STRUCTURE, STRATIGRAPHY, AND GEOCHEMISTRY OF THE UPPER ORDOVICIAN LAWRENCE HARBOUR FORMATION, EXPLOITS SUBZONE, NEWFOUNDLAND

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Structure, Stratigraphy, and Geochemistry of the Upper Ordovician Lawrence Harbour Formation, Exploits Subzone, Newfoundland

By

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Abstract

The Upper Ordovician Lawrence Harbour Formation is a significant lithostratigraphic and biostratigraphic marker horizon found throughout the Exploits Subzone. In the Grand Falls-Windsor-Badger region the Lawrence Harbour Formation grades from graptolitic siliceous black shale, to dark grey silty shale, and light grey silty shale, from base to top respectively. It conformably overlies grey bioturbated chert and is itself conformably overlain by sandstone and siltstone turbidites of the Point Leamington Formation. The gradational coarsening upward characteristics and transition into overlying units suggest that the Lawrence Harbour Formation should be included within the Badger Group.

Geochemical and lithological variation is documented vertically through the formation and appears to be related to increasing grainsize from base to top of the shales. The Lawrence Harbour Formation and inferred equivalents sampled from Notre Dame Bay to Bay D'Espoir, show no marked lateral variation in geochemistry. These trends support a coarsening upward sequence for the shales, and appear to support a model of deposition within a single interconnected basin for the Lawrence Harbour Formation. Geochemical signatures of the shales suggest a calc-alkaline source terrane, with deposition probably occurring in a back arc basin as hemipelagic distal turbidite sediments.

Regional mapping has defined a grey bioturbated chert unit at least 10 to 15 metres thick that conformably underlies the Lawrence Harbour Formation. The upper gradational contact defined within the study area comprises about 2 metres of chert with interbeds of siliceous black shale that yields graptolites of the *N. gracilis* Zone. The chert unit has been used as a reliable marker horizon both in this study and in previous work, and as a result is herein elevated to formation status with the name "Northern Arm Formation".

Extensive polyphase deformation of these Upper Ordovician units commonly produces complex regional outcrop patterns. Detailed outcrop-scale structural maps define reverse faults(D_3) that cross cut limbs of open to close folds(D_2). Regional penetrative cleavage is observed as axial planar to the F_2-folds. These structures were followed by a later stage of deformation that steepened the thrust faults, with a component of strike slip faulting with both sinistral and dextral sense along already formed D_3 thrust faults. Observations on a

macroscopic scale define several fault-bound belts that strike northeast-southwest and cross cut southeast facing F_2 regional folds. In all, a total of six phases of deformation are recognized with D_0-D_4 being regional, and D_5 being identified as localised in extent. The D_2 and D_3 deformation events are likely due to the continued compression related to the Salinic and Acadian orogenies.

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Chapter 1

Introduction

1.1 Objectives

Black shales of the Upper Ordovician Lawrence Harbour Formation and equivalents have played an important role in studies of central Newfoundland over the past century, including graptolite biostratigraphy, regional mapping, and sulfide mineralization. The aim of the present project is to clarify the geology of the Lawrence Harbour Formation through integration of detailed structural mapping, XRF, and ICP-MS trace-element geochemistry, and minor sedimentological aspects involving scanning electron microscope (SEM) analyses of shale samples.

One of the primary objectives of the project was to construct detailed outcrop (mesoscopic) maps of key localities where exposure is ideal and stratigraphy relatively intact. The aim was to combine these results with regional (macroscopic) observations in order to produce a revised structural interpretation, and a 1:50 000 scale map.

Several other Ordovician formations elswhere in the Exploits Subzone consist of black shales with similar biostratigraphic affinities to those of the Lawrence Harbour Formation. The second primary objective of the project was to conduct representative sampling of these other Caradoc shale units for further geochemical analyses. If it was determined that geochemical signatures of the Lawrence Harbour Formation were unique, then a basis for future analyses of deformed black shale units of unknown affinity would be created, aiding correlations with the Lawrence Harbour Formation. This was achieved through XRF and ICP-MS trace element analyses in an attempt to fingerprint the shales both vertically and laterally.

The transition between the Lawrence Harbour Formation and overlying Point Leamington Formation has been well documented in several previous studies (e.g., Bergström et al., 1974; Pickering, 1987a; S.H. Williams, 1991b). The lower transition, marked by the apparent gradation from underlying volcanics, turbidites and red cherts through grey bioturbated chert into siliceous black shale, has never been critically studied, nor has the sedimentology of the Lawrence Harbour Formation itself. Description of the basal chert-shale contact is discussed based on observations made over the course of 1996-1997 field seasons. Scanning electron microscope (SEM) analyses of shale samples, ranging from basal contact upwards into silty shales found within lowermost Point Leamington Formation, were conducted to define lithological variation observed vertically through the Lawrence Harbour Formation.

1.2 Previous Work

The first results of geological investigation's in insular Newfoundland were published in 1843 when J.B. Jukes published a geological map of Newfoundland. This was followed by the impressive regional and reconnaissance geological mapping of Alexander Murray in the 1860's through early 1880's. Murray, teaming up with Howley in 1881, produced the earliest recorded work on Upper Ordovician black shales of central

Newfoundland when they mapped and collected fossils from shale outcrops along the Exploits River. Sampson (1923) followed this by recognising a persistent black graptolitic shale of 'Llandeilo' age, thereby providing the first reference to these shales as a possible marker horizon. With discovery of mineralization associated with volcanic rocks in of central Newfoundland, geological mapping of the central volcanic belt by Snelgrove (1928) produced some of the first regional maps of the South Coast and Red Indian Lake areas. This was followed by Heyl (1936), working in Notre Dame Bay, who assigned some of Sampson's (1923) black graptolitic strata to the Lawrence Harbour Shale.

With advancing interpretations, workers such as McLean (1947), Baird (1953), and Kay and Williams (1963) began to view geological relationships in central Newfoundland as a result of stratigraphic repetition due to thrust faults that were later steepened. At about this time H. Williams (1962) described the first complete fossiliferous sequence in Notre Dame Bay involving Ordovician volcanic rocks, middle Ordovician limestone, graptolitic black shale and argillite, an upper Ordovician to lower Silurian greywacke sequence, and a lower Silurian conglomerate. These earlier works focused mostly on regional mapping and mineralization, with only occasional assignment of formational status given to individual units. Breaking this earlier trend, however, Helwig (1967, 1969) redefined the Exploits Group as seven distinct formations, which included Heyl's (1936) Lawrence Harbour Shale. Although the name was retained Helwig did, however, change the definition of the Lawrence Harbour Shale, and assigned it to the lowermost Caradoc. This left younger Caradoc shales to be referred to as "unnamed argillites". Other workers who identified similar Caradoc shales elected to provide alternative names, illustrating an uncertainty in the proposed correlation. For example in work involving the Dunnage Formation (melange?), Horne (1968) identified a unit of slaty argillite of Caradoc age that he assigned to the newly named Dark Hole Formation.

By the early 1970's, ideas on ocean closure sequences and island arc volcanic terranes were being applied to central Newfoundland. Bird, Dewey, and Kidd (1971) suggested that Newfoundland ophiolite complexes were related to the closure of a proto-Atlantic ocean, and that closure occurred in pre-Ordovician times. Dean (1978) applied an island arc model with subaqueous Arenig to lower Caradoc volcanism for central Newfoundland volcanic terranes. Dean (1978) also elaborates on a Caradoc transgression where "..island arcs sank to abyssal depths.." as marked by cherts and shales that overlie the volcanic rocks. This major transgression is marked by a global anoxic event that initialised onset of black shale deposition; it is correlated with the upper *N. gracilis* graptolite zone (Ross and Ross, 1992; Heredia and Beresi, 1995).

The majority of regional-scale (1:50,000) mapping involving the Lawrence Harbour Formation was conducted during the early 1980's by Kean and Jayasinghe, and more recently by S.H. Williams (1991a, 1995), Dixon (1994), S.H. Williams and O'Brien (1994), and H. Williams (1995a). Kean and Jayasinghe's (1982) project involved the mapping of several units including black shale outcropping throughout the Badger-Grand

Falls-Windsor-Millertown area. Due to the lack of exposure in central Newfoundland, the extent of the Lawrence Harbour Formation was identified mainly by extensive linear conductors as defined by airborne electromagnetic (EM) anomalies. The shale, and other units in the region, were interpreted as being folded (N-NE, E-W trending) by the folds cut by major NE trending faults (Kean and Jayasinghe, 1982). Other workers in the late 1980's and early 1990's focussed on more in-depth studies involving tectonics and paleodepositional settings (Colman-Sadd et al., 1992b; H. Williams et al., 1996). H. Williams et al. (1988), for example, subdivided the Dunnage Zone into the Notre Dame and Exploits subzones based on regional geology, geochemistry, and geophysics. Swinden et al. (1988) expanded geochemical interpretations and suggested that the volcanic rocks within the Dunnage Zone were part of an arc/back arc sequence that formed in separate parts of a closing Iapetus ocean.

In more recent times, the shales have been examined in greater detail in terms of structure, although complete structural mapping has yet to be carried out. O'Brien (1993) interpreted structures of the Shoal Arm and Lawrence Harbour formations north of the study area as folds, thrusts, and folded thrusts, applying a thrust fault model to the Upper Ordovician shales. Further work by Williams and O'Brien (1994) demonstrated that stratgraphically older strata (*C. bicornis* zone) structurally overlie younger rocks of the *D. clingani* zone in the central Notre Dame Bay region. Recent work by S.H. Williams (1991a) and S.H. Williams et al. (1992) in the Baie D'Espoir region may suggest that these structural implications can be extended to southern-most portions of Newfoundland.

1.3 Geological Setting: Newfoundland

At a continental scale, the Appalachian orogeny is preserved within a 100 to 1000 kilometre wide belt situated along the eastern coast of North America. It was formed during early to mid-Paleozoic deformation associated with closure of the Iapetus Ocean. This orogenic belt extends through the island of Newfoundland creating distinct tectonostratigraphic zones which consist of telescoped continental margins, island arc terranes, and ocean closure sequences. The Appalachian orogen can be traced into northwestern Europe where it is known as the Caledonian orogen.

On a regional scale, insular Newfoundland is geologically divided into several distinct tectonostratigraphic zones. From west to east, they are the Humber, Dunnage, Gander, and Avalon zones (Figure 1.1). The Humber Zone is part of the late Proterozoic to early Paleozoic northern (Laurentian) margin of the Iapetus Ocean. The Dunnage Zone is a composite of oceanic terranes taken to represent vestiges of the Iapetus Ocean. The Gander and Avalon zones are both terranes that are thought to have originated on the Gondwanan side of the Iapetus Ocean (H.Williams, 1995a). The Dunnage Zone of central Newfoundland is further subdivided into the Notre Dame and Exploits subzones (figure 1.1). The Exploits Subzone consists mostly of Ordovician volcanic, subvolcanic, and epiclastic rocks that are conformably and uncomformably overlain by a sequence of late Ordovician to Silurian marine, shallow marine, and subaerial sedimentary rocks (Colman-Sadd et al., 1992b). The Dunnage Zone is considered to

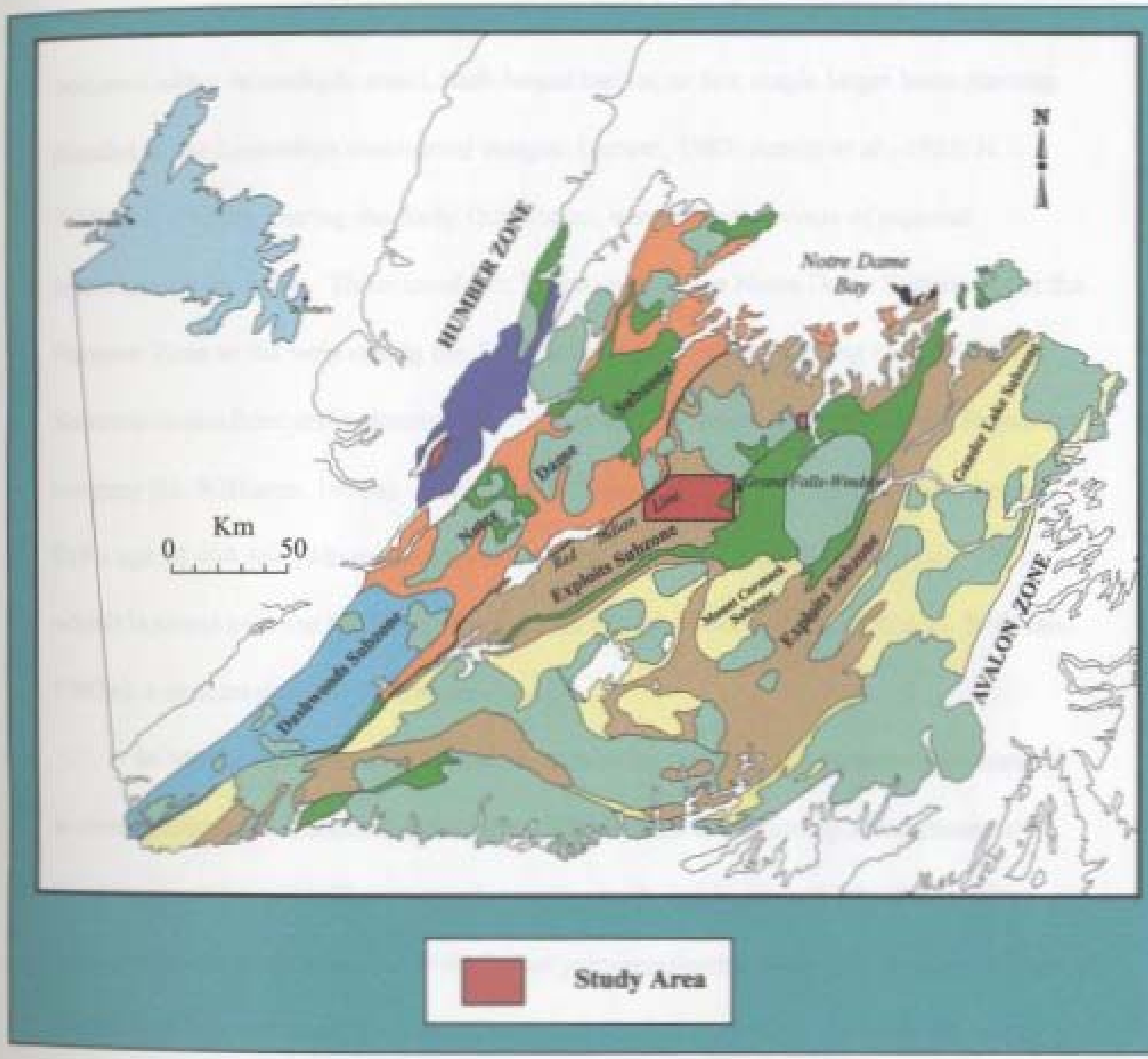


Figure 1.1: Regional geological terranes and location map indicating study areas as transparent red blocks (After H. Williams, 1995a).

have formed within an arc accretion and ocean closure environment. During the Cambrian to Early Ordovician, volcanism and deposition of marine clastic sediments occurred either in multiple small, fault-bound basins, or in a single larger basin running parallel to the Laurentian continental margin (Arnott, 1983; Arnott et al., 1985; H. Williams, 1995b). During the Early Ordovician, two orogenic events of regional importance took place. These involved: 1)Transport of the Notre Dame Subzone over the Humber Zone to the west during the Taconic orogeny; and 2) thrusting of the Exploits Subzone ocean floor and volcaniclastic rocks over the Gander Zone during the Penobscot orogeny (H. Williams, 1995a). Timing of the Penobscot orogeny is constrained by a U/Pb age of 494 +/- 2 Ma on the Pipestone Pond ophiolite (Colman-Sadd et al., 1992a), which is thrust over the Mt. Cormack Subzone (Colman-Sadd et al., 1992a; H. Williams, 1995a), a structural outlier of Gander Zone.

