation that density and magnetic susceptibility are correlated for igneous rocks - more mafic rocks being generally more dense and magnetic than their felsic counterparts - limit the usefulness of gravity and magnetic maps for classifying basement rocks except in combination with other data sets. Similarly, the depth to magnetic basement map of Spector (1979; Figure 3-4), based on the assumption that short wavelength anomalies are shallow and long ones are deep, has its failings. This approach provides compelling evidence of where basement is shallow - but its prediction of basement depth for deep anomalies (> 1 km say) differs dramatically from drilling and seismic results.

Finally, if the distribution of Carboniferous sediments is mapped, as in Figure 3-12, by the presence of reflective Horton strata in the subsurface, a first-order picture of the basin results. Yet such a map is not conclusive. While the presence of reflective Horton strata in the subsurface is mapped, its absence cannot be deduced from the lack of reflections. In chapter 4 it will be demonstrated that steep dips, complex structures and certain Horton lithofacies can also account for the absence of reflections. In summary, a logical test, as follows, is required which can qualitatively distinguish between effects due to the thickness of Carboniferous cover and those due to the distribution of basement units of varying physical properties.

Regarding sediment thickness: <u>if</u> the magnetic basement is shallow <u>then</u> Carboniferous cover is thin. If the seismic data show reflective Horton strata in the subsurface, then Carboniferous cover is thick (> .5 km). In both cases, coincident magnetic and gravity extrema may occur, in which case, their extent is a guideline to the lateral extent of the unit.

Regarding the distribution of basement terranes in the subsurface: the potential field maps are valuable in tracing subcropping basement units of like density and magnetic properties under the sedimentary cover from identified occurrences in boreholes and outcrop. In addition, there is a logical classification scheme which can be applied to a covered basement unit in terms of its density and magnetic susceptibility.

1) If a gravity high corresponds with a magnetic low the potential field characterizes the basement unit

as a high density, low susceptibility rock (e.g. Green Head dolomite). Similar reasoning applies to a gravity low which corresponds to a magnetic high.

2) If potential field maxima coincide with deep basement areas identified in seismic, or if minima coincide with shallow subcrop, the density and susceptibility of the basement unit can be classified as high or low accordingly, and again compared to sampled basement rock types.

In the following sections, this first-order approach to mapping the sedimentary basin extents and underlying units is pursued in two parts. First, the basement units are classified and, secondly, the basement structures are considered.

3.6.2 Distribution of Basement Terranes in the Subsurface

The Caledonia Terrane as mapped in Figure 3-2 correlates generally with the coincident gravity and magnetic highs observed in the Caledonia Highlands. The northern limit is constrained by fault-bounded slivers of Brookville terrane rocks found on the north side of the Clover Hill Fault west of Norton and near Elgin (Figure 3-2).

In apparent contradiction to the outcrop evidence is the seismically reflective basement mapped at depth beneath the

Brookville inlier at Elgin and stretching at depth between Pollett River and Albert Mines (which projected to the surface corresponds, in attitude and expected refection character, with outcropping Caledonia Terrane metasedimentary and volcanic rocks). The implication is that the Brookville Terrane is tectonically emplaced over the Caledonia Terrane.

Another observation is that the gravity and magnetic anomaly associated with the Mechanic Settlement gabbroic pluton extends some 8 km west of Goshen beneath the Carboniferous cover, showing no strike-slip displacement along the Caledonia/Clover Hill Fault and providing further evidence of the presence of Caledonia terrane rocks in the subsurface north of the surface trace of the Caledonia/Cloverhill fault zone. These observations are consistent with a thrust fault interpretation of the Clover Hill Fault (Gussow, 1953). The only way these observations can be consistent with strike-slip displacement is if the fault is a low-angle fault with the Mechanic Settlement pluton in its hanging wall.

Brookville terrane rocks have been mapped (Figure 3-2) north of the Clover Hill Fault in the southern map area and in the two faulted inliers discussed above and in a quarry at Calhoun. While the intrusive rocks of the Brookville terrane are not distinct geophysically from those of the Caledonia terrane, one widespread Brookville unit, the Green Head Group, is unique in having both high density and low magnetic susceptibility (Tables 3-2, 3-3).

North of Shediac, gravity anomaly G8 of Figure 3-8 corresponds with a magnetic low, where the depth to magnetic basement increases seaward. There are no boreholes or basement outcrops. Green Head Group dolomite with a density of 2.8 g/cm^3 is the most attractive source for this anomaly since it has very low susceptibility and has been intersected as far north as borehole 18 at Middlesex.

This interpretation is corroborated by the fact that marble clasts have been found in the northerly derived Memramcook conglomerates at Stoney Creek (St. Peter, 1992). Together with Green Head basement intersected in the Middlesex hole, the geophysical evidence suggests the roughly triangular area between Shediac, Calhoun and Middlesex - in effect the Westmoreland Uplift area - is Brookville terrane.

A basement arch in the central subbasin has a positive gravity anomaly (G5 of Figure 3-9) and no magnetic signature. It spans the gap between known Green Head Group subcrop at the Middlesex well and the outcrop near Elgin, suggesting that Brookville Terrane rocks underlie the central subbasin too. While in the northern subbasin, the potential field maps are dominated by the low associated with the thick Carboniferous cover, it is reasonable to interpolate the Brookville terrane along strike to the Westmoreland uplift.

The geophysical evidence suggests that the Brookville and

Caledonia terranes occupy linear NE-trending belts beneath the Moncton Subbasin (Figure 3-14), and that the Brookville is tectonically emplaced over the Caledonia.

The Kingston belt as mapped in the southern map area is characterized by a linear belt of coincident magnetic and gravity highs (M 13,4; G11,12,13) which extend northeast from the Kingston complex to a point just west of Moncton. This chain of anomalies implies an elongate mafic basement unit, the low separating individual maxima representing areas of thickest Carboniferous cover in the Kingston uplift. The Kingston belt is thus interpreted to underlie the Kingston uplift at least as far north as Lutes Mountain (Figure 3-14). An alternative explanation for the chain of anomalies is the presence of the Mascarene volcanic sequence in the subsurface, but it has not been observed south of the Belleisle Fault.

The gravity anomaly at Cocagne (G15) is slightly offset to the west along strike from the Kingston Uplift gravity high and exhibits slightly different geophysical character. The main body of the anomaly corresponds to a magnetic high, but its seaward extension to Cocagne does not. A dioritic intrusion outcrops between Lutes Mountain and Stiles Village (Norman, 1931) which is in fault contact along its southern margin with sheared pink granite. It is possible that the pluton belongs to the Precambrian bimodal volcanic suite which intrudes the Caledonia and Brookville terranes but the evidence is less than compelling. It is mapped in Figure 3-14 as an area of "unknown affinity".

The Ragged Falls - Long Reach Belt, represented in a long narrow meta-sedimentary unit along the north side of the Belleisle Fault, has no gravity or magnetic signature, except a strong magnetic anomaly (M16) at a depth of approximately 300 m (Spector, 1980) with a very weak positive gravity signature. This magnetic anomaly is similar in character and size to anomaly M15, located southwest along strike about 8 km west of Lower Millstream. This correlates with an early Devonian mafic intrusion, the Stewarton Complex (Williams et al., 1985), which intrudes Silurian rocks of the Long Reach Formation.

The St. Croix terrane, subcropping at shallow depths, is the likeliest cause of anomalies at Buctouche (G14), Coal Branch (G18) and north of Canaan River (G17). These gravity anomalies have no corresponding magnetic signature. Graphitic slate (which St. Peter and Fyffe ,1990, attribute to the St. Croix) was drilled at Buctouche (borehole 1, Table 3-1) while several boreholes on the Canaan River anomaly hit slate or phyllite, also probably of the St. Croix terrane. It is likely therefore that the St. Croix terrane does extend to the Northumberland coast, as suggested by St. Peter and Fyffe (1990). But what is causing the gravity and magnetic lows separating the St. Croix gravity highs? Possible causes include structural depressions filled with Fredericton or Carboniferous cover rocks - Fredericton rocks are known to overlie St. Croix rocks to the south and west and a small Fredericton inlier underlies gravity anomaly G17. A second possibility is the presence of low-density Piskahegan felsic volcanics. These may be present as erosional remnants among the structural highs of the much-deformed St. Croix terrane rocks.

Fredericton cover rocks are known to overlie the St. Croix terrane north and west of the study area and may subcrop beneath Carboniferous sediments in some areas north of the Belleisle Fault. Unfortunately, there is little predicted contrast between the magnetic and gravity responses of Fredericton and Carboniferous cover, so they cannot be differentiated on the potential field maps.

The Mascarene belt lacks a distinct potential field signature, comprised as it is of dominantly volcanic rocks south of the map area and the non-magnetic Long Reach Formation and Queens Brook Formation in a triangular outcrop pattern north of Belleisle Bay in Figure 3-2. The Mascarene may just pinch out altogether as shown in Figure 3-14 and not underlie the Carboniferous at all, but the geophysical data alone cannot prove this.

3.6.3 Structure

3.6.3.1 Sedimentary Depocentres

The goal of this section is to delineate the areas of thick sediment accumulation in the Moncton Subbasin. Figure 3-12 shows where reflective Carboniferous sediments are greater than .5 km thick and Figure 3-4 shows where less than .3 km of non-magnetic sediments are found.

Together, these observations constrain the location of Carboniferous depocentres. Where there is a lack of definitive seismic, or magnetic basement depth information, the coincidence of gravity/magnetic extrema can be used as a guide, to interpolate between areas of sediment accumulation. The result is Fig. 3-15, a schematic map showing the locations of sediment accumulations $\geq$ 500 m.

Two basement arches identified on the trend map of Figure 3-13 subdivide the central Moncton Subbasin into three depocentres which I have called the Sussex, Elgin an Hillsborough depocentres (Figure 3-15).

3.6.3.2 Faults

Of the faults mapped by St. Peter (1989a,b; Plate 2-1) in the Moncton Subbasin, several correspond with linear trends in potential field gradient representing an abrupt change in basement depth and/or lithology while others correlate poorly or not at all with potential field trends. This may reflect either a small fault displacement, a thick sedimentary section on both sides of the fault, a very shallowly dipping fault plane, or a need to revise the structural correlation.

Some of the mapped (Plate 2-1) structures which do not correspond to geophysical trends are: the Clover Hill Fault along the northern boundary of the Marchbank syncline north of Salt Springs; the Ratter Road, Wards Creek and Parsons Brook faults in the Sussex area; the Jordan Mountain Fault north of Jordan Mountain; the Smith Creek Fault north of Indian Mountain and the Harvey Hopewell Fault north of its mapped bend near Hopewell Cape (Plate 2-1).

Some of the faults which are clearly indicated in the trend map in Figure 3-13 are:

1) the Kennebecasis Fault from Hampton to Lower Millstream where a strong magnetic trend ("D" in FIgure 3-13) suggests it continues as the Jordan Mountain Fault passing south of Jordan Mountain, not north of it as shown in Plate 2-1 and Figure 3-2;
2) the Smith Creek Fault extending northeast some 25 km from Cornhill toward Indian Mountain ("E" in Figure 3-13), down-thrown to the north; and
3) the NE extension of the Belleisle Fault ("F" in Figure 3-13), extending ENE under Pictou Group cover from where it is exposed at Price Brook north

of Havelock to the Northumberland coast ca. 8 km SE of Buctouche, down-thrown to the south.

Some areas where steep fault scarps are suggested by the potential field trends, but not mapped in Plate 2-1 are:

1) the southern margin of the Horton Group basin beneath the Marchbank syncline along which post-Horton rocks are mapped as onlapping basement, but which potential field data ("G" in Figure 3-13) suggest conceal a down-to-the-north (Horton) basin-bounding fault. East of Salt Springs (Plate 2-1) the buried basin margin jogs abruptly west about 6 km ("H" in Figure 3-13), and then continues SE beneath the Marchbank syncline parallel to and possibly coinciding with the Clover Hill Fault; and

2) the Elgin/Goshen area, where the basin margin, represented by the NE trending Pollett River Fault is crossed by a strong E-W magnetic trend ("A" in Figure 3-13) which cuts across the Caledonia uplift at latitude 40 45'N and extends west under the subbasin for a distance of at least 5 km. South of Goshen this feature is mapped as the western end of the Gordon Falls Fault which has undergone dextral, post-Horton movement.

3.6.4 Summary

Potential field geophysical data suggest that the basement terranes of southeast New Brunswick continue underneath the Carboniferous cover of the Moncton Subbasin in northeast-trending belts as shown in Figure 3-14. The Green Head Group of the Brookville terrane can be traced geophysically as far northeast as the Northumberland coast. Seismic evidence suggest that metavolcanic/metasedimentary rocks of the Caledonia terrane underlie the Brookville beneath the central Moncton Subbasin south of Middlesex, and that the Caledonia rocks are distinctive seismically.

The Horton Group depocentres of the central Moncton subbasin form a series of three linked rhomb-grabens buried by Windsor and younger sediments. Although no depth to basement map of the subbasin as a whole was attempted, the map of basin "deeps" inferred from an integrated analysis of the seismic, borehole and potential field data differs significantly from published depth-to-basement maps of the area.

4.0 Seismic Contributions to Carboniferous Stratigraphy

4.1 Introduction

Reflection seismic data provide images of the subsurface with which to compare and improve present day ideas of basin structure and stratigraphy. Our understanding of the stratigraphy of the Moncton subbasin, and the Carboniferous of Atlantic Canada in general, suffers from a reliance on lithological correlations of unfossiliferous units. These units are placed in their present position in the stratigraphic column based on their perceived stratigraphic relationship to distinctive units such as the Windsor Group or Albert Formation. In this chapter, seismic reflection data is analyzed to test and expand upon the basin stratigraphic framework as it is understood from borehole and outcrop data, particularly as it relates to the assignment of proper stratigraphic level to observed unfossiliferous units.

The analysis of this chapter has two objectives. The first, which is applicable to the subbasin as a whole, is to tie the seismic data to synthetic well data. This serves the dual purpose of tying well-log depth information to seismic travel time, and also of understanding what causes the observed seismic reflections in terms of acoustic impedance contrasts within the geologic section. The second objective, which applies specifically to the undeformed, well imaged Horton section in the Elgin-Portage Vale area, is the interpretation of depositional environment and lithofacies from the seismic data. The structural interpretation of the seismic data will be the subject of Chapters 5 and 6 and will build upon the stratigraphic work of this chapter.

4.2 Well Control

4.2.1 Introduction

Many boreholes have been drilled in the study area (Figure 4-1), and a complete catalogue of borehole data is available from the New Brunswick government (St. Peter, 1987b). Oil exploration in the Stoney Creek area dating back to 1907 is the most prolific source of well information, but oil exploration elsewhere in the subbasin, as well as salt and potash exploration, furnishes deep lithological data. Numerous shallow boreholes (<250 m depth subsurface), drilled for uranium, coal, and oil shale exploration programs, bring the total number of wells in the area to more than 400, including several water wells drilled by the Geological Survey of Canada and described by Carr (1968).

All wells were plotted on the base map and logs obtained from the New Brunswick Government for all deep (>125 m) wells outside the Stoney Creek Oil and Gas Field. It was decided that since no seismic data within the oil and gas field licence area were released, and since an excellent report (Foley, 1989), in which well cuttings from many wells had been reanalysed and the well data summarized, had recently been published, that the 100+ wells in and around the Stoney Creek field could be considered represented by that report.

Of the total number of wells, 24 had been logged for sonic velocity. These wells are tabulated in Table 4-1 below.

Table 4-1 Boreholes Logged for Sonic Velocity

BCN*	DEPTH	NAME	STATUS	SYNTHETIC
37	949	Irving/Chevron Smithtown 1	Released	yes
38	2227	United Oils Macleod Brook 1	Released	no
41	1104	Kerr-McGee Urney 1	Released	yes
52	920	PCA E-4a	Confidential	yes
56	1350	IMC 1	Confidential	yes
60	1158	IMC 5	Confidential	yes
79	1207	BP Millstream 2	Confidential	no
80	1002	BP Millstream 3	Confidential	no
81	1372	BP Millstream 4	Confidential	no
82	1068	BP Millstream 5	Confidential	no
83	1140	BP Millstream 6	Confidential	no
84	1154	BP Millstream 7	Confidential	no
85	1220	BP Millstream 8	Confidential	no
132	878	PCA M-4A	Confidential	yes
142	1029	PCA Z-4	Confidential	no
146	1835	Irving/Chevron Middlesex 1	Released	yes
147	2100	Irving/Chevron Lee Brook 1	Released	yes
317	1346	NBO West Stoney Creek 71-1	Released	no
331	1592	Irving/Chevron Stoney Creek 1	Released	no
332	1435	Irving/Chevron East Stoney Creek 1	Released	yes
333	3013	Irving/Chevron Hillsborough 1	Released	yes
334	1615	Irving/Chevron Little River 1	Released	yes
350	609	Can. Oxy. Albert Mines 81-8	Released	yes
352	641	Can. Oxy. Shenstone 81-1	Released	no

*BCN= New Brunswick Borehole Catalogue Number in (St. Peter, 1987b)
PCA=Potash Corporation of America
IMC=International Minerals and Chemical Corporation
BP=British Petroleum Exploration Canada Limited
NBO=New Brunswick Oilfields Ltd.
CO=Canadian Occidental

Twelve wells for which sonic data were attainable tie to the released seismic data under study. These logs were digitized and used to determine time-depth curves for the basin, to make synthetic seismograms (Appendix A), and to tie seismic horizons and seismic facies boundaries to well data.

Velocity surveys were available for only two of these wells, Irving/Chevron Little River 1 and Irving/Chevron Lee Brook 1, the cost having been considered prohibitive for most holes since follow-up work was ruled out by the negative drilling results (W. Davitt, pers. Comm.). An attempt was made to obtain logs from the confidential wells drilled by PCA, BP and IMC which were all drilled for potash exploration. Brian Roulston of PCA made logs available for two of their wells and formation tops for all others and David Waugh of Denison-Potacan provided well logs for two IMC wells. Both the PCA and Denison sites are currently active potash mines. Wells from the BP Millstream prospect remain confidential.

4.2.2 Synthetic Seismograms

Synthetic seismograms were generated for all boreholes tying seismic lines with available sonic and density logs. These are presented in Appendix A. Horizon tops from well data were transferred to key seismic lines by comparison with the well synthetics as shown in Plates 4-1 to 4-6. The synthetics could be used not only as anchor points for the structural interpretation of the seismograms but also to help classify the seismic response of the rock column as discussed in section 4.3.

4.2.3 Time-Depth Conversion

Synthetic seismograms were used to determine the depth to mapped seismic horizons at the well locations, but clearly, the average velocity, and hence the time-depth rule, varies from place to place within the basin depending on the local geologic conditions.

Throughout the seismic discussion it will be necessary to convert from seismic two-way travel time, an observable quantity, to reflector depth. This requires a knowledge of the average compressional wave velocity to that depth and the details of any datum corrections.

In the Lee Brook well near Elgin, a velocity survey was available and a time-depth relationship had been already determined by the logging contractor. A velocity survey is an experiment conducted after drilling is completed, in which a geophone is clamped in the hole at various depths and a surface or near surface seismic source is fired repeatedly. By picking the arrival times of the first break energy as a function of geophone depth, an empirical time-depth curve is determined.

At depths greater than those penetrated by the drill, our only sources of velocity information are the seismic data themselves. Normal moveout velocities estimated from reflections in the seismic data are well known to approximate the RMS average velocity to the reflecting horizon in an earth model consisting of many horizontal layers of different velocities (see e.g. Sheriff and Geldhart, 1983). For the Lee Brook well the velocity-depth function derived from the velocity survey was extrapolated to depth using seismic velocities from nearby Line 11. This velocity-depth function is shown in Figure 4-3.

4.3 Seismic Data and the Origin of Reflections

4.3.1 Vibroseis Reflection data

Seismic reflection data collected by industry (Chevron, 1981, 1982, 1983, 1984) as part of a regional hydrocarbon exploration project have been released by, and are available from, the New Brunswick Department of Natural Resources. More than one hundred seismic profiles (Figure 4-2) have been released in the Moncton Subbasin and surrounding areas, most of which have been examined in relation to this study. Both unmigrated and migrated, coherency enhanced, sections are available. Reflection quality and continuity in the terrigenous clastic section is variable and complex faulting makes the Lower Carboniferous section uninterpretable in some areas although the data quality is generally good. Table 4-2 below lists the data acquisition parameters.

The following sections addresses the question "What is causing the reflections observed in the Moncton Subbasin seismic data?" In the dominantly terrestrial sedimentary succession, a wide variation in reflection continuity is

Table 4-2 Seismic Data Parameters

	1981	1982	1983	1984
Vibrators	4	4	4	4
Sweeps per V.P.	8	8	8	8
Sweep Length (s)	24	19	19(24)	18
Sweep Frequency (Hz)	12-56	56-12	56-12	12-56 (12-70)
Stacking Fold	12	12(20)	12(30)	30(60)
V.P. Spacing (m)	150	150(90)	150(60)	60
Group Spacing (m)	30	30	30	30

(Bracketed values indicate shooting parameters on selected high-priority lines)

apparent. This is partly due to signal to noise ratio and partly to geology. Most of the regional lines shot in 1981 are of 12 fold coverage. The stack fold in the shallow section (<0.3 s or 0 to 500 m depth) is considerably reduced by the prestack mute and virtually no continuous reflections are observed in that depth range. In general, the higher the fold of data coverage, the better shallow events can be detected in the Chevron /Irving data set. Alluvial sediments are not prolific reflectors of coherent seismic energy, but nevertheless, many reflections occur in the data. Only one reflection is regionally continuous throughout the subbasin, that of the base of the Windsor Group. In this section I will investigate the origin of reflections in the Carboniferous section beginning at its base. Six of the seismic lines which tie to synthetics (Plates 4-1 to 4-6) are used to illustrate this discussion.

4.3.2 Horton Group

The basal Horton unit, the Memramcook Formation, is penetrated by only one well for which sonic data are available, I/C Little River, shown in Plates 4-1 and 4-2 and in Plate A-11. Intersected at 1261 m depth in the borehole, the Memramcook consists locally of a monotonous red shale unit devoid of reflections over its >200 m thickness except near its top (reflector "B" of Plates 4-1 and 4-2) where the shales are interbedded with sandstones and siltstones over a 40 m thick interval, and at the base of the shale unit at 1504 m (reflector "A") which is marked by an abrupt downward increase in sonic velocity at the top of an interval dominated by tight sandstones and siltstones. Both of these reflections are continuous over a horizontal distance of 5 or 6 kilometres. Note that the southeasterly dip of these reflectors is out of the plane of line 60X and hence not properly migrated. This fact results in a substantial mistie between seismic line 60X and the reflectors as imaged at their actual depth on the synthetic of Plate 4-2.

The Albert Formation has been drilled in the I/C Little River and Hillsborough holes and is most reflective and best imaged on line 13Y (Plate 4-3) where it ties with the I/C Lee Brook well. The Lee Brook synthetic (Figure A-8) shows that the strongest reflections are associated with the sandstone facies intervals. Reflections with reflection coefficients R $\geq$ 0.15 occur at 0.4, 0.46 and 0.74 s two way time on the synthetic; all occur in the sandstone facies and coincide with the tops of tight, poorly sorted and sometimes conglomeratic sandstone units 15 to 30 m thick found at depths below kelly bushing (k.b.) of 967 m, 1140 m and 1773 m. The tight siliceous sandstone with dolomitic cement at 1140 to 1160 m depth is the highest velocity rock in the subbasin with velocity approaching 7.0 km/s. It is very important to note that these three events which yield the highest amplitude reflection coefficients do not coincide with the most laterally continuous events on the seismic section of Plate 4-3. Lower amplitude reflection coefficients in the interval 700-1000 m, at 0.3 to 0.4 s on the synthetic of Plate 4-3, arising from the interbedding of sandstones and mudstones on scales of 10 to 30 m, are much more laterally continuous. Here the high velocity (ca. 5.0 km/s), tight, poorly sorted sandstones are intercalated with lower velocity (3.5 - 4.0 km/s) lacustrine shales. The high degree of lateral continuity of these reflections is to be expected here even though the individual bed thicknesses are small compared to the seismic wavelength (see Appendix B). The interference of thin bed reflections yields a composite reflection (Sheriff, 1985) and it is the continuity of the entire package that governs the continuity of the reflection, and not the internal arrangement of the thin reflecting boundaries, which are sure to vary laterally within the package.

Both the kerogenous mudstone (1200-1450 m) and other mudstone units (1478 to 1611 m) in the Lee Brook well (Plate 4-3) give rise to weak reflections, primarily due to variations in sand and silt content which increase their velocity slightly. Oil shale velocities range from 4.2 km/s at the base (1425 m) to 3.6 km/s at the top (1250 m) again due to a decrease in silt-size particle fraction. Reflections in the oil shale unit are laterally discontinuous (see Plate 4.3 between 0.5 and 0.7 s). Similarly in the I/C Little River well (Plates 4-1 and 4-2), where only the mudstone facies is represented (760-1260 m), no reflection coefficients greater than 0.05 are represented in the reflectivity log but weak reflections can be seen between 0.4 and 0.6 s and are more prominent on the strike line (Plate 4-2; line 60X) than the dip line (Plate 4-1; line 93Y). These are generated by the constructive interference of many thin (5-10 m) intervals with higher velocities due to their higher (up to 35%) sand content.

Finally in the I/C Hillsborough well (Plate 4-4 and Plate A-10) another important factor in the Horton Group reflectivity is demonstrated: the effect of steeply dipping beds. Nearly 2.7 km of mainly mudstone and sandstone facies Albert rocks are penetrated at the Hillsborough well. There is a significant discrepancy in the seismic character of line 66YA (Plate 4-4) and the synthetic well log. Below 1900 m (0.8 s) several strong reflections are suggested by the synthetic associated with the tops and bases of high velocity >5000 m/s sandstone units, but none are visible on the record section. The dipmeter log shows that while dips average about 10° in the upper 1400 m of the borehole, faulting is indicated at several levels (1350, 1446, 1620 and 1675 m) in the hole, and dips generally increase with depth from 10° at 1300 m to 20° at 1500 m and generally exceed 40° NE at depths greater than 1900 m. Thus even reflective facies are not recognized seismically where dips exceed 40° or so, a fairly common occurrence in exposed Horton rocks.

The Weldon Formation is encountered in both the Hillsborough and Lee Brook wells. In both wells a monotonous redbed, dominantly sandstone unit generates no internal reflections at the well. Northeast of Hillsborough, however, in the north flank of the Weldon syncline (Plate 4-4), the Weldon seismic character consists of sub-parallel reflections continuous on the scale of 2 to 3 km. The Boyd Creek Tuff, imaged in the Hillsborough well, is prominent on the density log (Plate A-10) between 1074 and 1086 m where the density suddenly decreases downward from 2.75 to 2.55 g/cm^3 with a corresponding decrease in sonic velocity. Although the 12 m thickness of the unit is less than one quarter of the seismic wavelength, the synthetic indicates that a weak reflection should be visible. This reflection is visible on line 66YA (Figure 4-4). Gussow (1953) notes that the thickness of the tuff unit is variable, suggesting that we might expect a variation in amplitude along the reflector since for thin beds (Widess, 1973) amplitude decreases with bed thickness (Appendix B).

In the Little River well (Plates 4-1 and 4-2) a sandy Weldon lithofacies is intersected between 596 and 758 m depth (k.b.) which becomes increasingly conglomeratic toward the top. A strong reflection is generated at the base where the Weldon sandstones (4.7 km/s) lie in apparently conformable contact upon Albert Formation shales (3.5 km/s).

4.3.3 Windsor Group and Hillsborough Formation

The basal Windsor/Hillsborough unconformity is well marked on the seismic data by three criteria:

1. the erosional truncation of dipping Albert or Weldon Formation beds;
2. the transgressive onlap of the overlying reflections; and
3. the presence of a prominent, low frequency regional

reflector.

The low frequency regional seismic reflector associated with the base of Windsor Group is the most prominent reflection in the seismic data. In most places it coincides with the top Horton unconformity and the Hillsborough Formation is absent or thin relative to the seismic wavelength (ca. 100 m). Elsewhere there is a thin unit lying above the unconformity and below the basal Windsor reflection which is interpreted as Hillsborough.

In the Little River well (Plates 4-1, A-11), the base of Windsor is marked by an abrupt velocity decrease from 5.2 km/s in the basal limestone unit to 4.2 km/s in the underlying Weldon Formation clastics. The combined thickness of the high velocity Windsor evaporites (v_{avg} = 5.5 km/s) and limestone (V_{avg} = 5.2 km/s) is only 58 m, slightly more than one half the seismic wavelength. Sandwiched between redbed units (v_{avg} 4.6 to 4.8), this results in a strong continuous reflection which appears lower in frequency due to the interference of reflections from its top and base, and within which individual units cannot be resolved.

In the Middlesex well, (Plate 4-5, A-7), there is no significant decrease in velocity accompanying the transition from high velocity anhydrite and dolomite of the Windsor Group to the Brookville (Green Head Group) basement rocks. Rather, the contact is defined there on the basis of continuity in the

Windsor Group reflectors, and their onlapping relationship with, and diffractions generated by, the rugged basement protrusion.

At Salt Springs (Plate 4-6, line 31X[south]; Plates A-4 and A-5), the basal Windsor/Hillsborough unconformity is not drilled but the seismic expression of a thick Windsor evaporite section is sampled. The evaporite section starting at 808 m in the IMC #1 borehole (Plate A-4) is virtually reflection-free but the dramatic density decrease from 2.65 g/cm^3 in the Hopewell Group clastics to 2.05 g/cm^3 in the salt gives a significant negative reflection coefficient at the top of the salt unit.

Note that there is a disagreement between borehole and seismic data at the IMC #1 well. (Plate 4-6). The strong basal Windsor reflection arrives at 0.5 s on the record section but is not penetrated by the well. In this location the line 31X runs along the axis of the Marchbank syncline and the well is almost 800 m off-line. Both the well data and the basal Windsor reflection are out of the plane of section.

4.3.4 Hopewell and Younger Rocks

Hopewell Group rocks are imaged on lines tying the Little River, Middlesex and IMC #1 boreholes. At little River (Plates 4-1; 4-2), the monotonous arkosic sandstones of the Hopewell encountered below 400 m, where logging began, are devoid of reflectors. At Middlesex however (Plates 4-5 and A-7), the Hopewell is penetrated between 450 and 1282 m depth (k.b.) and numerous continuous reflections are generated by the interbedding of siltstones (overbank fines) and fining upward channel sequences on scales of a few tens of metres, between depths of 750 and 1000 m (0.25 - 0.45 s on Plate 4-5). These deposits represent the migrating channel and associated features of the low relief alluvial plain or meanderbelt. More monotonous, sandy alluvial deposits above and below this reflective interval are less reflective braid-plain deposits.

There is no seismic evidence for an angular unconformity within the Hopewell Group in the central Moncton Subbasin. Wherever the Windsor-Hopewell-Boss Point section is imaged on the seismic data, strata are apparently conformable. This does not prove there is no discontinuity. The 30 My time gap between Windsor (Mid-Visean) and Boss Point (Westphalian "B") is represented by only a few hundred metres of sediment and there is structural and stratigraphic evidence in outcrop for an episode of faulting during Hopewell deposition (Gussow, 1953). Where the upper Hopewell (Enragé Formation) has been mapped in the Hillsborough area by Gussow (1952) and McLeod (1979) as unconformably resting on folded and faulted Windsor, Hopewell and older rocks, the unconformity is too shallow to be imaged by the seismic data. What the seismic data do suggest is that Namurian deformation ("Hopewell episode" of Figure 2-1) is confined to the areas near the active fault zones.

Some good reflections are generated in the Upper Hopewell strata as evidenced by the strong reflection at 0.15 s at the Little River well (Plates 4-1 and 4-2). This "near top Hopewell" reflector can be correlated throughout the central part of the subbasin on the high-fold lines and corresponds to the top of a 65 m thick alluvial plain sandstone/siltstone body encountered in the Hopewell Group at 575 m in the Middlesex hole. It has a slightly higher velocity (v_{avg}=4.5 km/s) and is more massive than any of the overlying (logged) Hopewell or Boss Point rocks. This reflection is attributed to the mid-Hopewell unconformity by St. Peter (1992) but I cannot detect any angular discordance. When the same reflector is traced to the Pollett River Well on line 9, it falls within a massive tight sandstone unit near the top of the Hopewell Group. No sonic log is available there. This "near top Hopewell" reflector is present throughout the central subbasin and trends to the surface on line 31X near the mapped Hopewell/Boss Point contact on the flank of the Anagance axis. In the Pollett River (BCN 145) and Turtle Creek (BCN 319) holes, for which no sonic data are available and in the Middlesex well, the "near top Hopewell" reflection falls at the top of, or within a massive sandstone unit in the upper 200 m of the undifferentiated Hopewell Group. It is possible that the reflection is a disconformity surface within a few hundred metres of the Hopewell/Boss point contact.

Wherever massive sand bodies are encountered in the Hopewell Group similar seismic responses occur. For example, in the IMC #1 well (Plate A-4) a sandstone unit with minor siltstone and conglomerate is encountered between 655 and 814 m (k.b.) which has a higher velocity (v_{avg}=4.2 km/s) and is more massive than the overlying Hopewell units. It gives rise to a prominent reflection at 0.26 s at the well in Plate 4-6.

The Boss Point Formation and Pictou Group are generally found at depths of less than 100 m, and are therefore poorly imaged by the seismic data and are often not logged, lying above the first cased interval in the boreholes. Only the Middlesex sonic log (Plates A-7 and 4-5) documents the basal contact of the Boss Point formation, but it does not record its top or the Pictou Group log characteristics. At Middlesex there is little velocity contrast between the basal conglomerate of the Boss Point Formation and the sandstones and siltstones of the uppermost Hopewell Group.

The strong reflection marked "Basal Boss Point" in Plate 4-5 can be observed locally on the best quality lines of the central subbasin including line 89Y which ties to the Turtle Creek well, in which it corresponds with the top of the basal Boss Point conglomerate.

Pictou Group sediments are too shallow to be imaged by most of the seismic data and no light can be shed on the question of whether there is a subbasin-wide disconformity at the Boss Point/Pictou contact as Gussow (1953) suggests.

4.3.5 Summary

Marine deposits provide laterally continuous reflections in the Windsor Group, but in the remaining, dominantly terrestrial section, laterally continuous reflections fall into two categories. They are either:

1. the result of the constructive interference among thin beds; despite the fact that there are almost no distinct units within the Albert Formation as great as one quarter seismic wavelength (30 m) in thickness, the formation is a prolific reflector of seismic energy; or
2. the tops of massive, tight, high velocity sandstone units exceeding one quarter wavelength in thickness which are laterally extensive on a scale of several kilometres. In some cases these may coincide with disconformity surfaces.

No continuous reflections are seen in coarse proximal alluvial sediments, massive mudstone sections, thick evaporite sequences and beds interrupted by intense faulting or dipping at angles greater than 40°.

It is clear that any attempt to classify rocks in the subsurface seismically must rely on more than seismic character alone. In the following section a rigorous approach to classifying the Horton Group section using seismic stratigraphy will be presented.

4.4 Seismic Stratigraphy of the Elgin - Portage Vale Area

4.4.1 Introduction

The goal of seismic stratigraphy, as that term is used here, is to predict the environment of deposition and the timing of tectonic events governing sedimentation from seismic data. Seismic reflections in sedimentary sequences are formed by interference from many thin stratal surfaces and as such are time lines (Cross and Lessenger, 1988). The boundaries of seismic stratigraphic units, as I define them in this section, are discontinuities: unconformities or surfaces of non-deposition, and their correlative conformities. Seismic stratigraphic units mapped on this basis have stratigraphic significance; they correspond closely with what the North American Commission on Stratigraphic Nomenclature (1983) calls Allostratigraphic units. These are defined as follows:

> *"an allostratigraphic unit is a mappable stratiform body of sedimentary rock that is defined and identified on the basis of its bounding discontinuities."*

In this discussion I avoid using the jargon of seismic sequence stratigraphy in favour of descriptive terms defined here. Sequence stratigraphy is essentially interpretive and implicitly related to sea level fluctuations (Walker, 1992). Furthermore the original stratigraphic framework for the subbasin (Wright, 1922) was an unconformity based one, so it seems natural that a subdivision based on seismic discontinuities may prove to be an effective approach to understanding the subbasin stratigraphy.

Within each allostratigraphic, or seismic stratigraphic, unit, one expects to see the deposition of a sedimentologically related succession of facies. The series of linked contemporaneous depositional systems represented by such a unit is often called a "depositional systems tract" (Brown and Fisher, 1977). If the seismic stratigraphic units are of sufficient thickness and areal extent to be mapped in the seismic data, their external form, internal reflection characteristics, and relationships to adjacent units allow the unit to be classified by comparison to other documented examples (e.g. Sangree and Widermier, 1977; Brown and Fisher, 1977; Bally, 1987) with the goal of interpreting the environments of deposition, and predicting lithology within the context of applicable facies models.

The five steps I have followed in the seismic stratigraphic interpretation process are (modified from Vail, 1987).

1. Identify packages of seismic reflections which are separated from one another by bounding discontinuities. This

is done on the basis of reflection termination patterns such as onlap, downlap and truncation, and is performed objectively, independent of the well log interpretation.

2. Analyze lithostratigraphy from well logs, where possible identifying allostratigraphic boundaries.

3. Tie seismic data to well data using synthetics. After independent interpretation of well and seismic data, the allostratigraphic unit ties are adjusted to the best solution.

4. Characterize the seismic response of each reflection package including the amplitude, frequency, geometry and continuity of reflectors and interval velocity. Detailing observations of these properties and how they vary spatially within the reflection package constitutes "seismic facies analysis".

5. Interpret the depositional environment and predict lithofacies distribution within each seismic stratigraphic unit within the framework of a facies model constrained by the seismic facies analysis, well log analysis and knowledge of the regional geology.

An irregularly spaced grid of 6 lines (Figure 4-4) spans the area between Elgin and Portage Vale where the gravity and magnetic maps of Chapter 3 imply the existence of a Horton Group depocentre - the Elgin "subbasin" of Figure 3-15. The six lines span an area approximately 7 km square in which the data are unique in the subbasin in that the Horton section is well imaged and virtually unfolded. Good quality data are a prerequisite for stratigraphic interpretation of seismic data because of the underlying assumption that reflection continuity can be assessed and reflector terminations can be attributed geological significance.

In the following sections I will describe my seismic stratigraphic analysis and how it relates to St. Peter's (1992) lithofacies analysis for the Lee Brook well. In combination, the well and seismic data are used to make a unit-by-unit interpretation of depositional environment and lithofacies prediction.

Finally in section 4.4.5, a chronostratigraphic chart for the Horton Group on the Elgin-Portage Vale area is derived and its tectonic implications discussed.

4.4.2 Seismic Stratigraphic Units

Seven seismic discontinuities were identified on lines 11, 11Y, 13Y 29Y, 48X and 52Y in Figure 4-4. These discontinuities divide the Carboniferous section into six distinct reflection packages or seismic-stratigraphic units. The seismic characteristics of these units are tabulated in Table 4-3 on the following page. Seismic stratigraphic unit I, best seen on lines 13Y (Plate 4-3) and 11 (Figure 4-4)

Table 4-3 Seismic Stratigraphic Compilation

SEISMIC FACIES UNIT	TOP BOUNDARY	BOTTOM BOUNDARY	EXTERNAL FORM	REFLECTION CONFIGURATION	REFLECTION CONTINUITY	ENVIRONMENT
I	E:CONCORDANT	F: ONLAP	WEDGE?	DIVERGENT	DISCONTINUOUS HIGH AMPLITUDE	PROXIMAL FAN? SYN-RIFT CLASTICS
II	D:CONCORDANT WITH DISTAL EROSIONAL TRUNCATION	E: LOCAL DOWNLAP OTHERWISE CONCORDANT	FAN	PROXIMAL, CHAOTIC OR REFLECTION-FREE; DISTAL, SUBPARALLEL	DISCONTINUOUS HIGH AMPLITUDE	ALLUVIAL FAN
III	C:CONCORDANT TO TOPLAP TRUNCATION DISTALLY	D: CONCORDANT EXCEPT DOWNLAP TO SW ON LINE 48X	SHEET OR WEDGE WITH PROXIMAL MOUND	UNIFORM PARALLEL; CHAOTIC IN MOUND	DISCONTINUOUS	FAN DELTA COMPLEX
IV	B:CONCORDANT	C: PROXIMAL CONCORDANT, DISTAL DOWNLAP	BASIN FILL	UNIFORM PARALLEL	CONTINUOUS	LACUSTRINE
V	A: ONLAP OF OVERLYING UNITS	B: PROXIMAL CONCORDANT, DISTAL DOWNLAP	BASIN FILL (NE-SW TROUGH)	PROXIMAL, CHAOTIC OR REFLECTION-FREE; DISTAL, PROGRADING OBLIQUE CLINOFORMS	LOW AMPLITUDE DISCONTINUOUS	ALLUVIAL PLAIN
VI	EROSIONAL (PRESENT BEDROCK SURFACE)	A: ONLAP	BASIN FILL (SLOPE FRONT)	SUBPARALLEL	UPPER DISCONTINUOUS; LOWER CONTINUOUS HIGH AMPLITUDE	

consists of a series of fault-bounded units with wedge-shaped cross-section, but the unit is too faulted to allow a map to be made of its external geometry. High amplitude reflections within the sequence diverge towards the basin bounding faults indicating syn-depositional rotation of the basement fault blocks.

Seismic stratigraphic unit II, best shown on lines 11y and 13Y (Figure 4-4) has the external form of a dissected fan (Figure 4-5). Reflections within the unit range from chaotic or reflection-free near the basin margin grading to low-amplitude parallel discontinuous reflections with increasing distance from the southern basin margin. The base of the unit is marked by downlap onto unit I (Figure 4-4, Line 11), while the top shows erosional truncation distally (Figure 4-4, Line 13Y; Plate 4-3) and is elsewhere marked by a concordant boundary separating chaotic or reflection-free seismic character below, from parallel, continuous reflections above. On line 13Y (Figure 4-4), further subdivision of unit II is possible but, being largely reflection-free on most lines, no mappable subdivision of the unit is possible. Unit II is very thick, more than 0.7 s two-way time (ca. 2.1 km) near the middle of line 11Y. A restored depth section of the unit is shown in Figure 4-6(a).

Seismic stratigraphic unit III is distinctly more reflective than the underlying units. Its external form is that of a sheet or wedge being almost constant in thickness at about 0.25 s or 500 m in the map of Figure 4-7, with the exception of that part of line 48X which runs parallel to the basin margin between lines 13Y and 29Y. In that area the unit thickens, having the form of a fan-shaped mound that interdigitates with the more reflective strata. The mound displays a complex or chaotic fill pattern in cross-section. Reflections elsewhere within the unit are subparallel to parallel and discontinuous on both strike and dip lines, becoming generally less continuous closer to the basin margin and near the top of the unit (see, e.g. line 13Y, Figure 4.4).

Seismic stratigraphic unit IV overlies unit III. At its base its reflections locally lie in apparent conformity upon those of unit III, but distally (see line 11y, Fig 4-4) they downlap onto a condensed section. On line 48X they can be seen to onlap the alluvial fan mound of unit III and are to some extent draped over the mound presumably due to the greater compaction of the distal unit III sediments relative to the coarse alluvial sediments of the mound. The external form of unit IV is that of a basin fill, roughly rhomb-shaped with a NE-SW trend (Figure 4-8). Reflections within the unit are uniform parallel, but vary greatly in their continuity from discontinuous at the base and near the basin margin to continuous near the top of the unit and further from the basin margin. Maximum unit thickness is about 0.3 s (600 m) in the

Goshen area.

Seismic stratigraphic unit V, the uppermost Horton unit, is distinguished from the underlying unit by the marked disappearance of the modest amplitude discontinuous reflectors. Its external form is a NE-SW trending trough-shaped basin fill thinned by uplift and erosion in the north (Figure 4-9). Basal reflections, where they can be identified, are conformable with the underlying unit near the basin margin, and very low amplitude discontinuous reflections downlap onto a condensed section in the north (see Line 13Y, Figure 4-4; Plate 4-3). The upper surface is, near the basin margin, a surface of erosion, with a slope of ca. 6° (10%). Basinward the upper transgressive unit overlies unit V concordantly. Within Unit V, reflection character is chaotic or reflection-free grading to low amplitude continuous with increasing distance north. An interesting observation can be made on line 13Y (Figure 4-4). The distal prograding reflections are succeeded by flat-lying ones higher in the sequence: an observation often made in regressive systems tracts where prograding delta front sediments are succeeded by flat lying delta-top deposits (e.g. Hubbard et al. 1985, Fig 4). Another possibility is that the distal sediments of Unit V were deposited flat-lying, onlapping a surface tilted by central basin subsidence or uplift of the northern margin.

Unit VI, representing the post-Horton formations, has the form of a basin fill deepening to the northeast and its mapping is described in Chapter 5. Basal reflections are onlapping the eroded top of Unit V near the basin margin and lie with apparent conformity on Unit V in the northern half of the Elgin-Portage Vale area. High amplitude low-frequency continuous subparallel reflections grade upward and southward toward the basin edge into parallel discontinuous reflections. This uppermost seismic stratigraphic unit is in the mute zone of the seismic data, that is the upper 0.3 seconds, in which the data are not full fold and hence signal to noise ratio is not as great as in the deep section. Best imaged elsewhere in the subbasin, Unit VI is more widespread than the underlying Horton units. It is too noisy to subdivide in this area and is not penetrated by the Lee Brook well. For the purposes of this section the discussion will be confined to the lower five units which are both well imaged and drilled at Lee Brook.

4.4.3 Well Data Analysis

A comprehensive study of the lithofacies of the Albert Formation has recently been completed by St. Peter (1992). By studying outcrop and borehole data throughout the Moncton Subbasin, he has subdivided the Albert Formation into 5 distinct lithofacies representative of depositional environments in and around a Tournaisian lake. St. Peter's work includes an analysis of the Irving Chevron Lee Brook #1 well (Figure 4-10) which is adopted here as an independent interpretation of the well log for comparison with the seismic stratigraphy.

As shown in Figure 4-10 the borehole encounters a monotonous redbed, dominantly sandstone, unit which is correlated with the Weldon Formation. It in turn is underlain by more than 1300 m (>1100 m stratigraphic thickness) of Albert Formation which St. Peter subdivides into five distinct lithofacies to which generalized environmental interpretations have been attributed. These are summarized in Table 4.3 below.

Table 4-4 Albert Formation Lithofacies

LITHOFACIES LABEL (FIGURE 4-9)	ALBERT FORMATION LITHOFACIES	ENVIRONMENT OF DEPOSITION
A_C	Conglomerate facies	Braided stream and fan delta
A_S	Sandstone facies	Shallow lacustrine
A_M	Mudstone facies	Lake margin mudflats
A_X	Sandstone/mudstone facies	Alternating A_M/A_S environments
A_K	Kerogenous mudstone "oil shale" facies	Deep anoxic lacustrine

A dipmeter log of the Lee Brook well shows no major angular unconformities within the Weldon-Albert section. Only one abrupt discontinuity occurs in the well, at 1635 m. The dip profile of that discontinuity is suggestive of a reverse fault, emplacing north-dipping beds over nearly flat-lying ones. Fluctuations in lithotype occur at several scales. Small and meso-scale variations on the scale of a few metres to a few tens of metres were not subdivided by St. Peter (1992) because they could not be mapped at 1:20,000 scale. This coincides with the scale of stratigraphy to which the seismic data respond, which is governed by the seismic wavelength, λ. In this case λ is approximately

$$\lambda = (4 \text{ km/s}) \ / \ (30 \text{ Hz}) = 1.3 \times 10^2 \text{ m} .$$

Reflectors can be resolved which are greater than $\lambda/8$ to $\lambda/4$ (Sheriff, 1977), i.e. 20 or 30 m apart.

A notable large scale feature of the Lee Brook well log is the fining upward trend exhibited in the depth interval 2100 to 1200 m. from a thick conglomeratic unit at the base of the hole to the top of the oil shale unit.

Synthetic seismograms allow us to tie the seismic and well data for the Lee Brook well as discussed in the previous section. When the seismic-stratigraphic unit boundaries are correlated to the well, the result is shown in Figure 4.4. The top of Unit II falls just below the drilled interval. Unit III coincides with the fining upward succession mentioned above, unit IV with the uppermost oil shales and lake margin sediments above them and unit V with the Weldon Formation. It is notable that the Unit III/Unit IV boundary falls within the oil shale unit. Both its seismic expression, and lithological expression correspond to what sequence stratigraphers call a "maximum flooding surface", the high water mark as it is recorded in the rock record.

During a period of sea level or lake level rise, terrigenous clastic deposition is commonly very slow because most of the coarser sediments are confined to the alluvial plain or lake margins. After sea level stabilizes, sediments may again begin to build out into the basins generating marker horizons that downlap onto the older surface of deposition. This older surface of deposition is a maximum flooding surface (MFS) (Van Wagoner, et al., 1987). Lithologically, at the MFS the rate of clastic or carbonate sedimentation is at a minimum and there tends to be a relative concentration of organic material and chemical deposits (Walker, 1992).

4.4.4 Inferred Depositional Environment

Unit I is a localized syn-extensional unit. The origin of reflectors within this sequence is uncertain but high amplitude continuous reflections may be consistent with evaporites, volcanics or massive sand bodies. The stratigraphic position, below the Albert and at the very base of the Memramcook Formation, suggest the sediments are Late- or even Mid-Devonian in age. Upper Devonian clastic rocks are interbedded with basaltic flows in the Perry Formation found in two small fault-bounded basins near the Maine-New Brunswick border approximately 160 km southwest along strike from here. The Perry Formation is one possible model for the reflective rift-facies rocks of Unit I.

Although Unit II has not been drilled, its geometry is suggestive of what we would expect to see in a coarse alluvial fan of the Memramcook Formation in a setting such as that shown in Figure 4.6(b). Many examples of ancient alluvial fans that have developed in response to active normal faulting are documented. Examples include the Old Red Sandstone of S.W. Norway and the Permian of East Greenland (Reading, 1982). These deposits are characterized by great thicknesses of conglomerates, often measured in kilometres, close to the bounding fault where the facies reflect the proximity to the fan apex. Such deposits generally thin distally and are accompanied by lateral facies changes .

The Lee Brook borehole penetrates seismic sequence III near the eastern end of Line 13Y. There it consists of a basal conglomerate overlain in turn by sandstone, interbedded sandstone/mudstone, mudstone and kerogenous mudstone units all assigned to the Albert Formation by St. Peter (1992). This generally fining upward facies succession is *ca*. 0.31 s or

780 m thick at the well (600 m stratigraphic thickness).

The association of the fan and wedge forms with the demonstrably lacustrine deposits is characteristic of a lacustrine fan delta. A fan delta, as the term is used here, is a depositional system in which an alluvial fan progrades into a standing body of water, in this case a lake. Since the action of wave and tide are minor in lacustrine as compared to marine settings, such deltas are commonly dominated by fluvial processes. But the time-thickness contours of Figure 4-7 do not describe the typically lobate form of classic river-dominated deltas like the Mississippi. In a lake setting, delta geometry is greatly influenced by the topography of the lake, in this case the half-graben, boundaries. Recognizing the fan delta depositional system (Brown and Fisher, 1977) allows the prediction of facies distribution within the unit. Both Brown and Fisher (1977) and Xijiang (1987) present examples of lacustrine fan deltas imaged in seismic data as they relate to facies distributions within the seismic stratigraphic unit.

The best cross-section of unit III is provided by line 11Y. (Figure 4-4). The uniform, parallel reflections probably represent A_X of Table 4-4, the sandstone and interbedded sand and shale lithofacies which St. Peter (1992) interprets as marginal lacustrine. Considering the external geometry and seismic characteristics of this facies, it is likely a broad delta plain which, depending on lake level is also the lake floor. Still closer to the basin margin, the seismic reflections become less continuous, but this may be a function of the increasing dip rather than lithology. Although not imaged on line 11Y, the proximal chaotic mound likely represents the final facies making up the depositional systems tract: the alluvial fan feeding the lake. The borehole data suggest an overall transgressive facies succession, from proximal basal conglomerate representing the braided stream or sheet-flood deposits of the alluvial fan upward through: the wave-rippled sandstone which is fluvial-deltaic; interbedded sandstone/mudstone which represents the delta plain; mudcracked mudstone suggestive of a lower alluvial plain or periodically exposed prodelta; and kerogenous mudstone facies representing the deep, or at least anoxic, lake environment. Both Greiner (1962) and St. Peter (1992) recognized that the Lake Albert at this point in Tournaisian time, during deposition of the Frederick Brook (oil shale) member, was at its deepest and probably most areally extensive.

The upper boundary of unit III is a maximum flooding surface (Galloway, 1989). Three lines of evidence suggest Lake Albert was present for the duration of unit III deposition and hence lake level served as a base level for sediment deposition during that time. These observations are as follows.

1. Borehole data at the Lee Brook well show a monotonically deepening-upward facies succession in unit III suggestive of a single megacycle of lacustrine sediment deposition.

2. Seismic observations of the external form, bounding reflector configurations and internal reflection characteristics are analogous to those for well documented marine transgressive units.

3. Previous studies of the Albert Formation (Greiner, 1962; St. Peter, 1992) suggest that the Albert Lake was present throughout the subbasin, for most if not all Tournaisian time, based on fossil and lithological evidence.

This may seem quite laborious, but the legitimacy of seismic stratigraphic interpretation in non-marine successions has not yet been demonstrated in the literature. So far my analysis has been generic. The definition and description of the seismic stratigraphic units applied in the above analysis does not rely on assumptions that the sea is nearby, but the interpretation of the upper boundary of unit III as a maximum flooding surface is tacitly based on the model of a marine setting and transgressing shoreline. Given the above evidence for unit III I feel justified in drawing an analogy between sea level and lake level in interpreting the observed facies succession in terms of the interplay between lake level rise and fall, tectonic subsidence and sediment supply.

Greiner (1962) and St. Peter (1992) implicitly recognized the existence of a maximum flooding surface within the Frederick Brook oil shale member. The recognition of this surface based on seismic criteria makes it mappable geophysically and provides a powerful technique for predicting the presence of the oil shale unit in the subsurface.

Where unit IV is intersected in the Lee Brook Well, it consists of a thick succession (ca. 500 m stratigraphic thickness) with kerogenous shales at the base and sandstone facies at the top. Within the unit, St. Peter (1992) has divided the Albert into an alternating succession of sandstone, mudstone and interbedded sandstone/mudstone lithofacies units. The combined observations of the basin-fill form and the crudely shallowing upward (regressive) facies succession suggests the lake gradually receded during the time of unit IV deposition. Since the A_x lithofacies is present at several levels throughout the unit, and is interpreted by St. Peter as being the product of small scale transgression and regression of the lake margin, we might predict that deeper lake conditions will be found basinward from the borehole. However, the seismic stratigraphic evidence suggests that there is little or no lateral change in seismic facies so these upper Albert beds may represent the periodic transgression and regression of a shallow lake over a large area, perhaps in response to climatic variations.

Unit V, where it is encountered in the borehole (Figure 4-10), coincides almost exactly with the Weldon Formation, a thick succession of alluvial deposits traditionally differentiated from the Albert Formation on the basis of its colour, the Weldon shales being dominantly red and the Albert dominantly grey. Colour boundaries are not inherently reflected in seismic data so it is a challenge to explain first why the formation and seismic stratigraphic boundaries coincide and secondly, what implication this coincidence has for our understanding of the Weldon Formation.

The external form of Unit V is a northeast-southwest striking trough, the top of which is eroded in the north. The seismic facies, together with the basin-fill external form of Unit V, suggest that the thick sandy alluvial succession drilled in the Lee Brook well grades northward into a more layered and hence reflective facies. This is likely representative of the finer grained Weldon siltstones and shales found at this stratigraphic level elsewhere in the basin and described by Schroder (1963) as largely composed of red siltstone with minor amounts of interbedded shales locally containing caliche nodules, fine-grained sandstones and sandstones deposited in fluviolacustrine or playa environments.

The lower boundary of unit V shows a downlapping relationship with the sediment-starved distal upper surface of the upper Albert (Unit IV) with an apparent angle of discordance of about 11° seen at the north end of line 13Y (Figure 4-4; Plate 4-3). These distal fluvial sediments would have been flat-lying when deposited suggesting the unit IV sediments had been tilted at the close of Albert Formation deposition. Erosion of the distal sediments at the top of unit IV may accompany this tilting but this is hard to confirm from the data of Plate 4-3. Elsewhere in the subbasin, a playa evaporite facies (Gautreau Member) occurs at approximately this stratigraphic level indicative of an increasingly arid climate and the succession of the perennial lake by an ephemeral one.

Unit VI, although not drilled at Lee Brook, is bounded at its base by the Windsor marine transgression. Basal limestones and evaporites of the Windsor Group generate continuous reflections throughout the subbasin, and the overlying Hopewell Boss Point and Pictou Group rocks make up the remainder of the sedimentary wedge.

4.4.5 Chronostratigraphy

A chronostratigraphic chart can be prepared which represents the time and space relationships among seismic stratigraphic units in the Horton Group as shown in Figure 4-11(B). The vertical axis is geologic time, but can only be calibrated with detailed biostratigraphy, which is not available for the Lee Brook well. The approximate geologic age of the units (discussed in chapter 2) is shown at right. The chart displays the apparent geologic time span of each sequence with apparent time gaps between sequences based on the assumption that seismic reflectors are time lines and attempts to interpret variations in seismic reflection character within units in terms of facies.

The chronostratigraphic chart has two tectonic implications. The first is that fault-bounded subsidence occurred during time units I and II corresponding to the Late Devonian. Within that time period, fault movement was shifted back from normal faults near the basin centre to those nearer the basin margin. Within this succession there is a general trend for coarse proximal facies to build out into the basin in unit I and unit IIB time, and for facies boundaries to retreat toward the basin margin through unit IIA time. Downlap of reflectors at the bases of units I and II indicates at least two local time gaps in the rock record. These can be interpreted as periods of low preservation potential. Many more, unresolvable seismically may be present within units I and II. The simplest explanation for these observations is that the periodic rejuvenation of fault-bounded subsidence given a relatively constant sediment supply has governed both the gross facies patterns and the time gaps in the rock record with coarse facies building farther out into the basin when subsidence lags behind sediment supply (Blair and Bilodeau, 1990). Seismic stratigraphic units observed in this context have also been documented in the Devonian of northern Britain by another worker (Prosser, 1993) who refers to them as "tectonic stratigraphic units".

A second implication of the chronostratigraphic chart is that at the end of unit II and dawn of unit III time, the generally fining upward facies succession which extended until the end of unit III time had begun. Prolonged lake deposition requires the maintenance of a topographic depression, in other words, subsidence must accommodate or exceed the sediment supply or the lake will become overfilled. Although movement on the faults shown in the chronostratigraphic chart of Figure 4-11 had ceased, subsidence on step-back faults closer to the basin margin had apparently continued at least into Unit III time as evidenced by the coarse proximal facies at the base of Unit III. The timing and nature of subsidence is consistent with Hamblin's (1992) view that Tournaisian lacustrine sedimentation occurred during a stage of maximum fault-bounded extensional subsidence. He describes the Ainsley and Strathlorne Subbasins of Cape Breton, Nova Scotia, which are half-grabens similar in age, structural style, stratigraphy, and tectonic setting to the Elgin Subbasin. This period of maximum subsidence extended until the end of unit III time and is represented in the seismic data by the maximum flooding surface.

During unit IV time, accommodation and sediment supply were in approximate balance. Minor transgressions and regressions of the Lake shoreline may represent either climatic or tectonic factors. Time unit V marks the onset of red-bed diagenesis and the apparent disappearance of the perennial lake. The isopach map (Figure 4-10) indicates the Lake Albert depression had been filled and that either the climate or drainage patterns had changed markedly. Elsewhere in the Moncton Subbasin, near Weldon, this is a time of rapid localized subsidence, and as I discuss in Chapter 5, the close of Unit V time is a time of compression at the southeastern basin margin. Tectonic activity elsewhere in the basin in unit V time may have affected the drainage patterns at that time.

4.4.6 Quantitative Observations of Subsidence and Strain Rates

The ultimate transgression of the Windsor sea into the Elgin - Portage Vale area is marked by the strong reflections from the marine-nonmarine sediment contact at the beginning of time unit VI. At this time the basin floor was below sea level. Approximately 1.7 s of sediment lie beneath the Visean seafloor of unit VI and the floor of the Late Devonian intermontane valley which is the base of unit I in Plate 4-3. This places a lower limit of 4.2 km on the Late Devonian - Early Carboniferous subsidence without accounting for compaction. If the Late Devonian basins occurred on thickened crust after the Acadian orogeny, the valley floors may have been at altitudes of 1 to 2 kilometres such as those found today in modern post-orogenic extensional terranes such as the Basin and Range. Not knowing the exact age of the basal sediments also leaves some room for error in the depositional time span, but if the basal sediments are Frasnian, as spores in the Memramcook Formation imply, or Late Devonian as plant fossils in the Perry Formation suggest, then the time spanned by units I to V is 25-35 million years and the average post-Acadian subsidence rate was between 4.2 km/35 Ma (120 mm / 10^3 yr) and 6.2 km/25 My (250 mm / 10^3 yr). The effect of sediment compaction is not accounted for here, so these subsidence rates must be considered lower limits on the true value.

An important observation can be made from the time-thickness maps of successively younger Horton seismic-stratigraphic units. The depocentre, represented by the point of maximum unit thickness, can be seen to drift westward with geologic time as one examines the maps of Units II through V (Figures 4-5 to 4-9). The westward drift in the depocentre is approximately 3 km in the 25 My between Unit II and unit 5 deposition. If this westward shift in the locus of maximum sediment accumulation is allocyclic, that is representing tectonic processes, rather than autocyclic, representing sedimentary processes, such as delta lobe switching or fluvial channel avulsion, then it is evidence for a dextral strike-slip component of movement on the basin boundary faults during Horton Group deposition. The fact that the alluvial fan and fan delta deposits of units II and III (Figures 4-5, 4-7) exhibit this westward drift and are demonstrably deposited under tectonic control argues for a strike-slip component of Horton basin evolution, an idea which will be revisited in chapter 5.

4.4.7 Summary

The Horton Group basin fill can be subdivided using seismic stratigraphy. Both the Weldon Formation (unit IV) and the Memramcook Formation (units I and II) correspond with seismic stratigraphic units, and are thus mappable in the subsurface using seismic data. The Weldon Formation is widespread, while the Memramcook Formation occupies many linked fault-bounded wedges at the base of the Horton Group.

The Albert Formation consists of two seismic stratigraphic units (units III and IV; Figure 4-4) in which the thick lacustrine succession is analogous seismically to a marine succession consisting of a lower, transgressive systems tract separated from an upper, regressive systems tract by a maximum flooding surface. High grade oil shales of the Frederick Brook Member are associated with this maximum flooding surface and are therefore mappable seismically in the

Elgin - Portage Vale area. The applicability of these sequence stratigraphic concepts as tools for lithofacies prediction was unexpected since they have been developed for marine sediments deposited under the control of a transgressing or regressing shoreline. However, recent workers in lacustrine basin fills (Xue and Galloway, 1993; Oviatt et al., 1994) are detailing sequence stratigraphic observations associated with the occurrence of lacustrine source rocks.

A chronostratigraphic chart has been compiled for the Elgin Portage Vale area which indicates that fault-bounded subsidence was episodic in the Late Devonian and reached a maximum during the late Tournaisian, when the oil shales were deposited.

Average subsidence rate during Horton Group deposition (Frasnian to Tournaisian Tn_3) exceeded 120 mm / 1000 years in the Elgin "subbasin" and was accompanied by a westward drift of the Elgin alluvial fan, of approximately 3 km during that time.

5.0 Early Carboniferous Tectonic Evolution of the Moncton Subbasin

> *"The outstanding structural feature of the area is the amount of deformation shown by the Mississippian strata as compared with those of Pennsylvanian age. The Mississippian strata have been folded and faulted; show steep dips in many places; and have a generally northeasterly trend. The Pennsylvanian, Petitcodiac beds, on the other hand, are only gently warped and, commonly are nearly flat-lying."*
>
> *Stewart, J.S. 1941 (Salisbury map sheet)*

5.1 Introduction

The objective of this chapter is to characterize the Late Devonian and Early Carboniferous basin and its state of deformation and, if possible, to describe the kinematics of its inception and subsequent deformation. Even a cursory examination of the geologic features of the study area hints at a far different structural history for rocks of Hortonian age and older compared to those of the upper Carboniferous succession. Today Horton Group rocks, which had originally been deposited in an intermontane valley, are found uplifted, deformed and partially eroded. The style of deformation as revealed by a synthesis of geologic observation and geophysical data is discussed in this chapter and its timing is debated. The basin geometry and the kinematics of subsidence are documented with reference to the central

Moncton Subbasin and its southern margin with the Caledonia massif. The southern margin between Hillsborough and Goshen was chosen for this part of the study since it satisfies three main criteria:

1. A good compilation of Horton Group surface geology is available in the area; the Horton Group being exposed in streams along several creeks flowing north from the Caledonia Mountains.
2. Early Carboniferous structures along the southern basin margin are less obscured by late and post-Carboniferous events than those of the Kingston uplift. There is some tectonic overprint, but it is confined to the vicinity of the major fault zones; and
3. Good seismic control is available for this area, with eighteen dip lines approaching or crossing the southern basin margin between Hillsborough and Goshen.