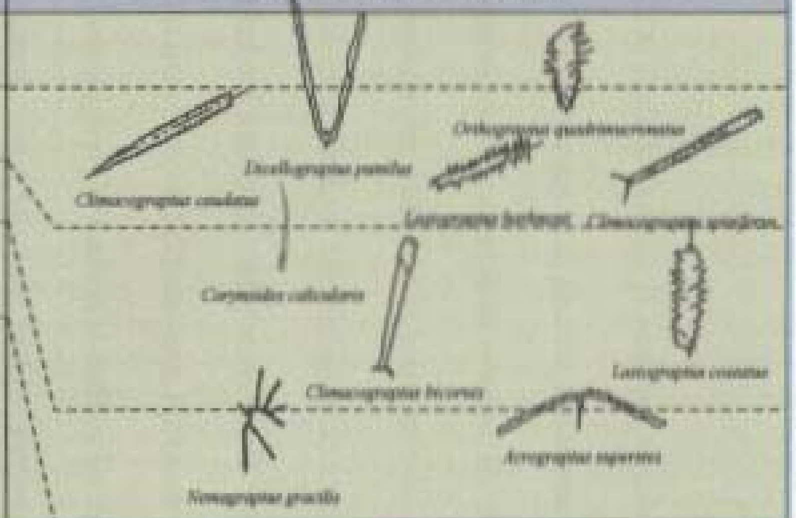
In Middle to Upper Ordovician times, volcanism ceased and rapid subsidence of accreting island arcs occurred (Pickering, 1987b). This is marked by the appearance of deep marine microcrystalline cherts that conformably grade upward into shales of the Lawrence Harbour Formation. With further juxtapositioning of suspect terranes within the closing Iapetus Ocean, the Notre Dame and Exploits subzones became positioned together along a structural lineament known as the Red Indian Line. The evidence suggests that the earliest interaction between the two Dunnage components was in latest Ordovician to early Silurian, when detritus from the Notre Dame Subzone was transported across the Red Indian line and deposited in the Exploits Subzone as melanges and turbidites of the Badger Group (H. Williams, 1995a).

During the Silurian to Devonian, the Salinic (Dunning et al., 1990) and Acadian orogenies resulted in final closure of the Iapetus Ocean. However, location of the fundamental Iapetus suture is still the cause of debate. Early interpretations centred on the Red Indian Line as marking the closure boundary (Kean and Jayasinghe, 1982; H. Williams, 1995a). However, Arnott et al. (1985), working in northeastern Notre Dame Bay provided a different interpretation based on the lack of associated formations across the Reach Fault. They positioned the Iapetus suture further to the east, and higher up in the stratigraphic record. Elliot and P.F. Williams (1986), however, argued against the Reach Fault as the suture citing the fact that although units and formations differ on either side of the fault, correlations can be made across the structure. Recent work by H. Williams et al. (1993) provided structural evidence for final closure further to the east of Arnott et al. (1985) along the Dog Bay Line. It is likely that many of these lineaments represent different episodes related to the successive accretion of multiple island arc terranes.

Focussing from regional scale to subzone scale, the Lawrence Harbour Formation is one of several major divisions exposed in the Exploits Subzone. It consists of deformed siliceous black shales and silty shales that span four Upper Ordovician graptolite biozones (S.H.Williams, 1995) representing some ten million years of deposition as defined by U/Pb ages (table 1.1; O'Brien et al., 1997).

The Victoria Lake Group (Kean, 1977) consists of early Ordovician volcanic and

Table 1.1: Upper Ordovician time scale for Newfoundland and British equivalents (After O'Brien et al, 1997).

U/Pb Age (Ma)	British Series	North American Series	British Graptolite Zones	Newfoundland Graptolite Zones	Common Graptolite Fauna Associated With Newfoundland Upper Ordovician Biostratigraphic Zones
	Ashgill	Cincinnatian	*P. linearis*	*P. linearis*	
448 450	Caradoc		*D. clingani*	*D. clingani*	
455		Champlanian	*D. multidens*	*C. bicornis*	
			N. gracilis	*N. gracilis*	
458 460	Llanvirn				
465					

epiclastic volcanic rocks, the Tally Pond Volcanics (Kean and Jayasinghe, 1980), an unnamed volcaniclastic and sedimentary rock unit, and the Lawrence Head Volcanics (O'Brien et al., 1997). These appear to be conformably overlain by the Lawrence Harbour Formation (Kean and Jayasinghe, 1982). The lower transition between the Victoria Lake Group and the Lawrence Harbour Formation is commonly marked by a distinctive unit of finely laminated red and grey bioturbated cherts which may represent discontinuous or slow deposition over 5 to 10 million years (O'Brien et al., 1997). The upper transition into the Point Leamington Formation is defined by the first occurrence of a distinct, thick sandstone bed directly overlying beds of the Lawrence Harbour shales (S.H.Williams, 1991b). Most of this overlying unit is composed of a sandstone-conglomerate turbidite sequence with basal black shale interbeds belonging to *D.clingani* and *P.linearis* zones, and upper conglomeratic units (Goldson Formation) of upper Ordovician to early Silurian age. H. Williams et al. (1995a) included the Point Leamington and Goldson formations as part of the Badger Group, which consists of marine turbidite and marine conglomerate sediments. These units, as well as Caradoc black shales and local Silurian melanges, are combined to form the Badger Belt (informal name), which extends from central Newfoundland to the Bay of Exploits. Correlation within the Badger belt is based on consistent ordering of stratigraphy such that Caradoc black shale is overlain by silt- to sand-dominated turbidites, followed by conglomerates, and melanges (H. Williams et al., 1995a).

In terms of deformation styles and stages for the Exploits Subzone, Pickering

(1987b) concluded that folding within the Point Leamington Formation in the Notre Dame Bay region was the result of thrust-related deformation in wet sediments. In addition, that study also defined four stages of deformation; a D_0 stage of wet sediment deformation, a D_1 stage of thrusts with NNW dip (post-Caradoc), a D_2 folding and cleavage event (associated with the Acadian orogeny), and a D_3 event that resulted in minor overprinting of D_2 structures. This represents one of several different interpretations on the number of deformation phases; most workers have emphasised two or three events (e.g. Kean and Jayasinghe, 1982; Blewett and Pickering, 1988; 1989; Colman-Sadd et al., 1992b), although O'Brien (1993) defined four events in the Notre Dame Bay area.

1.4 The Study Area

This study is focused on the Lawrence Harbour Formation (Exploits Subzone) and biostratigraphically equivalent units throughout the Dunnage Zone. It is centred mainly in the Grand Falls-Windsor-Millertown-Badger region, with geochemical sampling ranging from Notre Dame Bay to the north and Glenwood to the east. The Grand Falls-Windsor area is transected by a NE-SW striking belt of Cambrian to Lower Silurian volcanic and sedimentary rocks. Inland exposure is poor, with only sparse and scattered outcrop, the exception being several large shale outcrops along the banks of the Exploits River southwest of Badger, and at the Red Cliff Overpass west of Grand Falls-Windsor. Similar occurrences of the Lawrence Harbour Formation are found throughout the north-central Exploits Subzone, with good coastal exposure found in the Bay of Exploits region.

Within central Newfoundland, a majority of exposures are accessible by logging roads originating in the town of Grand Falls-Windsor. The remaining area was reached through the use of mountain bicycles, canoe, and on foot. Northern exposures in the Notre Dame Bay region were reached by road and on foot, with shoreline outcrop being the most accessible and useful.

1.5 Comparison with Scotland

The Southern Uplands of Scotland and the Exploits Subzone are considered to have been neighbouring terranes that were separated by rifting in the Mesozoic during the formation of the Atlantic Ocean (T.M.Williams et al., 1996). As a result, a great number of comparative studies have been conducted. As early as 1936, G.R. Heyl attempted to make detailed correlation between Newfoundland Ordovician and similar units in the British Isles. It was later recognised that a tripartite stratigraphic sequence of mafic volcanic rocks overlain by graptolitic black shales, which are subsequently overlain by greywacke, exists in both terranes (Colman-Sadd et al., 1992a). Extending this correlation to a regional scale, the Notre Dame and Exploits subzones are thought to be laterally equivalent to Midland Valley and Southern Uplands terranes of Scotland (Figure 1.3). Major structural lineaments are also correlative, with the Baie Verte Line equivalent to the Highland Boundary Fault, the Red Indian Line parallel to the Southern Uplands

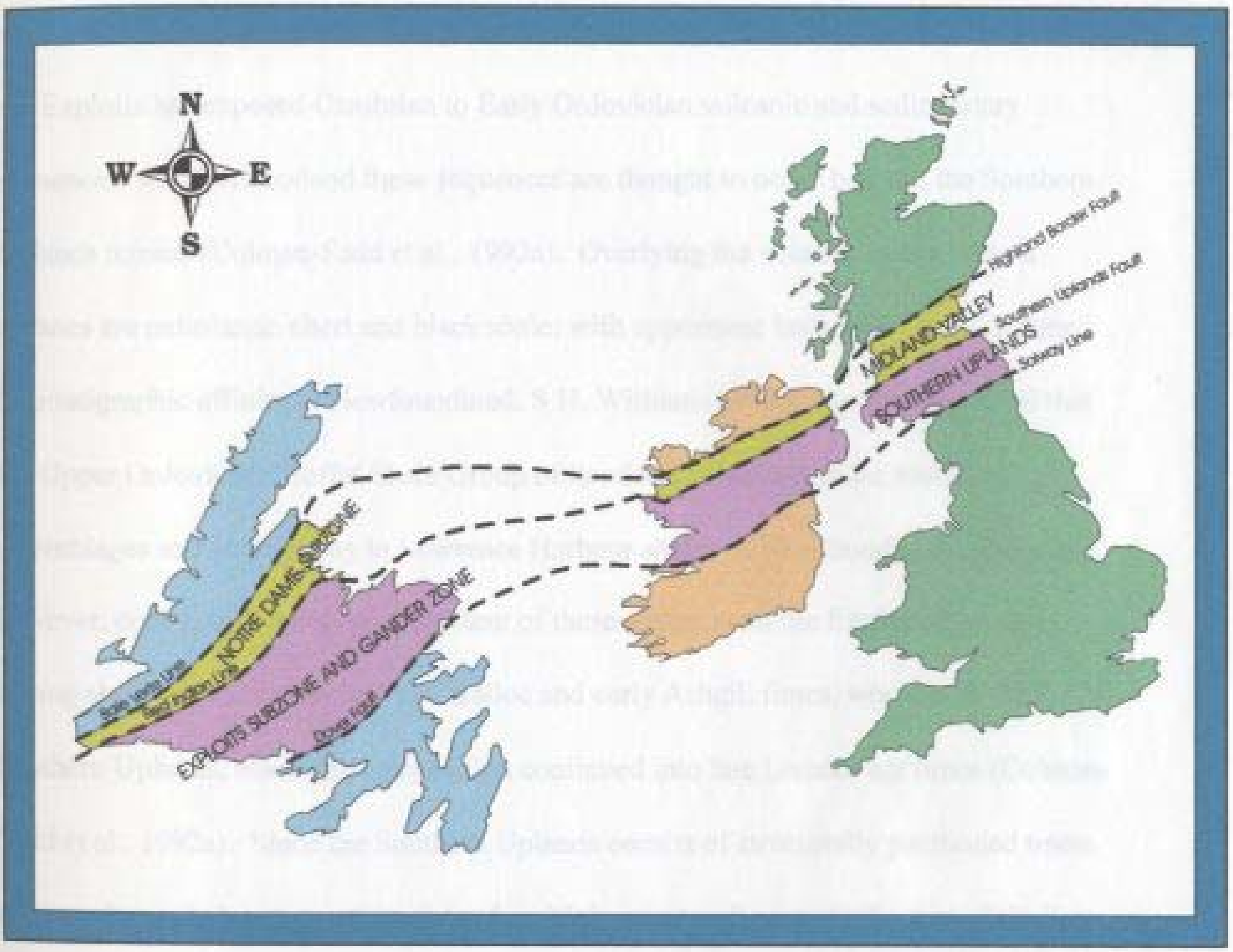


Figure 1.2: **Schematic geological terrane map illustrating correlative regions from Newfoundland and Scotland (Modified after S.H. Williams et al, 1996).**

Fault, and the Dover Fault equivalent to the Solway Line (Colman-Sadd et al., 1992a; S.H. Williams et al., 1992).

On the Newfoundland side, the Exploits Subzone experienced deposition of volcanic rocks with back-arc basin geochemistry in early Ordovician times. Erosion in the Exploits has exposed Cambrian to Early Ordovician volcanic and sedimentary sequences, while in Scotland these sequences are thought to occur beneath the Southern Uplands terrane (Colman-Sadd et al., 1992a). Overlying the volcanic rocks in both terranes are radiolarian chert and black shale, with uppermost beds of *N. gracilis* Zone biostratigraphic affinity in Newfoundland. S.H. Williams (1989b) has further noted that the Upper Ordovician Moffat Shale Group of Scotland contains similar faunal assemblages and stratigraphy to Lawrence Harbour shales of Newfoundland. There are, however, contrasts in the temporal extent of these shales, with the Exploits Subzone having shales that are restricted to Caradoc and early Ashgill times, whereas in the Southern Uplands, black shale deposition continued into late Llandovery times (Colman-Sadd et al., 1992a). Since the Southern Uplands consist of structurally positioned tracts of several ages (where a tract consists of multiple structurally repeated zones of similar lithologies), the age contrasts lead to the possibility that the Lawrence Harbour and equivalent shales of central Newfoundland are largely correlative with shales contained within a single Southern Uplands tract (Colman-Sadd et al., 1992a). Scottish correlative examples would be the *D. clingani* to *P. linearis* zone shales beneath the Kirkcolm, Portpatrick, and Shinnel formations of the Southern Uplands. Shale sequences common to both terranes are subsequently overlain by turbidite and conglomerate units deposited in Late Ordovician to Early Silurian times.

Structurally, the Moffat shales of the Southern Uplands are exposed in Scotland as groups of inliers with a NE-SW strike, that are repeated by SE-directed thrusting which occurred in late Ordovician to Wenlock (Mid-Silurian) times (Colman-Sadd et al., 1992b; Stone et al., 1987; Barnes et al., 1989). Southern Uplands bedding is vertical or steeply dipping and has younging directions within each tract that commonly face northwest. These tracts are thought to have formed through the progressive shearing of folds (Webb, 1983), with each tract becoming sequentially younger to the southeast. After the initial phase of southeast-directed thrusting, there was a transition from a thrust-dominated regime to one dominated by strike-slip faulting; first sinistral then dextral (Barnes et al., 1989; Piasecki et al.. 1990). The Southern Uplands and Exploits Subzone have both experienced correlative polyphase deformation events leading to several generations of structural styles. In central Newfoundland, diachronous thrust deformation is difficult to identify as there are few across-strike occurrences of lower Ordovician to Silurian sequences preserved (Colman-Sadd et al., 1992b). Further to the north of the study area, in the Notre Dame Bay region, fault-imbrication of a black shale and chert sequence has been identified (Williams and O'Brien, 1994). Field work conducted over the summer of 1996 also identified thrust faulting at several outcrops of the Lawrence Harbour shale in the Grand Falls-Windsor-Millertown region, suggesting that thrust faulting scenarios suggested for Scotland may also be applicable, in part, to Newfoundland.

Colman-Sadd et al. (1992b) also suggested that greater variety of stratigraphic and structural data recorded from central Newfoundland terranes is due, in part, to the nature of the Laurentian collisional margin. This involved the Exploits Subzone colliding with a Laurentian promontory, whereas the Southern Uplands terrane collided with its re-entrant pair. Paleotectonic setting of these regions places the Exploits Subzone as part of a back-arc basin sequence (Swinden et al., 1990) and Scottish equivalents as either a forearc accretionary prism (McKerrow et al., 1977; Needham, 1993) or a back-arc to foreland basin setting (Stone et al., 1987; Stone et al., 1994; Armstrong et al., 1996; T.M. Williams et al., 1996).

Chapter 2

Stratigraphy

2.1 Introduction

Upper Ordovician (Caradoc) black shales are distributed laterally throughout the entire Exploits Subzone. There appear to be several named and unnamed equivalents to the Lawrence Harbour Formation, including the Shoal Arm Formation, the Dark Hole Formation, and the Rodgers Cove Shale (Chapter 1), and several other age-equivalent shales in central Newfoundland. The Davidsville Group (Gander Lake Area) contains a black, graphitic shale unit that belongs to the *C. bicornis* Zone, thus indicating a temporal correlation with the Lawrence Harbour Formation. To the south, in the Baie D'Espoir Group, there are bio- and lithostratigraphic correlatives of the upper Lawrence Harbour and Point Leamington formations (S.H. Williams, 1991a,b). In west-central Newfoundland, drill core taken near Millertown south of the dam at the north end of Red Indian Lake contained Caradoc black shale of the Lawrence Harbour Formation. Reconnaissance field work conducted in this area during the winter of 1996 and summer of 1997 led to the location of several other outcrops of Lawrence Harbour shales that occur well outside its previously recorded geographic distribution. These include one outcrop on Noranda's Tally Pond Property that yielded graptolites indicative of the lower Lawrence Harbour Formation. Thus, correlation of named and unnamed Upper Ordovician black shale units suggests distribution of this unit throughout the entire

Exploits Subzone. There are no known equivalents to the Lawrence Harbour Formation within the Notre Dame Subzone.

The Lawrence Harbour shales were first described by Heyl in (1936) as consisting of a lower section of grey-green chert and cherty shale, followed by black shale with grey interbedded cherts, all overlain by a thick interval of graptolitic black shales. The unit was recognised in the areas around Lawrence Harbour and Upper Black Island on the Bay of Exploits. Espenshade (1937), working west of Lawrence Harbour, defined the Shoal Arm Formation as consisting of basal red-green cherty shale overlain by black slaty shales and slates with many red mud pellets, followed by light green cherty beds, and ending in 1200 feet of overlying interbedded black sandstone and shale. Although it is evident that the Lawrence Harbour shale description applies to the vast majority of black shale exposure cited in the literature and observed throughout the Exploits Subzone, some workers have preferred to use the term "Shoal Arm Formation" for some of the Upper Ordovician shales. For reasons of precedence cited above and discussed at the end of this chapter, this author chooses to use the name "Lawrence Harbour Formation" for all of these units.

Following the work of Heyl and Espenshade, Helwig (1969) redefined the Lawrence Harbour shale as comprising an older siliceous argillite belonging to the *N. gracilis* and *C. bicornis* zones and a younger silty shale conformable with the overlying flysch sequence and belonging to the *D. clingani* and *P. linearis* zones. These were termed the Lawrence Harbour shale and the "unnamed argillite" respectively. In so doing, Helwig (1969) divided what has since been observed as an apparently continuous sequence (S.H. Williams, 1995) into two shale units. This subdivision of the Lawrence Harbour shale has also contributed, in part, to the variation in formation names applied to correlative units of Upper Ordovician shales.

Bergström et al. (1974), described Ordovician faunas in west and north-central Newfoundland, including those in Lawrence Harbour, Upper Black Island, Red Cliff overpass (west of Grand Falls-Windsor), and in the Gander Bay area, and on the basis of these results expanded and redefined graptolite identifications from the Lawrence Harbour shale throughout north-central Newfoundland. As a result, Bergström et al. (1974) produced a biostratigraphic correlation between Upper Ordovician shales and related Newfoundland graptolite assemblages and the British standard sequence. Erdtmann (1976) subsequently applied a five-tiered zonal sequence to the upper part of the Lawrence Harbour shale using graptolites collected along the Exploits River, that was based mainly on the graptolite zonal sequence of the northeastern United States and eastern mainland Canada.

Following these earlier studies, S.H. Williams (e.g., 1989a, 1990, 1991a,b, 1995) worked extensively on graptolites from the Upper Ordovician black shales of the Exploits Subzone, establishing Newfoundland equivalent zonations to the British standards (Table 1.1) and redefining the boundaries of the Lawrence Harbour Formation. Owing to the abundant and diverse graptolite fauna, several biostratigraphic subdivisions for the Lawrence Harbour Formation were defined by S.H. Williams (1995), including the

Nemagraptus gracilis, *Climacograptus bicornis*, *Dicranograptus clingani*, and *Pleurograptus linearis* zones, from base to top respectively. The *N. gracilis* Zone is the lowermost of the four and is characterised by the presence of *N. gracilis* and *Acrograptus superstes*. Following this lies the C. *bicornis* Zone, which is marked by the presence of *C. bicornis* and *Diplograptus foliaceous* without *N. gracilis* and *A. superstes*. The next division is known as the *D. clingani* Zone, which is characterised by the presence of *Climacograptus spiniferus*, *Climacograptus caudatus*, and the last occurrence of *Cryptograptus tricornis*. The uppermost and final division is known as the *P. linearis* Zone and is distinguished by a lack of earlier species, including all *Dicranograptus*, and by the first occurrence of *Climacograptus tubuliferus* and *Dicellograptus pumilus*. Complete listings of the faunal assemblages present within each of the graptolite zones are given in S.H. Williams (1995).

Also in the same study, S.H. Williams (1995) defined the base of the Lawrence Harbour Formation at the type section at Lawrence Harbour, with Red Indian Falls as a parastratotype. The base is marked by the onset of continuous black shale deposition. Stratigraphy below and across the lower boundary of the Lawrence Harbour Formation appears in most cases to be transitional from underlying rocks through green-grey bioturbated cherts and sandstones with rare unfossiliferous black shales. Rocks stratigraphically below the cherts vary from turbidites of the Victoria Lake and Exploits groups to volcanic units of the Lawrence Head Volcanics and equivalents. The transitions between chert/sandstone and black shales have gradational contacts (Dean and

Meyer, 1982; S.H. Williams, 1988a) and are apparently conformable. The basal cherts are microcrystalline with some clastic influence, and have well-developed laminae. Beds are bioturbated and range from 2 to 20 centimetres in thickness. Total thickness of the unit itself is thought to vary laterally from 5 to 20 metres (Bruchert, 1992). Interbedded with these are thin (approximately 1 centimetre thick) siliceous black shale layers that, where fossiliferous, appear to indicate the *N. gracilis* Zone (Dean, 1978). Work done over the course of the present study at Black Duck Brook supports the *N. gracilis* Zone age of shales at the chert/shale transition. Rare poorly-preserved graptolites recovered from the unit at Lawrence Harbour appear to belong to *Pseudoclimacograptus* (S.H. Williams, pers. comm.); this would support an assignment to the *N. gracilis* Zone. Dean and Meyer (1982) also suggest that basal chert units may include cleaved tuffaceous interbeds, although no evidence for this was observed over the course of this study. Moving stratigraphically upwards, the basal chert and siliceous black shale grades into fissile black shales belonging to the upper *N. gracilis* to *C. bicornis* zones of the Lawrence Harbour Formation (S.H. Williams, 1988a). At Sandy Brook, south of Grand Falls-Windsor, rare graptolites from the Victoria Lake Group suggest a late Llanvirn age, indicating little or no depositional hiatus between the Victoria Lake Group and overlying chert-shale interbeds (S.H. Williams, 1988a).

Bergström et al. (1974) and S.H. Williams (1995) recognised lithological variation within black shales of the Lawrence Harbour Formation, indicating a possible vertical change in lithology. Present observations suggest a general stratigraphic change from black pyritiferous siliceous shale at the base of the formation to silty shale at the top. The upper silty shales appear to grade upwards into the turbidites of the Point Leamington Formation. It is important that the graptolites become rare and less diverse with increase in stratigraphic height, making it increasingly difficult to recognise definitive zonal assemblages in upper portions of the sequence. There is still some debate involving the timing of the upper transition into the overlying Point Leamington Formation, which is marked by the deposition of thick turbidite sand units (S.H. Williams, 1991b). Bergström (1974) identified the *D. clingani* and *P. linearis* graptolite zones within and just below the Lawrence Harbour-Point Leamington transition and concluded that the base of the Point Leamington Formation was diachronous and younged east to west regionally. In re-examining these localities, S.H. Williams (1991b) concluded that although stratigraphy within the basal Point Leamington Formation was commonly confused by complex tectonic and wet sediment deformation (Pickering, 1989) there was some evidence for diachroneity at the base of the Point Leamington Formation. He considered, however, that regional patterns could not be demonstrated owning to the limited number of exposures of the transition and paucity of graptolites within the interval.

2.2 Basal Chert

Although it has generally received little attention and has commonly been included within the Lawrence Harbour Formation and equivalents, the basal chert sequence below the lowermost black shale interval is as much a regional marker as the shales.

As early as 1936, Heyl recognised 120 metres of grey chert overlain by cherty shale and black shale at Lawrence Harbour and Upper Black Island. Espenshade (1937) also recognised a lower unit of banded red, green and black chert or cherty shale within the Shoal Arm Formation. Horne (1969), working on the south coast of New World Island and the north shore of Dildo Run, recognised a 150 to 300 metre thick sequence of tuffaceous dark chert overlain by slaty argillite of the Dark Hole Formation. Dean (1978) described similar Caradoc chert and argillite south of the Bay of Exploits as black-green chert to cherty argillite overlying the pre-Caradoc Loon Harbour Volcanics. S.H. Williams (pers. comm.) has observed green-grey mottled chert outcropping along the Salmon Pond Feeder in Glenwood, towards the eastern margin of the Exploits Subzone. Over the course of the present study, two excellent exposures of the basal chert were mapped (Figure 2.1). At Red Indian Falls, 10 to 20 metres of continuous grey-green bioturbated chert and black shale are exposed, although the entire package is fault bounded and the basal contact of the chert sequence is not exposed. At a second outcrop along Black Duck Brook, approximately 10 metres of the sequence and the upper contact with the Lawrence Harbour shales are exposed. It is evident, therefore, that the chert sequence is readily identifiable and has a regional distribution throughout the Exploits Subzone.

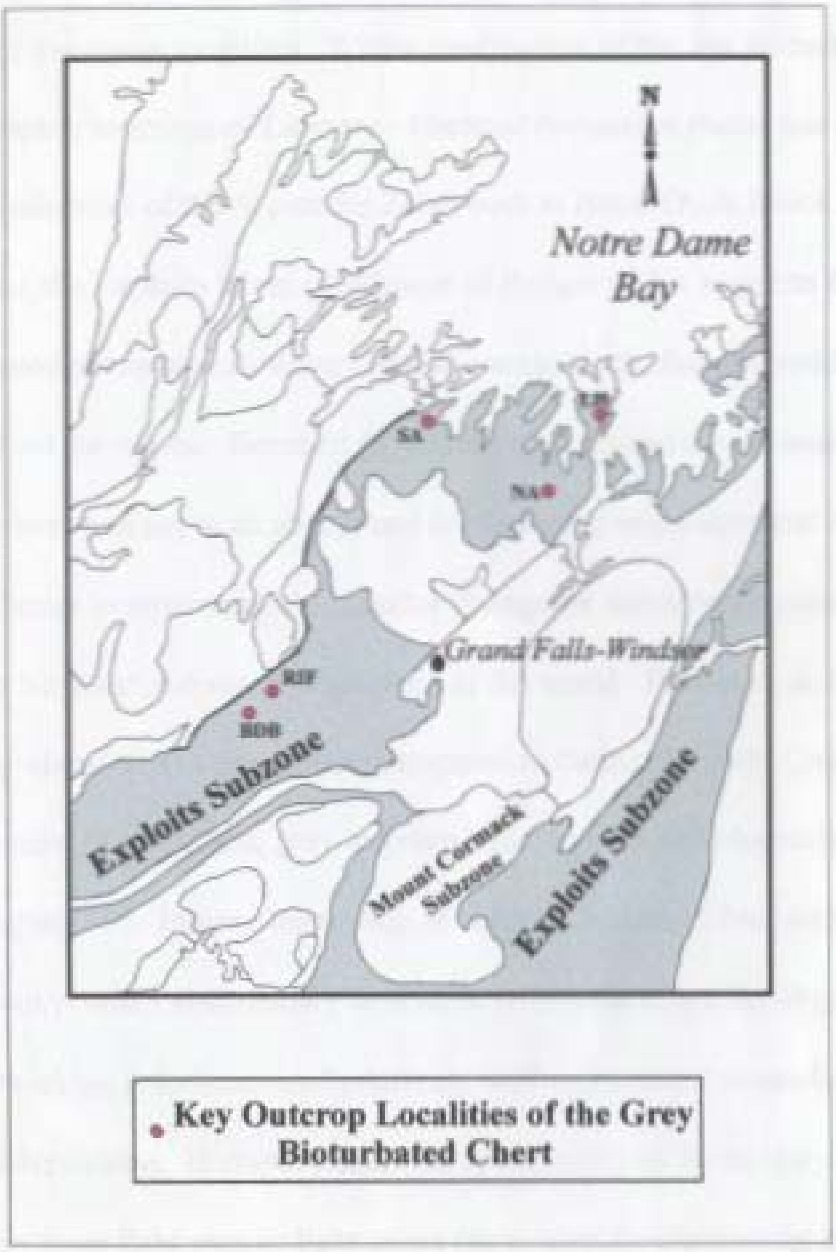


Figure 2.1: Schematic map of Exploits Subzone showing outcrop localities of grey, bioturbated chert. LH- Lawrence Harbour, SA-Shoal Arm, NA-Northern Arm, RIF-Red Indian Falls, BDB-Black Duck Brook (Subzone map modified from H. Williams, 1995a).

Dean (1978) speculated that the transition from mottled chert to siliceous black shale occurred within the *N. gracilis* Zone, based on graptolite sampling of overlying shales from several of the above localities. Within centimetres of the last bioturbated chert bed, biostratigraphic sampling of Lawrence Harbour Formation shales has now also revealed graptolites indicative of the *N.gracilis* Zone, both at Black Duck Brook and at Red Indian Falls along the Exploits River (southwest of Badger). This suggests that the change from oxygenated ocean bottom water chert to anoxic black shale deposition was synchronous throughout the region. Bruchert (1992) also recognised a pronounced change in oxygen content that led to an abrupt end in burrowing organisms and describes it as a 'fairly rapid change in environment'. Similar changes at this stratigraphic level are also seen in southern Scotland and many other parts of the world. Barnes et al. (1995) considered this to be related to a major global transgression during the early Caradoc.