No account of the kinematics of Horton basin inception has been published for this part of the Maritimes Basin. Foley (1989) has hypothesized a linked set of block faults bounding the Caledonia and Westmoreland uplifts upon which subsidence was accommodated in the Moncton area. This model, shown in Figure 5-1 and based primarily on well data, is the first attempt at a detailed kinematic model for basin development. Both Belt (1968) and Ruitenberg and McCutcheon

(1982) characterize the Late Devonian/Early Carboniferous tectonic style as block faulting during a period of "distension" (Ruitenberg and McCutcheon, 1982) following the Acadian Orogeny. At the same time major intrusions were emplaced in the St. Croix Terrane and locally the Avalon zone, and subsidence began in the Moncton and Cumberland Subbasins. Some authors (Belt, 1968; Bradley, 1982; Grierson et al., 1987) consider this period of subsidence to be the natural expression of regional wrench tectonics, but none has attempted any reconstruction of the southern New Brunswick kinematic history.

In the following sections I will present geophysical data, its analysis, and interpretation, with the goal of developing a kinematic synthesis of the Late Devonian/Early Carboniferous events in the Moncton Subbasin. In Section 5.2, key geological observations constraining the interpretation are discussed. In section 5.3 the data and analysis techniques are reviewed and in section 5.4 the results of that analysis are presented upon which, in section 5.5, a kinematic model of Horton basin evolution is hypothesized.

5.2 Geological Observations and their Tectonic Implications

In the sections which follow, key geological observations which bear upon the structural history of the subbasin's southern margin and hence upon any viable geophysical interpretation, are summarized. Since geological maps are themselves interpretations, I attempt to limit the discussion to the actual observations of structures, contact relationships and sedimentological indicators which bear upon the objectives of this chapter; separating as far as possible observation from hypothesis in the literature.

5.2.1 Provenance and Paleocurrents

It is important to begin this section with some key sedimentological observations, since sedimentation is profoundly affected by tectonics.

The Memramcook Formation, the focus of an M.Sc. thesis by a student of Belt (Popper, 1965) has seen little detailed sedimentological study since then. Clasts in the Memramcook are mainly Precambrian volcanics, metamorphics and plutonics derived from the Caledonia massif (Popper, 1965) shed northeast into the subbasin. A notable exception are the limestone clasts in conglomerates at Stoney Creek, recognized by St. Peter (1992) as Green Head Group marble. The most likely location of the Brookville Terrane source for these clasts is an inlier I have proposed in the subsurface north of Moncton (Figure 3-15), which must therefore have been exposed in the Late Devonian. Paleocurrent indicators, primarily crossbeds, in that area suggest a southerly (158 degrees) sediment transport direction (St. Peter, 1992), indicating that the Brookville rocks of the Westmoreland uplift formed a northern sediment source area at that time.

Albert Formation sediments, interpreted as having been deposited in and around a Tournaisian lake (Greiner, 1974) have been subdivided into distinct lithofacies by St. Peter (1989a,b, 1992) as discussed in Chapters 2 and 4. The distribution of the conglomeratic lithofacies provide clues to the location of the early basin margins. There were several separate alluvial fans feeding the intermontane Albert lake or lakes. In Chapter 4, an alluvial fan in the Elgin area was discussed. Surface geological mapping and borehole observations point to the locations of at least three more (St. Peter, 1992). Two fans are indicated by the presence of debris flow conglomerates at Prosser Brook and in the Caledonia-Boudreau areas (Plate 2-1). Debris flows are poorly sorted, matrix supported, deposits which are deposited on the steep slopes near the alluvial fan apex (Reading, 1982). Most other conglomerates are grain-supported, braided stream deposits or fan delta deposits with interbedded limestones suggesting the alluvial fan(s) shed coarse sediment right into the central lake. Albert conglomerates found in the subsurface south of Moncton occur at progressively higher stratigraphic levels from northeast to southwest suggesting a fourth alluvial fan must have been present in the north, perhaps in the Salisbury area, which prograded southwards during the

Tournaisian; another clue that there was positive relief on the Westmoreland Uplift in Horton time.

Published paleocurrent measurements for the Albert Formation are shown in Figure 5-2(a). When plotted on the linked-rhomb basin map from Chapter 3 (Figure 5-2) one sees that there is a spatial association between the measured paleocurrents and the linked depocentres as interpreted in this thesis. Some flows are transverse to the basin axis; others, located nearest the east-west fault boundary segments, are westward into the adjacent subbasin.

The Weldon Formation is marked locally by coarse angular conglomerate at the base grading distally and upwards into the fine-grained red sediments more widely typical of that formation. In much of the Moncton Subbasin the Weldon and Hillsborough formations are undivided and no paleocurrent analysis of the Weldon Formation or Gautreau evaporite member has been published.

5.2.2 Contact Relationships of the Southern Basin Margin

Evidence for thrusting at the basin margins is discussed by St. Peter (1992). The Caledonia Fault is probably a post-Horton reverse fault with some degree of oblique slip evidenced by its association with megascopic folds trending obliquely into the fault zone (Gussow, 1953; St. Peter, 1989a, 1992). The repetition of conglomerate beds, juxtaposition of offshore fine facies rocks with basement (Figure 5-13) and seismic evidence for a low-angle, northeast-dipping fault zone all support the thrust fault hypothesis.

Some motion on the southern basin-margin faults is demonstrably post-Windsor. Most notably the Prosser Mountain and Hillsborough faults both have post-Moncton displacements; the Prosser Mountain Fault places basement over Hillsborough conglomerate, and the Hillsborough Fault thrusts Weldon shales south over what Gussow (1953) considered to be Hillsborough conglomerate (Plate 2-1). The Hillsborough Fault has not moved since the Namurian. It is sealed by the Enragé Formation (Hopewell Group) north of the Petitcodiac River (St. Peter, 1989a).

Contact relationships at the southern basin margin suggest that the lower Horton sediments were deposited in a fault-bounded basin with its southeastern edge at or near the present-day subbasin margin. Most exposures of the Memramcook Formation along the southeastern subbasin margin are conglomerates forming immediately adjacent to the Caledonia Massif while finer-grained sediments are found more distally. The Memramcook is in fault contact with basement everywhere except in the Rosevale and Walker Settlement areas (Figure 2-1). Near Rosevale (see Fig 2-1, inset, for detail) fine facies Albert shales overlie rocks of the Caledonia Massif and dip gently to the North. Their contact has been interpreted as an unconformity (Gussow, 1953; St. Peter, 1989a). Near Walker Settlement (Plate 2-1), the Memramcook outcrops as a long thin strip dipping gently to the northwest at 25-30 degrees, onlapping basement, and overlain conformably by Albert limestone and conglomeratic sandstone.

5.2.3 Tectonic Implications of the Structural and Stratigraphic Observations

It is possible, given the observations of the preceding sections, to make some inferences about the basin-bounding fault system and the nature of subsidence during Horton Group deposition.

Most authors (St. Peter, 1992; Carter and Pickerel, 1985; Gussow, 1953) have taken the basin margin observations to suggest that, at the time of Horton deposition, it was approximately where it is today. If the subbasin is a wrench basin as suggested by Webb(1963), Bradley(1982) and Grierson et al. (1987), one might expect the bounding fault, if it is indeed the master fault, to be a long, linear, near vertical long-lived feature comparable to the strike-slip faults founding well documented pull-aparts such as the Ridge (Crowell, 1974) or Hornelen (Steel, 1976) basins. But the map evidence is apparently conflicting. The Caledonia Fault is neither straight nor throughgoing, and the southern Horton basin margin is fault-bounded in some places and not in others. Albert shales onlapping basement at Rosevale may have extended over much of the Caledonia Uplift and may have been subsequently eroded (Macauley, 1981). One possible basin-margin faulting style which would explain the observations is a fault system in which displacement is transferred from one fault to another along strike. In a summary of alluvial fan settings, Heward (1978) calls this the "limited back-faulting" setting and coincidentally chooses a Maritimes basin example (Belt, 1965; Figure 5-3[A]) to illustrate it. Progressive collapse of the footwall block in this way has also been described in half-grabens of the North Sea (Beach, 1984). *En echelon* series of normal faults as shown in Figure 5-3(B,C), account for similar map patterns (Ramsey and Huber, 1987).

Post-Horton faulting clearly overprints structures of the southern basin margin, and the activation of reverse faults dipping into the basin along the basin margin, which by their association with basin margin facies were likely once normal faults, is map evidence of an inverted basin margin.

The paleocurrent data suggest that the Elgin fan fed a depocentre to the West distinct from those ringing the northern (Hillsborough) "subbasin". The sedimentological data suggests the basin fill was mainly sourced from the southeastern side and that preservation was episodic due to fluctuations in either fault rate, or sediment supply, or both. Although hard to reconcile with a simple trough-shaped basin, the Horton Group paleocurrents (Figure 5-2) support the hypothesis of an early Moncton Subbasin consisting of a series of linked half-grabens.

5.3 Geophysical Data Analysis

5.3.1 Time-structure Mapping

In Chapter 4 the procedure for tying well and seismic data with the aid of synthetic seismograms was described. In this section the seismic mapping procedure is described, the results of which are presented in Section 5.4. For this part of the analysis, 35 seismic lines in the central subbasin (Figure 5-4) were interpreted using the following procedure. Four key horizons were identified from well ties: top reflective basement, top basement (base Horton), base Windsor/Hillsborough and near base Boss Point. These events were identified wherever possible and tied in closed loops from line to line. Two-way times were picked from migrated dip lines, posted and contoured to make time-structure maps of

1. base Horton Group unconformity; and
2. base Windsor Group.

Before picks could be correlated around the data grid, faults were identified and the fault traces rationalized. Faults were identified on the basis of three criteria: vertical reflector offset, fault plane reflections, and diffractions from abrupt reflector terminations. Diffractions were identified on all unmigrated seismic sections using a diffraction overlay.

Seventeen sections crossing the southern basin margin are shown on Figure 5-5 in the form of line drawings based on the migrated sections.

The pre-Carboniferous basement, as one might expect from the discussion of Chapter 3, exhibits a variety of seismic expressions making the identification of Horton/Basement contact problematic. In the area spanned by the seismic lines of Figure 5-5, five wells provide control on the seismic interpretation but only one intersects basement. Basement picks are constrained by the geological map of Plate 2-1, and by the Middlesex well on Line 1 (Figure 4-3), which intersects basement: Green Head Group marble of the Brookville Terrane. Basement is indicated on some lines by diffractions generated by topographic features at the basement-sediment interface which have small radii of curvature in relation to the seismic wavelength (e.g. lines 1, 97, 91 and 83Y beneath the basal Windsor reflection). Elsewhere, as on most of line 89y, the sediment-basement contact is defined by a reflection separating an upper, layered unit from a lower, reflection-free one. Figure 5-6 shows schematically the relationship between the reflection-free basement and the reflective basement facies discussed in Chapter 3.

5.3.2 Cross-section Balancing

Cross-section balancing (Appendix C) is a quantitative interpretation technique for assuring the kinematic viability of interpreted structures. The goal of cross-section balancing in this thesis was to determine whether observed low-angle reflections beneath the Horton section were in fact faults and whether there is a genetic link between the observed faults and the pattern of sedimentary basin fill which might give a feasible explanation of the magnitude and timing of the fault movement responsible for Horton basin subsidence. I will start by making the assumption of plane strain and evaluate that assumption *a posteriori*.

Having made the initial observation that the Horton Group sediments in the northern Moncton Subbasin (Hillsborough Subbasin of Worth, 1982) are deposited in a half-graben, cross-section balancing may help to validate the interpretation and make quantitative estimates of net fault movement since the Late Devonian.

Table 5-1

TWO-WAY TIME (S)	AVERAGE VELOCITY (km/s)
0.000	3.75
0.400	4.20
1.000	4.30
2.000	4.60

A line drawing of line 11 (Figure 5-7A[i]), was converted to depth using the time-depth rule from a velocity survey of the nearby Irving/Chevron Lee Brook well. The simplified average velocity profile used to convert time to depth is given in Table 5-1.

The next stage was to restore the post-Horton subsidence by flattening the basal Windsor/Hillsborough unconformity, an erosional peneplane (Figure 5-7A[ii]). Then it was possible to determine whether the low angle reflection dipping beneath the basin, interpreted as a fault, constitutes a viable fault plane given the structure of rocks in the hanging wall. To approach this problem the Chevron model of hanging wall deformation (Verrall, 1982) was used. All points in the hanging wall are allowed to collapse by vertical simple shear and heave, the horizontal component of displacement, is constrained to be the same for all points in the hanging wall. The adoption of this model does not presume the mechanics of the deformation to be governed by vertical faults, but rather that the bulk properties of the hanging wall can be approximated by such a model. If much of the hanging wall deformation is distributed among brittle synthetic and antithetic fractures, the vertical simple shear model may be expected to simulate the gross deformation.

The basin-bounding fault is a detachment (low-angle, soling) fault cutting the basal Albert reflector at "P" of

Figure 5-7A(i), but its surface trace, unknown since it is off the end of Line 11, is also required to calculate the fault projection to depth. Several fault trajectories were calculated on the hypothesis that one of the three faults mapped off the line's end may be the surface trace of the detachment. These faults are the Pollett River (A), Gordon Falls (B) and Gowland Mountain (C) faults of St. Peter (1989a). As shown in Figure 5-7A(iii), a fault whose surface trace is 3.4 km south of the end of Line 11, fault "C" in the figure, when constrained by the observed hanging wall structure, has a theoretical fault trajectory in the subsurface nearly coincident with the interpreted fault plane supporting that interpretation with minor modification. One can now attempt to retrodeform the section to the time of basal Horton Group deposition as shown in Figure 5-7B(i). The genesis of the Horton half-graben can be simulated (Figure 5-7B(i to iii) by progressively extending the restored section on the observed fault plane providing net heave on the detachment fault is approximately 7 kilometres.

Figure 5-7B(i) then, is the pre-Horton configuration of the basement rocks. Does it pass the test as a reasonable pre-extension template? In this Late Devonian restoration a 1 to 2 km thick wedge of transparent basement facies is shown overriding another, separated by a fault dipping 20 degrees northwest. This configuration fits well the description of a south-verging thrust mapped by McLeod and McCutcheon (1981) among post-Cambrian thrust faults in the Little Salmon River area of the Caledonia Massif. The basin-bounding fault then, is likely a pre-existing thrust fault reactivated in Late Devonian to accommodate some 7 km of extension in Late Devonian and Tournaisian time. Its present-day surface trace coincides with that of the Gowland Mountain Fault shown in Plate 2-1.

From this exercise a quantitative estimate of post-Acadian extension can be obtained. The extension ratio, ß, of a column of crust of original horizontal length *l* and present length , *L*, is *L/l*. For the half-graben of Figure 5-7, that is approximately 13 km/ 10 km or ß=1.3. As an estimate of post-Acadian extension the ß factor as calculated for a single fault block does not necessarily represent a mean for the region (Chenet et al., 1982): the distribution and width of adjacent fault blocks is not yet known but it does provide one quantitative estimate of strain in the study area which can be tested in the following sections by independent means.

5.3.3 Analysis of Basement Trend Map

The map of thick Carboniferous cover (Figure 3-15), like the total magnetic field map of Figure 3-5, exhibits the form of a linked series of rhombohedrons bounded dominantly by northeast-southwest lineations. Since the Visean and younger succession forms a broad blanket over the Horton half-grabens one can hypothesize that the map pattern of Figure 3-15 represents the pattern of Horton subbasins in the subsurface.

This elbow-shaped plan of the magnetic lineaments of Figure 3-13 is characteristic of the type of pull-apart basin which develops by the coalescence of smaller pull-aparts in a system of right-stepping en echelon strike-slip fault strands (Aydin and Nur, 1982). In this section quantitative estimates of the fault movements required to generate such a map pattern are attempted.

An implicit assumption is noted as inherent in any attempt to quantitatively interpret the map pattern: that insofar as the magnetic pattern represents Horton basin geometry, it is today's geometry, with all Carboniferous and younger folding and faulting superimposed, the effect of which should be assessed *a posteriori* (Chapter 6).

Considering the Sussex, Elgin and Hillsborough "subbasins" (Figure 5-1) as linked rhombochasms (Figure 5-8[A]), the north and south basin margins can be juxtaposed to close the Horton basins and determine the best "fit". That is the map configuration as it would have looked before the Horton basins opened if they are composite pull-apart basins as Bradley's (1982) theory suggests. Figure 5-8 shows the two best fits.

Fit 1: 34 km dextral slip on the Kennebecasis-Berry

Mills, Clover Hill-Caledonia and Hillsborough-Dorchester fault systems. This is a "tight" fit since closing the Sussex Subbasin completely requires some 100 km^2 of overlap in the Middlesex area; however, this does not invalidate the strike-slip construction. The total displacement may have been partitioned among the faults in such as way as to minimize the overlap.

1. Fit 2: 14 km net oblique extension on the same fault systems. This reconstruction gives a better pre-Late Devonian fit than the pure strike-sip solution and is more consistent with the magnitude of strike-slip component implied by the migrating Horton depocentre of Chapter 4. The north-south orientation of the extension axis furthermore provides map evidence that the plane strain assumption for the north-south cross-section of Figure 5.7 is realistic. Since 14 kilometres is the width of the Horton basin, and the basin itself is not infinitely deep, the extensional fault heave must be less than 14 km. If the extension factor of β=1.3 is representative, the actual fault heave which would give rise to the 14 km basin width would be

$$14 \times (\beta-1)/\beta.$$

The actual horizontal component of fault movement implied by this map reconstruction is therefore on the order of 3.2 kilometres.

5.4 Results

5.4.1 Horton Basin Architecture and Fault Geometry

Seismic reflection data across the southern subbasin margin are presented in Figure 5-9 in the form of interpreted line drawings. Seventeen lines crossing the central Moncton subbasin and the southern basin margin fault system image a southward-thickening sequence of Weldon and older sediments overlain with pronounced angular unconformity by a southwest-thickening wedge of Hillsborough and younger rocks.

In contrast to the Hillsborough/Windsor sequence, which is characterized, at its base, by continuous sub-parallel reflectors (see line 89Y, Plate 3-3) and is virtually unfaulted, the Horton section, particularly its lower part, exhibits poor reflection continuity, which is typical of alluvial fan deposits (Brown and Fisher, 1977). Furthermore, the Horton section is much faulted; dominated by NW-dipping normal faults which bound the half-graben in which Horton sediments were deposited. Most of these faults cut basement and have been active during sediment deposition, and some show evidence of reactivation as reverse faults. Total thickness of Horton sediments reaches 1.7 s or 4.2 km in the Goshen area (Line 13Y). Beneath the Horton half-graben, pre-Carboniferous basement rocks exhibit two distinct seismic characteristics, as discussed in Chapter 3. The structural relationship between the two basement types, discussed in Chapter 3, and the

Carboniferous sediments is shown on the line drawings of Figure 5-9 and schematically in Figure 5-6. The transparent basement occupies a wedge riding on a basal detachment whose extensional component of displacement has formed the half-graben in which Horton sediments were deposited.

Three sets of faults cutting the Horton section are evident on the cross-sections of Figure 5-9. These include:

1. listric basin-bounding faults, some of which appear to have been partially reactivated as thrusts;
2. synthetic and antithetic normal faults within the basin fill; and
3. late high-angle thrust or strike-slip faults with associated antithetic faults near the southern basin margin (eg. the Prosser Mountain and Hillsborough Faults).

The time structure map of the basal Horton unconformity (Figure 5-10) shows the relationship among these fault systems and the geometry of the central part of the subbasin. In map view the listric basin-bounding faults and smaller synthetic faults are concave-basinward exhibiting a crudely *en echelon* pattern stepping east as one heads from south to north toward the Westmoreland Uplift. In cross-section these basin-bounding faults step back into the footwall; but unlike the block faults of Figure 5-3(a), they are listric and are rooted in low-angle detachments well-marked by fault plane reflections on several lines of Figure 5-9. The basement surface shown in Figure 5-10 is generally saddle-shaped, showing clearly the central arch which distinguishes the Hillsborough and Elgin "subbasins". The Horton half-graben is well imaged, in most cases to within 5 km of the subbasin margin, where complex high angle faulting, steep dips, and non-reflective proximal alluvial lithofacies conspire to make the seismic interpretation of the fault pattern ambiguous. In particular, it is difficult to determine whether the high angle Prosser Mountain and Hillsborough faults are rooted in a near-vertical wrench fault zone, or whether all basin-margin faults are part of the linked system of low-angle faults which has accommodated basin subsidence. The question of timing and structural style of these high-angle faults in the "zone of intense faulting" (Figures 5-9, 5-10) is discussed in the following section.

The more steeply-dipping normal faults, both synthetic and antithetic, seen soling into the detachment in Figure 5-9, on line 11, are observed on most lines. It has been suggested by Wernicke and Burchfiel (1982) that such faults, which involve little or no rotation, may serve an important purpose as "space fillers" accommodating curvature in the underlying low angle fault while not themselves accounting for a significant component of the extension.

Unconformably overlying the Horton sediments is the

Windsor/Hillsborough sequence whose basal unconformity has been mapped wherever the Windsor Group is present (Figure 5-11). The base of the Windsor Group with accompanying limestones and evaporites is the most prominent reflector on the line drawings of Figure 5-9. The unconformity exhibits pronounced angularity in the central subbasin where Horton sediments in the middle of the subbasin show SE dips as great as 15° peneplaned before Hillsborough/Windsor deposition. Moving south, the dips gradually decrease so that at line 29Y the Windsor/Hillsborough lies with apparent conformity upon the Horton though at the basin margin Horton sediments appear to be tilted basinward (northwest) beneath the Windsor/Hillsborough cover.

The time-structure map of the basal Hillsborough/Windsor unconformity (Figure 5-11) shows a gentle NW dip of the Hillsborough/Windsor and younger strata into the Kennebecasis-Berry Mills Fault which must therefore be a Late- or Post-Carboniferous feature. Important for the Horton Group though, is the fact that little or no faulting is observed in the Windsor as it is mapped in the central subbasin. The post-Horton basin then, exhibits a broader, sag-style subsidence, contrasting markedly with the fault-bounded geometry of the Horton half-grabens. Furthermore, faults in the area of undisturbed "Near Base Windsor" reflectors must be due to pre-Hillsborough (Moncton Episode) deformation.

5.4.2 Structures Affecting Horton Group Rocks

Evidence for reactivation of the listric basin-bounding and synthetic normal faults is seen on the seismic data of Figure 5-9. Growth sequences in the lower Horton of Lines 62Y, 5Y, and 13Y have been rotated back up the basin-bounding fault to some degree and antithetic thrusts are seen on several lines (e.g. 83Y, 5Y, 97Y; Figure 5-9). On line 5Y, an antithetic normal fault has been reactivated in the manner observed by Hayward and Graham (1989) in the inverted Broad Fourteens Basin of the North Sea (Figure 5-12). Several of these lines display structures similar to those described in sandbox simulations of inverted half-grabens overlying faults with ramp-flat geometries (Figure 5-13(b) after McClay, 1989). Together with the geological evidence cited in section 5.2 for reactivation of basin margin faults as thrusts, the structures suggest the Horton Group basin has been partially inverted (Hayward and Graham, 1989). Basin-bounding faults have been reactivated, and the basin fill partially extruded as a consequence of the change from extension to compression.

As one moves from west to east across the basin, the style in which post-Horton compression is accommodated varies systematically. Lines 29Y and 66YA, at opposite ends of the rhomb, can be considered two end members of the structures observed.

Line 29Y shows no evidence of shortening in the basin fill, but Horton sediments near the basin margin have been tilted basinward. Lines 9Y through 1 exhibit compressional structures including back-thrusts in the basin fill, which are confined to within a few kilometres of the basin margin, while lines 1 through 83Y exhibit complex folding and faulting within 5 km of the basin margin (zone of complex faulting, Figure 5-9), and a wedge of basement, the Prosser Mountain Block, is involved (line 1 of Figure 5-9). Lines 75X to 66Y show a fault-bounded bulge of intensely faulted and folded Albert rocks. Some of this movement coincides with the deposition of the Weldon Formation which is folded in a synform near Weldon on lines 62YA and 66YA of Figure 5-9.

5.4.3 Basin-margin Fault Zone

The structures along the basin margin in the area labelled "zone of complex faulting" in Figures 5-9 and 5-10 are complex and poorly imaged by the seismic data. The probability that faults in this zone were active not only in the Moncton episode but also in the Namurian (Hopewell Episode) further complicates the structural interpretation problem. Two hypotheses are consistent with the data.

1. The deformed zone is a positive flower structure, a broad strike-slip fault zone which is deeply rooted and has dissected and locally expelled basin margin sediments or subsided as the strike-slip faults converge or

diverge. This is a classic "flower structure" (e.g. Harding, 1985) interpretation proposed by St. Peter (1992), in the tradition of Webb (1963).

2. The deformed zone is an inverted basin margin, where reversal of earlier movement on the basin-bounding faults has resulted in folding and high-angle reverse faulting along the southern basin margin, and a map pattern whose apparently dextral basement offsets are a consequence not of lateral offset but of the original *en echelon* arrangement of normal faults reactivated in compression.

Figure 5-14 shows alternative interpretations of the "zone of intense deformation" for lines 62Y, 75X, 91, 5Y and 11. Each of these interpretations is consistent with the cross-sectional form of the data of Figure 5-9. Harding (1990) has discussed the inherent problems of wrench fault identification from cross-sectional data alone. Unless the map patterns of the faults imaged seismically can be determined with some certainty, the seismic data cannot resolve the ambiguity. In Chapter 7, the basin margin fault zone will be revisited in the context of regional stresses and structures in an attempt to resolve the timing and style of faulting observed there.

5.5 Summary

5.5.1 Horton Basin Development

The observations of this chapter enable us to characterize the main features of Horton basin geometry and speculate on its kinematic development. Several authors have cited evidence for dextral wrench tectonics in late Devonian and early Carboniferous time in the Atlantic provinces (Webb, 1969; Belt, 1968; Hyde et al., 1988; Knight, 1980). Bradley (1982) has proposed that the Moncton Subbasin, like the Maritimes Basin, developed in response to regional strike-slip faulting.

From the fault pattern evidence it appears the Horton basin opened as a series of transtensional pull-aparts in a dextral fault system trending northeast-southwest through the region. Within the pull-apart system, extension has apparently been accommodated by normal or oblique slip on low-angle, ramped detachments as observed on line 11. Displacement on the faults in the system has been transferred eastward from the Kennebecasis to the Caledonia to the Hillsborough-Dorchester and Harvey-Hopewell faults, which *in toto* form a series of right-stepping *en echelon* fault strands (Rogers, 1980) which may be inherited elements from a previous Appalachian thrusting event. Post-orogenic listric normal faulting associated with the stretching and shearing of an orogenic system has been documented in the Great Basin and Pannonian

Basins (Bally, 1981), but the Vienna Basin (Royden, 1985) and Solway Basin (Gibbs, 1987) seem to be closer analogies to the Moncton Subbasin, experiencing oblique slip on systems of low-angle inherited detachments.

The apparent low-angle extension, seen in profile on line 11, combined with the complexity observed along strike in both profile and map view, suggest the Horton group basin is neither purely extensional nor purely strike slip, but is rather a "mixed-mode" basin (Gibbs, 1987) which has subsided on a system of linked faults, possibly the reactivated thrust surfaces of a previous Appalachian tectonic episode. Figure 5-15 from Gibbs (1987) shows an example of the pattern of reverse and normal faults which can develop in the hanging-wall of an oblique slip extensional fault. Unlike a purely extensional half-graben, where oblique slip occurs on the detachment surface, one might expect a combination of wrench, reverse faults and folding components of deformation in the hanging wall.

Geophysical estimates of the amount of post-Acadian north-south extension accommodating the Horton grabens between the Kennebecasis and Harvey Hopewell faults range from 3.2 to 7 km. The magnitude of Late Devonian and Tournaisian vertical subsidence exceeds 4.2 km. This is indicated by the thickness the Horton sediments near Goshen. Basal Horton sediments occupied an intermontane valley in Frasnian time which accommodated 4.2 km of sediment before being flooded by the sea in Mid-Visean time.

A consequence of these observations is that the Albert Formation rocks of the Kingston Uplift, which are distinct lithologically (Greiner, 1962) from those of the central subbasin, were not deposited in a lake connected to those of the Hillsborough and Elgin areas.

5.5.2 The Moncton Episode

Subsidence and sedimentation in the Moncton Subbasin were interrupted in late Tournaisian or early Visean time by an episode of folding, faulting and volcanism. The "Moncton episode" gives rise to the angular unconformity between the Weldon and Hillsborough formations. Map and cross-section data presented in this chapter suggest that this was an episode of compression, strike-slip faulting, or, more likely, a combination of the two.

The Hillsborough and younger section is gently tilted, but otherwise virtually undeformed in comparison to the Horton section as shown by the time structure map on the basal Windsor seismic reflection shown in Figure 5-11. Faults cutting the basal Windsor unconformity have only minor vertical displacement, and the general lack of deformation of the post-Windsor section suggests that any folding associated with later episodes is mainly restricted to areas near the present-day basin margin faults.

The zone of intense faulting along the basin margin does not allow a detailed structural interpretation of the seismic data. Two distinct episodes contributed to the deformation - the Moncton and Hopewell episodes.

The observations at the basin margin fault zone are summarized briefly below.

1. Geologic observations suggest that both convergence and oblique slip have occurred.
2. Some of the movement is post-Hillsborough.
3. High-angle faults with apparent reverse movement are observed in the seismic data.
4. Each of the interpretations of Figure 5-14 is consistent with the observations.

Timing of the structural deformation, or at least the amount of deformation which is attributable to the Moncton episode (Late Tournaisian or Early Visean), as opposed to the later Hopewell (Namurian) one, is difficult to quantify at this point. Our main clues, as mentioned in a previous section, are the structural relations involving the undatable Hillsborough Formation sediments. Line 66YA of Figure 5-9 (Plate 4-4) shows Moncton Group sediments in the hanging wall of the Hillsborough Fault folded into a broad syncline whose axis passes through the town of Weldon (Plate 2-1). The sediments in the syncline also thin toward the edges of the syncline, indicating that there was some degree of structural control on their deposition. The seismic evidence then, suggests that Moncton Group sediments of the Weldon syncline were being deposited during the Moncton episode. This classifies them as Weldon Formation and adds the first evidence that localized subsidence was occurring even as compressive structures were forming along strike during the Moncton episode, a common feature of strike-slip fault zones.

The Moncton episode, then, which signalled the end of Horton Group sedimentation, exhibits both compressional and strike-slip characteristics and is overprinted to an uncertain degree by a later faulting episode. To fully understand the Moncton event, one must first estimate the style and timing of that overprint. That task is the subject of the next chapter.

6.0 Tectonic Overprint of Late Carboniferous and Younger Events

6.1 Introduction

This thesis concerns the development of Horton basins in the Late Devonian and Early Carboniferous in a cycle of fault-bounded subsidence, deformation and erosion. This Horton cycle was later followed by a period of broad sag-style subsidence in the Moncton Subbasin and, on a larger scale (Bradley, 1982), in the Maritimes Basin as a whole. This broad regional subsidence was punctuated by multiple faulting episodes, and Horton structures are overprinted by tectonism, at least locally, in the Visean, Namurian, Westphalian and Triassic.

Crucial to characterizing the end of Horton event is the task of separating its effects from younger ones.

The best timing criterion is the presence of undisturbed cover strata: in seismic map and cross-section, deformation which affects the Horton section and overstepped by the Hillsborough/Windsor sequence must be Moncton episode deformation. The geologic map of Plate 2-1 also shows which faults are sealed by Windsor and younger rocks, although, in some key areas such as the Kingston uplift, the geologic map is itself largely interpretive, based on limited outcrop, and so cannot be given the same weight as direct seismic evidence or a well described section from borehole or outcrop. Where stratigraphic evidence is not available and there is some question as to how much if any of the local deformation is post-Horton then the approach followed in this chapter is to:

1. identify structural features which have a demonstrable post-Hillsborough component of deformation; and
2. characterize, where possible, their age and structural style.

If a good model for the regional stress distribution or an analogue to the tectonic setting of the time can be developed, then it may be possible to use the model to predict the style, extent and relative importance of each post-Horton tectonic event and its role in developing the basin and obscuring Hortonian geologic structures.

In the discussion which follows, I shall start with the youngest tectonic events and work back in time in an attempt to reconstruct the Horton basin and its state of deformation.

6.2 Triassic Overprint

The Bay of Fundy has long been recognized (Ballard and Uchupi, 1975) as a Late Triassic rift. Crustal thinning, part of the Pallisades disturbance (McWhae, 1981) formed grabens filled with redbeds and volcanic rocks in the northeastern U.S., Gulf of Maine and Bay of Fundy, where up to 4 km of Triassic and Early Jurassic sediments are preserved. Based on industry seismic data, Brown and Grantham (1992) identify two main depocentres, one at the southwest end of the Bay of

Fundy, the other in Chignecto Bay. Rifting in the Bay of Fundy was accompanied by abundant volcanism, but subsidence apparently stalled in the Early Jurassic by the time Atlantic seafloor spreading became active along the southern margin of the Scotian shelf.

It is clear that the Cobequid-Chedabucto Fault zone (Minas Geofracture of Keppie, 1982) served as a late Triassic sinistral transform, linking the Fundy and Orpheus rift grabens (Keppie, 1982; Wade, 1991). The magnitude of net Triassic displacement on the fault system is unclear. Keppie (1982) estimates that ca. 75 km of sinistral motion is implied on the Minas Geofracture. East-west fault movement of this magnitude would close the present day Bay of Fundy shorelines, but the half-graben profile imaged in the Bay of Fundy seismic data (Figure 6-1, modified from figure 9 of from Brown and Grantham, 1992) in which basal Triassic sediments dip ca. 14° NW into a graben-bounding fault dipping ca. 25° SE allows us to calculate a percentage of extension according to a simple geometrical rule (Wernicke and Burchfiel, 1982) for domino-style faulting where ϕ and θ are defined in the sketch of Figure 6-2:

$$\text{Percentage extension} = 100 \cdot \{ [\sin(\phi - \theta) / \sin \phi] - 1 \}$$
$$= 100 \cdot \{ [\sin(25°+14°) / \sin(25°)] -1\}$$
$$= 49 \%$$

If, as Brown and Grantham (1992) suggest, the graben bounding faults are listric, then an equivalent amount of subsidence can be accommodated by significantly less extension. Thus net extension in the Fundy rift is at most half its width, or 40 km, and is likely even less. Seismic evidence (Brown and Grantham, 1992) indicates some degree of late-stage compression on faults bounding the Fundy half-graben which must further reduce any estimate of net Triassic sinistral fault movement.

A second striking feature of the Bay of Fundy is the remarkable coincidence in its shape and that of the Red Sea with its northern extensions the Gulf of Suez and Gulf of Aquaba (Figure 6-3). The Cumberland Basin and Shepody Bays, together with their linear, branching northern extensions, the Petitcodiac, Memramcook and Tantrumar Rivers are remarkably similar in plan and Late Triassic tectonic setting to the rift splay faults at the northern end of the Gulf of Suez (Figure 6-3(B)). The formation of rift splay faults, where the rift encounters a region of thicker, or more competent crust, is one way rift segments stop propagating (Nelson et al. 1992). Rift splay geometry is typically a fanning-out of planar normal faults emanating from the end of a rift segment and displacement decreases rapidly along the fault traces as the extensional strain is partitioned over a broader area. Fault motions change from predominantly dip-slip within the rift segment proper to oblique-slip within the splay as the fault pattern fans out from the end of the segment. Most striking is the correspondence between the Triassic role of the Minas Geofracture and the Dead-Sea transform, which is presently undergoing sinistral strike slip motion related to the opening of the Red Sea.

A third and final observation bearing on the regional Triassic overprint is that throughout southern Nova Scotia a series of northwest-trending brittle faults can be found that occur at a variety of scales and are interpreted by Williams and Hy (1990), as transfer faults associated with the opening of the Atlantic. The motion on these is mainly sinistral, although a dip-slip component is also observed. Williams and Hy (1990) note that southeastern New Brunswick is also affected by this fault system and that the NW-trending Oak Bay fault near the Maine-New Brunswick border is likely one of these faults. This is significant since it provides an alternative view to that of McCutcheon and Robinson (1987). Those authors interpreted an untested magnetic anomaly in the Bay of Fundy near Campobello Island as the southeastern continuation of the Kingston complex. This allowed them to postulate 50 km of Devonian sinistral strike-slip on the Oak Bay Fault. With no post-Acadian motion on the Oak Bay fault they argue that there can be no net post-Acadian strike-slip motion on the Belleisle Fault (or the Kennebecasis Fault) which it offsets. Robinson and McCutcheon's reasoning is inconsistent with the observations of this thesis that the major southwest-northeast trending faults in southern New Brunswick have undergone Carboniferous strike-slip displacement. The Petitcodiac River, south and east of Moncton, and the series of northwest trending faults cutting the Caledonia Fault in the Parkindale to Rosevale area, are both held suspect as possible Triassic features. Recent earthquake activity in both the Oak Bay Fault and Petitcodiac River areas (Bell and Adams, 1991) is further evidence of post-Carboniferous motion on these faults This activity is likely due to isostatic post-glacial readjustment activating pre-existing zones of weakness (Mesozoic faults?) in the crust.

In summary, although none of the folding or faulting in the study area north and west or the Caledonia Uplift has been previously mapped as Triassic or younger, there _is_ a Triassic overprint which is responsible, after some Quaternary glacial modification (Swift and Lyall, 1968), for the present-day form of the Bay of Fundy and certain of the faults and physiographic features of the Moncton Subbasin. A palinspastic reconstruction of the pre-Late Triassic map pattern is shown in Figure 6.4 and has the following features:

1. Shepody Bay, Cumberland Basin, Chignecto Bay and Minas Basin together are Triassic features, which by analogy with

the Red Sea Rift can be entirely attributed to Late Triassic rifting; and

2. rivers splaying from the northern extensions of the Bay of Fundy are the expression of Mesozoic rift splay faulting. These include the Memramcook and Tantrumar Rivers and the Petitcodiac River East of Moncton. Displacement on these faults was likely minor oblique slip decreasing in magnitude along trace to the north.

3. Approximately 40 km (upper limit) of Late Triassic and Early Jurassic sinistral motion on the Minas Geofracture has been restored which, linked to the offshore "Fundy Fault" (Ballard and Uchupi, 1975), accounts for the observed extension in the Bay of Fundy south of Minas Basin.

4. Linear northwest-trending topographic features and faults in southern New Brunswick including the Oak Bay Fault, the Petitcodiac River and several faults west of Rosevale are candidates for a regional Late Triassic sinistral oblique slip fault system and have all been restored or removed from the reconstruction of Figure 6-4. In particular, 8 km of sinistral displacement has been restored on the Oak Bay Fault.

6.3 Late Carboniferous Tectonic Overprint

6.3.1 Observation

Structures in the Moncton Subbasin which are demonstrably Late Carboniferous fall into two categories;

i) Namurian features which Gussow refers to as Pre-Enragé, being sealed by the upper Hopewell (Enragé) and Boss Point formations, and

ii) those which affect the Boss Point (Westphalian A), but not the Pictou Group (Westphalian "C") and younger strata.

There is some evidence that late- or post-Carboniferous faulting affects the Pictou Group too, for example the Indian Mountain Fault northeast of the Kingston Uplift cuts Pictou Group rocks (St. Peter, 1992), but by and large the post Boss Point and Pictou beds are flat-lying, or nearly so.

The first set of structures which are demonstrably Late Carboniferous are the thrusts observed on the Fundy coast of the Caledonia Uplift. Discussed in detail by Nance (1986), and exhibiting the characteristic of doubly vergent thrusts, these were believed to be not younger than Westphalian "C" nor older than Westphalian "A" in age. But recent dating of muscovite in the sole thrust of an allocthonous granite body involved in the thrusting yields a Namurian age (315 Ma) of tectonic emplacement (Dallmeyer and Nance, 1990) .

Within the Moncton Subbasin proper, structures affecting Windsor/Hopewell and older rocks are described by Gussow (1953) as the result of an intense period of folding and faulting which saw southeast-vergent thrusting on the Belleisle, Kennebecasis and Caledonia fault systems and northwest-directed thrusting on the Harvey Hopewell Fault. Folds associated with these structures, as opposed to older ones, have axes generally parallel to the fault traces (Webb, 1963).

Figure 6-5 is a vertical cross-section constructed from the map expression (St. Peter, 1989c) of the anticlinal structure near Urney using the method of down-plunge projection method described by Ramsey and Huber (1987, p.368). This construction accounts for topography and makes the simplifying assumption that the folding is cylindrical with fold axes west of the Clover Hill Fault plunging 20° to the northeast, those east of the fault plunging 25° to the southwest, as estimated by the dip of beds in the fold hinges. Figure 6-5 shows several features of the basin margin structure which were not as well imaged by the seismic data collected along strike from the Urney transect (Figure 5-14) namely:

1. the presence of northwest verging high angle reverse faults antithetic to the Horton basin bounding faults; and

2. thrusting on the Clover Hill Fault which reactivates the Horton basin-bounding fault.

Evidence from Figure 6-5 that the basin-bounding fault has been reactivated includes the fact that coarse facies (basin margin) Albert Formation lies adjacent to the fault, and that the Albert Formation is thick in the hanging wall but absent in the foot wall of the Clover Hill thrust.

The idea that reverse faults such as the Dutch Hazens Fault of Figure 6-5 thrust basement and younger rocks northeast into the basin is not new, although none of the faults on the maps of St. Peter (1989a,b)(Plate 2-1) are attributed with such displacement. Reverse faults of both vergences cut the Hopewell Group in the Waterford area, and as such are Namurian or later. Gussow (1953) mapped the Pollett River and Coverdale faults as backthrusts emplacing basement over the Carboniferous formations to the northwest even though most of the thrusting on the Clover Hill-Caledonia fault system was considered southeast verging. The seismic time structure map of Figure 5-10 shows the depth to pre-Carboniferous Basement as mapped seismically to be in excess of 4 km beneath basement outcropping at the present-day basin margin at Elgin. This indicates either a near vertical basin edge or thrusting of the Caledonia basement rocks over the Carboniferous along the Elgin-Parkindale basin margin. Antithetic faults are indicated on the some of the seismic lines of Figure 5-9 along the southern basin margin, but due to the lack of Windsor Group cover there, it is impossible to say whether they are associated with the Moncton episode or a later one.

Other structures that are demonstrably late Carboniferous are the Anagance Axis (Plate 2-1), a salt cored anticline running NE from Penobsquis and its associated syncline. Plate 6-1, seismic line 29Y, images the structure and shows stratigraphic evidence that most of the salt movement is post-Namurian since the near top Hopewell reflector is folded and there is little thinning of the thick Windsor-Hopewell section to indicate that salt-induced topography existed at the time of Windsor and Hopewell Group deposition. Gussow (1953) speculates that the Anagance axis may be partly tectonic in origin. Two more recent observations supporting that contention are made here.

1. There is a strong association between Late Carboniferous faulting and salt mobilization. This can be seen at the end of line 29Y (Plate 6-1) and is observed in seismic data all along the eastern margin of the Kingston Uplift.
2. Detachment faulting within the salt in the Basal Windsor Group is a common structural style of Late Carboniferous deformation elsewhere in the Maritimes Sedimentary Basin. This phenomenon is commonly observed in areas which border the major fault zones and are well imaged by seismic data such as the Cabot Strait (George Langdon, pers. comm. 1994).

Other structures which are demonstrably Late Carboniferous are the faults and associated structures of the

Kingston Uplift. Parallelism of faults and the traces of fold axes in the Windsor and younger formations is demonstrated in and near the Kingston Uplift including the gently folded Dunsinane and Havelock synclines shown in Plate 2-1. Disagreement still exists over the nature of the structures in the Kingston uplift. Figure 6-6 shows the interpretations by both Gussow (1953) and Webb (1963) of a transect across Indian Mountain. A line drawing of a composite seismic line near the same transect is shown in Figure 6.6c. The seismic data cannot completely resolve the detailed structure of the Indian Mountain beds since they are so steeply dipping, but three observations can be made:

1. that both near-vertical and northwest-dipping fault structures are present in the Kingston uplift;
2. that salt movement and fault movement are related; and
3. that near vertical faults seem to cut (and hence postdate) the low angle ones.

A final, large scale observation of Kingston Uplift structure is that trends of the major fault traces which are northeast-southwest in the western part of the map area near Belleisle and Kennebecasis Bays (Figure 3-2) bend to the east as they approach the Northumberland Coast. The total curvature observed as the faults cross the map area in the map area is about five degrees.

6.3.2 San Andreas "Big Bend" Analogue

Nance (1987) has put forward an analogy between the Minas Geofracture - Fundy Fault system in Late Carboniferous (Westphalian A - C) time and the present day tectonics of the Big Bend (Hamilton, 1961) in the San Andreas Fault system north of Los Angeles (Figure 6-7[a,b]). The analogy between the Minas Geofracture and the San Andreas places the Moncton Subbasin within the transverse ranges of California; an analogy more apt than Nance (1987) imagined. In this section I shall demonstrate that there is a remarkable correspondence in structural style between late Carboniferous structures observed in the Moncton Subbasin seismic data and published accounts of the southern California basins, particularly the Ventura Basin and the western Transverse Ranges. This analogue will be exploited both as a template to help understand the deformation observed and also as a predictive tool to help estimate the scope of the Late Carboniferous overprint.

In Nance's (1987, figure 2) hypothesis, the Minas Geofracture-Fundy Fault system played a kinematically analogous role in Late Carboniferous time to today's San Andreas, the Harvey Hopewell Fault to the Big Pine Fault and the Belleisle Fault to the Malibou Coast - Santa Monica Fault system. When the locations of the Cenozoic sedimentary basins of California are superimposed on the map (Figure 6-7[b]) we see that the Moncton Subbasin occupies the geographic setting of the Ventura Basin, and that its bounding faults in both the Kingston and Caledonia uplifts are disposed in a pattern similar to that of today's Transverse Ranges.

Recent paleomagnetic evidence suggests that the Transverse Ranges of California underwent significant rotation in the Neogene to get to their present configuration (Hornafius et al. 1987) and, while the Moncton Subbasin has not been rotated (or at least no paleomagnetic evidence is available to suggest it has), it has by virtue of inheritance of older structural fault trends a similar disposition to a major bend in a transform margin. Since the tectonic history of the Moncton Subbasin is polyphase, as is that of the California basins, it is valid only to compare the late Carboniferous deformation of the Moncton Subbasin and the Quaternary to recent deformation in the western Transverse Ranges to ensure the stress field and tectonic setting are analogous.

The similarity of structure and tectonic setting between thrusts of the Fundy cataclastic zone and similarly disposed thrust faults south of the San Gabriel Fault was exploited by Nance (1987). He interprets the periodically reactivated, doubly-verging thrusts and associated stratigraphic evidence in the Upper Carboniferous formations of the New Brunswick Fundy Coast (Rast and Grant, 1973; Plint and Poll, 1984) as consistent with late (Westphalian A-C) Carboniferous compression associated with major dextral motion on the Minas geofracture (Nance, 1987, figure 2). Good evidence exists for dextral strike-slip motion on the Minas geofracture at that time (Eisbacher, 1969; Yeo and Gao, 1986) but the magnitude of displacement is uncertain (Keppie, 1982). Yeo and Gao (1986) have estimated 20 to 25 km of dextral motion on the Cobequid - Hollow fault system as the amount required to form the Stellarton pull-apart graben in Westphalian A-C time. Unspecified movement also occurred on the same fault system in the Namurian.

The location of the Urney transect (Figure 6-5; transect A-A′ of Figure 6-7[c]) in the western Transverse Ranges analogue is shown in Figure 6-7(c) as transect C-C′. The Californian transect falls in the Sulphur Mountain, Upper Ujai Valley, at the southern edge of the Ventura Basin, for which balanced cross-sections have been published (Yeats et al., 1988, figure 2). The Ventura Basin section C-C′ is shown in Figure 6-8 and it displays several key similarities to the Late Carboniferous structures of the Moncton Subbasin. The activation at the basin margin of doubly verging thrust faults is a distinctive structural style resulting from the inheritance of pre-existing high angle fault zones, which gives rise to almost identical cross-sections at Urney and Sulphur mountain. The relative timing of movement in both areas is similar, in that the out-of-basin thrusts postdate those at the basin margin.

Detachment faulting in the California analogue occurs at incompetent mud layers in the stratigraphic column (Figure 6-8, cross-section D-D′) and gives rise to "rootless" anticlines such as the Ventura Anticline. The analogous timing and orientation (Figure 6-7[c], cross-section B-B′) of the Penobsquis salt structure and Ventura Anticline implies that the Anagance Axis is most likely a tectonic feature, part of the Late Carboniferous overprint. The axial trace of the anticline, imaged as a linear gravity anomaly due to the salt in the potential field trend map of Figure 3-13, is at an oblique angle, about 12° to the Kennebecasis and Belleisle faults in the southern map area. This may serve as a strain marker indicating that the principle axis of compressive strain at that time was oriented roughly NW - SE.

As for the Kingston Uplift, the Ventura Basin analogue may provide clues to understanding its structure too. The Oak Ridge Fault, which shares a location analogous to the Jordan Mountain Fault in the Californian analogue, experienced (as did the San Cayetano Fault) left lateral strike slip movement in the Miocene during the rotation of the Transverse Ranges (Hornafius et al., 1986). The Oak Ridge Fault has subsequently been reactivated as a high angle oblique slip fault since late Pliocene. Cross-section D-D′ of Yeats et al. (1988) in Figure 6-8 shows 4 km of post-Late Pliocene displacement on the Oak

Ridge Fault, while a slip vector derived from a 1965 earthquake on the fault near Santa Paula is roughly parallel to the fault, indicating sinistral strike slip motion. Yeats et al. (1988) note that displacement on the Oak Ridge Fault decreases to the east and believe this to be due to progressively more of the displacement being transferred to the Sisar detachment to which the Oak Ridge is linked at depth.

Can this be the situation in the Kingston Uplift during the Late Carboniferous, that faulting at the basin margin, and on the Kingston Uplift are linked by a detachment at depth?

There is evidence for planar northwest-dipping low angle structures which could be thrust surfaces in Figure 6-6(c). Gussow (1953, figure 8) interprets similar surfaces beneath parts of the Kingston Uplift. Gussow interpreted the thrust plane beneath Jordan Mountain as the basal Windsor detachment, and although this has never been corroborated by drilling or outcrop observation, it is consistent with the Californian analogue.

Thus while the Ventura Basin analogy seems less applicable to the little understood structure of the Kingston uplift then to the rest of the Moncton Subbasin, three things are clear.

1. The Basal Windsor salt layer has acted as a

décollement surface at some time in the Late Carboniferous. The tip of a blind thrust is imaged at that level In Figure 6-5(c).

2. Low angle faults seem to be cut by later, more steeply dipping ones.
3. The Belleisle and Kennebecasis-Berry Mills Faults have the external form of strike-slip faults; they are long, straight through-going faults which are near-vertical on the seismic section of Figure 6-6(c).

A fifth and final element of the California analogue is the oroclinal bending of the Western Transverse ranges, seen in Figure 6-7 at the coastal end of the Oak Ridge and neighbouring faults. Hornafius et al. (1986), conclude that this bending is a consequence of the formation of the Big Bend in the San Andreas Fault, and that it has occurred in the last 6 Ma since it postdates the Miocene rotation of the Transverse Ranges. The change in fault trends of the main northeast trending fault systems, which veer slightly to the east as they traverse the Moncton Subbasin from south to north is particularly evident in the mapped trend of the Belleisle Fault (Plate 2-1) and in the geophysical trend map (Figure 3-13). It would therefore be consistent with the tectonic regime of the late Carboniferous, which saw considerable dextral movement on the Minas Geofracture buttressed by the "transverse ranges" of southern New Brunswick, that this bending of the fault trends may have occurred in Late Carboniferous time.

We can now speculate on the nature of the Late Carboniferous tectonic overprint in parts of the Moncton Subbasin where the timing of tectonic events is ambiguous, and assess the validity of our findings about Early Carboniferous tectonic events from Chapters 3, 4 and 5.

6.3.3 Basin Margin Overprint

It is clear that the southern basin margin fault system (the Clover Hill - Caledonia Fault system) may be expected to be reactivated as an oblique thrust system in the Late Carboniferous throughout its length although the degree of shortening experienced on the system may be expected to decrease to the northeast as it does in the analogue. Doubly verging compressive structures are apparent both in the southern subbasin and the analogue, and are likely candidates for the "zone of intense faulting" identified in the seismic lines of Figure 5-9.

The northwest-vergent thrusting of uncertain age in which Caledonian basement is thrust over Carboniferous sediments for the Pollett River and Coverdale faults (Gussow, 1953) is entirely consistent with the Late Carboniferous strain orientations inferred here. That is with a axes of maximum compressive strain oriented roughly northeast-southwest. It is also consistent with the seismic data of Figure 5-9.

The implication of this is a reduced role for "Moncton Episode", the tectonic event at the end of Hortonian time. Observed basin margin thrusts are consistent with the late Carboniferous tectonic overprint, so much of the "basin inversion" has probably occurred in the Late Carboniferous. Only structures demonstrably sealed by undisturbed Windsor-Hillsborough sediments or exhibiting strain inconsistent with the Late Carboniferous stress regime can be considered part of the end of Horton "basin inversion" event.

The Late Carboniferous tectonic overprint does not affect my discussion of the timing, nature and rate of Horton basin subsidence since all observations on which these conclusions were based are made under undisturbed Windsor cover sequence, and are hence unaffected by Late Carboniferous tectonics.

The estimate of 7 km of extension required to open the Horton half-graben imaged on line 11 is valid since that entire section was sealed by undisturbed Windsor. But that estimate must be considered a minimum since it is made after partial reversal of the original extension.

The Late Carboniferous overprint does affect any conclusions made from the plan map of Horton rhomb basins deduced from potential field data (Figures 3-15 and 5-8).

Before we can consider these representative of the Horton basin distribution we must first remove the Late Carboniferous tectonic overprint. That overprint consists of oroclinal bending of entire Moncton Subbasin in the amount estimated as required to straighten the Kingston uplift geophysical trends, and northwest-southeast shortening of an unknown magnitude.

Since Gussow interpreted all major faults in the Moncton Subbasin as NW-SE thrusts I will use his estimates of fault throws as an estimate. Gussow assigns 5-6 km throw on the Berry Mills Fault, interpreted as a low angle thrust; 2-3 km on the Lutes Mountain Fault, interpreted as a high angle thrust; and 1-2 km on the Prosser Mountain Fault, for a total throw of at least 8 km. If average fault dip is 45°, then the minimum total amount of Late Carboniferous horizontal shortening should also be on the order of 6 km. Thus my estimate of the Late Devonian oblique extension, should be increased from approximately 3 km to 9 km to account for this unrestored shortening.

7.0 Synthesis

7.1 Introduction

In this chapter an hypothesis, or model, is put forward which seeks to describe the tectonic evolution of the Moncton Subbasin. Such a hypothesis must explain how a Silurian/Devonian mountain belt collapsed to form a series of sedimentary basins, and eventually foundered beneath a Visean sea. It must do so within the framework of the plate tectonic paradigm, be physically viable and testable, and be consistent with observations published in the earth science literature and the geophysical observations of the preceding chapters. Future research may well demand modifications to this model. That is the normal progression of science (Kuhn, 1978). The challenge here is to build an internally consistent tectonic model which future researchers and explorationists can use as a prediction tool, test, and build upon.

In the first section of this chapter the geophysical findings of this study are summarized with reference to the type of contribution of each. Some confirm or expand upon findings of workers in related fields, while other findings are presented here for the first time.

In subsequent sections a kinematic model for Late Devonian and Carboniferous evolution of the Moncton Subbasin is presented and implications of this hypothesis for the Maritimes Sedimentary Basin, the dynamics of its inception, and the validity of Carboniferous reconstructions for this part of the world are discussed.

7.2 Summary of Findings

The geophysical data of Chapter 3 contribute to our understanding of the basement rocks of the Acadian orogen in three ways. First the disposition of basement terranes in northeast trending belts beneath the subbasin proposed by St. Peter and Fyffe (1990) on lithology and Barr (S.M. Barr, pers. comm.) on geochemical data is confirmed geophysically and detailed in Figure 3-15. Geophysical evidence that the Brookville terrane has been tectonically emplaced over the Caledonia terrane from the northwest, and that it subcrops north of Moncton, where it sourced late Devonian sedimentation in that area, is presented here for the first time. Horton Group depocentres, which Bradley (1982) suspected formed a complex pull-apart basin, are in fact three linked pull-aparts, transtensional "mixed mode" basins which have coalesced south of the Kennebecasis Fault. One or more separate depocentres lie beneath the Kingston uplift.

Regarding the faults mapped by St. Peter (1989 a,b), some do not show up in the geophysical data and may be mapped improperly. These include the Jordan Mountain Fault north of Jordan Mountain, the Smith Creek Fault north of Indian Mountain, and the Harvey Hopewell Fault north of its bend at Hopewell Cape. This latter observation is particularly important since it adds weight to Poll's (1970) long held view that Webb (1963) was mistaken in mapping the Harvey-Hopewell fault north of Hopewell Cape, with the implication that Webb's (1963) often cited evidence for sinistral strike-slip offset of an alluvial fan is cast in doubt. Several of the major faults in the area, such as the Belleisle, Smith Creek and Kennebecasis-Berry Mills faults (compare Plate 2-1, Figure 3-12), are well defined in the potential field data, because they offset basement significantly or juxtapose differing basement types. Additionally, some prominent linear discontinuities in the potential field data suggest unmapped basement discontinuities. These include the southern margin of the Marchbank syncline and several east-west structures, one defining the southern end of the subbasin, and another south of Elgin, the northern boundary of the Mechanics Settlement magnetic anomaly.

Specular reflections play a minor role in the seismic response of the terrestrial lacustrine sediments as revealed in Chapter 4. Rather, the main mechanism for reflection generation is interference of continuous thin beds in the lacustrine sequences. The stratigraphic interpretation of the seismic data demonstrates the efficacy of seismic stratigraphy in identifying depositional systems in a terrestrial succession, allowing prediction of depositional systems tracts. Detailed lithofacies prediction is not possible in the absence of a sea-level based stratigraphic model but, significantly, the kerogenous Albert Formation shale is mappable seismically as a maximum flooding surface in a thick perennial lake sequence. Additionally, allostratigraphic units which can be mapped seismically, correlate with local lithostratigraphic units, themselves originally defined as unconformity-bounded units by Wright (1922). The cyclic episodes of coarse sediment aggradation, fine sedimentation and hiatus recorded in the seismic data provide a history of the interplay between subsidence and sediment supply, which, barring sudden climate change, may be interpreted as a record of a subsidence rate which was episodic in the late Devonian and maximum in Tournaisian Tn_3 time. Total subsidence in that time exceeded 4 km in the Elgin "subbasin". Subsidence there occurred at a rate averaging more than 120 mm / 1000 years and was accompanied by a 3 km southwest migration of the basin depocentre indicating that there was a component of dextral strike-slip motion on the basin-bounding fault system at that time. This magnitude of strike-slip displacement is significantly less however than the transcurrent motion implied by Webb (1963, 1969) for the basin-bounding fault zone.

Structural aspects of the subbasin discussed in Chapter 5 indicate that the Horton basin consists of a linked series of half-grabens bounded to the southeast by a series of crudely *en echelon* low-angle normal faults. A broad sag-style subsidence characterizes the Visean and younger section above the basal Windsor/Hillsborough unconformity, distinct from the fault-bounded Late Devonian and Tournaisian subsidence regime. The 4.2 km subsidence in Late Devonian to Late Tournaisian time indicated near Elgin was accompanied by a north-south component of displacement on the basin-boundary oblique normal fault of approximately 7 km, deduced by cross-section balancing. The net displacement on the NE-SW fault system which opened the oblique pull-apart was estimated from the geophysical map pattern. By this reasoning, 9 km of oblique normal slip NNE-SSW would explain the present-day offsets of basement structures bounding the Horton Basins. This measurement is not as rigorous as the migrating isopach (Chapter 4) and cross-section balancing arguments, but all point to a Horton basin opening by oblique extension with a dextral component of slip on the basin-bounding faults and a net displacement on the order of 10 km.

Late and post-Carboniferous structures are poorly imaged in the seismic data, but those structures which are imaged confirm the contention of Nance (1987) that the tectonics of the area were dominated by dextral wrenching in the late Carboniferous. Structures of that age observed in the Moncton Subbasin, located as they are in the restraining bend of a major transform fault, the Minas Geofracture, have analogues in the Ventura Basin behind the so-called "big bend" in the San Andreas Fault. An implication of this analogue is that the Moncton Subbasin has undergone northwest-southeast shortening in the Late Carboniferous and the strain estimates of the earlier deformation should be increased accordingly. A Triassic overprint consisting of brittle faulting with minor displacements is also recognized.

7.3 Hypothesis

7.3.1 Introduction

In this section, a model for the tectonic evolution of the Moncton Subbasin is presented in four parts. Firstly, the post-Acadian, pre-Carboniferous, setting of southeastern New Brunswick is described. Secondly, the Late Devonian and Early Carboniferous events, which are recorded by Horton Group sediments, are discussed. Thirdly, the deformation of Horton basins and renewal of Carboniferous subsidence in the Visean and Namurian is detailed (7.2.3) and finally in section 7.2.4 the Namurian dominance of wrench tectonics is discussed, followed by the author's speculation on the nature of late- and post-Carboniferous faulting.

7.3.2 The Acadian Orogeny in New Brunswick and Maine

The "Acadian orogeny" as the term is used here, refers to all folding, faulting, metamorphism and igneous intrusion of the N. Appalachians during the Early to Mid Devonian, although increasing evidence for Late Silurian tectonism, sometimes referred to as the "Salinic Phase" (Boucot, 1962; Dunning et al., 1990) is also coming to light. Some authors (e.g. Keppie, 1985) include events of the Late Devonian and Early Carboniferous in a broader definition of Acadian which is not adopted here since the distinction of these later events is important to this thesis.

In Silurian time the Avalon Composite Terrane, upon which the Moncton Subbasin rests, was still separated from Laurentia by the sea in which Fredericton and Mascarene sequences were deposited - the "Fredericton Trough" (McKerrow and Ziegler, 1972). This narrow ocean was subducted in the Late Silurian and by mid-Devonian time the entire orogen was emergent as indicated by an unconformity across all terranes at that level. The main compressive phase of Acadian deformation was pre Mid-Devonian and resulted in deformation accompanied by a penetrative cleavage and low grade metamorphism in St. Croix terrane rocks, Fredericton and some Mascarene cover. A second compressive phase caused recumbent folds in the cleavage and thrust faulting (Ruitenberg and McCutcheon, 1982). In the Avalon rocks of southeastern New Brunswick it is difficult to date specific deformation since most faults have been reactivated in the Carboniferous.

The seismic data suggest that beneath the Moncton

Subbasin, the Brookville terrane lies allocthonous upon the Caledonia terrane. The contact between the two units is a series of northwest-dipping fault planes along which the Brookville was apparently thrust southeast over the Caledonia terrane, and highly reflective strata which correlate geophysically with interbedded meta-sedimentary and meta-volcanic rocks of the Caledonia massif are imaged seismically deep beneath the central Moncton Subbasin.

Northwest-dipping basement-cutting structures have previously been identified in the Carboniferous by Gussow (1953) and are here interpreted as Acadian, or older, thrusts reactivated as normal faults to accommodate Late Devonian and Carboniferous subsidence. Acadian southeast-vergent thrusting has been documented in Fredericton cover rocks of the St. Croix terrane (Fyffe, et al., 1991) and in Eastern Maine (Ludman et al., 1993), and pre-Carboniferous thrusting of unknown age is documented in the Caledonia massif (McLeod and McCutcheon, 1981). Figure 7-1(A) shows schematically, the style of southeast vergent Acadian thrusting which is implied by the pre-extension template of Figure 5-7 and the fault-plane reflections imaged seismically in Figure 5-9.

At the end of the Acadian orogeny in southern New Brunswick, ranges of Caledonia and Brookville terranes were prominent and served as source areas for the deposition of Horton Group sediments. It is also possible, but not clear from the potential field and seismic data, that the Kingston Complex has a northern extension beneath the Carboniferous sediments of the Kingston uplift (Figure 5-15).