The cherts consist of laminated, grey to green beds that are bioturbated in their uppermost layers (Figure 2.2). Intense burrowing of benthic organisms has led to localised destruction of primary sedimentary structures within the chert, leaving a mottled appearance. This reworking is indicative of relatively well-oxygenated ocean bottom waters at the time of deposition. Burrows within the uppermost part of the grey-green cherts commonly vary from light grey to light green (more clay rich?) creating a contrast with the surrounding matrix. Burrow traces are 1 to 5 centimetres long in cross-section on average, and can be as long as 8 centimetres. In lowermost beds of the chert unit, bioturbation is not present and primary sedimentary structures are preserved. Bruchert

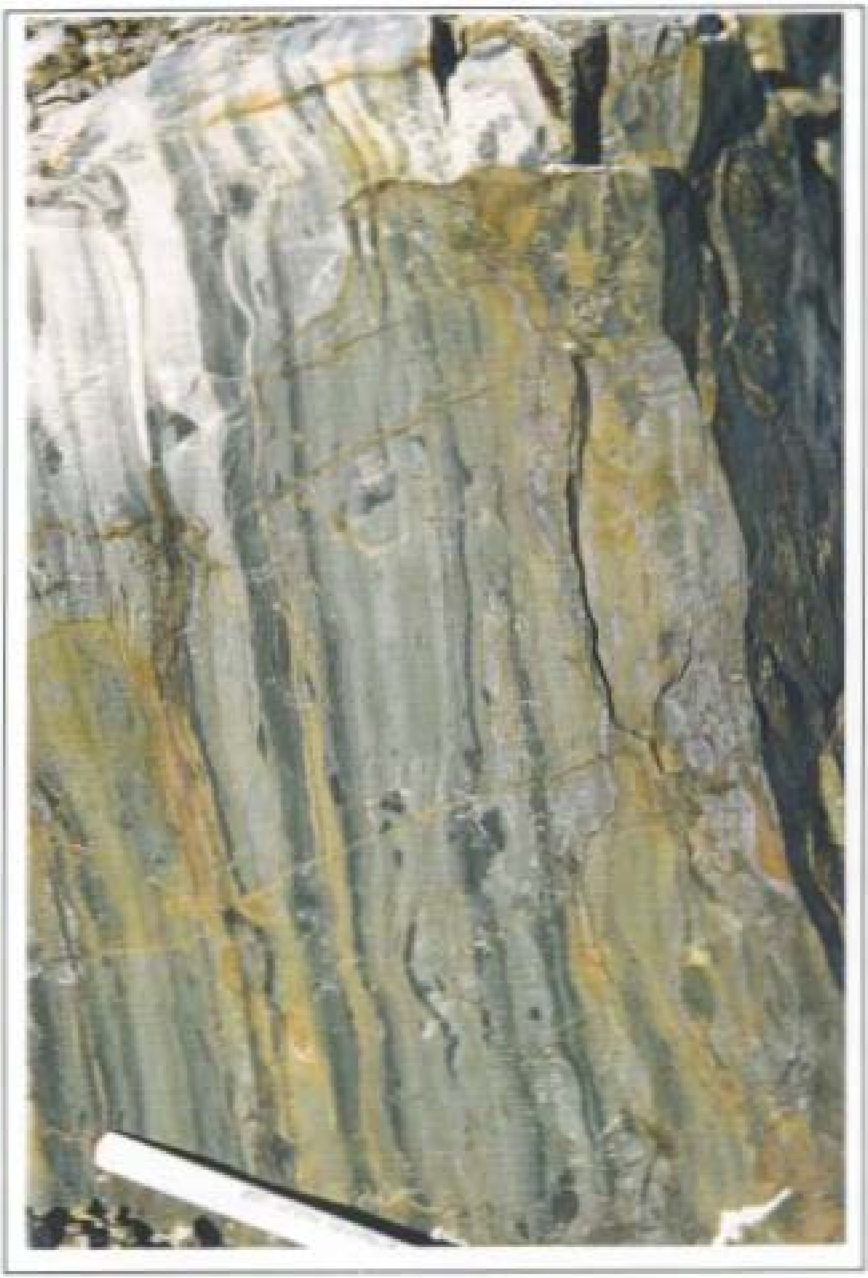


Figure 2.2: Photograph of grey bioturbated chert 5 kilometres north of Northern Arm. Pen in lower region is approximately 15 centimetres in length.

(1992), working in the Northern Arm region, described evidence of resedimentation structures such as ripples, graded bedding, and rare silt layers within cherty horizons. Indications of possible graded chert beds were also observed at Red Indian Falls within some of the less bioturbated/reworked layers. This may suggest that the grey-green chert beds are in fact siliceous turbidites. Nisbet and Price (1974) recognised a clastic-derived chert sequence in central Europe with well-defined turbidite structures such as graded bedding, parallel laminae, and cross-bedding. They also concluded that in order to produce a turbidity current deposit of this type, deposition must be extremely distal to the source terrane.

Bruchert (1992) described the basal contact of the chert unit within the Shoal Arm Formation as making a change from lower red chert to overlying grey chert. The underlying hematitic argillites end abruptly, with the red chert appearing to consist of variable and higher energy lithologies. It was suggested that this change might reflect increases in water depth and/or distance from clastic source areas, such as a change from continental margin setting (siliciclastic/biogenic deposition) to distal pelagic (biogenic) deep sea environment (Bruchert, 1992). It should be noted, however, that such changes can be related to a decreased oxygenation related to reduced oceanic overturn and to the position of the oxygen minimum, which commonly occurs relatively high on the continental slope. Colour changes within these cherts can also be the result of secondary diagenetic processes resulting in localised alteration. S.H. Williams and O'Brien (1994) drew the lower boundary of these cherts at the first underlying interbed of wacke or variegated chert. The lower contact was not observed over the course of present fieldwork to the south of Williams and O'Brien's (1994) study area.

The upper contact of the chert, exposed 8 kilometres west of Pamehoc Lake along Black Duck Brook (approximately 40 kilometres southwest of Grand Falls-Windsor), consists of a gradation between underlying grey-green bioturbated chert and overlying siliceous black shale. The gradational zone is approximately 1 to 2 metres thick, supporting a relatively rapid change from chert to black shale deposition.

Bruchert (1992) reliably used the first appearance of grey, burrowed cherts to correlate a section from Northern Arm (Bay of Exploits) with a Badger Bay composite section. During the course of the present study the chert unit was confirmed to be a reliable marker interval and to be a mappable unit on a regional scale. Kusky (1985), also mapping in the Northern Arm and New Bay Pond area, informally divided the chert units into formations, but this work was never published and his units were not formally adopted or discussed in later studies. Type section exposures were described in Moose Cove at the north end of New Bay Pond. Kusky's (1985) White Point Formation, bound by red chert of the Moose Cove Formation at its base and black to light grey shales of the Drowning Point Formation at its top, is equivalent to the basal bioturbated chert of this study. It consists of blue-grey bioturbated chert gradational with argillite horizons over 2 metres at the upper contact, much the same as the Black Duck Brook exposure described earlier. The basal contact of Kusky's (1985) White Point Formation is described as sharp and conformable from red chert into blue-grey bioturbated chert. Again, this supports the argument that the basal chert unit is mappable on a regional scale and has been considered for formational status in past studies. Unfortunately, Kusky (1985) failed to assign formal lithostratigraphic names based on type location to his formational divisions, leaving the entire package of basal chert unnamed. The present study is solely concerned with the grey bioturbated section of chert, as below this level the correlation of cherty horizons becomes problematic (B. O'Brien, pers. comm.). It is therefore recommended that the grey bioturbated chert be elevated to formation status and be named the Northern Arm Formation. It is proposed that the base of the Northern Arm Formation be drawn at the first grey chert bed overlying interbedded wacke or red-purple chert exposed along Highway 350 near Northern Arm, and along the shoreline of the pond directly east of the highway (UTM easting, 617660; northing, 5451750). This section near Northern Arm will be the stratotype locality. Localities at Red Indian Falls and Black Duck Brook (see 1:50 000 map inserted in the back pocket for location of these exposures) clearly illustrate the upper transitional contact between cherts of the Northern Arm Formation and the overlying black shales of the Lawrence Harbour Formation, although a complete section is not exposed. They are here given parastratotype status.

2.3 Lawrence Harbour Formation: Scanning Electron Microscope (SEM) Analysis

2.3.1 Introduction

The fine-grained nature of shales precludes their critical investigation with petrographic light microscopy. Thus, SEM analysis was conducted in order to document their mineralogy/texture and possible vertical changes in lithology and to compliment field-based observations. All samples were examined by the SEM to determine grainsize characteristics, such as diameter and shape. Also, energy dispersive (EDS) backscatter analysis was employed to examine basic mineralogy. Photomicrographs (secondary electron images) were all taken at X1000 magnification with a visible scale of 24 microns in order to preserve consistency. A total of eleven samples were selected from base to top of the gradational sequence. Two were from the basal siliceous shale, two from the black-silty shale lithology, three from a dark grey silty shale, one from the basal portion of the Point Leamington Formation and one sample that had been diagenetically altered. In addition, two samples from Scotland of shales equivalent to the Lawrence Harbour Formation were also examined. Primary grains were distinguished on their shape, as floccules or massive chert, and mineralogy. The SEM work was conducted in order to determine the extent of diagenetic alteration, with its absence supporting the validity of geochemical signatures and its presence increasing uncertainty in conclusions drawn from the geochemistry.

2.3.2 Basal Siliceous Black Shale

Two representative samples from basal shales of the Lawrence Harbour Formation were examined. In outcrop, the preservation of sedimentary structure is poor due to intense deformation. Slaty beds are commonly black and siliceous throughout this interval. In places, these basal shales appear cherty (Figure 2.3c) with weathered surfaces commonly accompanied by yellow and orange staining caused by weathering of iron sulfides. SEM examination revealed that the grainsizes for these sections ranged from 2 to 5 microns with rare grains of 10 to 15 microns. Larger grains were generally composed of quartz and secondary pyrite. Mineralogically, the shales are composed predominantly of quartz, pyrite, and clay minerals, in order of modal abundance. Quartz grains occurred as primary floccules and as secondary microveins, although over this interval the secondary electron images appear cherty. Pyrite is usually the largest mineral viewed, occurring as bedding parallel stringers of euhedral cubes, and locally as framboidal clusters. Clay minerals (illite-smectite) were observed as interstitial constituents and exhibit lower relief when viewed in SEM (Figure 2.3a,b). These grains were secondary and locally form long blade-like shapes (Figure 2.3a).

The other sample examined was examined because it exhibited trace element signatures which were different from other basal Lawrence Harbour shales. SEM analysis revealed that it was extensively silicified primary grains are rare (and overprinted) although primary sedimentary lamination is still preserved. Where remnant quartz grains were observed their diameters averaged between 2 and 5 microns. It is suspected that the

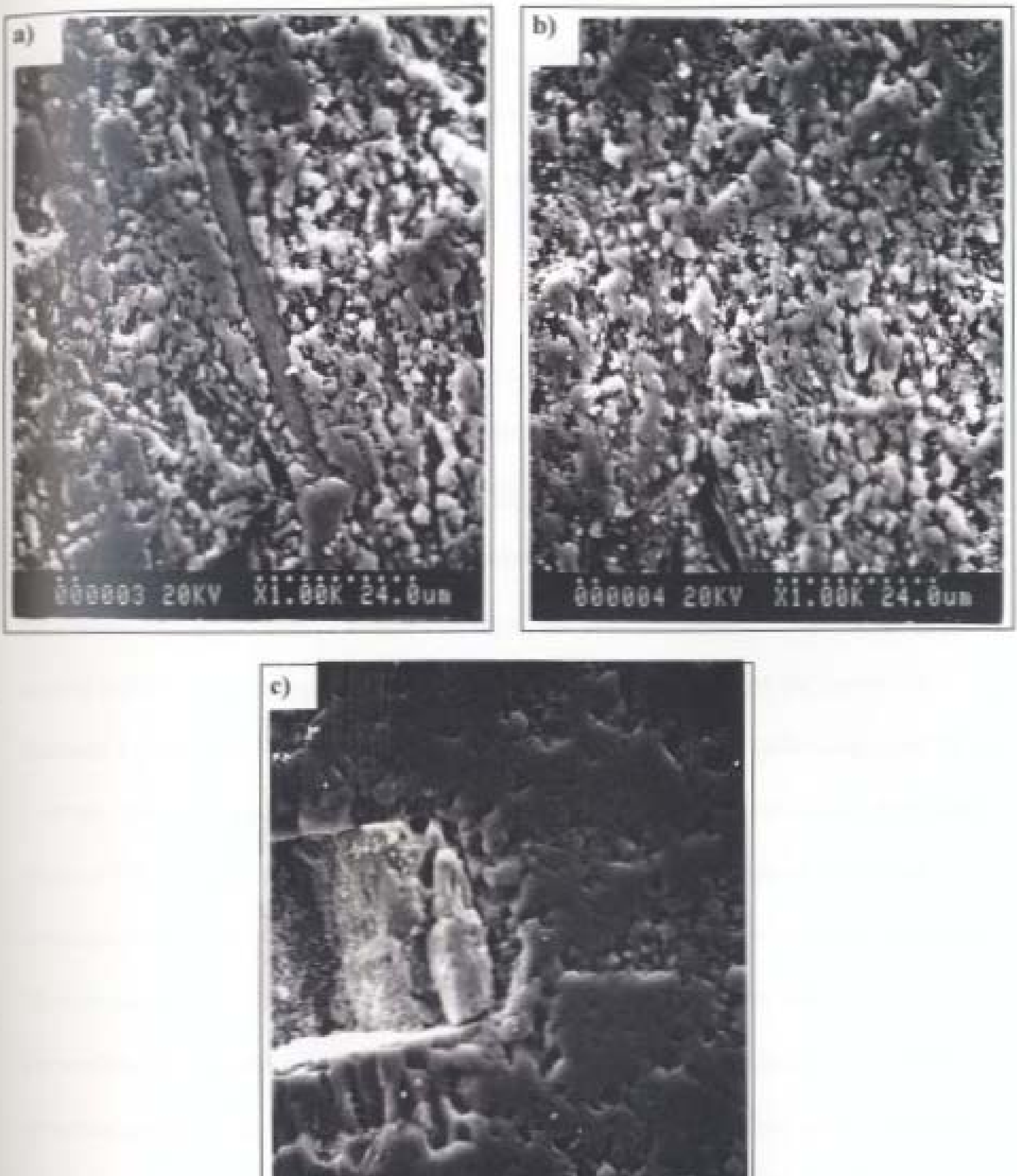


Figure 2.3: a) and b) Secondary electron images of basal siliceous black shale (X1000) c) Secondary electron image of altered basal siliceous black shale with pyrite cube at left (X1000).

different geochemical characteristics of this sample are a result of secondary, diagenetic alteration processes that affected original rock chemistry. No clay minerals were observed within this sample, although there are significant amounts of pyrite (Figure 2.3c).

2.3.3 Silty Shale

Three representative samples were examined from the silty shale lithology. Two were taken from transitional silty shale within the *D. clingani* Zone, and a single sample was taken from the top of the Lawrence Harbour Formation near the upper contact with the Point Leamington Formation. Outcrops of this interval consist of black to grey-silvery black beds, grading from shale to silt in the upper sections of the Lawrence Harbour Formation. Yellow and orange weathering beds are rare, indicating a low pyrite content. The silicification observed in lowermost units is also absent in the upper shales. Under SEM analysis, the *D. clingani* Zone samples were observed to be composed predominantly of quartz floccules and pyrite with grainsize diameters ranging from 5 to 10 microns (Figure 2.4a,b). There are also minor quartz microveins oriented perpendicular to bedding planes found within the sample. Clay minerals were again observed as secondary minerals interstitial to quartz and pyrite grains, and comprised approximately 10 percent of the sample. Another specimen, located below the Point Leamington transition, consists of quartz, pyrite, clay minerals, and less than one percent chlorite (Figure 2.4c). Grainsize diameters ranged from 5 to 20 microns, with locally larger grains of 30 microns. Also present is an unknown titanium-bearing mineral that comprised less than one percent of the sample.

2.3.4 Distal Turbidite Shale

A single sample from within basal Point Leamington turbidites was examined. It was collected from a silty shale horizon approximately 10 centimetres thick that yielded graptolites indicative of the *P. linearis* Zone. This shale horizon was bound by fine- to medium-grained sandstone beds of the Point Leamington Formation. The specimen consists of quartz, pyrite, and clay minerals (Figure 2.5a). Again, quartz was the dominant component with grainsizes averaging 10 to 15 microns in diameter and ranging from 5 to 20 microns. Clay minerals (illite-smectite) occur as secondary interstitial grains, and comprise approximately 20 percent of the total composition. Pyrite is a secondary phase and is commonly euhedral with rare framboidal clusters. A single grain of an unknown titanium-bearing clay mineral was found.

2.3.5 Scottish Equivalent Shale

Two samples from Scottish temporal correlatives of Lawrence Harbour equivalent shales were included in the SEM work in order to explore aspects of regional lithological correlation. The samples, from the Glenkiln and Lower Hartfell Shale formations, were located within *C. bicornis* and *D. clingani* zones respectively. Both samples consist of quartz, pyrite, and clay minerals, with a minor percentage of chlorite (figure 2.5b,c).

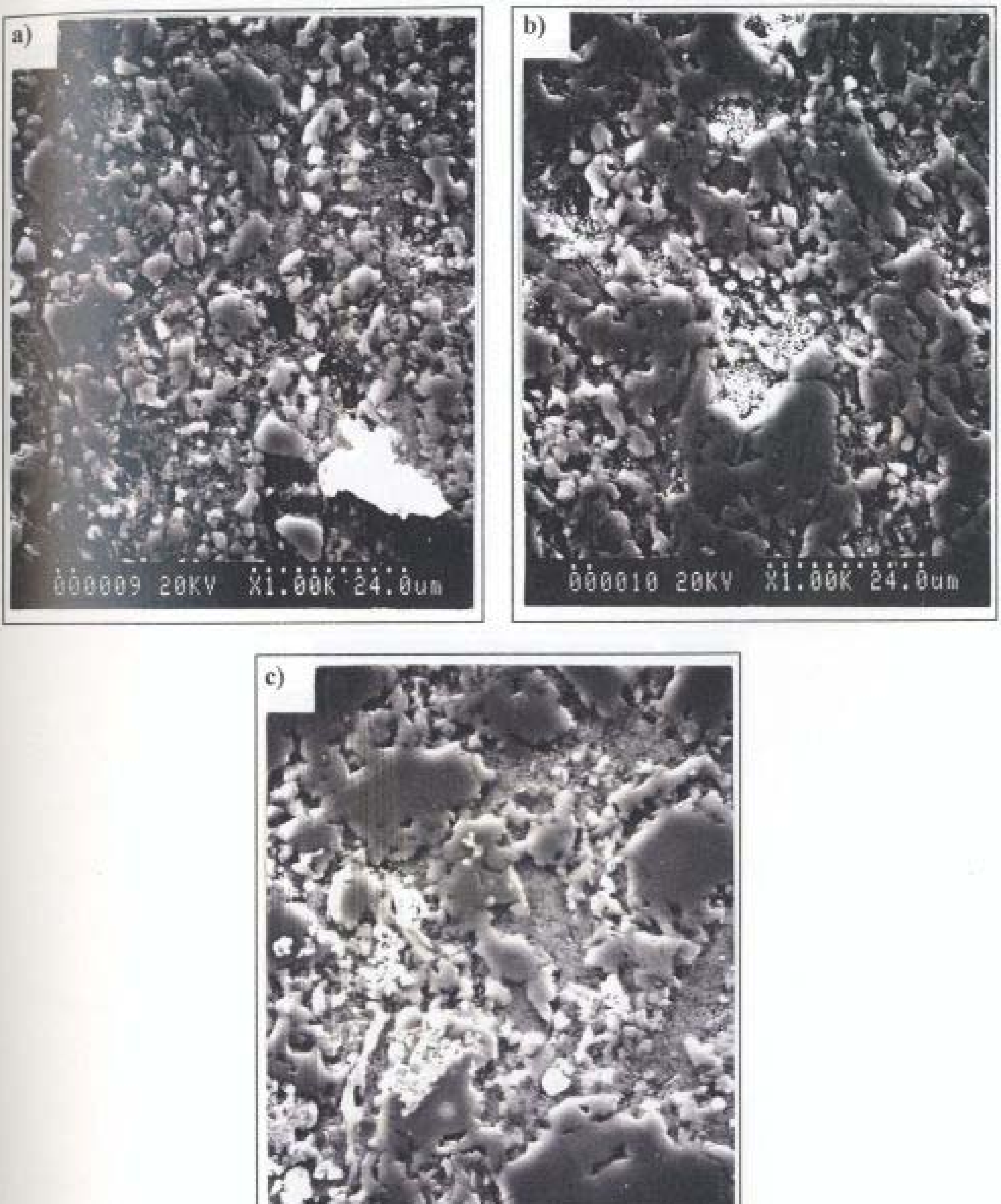


Figure 2.4: **a) and b) Secondary electron images of silty black shale (X1000).
c) Secondary electron images of uppermost silty black shale from directly below the Point Leamington/Lawrence Harbour transition (X1000).**

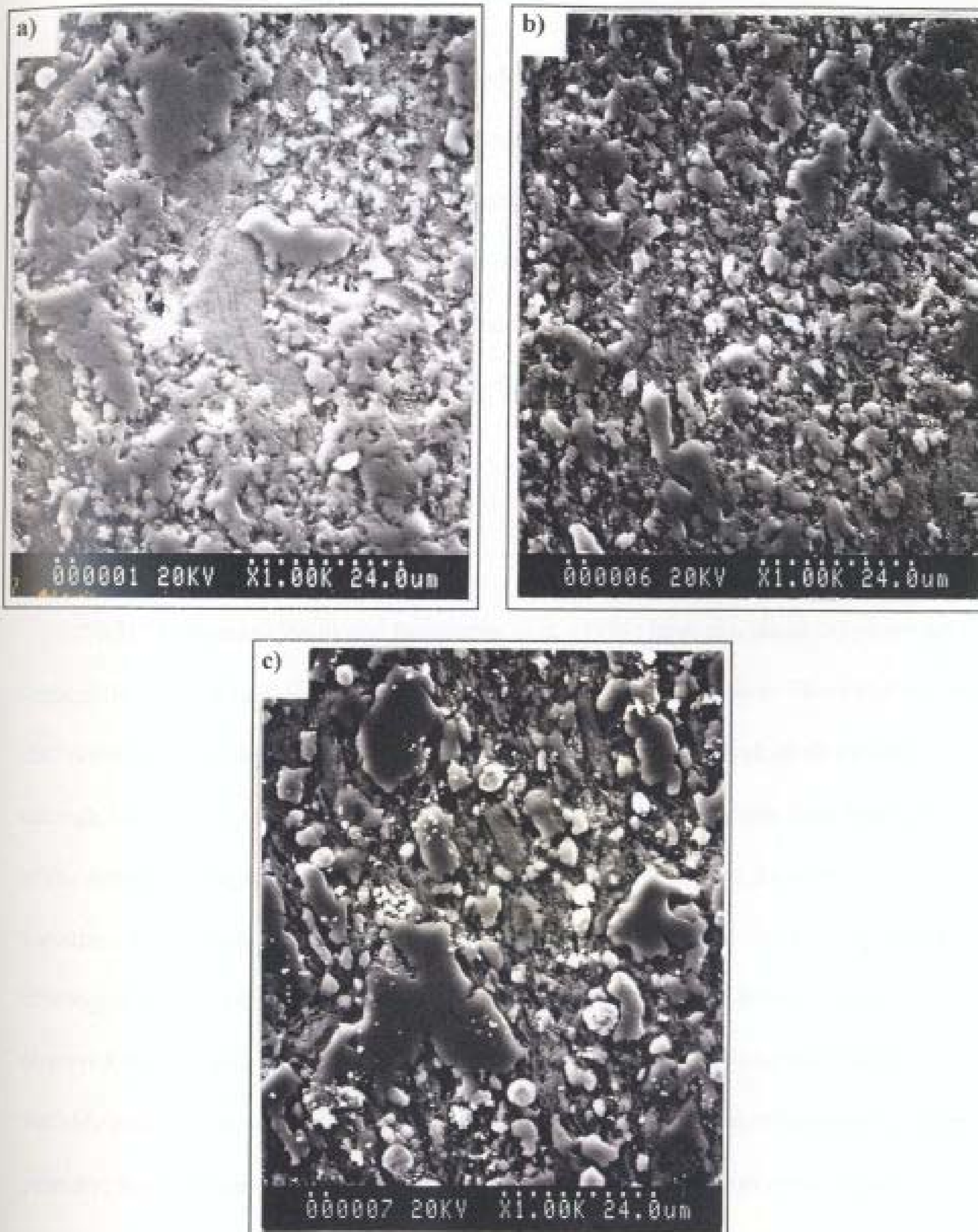


Figure 2.5: **a) Secondary electron images of distal turbidite silty shale from within lowermost Point Leamington Formation(X1000). b) and c) Secondary electron images of Scottish shales equivalent to those of the Lawrence Harbour Formation; b) *C. bicornis* Zone, and c) *D. clingani* Zone (X1000).**

Quartz grains occur as floccules that are 2 to 5 microns in diameter. Clay minerals are a secondary interstitial phase, with the rare occurrence of long blade-shaped grains. Pyrite is second in abundance and consists of 2 micron diameter framboidal clusters. The *D. clingani* sample thus resembled the *C. bicornis* sample in terms of grainsize, further supporting extended deposition of fine-grained shale in the Southern Uplands of Scotland at the time that age-equivalent shales in Newfoundland were becoming coarser in grainsize.

2.4 Summary

S.H. Williams (1991b) and Bergström et al. (1974) have discussed the observed vertical lithological variation within the Lawrence Harbour Formation. The variation was also noted over the course of this study, and comprises siliceous black shale passing through fissile black shale, and black silty shale to dark grey silty shale from base to top of the formation respectively. Detailed field observations show that the vertical variations are gradational. SEM analyses of representative samples from each of these lithologies confirms that they are mineralogically and texturally different. It was observed that the majority of samples consist of quartz, pyrite, and clay minerals in variable proportions, with quartz being the major constituent. Most of these minerals are primary, but the lowermost siliceous black shales contain local zones of secondary diagenetic quartz. Therefore, lithological changes observed in outcrop appear to be related to increasing grainsize vertically through the shale sequence, as observed in the SEM analyses (Figure 2.6).

Helwig (1969) redefined the Lawrence Harbour shale by dividing it in two, a basal siliceous Caradoc black shale (Lawrence Harbour shale), and an upper silty shale that was termed the 'unnamed argillite'. Although no complete sequence had been observed due to complex tectonic deformation, S.H. Williams (1991a) considered the shale units to be continuous and suggested that the 'unnamed argillite' be combined with the Caradoc black shales to form one unit known as the Lawrence Harbour Formation. Fieldwork during the course of the present study suggests that both lithologies occur in close proximity to each other. SEM analyses illustrate the grainsize gradation between basal siliceous and upper silty, dark grey shale. Finally, the shale sequence described has been identified consistently throughout the Exploits Subzone. All of these factors, when combined, are in agreement with S.H. Williams' (1991a,b; 1995) grouping of Helwig's (1969) Lawrence Harbour shale and 'unnamed argillite'.

There is still some debate as to whether Lawrence Harbour or Shoal Arm Formation is the more appropriate term for the black shale formations (S.H. Williams, 1995). Supporters of the Shoal Arm cite the fact that it was the first formational name applied to the shales, and thus should be used because of historical precedence. The description provided for the early Shoal Arm sequence lists it as black argillaceous sandstone and shale that is alternately bedded, with 300 feet of red and green cherty shale at its base (Espenshade, 1937, p.9). When one considers the Shoal Arm description in

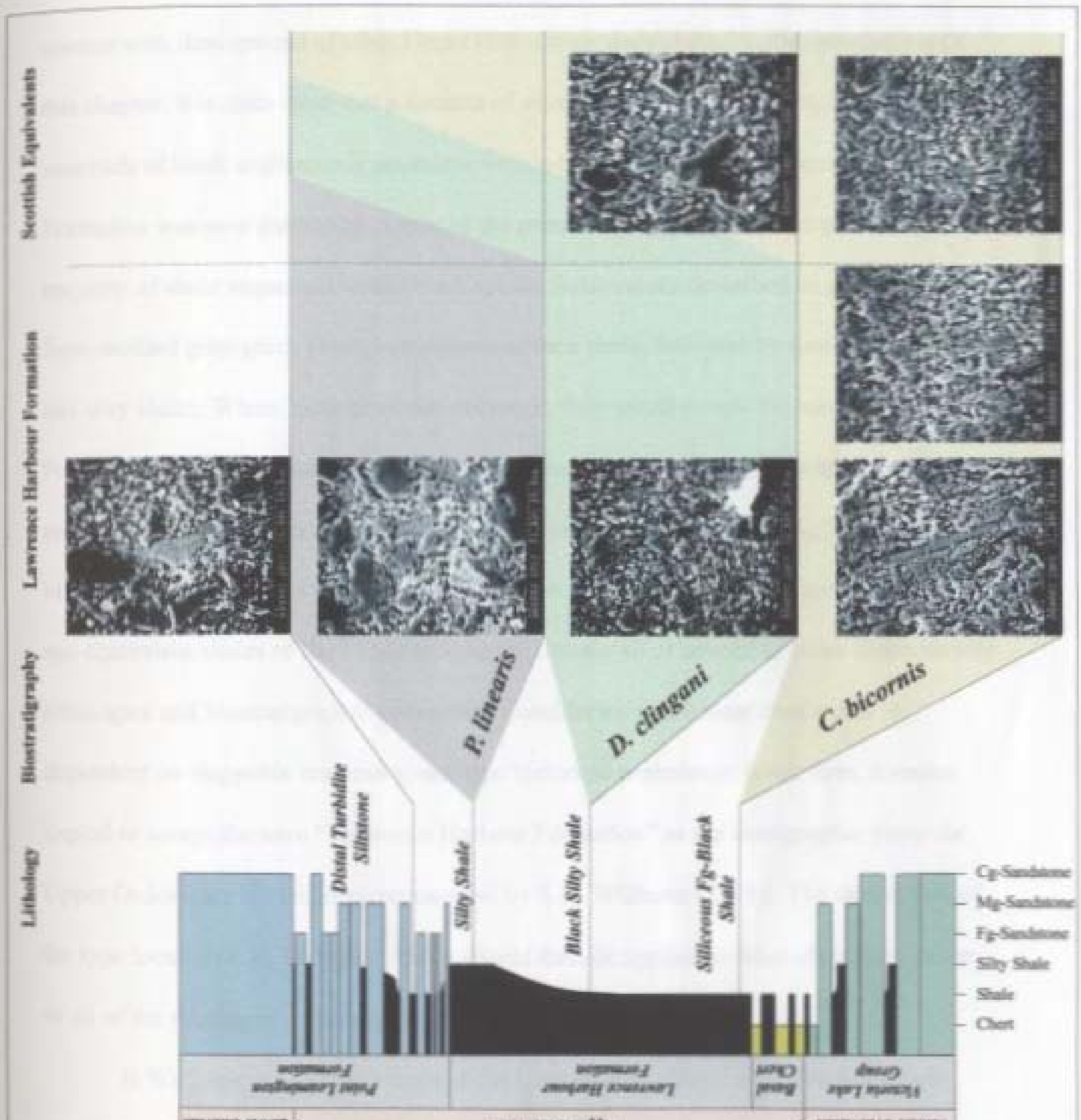


Figure 2.6: Schematic section illustrating clay grain size variation vertically through the Lawrence Harbour Formation. Far right illustrates Scottish equivalent samples. Note deposition of finer-grained sediment continues over longer time periods than the Newfoundland equivalents (shown as brown and green shaded regions).

context with descriptions of other Upper Ordovician shales listed in the introduction of this chapter, it is quite clear that a number of aspects are dissimilar. First, no evidence for interbeds of black argillaceous sandstone within black shales of the Lawrence Harbour Formation was seen during the course of the present study. For the most part, the majority of shale sequences within the Exploits Subzone are described as gradational from mottled grey-green chert, into siliceous black shale, followed by fissile black shale, and silty shale. Where sandstones are observed, they usually mark the basal beds of the Point Leamington Formation. The type sequence of the Lawrence Harbour Formation exposed at Lawrence Harbour is composed of these lithologies, spanning four graptolite biostratigraphic zones recording some 40 million years of black shale deposition. Other age equivalent shales of the Exploits Subzone contain all or several of these characteristic lithologies and biostratigraphic zonations. Considering that formational status is dependent on mappable continuity, and that historical precedence is not firm, it seems logical to accept the term "Lawrence Harbour Formation" as the stratigraphic name for Upper Ordovician shales, as recommended by S.H. Williams (1995). The description of the type locality (S.H. Williams, 1995) should then be applied to other shales with some or all of the stratotype's characteristics.

H.Williams et al. (1995) omitted the Lawrence Harbour Formation from their definition of the Badger Group, whereas the Point Leamington Formation turbidites were included. With a gradational, coarsening upward sequence defined within the shales, it seems likely that they represent pre-turbidite or distal turbidite deposition, and are linked closely to the Point Leamington Formation. With this in mind, it would seem logical to include the Lawrence Harbour Formation within the Badger Group.