7.3.3 Late Devonian and Early Carboniferous Oblique Extension

Both rift and wrench tectonic settings have been proposed for the inception of Late Devonian and Early Carboniferous basins in the Canadian Maritimes. The geophysical observations of this thesis suggest the Moncton Subbasin in Hortonian time was in fact a hybrid of the two: what Gibbs (1987) has called a "mixed mode" basin. Plan and profile structural seismic observations are consistent with map view potential field data and seismic stratigraphic evidence for a style of basin development on linked, scoop-shaped, low-angle oblique slip faults in a transtensional tectonic regime. Basin geometry and timing of subsidence is remarkably similar to that implied by a detailed sedimentological study of a Horton basin in Cape Breton (Hamblin and Rust, 1989; Hamblin, 1992).

The geologic setting inherited from the Acadian orogeny in southeastern New Brunswick was a thrust belt which saw series of fault-bounded, tilt-block ranges. These ranges bounded valleys into which rivers flowed from the Caledonia and Brookville ranges shedding alluvial fans that coalesced in a central valley. Normal faults along the southern basin margin accommodated half-graben-style subsidence of the valley floor. The normal faults had a crudely *en echelon* map pattern and slip was oblique dip-slip motion on the low-angle, generally concave-upwards fault planes. Figure 7-1(B) shows schematically the kinematic model inferred from the geophysical data: low angle normal faults, likely pre-existing Acadian fault planes, acting as a family *en echelon*, accommodated the oblique extension. East-west trending faults formed in the transfer zones between overlapping fault segments ("relay ramps" of Peacock and Sanderson, 1992)). Key observations with which this model is consistent include:

1) fault patterns inferred from both seismic and potential field data;
2) sediment thickness data including observation of half-graben geometry and "deeps" associated with eastward jogs of the basin margin (Figure 7-1[C]);
3) temporal and spatial variation in subsidence rate as reflected in the allostratigraphy of the basin fill; and
4) north-south component of extensional strain is on the order of 10 km, while isopachs of individual alluvial fan deposits in the Elgin area are offset laterally with time.

7.3.4 Moncton Deformation Episode

Structures described in Chapter 5 document deformation due to a Late Tournaisian or Early Visean tectonic event which exhibits two of the hallmarks of basin inversion (Hayward and Graham, 1989): the reactivation of extensional faults in compression and, at least partial extrusion of the basin fill. This event marked the end of Horton Group deposition, and was a period of erosion which saw the peneplaning of Horton sediments before the onset of the much broader regional subsidence of the Visean when Maritime Canada was flooded by the Windsor Sea. But the fault pattern related to the inversion is poorly constrained by the outcrop and geophysical data and has been overprinted to some extent by later events. The seismic cross-sections of Figure 5-9 can be interpreted as imaging either a positive flower structure, or an inverted basin margin (Figure 5-14). In the following section, a transpressional kinematic model of post-Horton events is presented which removes the apparent ambiguity.

The deformation observed in the Horton Group rocks in the seismic sections of Chapter 5 consists of some structural elements which must be 'Moncton episode' by virtue of undisturbed overlying sedimentary cover, and other elements, which *may* be attributed to the Moncton episode. This latter group consists of structures which deform Horton Group rocks but which are neither sealed by cover nor consistent with style of tectonic overprint deduced in Chapter 6. Key observations in the first group are the tilting and erosion of

Horton beds prior to Windsor/Hillsborough deposition observed in the central Hillsborough "subbasin" (lines 89Y, 91, 93 of Figure 5-9). This tilting and erosion is apparently contemporaneous with tilting of Horton beds in the opposite sense, near the basin margin farther south (line 29Y; Figure 5-9). Uplift, folding and erosion of Horton sediments near the present day basin margin along the Caledonia fault zone are also observed in outcrop. Gussow (1953), Webb (1963) and St. Peter (1992) point to the fact that Horton Group fold axes are oblique to the basin margin. The tilting, folding and faulting at that time is not accompanied by any long, through-going, near vertical fault zone as one might expect for a master wrench fault, but rather seems to be accommodated, as best imaged on line 5Y (Figure 5-13), by a combination of normal faults reactivated as out-of-the-basin thrusts and high angle antithetic reverse faults.

It has been established that there was a component of dextral strike-slip faulting in the Early Carboniferous. There are three mechanisms which might explain the local uplift and apparent compression at the basin margin without invoking the complete stress reversal implied by an inversion interpretation. These are:

(i) uplift of sediments in the hanging wall as they are transported by strike slip, or even continued oblique extension, over a lateral ramp in the detachment surface at depth (Figure 7-2[A]);

(ii) a shift in regional stress regime from transtensional to transpressional (Sanderson and Marchini, 1984) resulting in structures which exhibit a component of shortening at the basin margin fault zone (Figure 7-2[B]); or

(iii) uplift and thrusting of basin sediments in the localized compressional regime of a restraining bend in the strike-slip fault system (Figure 7-2[C]).

Which, if any, of these models is most consistent with the observations at the basin margin during the Moncton episode?

Regarding model (iii) above, there is no bend in the observed geometry of the NE trending fault system which would result in convergence in a dextral strike-slip environment (Christie-Blick & Biddle, 1985). On the contrary, the E-W trending dextral jogs in the fault system such as those observed in Figure 7-1[C] would be expected to act as *releasing* bends or localized loci of extension rather than compression in a dextral strike-slip regime. As for (i) above, the possibility that the basal detachment is ramped in the subsurface (Figure 7[A]) is quite realistic. In fact it is indirectly suggested by the along-strike depth variations to top of reflective basement (Figure 3-12) and by the transverse arch-type structures in the central subbasin gravity and magnetic maps (Figure 3-13). Such basement arches could well serve as ramps which would give rise to a ramp anticline in an over-riding unit. The fact that Horton Group sediments have been uplifted and eroded over the basement arch is reflected in the saddle-shaped basin structure of Figure 5-10 and is consistent with the type of structure shown in Figure 7-2(A) after the lateral ramp anticline has been eroded. Large scale subbasin margin observations on the other hand, in the absence of detailed structural measurements, are best explained by a transpressional kinematic model (Figure 7[B]) which predicts basin margin uplift and folding oblique to the fault trend.

In summary, the apparent inversion of strain pattern from extensional to compressional at the end of Horton Group deposition can be explained as a shift from the oblique extension which had dominated in Late Devonian and Tournaisian time to dextral transpression in the Visean. A slight clockwise rotation of the local strain ellipse (Figure 7-3) coupled with irregularities in the underlying detachment fault surface summarizes the style and variability of the end-of-Horton ("Moncton") tectonic episode. Furthermore, the regional nature of end-of-Horton tectonic or depositional events favours a change in the kinematic regime over a localized fault geometry effect such as a restraining bend (Reading, 1980). The Moncton episode then signals the end of the extensional component of movement on the NE-SW trending master faults and marks the beginning of the overall dextral wrench tectonic regime which affects the Carboniferous of eastern Canada for the remainder of the Carboniferous era.

7.3.5 Late Carboniferous Tectonics: Strike-slip and the Big Bend

The period following the Moncton episode is not recorded by preserved sediments in many parts of the subbasin. Erosion of the "uplifted" sediments in the fault-bend folds of the Westmoreland uplift and parts of the basin margin was accompanied by an apparent lack of faulting and a widespread sag-style subsidence which generated the much broader basin, into which Hillsborough Formation alluvial deposits aggraded and the Windsor Sea eventually flooded. This more widespread subsidence gives the basin a steers-head geometry, (Bradley, 1982) and in the following 50 million years up to 4 km of Middle and Upper Carboniferous sediments accumulated. The Hillsborough and younger sedimentary wedge is undeformed in the central subbasin with the exception of local salt migration features. Renewal of fault activity occurs in the Namurian with a strain pattern consistent with a NW-SE principal axis of compressive stress. The analysis of chapter 6 shows this to be entirely consistent with the dextral strike-slip motion documented on the major regional E-W fault system in Nova Scotia. In this case the Moncton Subbasin lies in the outer edge of a restraining bend in the Minas

Geofracture/Fundy fault system and right lateral motion on that system manifests itself as compressive strain along a NW-SE trending axis of maximum compression. The resulting strain is manifested as high angle reverse faulting along the southeastern basin margin, thrust faulting in the Kingston uplift and broad NW trending folds in the middle Carboniferous formations. This latter family of structures includes the salt-cored Anagance Axis as well as the Havelock, Marchbank and Havelock synclines (Plate 2-1).

7.3.6 Latest and Post-Carboniferous Deformation

Latest (post Westphalian "B") Carboniferous or Permian deformation has resulted in little or no folding, but several long, straight SW-NE trending faults (e.g. Kennebecasis-Berry Mills fault system) have moved since the Boss Point Formation was deposited and today apparent vertical displacement of the Windsor Group is nearly 4 km on the Indian mountain transect of the Kingston Uplift (Figure 6-7). It is not clear how much of this displacement is Namurian and how much is post Boss Point, that is Westphalian "B" and younger, but the effect of these late faults is to dissect the Carboniferous into a series of gently-dipping, internally undeformed fault blocks (Poll, 1970). These late faults have the following characteristics:

1) near vertical faults cut older, low angle ones;

2) northwest-southeast trending faults in the Kingston uplift are activated; and

3) most of the faults involved are long and linear.

These observations are suggestive, although not conclusive, evidence for a late Carboniferous or Permian episode of strike-slip faulting which has affected the Kingston uplift, but apparently not the southern basin margin.

Mesozoic structures have been superimposed on the Palaeozoic ones, mainly in areas bordering the Bay of Fundy which is an aborted Triassic rift. The following features are attributable to the physical consequences of strain partitioning at the end of a rift zone as observed today at the northern end of the Red Sea: the disposition of rivers feeding Shepody Bay (Figure 3-2) since the river channels have eroded along the faults in the rift splay zone; anticlinal structures at the head of the Bay of Fundy; the Petitcodiac, Memramcook and Tantrumar faults; and the gentle folding and dyke emplacement in the Permian sediments of Prince Edward Island (Poll, 1984).

7.4 Implications for Regional Late Palaeozoic Tectonics

7.4.1 Horton Basins of Eastern Canada

Devonian and Lower Carboniferous sediments of the Horton Group and its correlative units are exposed in a narrow trough which Belt (1968) characterized as a complex rift system stretching from southeastern New Brunswick to White Bay in Newfoundland. The extent of Horton basins under the Gulf of St. Lawrence has been poorly documented, but industry seismic data indicates that Horton basins are widespread beneath the Windsor and younger sediments of the Gulf of St. Lawrence, and that they are imaged in graben and half-graben structures beneath the central Gulf (Durling and Marillier, 1990). The observation that Horton Group sediments and hence Late Devonian to Early Carboniferous basins are in fact broadly distributed in plan among a series of Acadian ranges, reinforces Belt's (1968) Basin and Range notion of post-Acadian depositional style, but details of the stress system which caused Horton graben formation "will not be known until the precise outlines of the rift at various stages of its development are better defined" (Belt, 1968).

The style and timing of Late Devonian and Tournaisian tectonic events, their effect on the type and distribution of Horton sediments and the inferred tectonic strain orientations have been determined for the central Moncton Subbasin in the preceding chapters. Can these results be extended to Horton basins of the entire region? To answer this question one must compare the results of this study with those of others in the region.

It is well known that the Albert formation has corresponding units throughout the central corridor (Fundy

Rift of Belt, 1968) of the Maritimes Basin. Spore zone g of Hacquebard (1972), (Tournaisian) is found throughout the region and in most sections consists of three rock units: one of fine clastics lying between two units of coarse clastics (Hacquebard, 1972). In the Moncton Subbasin these would be the Albert Shales (Unit 4) of Chapter 4 lying between the lower Albert (Unit 3) and upper Albert and Weldon formations (Units 5, 6 of Chapter 4). In Cape Breton the equivalent strata are particularly well exposed and are called in ascending order, the Craignish, Strathlorne and Ainsley formations (Hamblin and Rust, 1989). The lower formation contains alluvial fan and fine fluvial sediments, while the medial unit, like deposits at about the same stratigraphic level throughout the maritimes, contains sediments laid down in lake, fluvial plain and swamp environments as attested by the occurrence of thinly laminated black shale, bituminous shale, siltstone, sandstone and coal. The uppermost unit, the Ainsley Formation, consists of red and grey fluvial sediments with similar deposits occurring in the upper part of zone g throughout the region (Hacquebard, 1972). The Ainsley, Weldon and time equivalent units have been traditionally interpreted as recording a renewed time of epeirogenic subsidence as compared to the preceding, stable lacustrine phase.

There is no proof that the Tournaisian lakes were interconnected. In fact this study suggests the Albert

Formation represents more than one lake in eastern New Brunswick, but within the limitations of the palynological correlations, all the lakes, in which the Albert Formation of New Brunswick (1.4 km thickness), Strathlorne Formation of Cape Breton (0.7 km thick) (Hamblin, 1989) and Snakes Bight Formation of Newfoundland (0.8 km thick) (Knight, 1983) were deposited, existed at the same time.

A recent detailed sedimentological study of the Horton Group in Cape Breton has been published by Hamblin and Rust (1989). To briefly summarize that work, the authors recognize two separate Horton Subbasins in Cape Breton. Lower Horton rocks of the Upper Craignish Formation are braided stream and playa mudflat deposits which exhibit a fining-upward trend over hundreds of metres of section. Their paleocurrent indicators suggest two distinct depocentres with internal drainage-half-grabens of opposing polarity. This pattern is best illustrated in the Strathlorne Formation deposits which demonstrate:

(1) asymmetrical distribution of lake margin facies - sandy shoreline deposits on the hinged side, versus fan delta deposits on the faulted sides, of the Horton half-grabens; and

(2) paleocurrent distributions that are consistent with dips of half-graben floors, i.e. the floor of the "Cabot Subbasin" dipped northwestward, while that

of the "Ainsley Subbasin" sloped to the southeast.

Hamblin (1992) argues further that the sedimentological evidence suggests subsidence rate was maximum during Tournaisian Tn_3 time and that extension was accommodated on scoop-shaped listric normal faults of opposing polarity.

There is a strong coincidence in the style and timing of basin formation in Cape Breton and southern New Brunswick. Not only are both half-grabens of equivalent age, but the sedimentological history of the Cape Breton basins is directly analogous to that of the Elgin "subbasin" as revealed using seismic stratigraphy in Chapter 4. The main difference between the New Brunswick and Cape Breton basins seems to be that the Cape Breton basin geometries suggest a purely extensional tectonic regime while Moncton Subbasin extension was by oblique slip at that time. But this apparent discrepancy also illustrates the basins' similarity because basin bounding faults in New Brunswick trend NE-SW, while those bounding the Cape Breton basins trend approximately E-W. Hence extensional fault movements observed in both areas are consistent with the same regional strain field. The principal axis of extension is approximately north-south.

In summary, the coincident style, timing and sedimentological response to Late Devonian and Tournaisian extension in New Brunswick and Cape Breton lends credence to the idea that Maritimes Basin formation was not purely strike-slip in its early stages, and that the Hortonian stage ended with a change in kinematic regime to transpressive. The implication of this observation on the validity of Bradley's (1982) pull-apart model of Maritimes Basin evolution will be explored below.

The Bradley model relies on significant dextral strike slip movement on the Belleisle Fault in Late Devonian/Early Carboniferous times. While this study provides no quantitative estimate of displacement on that fault, it does shed light on other fault movements in the area at that time. I have demonstrated that post-Acadian shearing is not confined to the Belleisle Fault, but rather is distributed across several linked northeast-trending faults in the Moncton Subbasin. Transtensional shear totalling at most a few tens of kilometres was distributed over three faults between today's Kennebecasis-Berry Mills Fault and the Harvey-Hopewell Fault. By the end of Tournaisian there was no longer an extensional component of motion on the NE-SW fault zones. Overprinting structures, both in the Namurian (Hopewell Episode) and late- or post-Carboniferous are consistent with ongoing, episodic wrench tectonism being active throughout the Carboniferous.

This hypothesis then requires a modification to Bradley's model to subdivide the early pull-apart stage into:

a) an early period of oblique extension from Late Devonian through Tournaisian time; with

b) pure dextral wrench tectonics later, at the end of Tournaisian and continuing, albeit episodically, throughout the Carboniferous.

This modification resolves some of the lingering questions about the strike-slip model such as:

a) why are Carboniferous volcanics more suggestive of a continental rift than a transform margin (Barr et al., 1985; Dostal et al., 1983); and

b) why do the duration and magnitude of post-Windsor Group thermal sag phase far exceed those predicted by quantitative examination of Bradley's model (G. Quinlan, pers. comm.)?

7.4.2 Plate Tectonics in the Late Palaeozoic

The plate tectonic setting of Late Devonian and Early Carboniferous events in Maritime Canada is the assembly of the supercontinent Pangea. The Horton Group basins were localized among ranges along the southern margin of the Old Red Continent, Laurussia (Ziegler, 1989). That continent comprised Laurentia-Greenland and Baltica and had been assembled in the Devonian. Tectonic events of the Carboniferous in eastern North America are related by plate theory to the collision of Laurussia with Gondwana, the southern supercontinent comprising South America, Africa, Madagascar, India, Antarctica and Australia.

The local scenario is more complicated due to the presence of at least two microcontinents whose vestiges, the Avalon and Meguma terranes also docked with Laurentia in the Late Paleozoic (Williams and Hatcher, 1982).

Some disagreement reigns about the distribution of the Palaeozoic plates, and in the absence of a seafloor magnetic record, reconstructions must be based on palaeomagnetism, paleobiology, paleoclimate and the continuity of known, or geophysically inferred geological features. Several recent summaries have been published (LeFort, 1989; Vander Voo, 1988; Scotese and McKerrow, 1990; Ziegler, 1989) which propose slightly different Late Devonian and Carboniferous plate configurations. In the following sections the implications of this study are discussed with regards to the larger plate tectonic picture.

7.4.3 Late Devonian and Tournaisian

My hypothesis that post-Acadian subsidence was the result of oblique extension rather than rifting or pure strike-slip cannot be used to test Late Palaeozoic plate reconstructions, but may have important implications for the mechanics of Late Devonian basin development. In fact, different mechanical processes may have been at work in the Canadian Appalachians before and after the Moncton Episode to account for the different strain orientations and subsidence styles observed in the Moncton Subbasin. The fact that oblique extension follows so closely on the heels of the Acadian Orogeny and coincides as it does with the suture between the Brookville and Caledonia terranes raises an important question. That is, whether dynamic processes giving rise to the Late Devonian/Tournaisian events are due to plate boundary forces at all or whether they are simply a consequence of the Acadian orogeny.

7.4.3.1 Post-orogenic Collapse

It has been suggested (McClay et al., 1986) that the Devonian fault-bounded basins within the Caledonides formed by extension which was a natural consequence of the thickened crust resulting from orogeny. The gravitational collapse of such an over-thickened "crustal welt" would naturally result in extension as Coney and Harms (1984) suggest for the Basin and Range province of western North America. Dewey (1988) generalized the observation that extension commonly occurs at a catastrophic rate in orogens soon after collision has ceased. He identified five stages, typified by present-day orogens, which characterize the process. The five stages are given below.

1. The main compressive stage of the orogeny. In this stage lithospheric shortening is accompanied by crustal thickening, a decrease in geothermal gradient, an absence

of magmatism, and the development of high-pressure/low temperature metamorphic assemblages. Elevation of 3 km or more is likely to be sustained isostatically by the buoyant crustal root. This stage is typified by the initial collision of India and Eurasia between 45 Ma and 30 Ma, and the consequent isostatic uplift of a thickened Tibetan Plateau.

2. A post- or slow convergence period in which compression stops, or is slowed, by a change in plate boundary conditions but uplift continues. The proposed mechanism for continued uplift is slow thinning of the basal lithospheric mantle - the "thermal conduction boundary layer" (England and Houseman, 1988). Geothermal gradient rises and minor post-tectonic granitic intrusions may occur. An example of this stage is the continued convergence of India and Eurasia between 30 Ma and 15 Ma during which time strain was largely accommodated by conjugate strike-slip faulting within the Plateau. The duration of this stage varies from a few million to 40 million years (Dewey, 1988).

3. Rapid uplift and extension of the plateau. The proposed mechanism is now rapid convective erosion of the mantle layer at the base of the lithosphere. Geothermal

gradient rises rapidly, isobaric heating gives rise to high temperature metamorphism and intrusion of the post-tectonic granite suite. This is analogous to the Tibetan Plateau of the past 5 million years.

4. Accelerating extensional collapse occurs. The uplifted crust thins by extension and rapid subsidence leads to non-marine sequences being deposited in extensional basins. The geothermal gradient increases further and mafic magmas may intrude the lower crust. The decrease in pressure associated with the thinning lithosphere leads to high-temperature/low-pressure metamorphism. Subsidence may continue to below sea-level and culminate with evaporites and flood basalts. This stage may follow closely on a phase of shortening as it does in the Basin and Range province of North America, but the time lag may vary from orogen from orogen.

5. Post extensional thermal recovery occurs, accompanied by a broad sag-style subsidence. Thickening of the lithospheric mantle is accompanied by lower geothermal gradients, less igneous activity and possibly sedimentary evidence for a rapid incursion of the sea.

The key observation here, which has been contributed to by many workers, is that there is an interplay among the plate boundary forces, the gravitational body force acting on the rocks, and processes occurring at the base of the lithosphere. Inter-plate forces cease to dominate the tectonic events in the upper crust when it becomes too thick. Once a plateau, such as the Tibetan plateau (England and Houseman, 1988), becomes greater than 3 km high, it can no longer support its own weight and will begin to spread out, which it achieves by normal and/or strike-slip faulting with a bulk strain pattern that allows it to spread in the direction in which it meets the least resistence. The direction, rate and amount of extension depend on the geometry of the thickened crustal welt and the plate boundary forces active during and after convergence (Dewey, 1988).

Has extensional collapse played a role in Maritimes Basin subsidence? The rapid post-Acadian Horton basin extension, and the flooding and broad sag-style subsidence beginning in Windsor/Hillsborough time are good candidates for stages 4 and 5 of the collapse cycle respectively. In the following section I shall compare the timing and quantitative observations of Moncton Subbasin subsidence from this thesis, together with a recent synthesis of the Acadian orogeny in the Northern Appalachians (Hibbard, 1994) with the predictions of stages 1 to 5 of Dewey (1988) with the goal of evaluating the applicability of the orogenic collapse model to the Moncton

Subbasin. If the events fit the model predictions one might infer (but not consider it yet proven) that body forces and not just plate boundary interactions played a dominant role in this part of the orogen in the Late Devonian and early Carboniferous causing the part of the orogen upon which the Maritimes Basin lies to founder, while the rest of the orogen remained emergent.

Figure 7-4 summarizes the timing constraints on the compressive phases preceding Moncton Subbasin subsidence in southern New Brunswick and surrounding regions. A dominantly Silurian phase, called the Salinic (Boucot, 1962; Dunning et al. 1990) or early Acadian (Williams, 1992; Hibbard, 1994) phase was followed in the Early and Middle Devonian by the Acadian ("classic Acadian" of Hibbard, 1994) phase. Hibbard notes that the Acadian phase is marked by a distinct change in the convergence direction in the northern Appalachians from north-south in the Silurian to northwest-southeast in the Devonian. This change is interpreted as due to a shift in plate interactions, specifically the docking of the Meguma zone on the southeast flank of Avalon (Nance and Dallmeyer, 1993) or the interaction of Laurentia, Baltica and Avalon at an apparent triple junction (Soper et al. 1992). But no matter what the details of the plate interaction, these observations nominate the Salinic and Acadian phases for stage 1 and stage 2 respectively.

Stage 3 predicts rapid uplift, prograde high-temperature metamorphism and the intrusion of post-tectonic granites. A widespread mid-Devonian unconformity is present in New Brunswick (Donohoe and Pajari, 1974) indicating the orogen was emergent. Post-orogenic Devonian granites are also present in southern New Brunswick. The Mount Douglas Pluton (McLeod et al. 1994; Whalen et al. 1994), covering an area of approximately 500 km^2, intrudes rocks of the St. Croix, Ragged Falls - Long Reach and Mascarene Belts southwest of the study area and overprints Acadian textures. It consists of a suite of silica-rich metaluminous biotite granitic rocks (McLeod et al. 1994) with crystalized at a high level in the crust and are classified as "within plate" granite by Whalen et al. (1994). The Mount Douglas Pluton yields an ($^{40}Ar/^{39}Ar$) age of 367 Ma. Late Devonian bimodal volcanic rocks of the Harvey and Piskahegan volcanics are found nearby (McLeod et al. 1994; McCutcheon and Robinson, 1987). Thus there is evidence for stage 3 plutonism immediately preceding, if not coinciding with the onset of rapid Moncton Subbasin subsidence.

At the end of Stage 3, rapid, and accelerating extensional collapse begins, provided there is sufficient relief (3 km). Two observations from this thesis are consistent with the extensional collapse prediction.

1. Subsidence was accompanied by extension and was rapid - averaging least 120 mm / 1000 yr - in the Frasnian

through Tournaisian. The fact that subsidence consistently exceeded sediment supply in the Tournaisian gave rise to perennial lake conditions and suggests that subsidence rate was greatest at that time. Subsidence was apparently accelerating.

2. Observed total subsidence locally exceeded 4 km culminating in deposition of the Gautreau evaporites and was followed soon after by the catastrophic invasion of a Visean sea. This observation is consistent with, but does not necessarily require, a pre-extension template which is a Tibetan-type plateau which has simultaneously undergone both extension and isostatic subsidence so that the tilt-block graben in which basal Horton Group sediments were initially deposited - initially an intermontane valley some 2 or 3 kilometres above sea-level - extended rapidly by faulting as the region subsided isostatically. After accommodating more than 4 km of sediment the valley had subsided to below sea level and was flooded by the Visean sea in which Windsor Group evaporites were deposited.

Finally, volcanism (stage 5) occurs in the Visean to Westphalian (Dostal et al. 1983; Barr et al., 1985; Fyffe and Barr, 1988) which is generally alkalic with a within-plate geochemical signature. While Visean volcanism is not voluminous in the exposed Carboniferous, it may be widespread beneath the Gulf of St. Lawrence. Basalts outcropping in the Magdalen Islands have been interpreted as having erupted on a thick sequence of evaporites. They are exposed only by virtue of having been transported nearly 4 km vertically by a salt diapir. The thousands of square kilometres of Windsor Group in the surrounding subsurface remain untested. An extensive basaltic horizon overlying the Windsor evaporites cannot be completely ruled out for the central Maritimes Basin. Although some observations of late-stage extensional collapse - such as the unroofing of metamorphic core complexes or the occurrence of flood basalts - have not been observed in the Maritimes Basin, neither is the degree of extension as great as that experienced in Dewey's stage 5 examples such as the Basin and Range province of western North America.

The geophysical observations then, are consistent, on a qualitative level, with extensional collapse driving extension in the Moncton Subbasin in Frasnian to Tournaisian time. The time scale of events, though only weakly constrained by the qualitative orogenic collapse model, is consistent with those of Dewey's (1988) world-wide analogues. A component of dextral shearing was superposed on the extension in Late Devonian time and became dominant when extension waned, resulting in the transpressive Moncton episode. Dextral shearing, in response to tectonic boundary forces continued to be superposed at intervals (e.g. Hopewell episode) on the thermal subsidence phase.

The coincidence in timing and style of post orogenic collapse observed here with those documented in other orogens by Dewey (1988), suggests that gravitational forces acting on the uplifted orogen could cause the Late Devonian Horton basins to form regardless of the boundary forces. This constitutes an alternative view to that of Bradley (1982, 1983) in which the Late Devonian and early Carboniferous basin formation is due to shearing boundary forces, which result from local plate interaction by a tectonic escape mechanism.

The post-orogenic collapse model then provides an appealing explanation for the timing and style of Horton basin subsidence observed in the Moncton Subbasin and elsewhere in the maritime provinces. Questions remain as to possible driving mechanism for post-Visean sag-style subsidence. Broad subsidence accompanying thermal equilibration of the crust and lower lithospheric mantle is to be expected after extension, but the ongoing wrench tectonic activity in the Late Carboniferous must also have played a role in Maritimes basin subsidence.

Further work, particularly in the area of quantitative modelling based on realistic earth models is needed to resolve the question of which of the mechanisms best quantitatively predicts the observed basin subsidence.

7.4.4 Visean Through Permian

According to the hypothesis of section 7.3, middle and late Carboniferous events recorded by the Moncton and Hopewell episodes represent, in the first case, Visean transpression on the NE-SW fault zones, and in the second, a response to dextral wrenching on the Cobequid-Chedabucto Fault Zone in the Namurian. These events were followed by brittle strike-slip faulting late in the Carboniferous or in early Permian time. These observations support the view of LeFort and Vander Voo (1981) and others (Figure 7-5) that distributed dextral shearing along east-west trending shear zones associated with the docking of Gondwana, with which Meguma had already docked, was pervasive and formed the late stage of the Variscan Orogeny. Brittle fracturing at all scales across a broad zone extending from the Urals to the southern U.S. constituted a zone of "megashear" in the Stephanian and Permian (Arthaud and Matte, 1977) in the final stages of the Variscan orogeny. The megashear model predicts that brittle, steep, strike-slip faulting accompanied by little deformation within individual fault blocks affected an area broader than the Variscan orogen itself. The style and orientation of the predicted fault movement is consistent with the late (Post Westphalian B) movements of the Berry Mills Fault and implies that these late movements, which are largely responsible for today's Carboniferous outcrop pattern, may have occurred as recently as Permian time.

In conclusion, the strain history in the Moncton Subbasin is consistent in the Late Devonian and Tournaisian, with the oblique extensional collapse of the Acadian orogen, followed by a prolonged period of dextral wrench tectonics, locally episodic, which may have been active as late as Permian time - a response to the final assembly of Pangea.

Plates and Figures

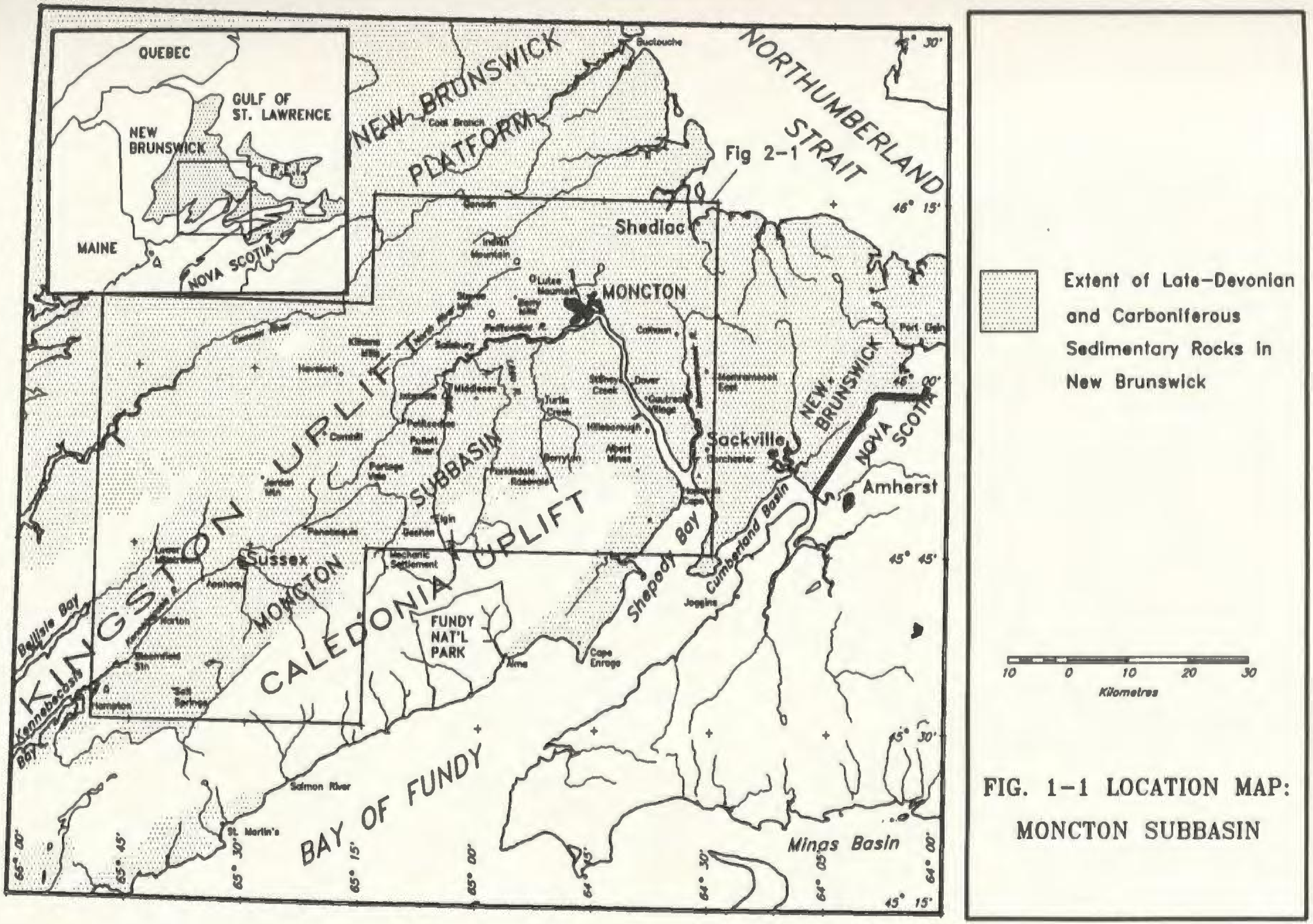
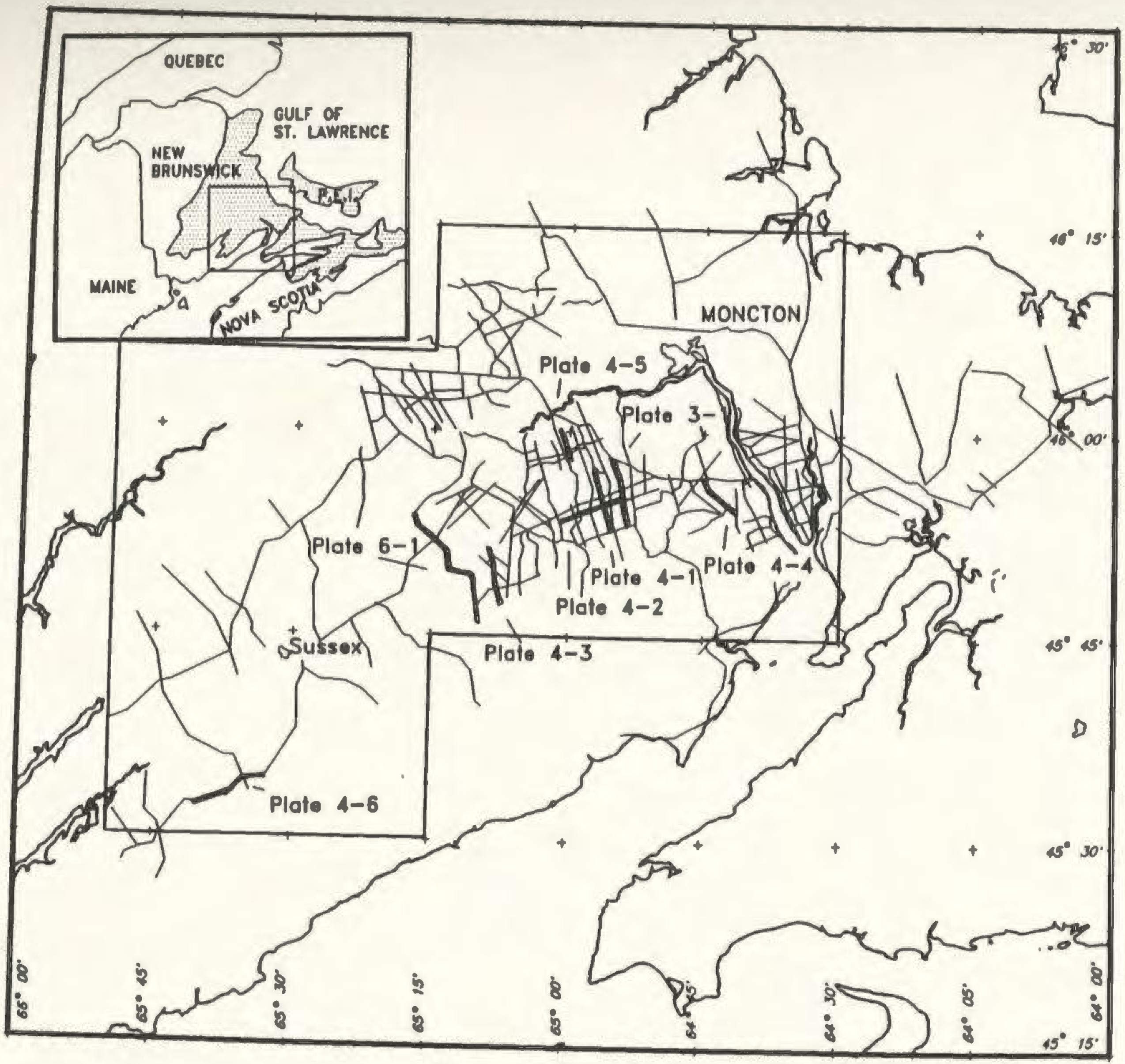


FIG. 1-1 LOCATION MAP: MONCTON SUBBASIN



LEGEND

Location of seismic lines included as plates in this thesis

Chevron/Irving Seismic Line location, 1981-1984 surveys

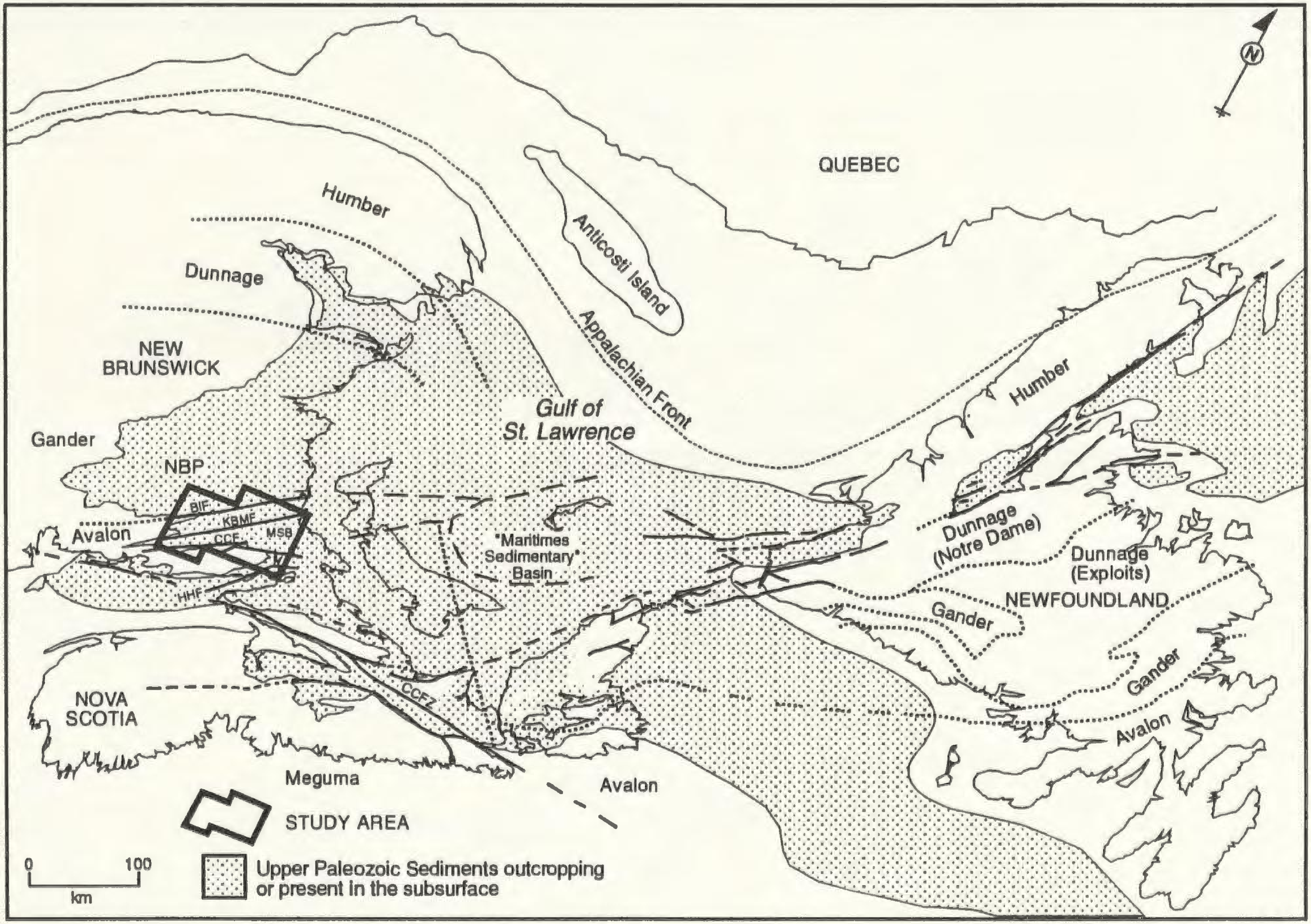
Scale

10 0 10 20 30

Kilometres

FIG. 1-2 SEISMIC LINE LOCATIONS MONCTON SUBBASIN

Fig. 2-1 Present day distribution of Upper Paleozoic sediments in Atlantic Canada showing the study area in relation to principle fault zones (solid lines): BIF = Belleisle fault; CCF = Clover Hill-Caledonia Fault; KBMF = Kennebecasis-Berry Mills fault; HHF = Harvey-Hopewell fault; CCFZ = Cobequid-Chedabucto Fault Zone (Minas Geofracture); Meguma, Avalon, Gander, Dunnage and Humber tectonostratigraphic zone boundaries for the Candian Appalachians are indicated with dashed lines. MSB = Moncton Subbasin; NBP = New Brunswick Platform (Modified from Langdon and Hall, 1994).


QUEBEC
Humber
Anticosti Island
Dunnage
Appalachian Front
NEW BRUNSWICK
Gulf of St. Lawrence
Humber
Gander
NBP
BIF
KBMF
CCF
MSB
Avalon
"Maritimes Sedimentary" Basin
Dunnage (Notre Dame)
Dunnage (Exploits)
HHF
NEWFOUNDLAND
Gander
Gander
NOVA SCOTIA
CCFZ
Avalon
Meguma
Avalon
STUDY AREA
0
100
km
Upper Paleozoic Sediments outcropping or present in the subsurface
N

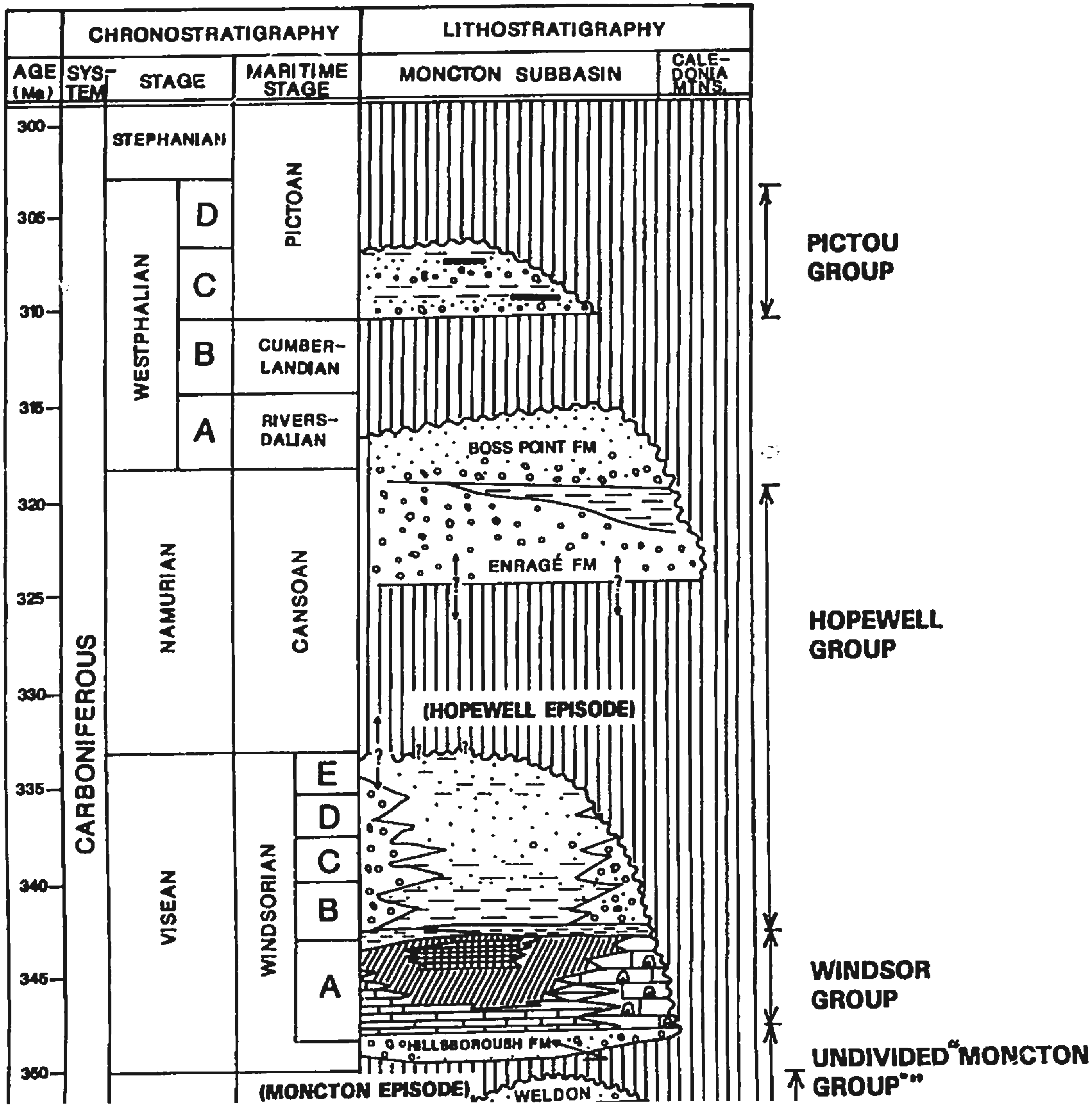

CHRONOSTRATIGRAPHY
LITHOSTRATIGRAPHY
AGE (Ma)
SYSTEM
STAGE
MARITIME STAGE
MONCTON SUBBASIN
CALEDONIA MTNS.
300
305
310
315
320
325
330
335
340
345
350
CARBONIFEROUS
STEPHANIAN
WESTPHALIAN
D
C
B
A
NAMURIAN
VISEAN
PICTOAN
CUMBER-LANDIAN
RIVERS-DALIAN
CANSOAN
WINDSORIAN
E
D
C
B
A
BOSS POINT FM
ENRAGÉ FM
(HOPEWELL EPISODE)
HILLSBOROUGH FM
(MONCTON EPISODE)
WELDON
PICTOU GROUP
HOPEWELL GROUP
WINDSOR GROUP
UNDIVIDED "MONCTON GROUP"

Fig. 2-

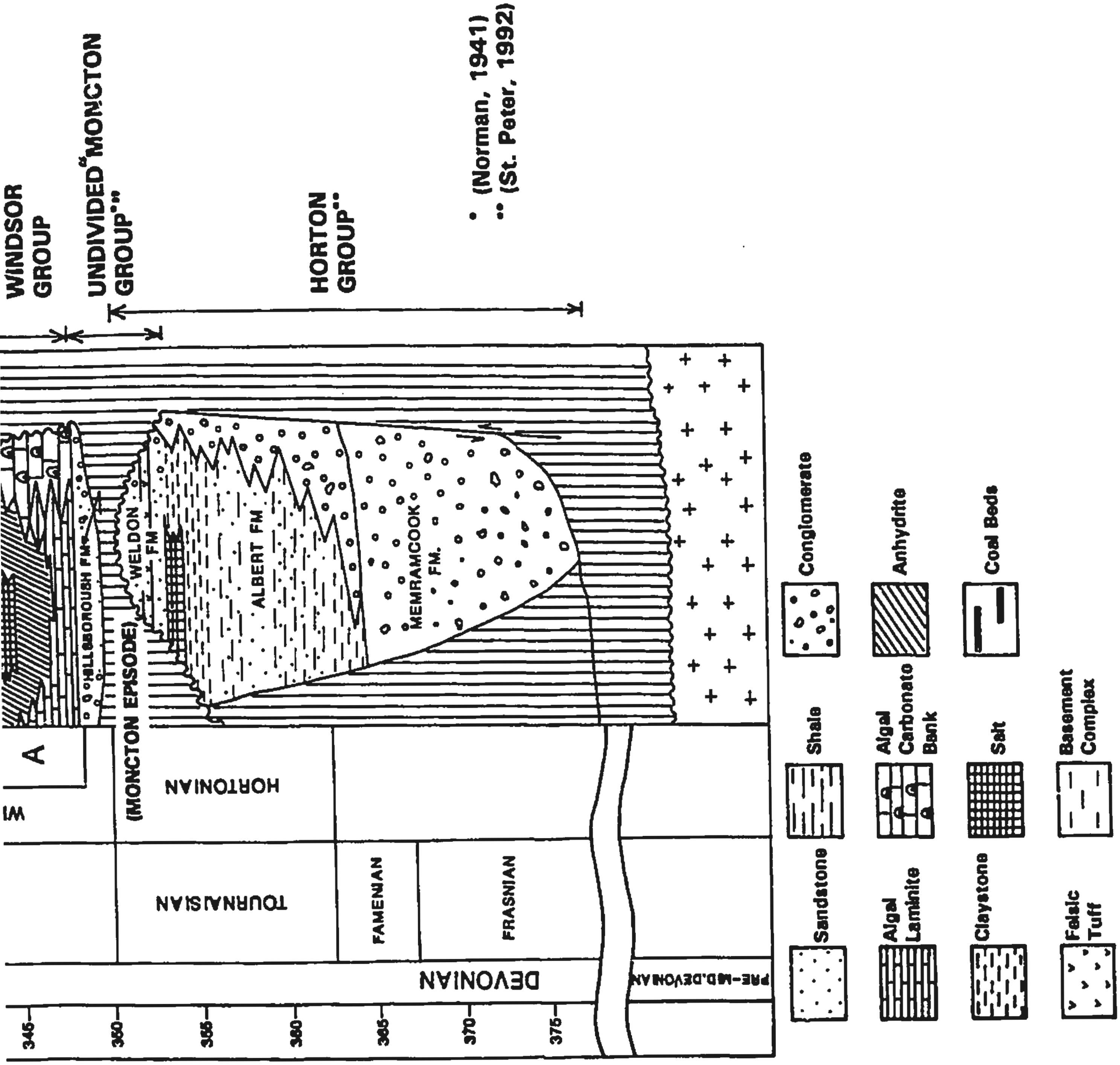
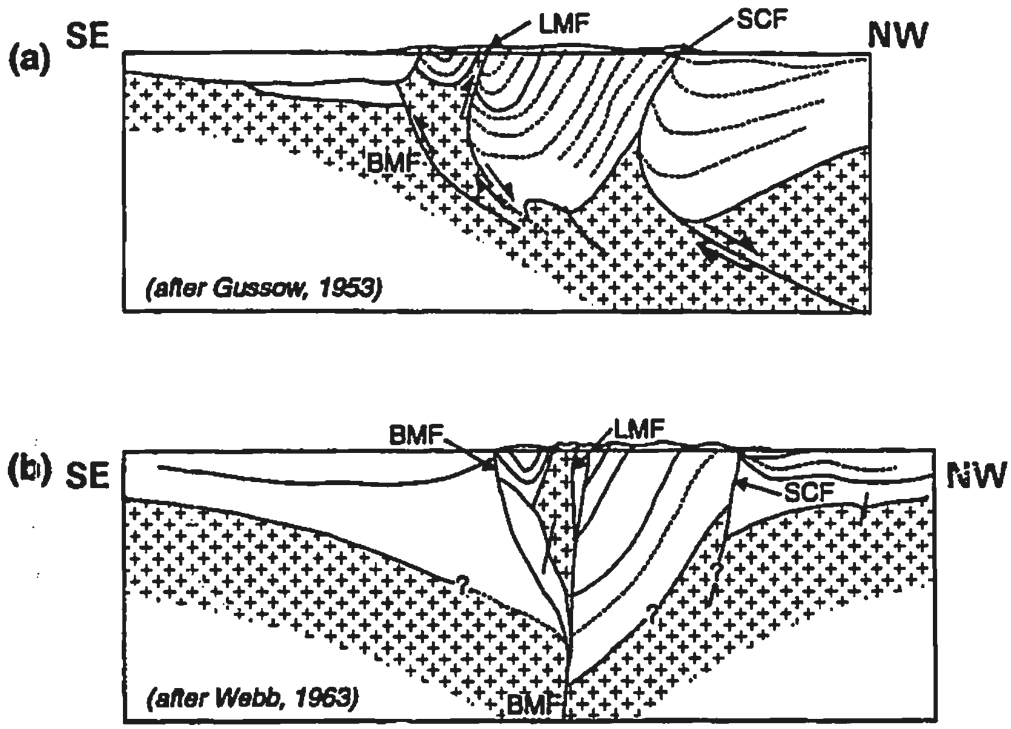


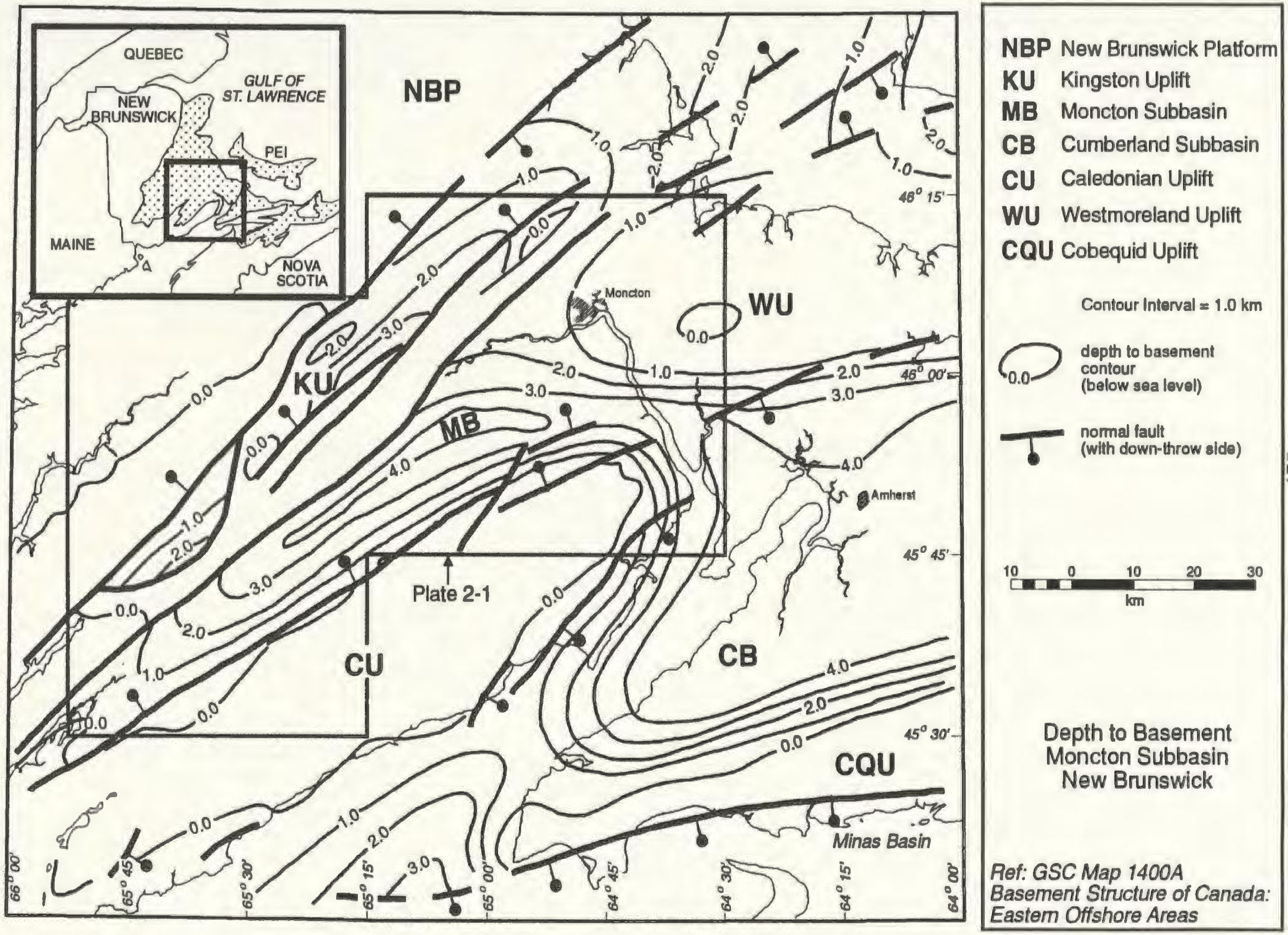
Fig. 2-2 Chronostratigraphic Chart, Moncton Subbasin, showing lithostratigraphic units identified in Plate 2-1. Note ** that Horton Group includes Weldon Formation except in areas mapped as "Moncton Group (undivided)" (Norman, 1941) where the Weldon and Hillsborough Formations have yet to be recognized. (Compiled from Gussow, 1953; Greiner, 1962; McCutcheon, 1981; Anderle et al., 1985; Poll, 1970; St. Peter, 1992; Maritime stages from Kelly, 1970; time scale due to Harland, 1990)



BIF - Belle Isle Fault
SCF - Smith Creek Fault
IMF - Indian Mountain Fault
LMF - Lutes Mountain Fault
BMF - Berry Mills (Kennebecasis) Fault

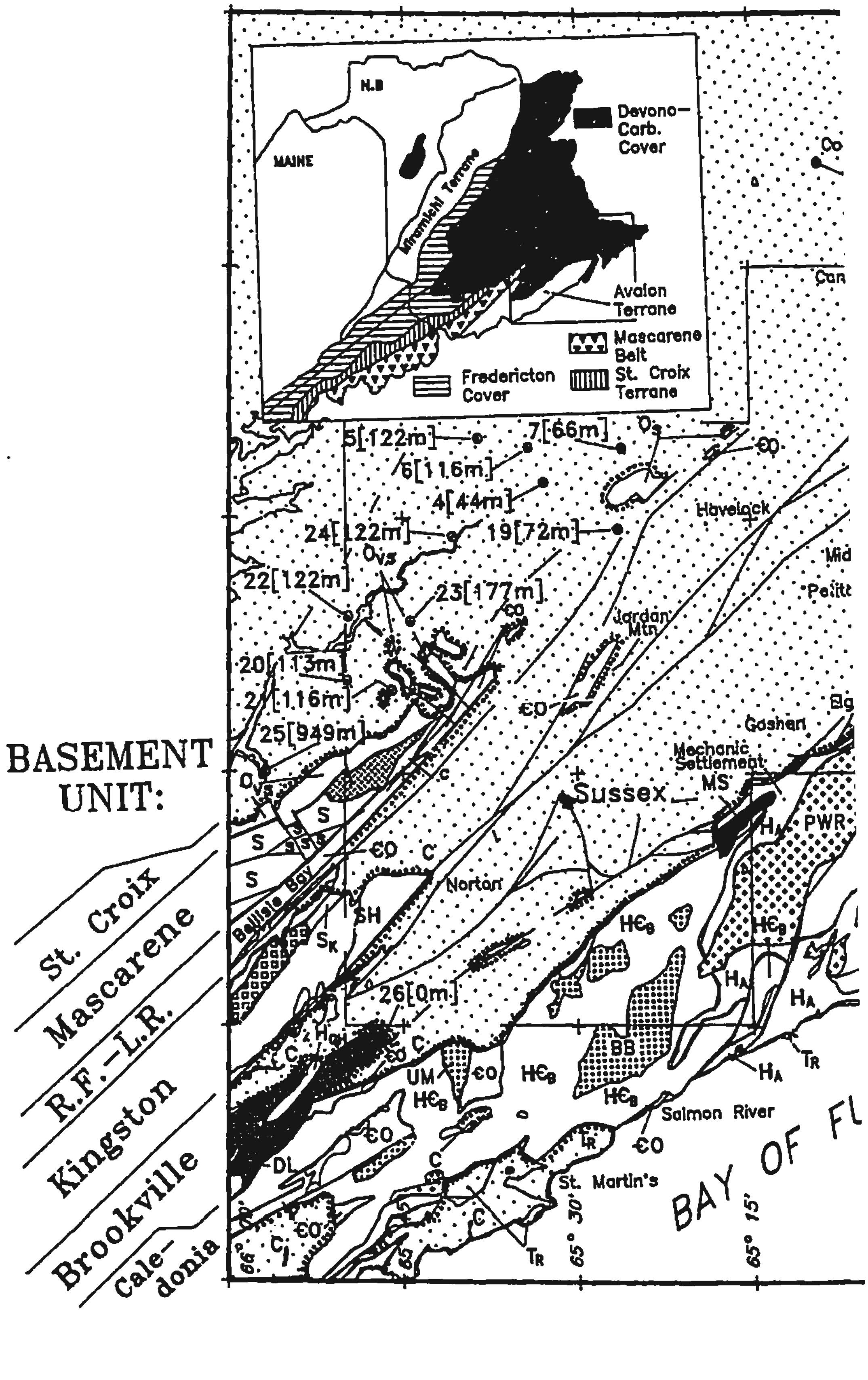
Fig. 2-3 Indian Mountain Cross-section. Two alternative hypotheses proposed for structures observed in the Kingston Uplift are: a) thrust interpretation (Gussow, 1953); and b) wrench fault interpretation (Webb, 1963). See Plate 2-1 for location.

Fig. 3-1 Geological Survey of Canada Depth-to-Basement Map showing locations of "uplifts" and subbasins referred to in the text. Map is based mainly on borehole and potential field data to 1976; all depths are referenced to sea level.



Depth to Basement
Moncton Subbasin
New Brunswick

Ref: GSC Map 1400A Basement Structure of Canada: Eastern Offshore Areas


BASEMENT UNIT:
St. Croix
Mascarene
R.F.-L.R.
Kingston
Brookville
Caledonia
Devono-Carb. Cover
Avalon Terrane
Mascarene Belt
Fredericton Cover
St. Croix Terrane
Miramichi Terrane
MAINE
N.B
Havelock
Jordan Mtn
Goshen
Mechanic Settlement
Sussex
MS
PWR
Norton
Belleisle Bay
Salmon River
St. Martin's
BAY OF FU
65° 30'
65° 15'

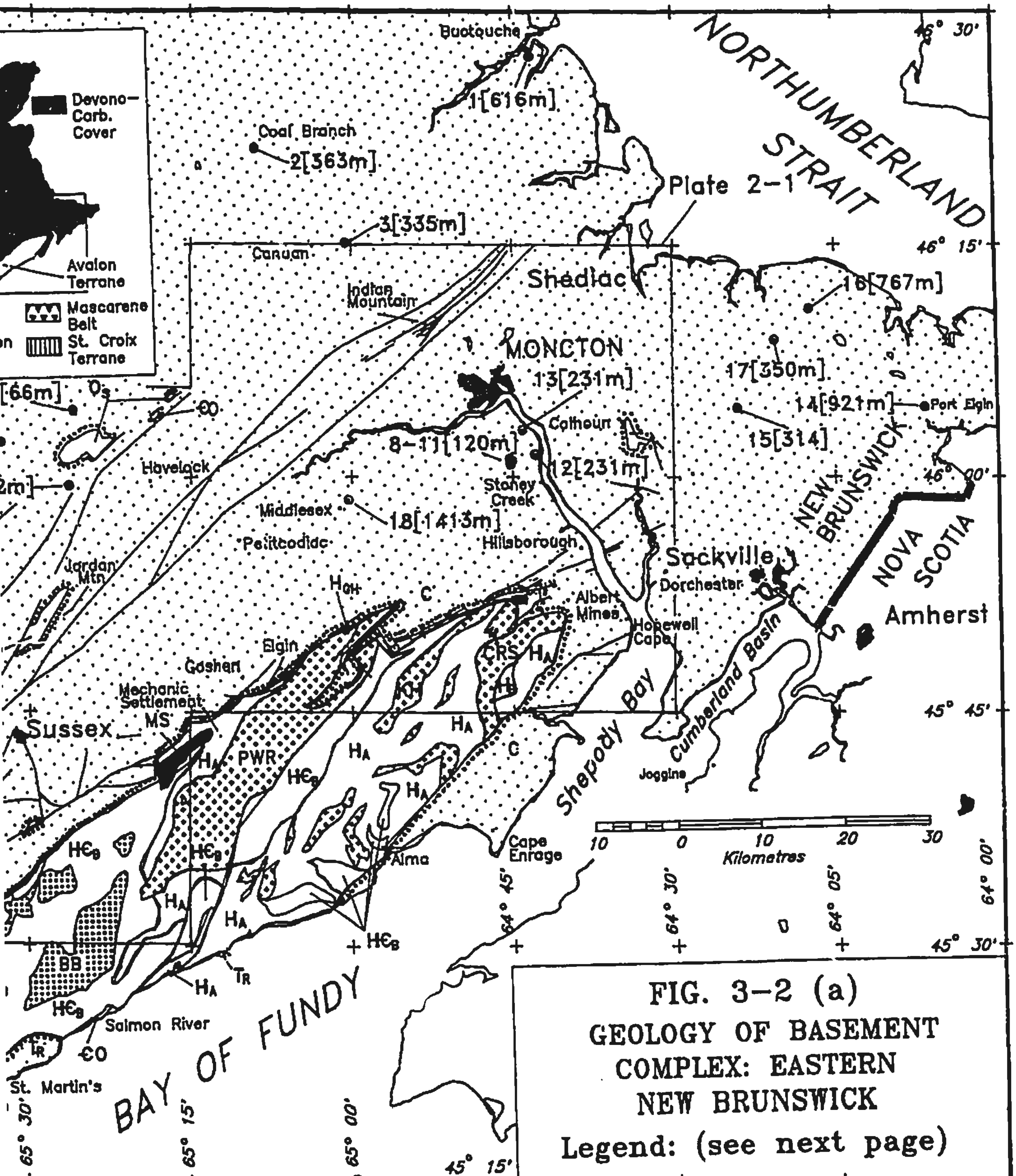


FIG. 3-2 (a)

GEOLOGY OF BASEMENT COMPLEX: EASTERN NEW BRUNSWICK

Legend: (see next page)

Ts — Triassic: Sandstones, siltstones conglomerate (Basal unconformity stippled)

C — Devonian and Carboniferous: Sandstone siltstone, limestone, conglomerate (Basal unconformity stippled)

Devonian: Fairfield Volcanics: (367 Ma.)