During the course of the present study the grey-green bioturbated chert unit was confirmed to be a reliable marker interval that is somewhat mappable on a regional scale. Kusky (1985) and Bruchert (1992) have used this horizon as a marker for correlation and have considered it for formational status in their unpublished theses. Kusky (1985), however, failed to assign formal lithostratigraphic names to the unit, leaving the cherts unnamed. It is therefore recommended in section 2.2 of this chapter that the grey bioturbated chert unit be elevated to formational status, and be named the "Northern Arm Formation".

Chapter 3

Structural Geology

3.1 Introduction

Many studies have been made on the regional geology and stratigraphy of the Exploits Subzone, a number of which refer to polyphase deformation histories for the region. There have also been several studies that have focussed on the deformational histories of rocks in central Newfoundland. Karlstrom et al. (1982), working on rocks in the Bay of Exploits region, concluded that complex map patterns were the result of several superimposed deformation events. They identified a regional F_1 deformation event that combined thrusting and recumbent folding with steeply plunging F_1 axes preserved in intrafolial folds. This was followed by post Mid-Silurian D_2 with thrusting and F_2 tight, upright asymmetric folding with shallowly plunging fold axes. It was implied by Karlstrom et al. (1982) that this second phase led to the stratigraphic repetition observed in graptolitic Caradoc shales. The final deformation stage proposed by Karlstrom et al. (1982) led to kinking and chevron folding. The implications of this interpretation are that F_1 recumbent folds and thrusts are completely folded by D_2 events, and that parts of the area must be allochthonous. Elliot and Williams (1986) concluded that at least three major generations of folding were present in the Notre Dame Bay area, and also observed thrust faulting on both a regional scale and as duplexing within a single Bouma sequence. This result was expanded upon by Arnott et al. (1985) and

Pickering (1987a) who described a Late Ordovician to Early Silurian thrust imbricate system that was active during sedimentation.

Blewett and Pickering (1988) made detailed structural observations from the Bay of Exploits are and observed that cleavage was commonly not axial planar, but transected fold hinges obliquely, being rotated about 10 degrees in a clockwise direction. Blewett and Pickering (1988) concluded from this relationship that there was a dominant phase of sinistral transpression during the Acadian orogeny (Silurian to Devonian) that was followed by a later phase of dextral shear with only local significance (Devonian to Carboniferous).

Lafrance and Williams (1992), in the Bay of Exploits region, concluded that Mid-Ordovician to Early Silurian clastic sediments were deposited within a single basin, which underwent south-directed thrusting over the Gander Zone, and was then deformed by dextral faulting. An Early Silurian D_1 thrusting event, associated with isoclinal intrafolial folds, was followed by Late Silurian dextral faulting and three phases of folding, and a final D_3 stage of brittle faulting. During D_3, Lafrance and Williams (1992) note that a regional S_3 cleavage formed along with the dominant F_3 northeast plunging dextral folds. Working in the Dog Bay Line area of the eastern Exploits Subzone, H. Williams et al. (1993) also describe a pervasive dextral, transpressive ductile deformation phase that was followed by brittle extension.

A summary of structural elements of the Exploits Subzone within Notre Dame Bay is given by O'Brien (1993), who concluded that there were four main phases of deformation in this region. D_1 and D_4 encompass all northwest-trending structures, whereas D_2 and D_3 events are defined by northeast-trending structures. Of these, the most significant is the D_2 phase which produced regional anticlinoria and synclinoria, major thrust-sense fault zones, and widely developed slaty cleavage. Folds of this event are overturned to the northwest and are gently doubly plunging. O'Brien (1993) also noted that the lithostratigraphic unit most commonly excised by faulting is the Lawrence Harbour Formation.

Preliminary field excursions and conversations with S.H. Williams and B. Kean were conducted at the outset of this project in order to determine areas suitable for mesoscopic scale, detailed structural mapping. Previous work in the Badger region by Kean and Jayasinghe (1982) recorded regional 1:50 000 scale structural trends; sparse outcrop distribution and little attention to detailed outcrop mapping, however, left many aspects of the structural history of these rocks unknown. Attempts by S.H. Williams (1991) to map Red Indian Falls employing a biostratigraphic approach with minor attention to structural features led to indications of fault imbricated slices of Lawrence Harbour Formation. Subsequent field mapping for this study has led to the discovery of previously unmapped localities, including those of black graptolitic shale that lie outside Kean and Jayasinghe's (1982) mapped geographic distribution of the Lawrence Harbour Formation.

As part of this study, a detailed structural analysis at mesoscopic and regional scale was undertaken to better define the extent of faulting and its relationship to folding, and to resolve conflicts involving geographic distributions of these Upper Ordovician shales. Measurements of structural elements such as bedding, cleavage, bedding-cleavage intersection lineations, F_1- and F_2 fold axial planes, and fold axes were collected along with lithological observations to produce the structure maps.

3.2 Mesoscopic Structural Maps

Limited outcrop exposure throughout central Newfoundland has made study of the Lawrence Harbour Formation difficult; historically, regional structures were derived from sparse data sets. This has ultimately led to problems with relating new outcrop exposures to existing geological maps, and structural observations with regional trends. One way to refine the geological interpretation of an area with poor exposure is to construct mesoscopic or outcrop-scale detailed structural maps. These maps can then be combined with regional data sets and used to extrapolate structures through regions of poor constraint, thus creating a regional geological map with refined structural and lithological distributions.

Three detailed structural maps were constructed over the course of this study at Red Indian Falls, Exploits River Fold exposure, and Red Cliff Overpass, covering west, central, and eastern portions of the region respectively (Figures 31, 36, and 38). The structural elements presented in section 3.3 of this chapter include measurements made from all three detailed mapping localities.

3.2.1 Red Indian Falls Structural Map

The Red Indian Falls locality is located approximately 35 kilometres south of the town of Badger, along the Exploits River. It was mapped and sampled for biostratigraphy by S.H. Williams (1995) who recognised possible imbrication of black shale biozones at this locality. Lithologies present at this location include fine- to medium-grained sandstone turbidites of the Point Leamington Formation, siliceous through silty black shale of the Lawrence Harbour Formation, and grey bioturbated chert beds overlying cherts and sandstones of the Victoria Lake Group. This locality consists of outcrop lining both banks of the Exploits River, with the most significant outcrop exposed at the falls themselves (Figure 3.1 and 3.2).

Structurally, there appears to be a complex mesh of several deformation stages beginning with synsedimentary deformation within sandstone beds and progressing into complex folding and faulting. Equal area stereoplots for contoured values, and equal angle for planar and linear elements, are located on the detailed structural map (Figure 3.1). Bedding at this locality strikes northeast-southwest and dips predominantly to the northwest and southeast (see stereoplot on map). Synsedimentary deformation (D_0) is observed within overlying sandstone beds as convolute bedding. Younging directions were obtained through observation of graded bedding and load casts in these sandstone beds, as well as through graptolite biostratigraphy (S.H. Williams, 1995).

The next deformation stage (F_1) recorded at Red Indian Falls involved a folding event that is preserved as mesoscopic, northwest-plunging asymmetric folds within Lawrence Harbour Formation shales (Figure 3.3). These have been overprinted by a later

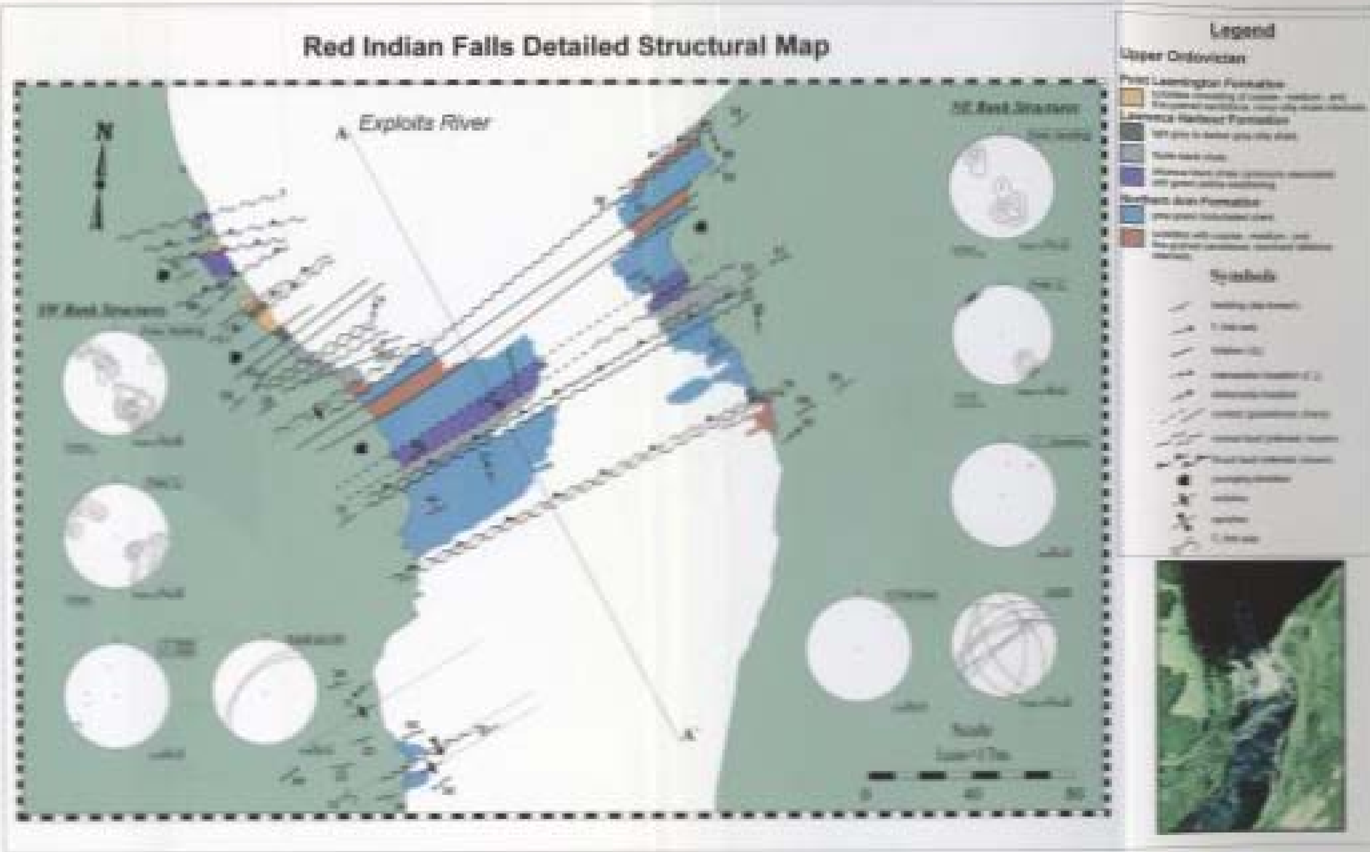


Figure 3.1: Red Indian Falls detailed structural map.

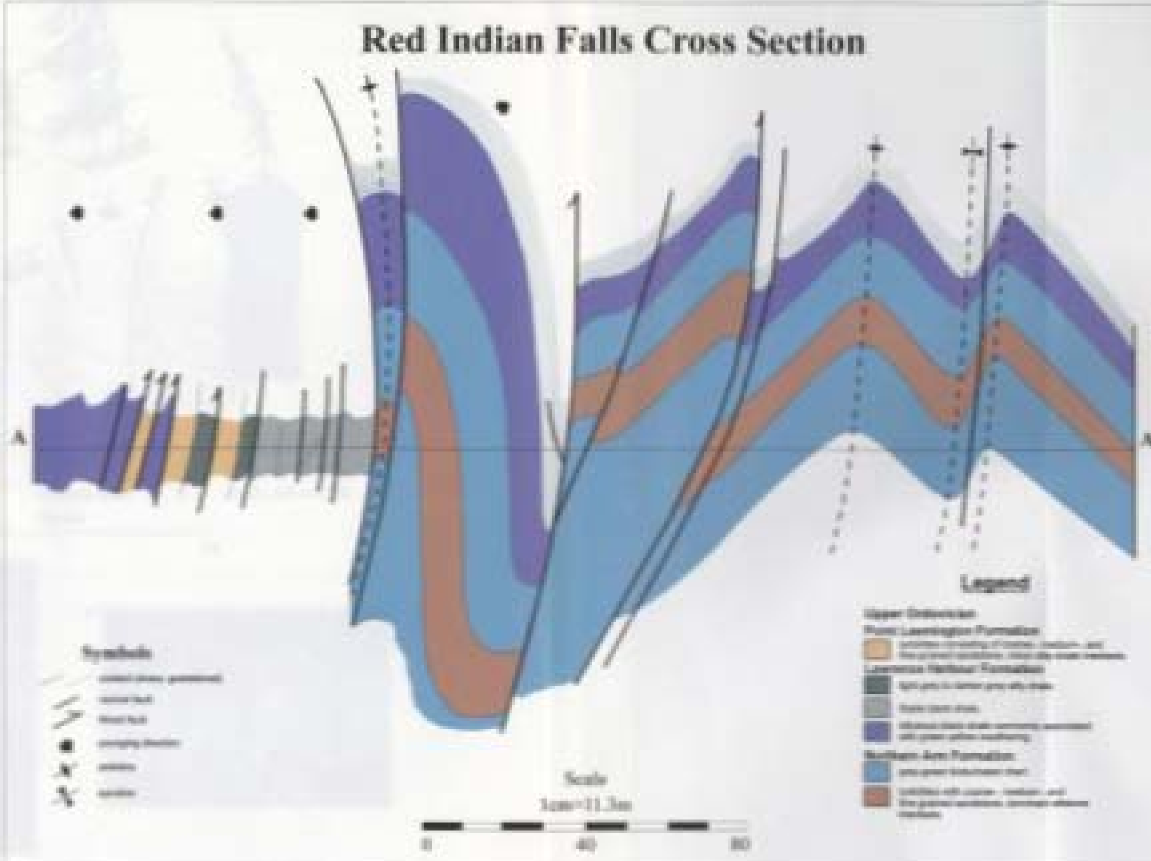


Figure 3.2: Red Indian Falls cross section.

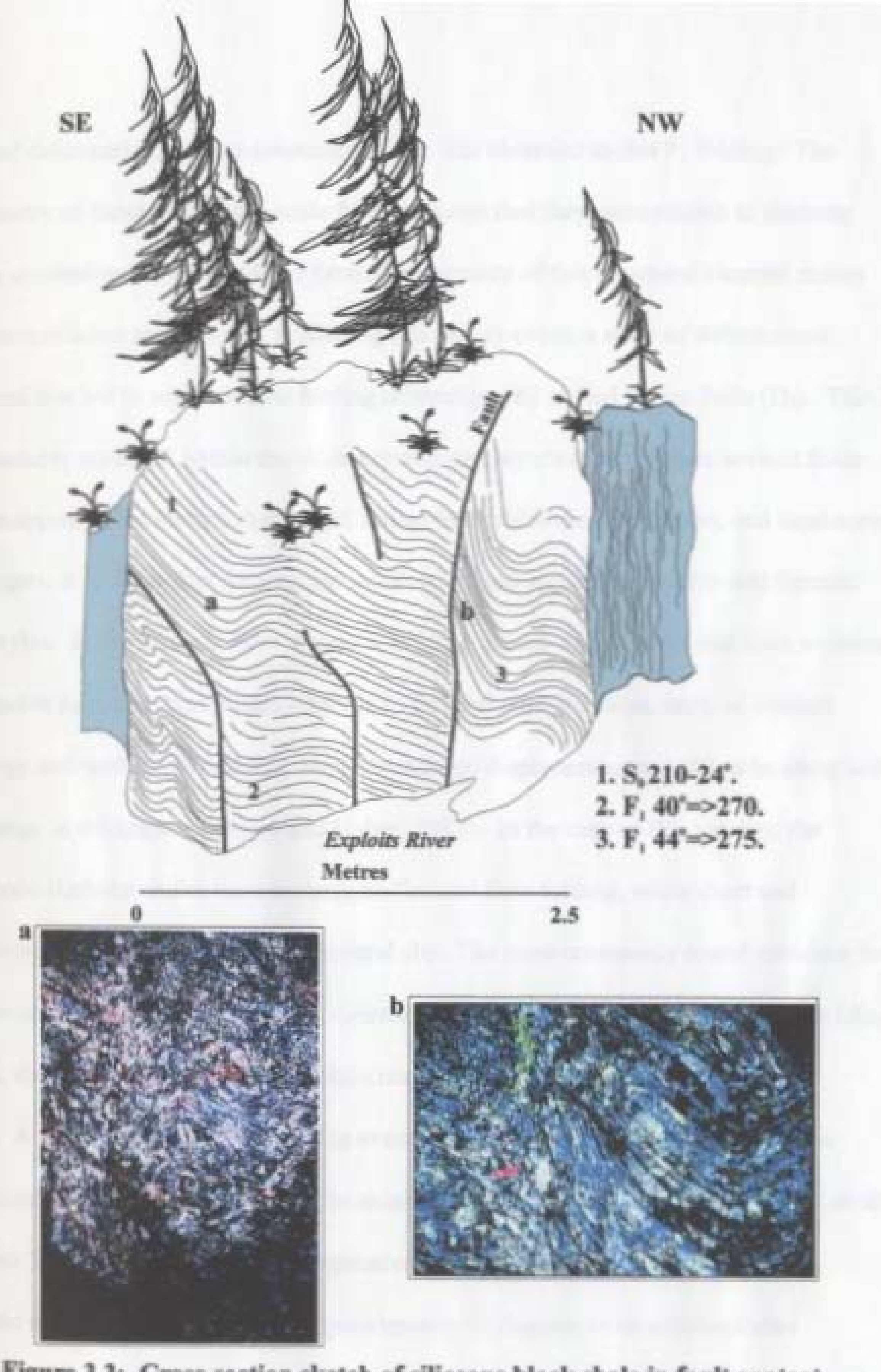


Figure 3.3: **Cross-section sketch of siliceous black shale in fault contact with sandstone (SE) at Red Indian Falls. View is Southwest into the page. Note F_1 mesoscopic folding within shales as illustrated in the photographs of horizontal outcrop exposures.**

stage of deformation, and no associated fabric was observed to this F_1 folding. The asymmetry of these centimetre-scale folds suggests that they were related to shearing with a sinistral sense, although the limited occurrence of this structural element makes this interpretation speculative. Following this earlier event, a stage of deformation occurred that led to open to close folding of stratigraphy at Red Indian Falls (D_2). This is most notably recorded within the microcrystalline grey chert beds where several folds were mapped. Considering that at Red Indian Falls there are shale, chert, and sandstone lithologies, it is likely that folding has involved mixed mode flexural slip and flexural flow styles. In the flexural flow situation, folding occurs within rocks that have an initial penetrative fabric such as shales whereas in flexural slip situations, units of distinct lithology and with sharp bedding contacts undergo displacement parallel to bedding with no change in thickness (Ramsay and Huber, 1987). In the case of this locality, the Lawrence Harbour shales have undergone flexural flow folding, while chert and sandstone layers have experienced flexural slip. The most commonly found evidence for this occurs in the form of slickenside lineations found along chert and sandstone bedding planes, that occur perpendicular to fold axes.

Associated with this D_2 folding event is a penetrative cleavage fabric that in contoured stereonet plots appears to be axial planar. At the southern-most outcrop on the Exploits River's southwest bank, penetrative cleavage was observed transecting a parasitic anticline-syncline pair at approximately 10 degrees in an anticlockwise direction. This may indicate a shearing component that has created local non-axial planar cleavage relations. Alternatively, it may indicate a later regional transpression event, in this case with a dextral shear sense. In central Newfoundland, stereoplots of structural data for the Red Indian Falls area and structural relations at other localities provide evidence that this penetrative cleavage is in fact axial planar to observed F_2 folding, suggesting that Red Indian Falls preserves a local shearing component that led to this localised non axial-planar transecting cleavage. Figure 3.4 illustrates the low angle that cleavage makes with shale beds at this locality. The high angle between fabric and chert beds appears at first glance to be refracted cleavage. This extreme angle, however, produces contradictory maximum extension directions between cleavage within shales and cleavage within chert. An interpretation more compatible with the strain implications of this penetrative cleavage involves competency contrasts between the two lithologies. The incompetent shales, when exposed to approximately northwest-southeast compression developed a slaty cleavage and were extended in a northeast-southwest direction. The cherts, being competent themselves and bound by incompetent layers, were also extended in the same direction, but did not develop a cleavage fabric. Instead, tension fracturing occurred producing the closely spaced cracks observed in Figure 3.4. This is consistent with expected strain relations, and field observations of open spaced fractures with minor quartz veining are also supportive of this interpretation. L^2_0 intersection lineations for this outcrop plunge shallowly (5 to 10 degrees) in a northeast-southwest direction. This is in close agreement with measured F_2 fold axes providing support of the penetrative cleavage as being axial planar in nature.

A final D_3 event involving normal and reverse faulting is also recorded in outcrop surrounding Red Indian Falls (Figure 3.5). In cross-section, these faults are found to

Figure 3.4: Photograph of S_1 cleavage in shale parallel to knife. Note tension fractures within grey bioturbated chert, and cleavage within shale beds. Map view profile looking down on outcrop with steeply dipping beds. Pocket knife approximately 11 centimetres in length.

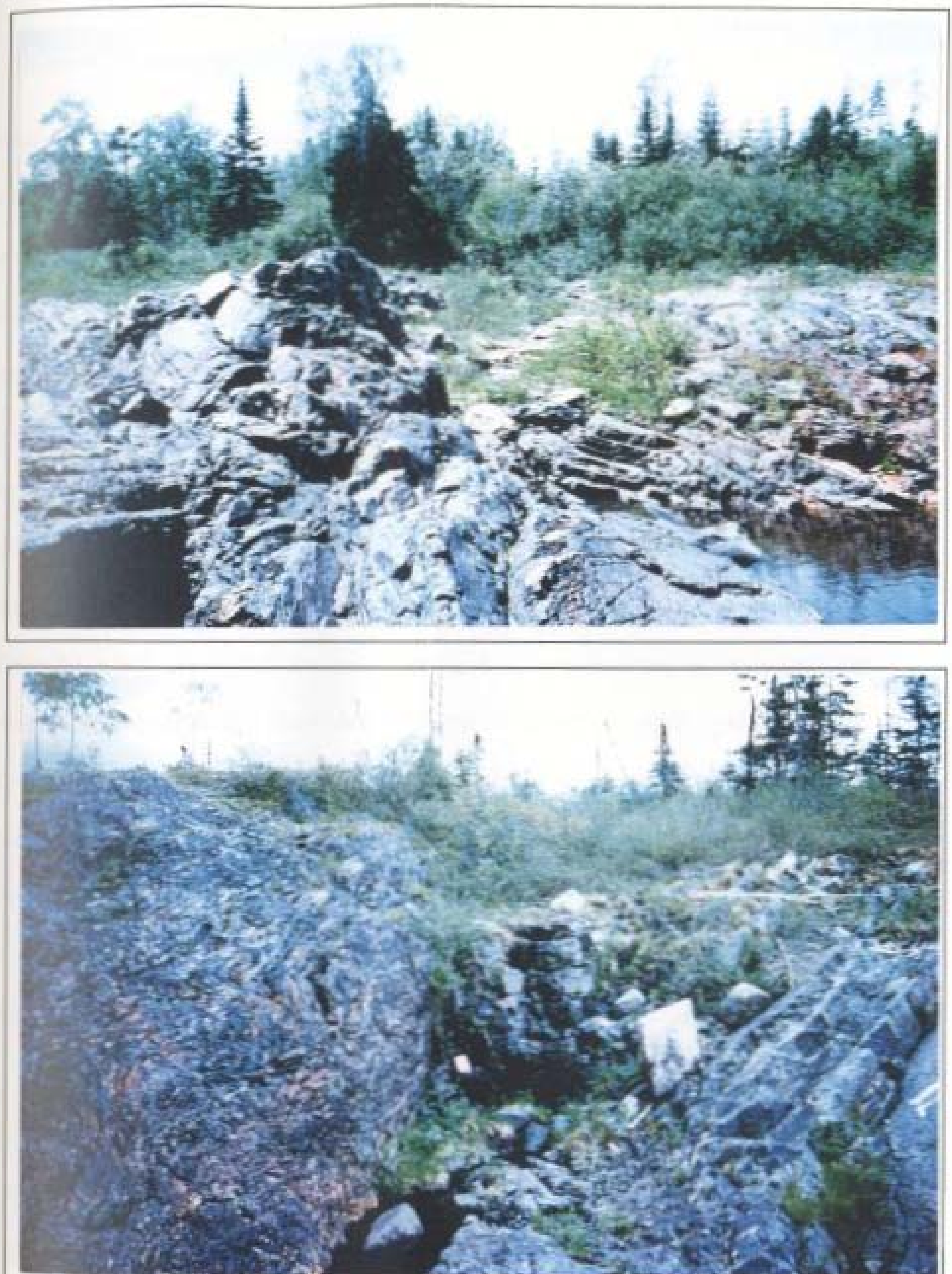


Figure 3.5: **Normal faults superposing siliceous black shale and grey bioturbated chert beds (field of view 5 metres). Upper photograph looking southwest, lower photograph looking northeast.**

cross-cut earlier F_2 folds. Displacement directions on fault planes are preserved locally in slickenside lineations which give both a northwest block up and northwest block down sense. Within shales of the Lawrence Harbour Formation stratigraphic relations are somewhat clear due to biostratigraphic constraints. They imply that there are several imbricate slices of Point Leamington Formation sandstones and black silty shales. This evidence is supportive of a phase of thrust faulting, with shales as the decollement horizon, and is likely related to the progression of F_2 folding. Within more competent chert beds, reverse and normal dip separation faults, with little to no observed strike separation, are found cross-cutting fold hinges. The majority of slickenside lineations along these fault planes indicate northwest-block up motion sense, but analysis of the cross section suggests that there are some cases indicative of overall northwest block down movement. Since slickenside lineation and fault grooves are not apparent on all fault surfaces, it is uncertain as to which phase of faulting is dominant at the Red Indian Falls locality.

3.3.2 Fold on the Exploits River Structural Map

Occurring about 25 kilometres west of Grand Falls-Windsor, along the Exploits River, there is a sequence of outcrops in which a succession of regional anticlinal folds cross-cut by several reverse faults is exposed. A detailed structural map and associated cross-section of this locality are illustrated in Figures 3.6 and 3.7. In the western portion of this area greywacke and interbedded fine-grained conglomerate are present. Farther east towards the hinge of the large regional fold, finer-grained sandstone and siltstone

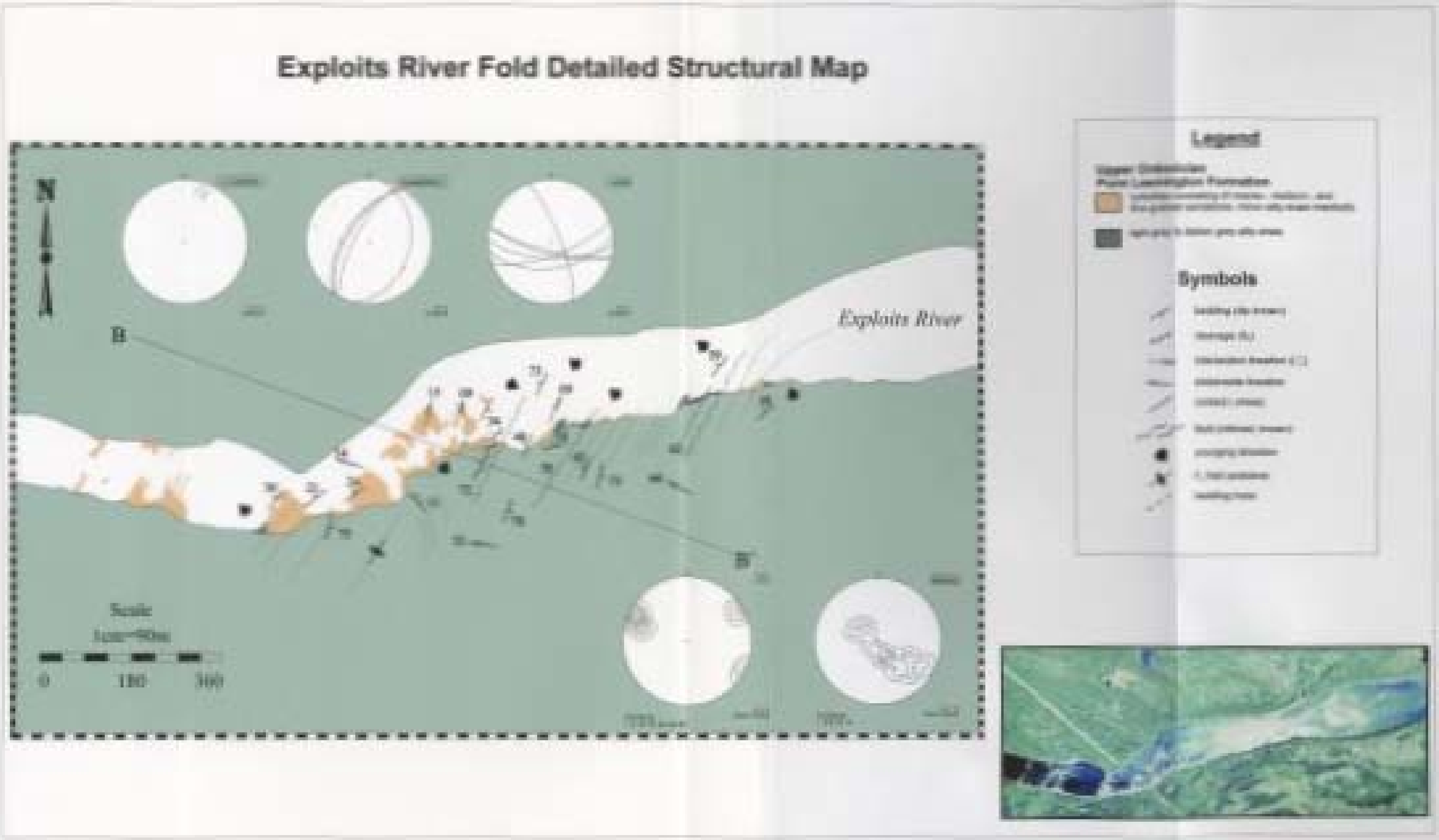


Figure 3.6: Exploits River fold detailed structural map.