Mascarene Cover Seq. — S — Silurian: Medium to thick bedded sandstone siltstone and slate; minor conglomerate

Kingston Belt
- S_x — Silurian: Mafic and felsic dykes
- SH — Silurian or Hadrynian: Bayswater Volcanics; Felsic volcanic and assoc. sedimentary rocks

St. Croix Terrane
- O_s — Ordovician: Felspathic sandstone with interbedded siltstone, shale; minor carbonaceous shale
- O_{vs} — Ordovician: Mafic volcanic flows, pillow lavas, breccias and tuffaceous rocks locally interbedded with sandstone, siltstone and minor carbonaceous shale

Caledonia Terrane
- €O — Cambro-Ordovician: Saint John Group and Brown's Flat Beds: sandstone, siltstone, shale and congl., locally interbedded with mafic and felsic flows, tuffs and breccias
- HC_s — Hadrynian: Coldbrook Group; Basalt flows, rhyolite flows rhyolitic and basaltic tuff, minor dacite and dacitic tuff
- H_A — Hadrynian: Broad River Group; Felsic crystal tuff, minor red siltstone/tuff, dacitic porphyry, grey intermediate

Brookville Terrane
- H_{BG} — Hadrynian: Brookville Gneiss; Banded cordierite-biotite-K-feldspar paragneiss, hornblende-bearing paragneiss, marble, and granodioritic to tonalitic orthogneiss
- H_{GH} — Helikian: Green Head Group; Limestone, dolomite, conglomerate quartzite and argillaceous quartzite.

PLUTONIC ROCKS

Mascarene Belt — Devonian and Silurian: Granitoid intrusive rocks

Kingston Complex — Silurian or older: Felsic intrusive rocks (granitoid rocks and felsic porphyries)

Caledonia Terrane
- Gabbroic Plutons
- Bimodal Granite and Gabbro/Diorite (ca. 550 Ma)
- Granodiorite plutons (ca. 610-630 Ma)

Brookville Terrane — Diorite and granodiorite plutons (ca. 530-560 Ma)

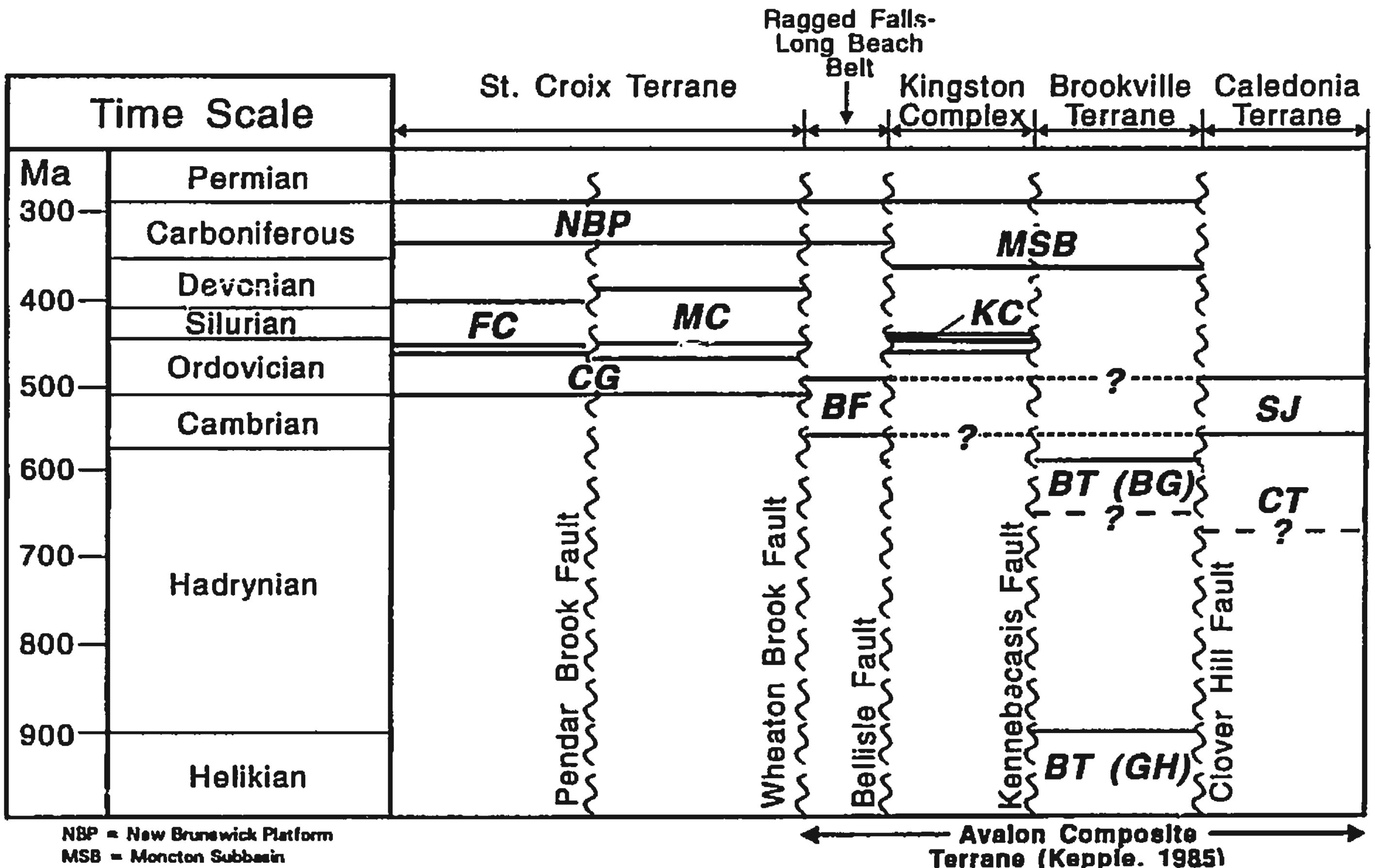
o 2[363m] BOREHOLES INTERSECTING BASEMENT
(Basement depth bracketed)
Boreholes described in Table 3-1

DL Duck Lake Gabbro
KH Kent Hills Granodiorite
CRS Caledonia Road Suite
BB Bonnell Brook Pluton
PWR Point Wolf River Pluton
UM Upham Mountain Pluton
MS Mechanic Settlement Pluton

Map compiled from:

Barr and White (1991)
Fyffe et al (1991)
St. Peter (1989 a,b)
Barr and White (1989)
Barr and White (1991) in Abbot (1991)
St. Peter and Fyffe (1990)
McLeod et al. (1994)

FIG. 3-2 (b) LEGEND
GEOLOGY OF BASEMENT COMPLEX
EASTERN NEW BRUNSWICK



NBP = New Brunswick Platform
MSB = Moncton Subbasin
FC = Fredericton Cover Sequence
MC = Mascarene Cover Sequence
KC = Kingston Complex
SJ = Saint John Group
BF = Browns Flat Beds
BT (BG) = Brookville Terrane (Brookville Gneiss)
BT (GH) = Brookville Terrane (Green Head Group)
CT = Caledonia Terrane
CG = St. Croix Terrane

Fig. 3-3 Simplified table of terranes and overstep sequences in New Brunswick east of the Fredericton Fault.

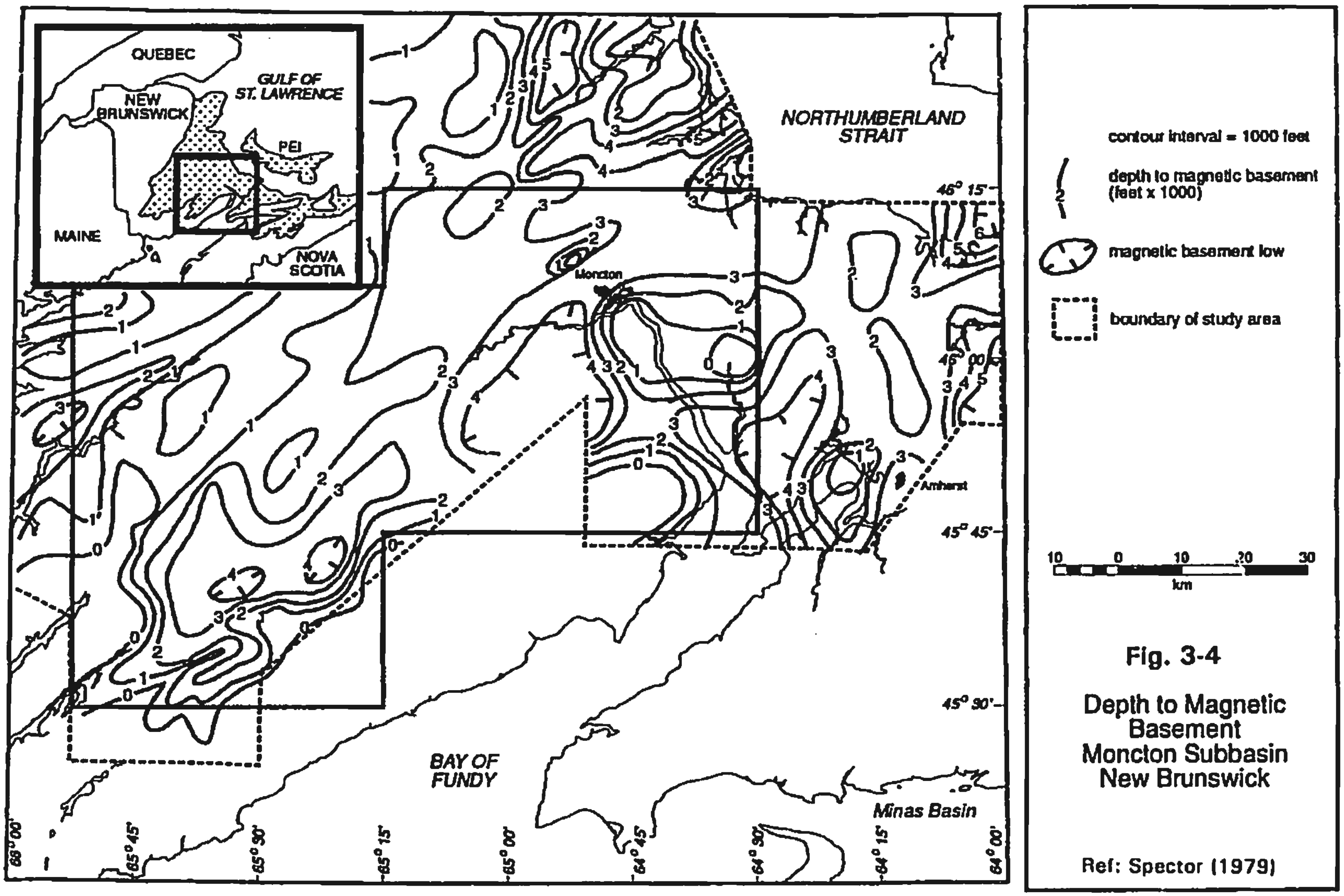


Fig. 3-4

Depth to Magnetic Basement Moncton Subbasin New Brunswick

Ref: Spector (1979)

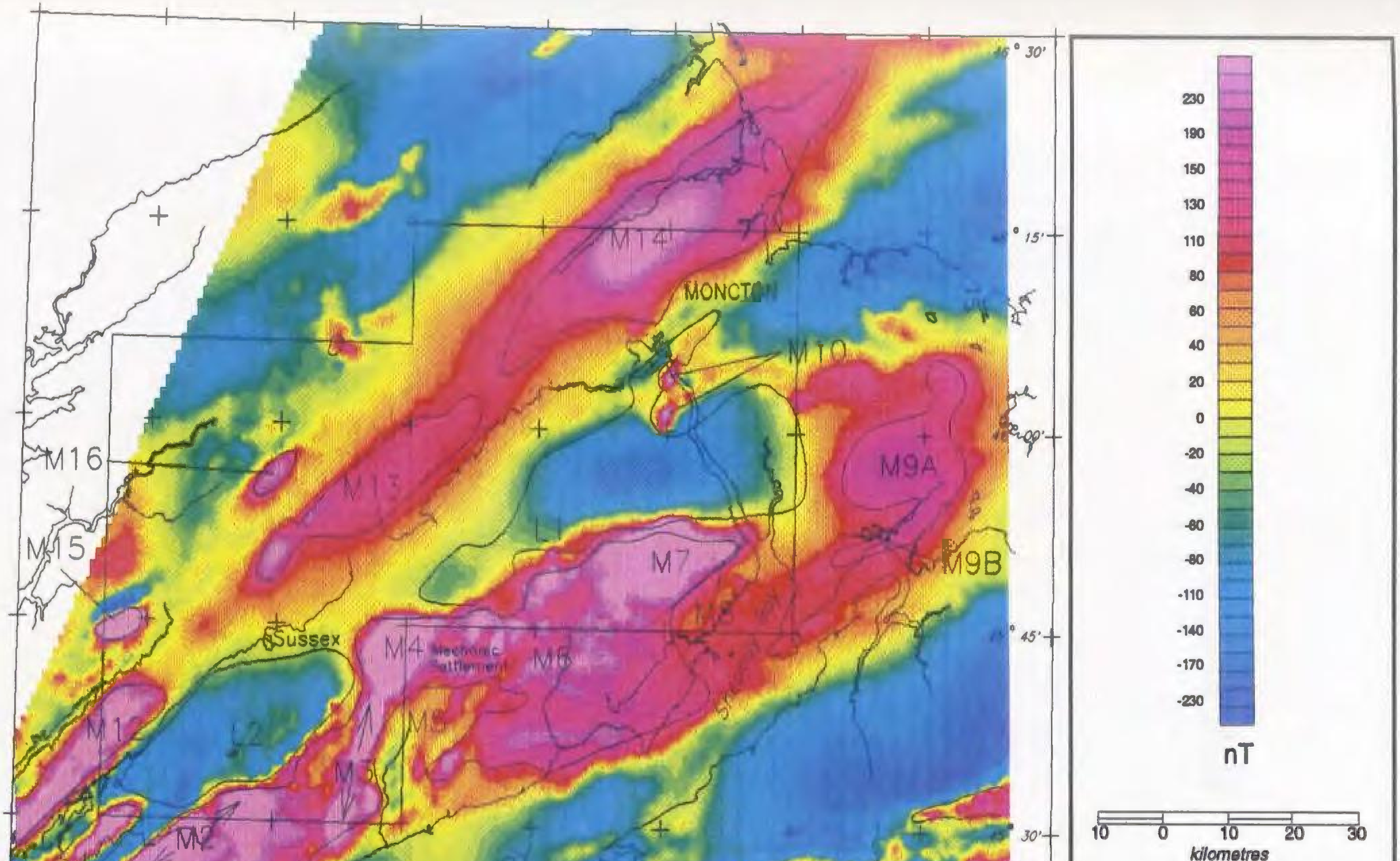


Figure 3-5

Magnetic Total Field Residual Anomay Map Moncton Subbasin

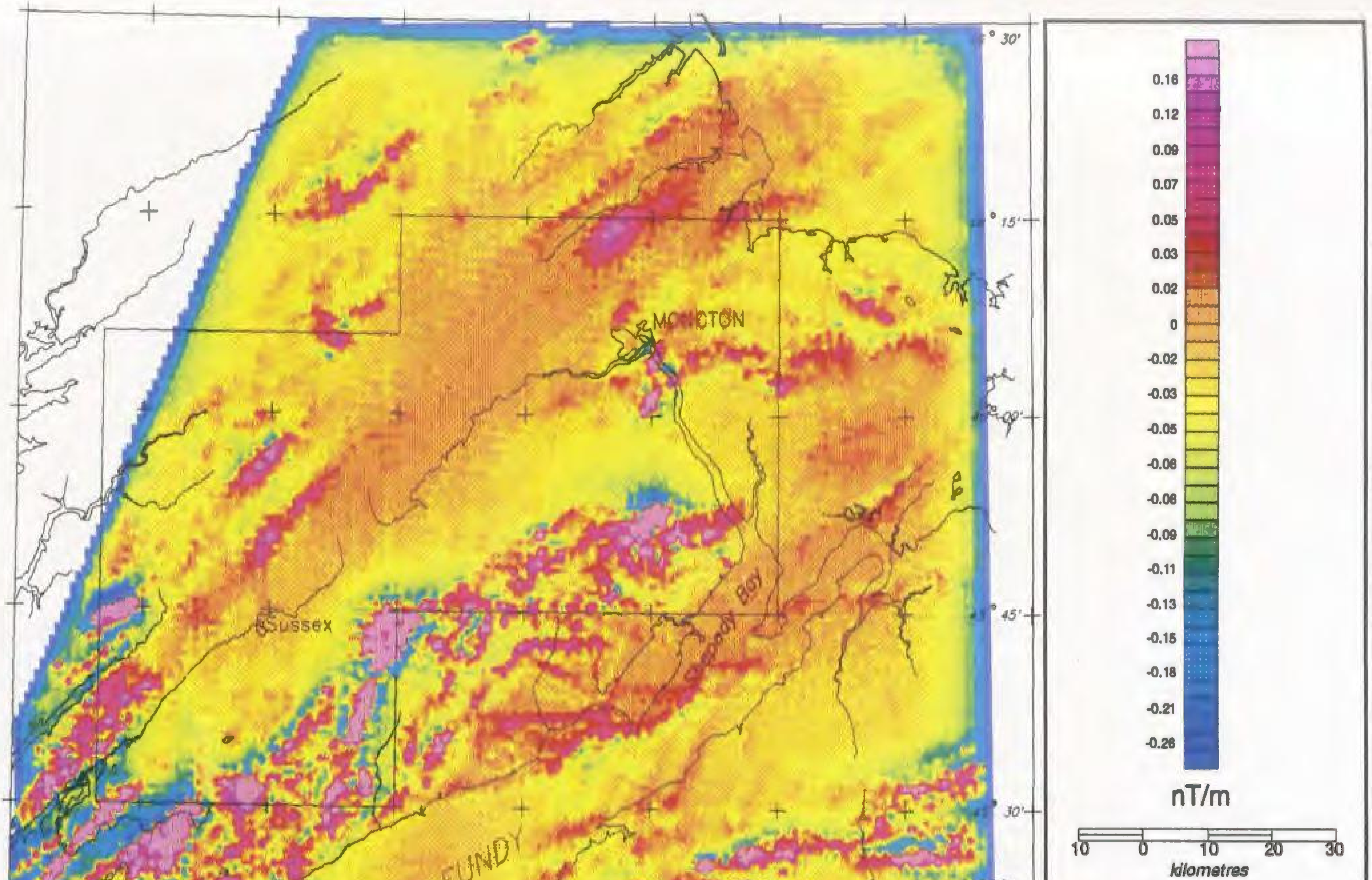


Figure 3-6
Magnetic First Vertical
Derivative Map
Moncton Subbasin

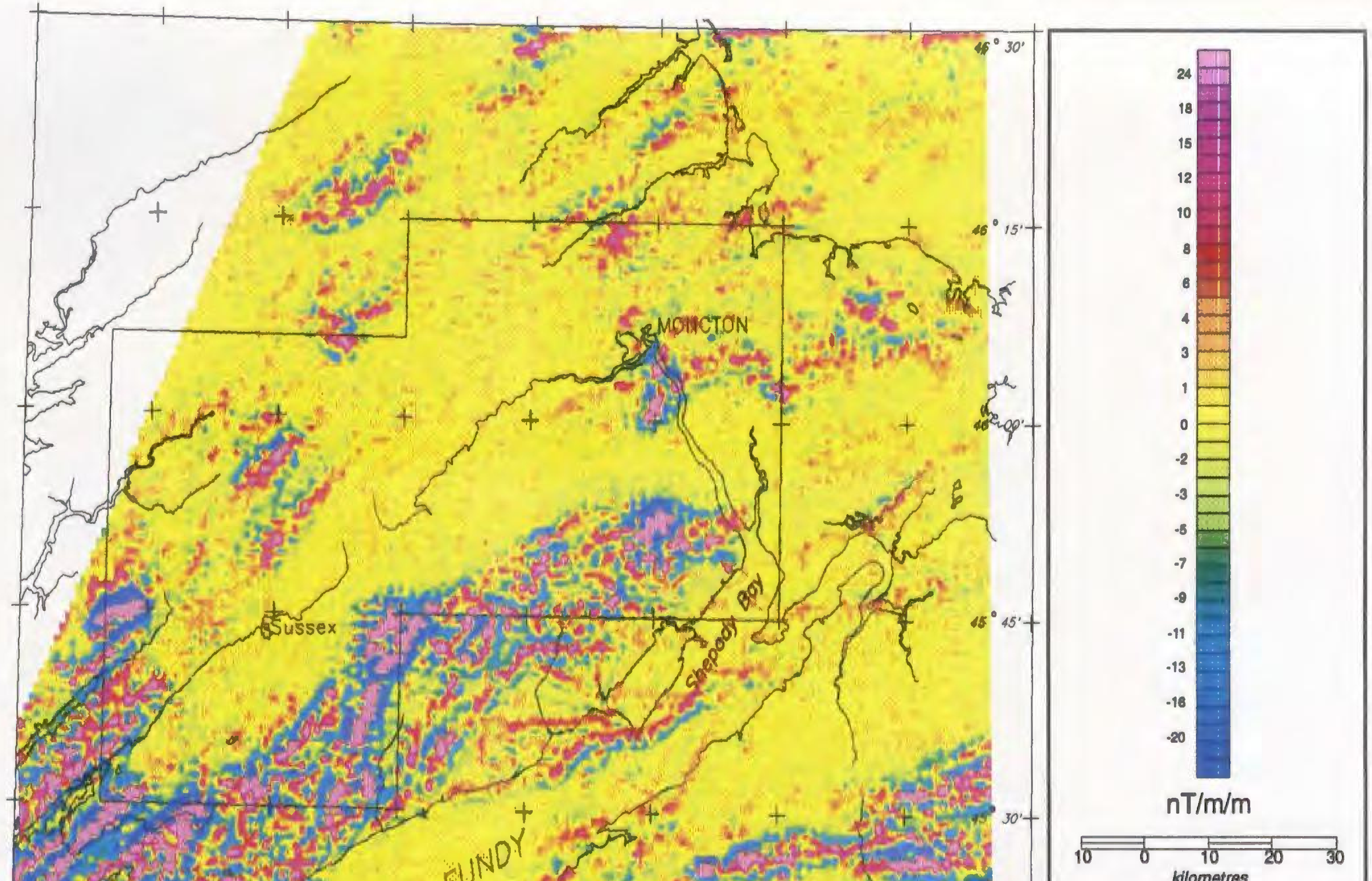


Figure 3-7
Magnetic Second Vertical Derivative Map
Moncton Subbasin

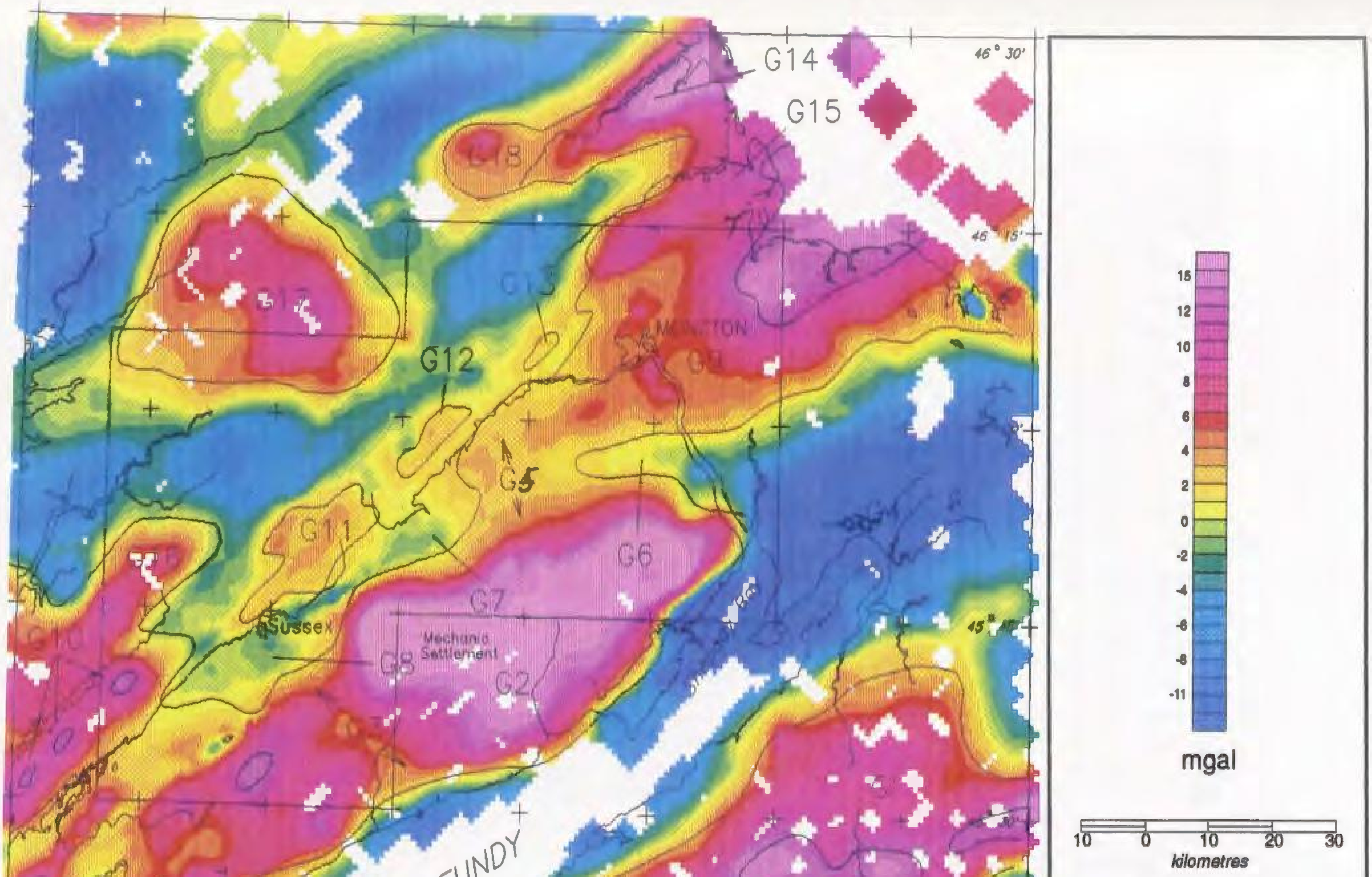


Figure 3-8
Residual Bouguer Gravity
Anomaly Map
Moncton Subbasin

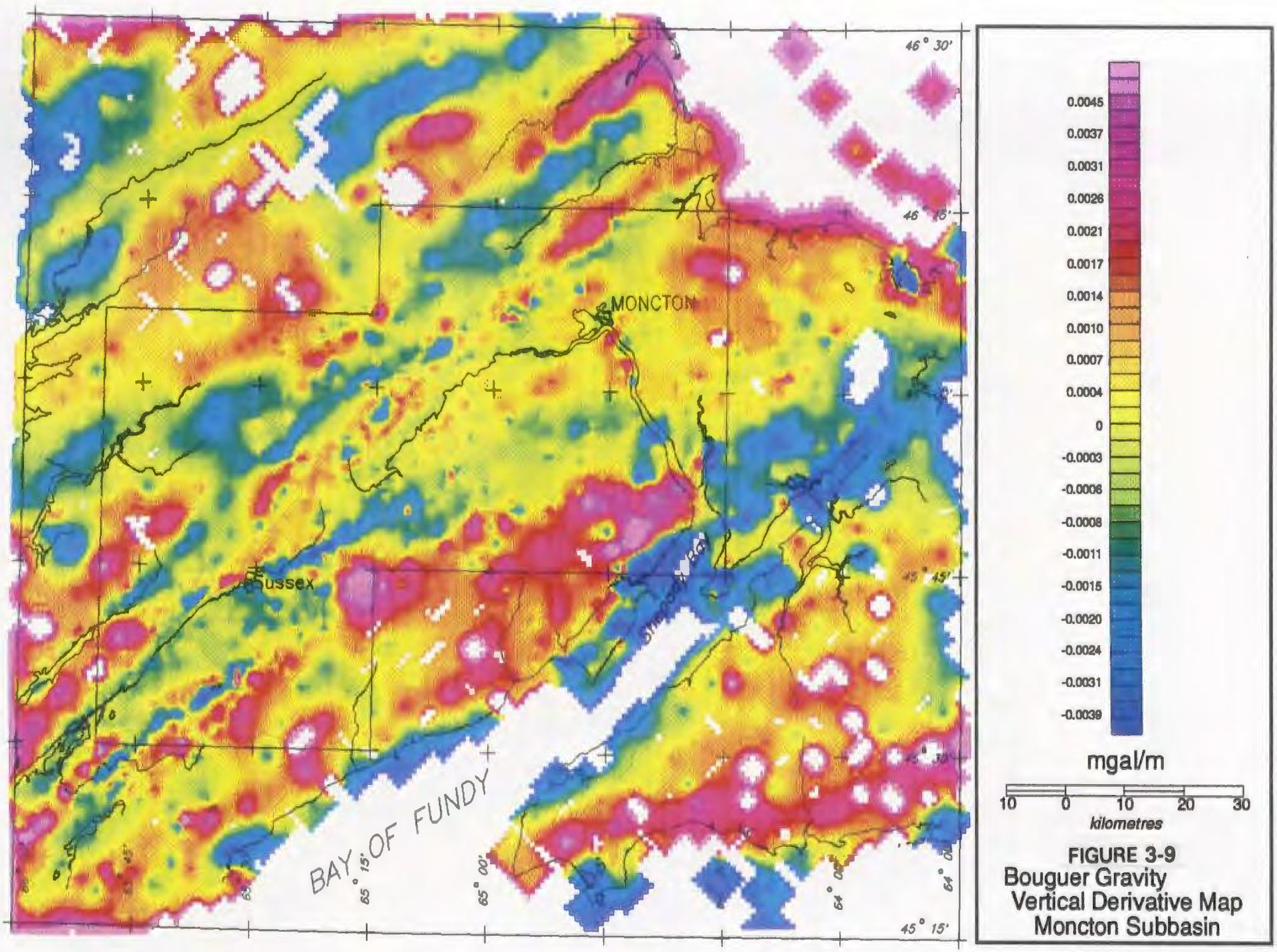


FIGURE 3-9
Bouguer Gravity
Vertical Derivative Map
Moncton Subbasin

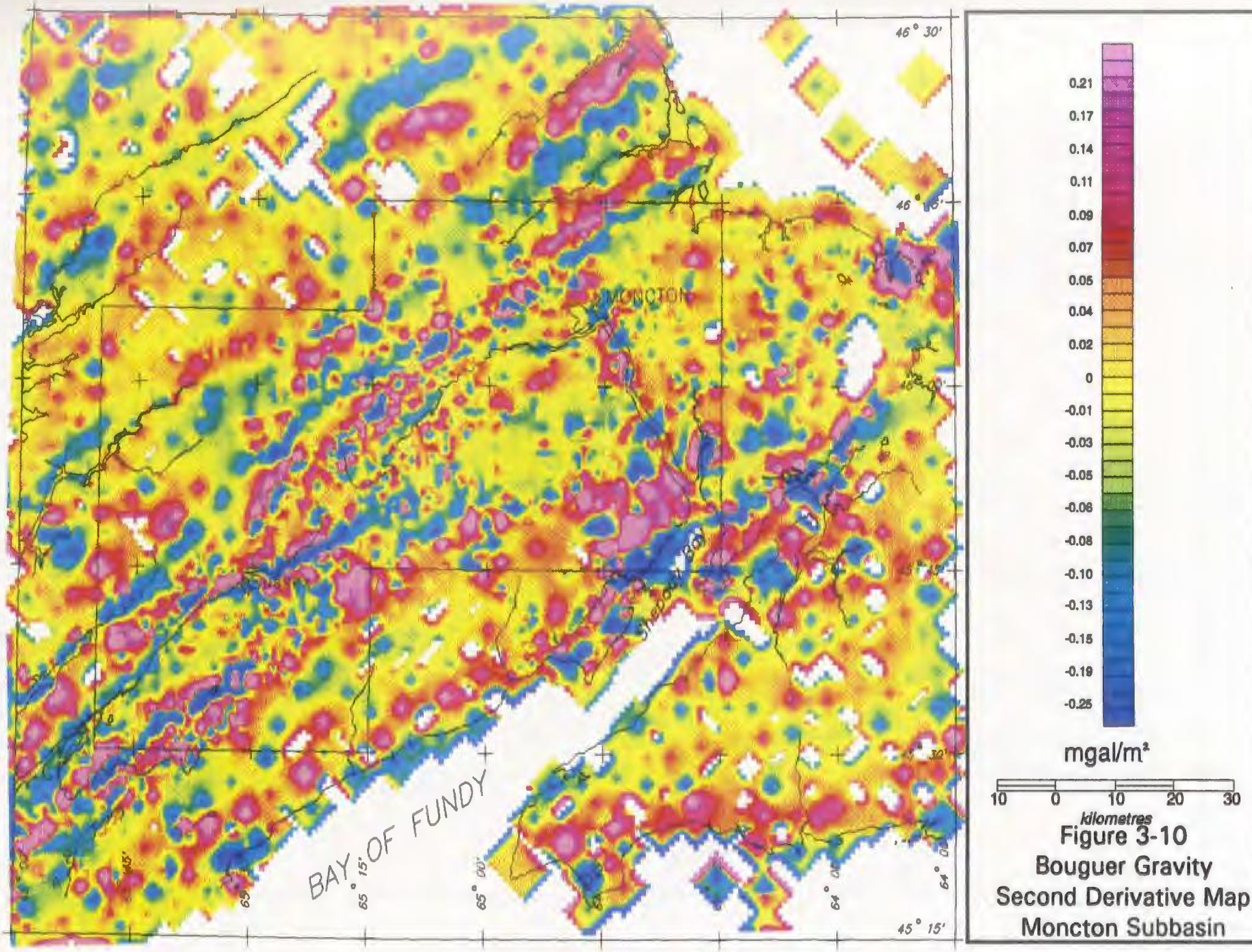


Figure 3-10
Bouguer Gravity
Second Derivative Map
Moncton Subbasin

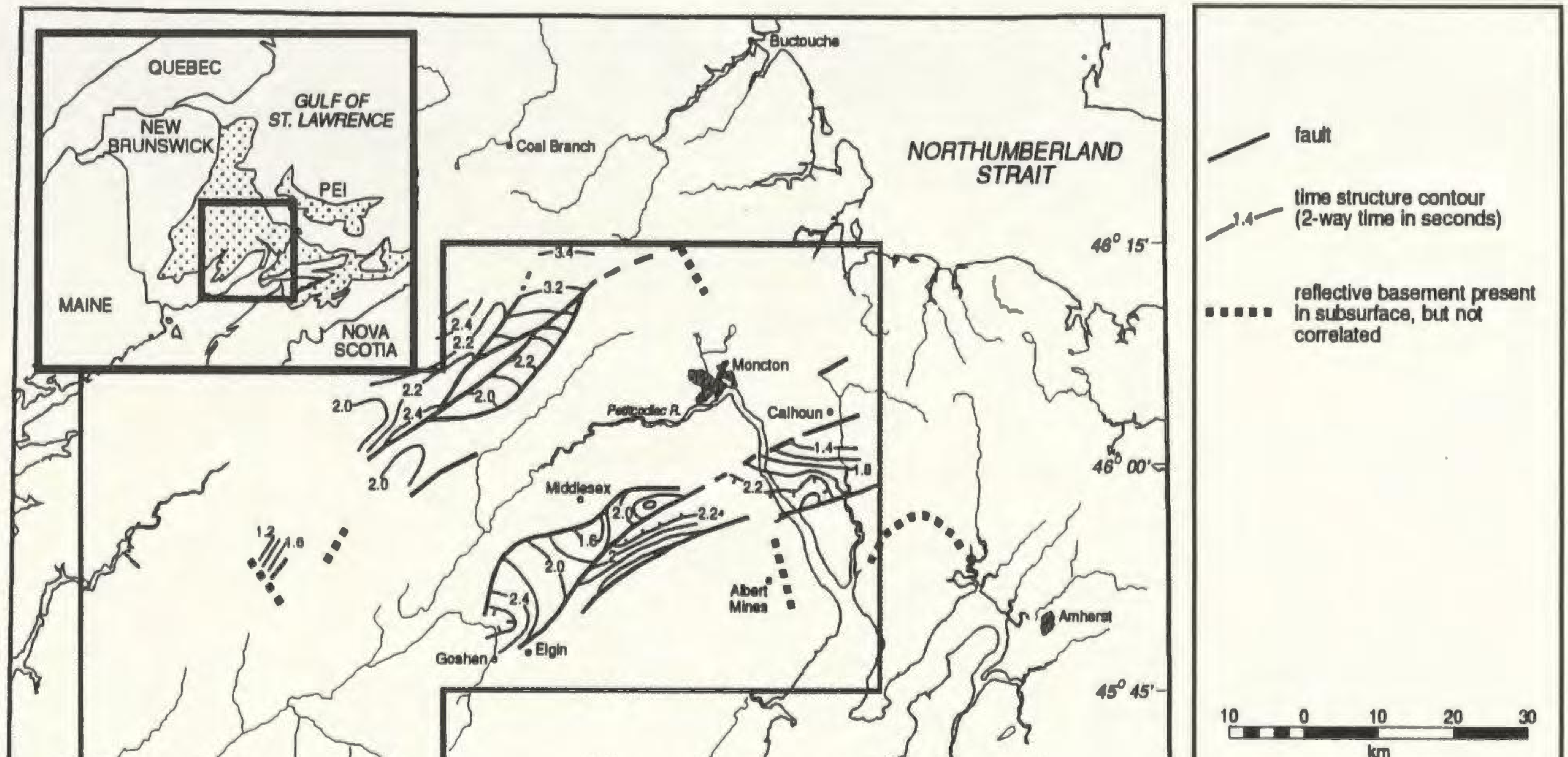


Fig. 3-11

Seismic Time Structure: Top of Reflective Basement Facies Moncton Subbasin New Brunswick

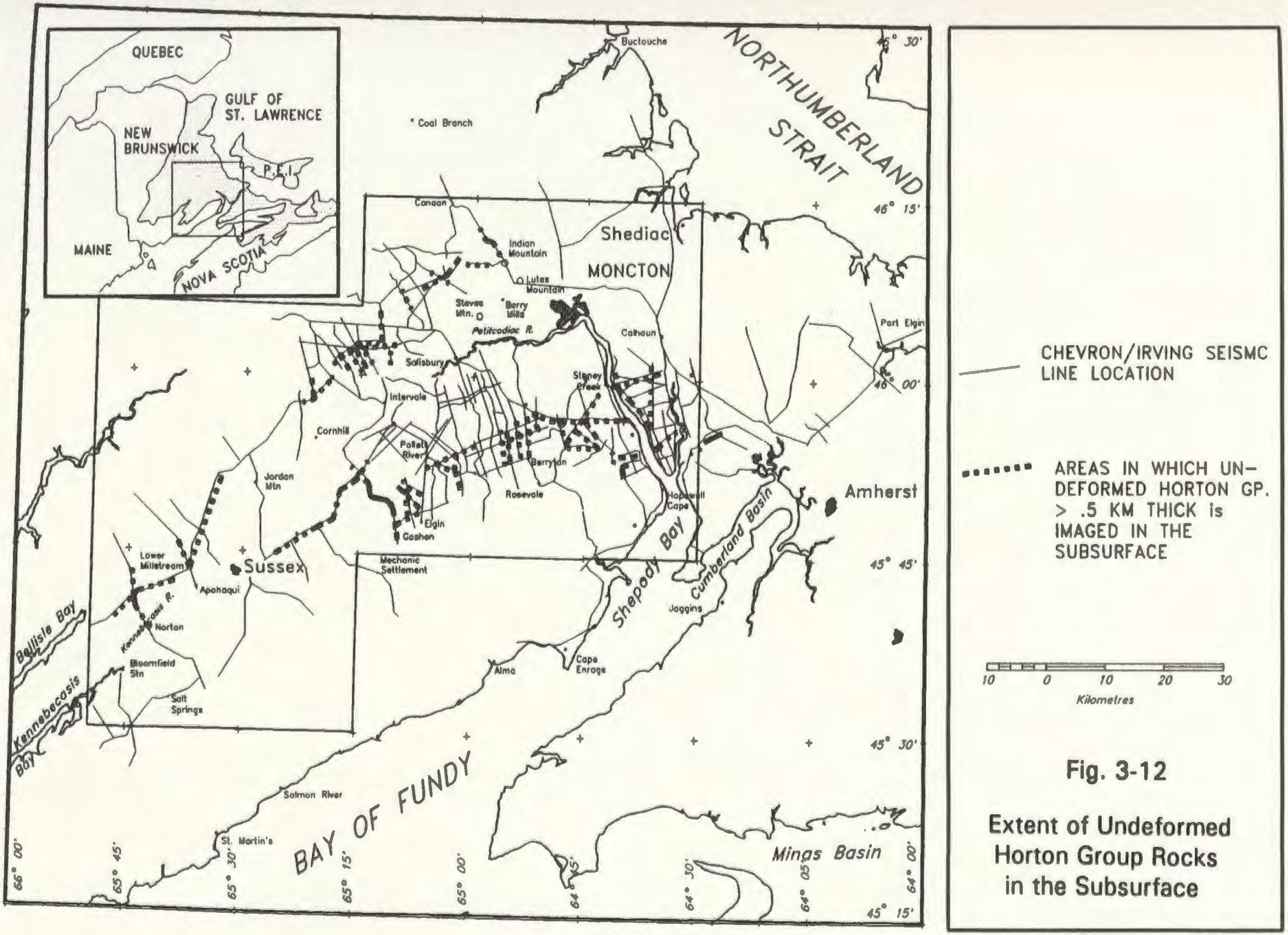


Fig. 3-12

Extent of Undeformed Horton Group Rocks in the Subsurface

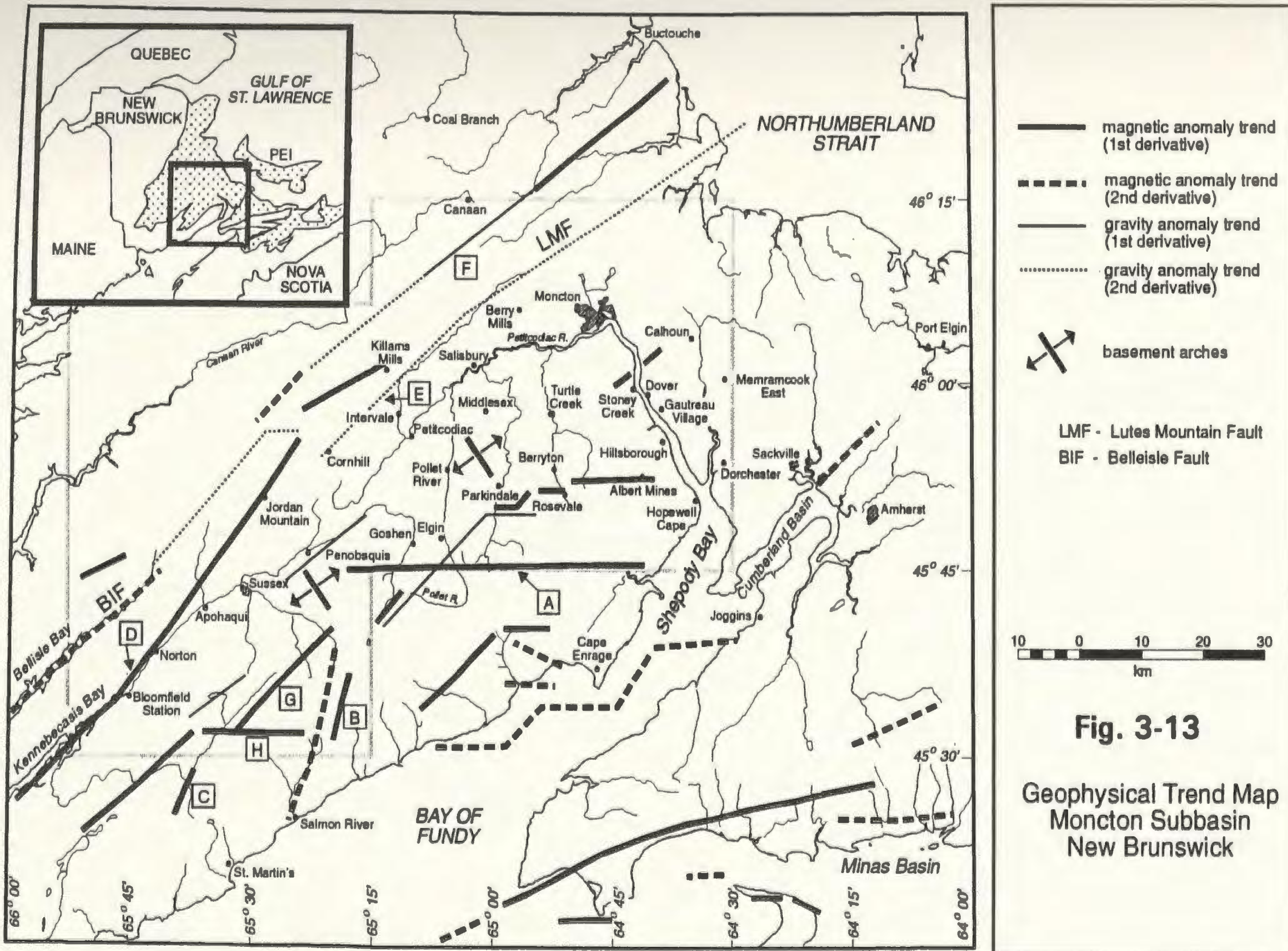


Fig. 3-13

Geophysical Trend Map
Moncton Subbasin
New Brunswick

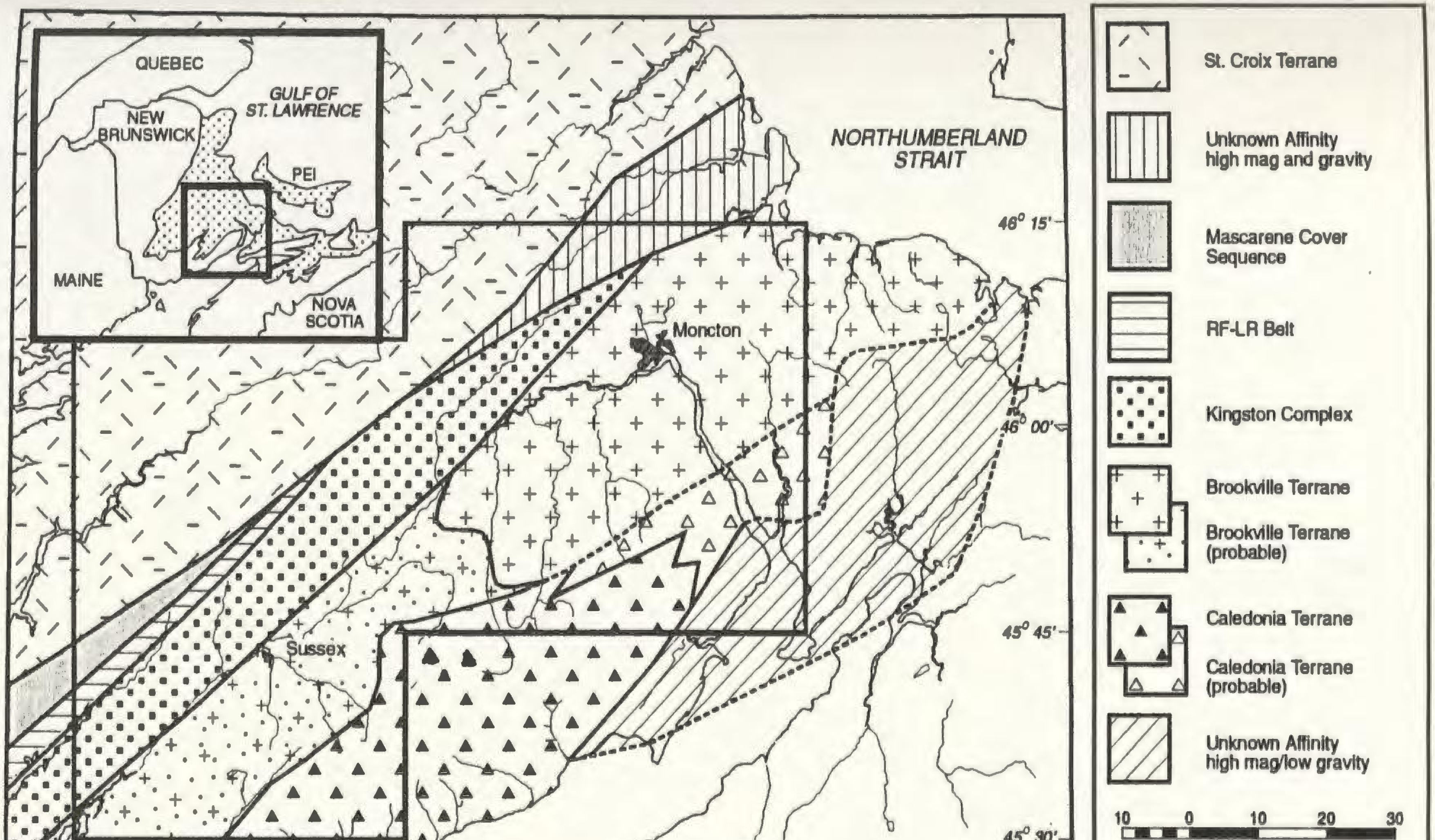
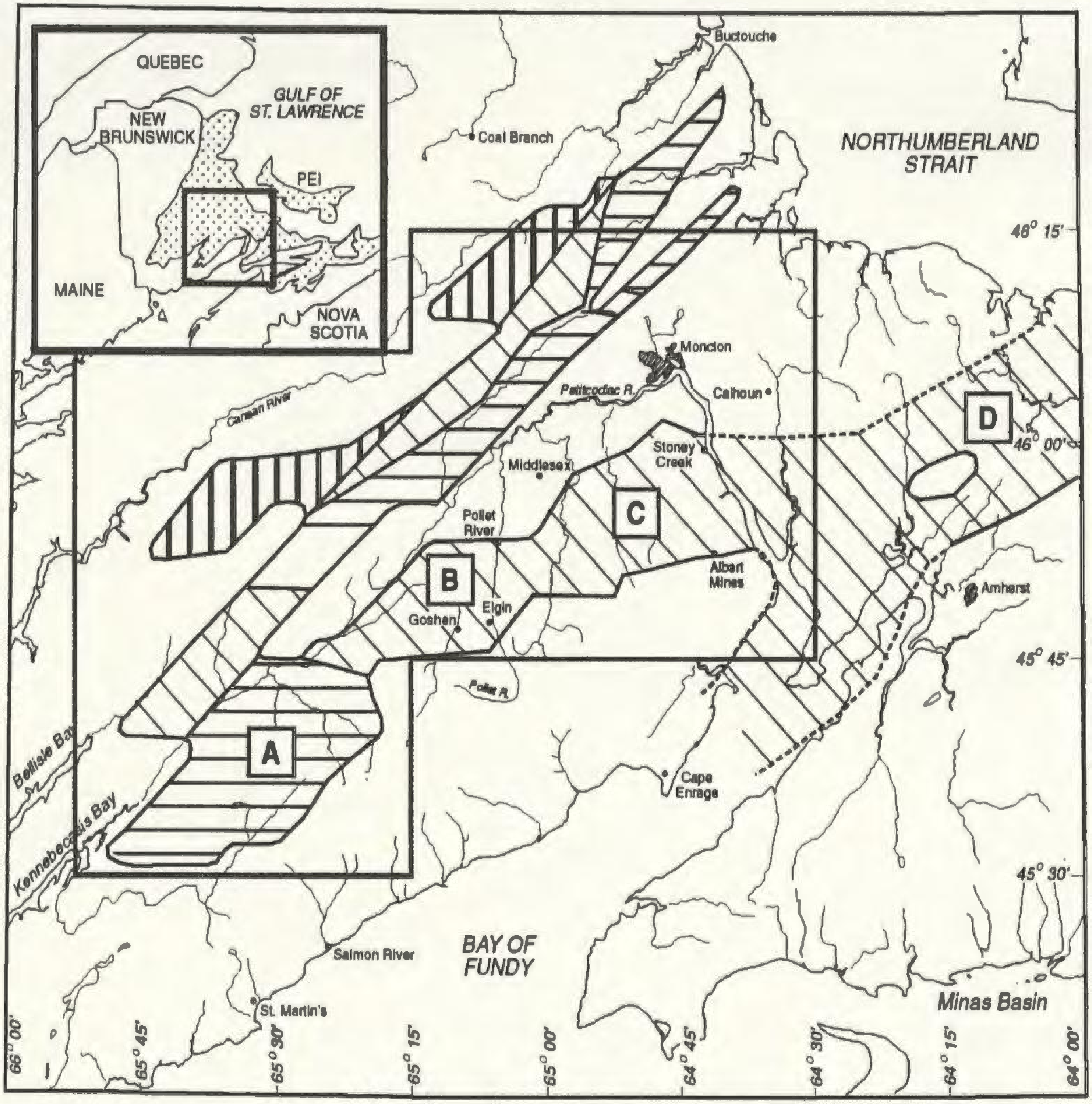


Fig. 3-14
Hypothesized Distribution of Basement Units beneath the Carboniferous Cover Sequence Moncton Subbasin New Brunswick



Relatively undeformed Horton sediments (observed on seismic and potential field data)

Steeply dipping and deformed Horton sediments (identified from outcrop and potential field data)

Horton or older sediments (pre-Carboniferous sequence) interpreted from potential field data

A Sussex Subbasin

B Elgin Subbasin

C Hillsborough Subbasin (Worth, 1977)

D Sackville Subbasin (Martel, 1987)

10 0 10 20 30
km

Fig. 3-15

Distribution of thick (>0.5 km) Horton Sediments (inferred from regional geophysical data) Moncton Subbasin New Brunswick

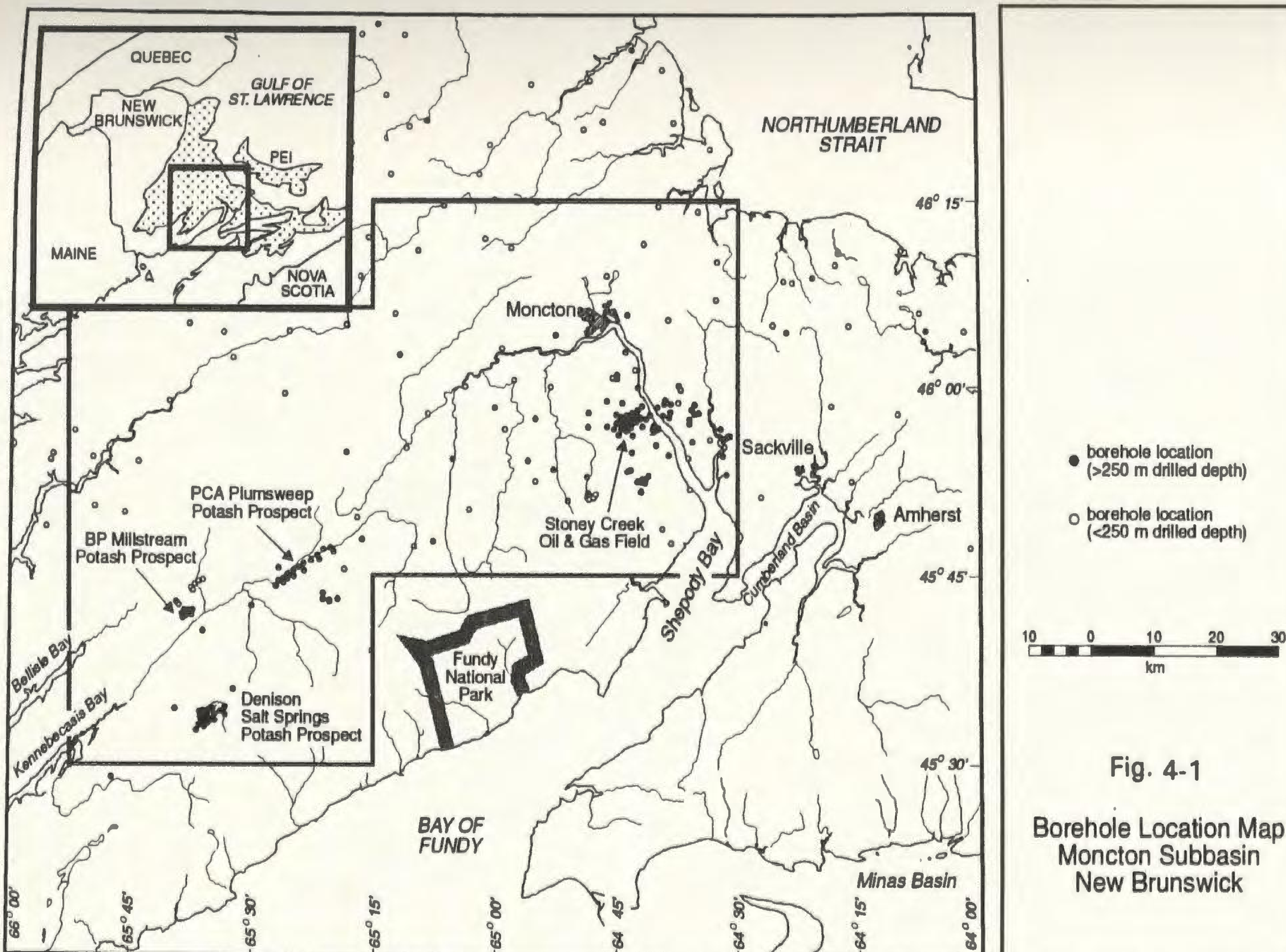
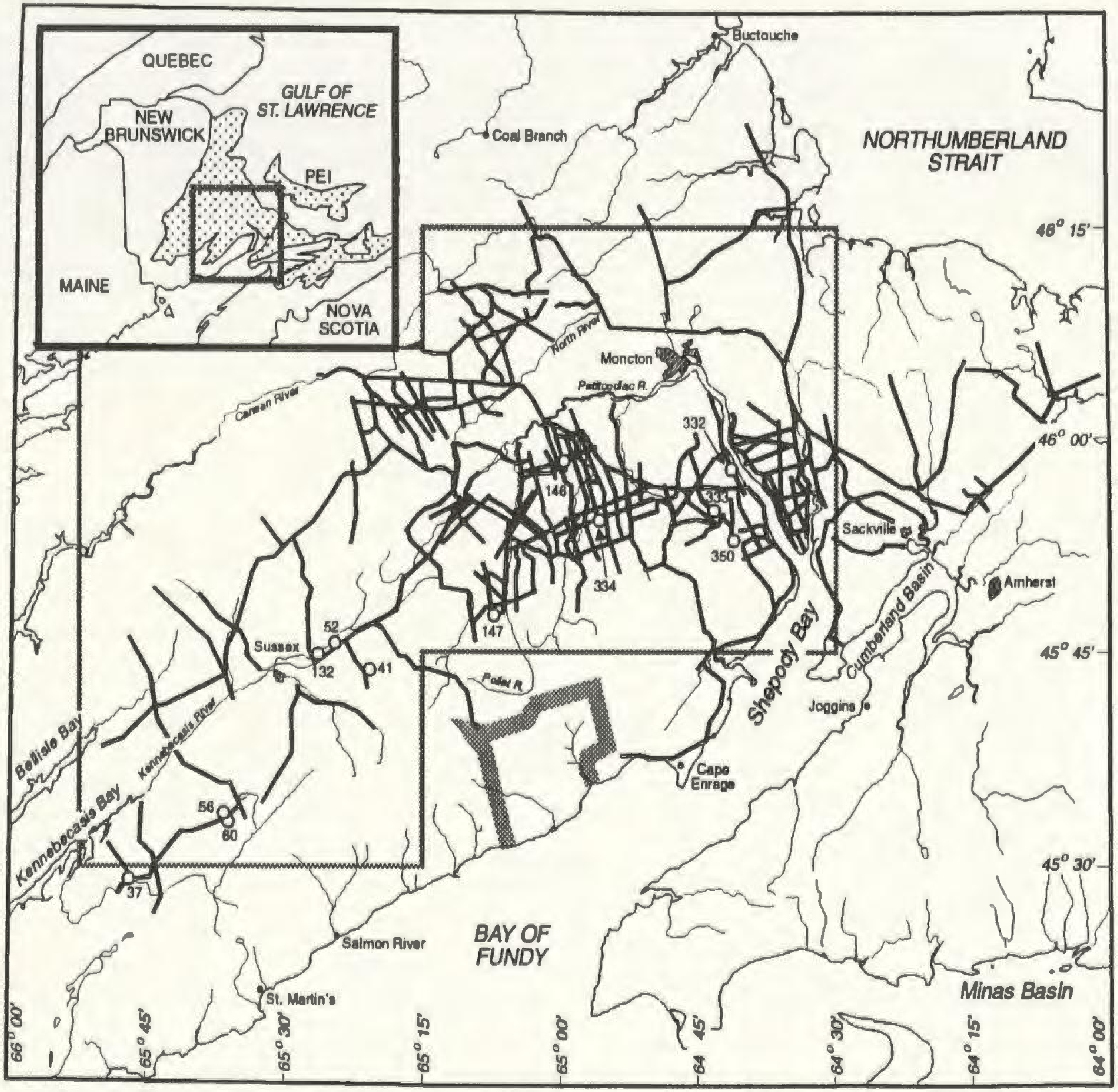


Fig. 4-1

Borehole Location Map
Moncton Subbasin
New Brunswick



Well No.	Well Name
37	I/C Smithtown #1
41	KMG Urney #1
52	PCA #22
56	IMC Salt Springs #1
60	IMC Salt Springs #5
132	PCA #23
146	I/C Middlesex #1
147	I/C Lee Brook #1
332	I/C East Stoney Creek #1
333	I/C Hillsborough #1
334	I/C Little River #1
350	Can. Oxy. Albert Mines 81-1

350 borehole with synthetic seismograms

Irving/Chevron seismic line location

10 0 10 20 30
km

Fig. 4-2

Seismic Line Location
Moncton Subbasin
New Brunswick

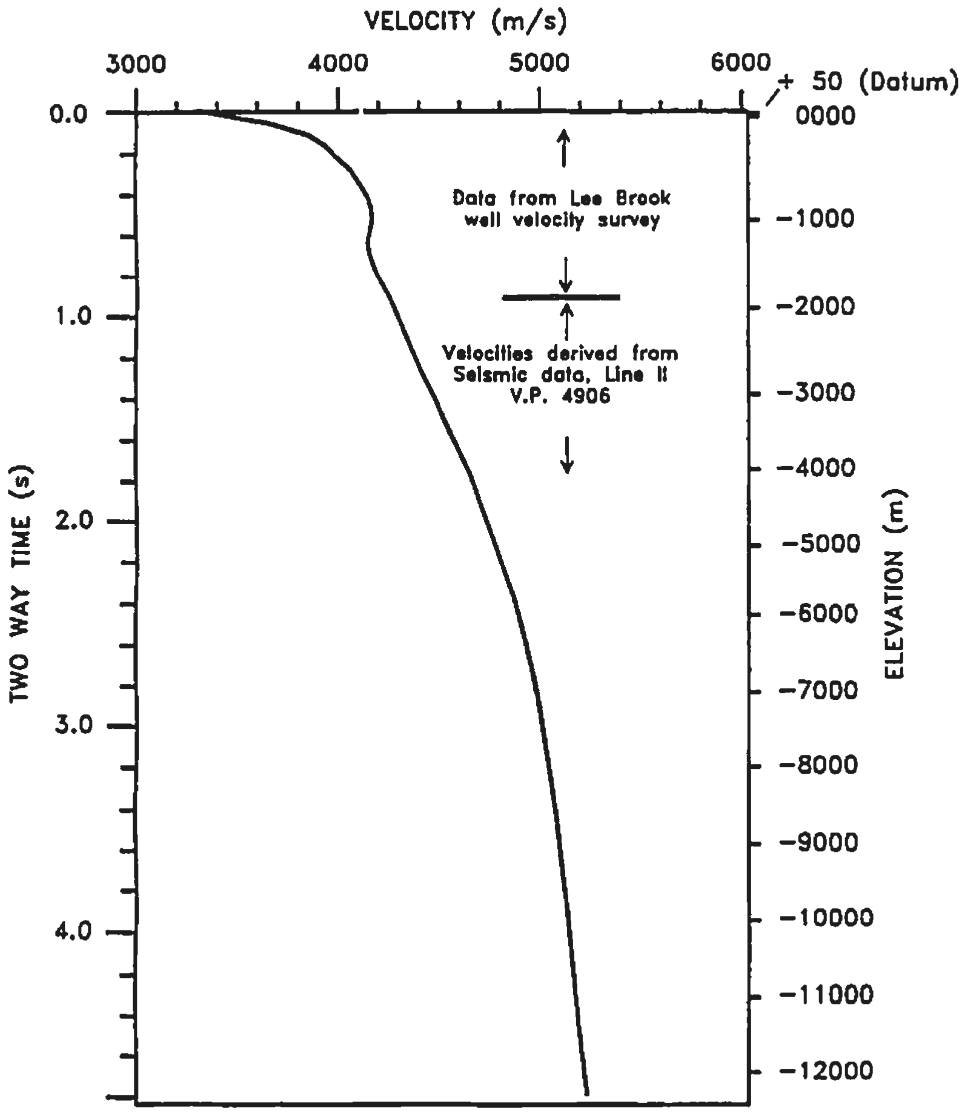
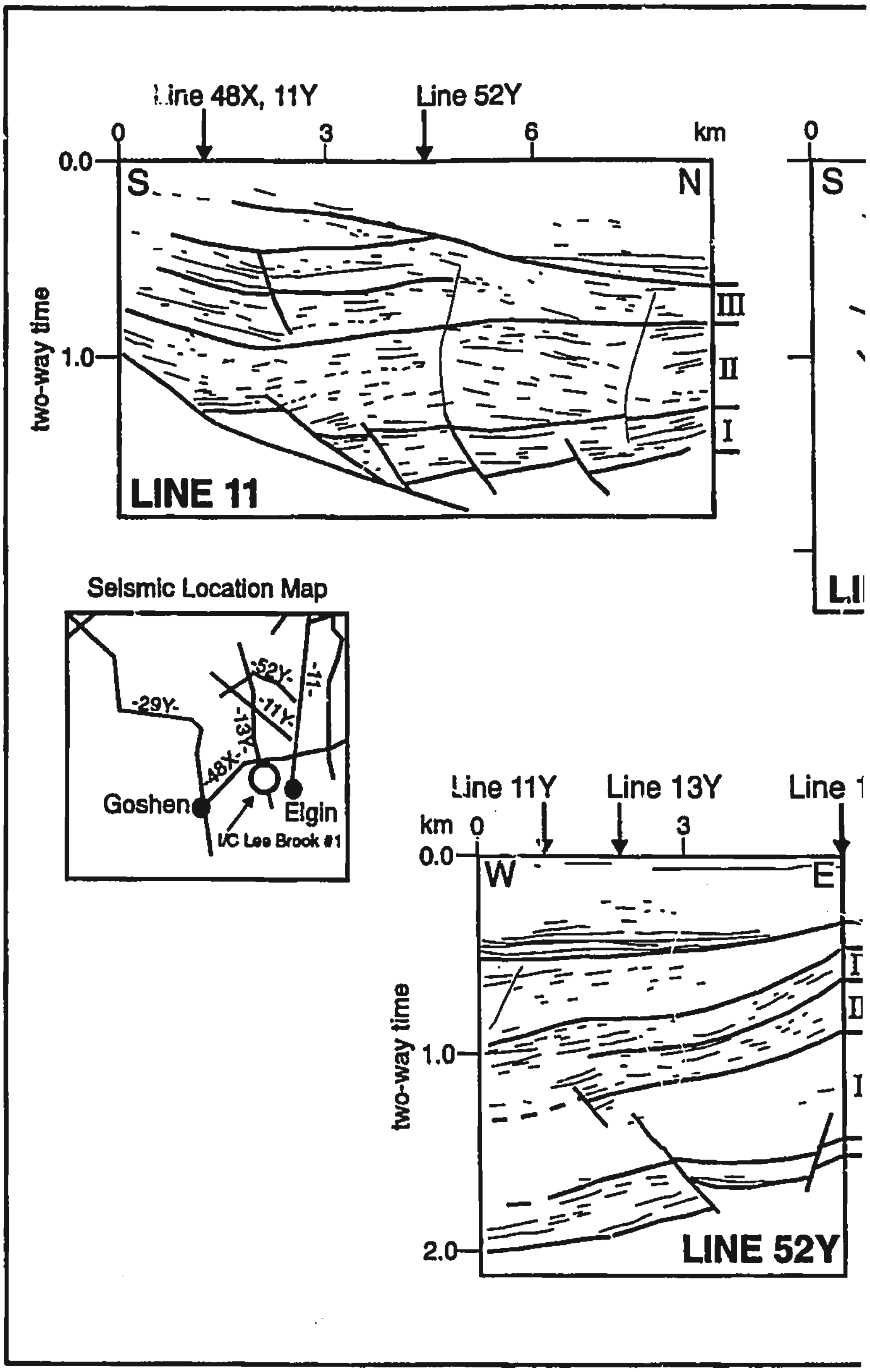
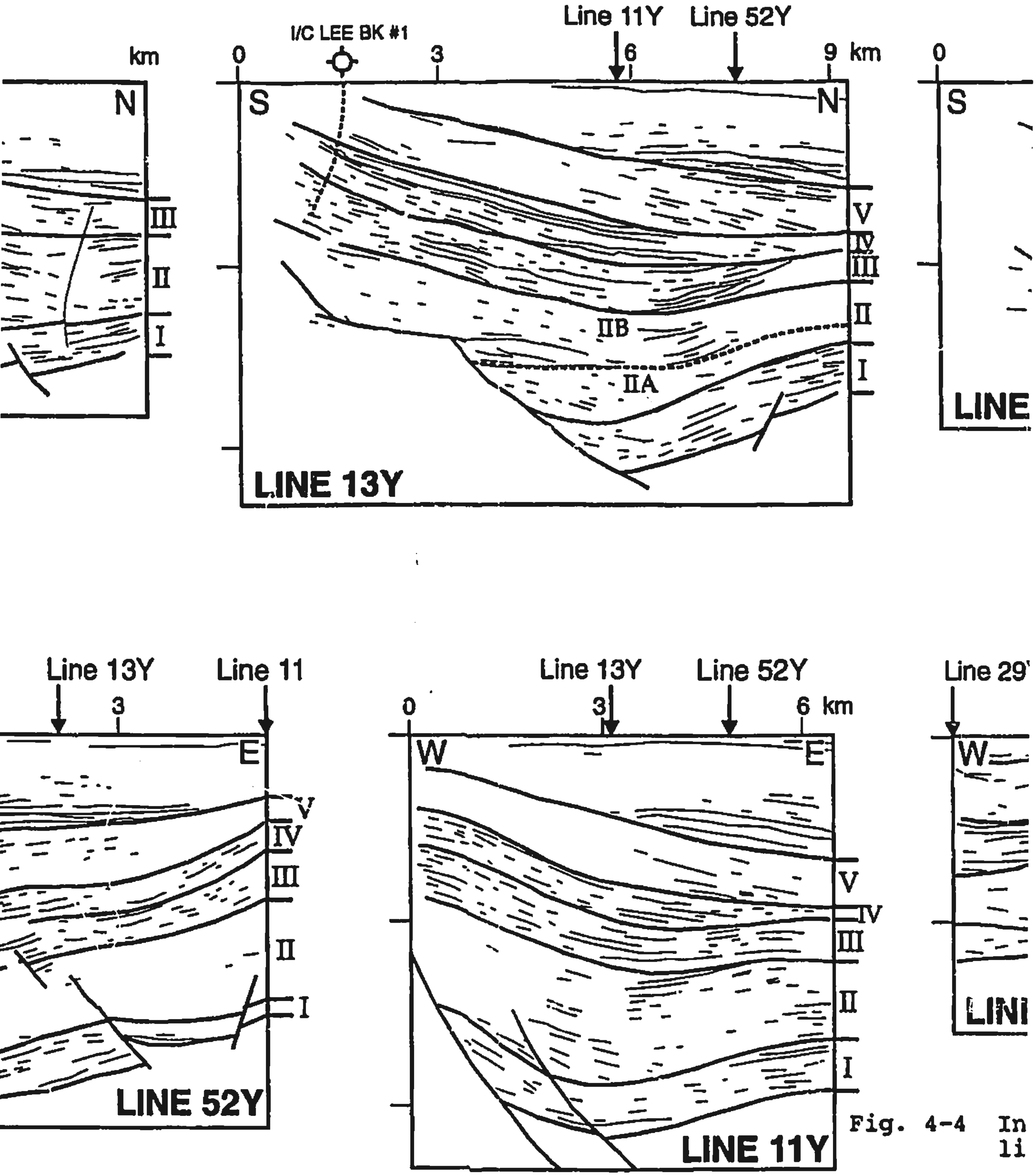


Fig. 4-3 Velocity - depth Curve, Moncton subbasin, Elgin area


Line 48X, 11Y
Line 52Y
0
3
6
km
0.0
1.0
two-way time
S
N
III
II
I
LINE 11
0
S
Seismic Location Map
-29Y-
-52Y-
-11-
-11Y-
-13Y-
-48X-
Goshen
Elgin
I/C Lee Brook #1
Line 11Y
Line 13Y
km
0
3
0.0
1.0
2.0
two-way time
W
E
LINE 52Y



km
N
III
II
I
I/C LEE BK #1
Line 11Y
Line 52Y
0
3
6
9 km
S
N
V
IV
III
II
IIB
IIA
I
LINE 13Y
0
S
LINE
Line 13Y
Line 11
3
E
V
IV
III
II
I
LINE 52Y
Line 13Y
Line 52Y
0
3
6 km
W
E
V
IV
III
II
I
LINE 11Y
Line 29
W

Fig. 4-4 In
li

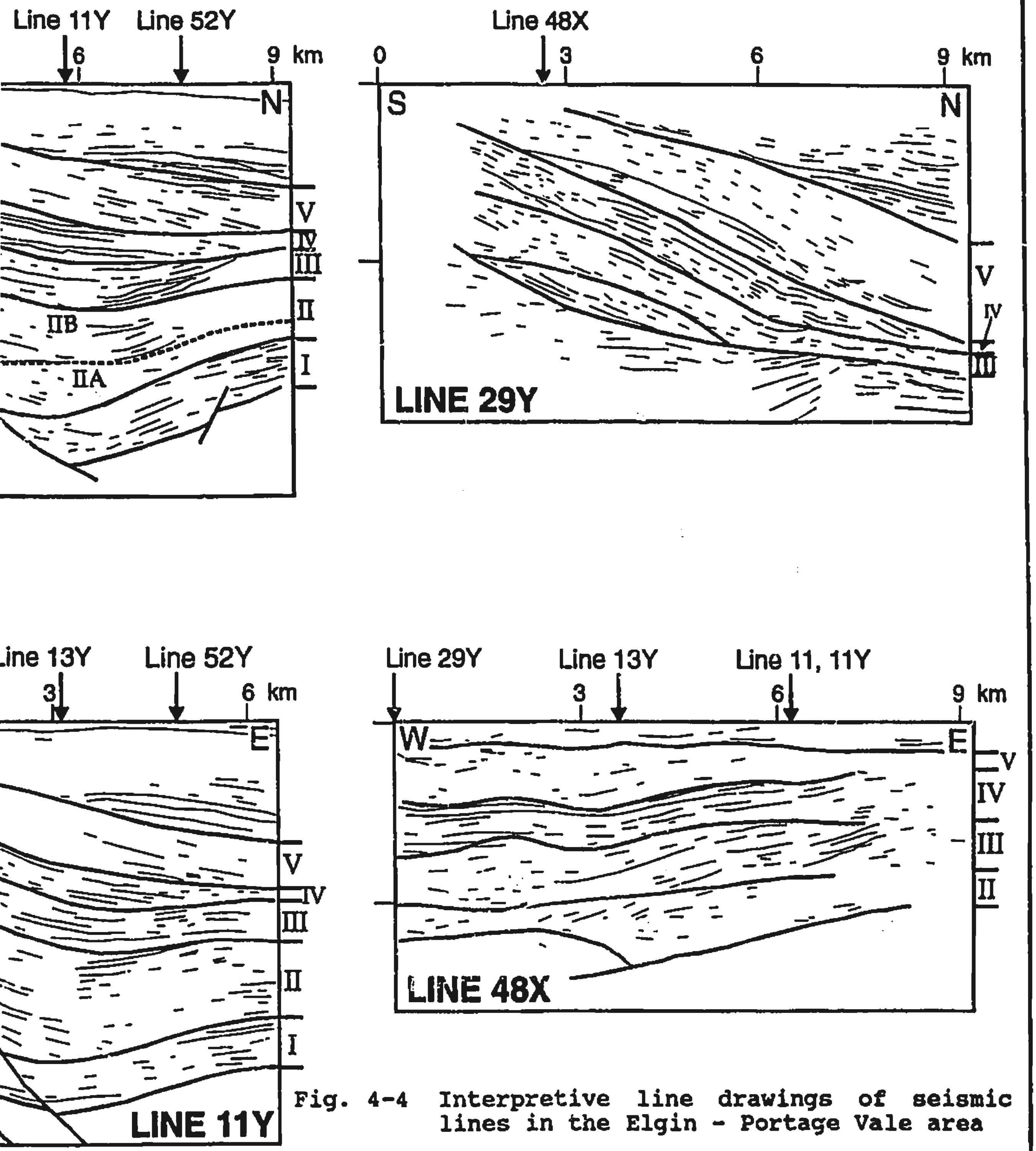


Fig. 4-4 Interpretive line drawings of seismic lines in the Elgin - Portage Vale area

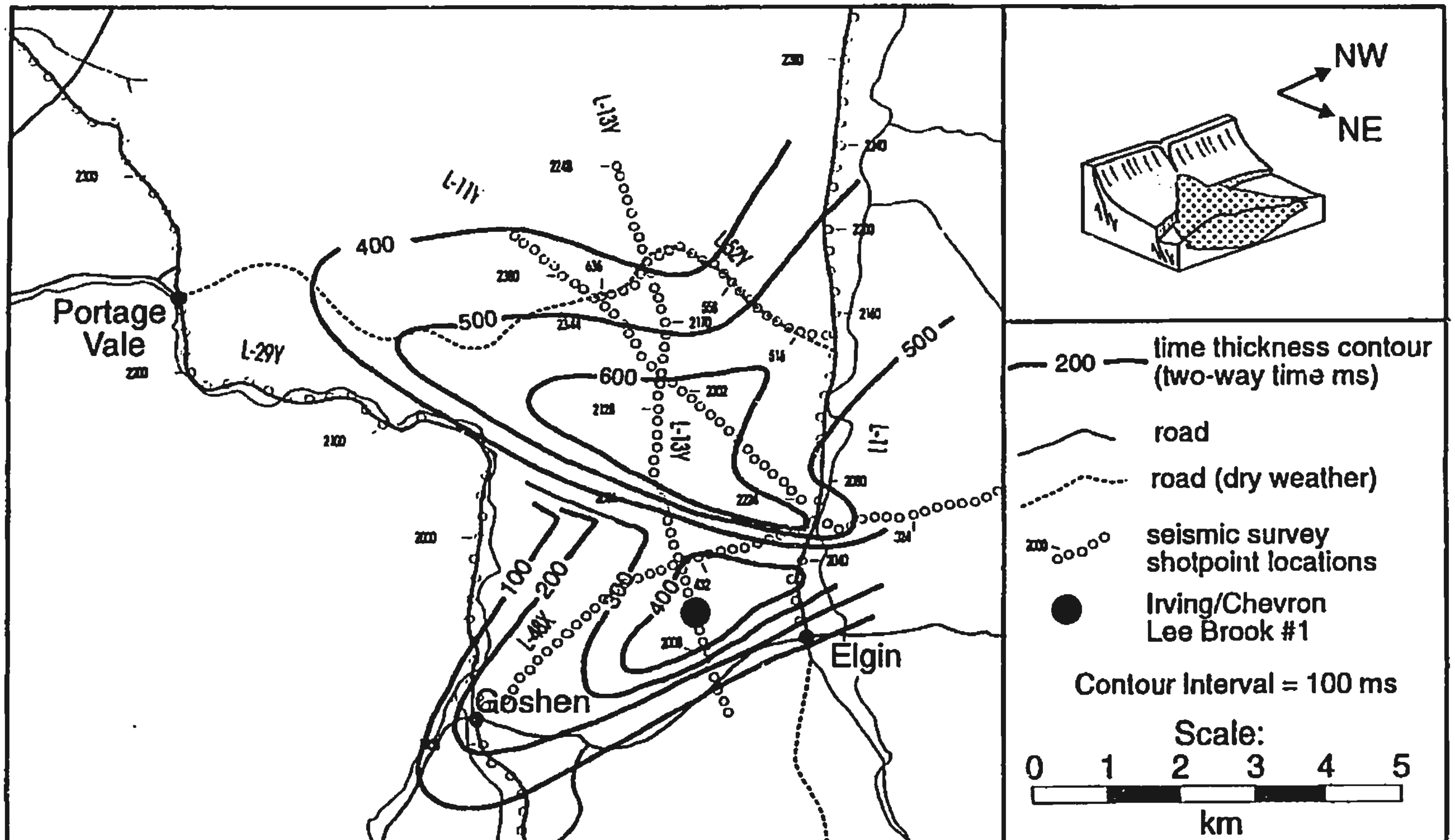
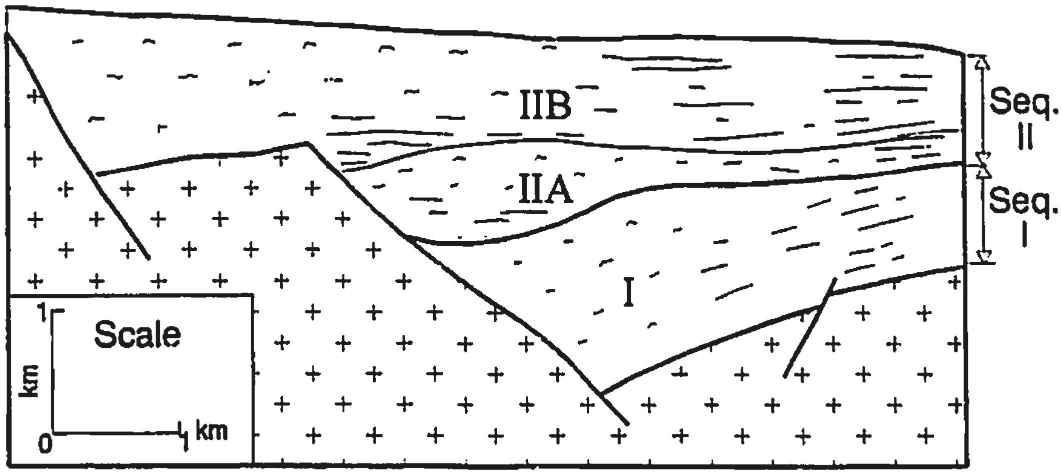
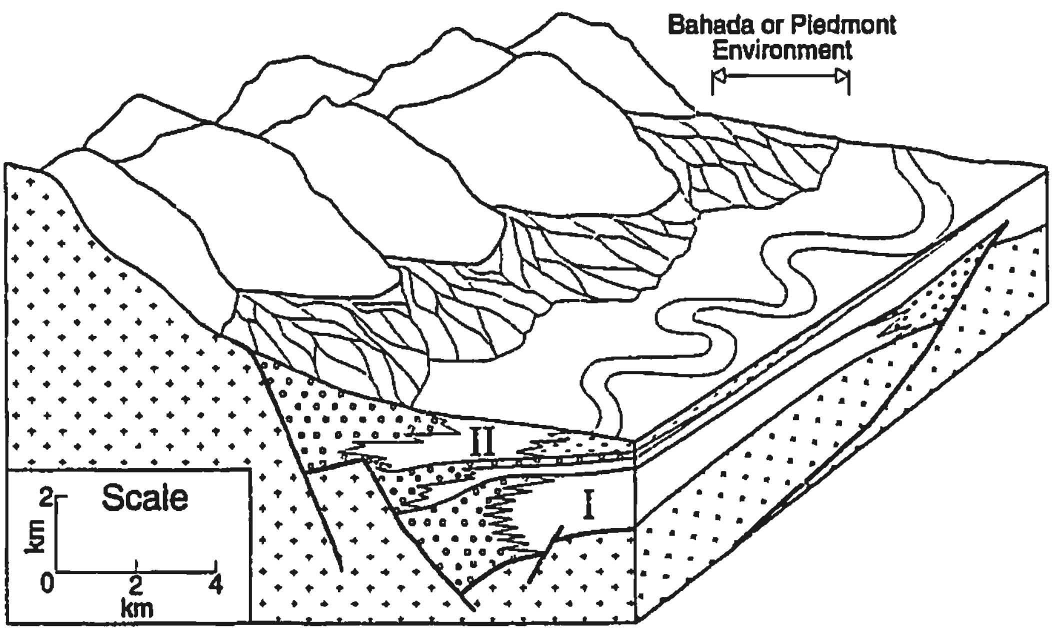


Fig. 4-5

SEISMIC TIME INTERVAL MAP: SEISMIC STRATIGRAPHIC UNIT II



A. Observed seismic stratigraphic units of line 13Y converted to depth for a velocity of 6000 m/s. No vertical exaggeration.



B. Environment of deposition envisaged for seismic sequence II. Vertical exaggeration is approximately 2:1.

Fig. 4-6 Seismic stratigraphy and environment of deposition of the Memramcook formation, Line 13Y

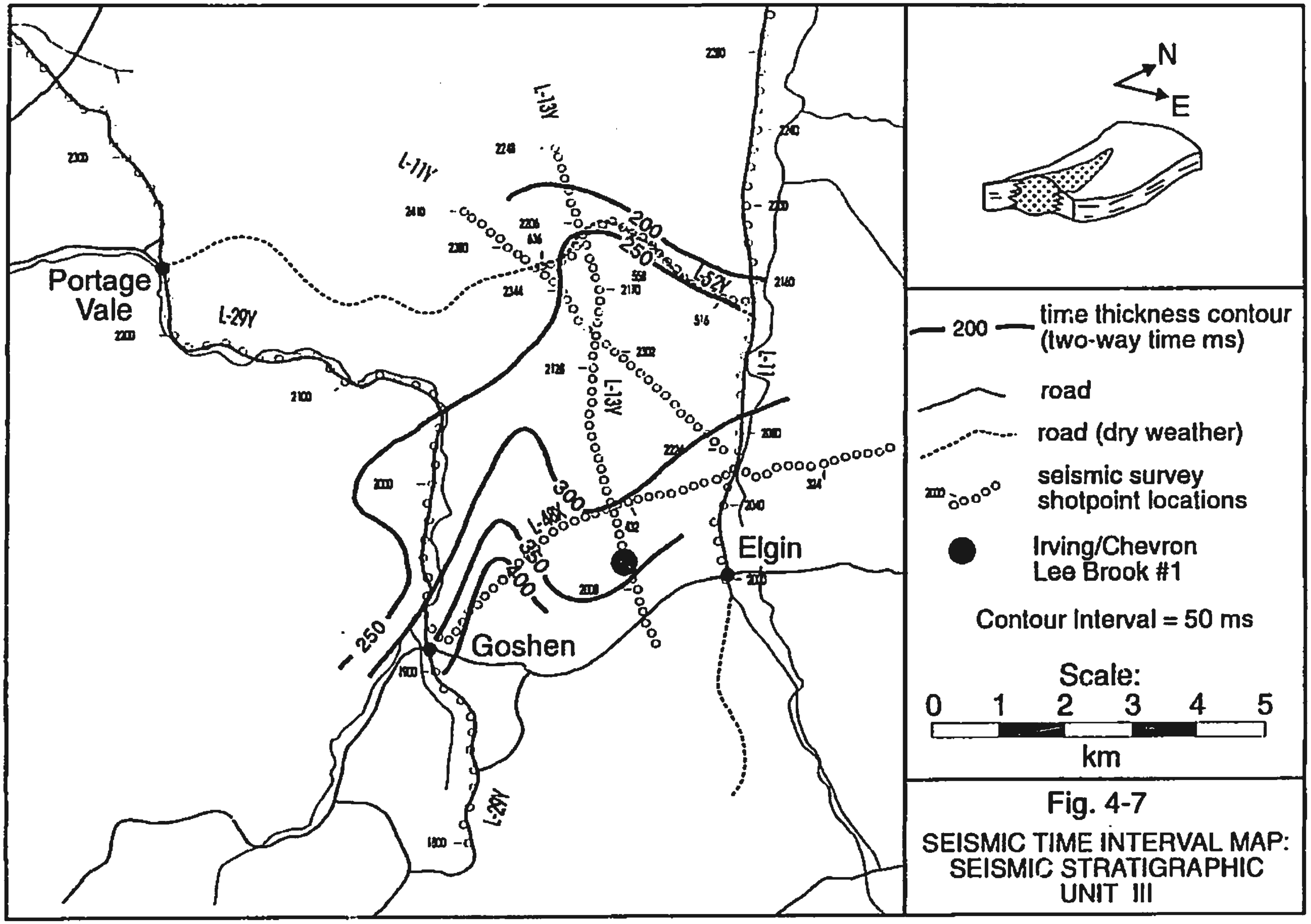


Fig. 4-7
SEISMIC TIME INTERVAL MAP: SEISMIC STRATIGRAPHIC UNIT III

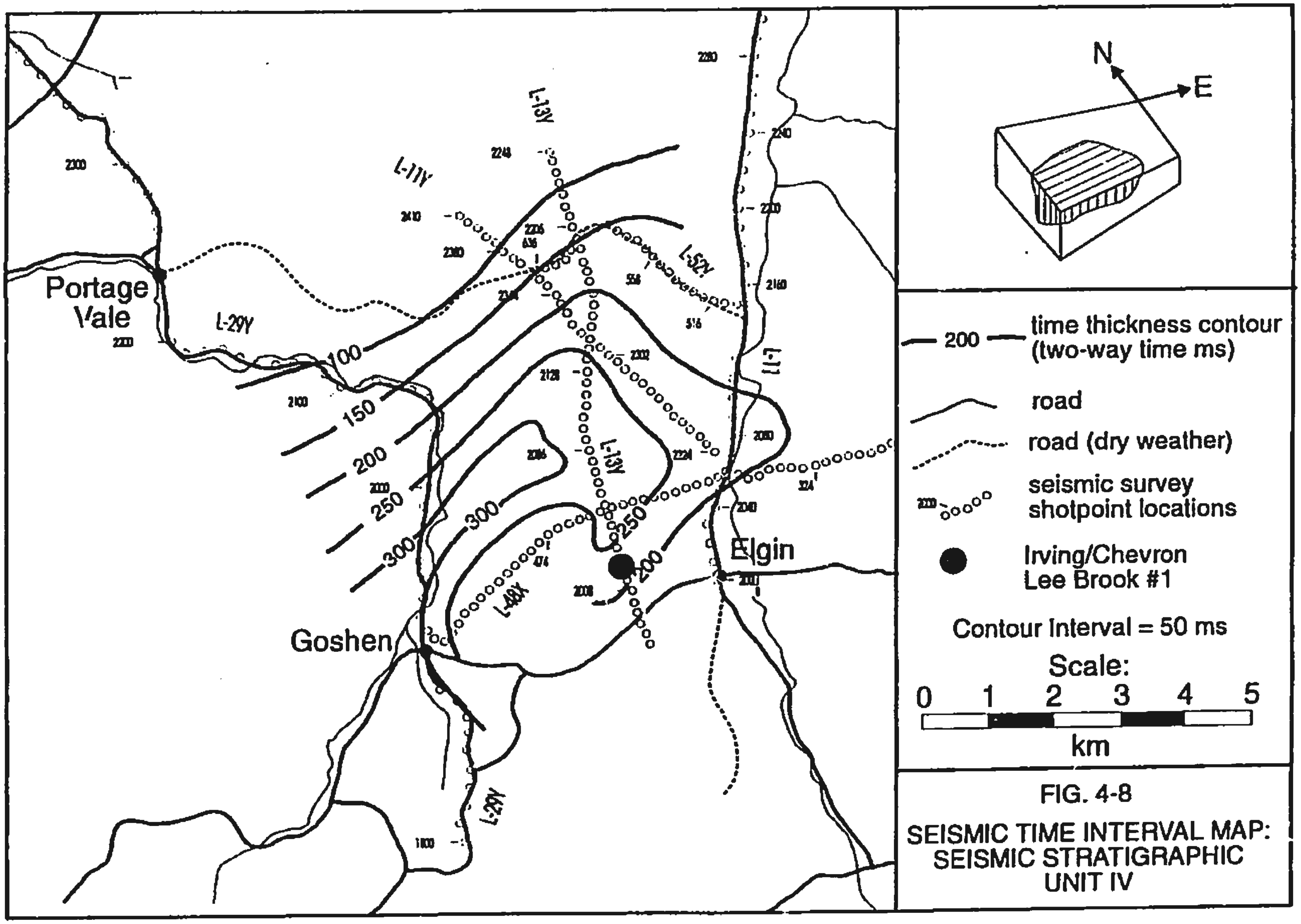


FIG. 4-8

SEISMIC TIME INTERVAL MAP: SEISMIC STRATIGRAPHIC UNIT IV

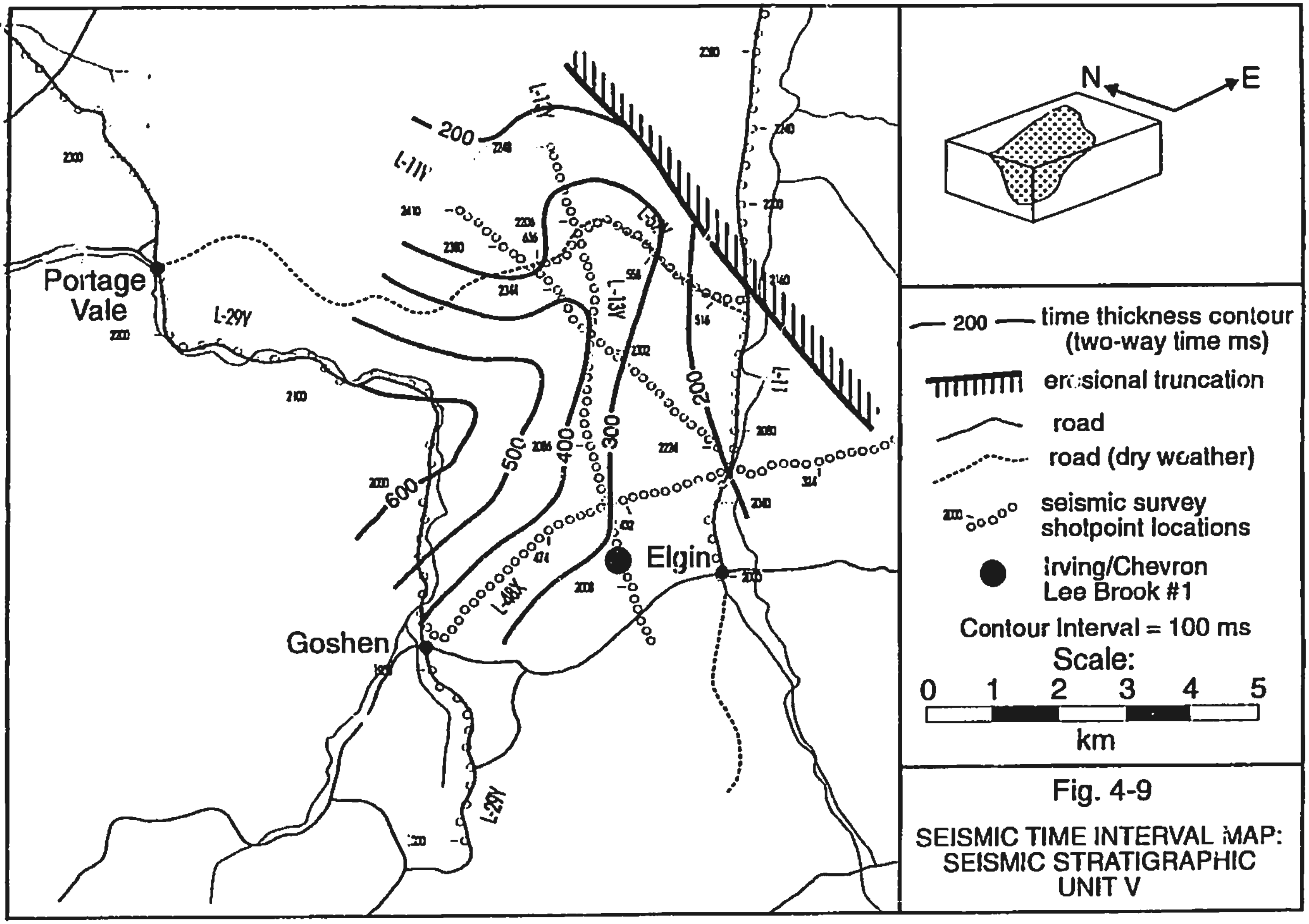


Fig. 4-9

SEISMIC TIME INTERVAL MAP: SEISMIC STRATIGRAPHIC UNIT V

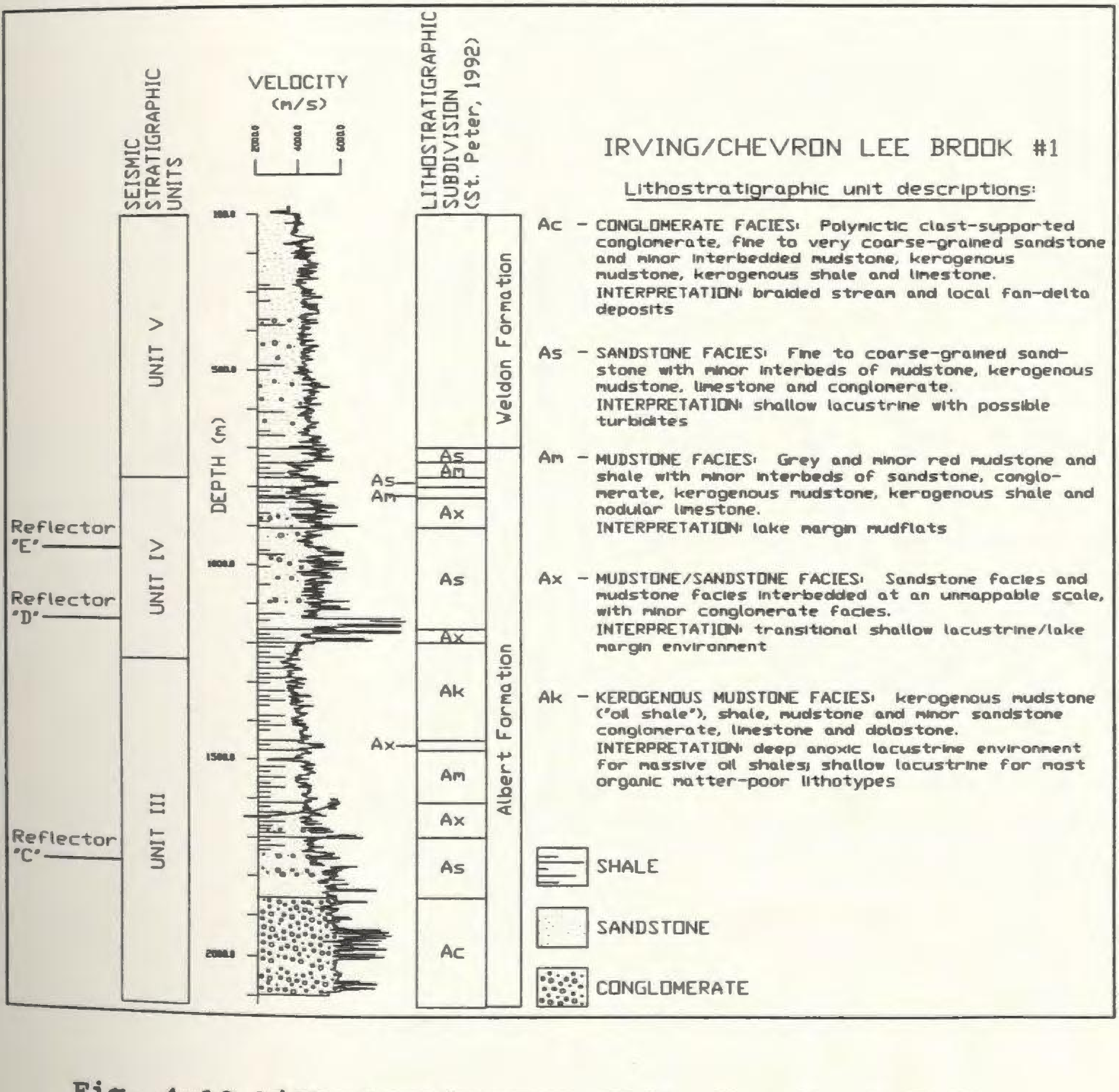


Fig. 4-10 Lithostratigraphy of the Lee Brook Well

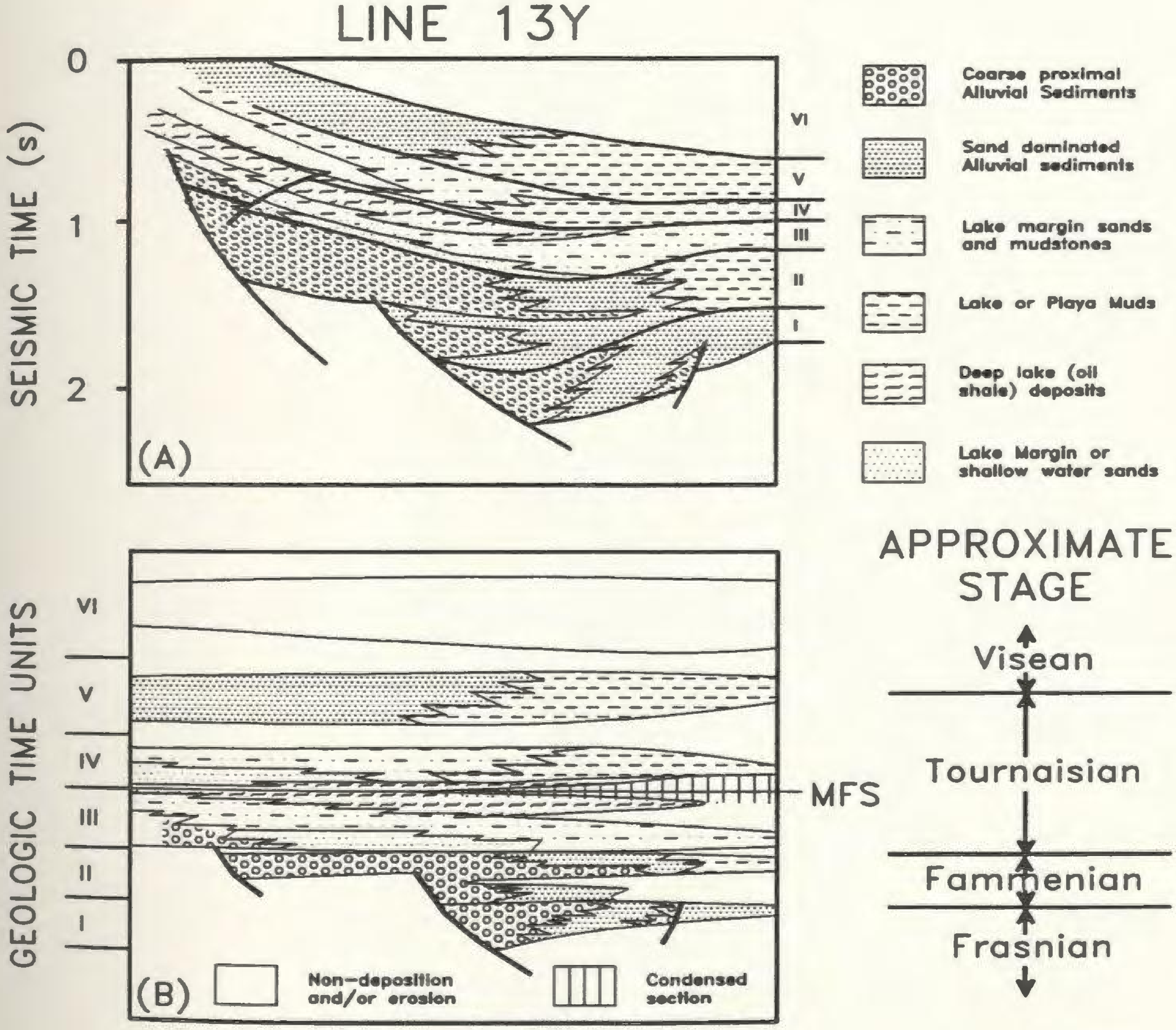
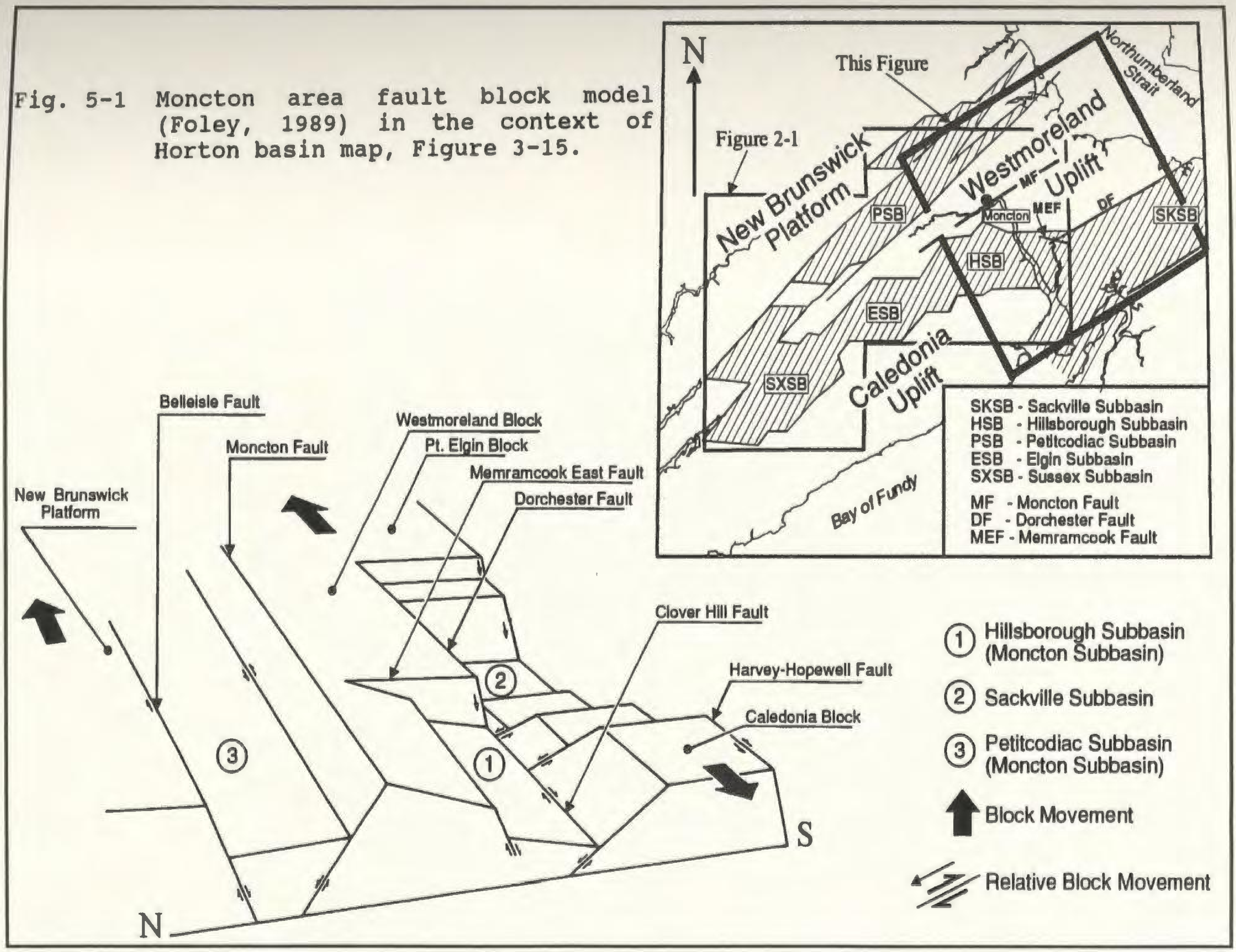


Fig. 4-11 Chronostratigraphic chart (B) corresponding to interpreted seismic line 13Y (A). Geologic time units correspond to seismic stratigraphic units with no absolute age implied. Approximate stages at right from Fig 2-2; MFS = Max. flooding surface

Fig. 5-1 Moncton area fault block model (Foley, 1989) in the context of Horton basin map, Figure 3-15.



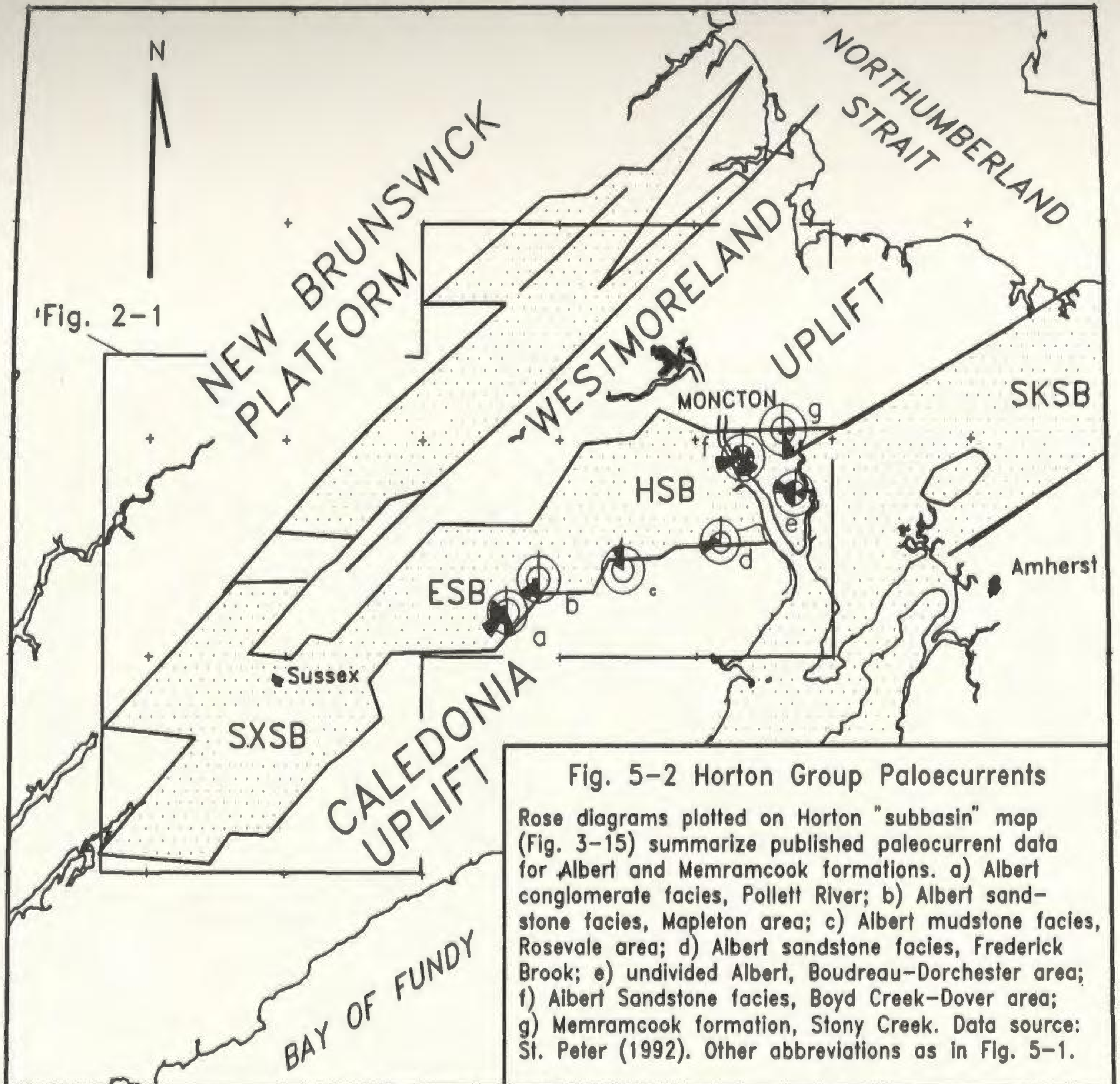


Fig. 5-2 Horton Group Paloecurrents

Rose diagrams plotted on Horton "subbasin" map (Fig. 3-15) summarize published paleocurrent data for Albert and Memramcook formations. a) Albert conglomerate facies, Pollett River; b) Albert sandstone facies, Mapleton area; c) Albert mudstone facies, Rosevale area; d) Albert sandstone facies, Frederick Brook; e) undivided Albert, Boudreau-Dorchester area; f) Albert Sandstone facies, Boyd Creek-Dover area; g) Memramcook formation, Stony Creek. Data source: St. Peter (1992). Other abbreviations as in Fig. 5-1.

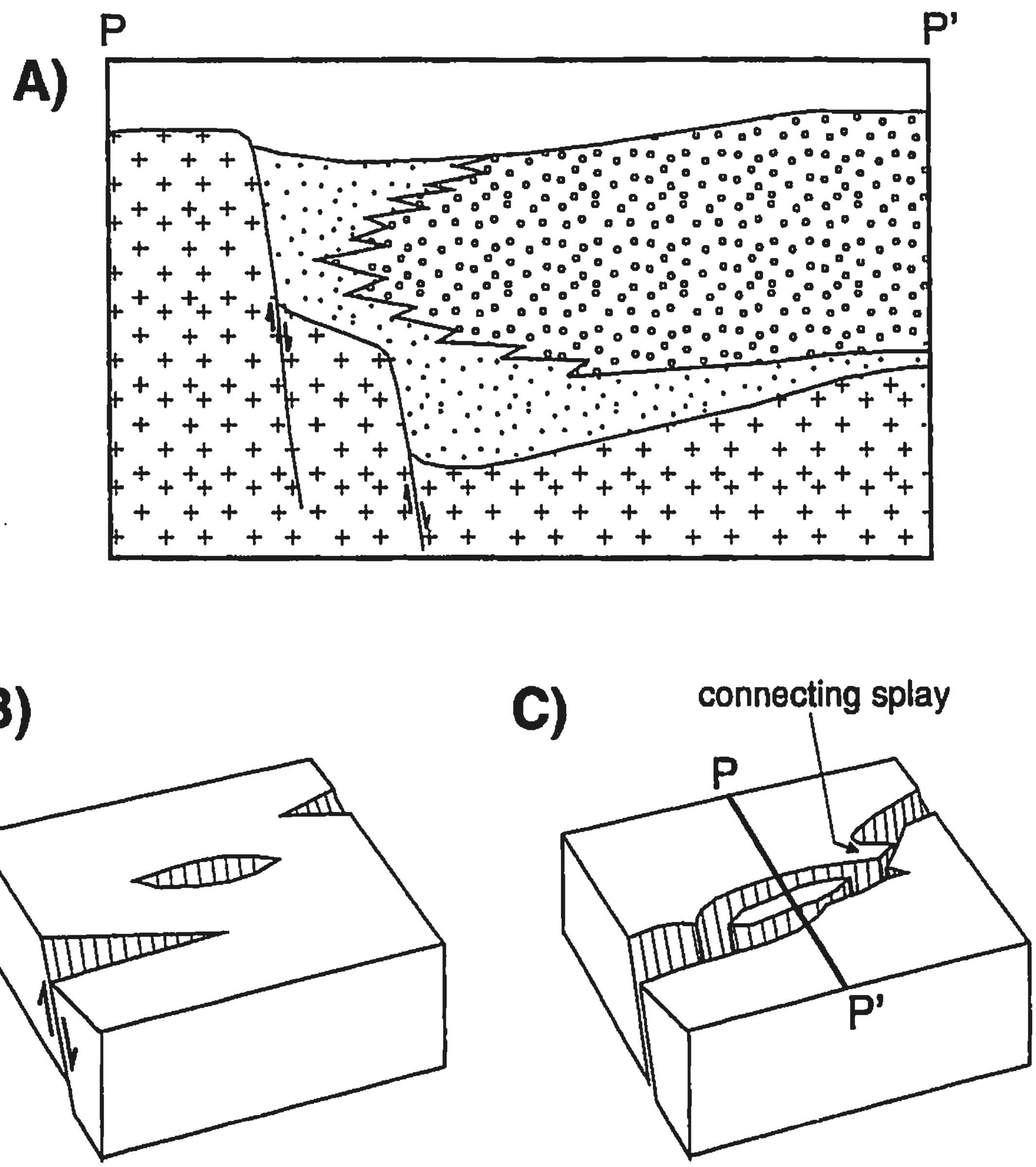


Fig. 5-3 Basin margin alluvial fan setting suggested by geological data: Limited back-faulting model (A) is consistent with faulted margin showing local onlap (Heward, 1978); while an *en echelon* fault system (B), possibly modified by connecting splay faults (Ramsey and Huber, 1987) is consistent with the large-scale Clover Hill-Caledonia fault pattern.

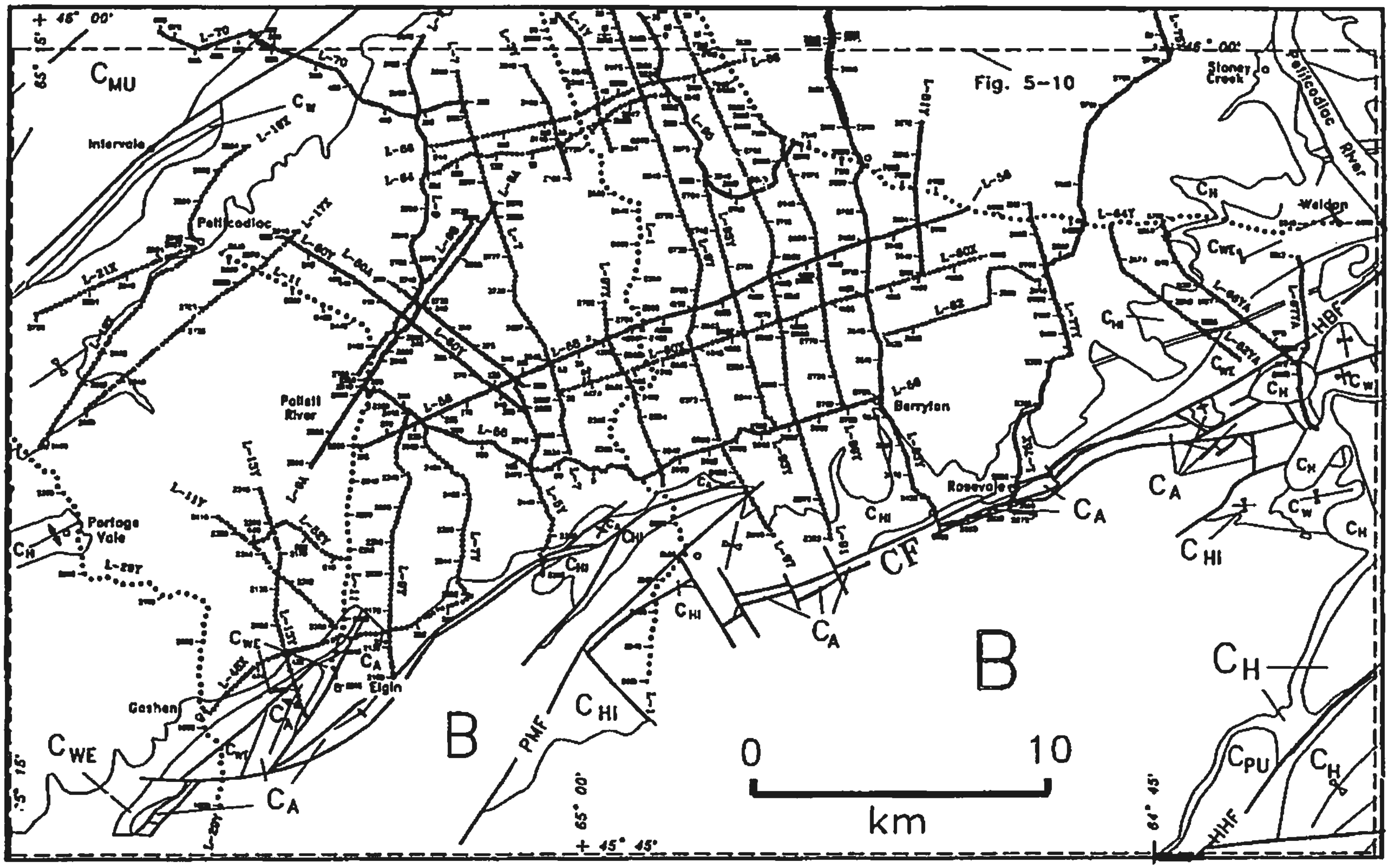
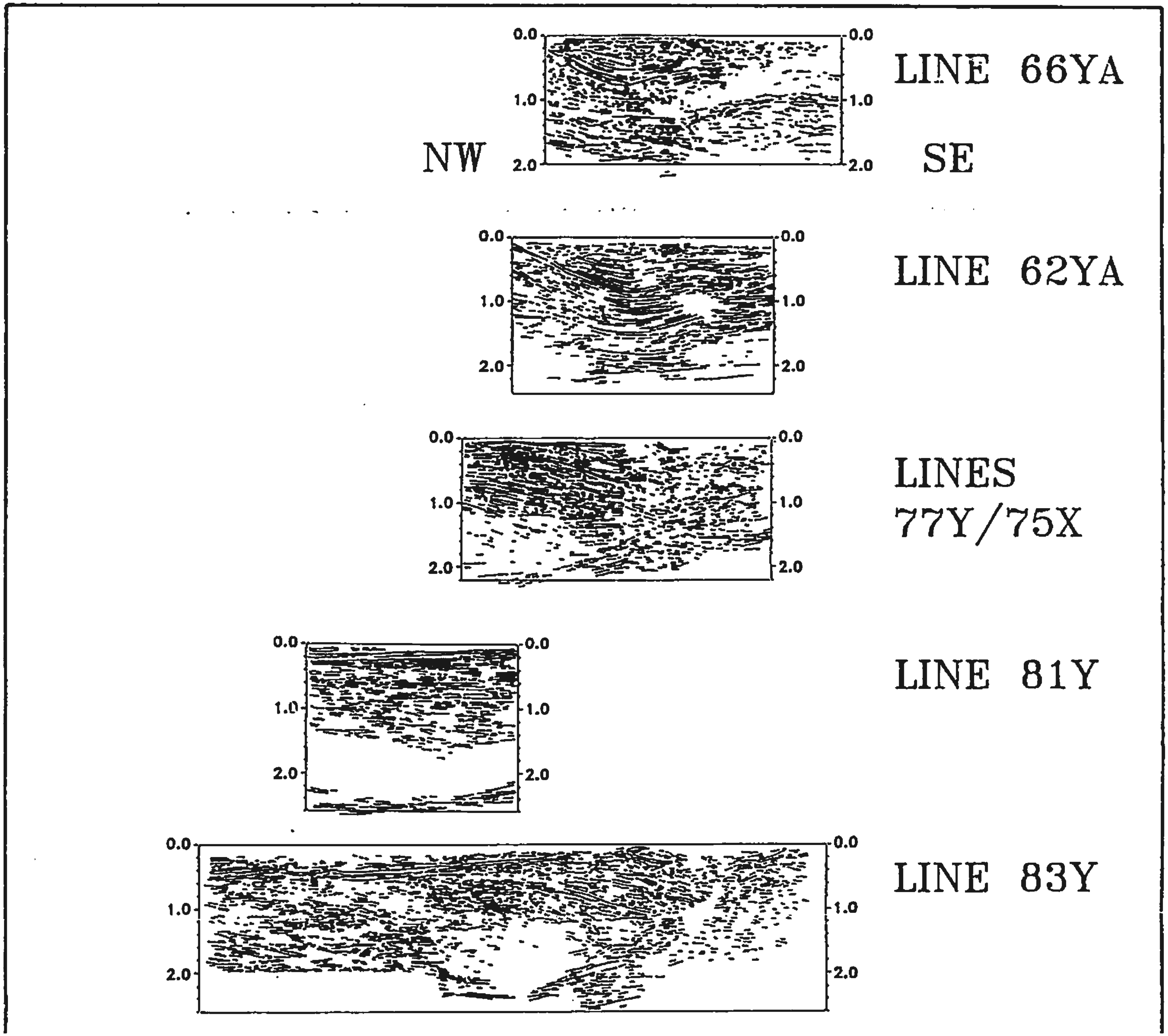
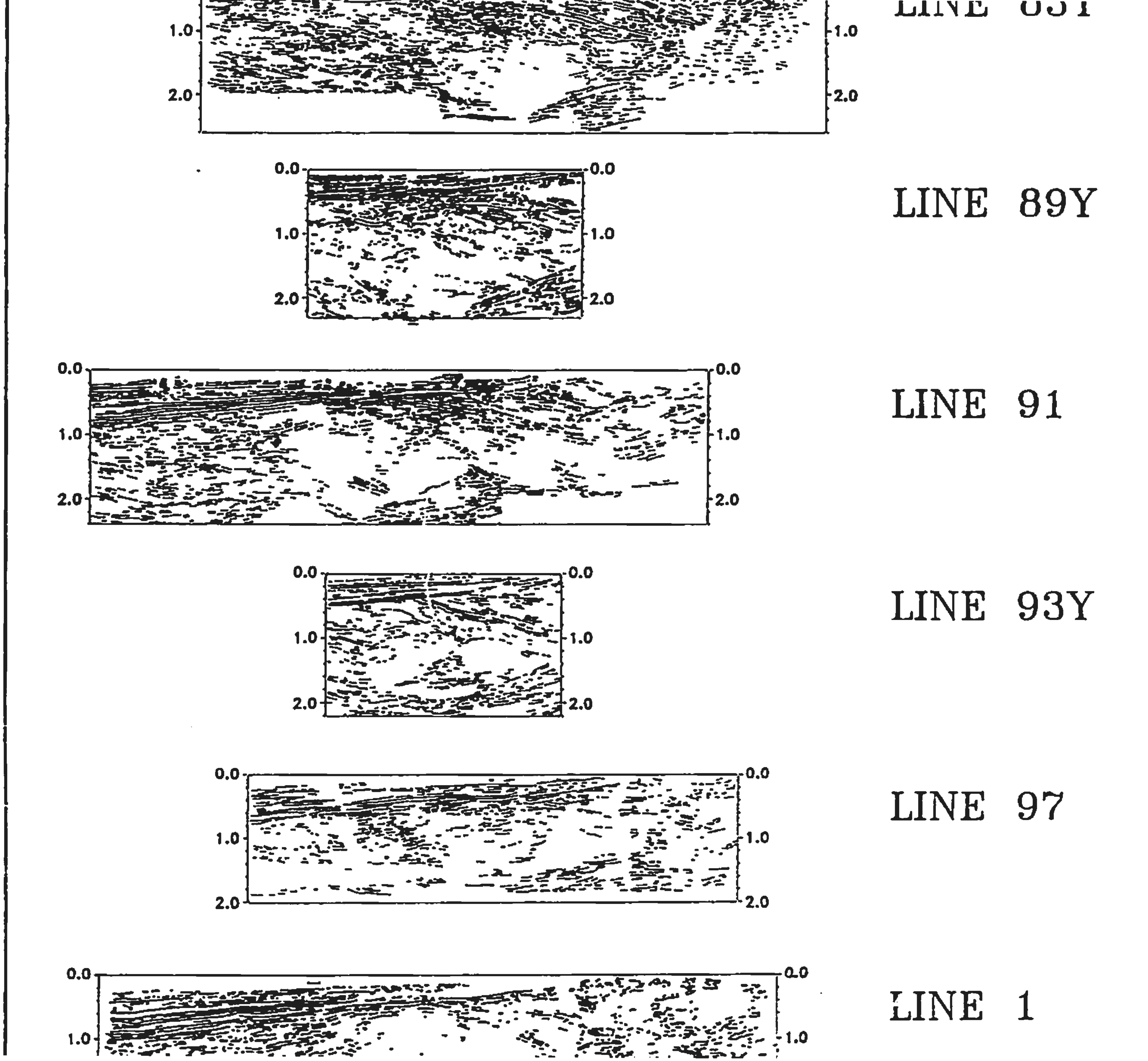
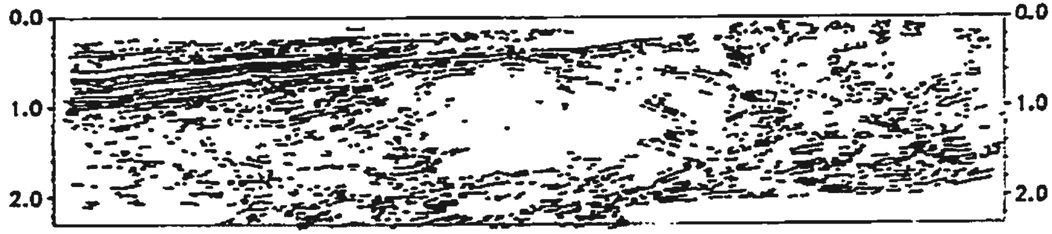


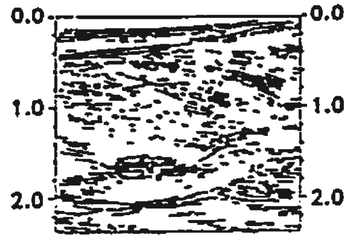
Fig. 5-4 Seismic shotpoint map, central Moncton subbasin.


LINE 66YA
NW
SE
0.0
1.0
2.0
LINE 62YA
LINES
77Y/75X
LINE 81Y
LINE 83Y


LINE 89Y
LINE 91
LINE 93Y
LINE 97
LINE 1
0.0
1.0
2.0

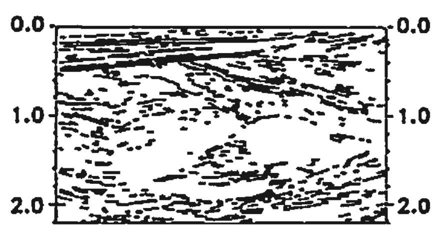


LINE 1

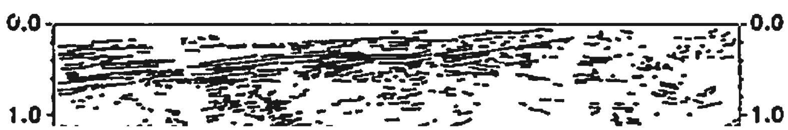


LINE 97Y

LINE 91



LINE 93Y



LINE 97

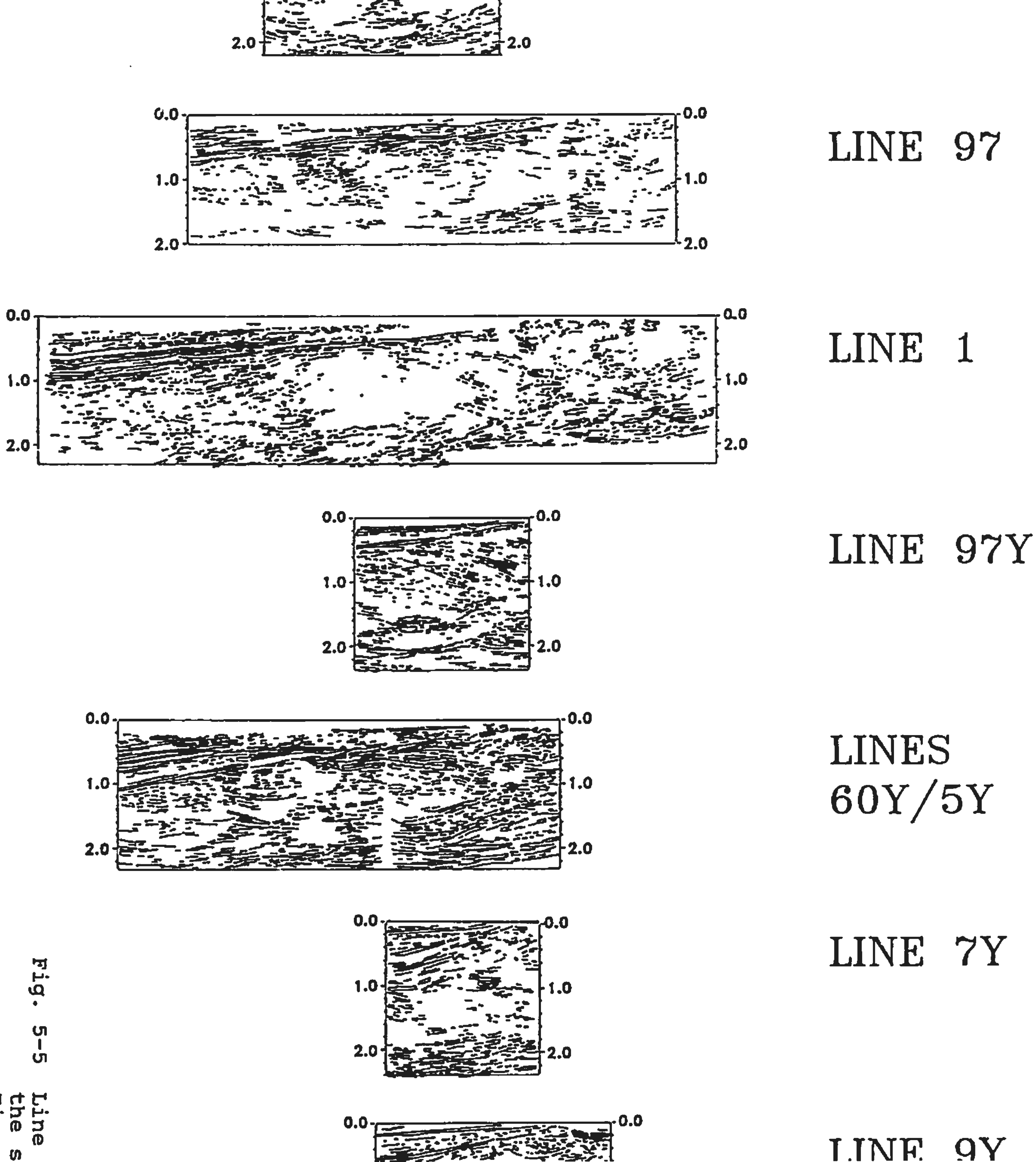


Fig. 5-5 Line
the s
Figur
commo

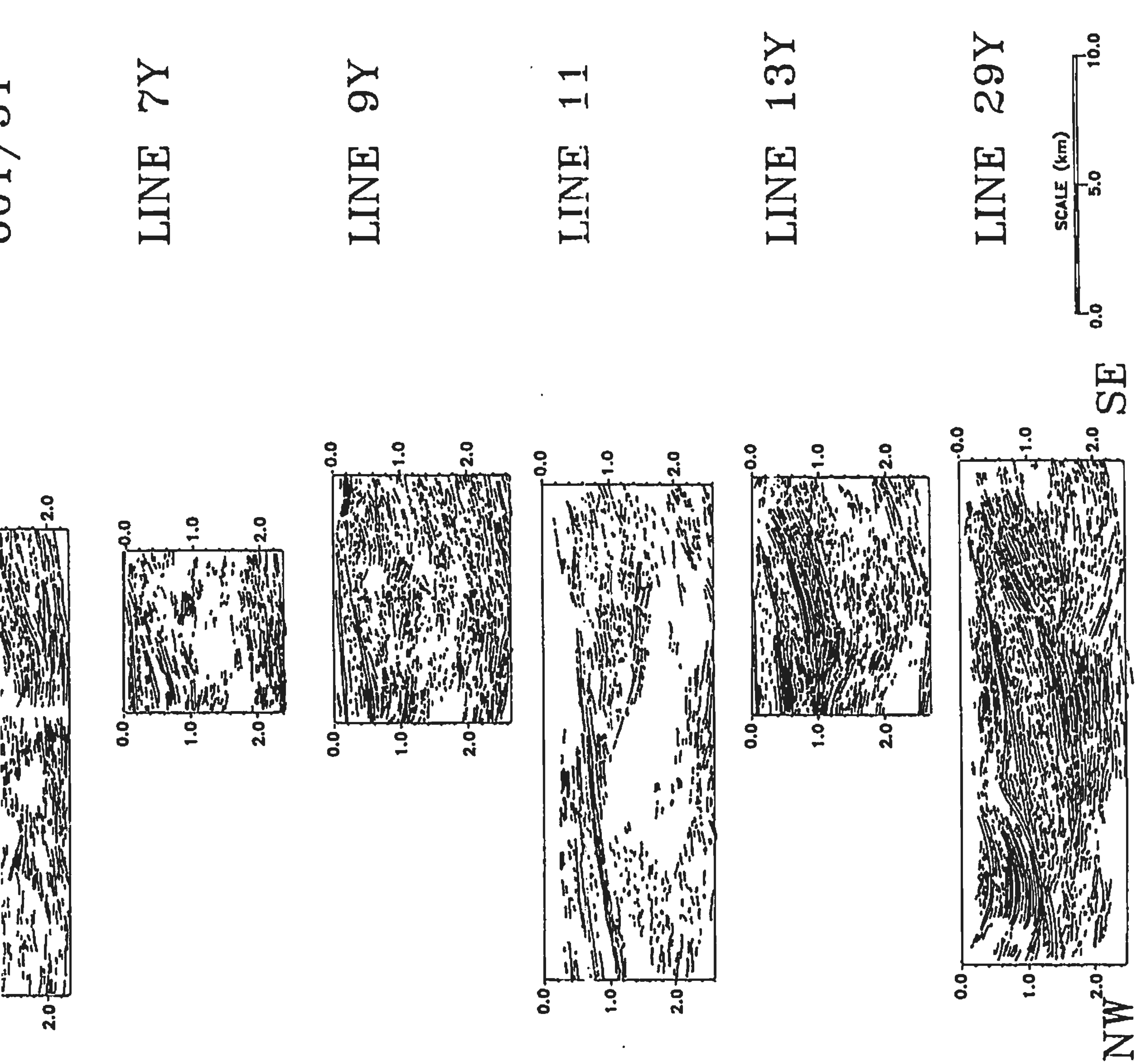


Fig. 5-5 Line drawings of Chevron/Irving seismic lines crossing the southern basin margin. Line locations are shown in Figure 5-4. Sections are aligned with reference to a common NE-SW axis. Two-way times are given in seconds.

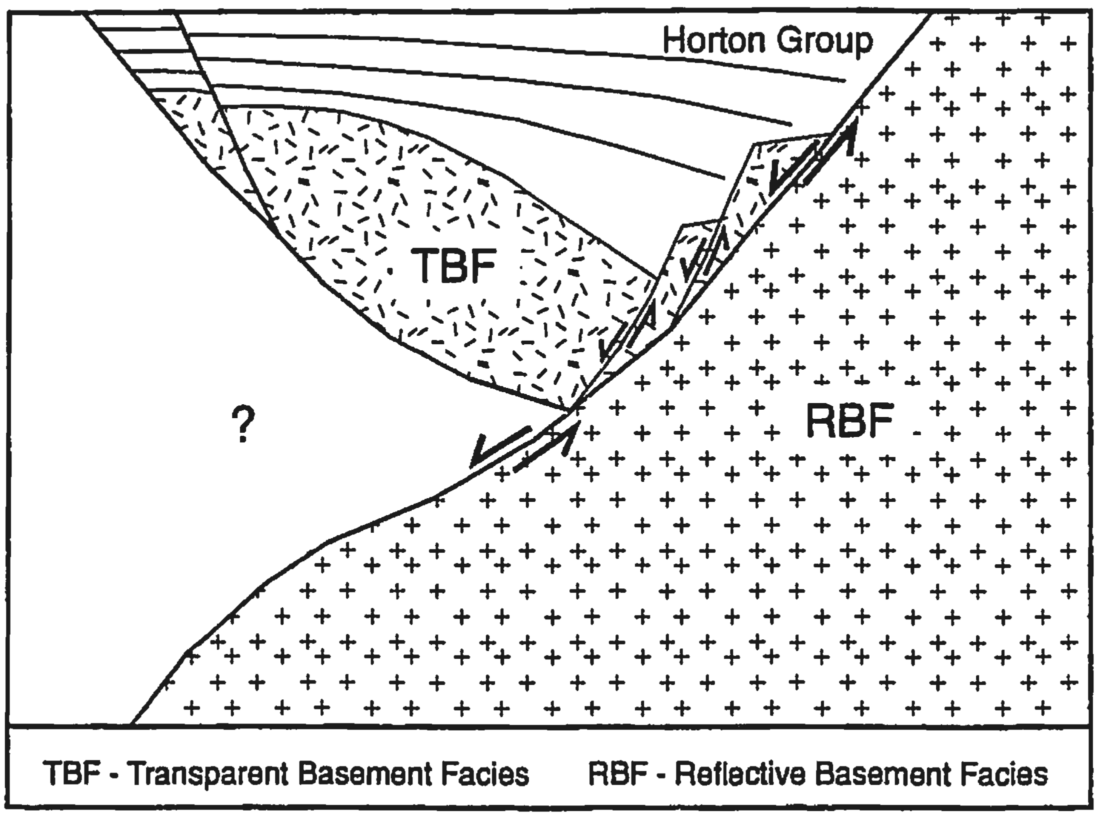


Fig. 5-6 Schematic cross-section showing the relationship between reflective basement, transparent basement and Horton Group sediments.

Fig. 5-7 Cross-section balancing: line 11.

A. Interpreted seismogram, A(i) showing preliminary interpretation of dipping events as basin bounding fault plane (dashed); A(ii) Section converted to depth and restored to base Windsor/Hillsborough unconformity; A(iii) fault planes predicted from hanging wall geometry; fault planes A',B' and C' were generated for hypothetical faults with surface traces at A, B, and C. Note fault trajectory C' coincides with the observed fault plane reflection.

B. Retrodeforming the basin-bounding fault system (using fault plane C') to Late Devonian (Frasnian) time requires 7 km dip-slip displacement and yields pre-extension template B(i).

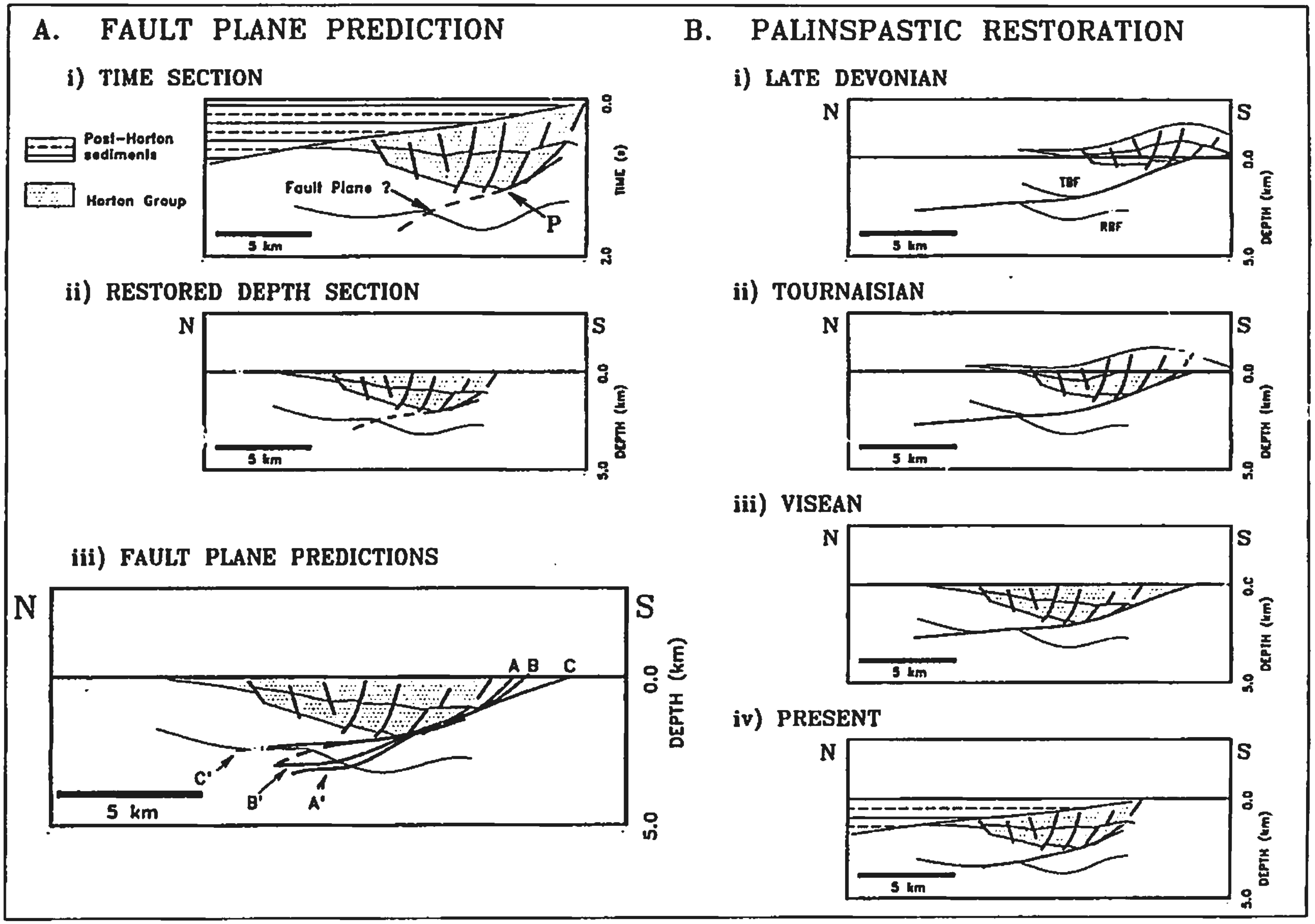
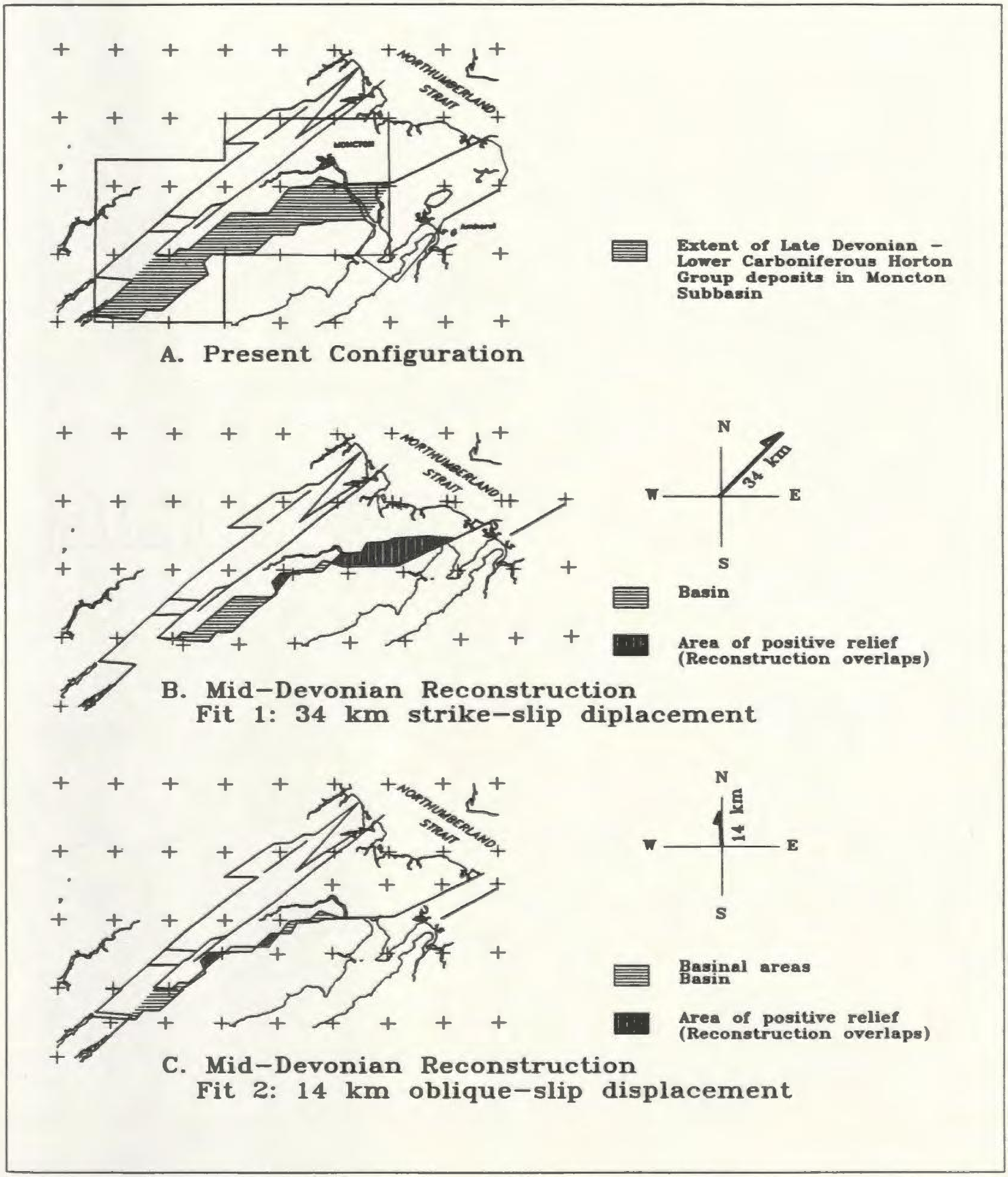
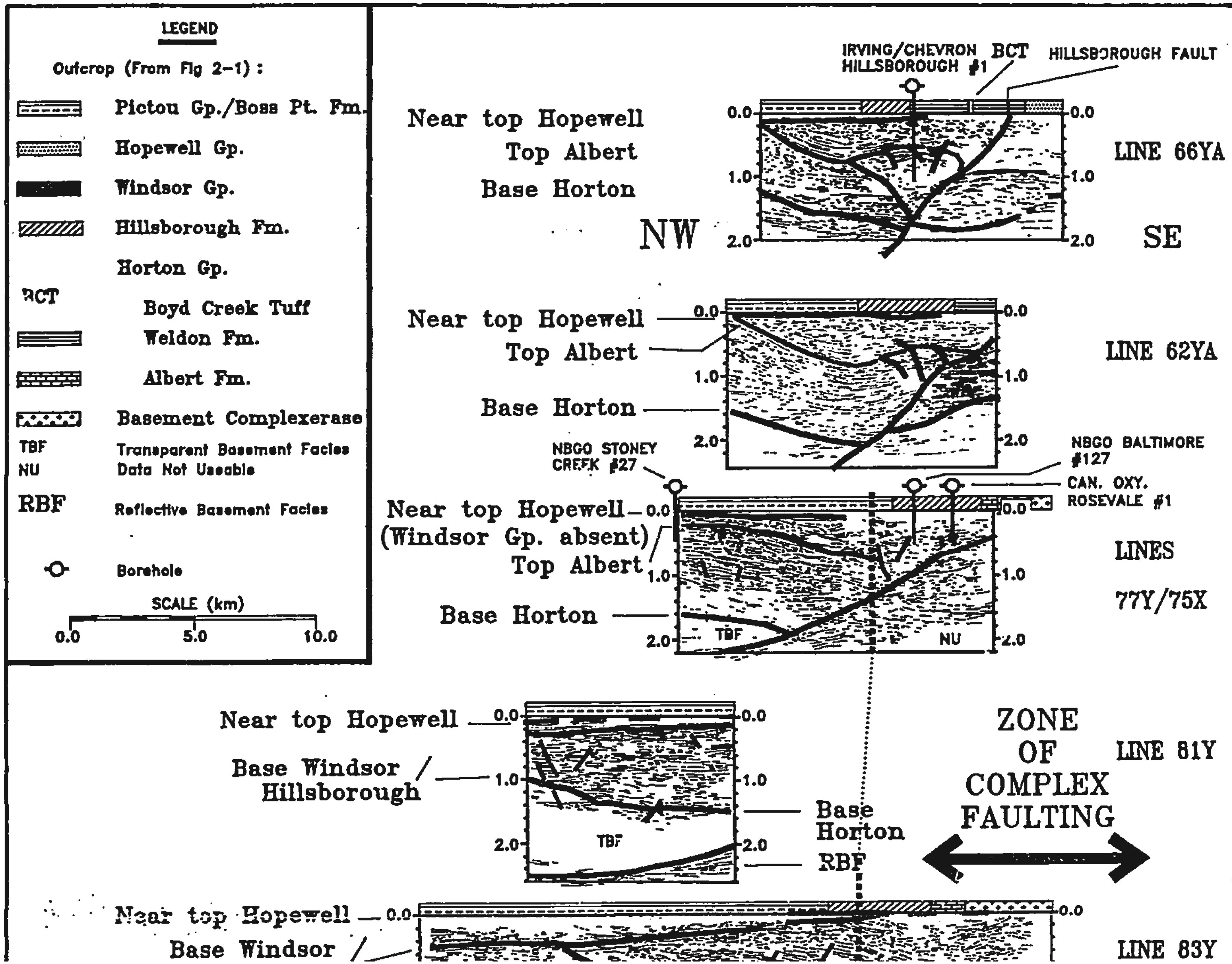
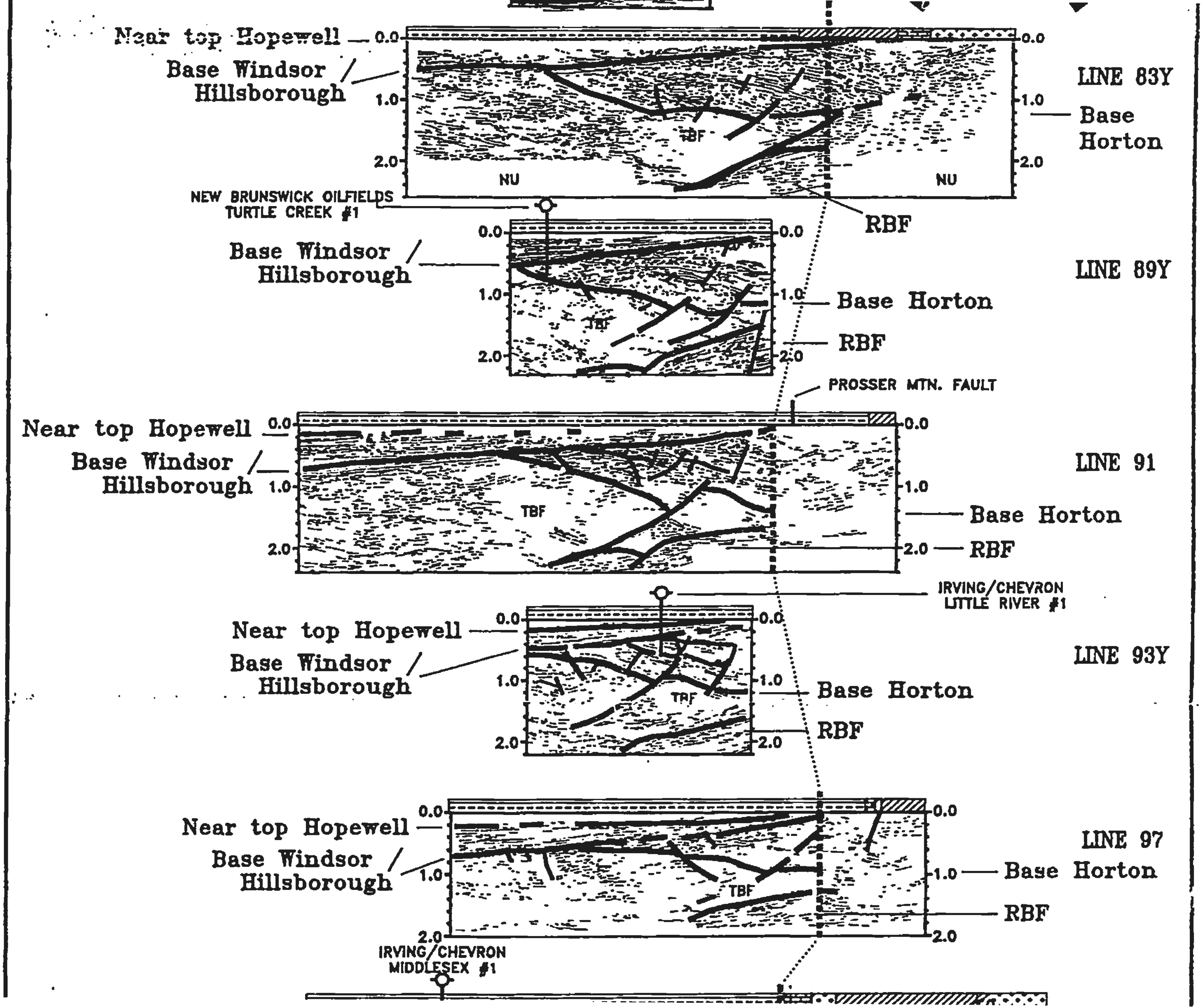

A. FAULT PLANE PREDICTION
i) TIME SECTION
Post-Horton sediments
Horton Group
Fault Plane ?
P
5 km
0.0
TIME (s)
2.0
ii) RESTORED DEPTH SECTION
N
S
5 km
0.0
DEPTH (km)
5.0
iii) FAULT PLANE PREDICTIONS
N
S
A B C
C'
B'
A'
5 km
0.0
DEPTH (km)
5.0
B. PALINSPASTIC RESTORATION
i) LATE DEVONIAN
N
S
TBF
RBF
5 km
0.0
DEPTH (km)
5.0
ii) TOURNAISIAN
N
S
5 km
iii) VISEAN
N
S
5 km
iv) PRESENT
N
S
5 km

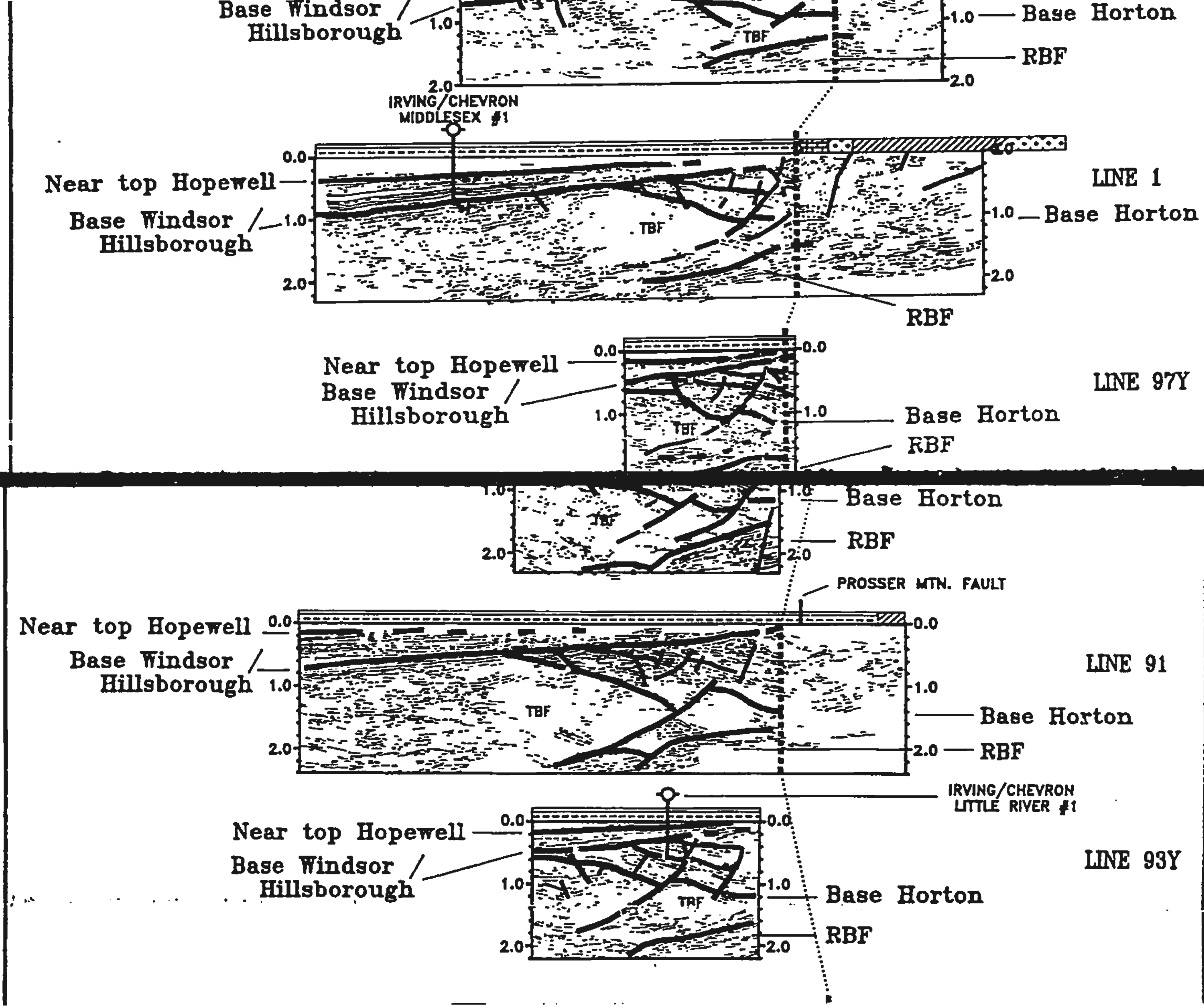
Fig. 5-8 Two possible pre-Late Devonian map reconstructions: A. Present Horton basin configuration; B. Dextral strike-slip model; C. Oblique extension model. Vector at right shows displacement of southern basin margin block in each case.


NORTHUMBERLAND STRAIT
MONCTON
Extent of Late Devonian – Lower Carboniferous Horton Group deposits in Moncton Subbasin
A. Present Configuration
N
W
E
S
34 km
Basin
Area of positive relief (Reconstruction overlaps)
B. Mid-Devonian Reconstruction
Fit 1: 34 km strike-slip diplacement
14 km
Basinal areas
Basin
Area of positive relief (Reconstruction overlaps)
C. Mid-Devonian Reconstruction
Fit 2: 14 km oblique-slip displacement


LEGEND
Outcrop (From Fig 2-1) :
Pictou Gp./Boss Pt. Fm.
Hopewell Gp.
Windsor Gp.
Hillsborough Fm.
Horton Gp.
BCT
Boyd Creek Tuff
Weldon Fm.
Albert Fm.
Basement Complexerase
TBF
Transparent Basement Facies
NU
Data Not Useable
RBF
Reflective Basement Facies
Borehole
SCALE (km)
0.0
5.0
10.0
IRVING/CHEVRON HILLSBOROUGH #1
BCT
HILLSBOROUGH FAULT
Near top Hopewell
Top Albert
Base Horton
NW
SE
LINE 66YA
LINE 62YA
NBGO STONEY CREEK #27
NBGO BALTIMORE #127
CAN. OXY. ROSEVALE #1
Near top Hopewell
(Windsor Gp. absent)
Top Albert
Base Horton
TBF
NU
LINES 77Y/75X
Near top Hopewell
Base Windsor / Hillsborough
Base Horton
RBF
TBF
ZONE OF COMPLEX FAULTING
LINE 81Y
Near top Hopewell
Base Windsor
LINE 83Y
0.0
1.0
2.0



Near top Hopewell
Base Windsor / Hillsborough
LINE 83Y
Base Horton
TBF
NU
NU
NEW BRUNSWICK OILFIELDS TURTLE CREEK #1
RBF
Base Windsor / Hillsborough
LINE 89Y
Base Horton
RBF
PROSSER MTN. FAULT
Near top Hopewell
Base Windsor / Hillsborough
LINE 91
TBF
Base Horton
RBF
IRVING/CHEVRON LITTLE RIVER #1
Near top Hopewell
Base Windsor / Hillsborough
LINE 93Y
Base Horton
TBF
RBF
Near top Hopewell
Base Windsor / Hillsborough
LINE 97
Base Horton
TBF
RBF
IRVING/CHEVRON MIDDLESEX #1


Base Windsor / Hillsborough
Base Horton
TBF
RBF
IRVING/CHEVRON MIDDLESEX #1
Near top Hopewell
Base Windsor / Hillsborough
LINE 1
Base Horton
TBF
RBF
Near top Hopewell
Base Windsor / Hillsborough
LINE 97Y
Base Horton
RBF
TBF
Base Horton
RBF
TBF
PROSSER MTN. FAULT
Near top Hopewell
Base Windsor / Hillsborough
LINE 91
TBF
Base Horton
RBF
IRVING/CHEVRON LITTLE RIVER #1
Near top Hopewell
Base Windsor / Hillsborough
LINE 93Y
Base Horton
TBF
RBF
0.0
1.0
2.0

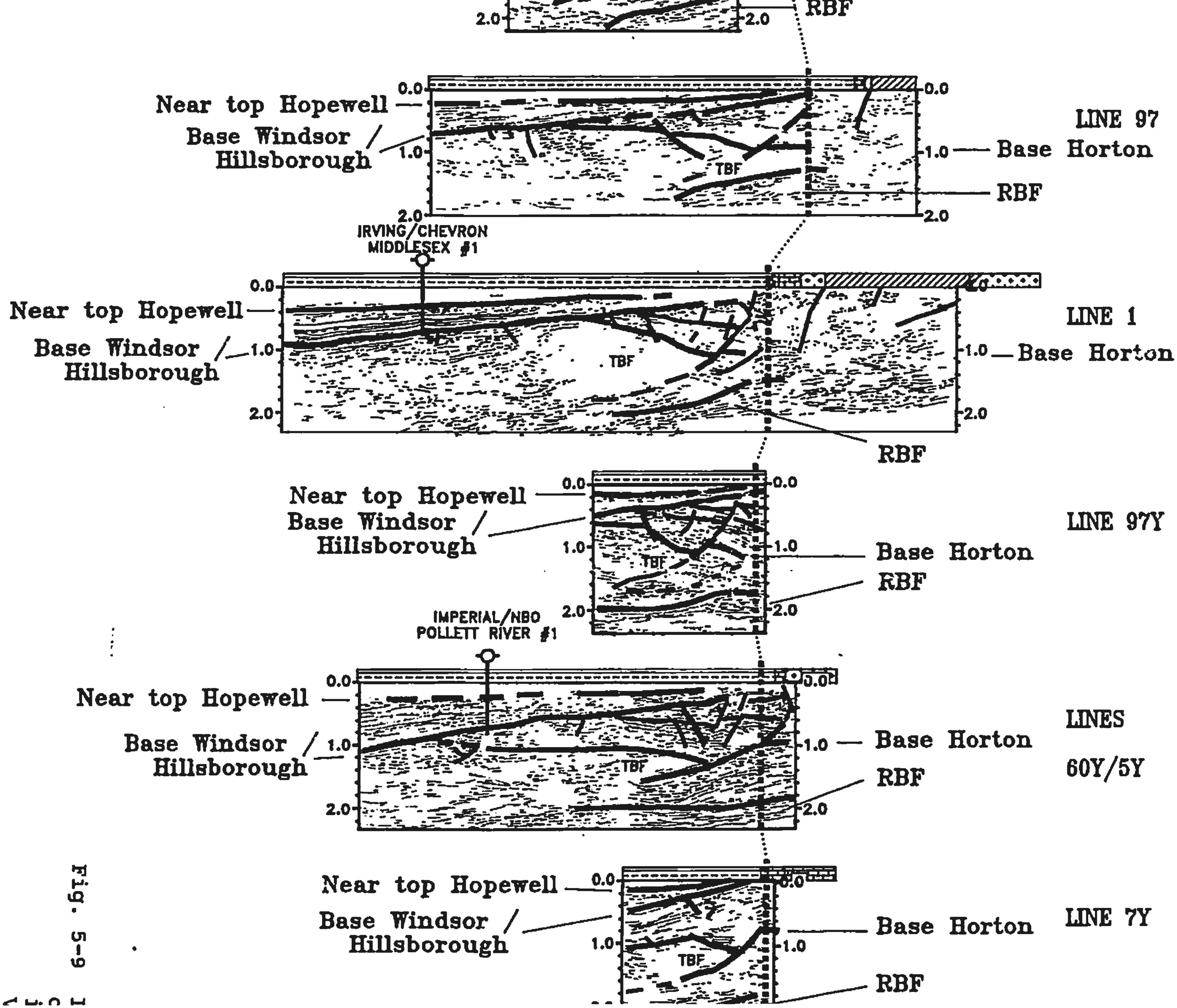
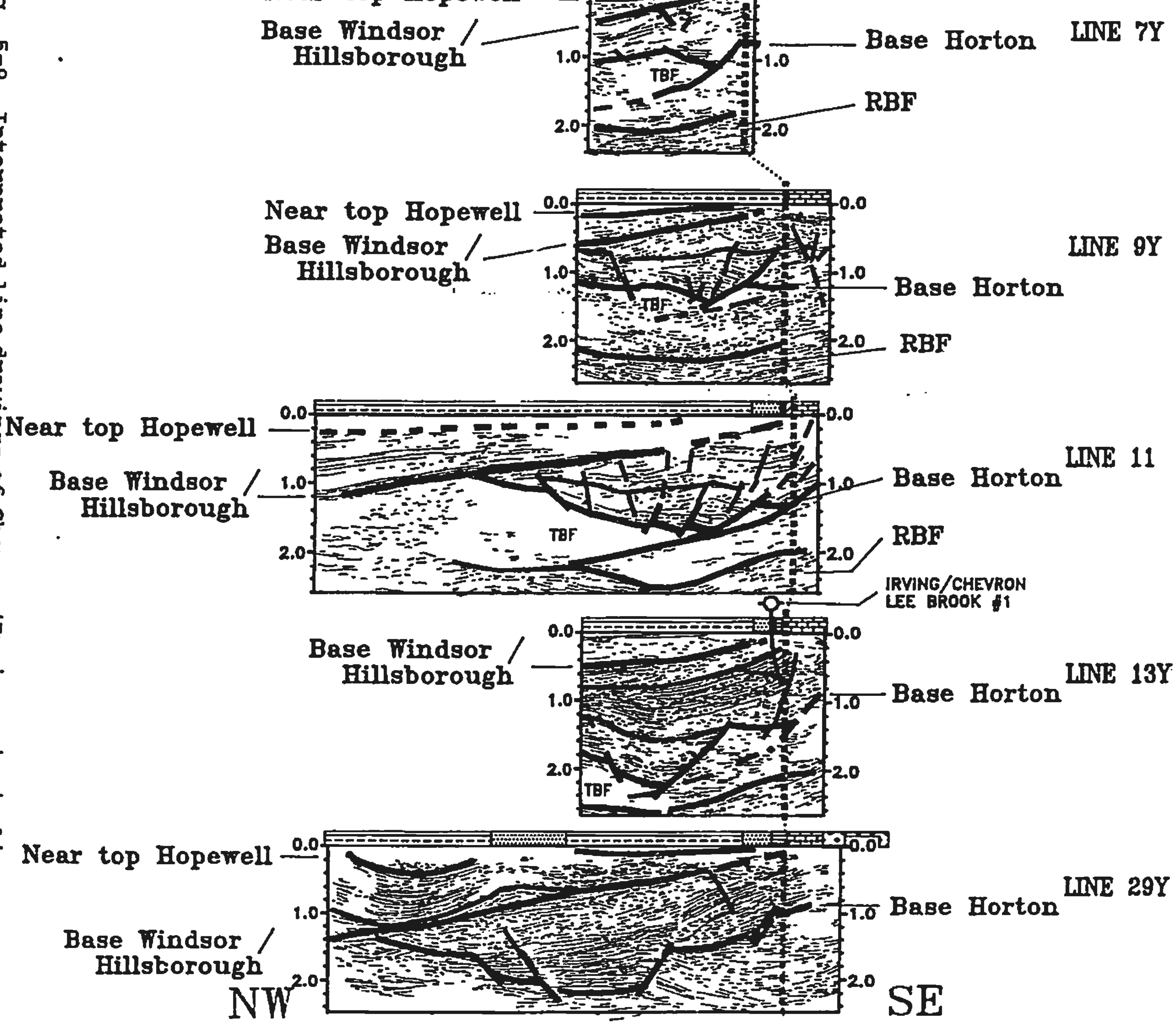

RBF
2.0
2.0
Near top Hopewell
Base Windsor / Hillsborough
TBF
0.0
1.0
2.0
LINE 97
Base Horton
RBF
IRVING/CHEVRON MIDDLESEX #1
Near top Hopewell
Base Windsor / Hillsborough
TBF
LINE 1
Base Horton
RBF
Near top Hopewell
Base Windsor / Hillsborough
TBF
LINE 97Y
Base Horton
RBF
IMPERIAL/NBO POLLETT RIVER #1
Near top Hopewell
Base Windsor / Hillsborough
TBF
LINES 60Y/5Y
Base Horton
RBF
Near top Hopewell
Base Windsor / Hillsborough
TBF
LINE 7Y
Base Horton
RBF

Fig. 5-9



...g. 5-9 Interpreted line drawings of Chevron/Irving seismic lines crossing the southern basin margin. Geological map data is shown by hatch pattern at the top of each section. Vertical dashed line marks edge of zone of intense faulting.

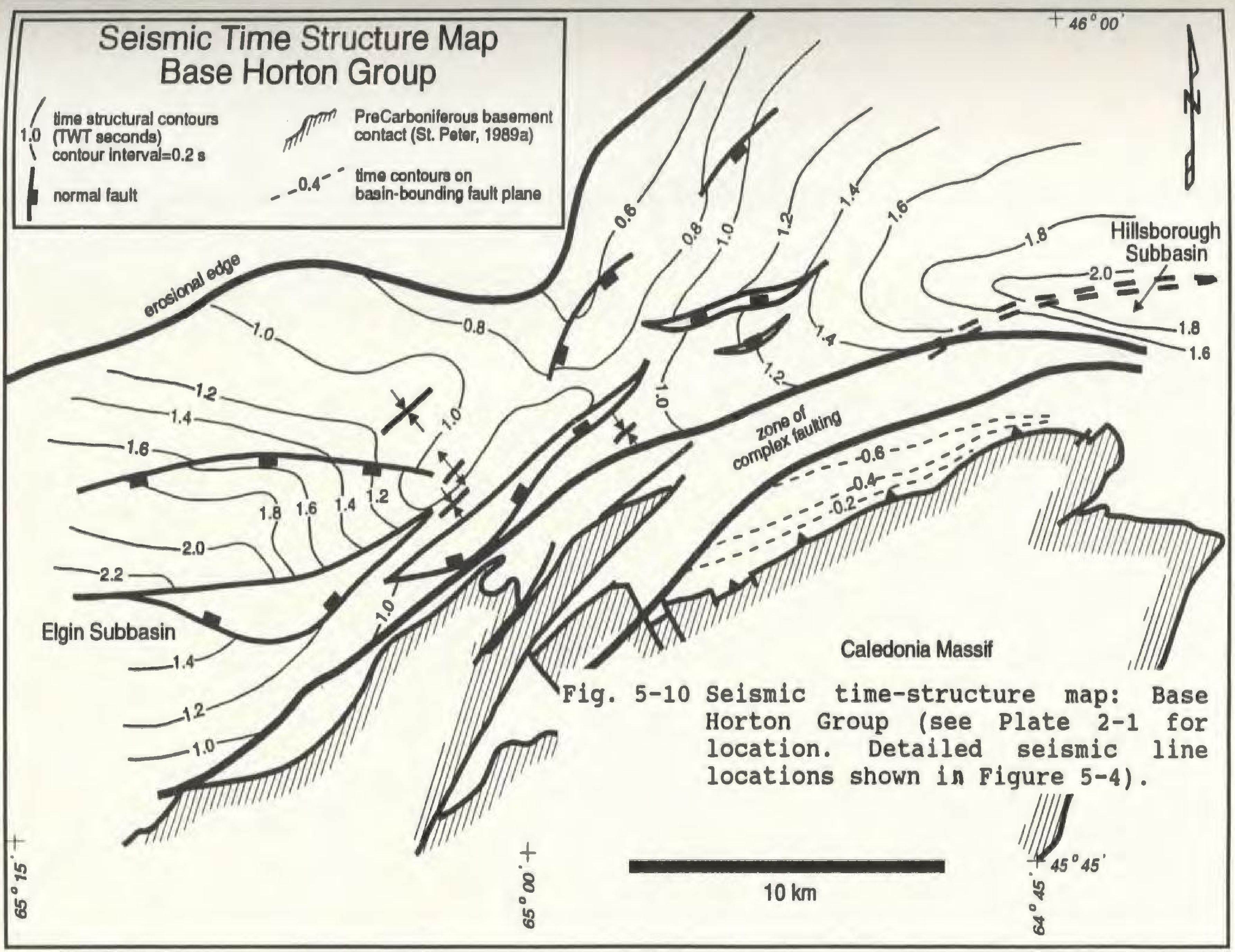


Fig. 5-10 Seismic time-structure map: Base Horton Group (see Plate 2-1 for location. Detailed seismic line locations shown in Figure 5-4).

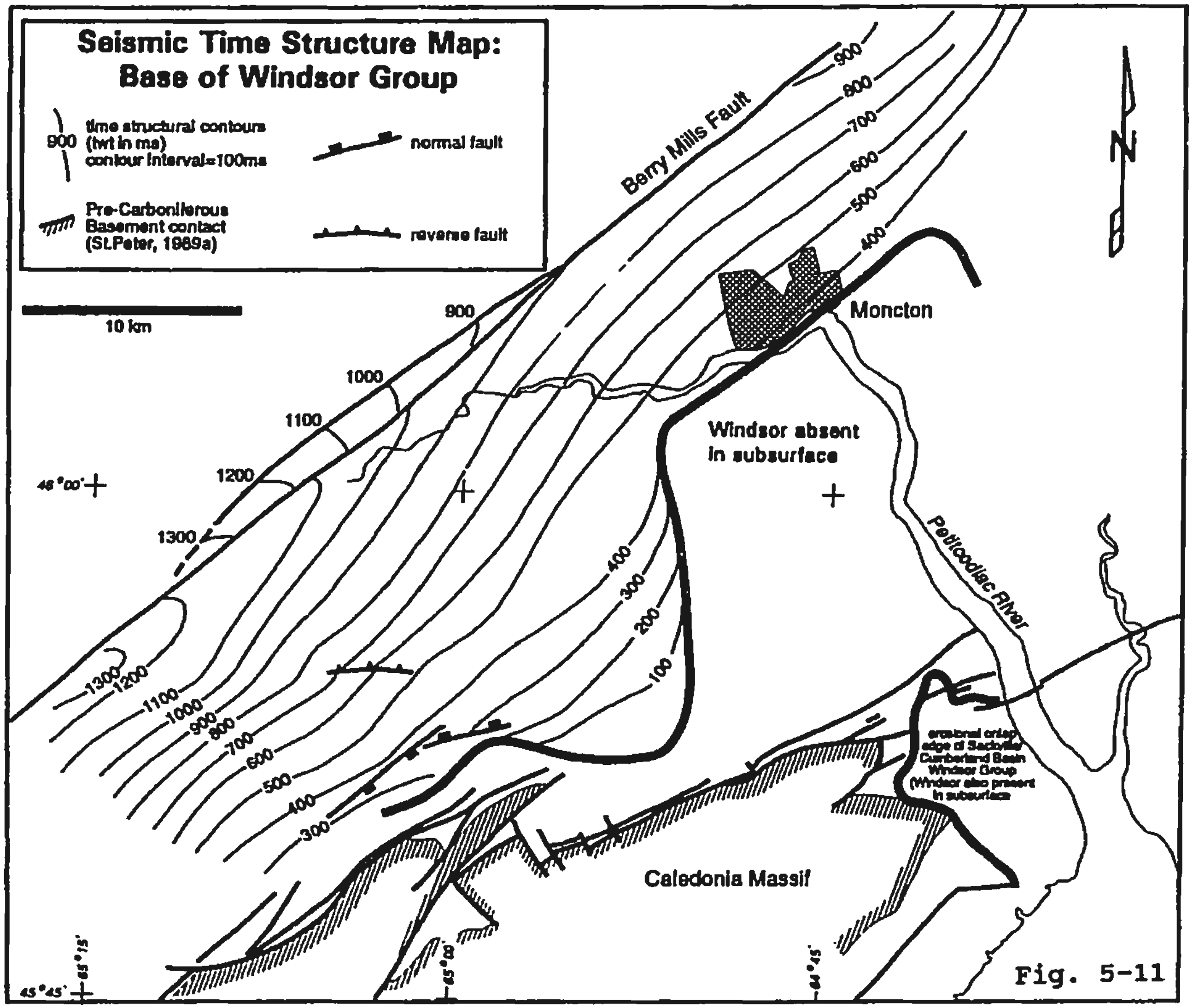
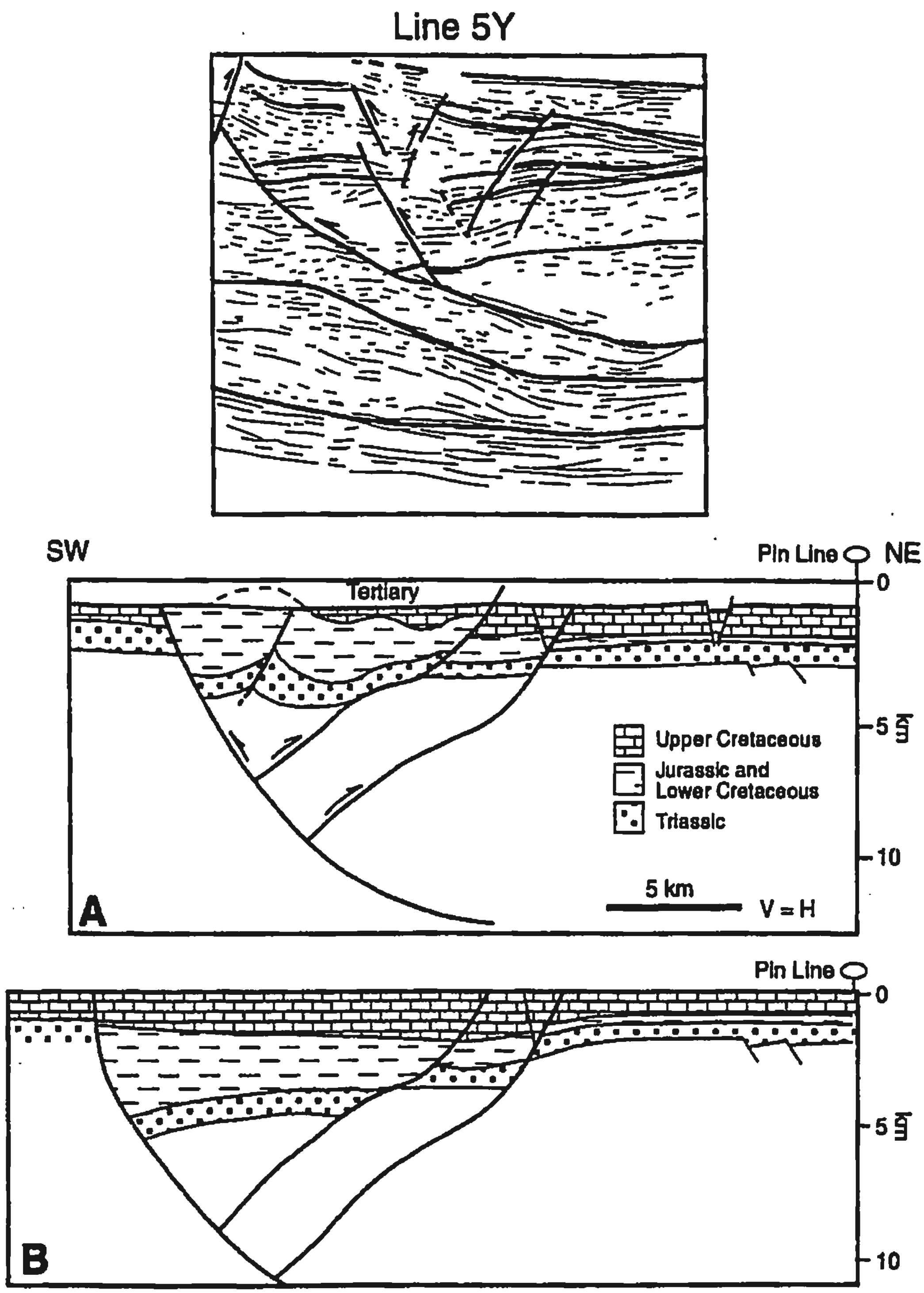

Seismic Time Structure Map:
Base of Windsor Group
900 time structural contours (twt in ms) contour interval=100ms
normal fault
Pre-Carboniferous Basement contact (St.Peter, 1989a)
reverse fault
10 km
Berry Mills Fault
Moncton
Windsor absent in subsurface
Petitcodiac River
Caledonia Massif
900
1000
1100
1200
1300
800
700
600
500
400
300
200
100
46°00'
45°45'
65°15'
65°00'
64°45'

Fig. 5-11

Fig. 5-12 Line 5Y inversion structure. Interpretation of fault pattern observed on line 5Y shows normal fault system reactivated in compression similar to documented inversion structure in Broad Fourteens basin (A); B, section A restored to its pre-inversion template (after Hayward and Graham, 1989).


Line 5Y
SW
Pin Line
NE
Tertiary
0
5
10
km
Upper Cretaceous
Jurassic and
Lower Cretaceous
Triassic
5 km
V = H
A
Pin Line
0
5
10
km
B

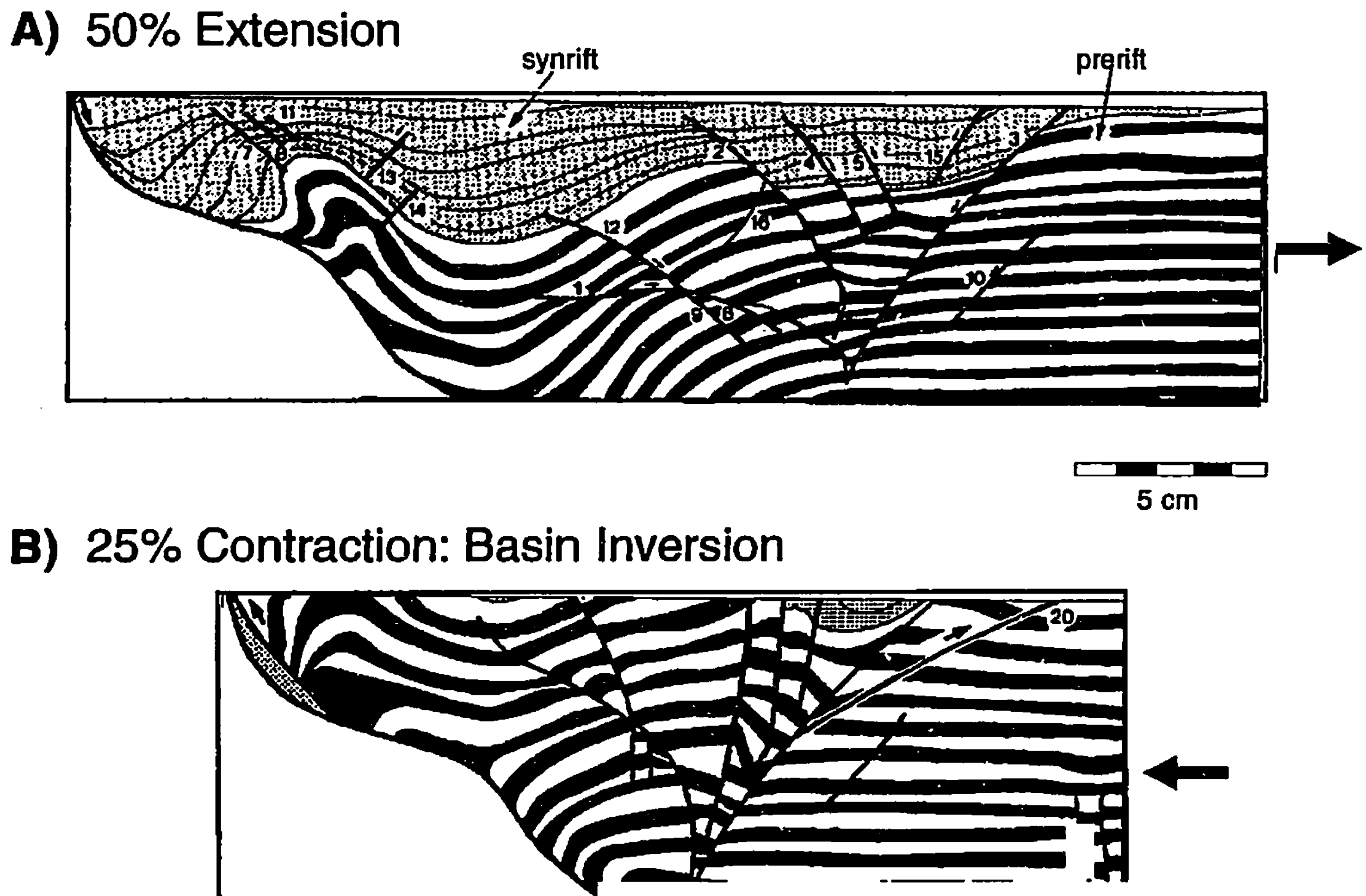


Fig. 5-13 Sandbox simulation of inverted half-graben geometry (from McClay, 1990).

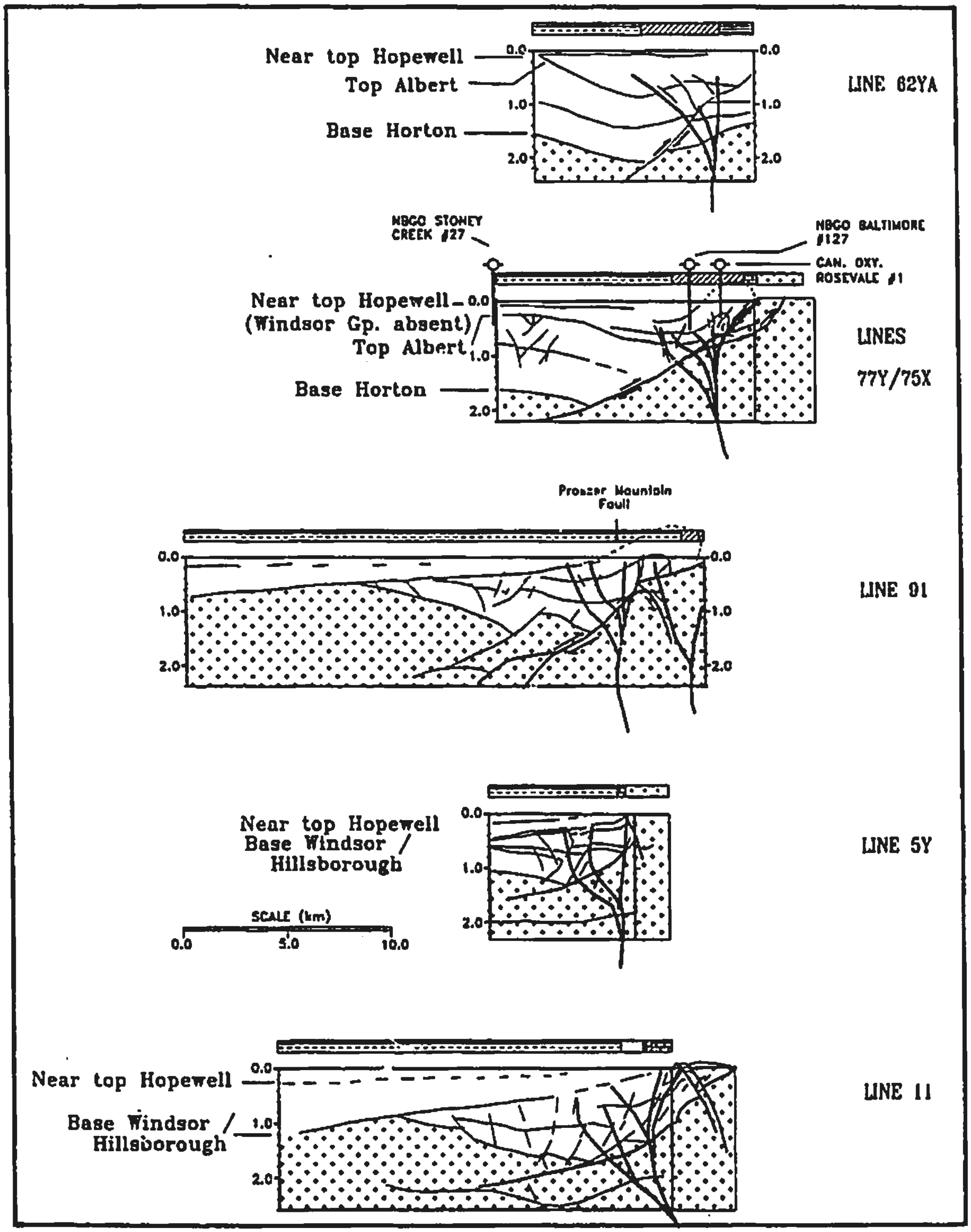


Fig. 5-14 Alternative interpretations for the "zone of intense faulting of Figure 5-9" showing (strike-slip) interpretation in bold lines, and inversion (compressional) interpretation in fine lines.

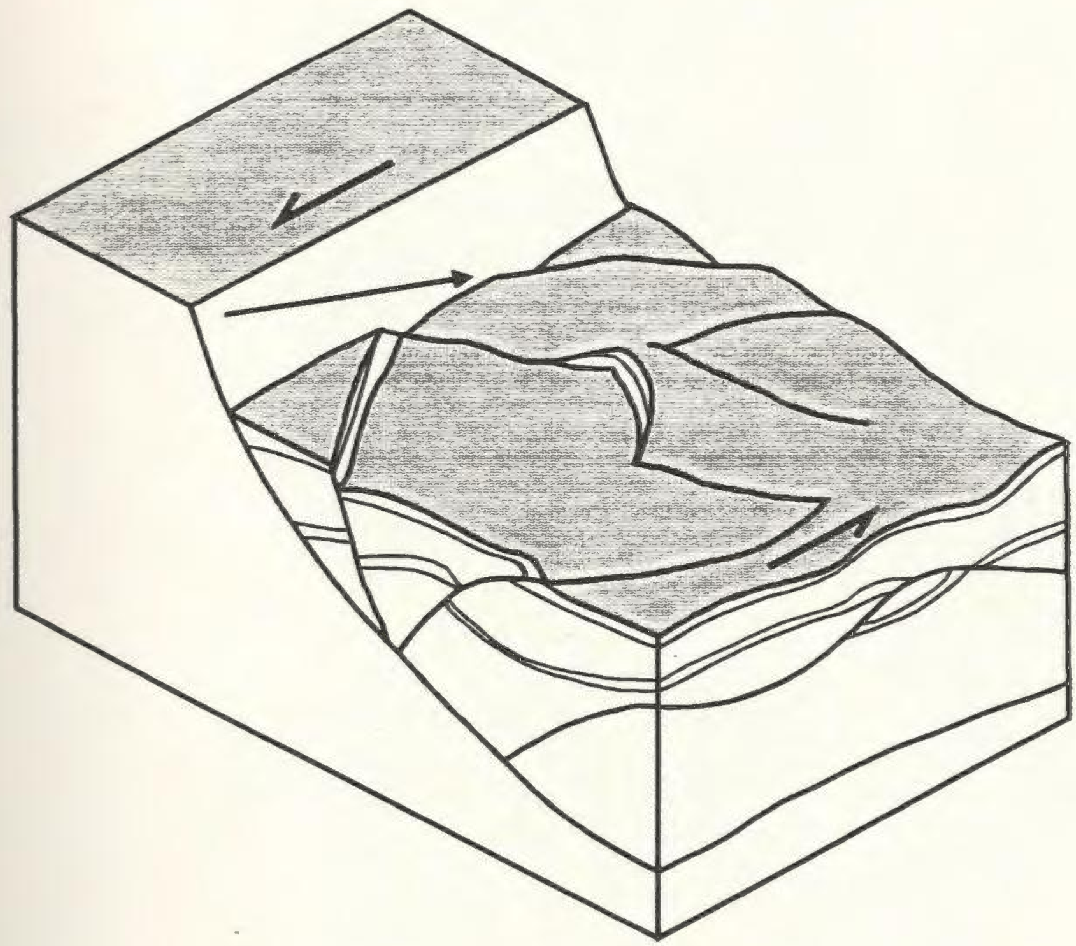


Fig. 5-15 Schematic representation of a "mixed mode" oblique slip extension on a ramp-flat fault system (after Gibbs, 1988).

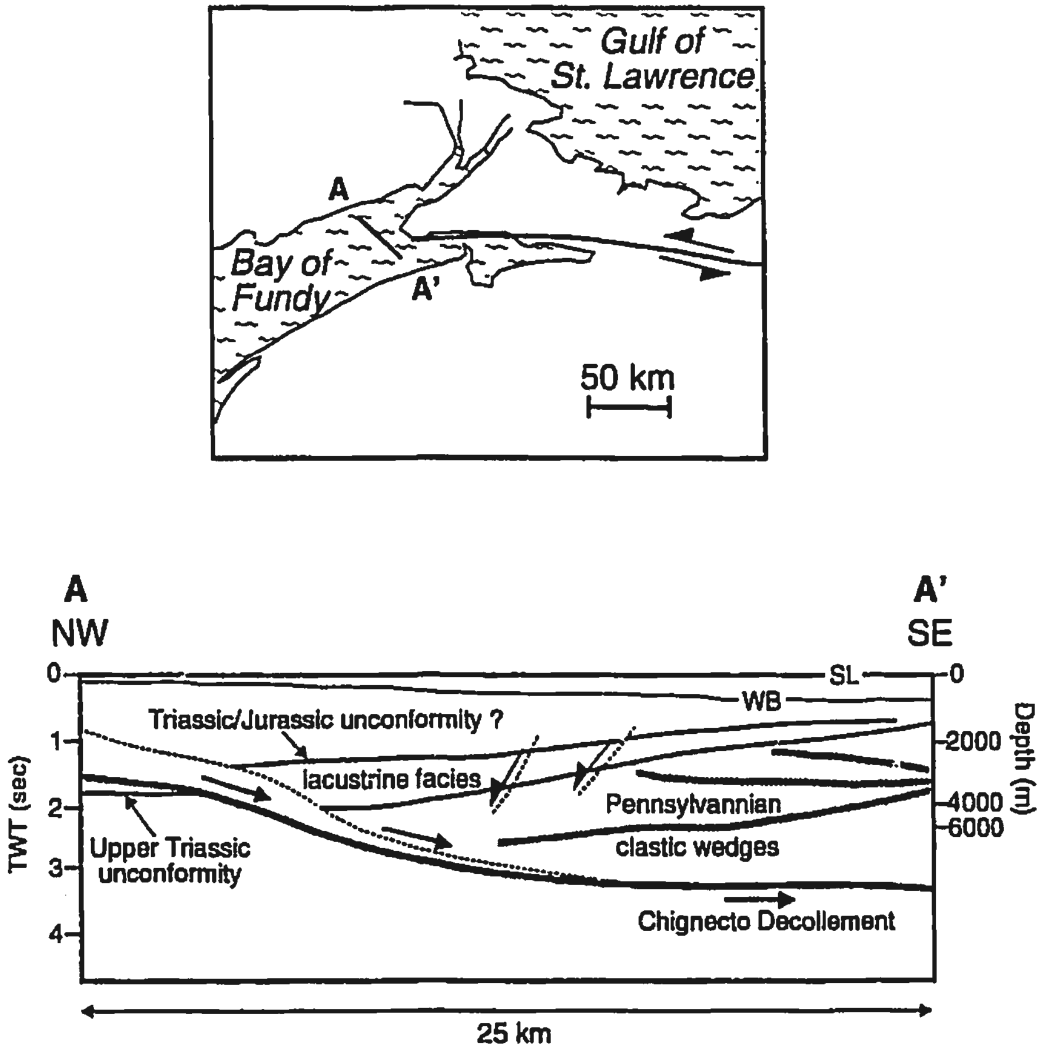


Fig. 6-1 Cross-section of Triassic Fundy rift basin (after Brown and Grantham, 1992); location shown in schematic at top.

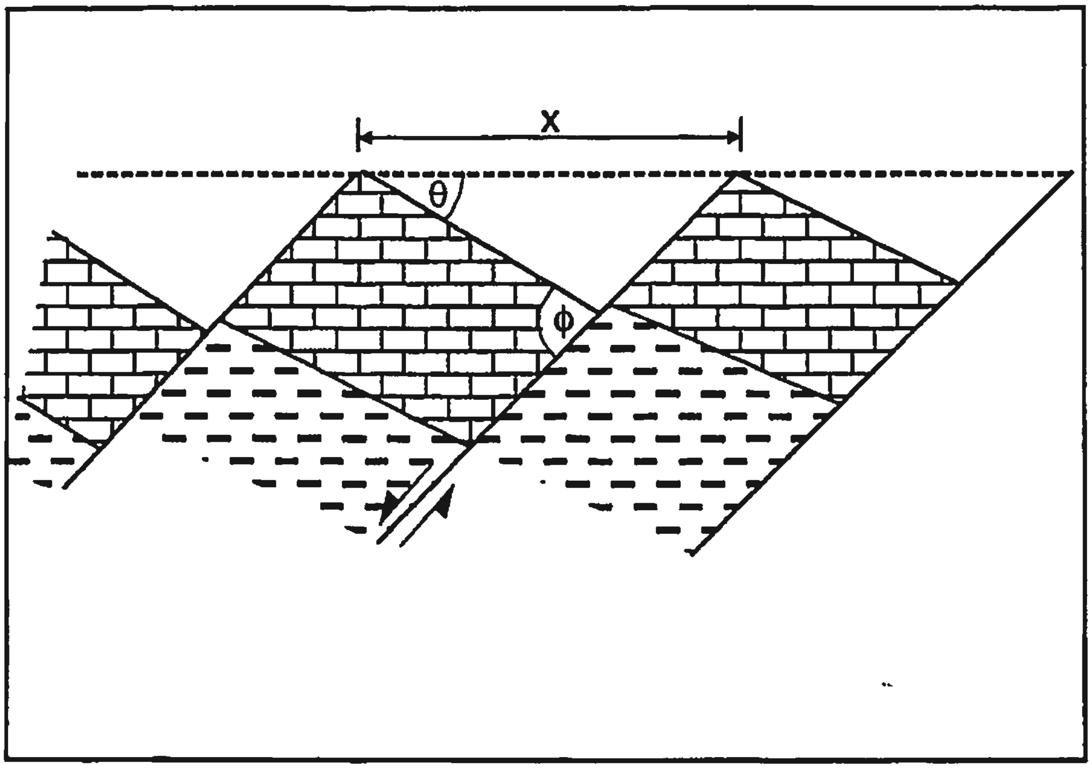


Fig. 6-2 Schematic diagram showing relationship between sediment dip, fault dip and stretching factor for domino-style faults (after Wernicke and Burchfiel, 1982)

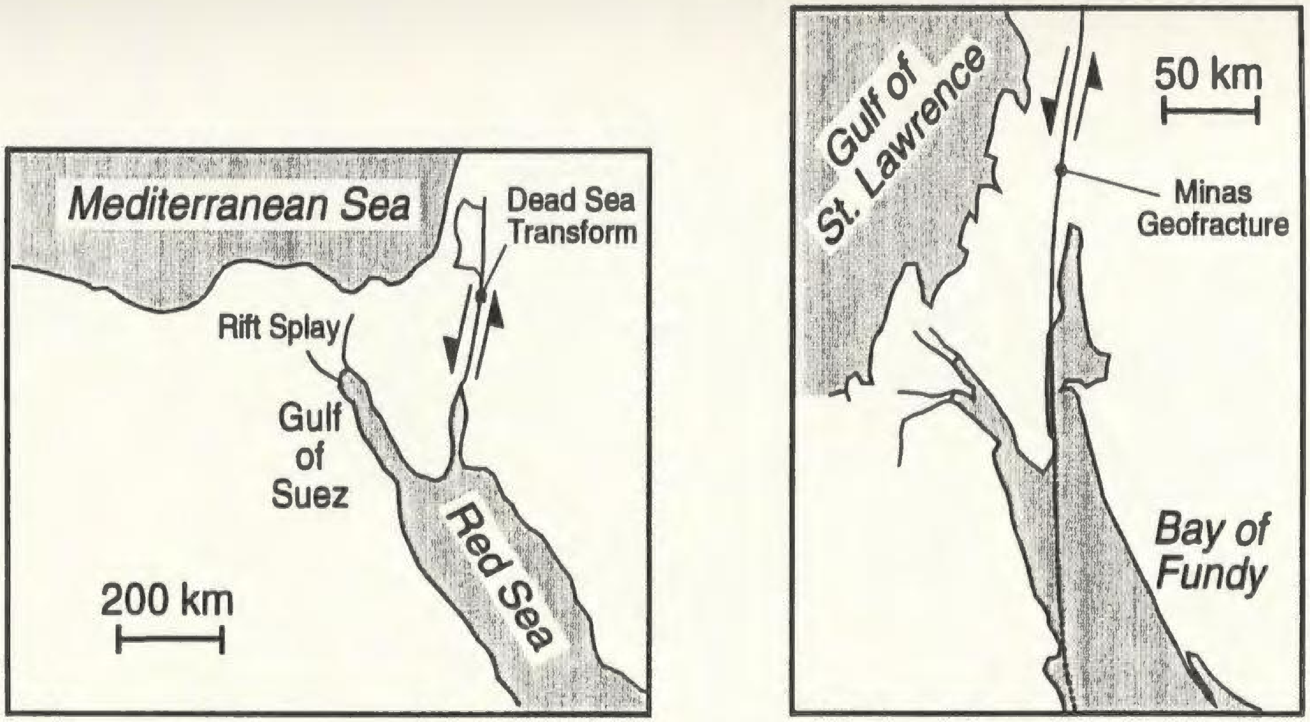


Fig. 6-3 Comparison of gross map and tectonic elements, Red sea rift and Fundy rift basin.

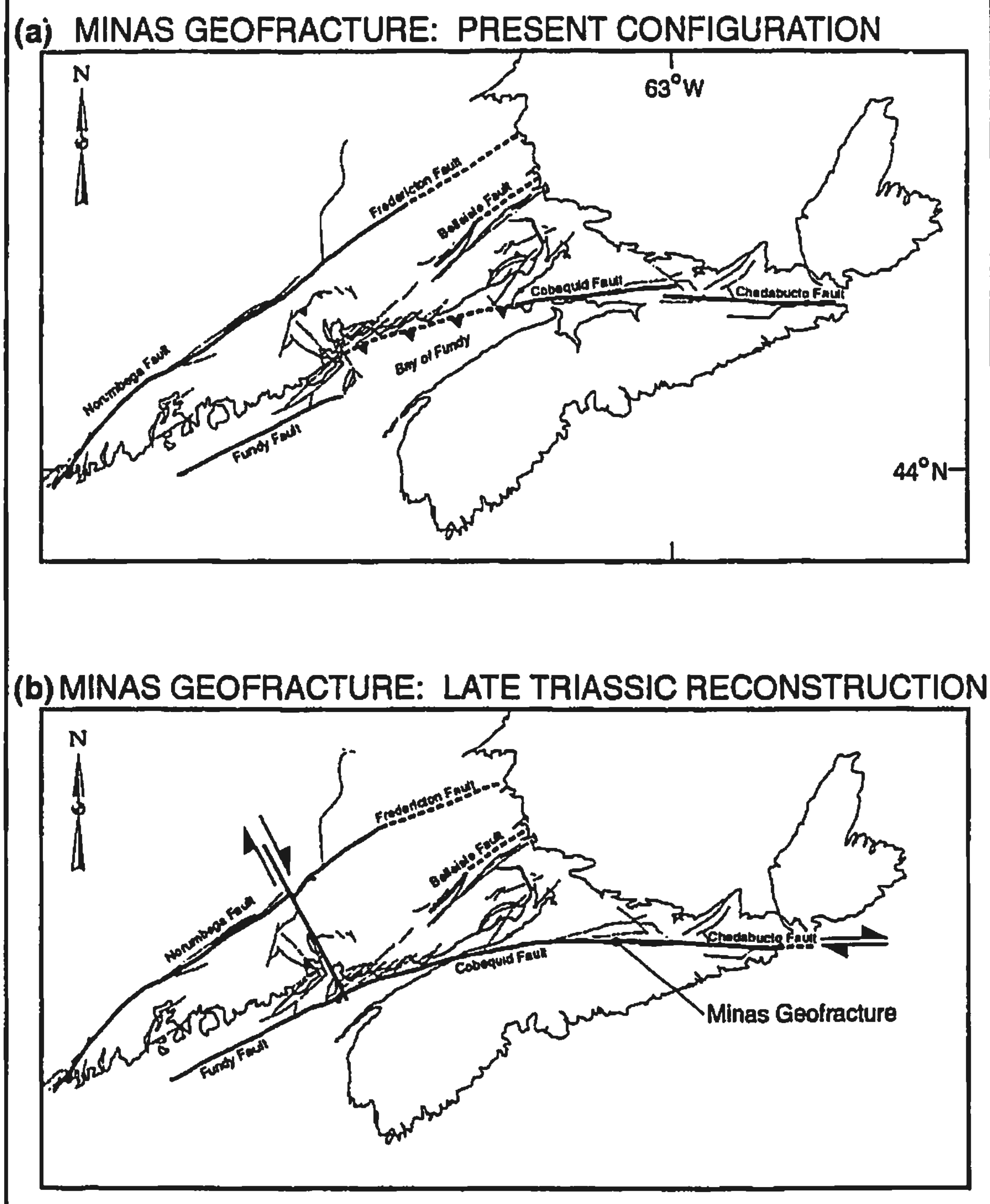
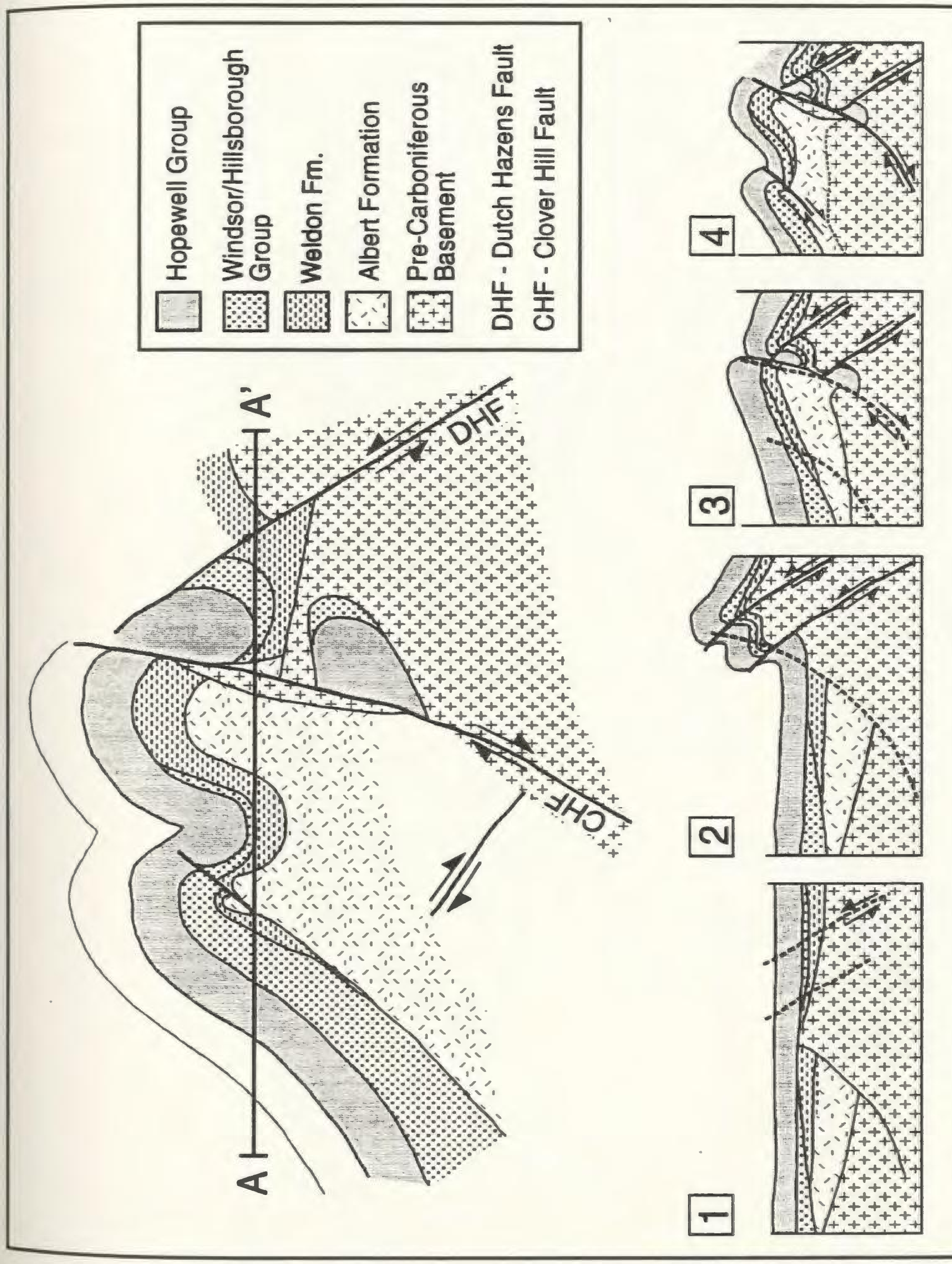


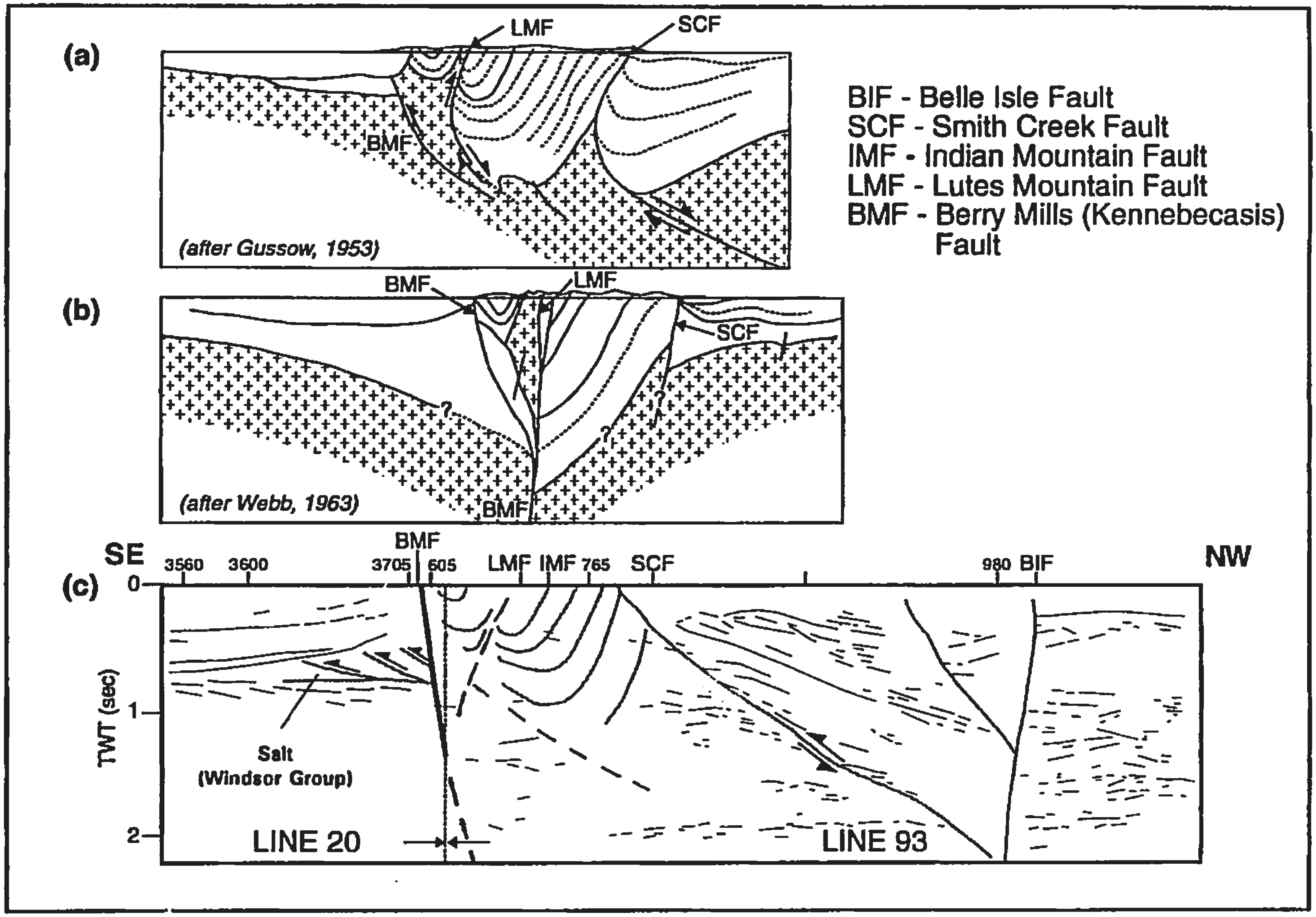
Fig. 6-4 Palinspastic restoration of Bay of Fundy to pre-Late Triassic configuration; a) present configuration; b) restored to pre-Late Triassic.

Fig. 6-5 Vertical cross-section A-A′ constructed from geological map (St. Peter, 1989c; 1:20,000 scale) near Urney. See Plate 2-1 for location.



Hopewell Group
Windsor/Hillsborough Group
Weldon Fm.
Albert Formation
Pre-Carboniferous Basement
DHF - Dutch Hazens Fault
CHF - Clover Hill Fault
A
A'
DHF
CHF
1
2
3
4

Fig. 6-6 Kingston Uplift seismic transect at Indian Mountain (see Plate 2-1 for location); a) Interpretation of Gussow (1953); b) Interpretation of Webb (1963); c) interpreted line drawing of Chevron/Irving lines 20 and 93 showing low angle (compressional?) features cut by later high angle (wrench?) faults (e.g. BMF, BIF).



(a)
LMF
SCF
BMF
(after Gussow, 1953)
BIF - Belle Isle Fault
SCF - Smith Creek Fault
IMF - Indian Mountain Fault
LMF - Lutes Mountain Fault
BMF - Berry Mills (Kennebecasis) Fault
(b)
BMF
LMF
SCF
?
(after Webb, 1963)
BMF
(c)
SE
NW
3560
3600
3705
605
BMF
LMF
IMF
765
SCF
980
BIF
0
1
2
TWT (sec)
Salt (Windsor Group)
LINE 20
LINE 93

Fig. 6-7 Minas Geofracture/San Andreas 'Big Bend' analogy. A) Pre-Late Triassic reconstruction showing location of Moncton subbasin with respect to Cobequid-Chedabucto (Minas Geofracture of Keppie, 1982) fault zone; B) San Andreas Fault analogue originally proposed by Nance (1987) with California Cenozoic basins superimposed; C) Fault map of Moncton subbasin, location shown in A; D) Ventura Basin fault map, location shown in B; A-A' = Urney transect (Figure 6-5); B-B' = Line 29Y (Plate 6-1); C-C', D-D' are analogous Ventura Basin transects shown in Figure 6-8.

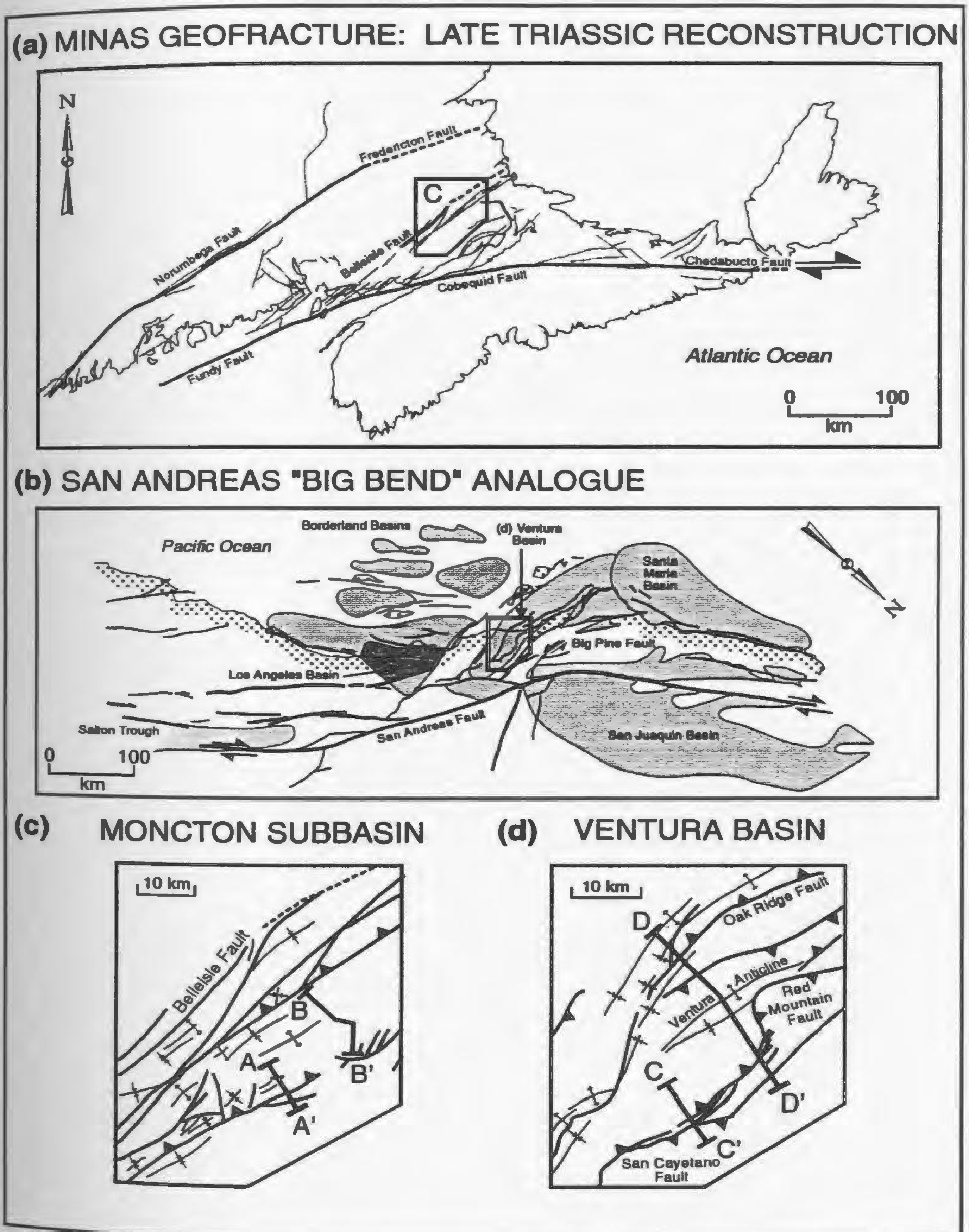

(a) MINAS GEOFRACTURE: LATE TRIASSIC RECONSTRUCTION
N
Fredericton Fault
C
Norumbega Fault
Belleisle Fault
Chedabucto Fault
Cobequid Fault
Fundy Fault
Atlantic Ocean
0 100
km
(b) SAN ANDREAS "BIG BEND" ANALOGUE
Borderland Basins
(d) Ventura Basin
Pacific Ocean
Santa Maria Basin
N
Big Pine Fault
Los Angeles Basin
Salton Trough
San Andreas Fault
San Juaquin Basin
0 100
km
(c) MONCTON SUBBASIN
10 km
Belleisle Fault
B
B'
A
A'
(d) VENTURA BASIN
10 km
D
Oak Ridge Fault
Ventura Anticline
Red Mountain Fault
C
D'
C'
San Cayetano Fault

Fig. 6-8 Central Ventura Basin Cross-sections (after Yeats et al., 1988) showing Pliocene to recent movement on key faults. Cross-section C-C′ is analogous to Urney transect (A-A′ of Figure 6-5) showing shortening to be accommodated partly by high-angle reverse faults at the basin margin and partly by detachment faulting on the Sisar fault beneath the basin fill. Compare cross-section D-D′ with detachment faulting at the base of Windsor Group salt horizon which gives rise to the anticlinal feature shown at shotpoint 2300 in Plate 6-1.

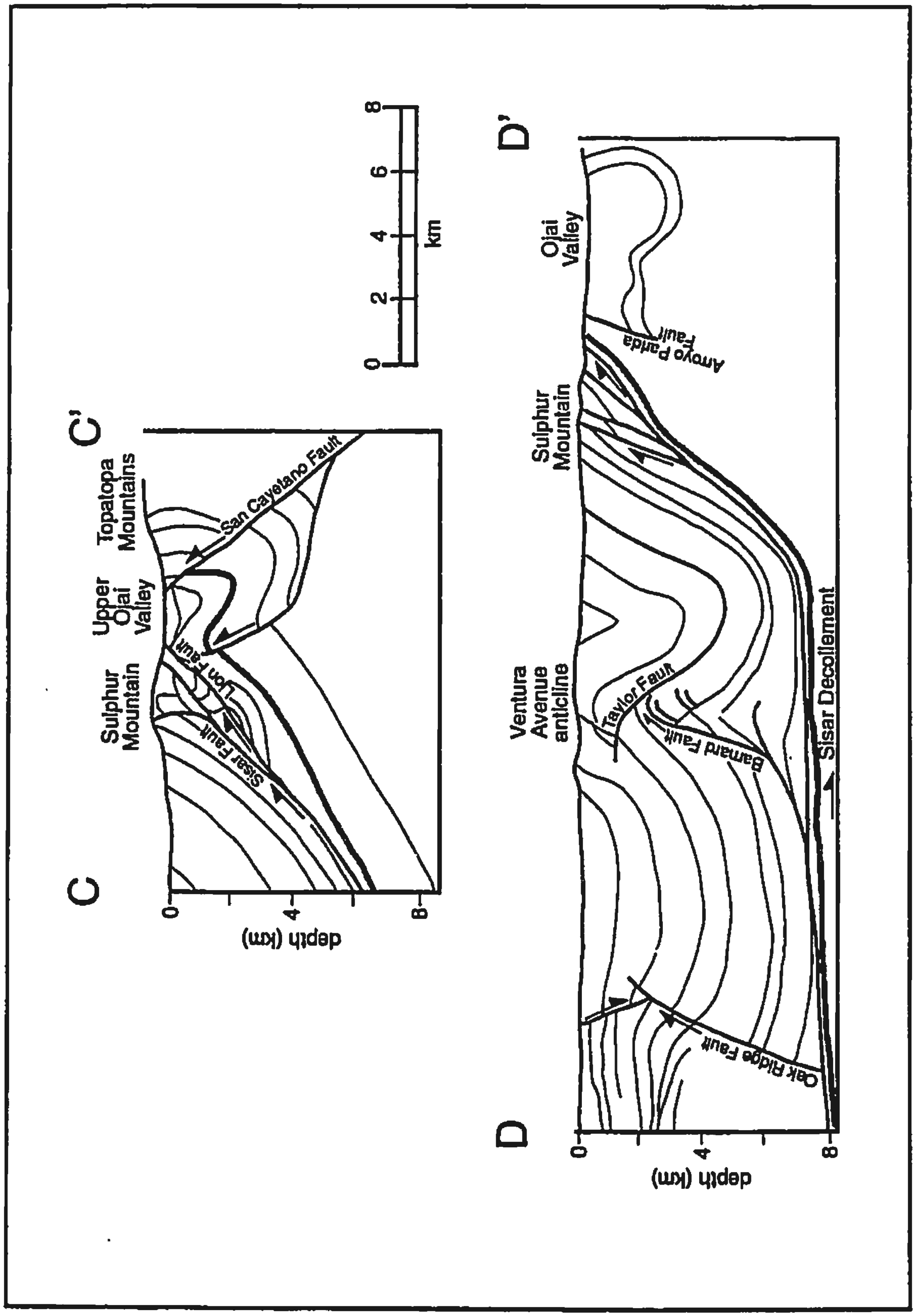
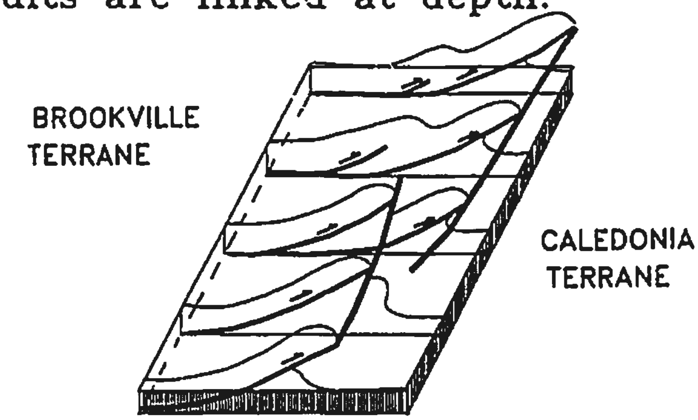
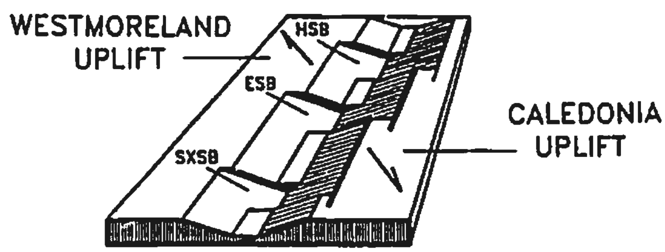

C
C'
Sulphur Mountain
Upper Ojai Valley
Topatopa Mountains
San Cayetano Fault
Lion Fault
Sisar Fault
depth (km)
0
4
8
0
2
4
6
8
km
D
D'
Ventura Avenue anticline
Sulphur Mountain
Ojai Valley
Arroyo Parida Fault
Taylor Fault
Barnard Fault
Sisar Decollement
Oak Ridge Fault
depth (km)
0
4
8

Fig. 7-1 Kinematic model showing development of Moncton Subbasin Horton Group depocentres: A. Schematic pre-extension template (linked thrusts after Dahlstrom, 1972); B. Block model of oblique extension on reactivated en echelon fault system; C. Moncton subbasin, showing isopachs predicted from model above are consistent with those of Figure 5-10.

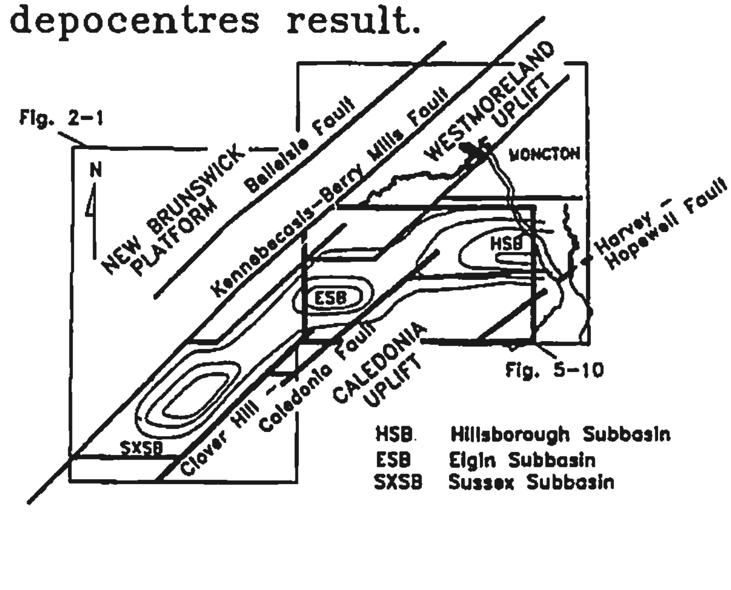
A. Acadian Orogeny: *En echelon* thrust faults are linked at depth.



B. Late Devonian: *En echelon* faults are reactivated in oblique extension.



C. Tournaisian: Linked Horton Group depocentres result.



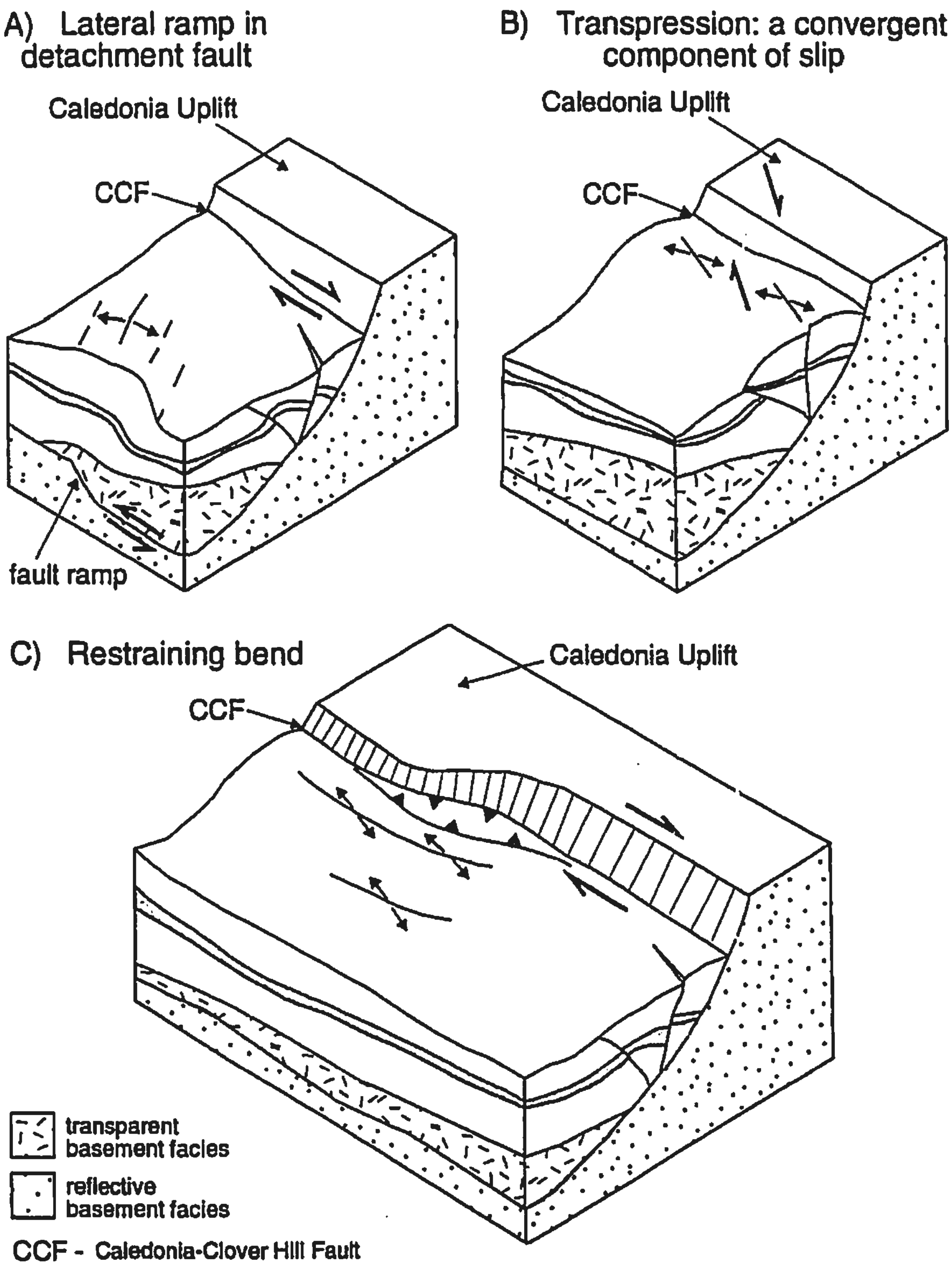


Fig. 7-2 Three possible mechanisms for localized uplift during the Moncton episode

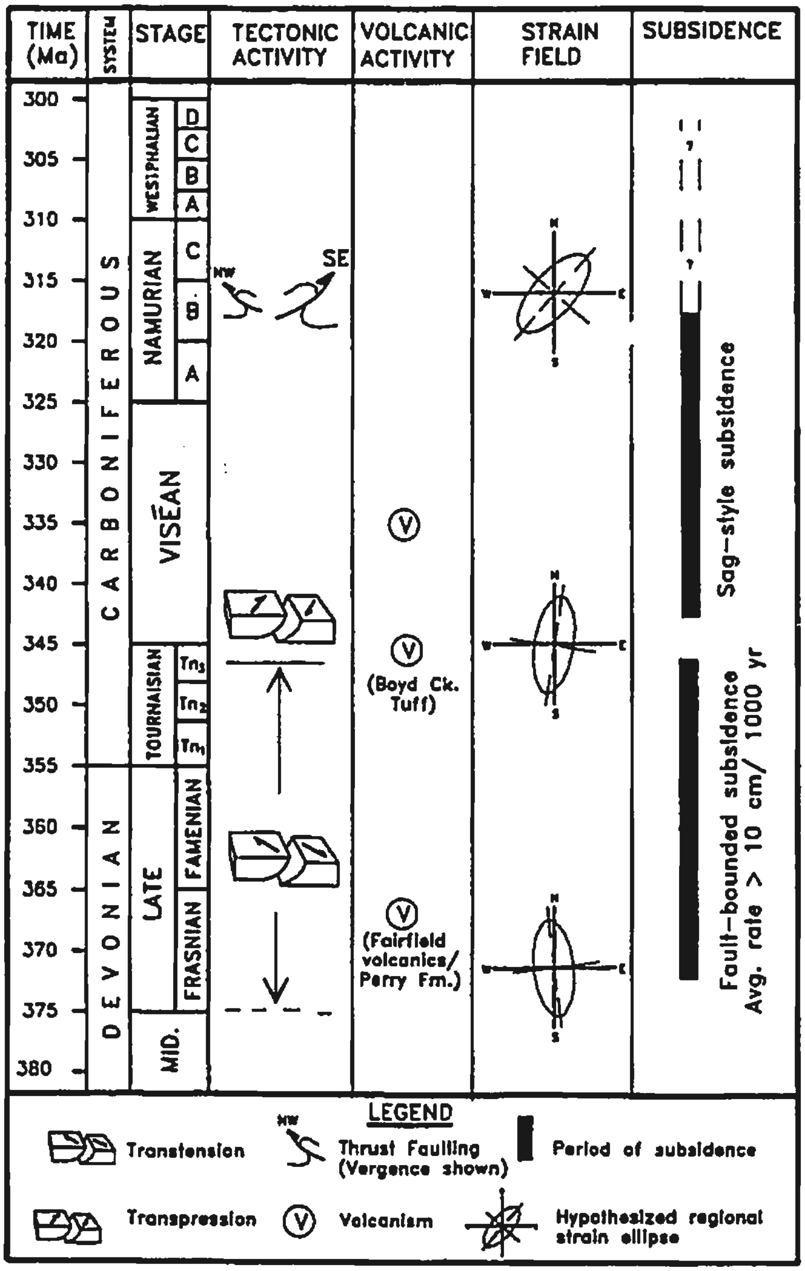
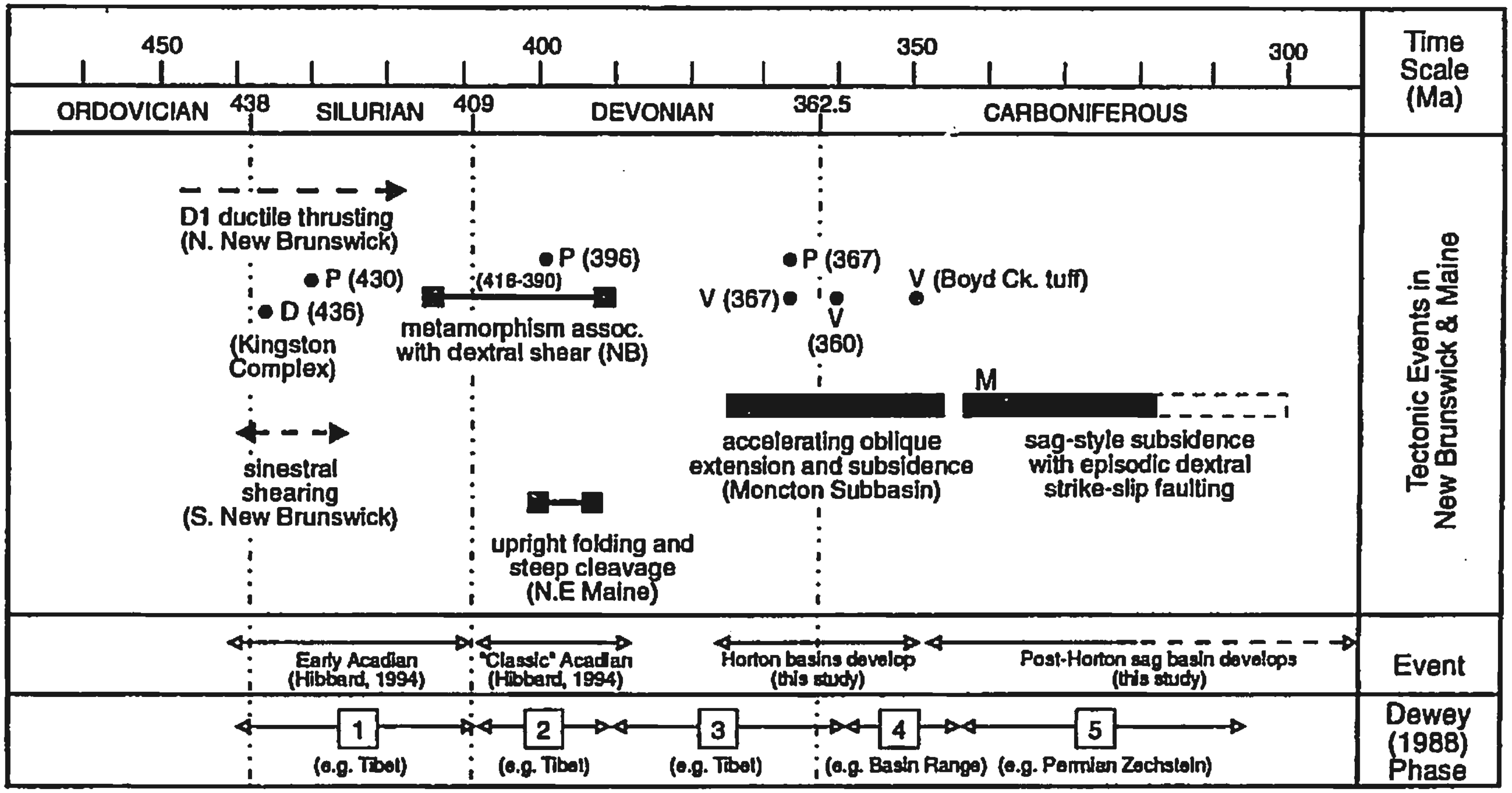


Fig. 7-3 Chronological summary of tectonic events in the Moncton Subbasin. Time scale from Harland (1989). Post-Westphalian B strike slip faulting not shown due to timing uncertainty.



P = plutonism, Avalon Zone V = volcanism, Avalon Zone D = dike swarm M = marine incursion

Fig. 7-4 Summary of tectonic events preceding Moncton Subbasin subsidence and their relationship to Dewey's (1988) phases of orogenic collapse. Hibbard (1994) recognizes a regional realignment of convergence direction between the "early" and "classic" stages of Acadian orogeny. (Compiled from Hibbard, 1994; McLeod et al., 1994; Whalen et al., time scale from Harland, 1991)

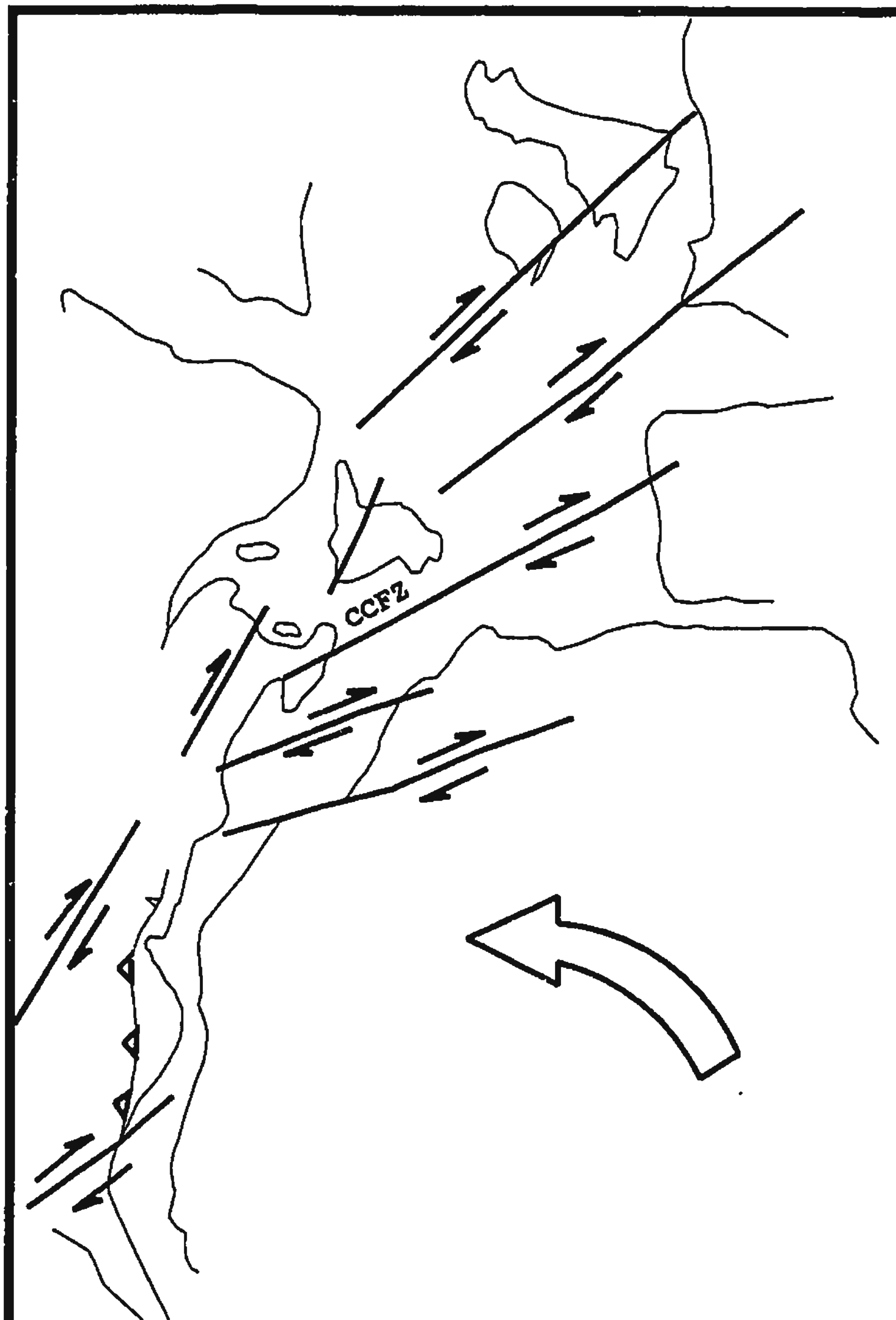


Fig. 7-5 Dextral shearing on East-West fault zones in the Carboniferous is related to docking of Gondwana with Laurussia. CCFZ: Cobequid-Chedabucto Fault Zone; after Lefort, 1989.

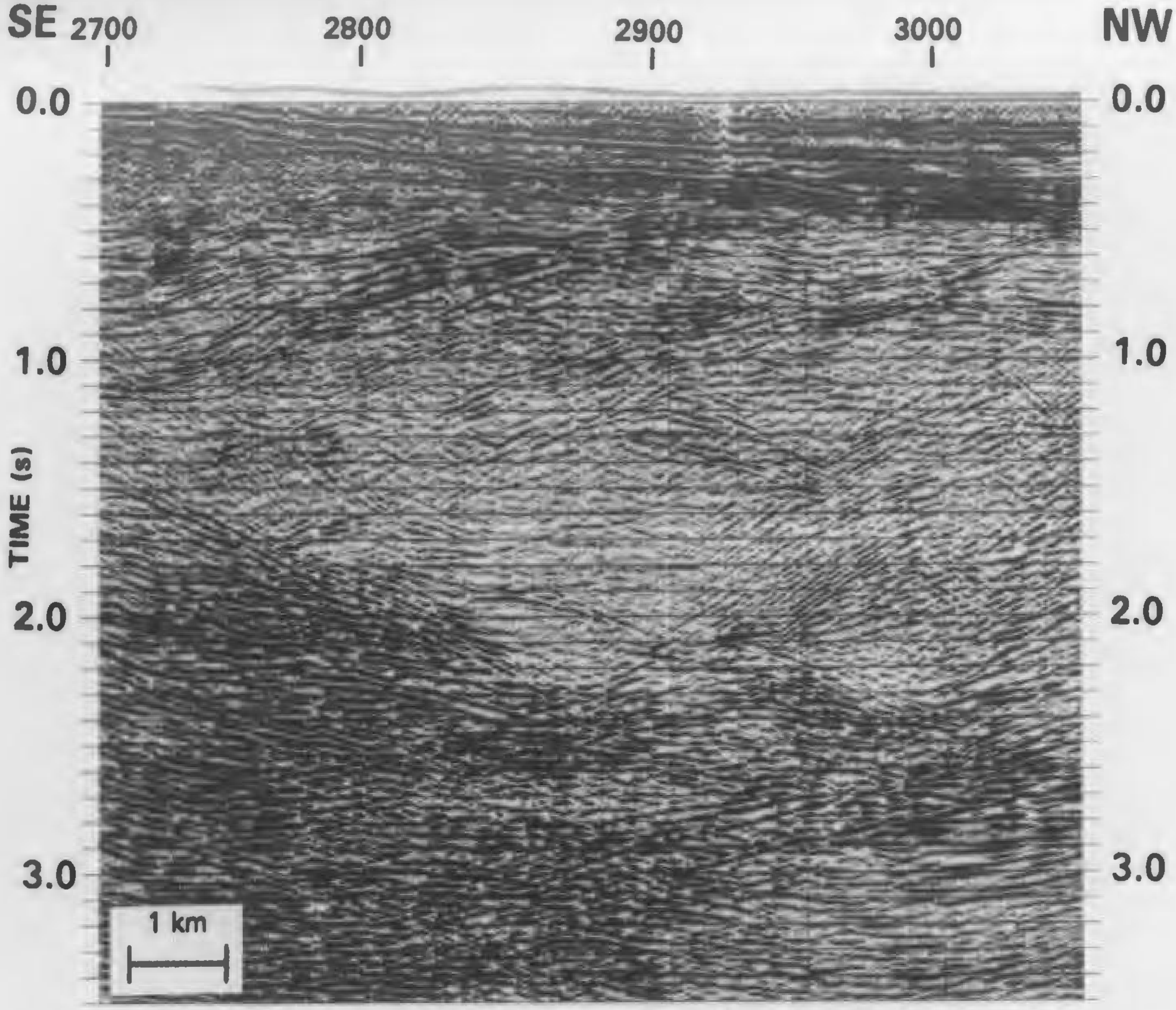


Plate 3-3(a) **Seismic Line 89Y (30 fold Vibroseis, coherency enhanced, migrated stack). See Figure 1-2 for line location.**

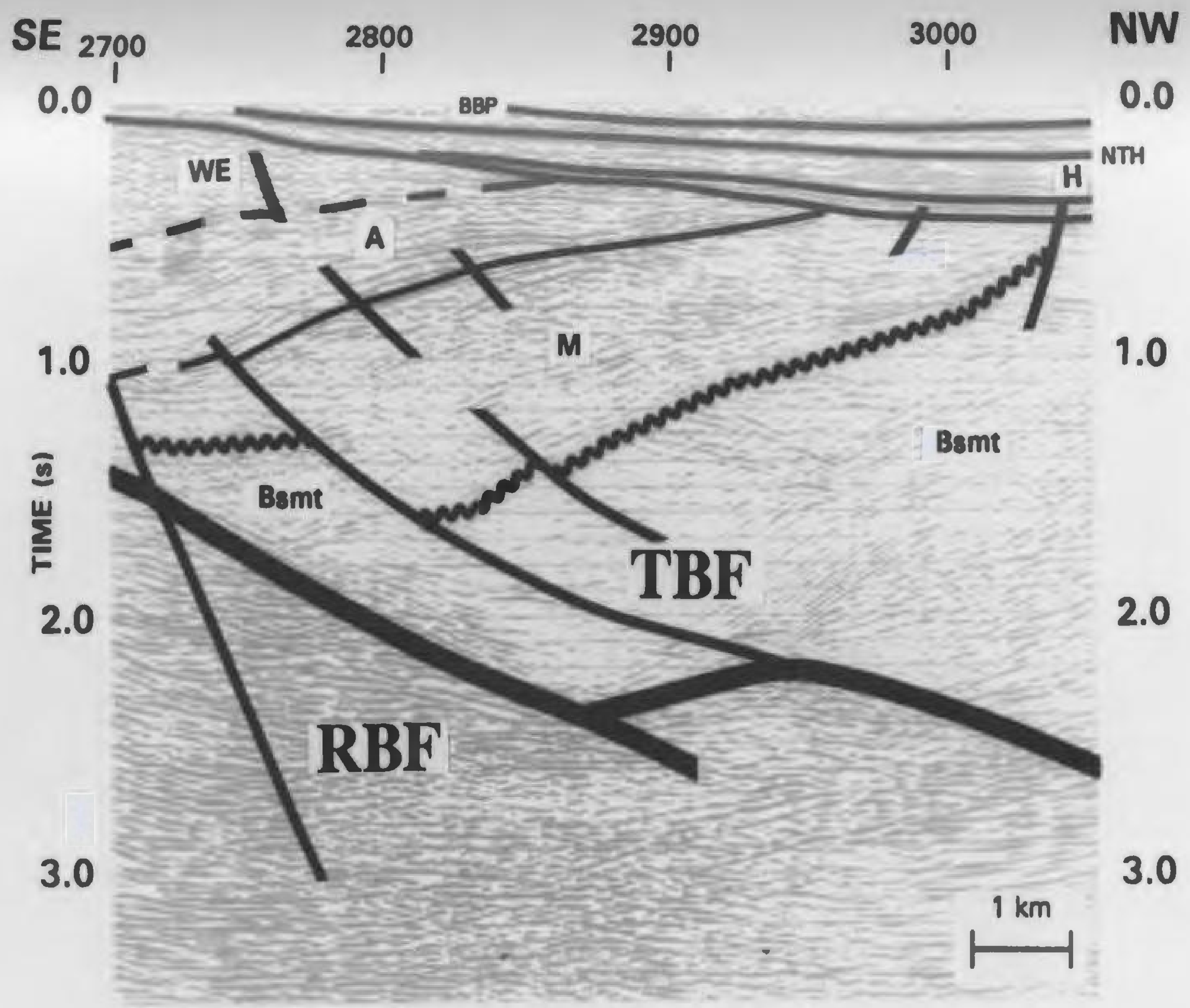


Plate 3-3(b) **Seismic Line 89Y (interpreted) showing seismic character of basement complex; TBF = Transparent basement facies; RBF = Reflective basement facies; M = Memramcook Fm.; A = Albert Fm.; WE = Weldon Fm.; H = Hopewell Group; NTH = Near top Hopewell reflector; BBP = Base of Boss Point reflector.**

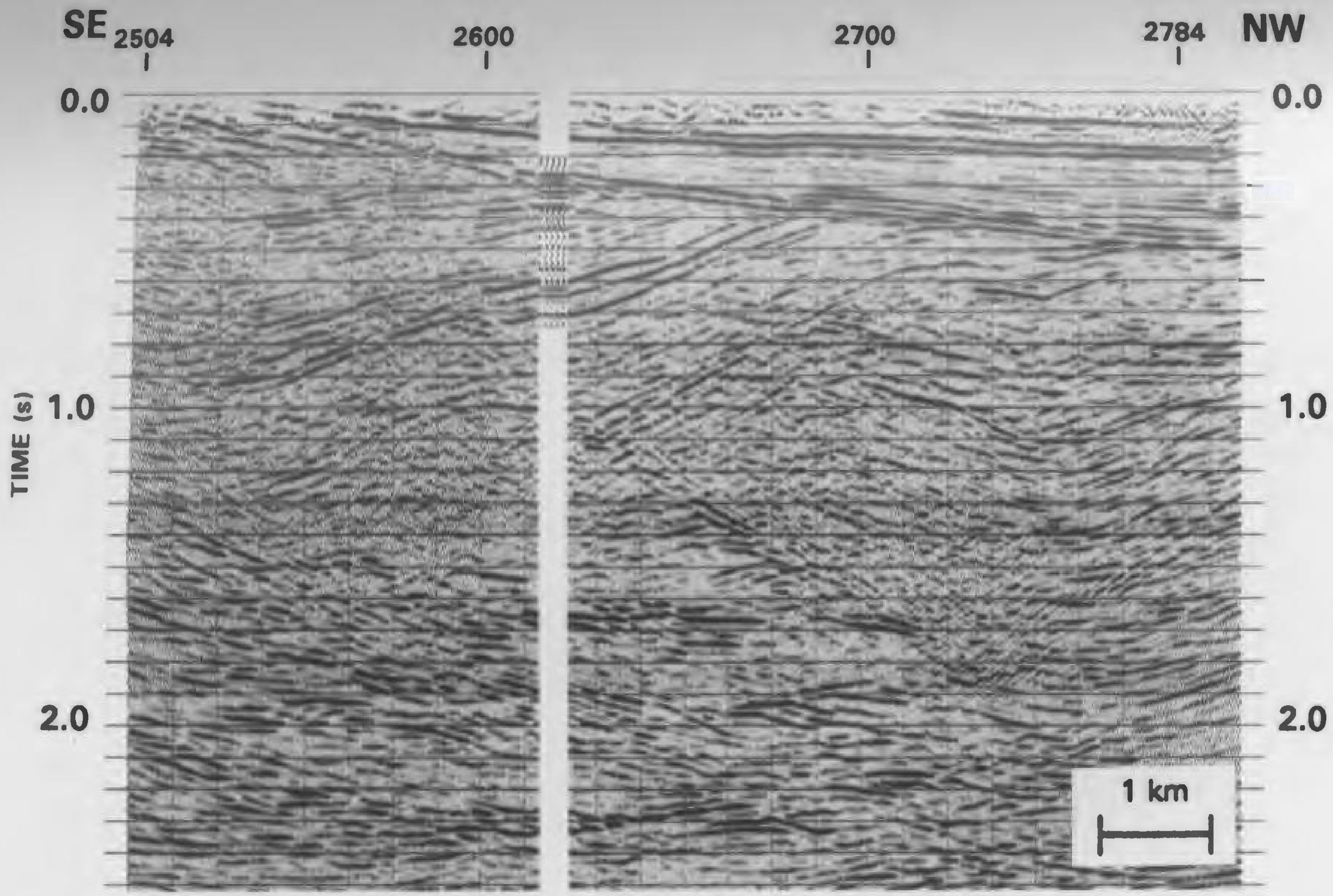


Plate 4-1(a) Seismic Line 93Y (30 fold Vibroseis, coherency enhanced, migrated stack). See Figure 1-2 for line location.

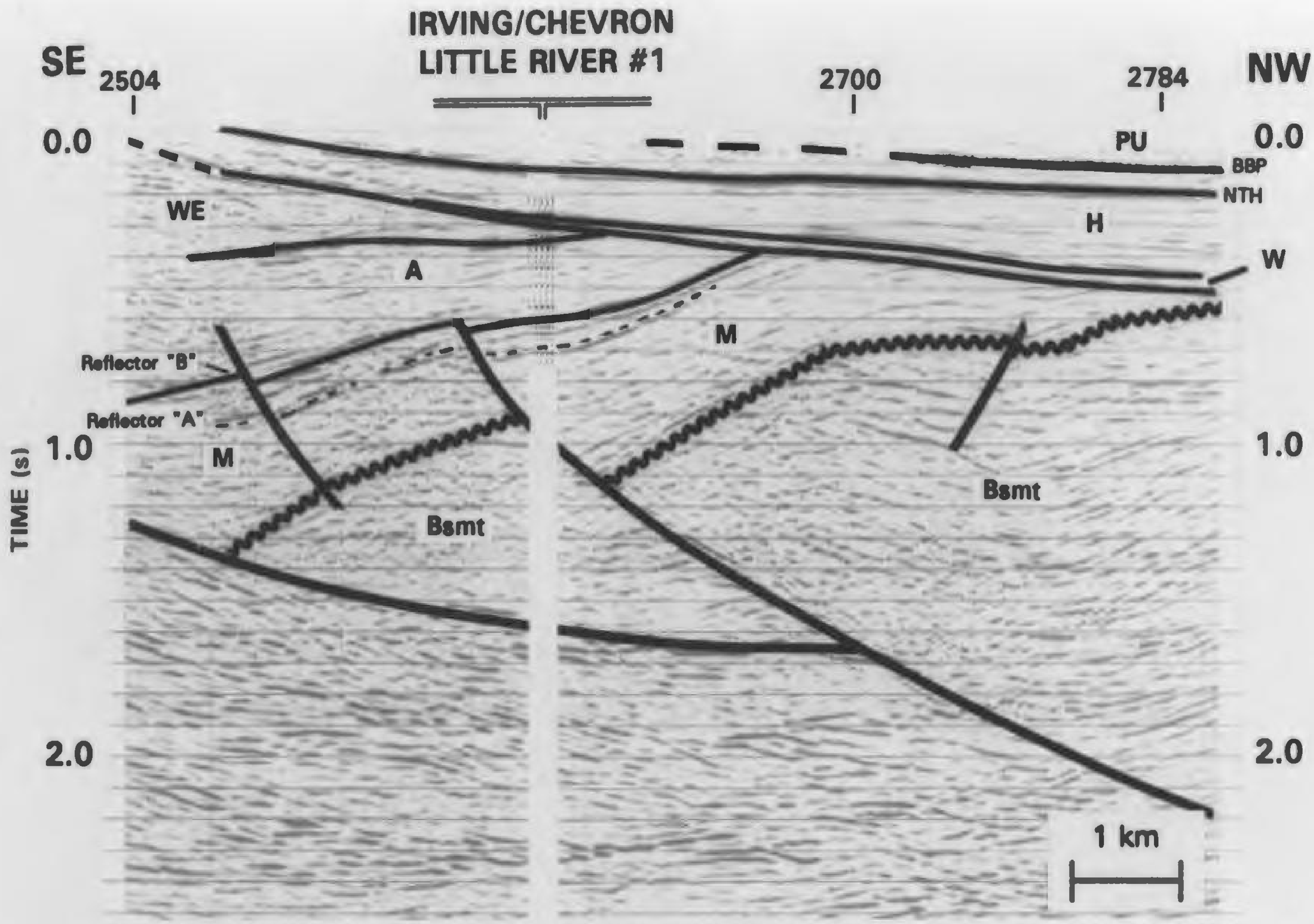


Plate 4-1(b) Seismic Line 93Y (interpreted) showing borehole tie with synthetic seismogram at I/C Little River well (Plate A-11); M = Memramcook Fm.; A = Albert Fm.; WE = Weldon Fm.; W = Windsor Gp.; H = Hopewell Gp. ; PU = Boss Point Fm. and Pictou Gp. ; NTH = Near top Hopewell reflector; BBP = Base of Boss Point reflector.

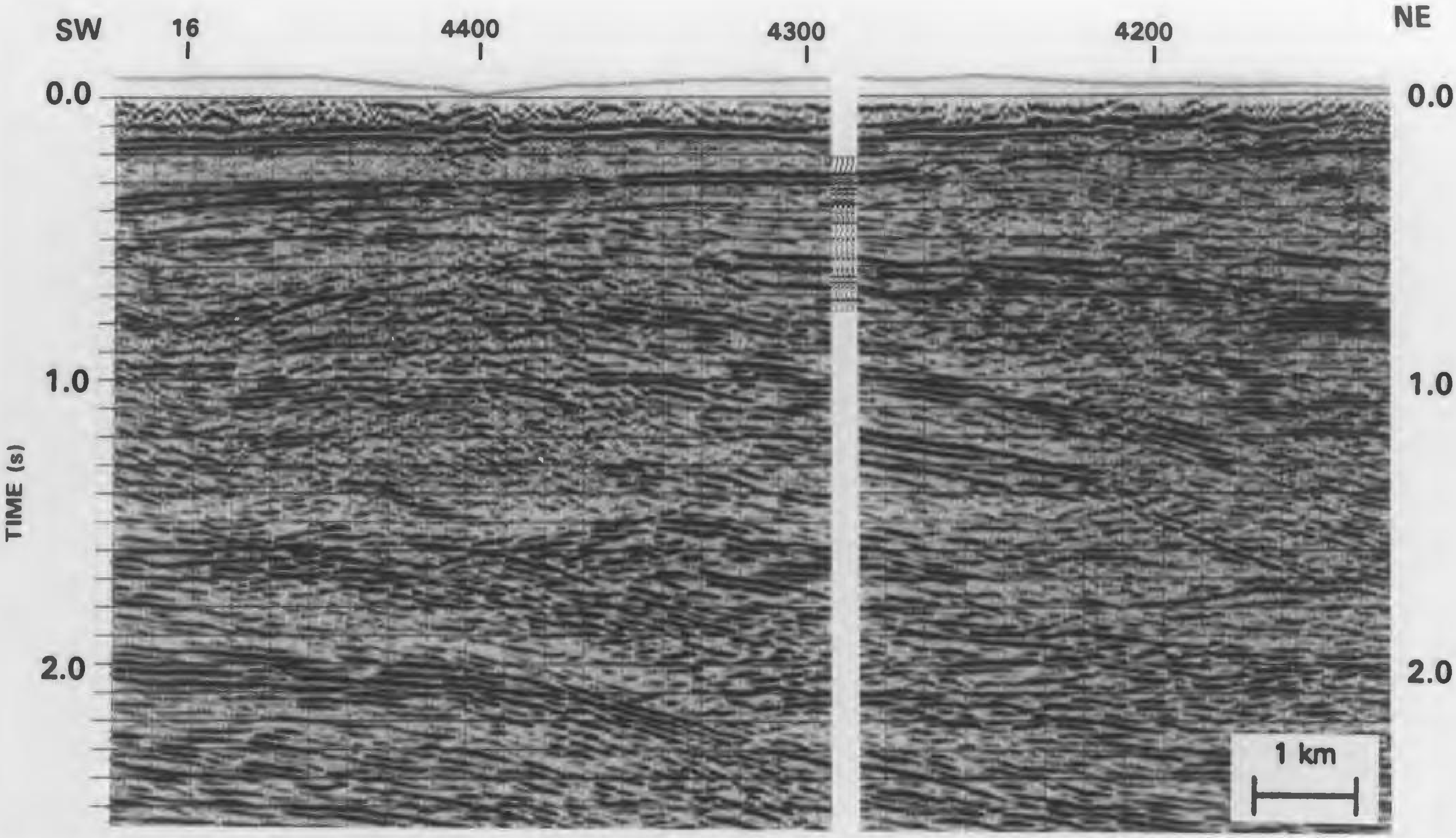


Plate 4-2(a) Seismic Line 60X (30 fold Vibroseis, coherency enhanced, migrated stack). See Figure 1-2 for line location.

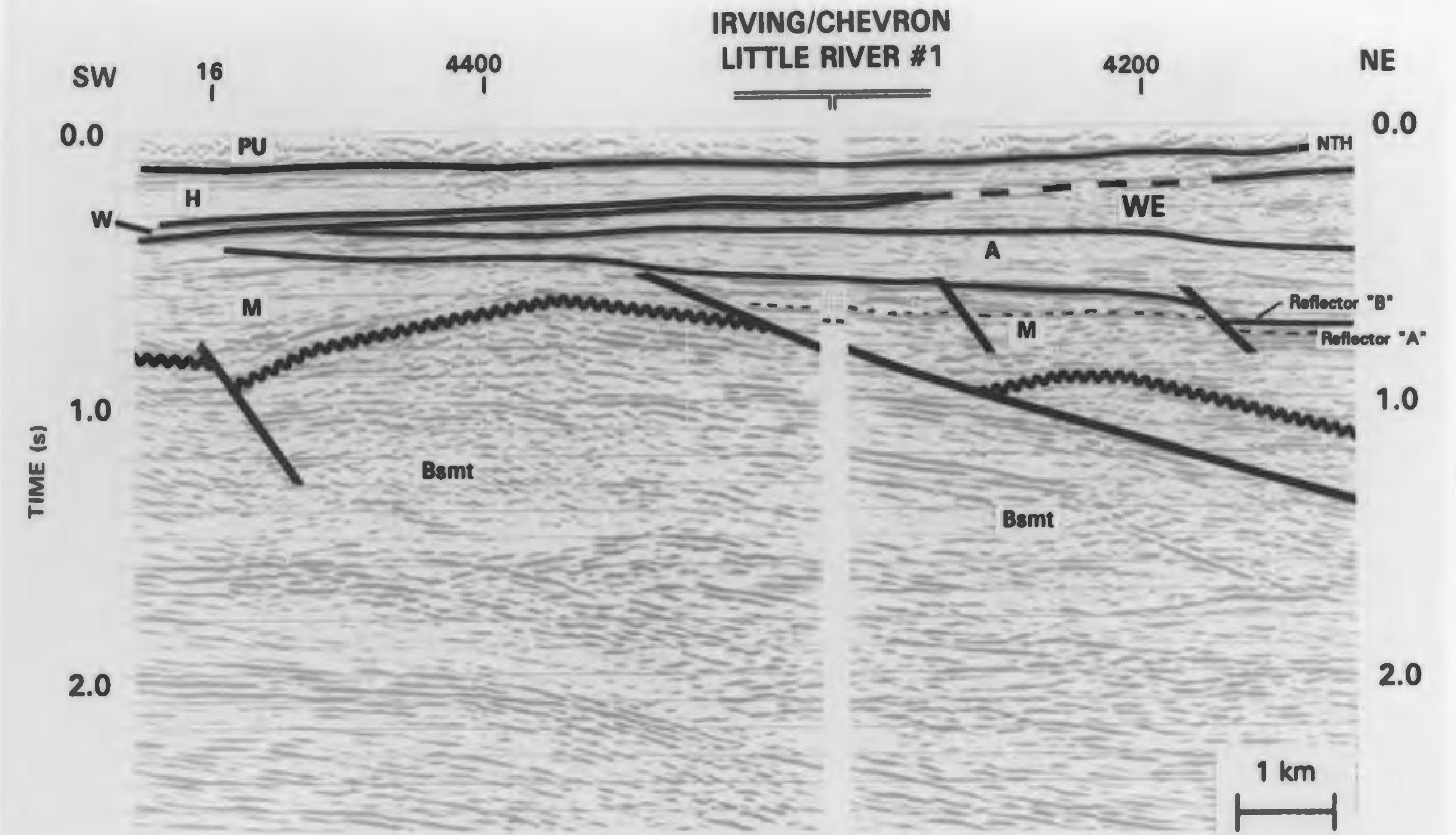


Plate 4-2(b) Seismic Line 60X (interpreted) showing borehole tie with synthetic seismogram at I/C Little River well (Plate A-11); M = Memramcook Fm.; A = Albert Fm.; WE = Weldon Fm.; W = Windsor Gp.; H = Hopewell Gp. ; PU = Boss Point Fm. and Pictou Gp. ; NTH = Near top Hopewell reflector.

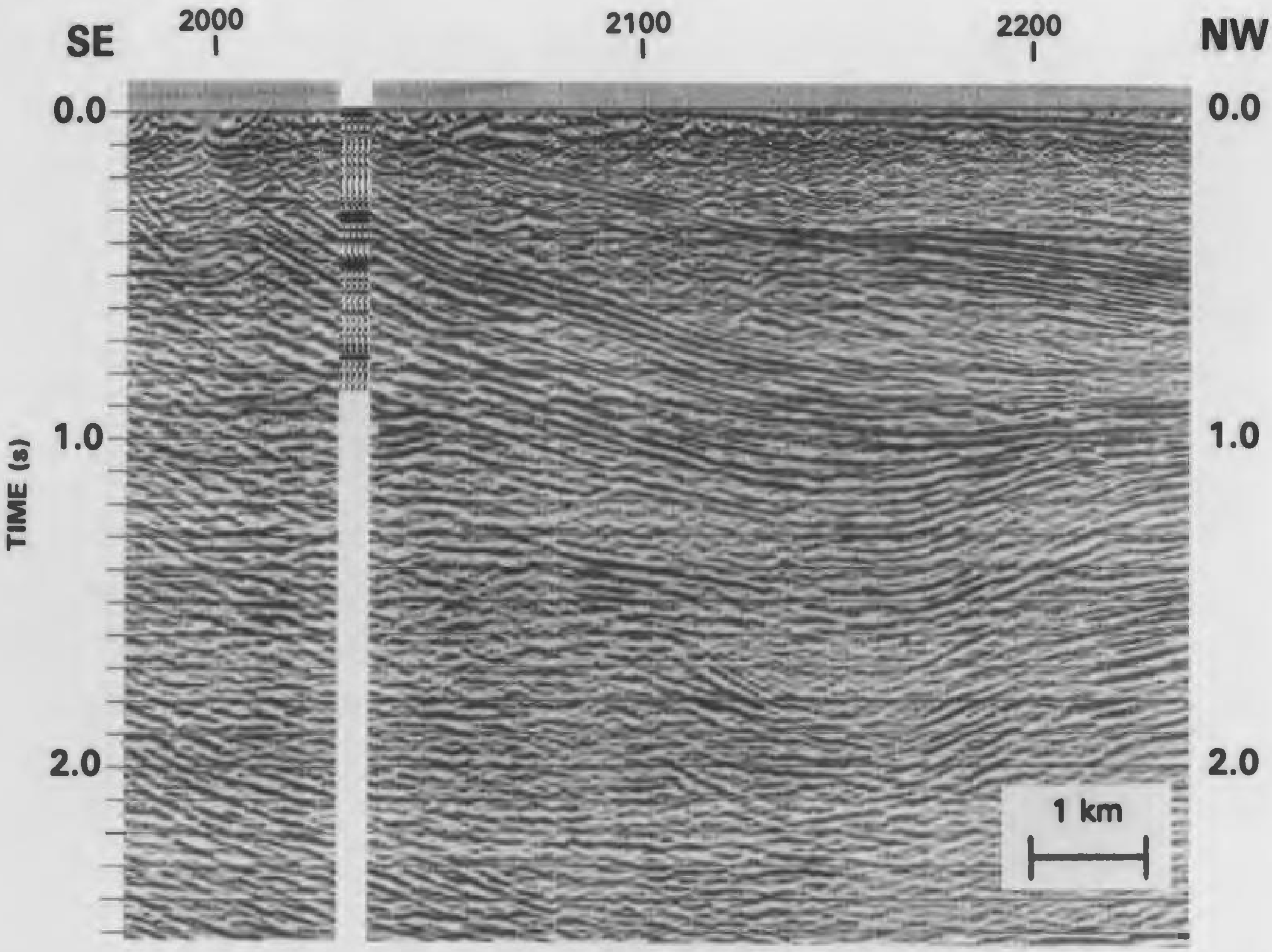


Plate 4-3(a) Seismic Line 13Y (30 fold Vibroseis, coherency enhanced, migrated stack). See Figure 1-2 for line location.

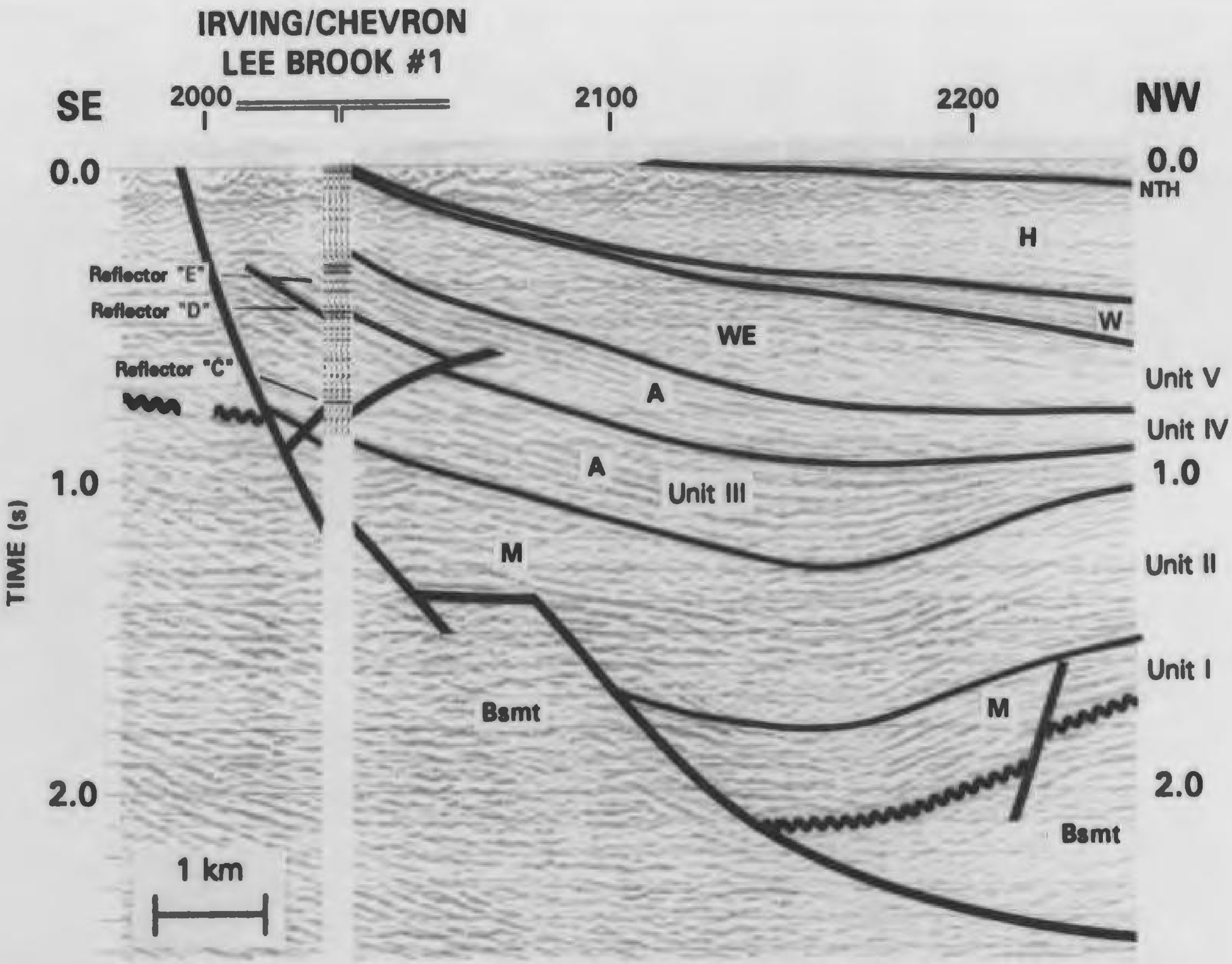


Plate 4-3(b) Seismic Line 13Y (interpreted) showing borehole tie with synthetic seismogram at I/C Lee Brook well (Plate A-8); M = Memramcook Fm.; A = Albert Fm.; WE = Weldon Fm.; W = Windsor Gp.; H = Hopewell Gp. ; NTH = Near top Hopewell reflector; Units I to V are seismic stratigraphic units discussed in the text; Reflectors "C","D" and "E" as shown in Figure 4-10, Plate A-8.

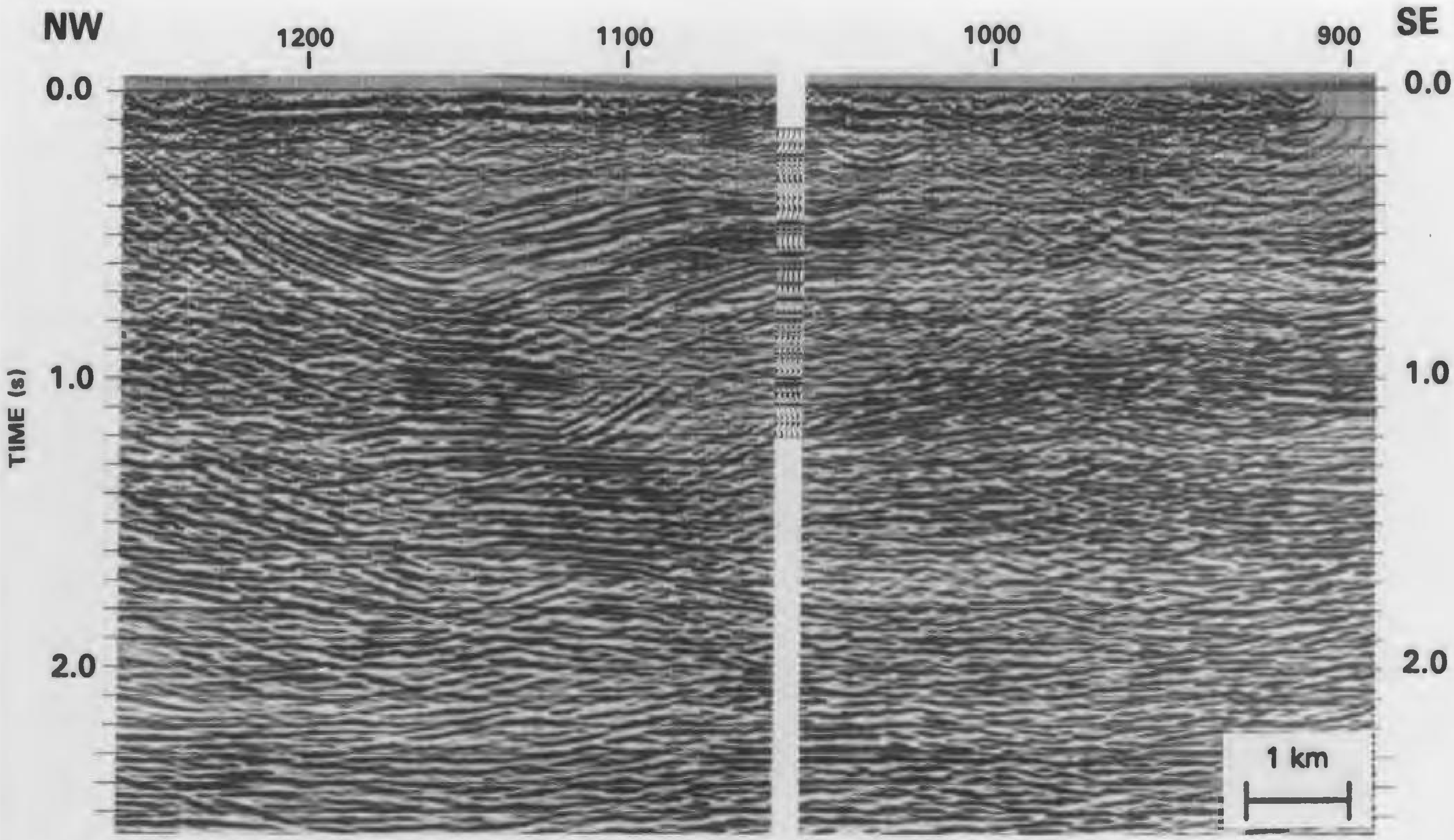


Plate 4-4(a) Seismic Line 66YA (30 fold Vibroseis, coherency enhanced, migrated stack). See Figure 1-2 for line location.

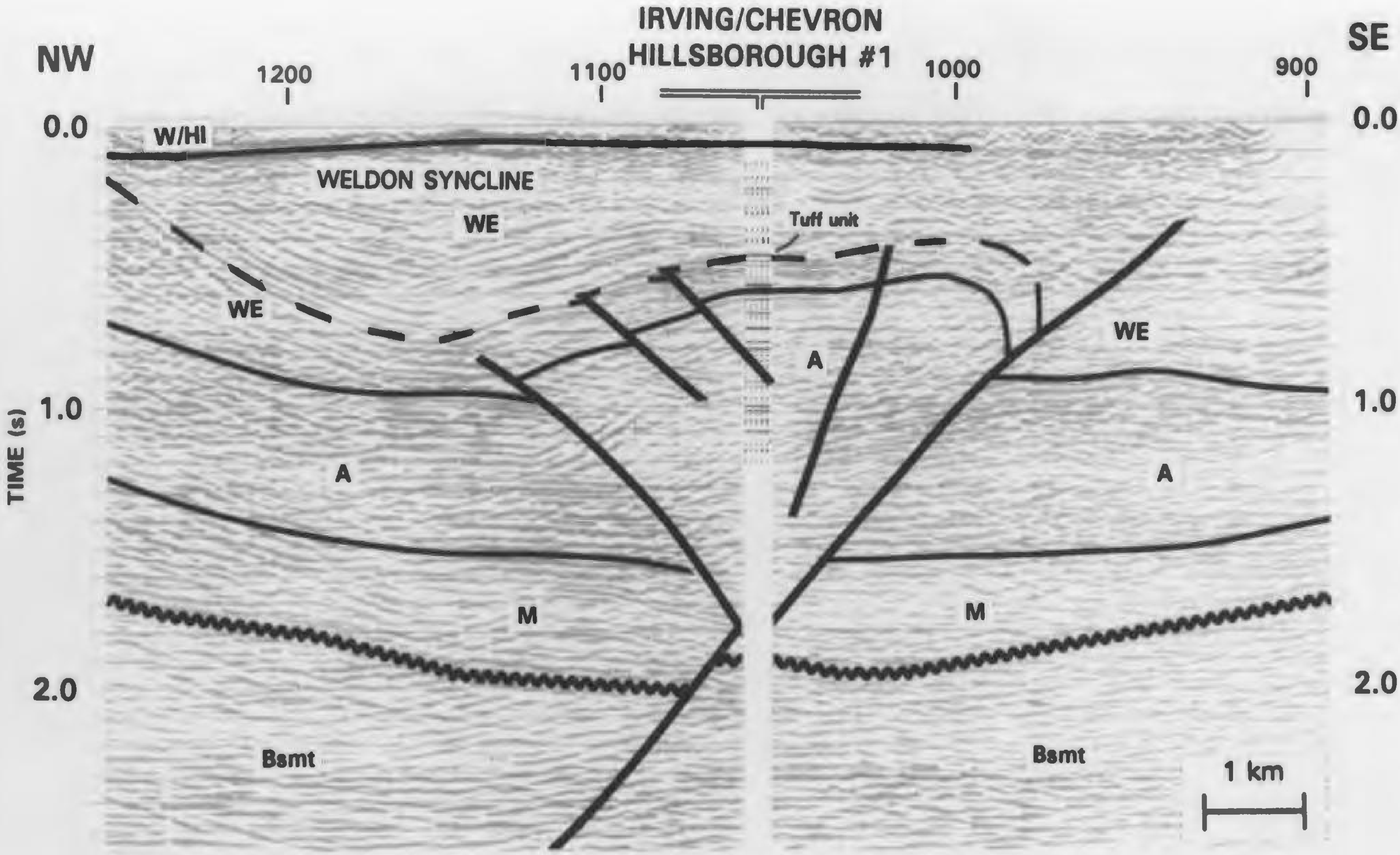


Plate 4-4(b) Seismic Line 66YA (interpreted) showing borehole tie with synthetic seismogram at I/C Hillsborough well (Plate A-10); M = Memramcook Fm.; A = Albert Fm.; WE = Weldon Fm.; W/HI = Windsor Gp. and/or Hillsborough Fm.

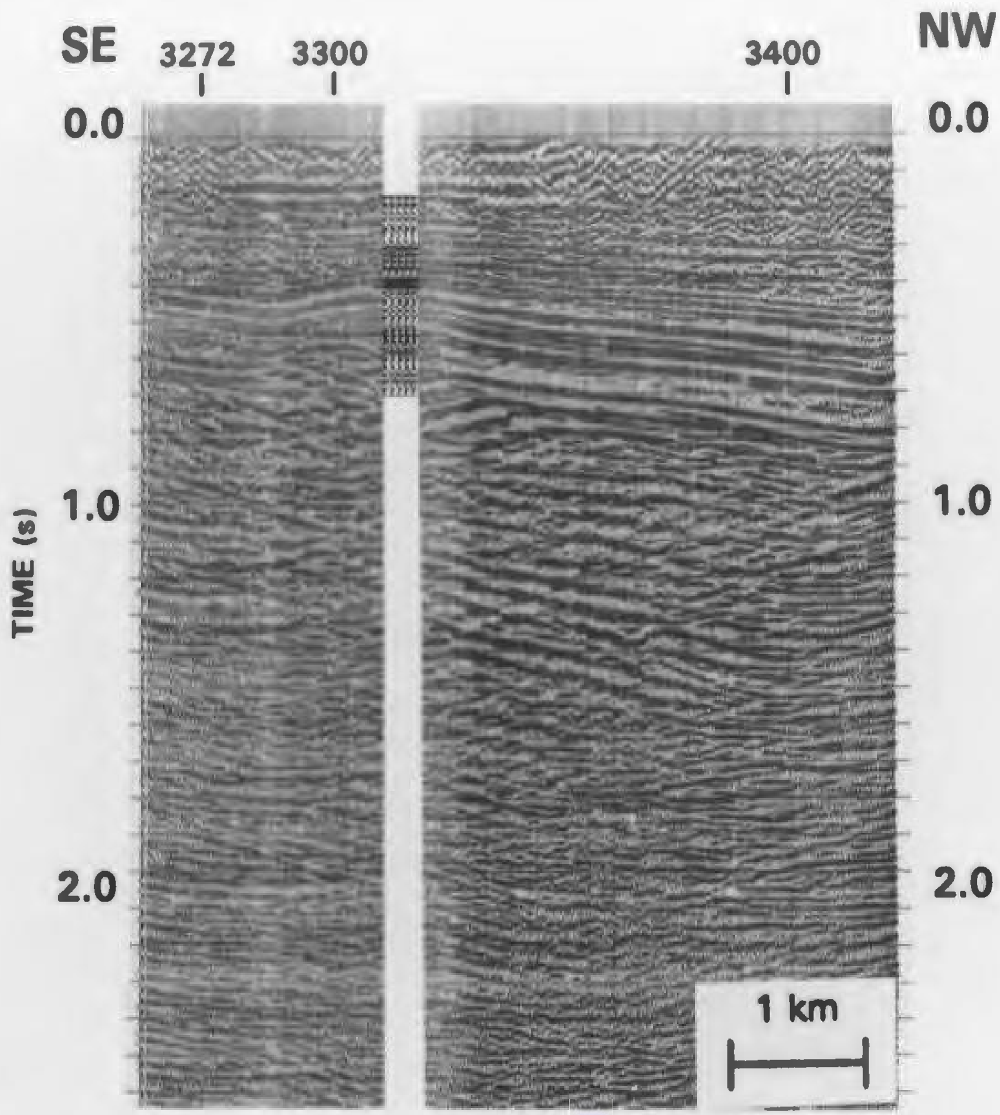


Plate 4-5(a) Seismic Line 1Y (20 fold Vibroseis, coherency enhanced, migrated stack). See Figure 1-2 for line location.

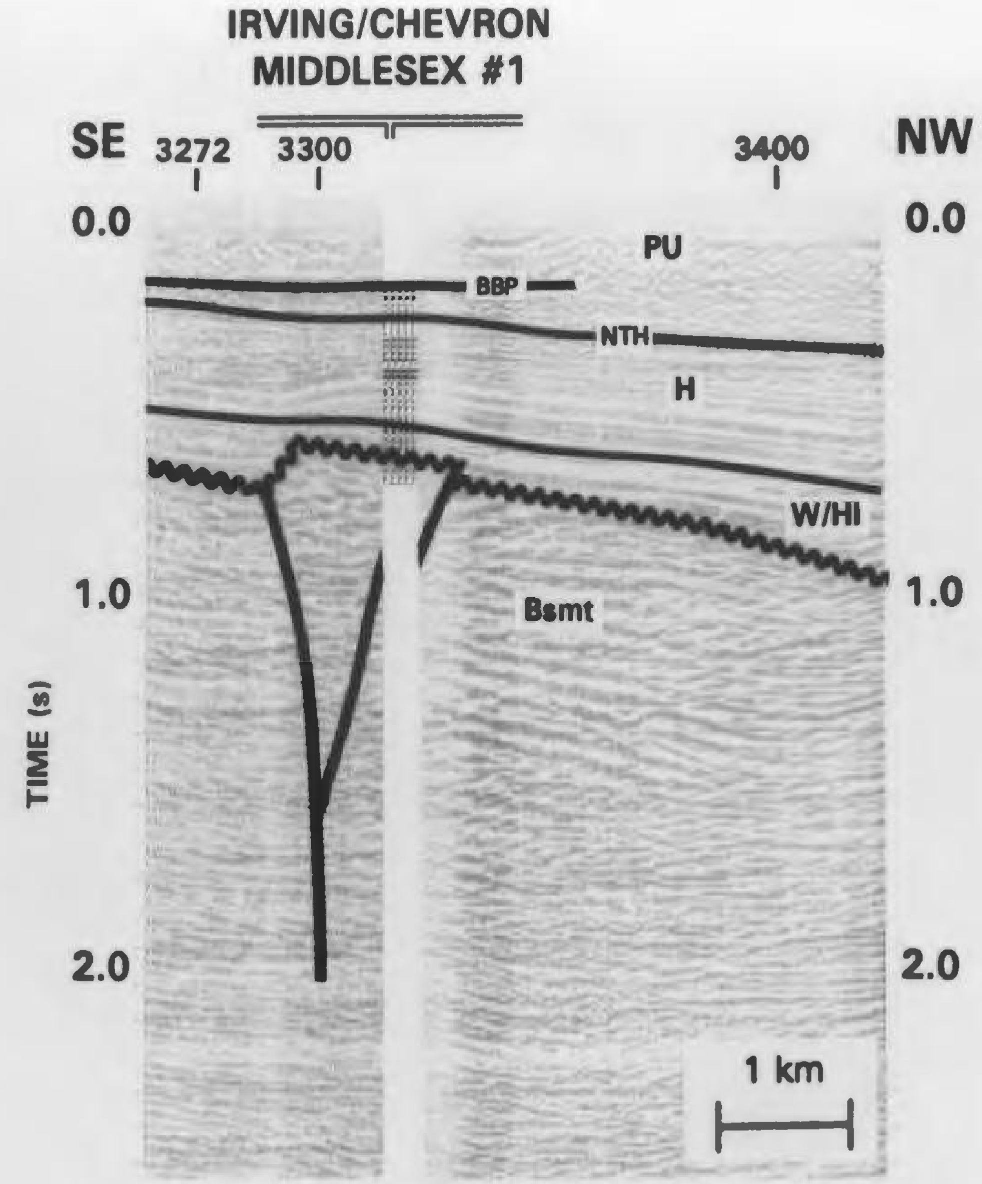


Plate 4-5(b) Seismic Line 1Y (interpreted) showing borehole tie with synthetic seismogram at I/C Middlesex well (Plate A-7); W/HI = Windsor Gp. and Hillsborough Formation; H = Hopewell Gp. ; PU = Boss Point Fm. and Pictou Gp. ; NTH = Near top Hopewell reflector; BBP = Base Boss Point reflector.

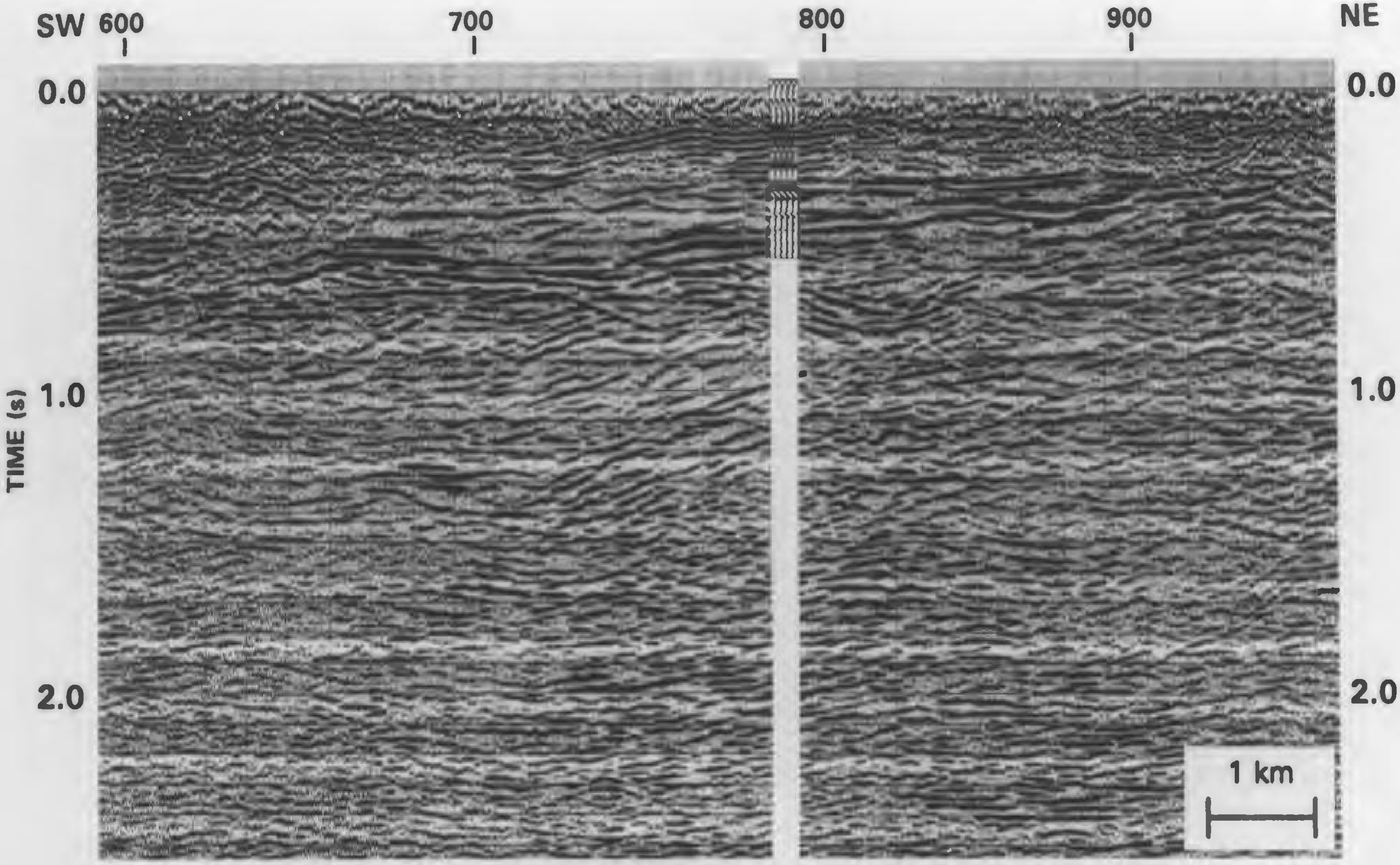


Plate 4-6(a) Seismic Line 31X, Stations 590-990 (12 fold Vibroseis, coherency enhanced, migrated stack). See Figure 1-2 for line location.

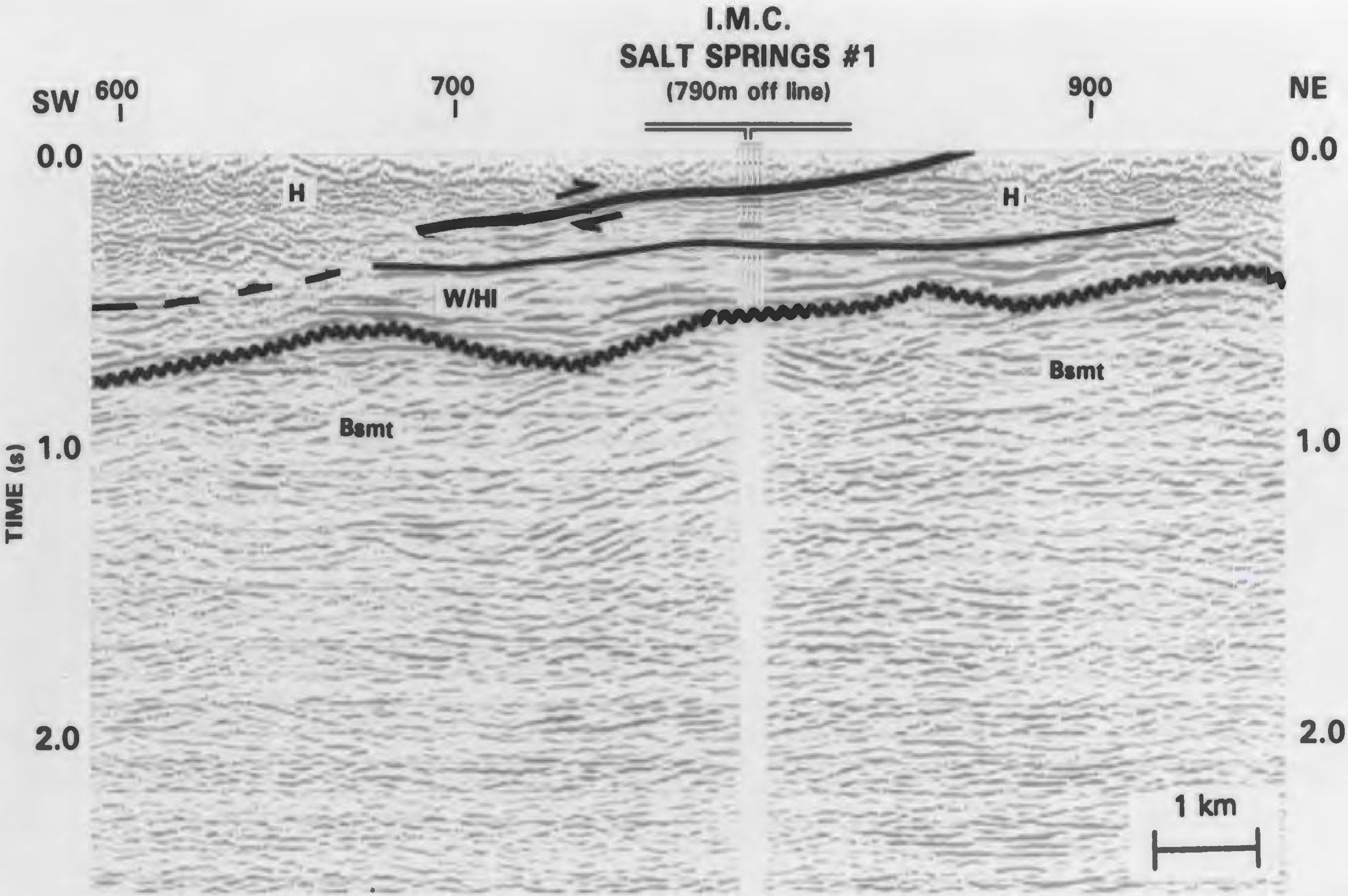


Plate 4-6(b) Seismic Line 31X, Stations 590-990 (interpreted) showing borehole tie with synthetic seismogram at IMC Salt Springs #1 well (Plate A-4); W/HI = Windsor Gp. and Hillsborough Fm.; H = Hopewell Gp. ; Bsmt = Pre-Carboniferous basement complex or possibly deformed Horton Group.

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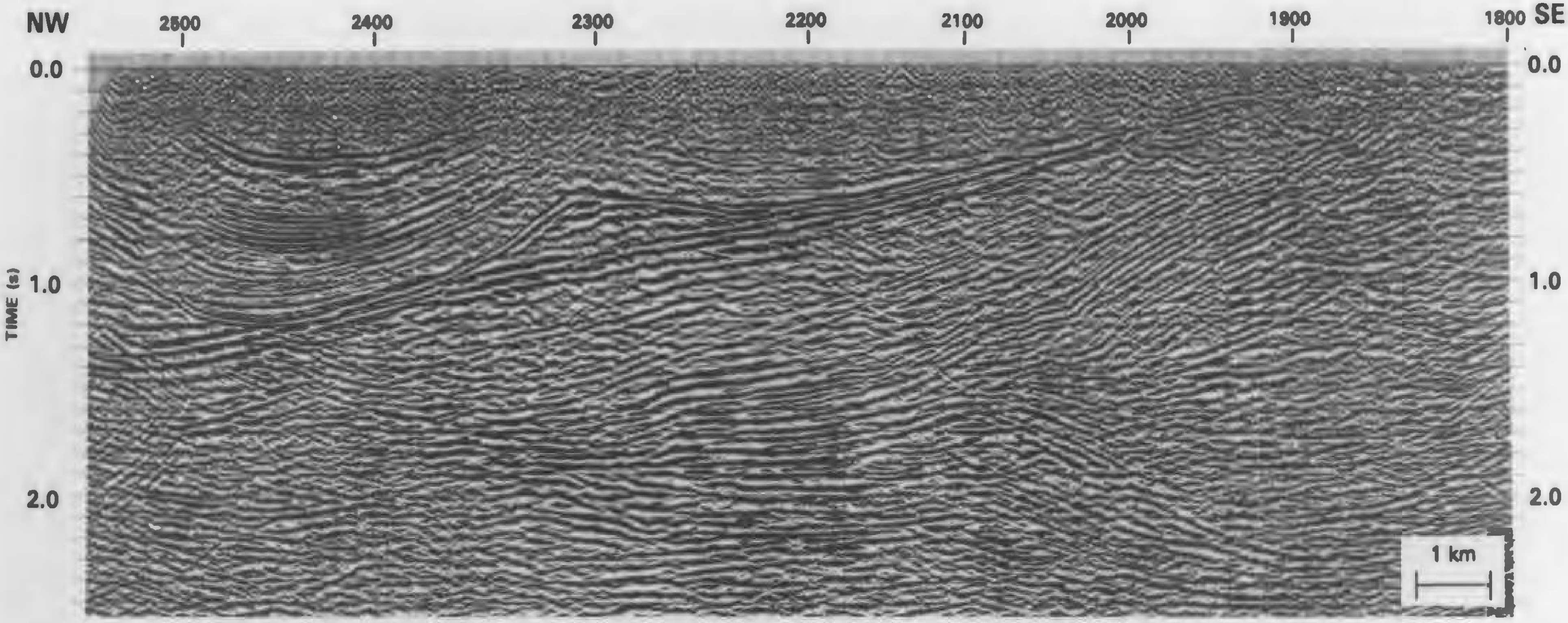

Plate 6-1(a) Seismic Line 29Y (12 fold Vibroseis, coherency enhanced, migrated stack). See Figure 1-2 for line location.

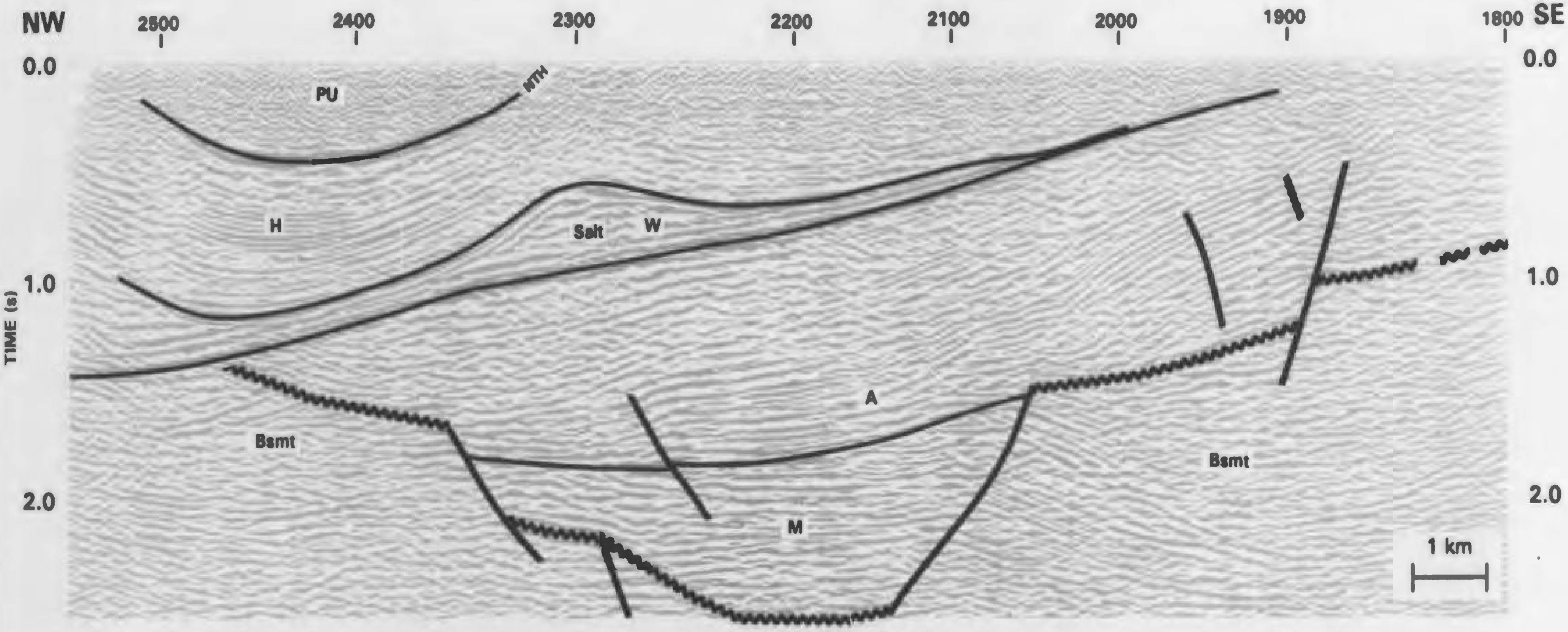

Plate 6-1(b) Seismic Line 29Y (interpreted) showing anticlinal feature (Station 2300) associated with salt flowage in basal Windsor Group. The same structure is mined for Potash at Penobsquis; Antiformal structure at northwest end of line coincides closely with surface trace of Kennebecasis-Berry Mills Fault; M = Memramcook Fm.; A = Albert Fm.; WE = Weldon Fm.; W = Windsor Gp.; H = Hopewell Gp. ; PU = Boss Point Fm. and Pictou Gp. ; NTH = Near top Hopewell reflector.

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Appendix A: Synthetic Seismograms

Synthetic seismograms are theoretical vertical incidence seismic traces generated from sonic and density logs at a borehole. Their primary application is to "tie" seismic reflection picks to known geologic tops where a seismic line passes near a borehole. Both the sonic and density logs for the borehole were digitized and an acoustic impedance (velocity x density) log calculated as a function of depth. The depth axis is then converted to time by integrating the velocity curve and, if no multiple reflection paths or transmission losses are to be accounted for, the seismogram is calculated as the convolution of the reflectivity series and the seismic wavelet. Of course the seismic wavelet is itself not known exactly, so a suite of wavelets with the appropriate amplitude spectrum and different phase spectra are generated and the wavelet which best matches the seismic record is chosen. Another important consideration in generating synthetics is calibration of the time axes (McQuillin et al., 1984). There are two aspects to this problem. The first consideration is matching the zero time on the synthetics and seismic records of the Irving Chevron data set. All seismic data in the Irving Chevron survey have a zero time which corresponds to a datum elevation of +50.0 m. As calculated, the synthetic seismograms are referenced the start depth of the logged interval, which may vary from 50 to 200 m below the rig's kelly bushing. Time corrections have been calculated (Table A-1) and applied to the synthetics so that time axes of the synthetic seismograms conform to the seismic datum. A second aspect of the timing problem is the question of accuracy in integrating the velocity depth curve to obtain travel times. Most wells had no velocity survey with which to constrain the time axis, but for those in which velocity surveys have been performed, the checkshot times can be used to constrain the time axis of the synthetic. For the two boreholes for which velocity surveys were available, integrated travel-times from velocity logs were compared with empirically measured travel times and found to be in agreement to within 15 m, the seismic resolution, at all depths.

Synthetic seismograms have been computed for all wells in the Moncton Subbasin for which sonic and density logs are available and which tie in to the Irving/Chevron seismic grid. Not all of these seismograms were displayed in Chapter 4 but the complete synthetic seismogram database is included here for the benefit of future users of the Irving/Chevron data set.

Synthetic seismograms presented below were produced using the VISTA software package version 6.5 (Seismic Image Software Inc., Calgary). All logs were digitized and edited by hand and tops taken as picked from the lithologic logs.

The vertical axis of the synthetic seismograms is two-way travel time as calculated from the integrated velocity-depth function of the log. No stretching of the logs to accommodate check shot (velocity survey) results, which were not generally available, has been done. Time on the seismogram axis corresponds to the start of the depth interval logged for sonic velocities; typically this is the base of the first cased interval in the borehole. The seismic data, on the other hand, has a datum chosen as 50 m above sea level as time zero. To account for the difference in datum and facilitate proper alignment of the synthetic and actual seismograms, a travel time correction Δt, must be added to the synthetic:

$$\Delta t = 2.0 \times (h_{datum} - h_{log}) / v_{replacement}$$

where Δt = time shift for start of seismogram

h_{datum} = elevation of seismic datum

h_{log} = elevation of start of logged interval

$v_{replacement}$ = average replacement velocity for rocks in the interval $(h_{datum} - h_{log})$

The values of h_{datum} and h_{log} are readily available but $v_{replacement}$ must be estimated and is chosen to be representative of the shallow bedrock velocity. The weathered surface layer has already been accounted for in the static corrections stage of the seismic data processing. In the Table A-1 below $v_{replacement}$ has been estimated from the sonic log for each hole as a representative velocity of the uppermost logged interval. For all but one of the thirteen wells density logs were also available. Two sets of synthetic seismograms were generated with and without the density logs. When sonic data only is available density is estimated using an empirical relationship between velocity and saturated bulk density determined by Gardner (Sheriff and Geldhart, 1982):

$$\text{density} = 0.23\ (\text{velocity})^{1/4}.$$

Gardner's rule is a good estimator for clastic rocks and limestones, but evaporites are well known to disobey this empirical rule. Nevertheless, the synthetics calculated from the sonic log provide in every case a better fit to the seismic data presumably due to the adverse effect of hole cave-in on the density logs. It is the sonic-only logs and reflectivities which are presented in this section.

Table A-1

Time Corrections for Synthetic Seismograms

BCN	WELL NAME	h_{datum}(m)	h^{A}_{log}(m)	h^{B}_{log}(m)	$v_{repl.}$(m/s)	Δt^{A}(ms)	Δt^{B}(ms)
37	I/C Smithtown 1	50.	-48.0	-55.0	3500.	56.	60.
41	KMG Urney 1	50.	89.6	-89.3	4200.	-19.	66.
52	PCA-22 (E-4A)	50.	-27.4	-30.5	3000.	52.	54.
56	IMC Salt Springs 1	50.	131.7	131.7	4700.	-35.	-35.
60	IMC Salt Springs 5	50.	46.3	46.3	3500.	2.	2.
132	PCA-23 (M-4A)	50.	-37.5	-37.5	3000.	58.	58.
146	I/C Middlesex 1	50.	-329.0	-329.0	4000.	190.	190.
147	I/C Lee Brook 1	50.	89.0	89.0	3200.	-24.	-24.
332	E. Stoney Ck. 1	50.	-134.0	-134.0	3600.	102.	102.
333	I/C Hillsborough 1	50.	-264.0	-329.0	4100.	153.	185.
334	I/C Little R. 1	50.	-227.0	-227.0	4700.	118.	118.
350	Can. Oxy. 81-8	50.	-80.0	-80.0	3500.	74.	74.
NC*	Denison 2	50.	-75.0		4000.	62.	25.

*NC - Not Catalogued

Superscript A refers to sonic-only seismograms

Superscript B refers to sonic plus density seismograms

Appendix B: Thin- versus Thick-bed Reflections

In understanding the paradoxical observation that reflections caused by the interference of thin layers are the most continuous and constant in waveform of all refections in the non-marine section I review the concept of thin- versus thick-bed resolution (Sheriff, 1985). The seismic response of a layer or package of layers whose total thickness is less than a quarter of the seismic wavelength is very different from one which is thicker. Widess (1973) convolved two spikes of equal and opposite magnitude, representing the reflection coefficient of the top and base of a reflective unit, with a symmetrical seismic wavelet and found that separate distinguishable reflections resulted where the spikes were separated by more than a half wavelength; that the two reflections began to interfere constructively as the separation approached a quarter wavelength producing an increase in reflection amplitude ("tuning"); amplitude decreased and the waveform became distorted as the separation approached an eighth wavelength; and for still thinner beds the waveform stabilized, approximating the derivative of the seismic wavelet, and decreased in amplitude as the spike separation decreased. One quarter wavelength then, is the bed thickness dividing two types of seismic behaviour. If beds are thicker than one-quarter wavelength, individual reflections can be discerned. If they are thinner, individual reflections are not, only amplitude variations are observed. Furthermore, empirical studies (Sheriff, 1985) show that a reflection does not carry information about the distribution of reflections within the thin bed if that thin bed is further subdivided. A package of reflectors which is less than a quarter wavelength thick gives almost the same refection signature regardless of how the component layers are arranged.

A typical value for the quarter wavelength in the Chevron data set would be

$$\lambda/4 = .25 * (4 \text{ km/s}) / (30 \text{ Hz}) = 30 \text{ m} .$$

The quarter wavelength criterion suggests that sedimentary processes which give rise to units of that thickness will be those represented in the seismic data. In the facies architecture terminology of Miall (1988), these would be units separated by bounding surfaces of rank 5 or 6 and internal (lower rank) bounding surfaces are not likely to be significant contributors to the coherent seismic signal.

Appendix C: Cross-section Balancing

An interpreted seismic depth section is a deformed state cross-section which represents the end result of one or more episodes of fault-driven subsidence and later folding, faulting and erosion of the basin-fill. Although it is not generally possible to deduce uniquely the kinematic history of faulting and folding from the rocks' final geometry, the interpreted seismic section contains implicit information about the structural and stratigraphic evolution of the subbasin. It has become preferred practice in structural geology for authors to confirm the geological feasibility of their interpretations of deformed cross-sections by demonstrating they can be produced from a reasonable undeformed section by a mechanically viable deformation path; a process referred to as "cross-section balancing". Originally section balancing was used only by structural geologists working in thrust belts (Dahlstrom, 1969; Boyer and Elliot, 1982) but the same general principles can be applied to constrain interpretations in extensional terranes (Gibbs, 1983) and software is now available (Rowan and Kligfield, 1986; Dentith et al., 1990) to substantially automate the process of balancing seismic interpretations of deformed sections. In extension, rocks of the hanging wall of a normal fault deform in a predictable way as they are displaced by a fault of known geometry. But still the process involves one key assumption: that the deformation is "plane strain", i.e. all displacement vectors are confined to the plane of section. No movement of mass is allowed into, or out of, the plane of section because the balancing technique is two-dimensional. Cross-section balancing cannot be considered valid for cross-sections where there is a significant component of oblique slip or strike-slip motion. Several other assumptions must be made, which can be controlled by making informed choices of model parameters. These assumptions include: choosing an appropriate model for hanging-wall deformation; accounting for sediment compaction; and converting seismic data from time to depth. Each is briefly discussed below.

Mathematical models simulating the kinematics of hanging wall deformation have been presented by several authors. These include: models in which the hanging wall shears like a deck of cards along vertical shear planes (Gibbs, 1983); ones in which the shear planes are inclined to simulate small scale antithetic faulting (White et al., 1986); methods which simulate rigid block rotation (Moretti and Colletta, 1988); and those which simulate flexural slip along bedding planes (Davison, 1986; Suppe, 1983). Each method yields slightly different retrodeformed sections and fault plane predictions from a given hanging wall geometry (Rowan and Kligfield, 1986; Dentith and Hall, 1990). One must select that algorithm which best approximates the perceived deformation mechanism in effect.

Compaction and decompaction of sediments can account for a volume change exceeding 40 percent in sediments as their porosity decreases and pore fluids are expelled with increasing depth of burial. This effect contributes significantly to the finite strain in extensional basins (Gibbs, 1983) and also contributes to the downward flattening of faults in the sedimentary section (Xiao and Suppe, 1989). It is necessary to account for this compaction by increasing sediment volume as the section is retrodeformed. Sclater and Christie (1981) recommend this be done by setting up a porosity vs depth curve based on well data in the area and adjusting the thickness of geologic units accordingly as they are restored to their former depths. But the porosity/depth relationship does not represent the effect of compaction alone. Cementation also decreases porosity and the relative contribution of cementation and compaction on porosity are little studied, but certainly depend upon the diagenetic history of the rocks. Lundegard (1992) notes that compaction is probably the dominant mechanism in sandstone porosity loss in general, but to assume it is the only factor will result in an overestimation of the amount of compaction for a given set of porosity observations. Present day porosity measurements from Horton Group rocks in southern New Brunswick reflect mainly diagenetic effects and are not useful in compaction estimates, so published values from other areas must be used.

The MUNSEC4 software package used in this study implements the empirical porosity-depth rule of Athy (1930) which relates porosity P at depth z to a surface value P_0 and a decay constant z

$$P = P_0 e^{-bz} .$$

In the absence of local compaction data and under the assumption that the conglomerates will be volumetrically insignificant compared to sandstones over the Horton interval, I have used the average parameters for sandstones from the North Sea, published by Sclater and Christie (1980):

$$P_0 = .63$$

$$z = .27.$$

Since cross-section balancing should be performed on depth sections, the migrated time sections in the form of an interpreted line drawing must be converted to depth using an appropriate earth velocity-depth function. Wherever possible velocity data from a nearby well was used for this purpose.

Name: (037) Irving Chevron Smithtown #1

Seismic ties: Line 31X Stn. 180 (offset approximately 400m N)
Line 28X Stn. 109 (offset approximately 600m E)

Borehole Locn:	45.4851N, 65.7823W	Elev of K.B.:	44.6
Start Depth:	100.0	Ground Elev.	40.9
End Depth:	947.0	Depth Sample Interval (m)	2.5
Total Depth:	950.0	Time Sample Interval (ms)	4
Date Completed:	02 Mar 80		

Depth (From KB)	Formation Name	Log time (ms)	Seis. Time (ms)
0	Spudded in Granite Basement		-
93	START OF LOG	0	56
415	Top Hopewell	160	216
950	END OF LOG	384	440