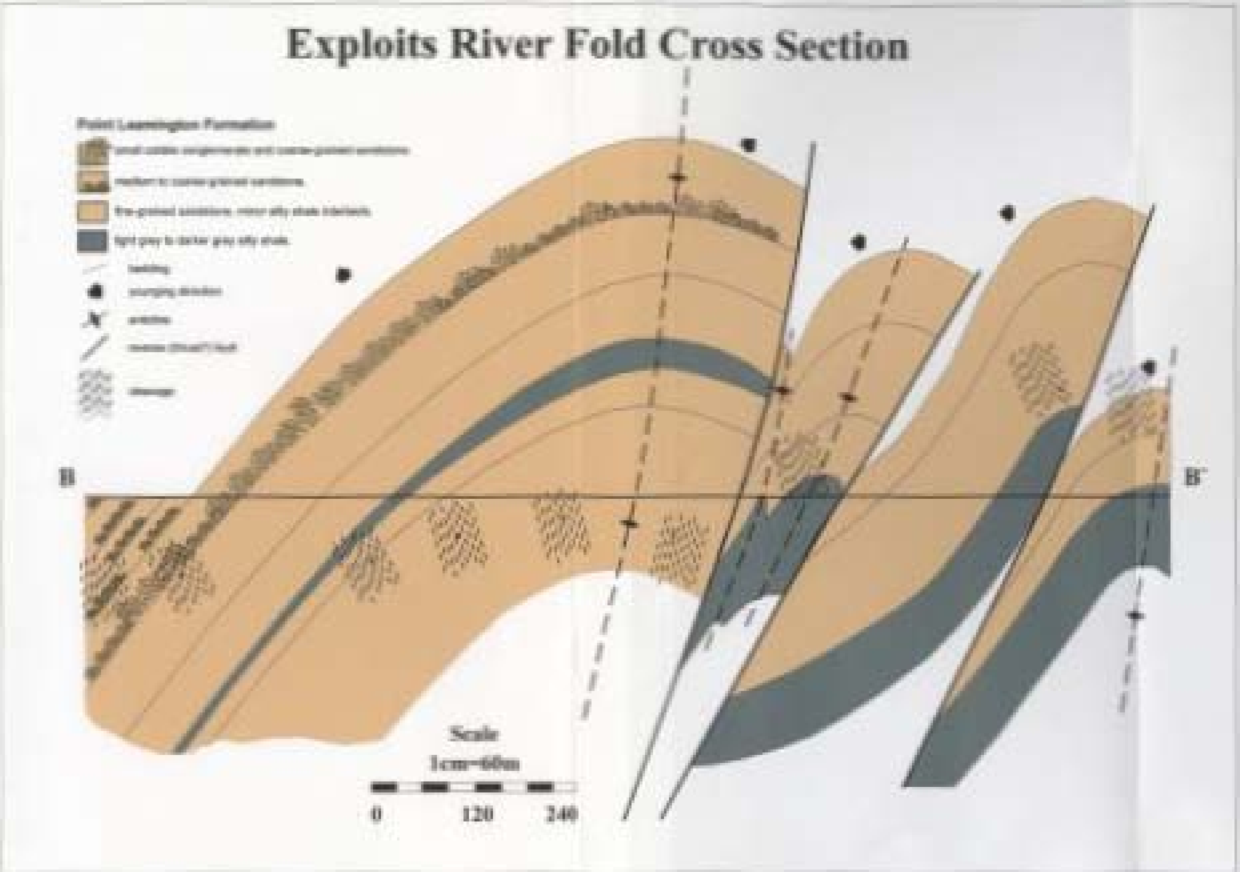


Figure 3.7: Exploits River fold cross section.

turbidite interbeds predominate. Younging directions are easily obtained in these layers as graded bedding is dominant. The eastern half of this map area consists of multiple packages of sedimentary rocks bound by steepened thrust faults. Coarser lithologies encountered in the west are not observed in the east suggesting that the east-facing limb of the anticline has been removed through faulting, and replaced by stratigraphically lower finer-grained lithologies. Bedding strikes predominantly northeast-southwest, and contoured poles to bedding have a common orientation such that the pole to a great circle girdle would approximate the orientation of measured fold axes, adding stereonet support to observed F_2 folding trends. Note that the poles to bedding plot on the map is lacking beds that dip steeply to the southeast reflecting the lack of southeast-facing fold limbs. Cleavage throughout the area is axial planar and fans through fold hinge regions producing slight variation to the strike of this fabric, although it is predominantly northeast-southwest (Figure 3.7)). Fold axial planes are vertical to steeply dipping towards the northwest, and fold axes plunge shallowly to the northeast at about 10 degrees on average. Again, slickenside lineations on bedding planes occur perpendicular to fold axes and indicate the presence of flexural slip folding along the turbidite layer contacts.

Fault planes strike northeast-southwest and dip steep to moderately towards northwest. Slickenside fibre lineations along these fault planes provide a displacement sense that indicates motion of the northwest block up, suggesting that these are reverse faults.

3.2.3 Red Cliff Overpass Structural Map

The Red Cliff Overpass locality is approximately 10 kilometres west of Grand Falls-Windsor along the Trans-Canada Highway. It consists of roadside and railbed exposure of Lawrence Harbour shales and Point Leamington Formation greywackes. Exposure also occurs along Leech Brook (Thunder Brook) and in scattered outcrop north of the highway (Figures 3.8 and 3.9)

Structurally, many of the same elements were observed here as were seen at the previous two localities. Bedding was found to strike northeast-southwest with variable dips due to folding. Evidence for the earlier F_1 folds was not observed at Red Cliff Overpass, but several F_2 regional and parasitic outcrop scale folds were mapped. Shales of the Lawrence Harbour Formation appear to be folded erratically in the northeast portion of the map area. Some of these may represent remnant F_1 folds or overprinting of F_1 folds by F_2 events. It is more likely, however, that these represent reorientation effects due to the Hodges Hill Granite intrusion that lies several hundred metres to the north. F_2 parasitic folds (Figure 3.10) also exhibited a spaced, fanning axial planar cleavage. F_2 folds are open to close with steep to vertical axial planes and predominantly shallowly plunging axes, although steeper plunges were recorded locally. F_2 fold axes and L^2_0 intersection lineations vary as illustrated on stereonet plots located on the detailed map (Figure 3.8). S_2 cleavage was also found to vary in strike and dip, especially nearest to the contact between the Hodges Hill Granite and the sediments.

Red Cliff Overpass Detailed Structural Map

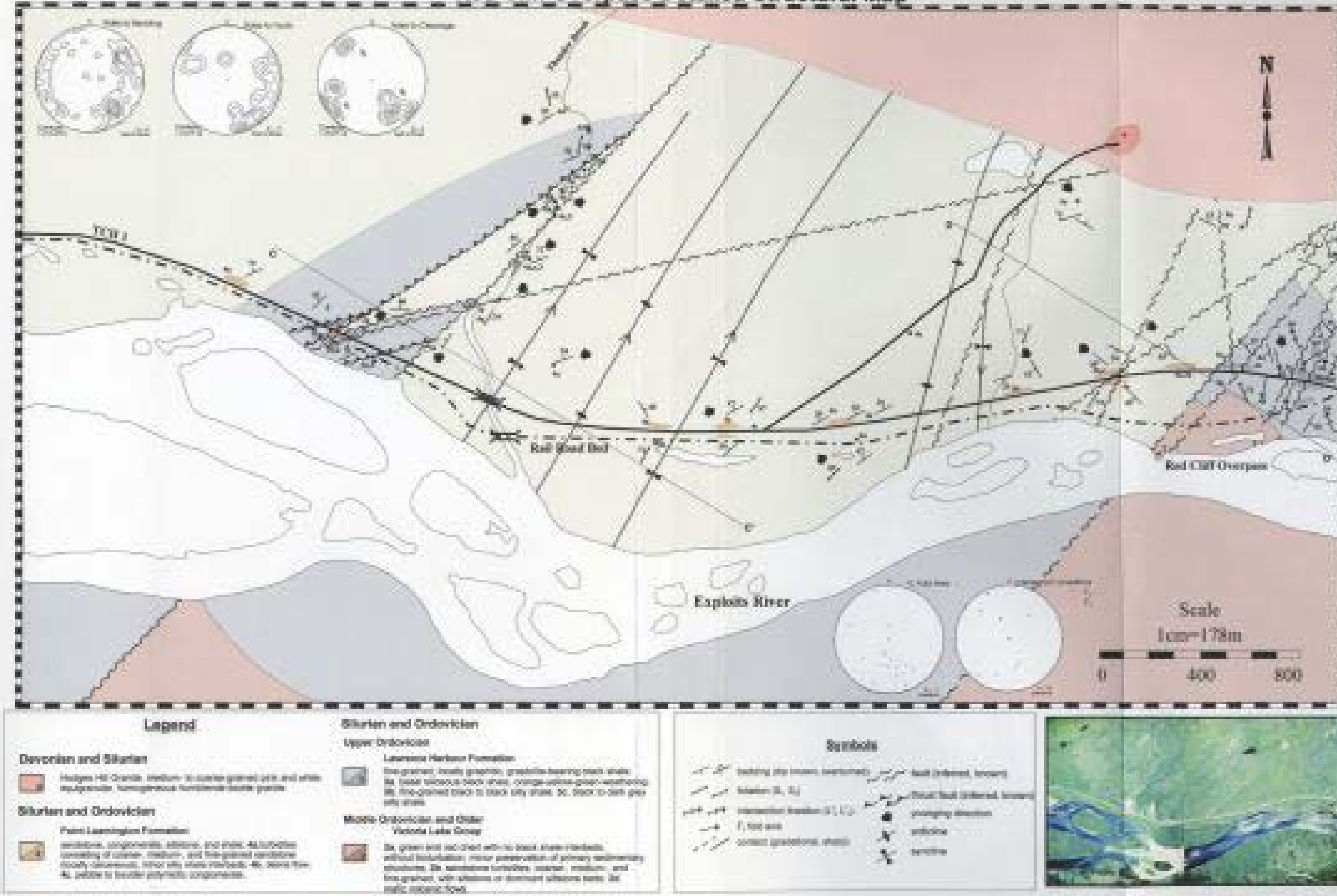


Figure 3.8: Red Cliff Overpass detailed structural map.

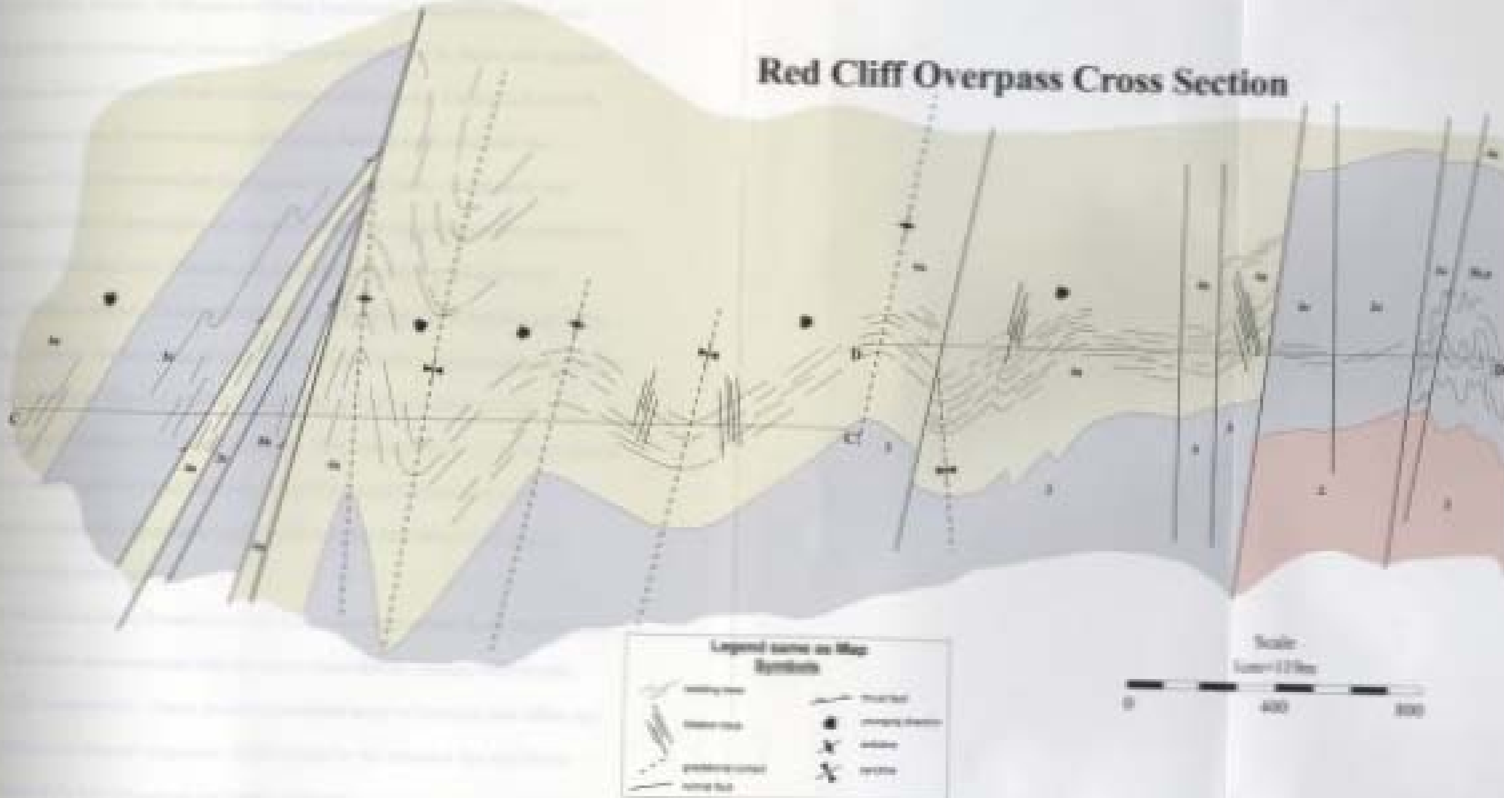


Figure 3.9: Red Cliff overpass cross section.

F_2 folds are cross-cut by D_3 faults, although there appear to be several different phases of faulting present. A sequence of Point Leamington Formation sandstones overlying black silty shales and siliceous black shales is bound by faults, and repeated several times across the are of Red Cliff Overpass detailed map (Figures 3.8 and 3.9). This is interpreted as D_2 reverse (steepened thrust) faulting associated with the progression of D_2 compression and faulting out of F_2 fold limbs. Imbrication and interbedding of Point Leamington and Lawrence Harbour formations is also observed in the Red Cliff Overpass area. Repetition occurs predominantly in the uppermost Lawrence Harbour shales. This is interpreted as earlier thrust faults that formed during F_2 folding, with the shales acting as a decollement plane below gradational contacts with overlying turbidites. The end result is a thickening and intermingling of Point Leamington and Lawrence Harbour lithologies. This faulting has led to regional outcrop patterns of mixed areas of Point Leamington and Lawrence Harbour formation. Imbrication of these two formations was also observed at Red Indian Falls, and is supportive of this interpretation.

In addition to these thrusts, there are also reverse and normal faults present in the Red Cliff area that are associated with D_3 deformation and the Hodges Hill Granite intrusion (D_5) respectively. These produce a complex array of fractures that offset and reorient previously formed structures. Uplift related to the intrusion has also led to reorientation of F_2 fold plunges to the south-southwest.

3.3 Revised 1:50 000 Geology

Due to the recognition of several additional structural elements and the location of previously unmapped outcrop localities, several revisions have been made to the 1:50 000 geology map (NTS 12A/16 east and 2D/13 west), of central Newfoundland. Overall, similar regional fold structures to those of Kean and Jayasinghe (1982) were observed; however, it was found that several new outcrops do not fit within the geographic distribution defined by their map sheets. The revised 1:50 000 scale map can be found as an insert at the back of this thesis. The regional cross-section constructed for the 1:50000 scale map was done by projecting structural measurements into the plane of cross section based on the assumption that F_2 regional folding was concentric with an average fold axis plunge of approximately 15 degrees northeast. Structures that are inferred in cross section appear as dashed, and are commonly based on mesoscopic scale observations. Note that when projecting data points nearest to inferred regional faults, gaps occur between footwall and hangingwall cutoffs. Even though correlation of lithologies throughout the map area suggests regional faulting, the implications of these projection gaps means that the faults may only be inserted as inferred structures.

It is important to note that although detailed mesoscopic maps define multiple stages of polyphase deformation, any inference of these mesoscopic details to the macroscopic regional picture is problematic. Reasons for this hinge on the fact that the main outcrops used for mesoscopic mapping occur on the fringe of the 1:50 000 map sheet, and are at a large distance from each other. It would be inaccurate to strictly apply the structural relations from each of these localities to the regional picture without knowing how they compare to more central localities within the mapped area. Since there were no ideal exposures within the central portions of the Grand Falls-Windsor-Badger region, no detailed mesoscopic maps exist for correlation with those from the fringe outcrop. It is apparent, however, that some regional trends do exist.

In addition to this, although the Lawrence Harbour Formation has been subdivided into different lithological units within mesoscopic maps, this was not done on the regional geology map. This is due to the limited exposure in the region leading to problems with correlating the shale lithologies over larger distances. Therefore, lithological variation is noted by a numerical identifiers (see legend 1:50 000 map), but with all lithologies of Lawrence Harbour Formation grouped together to define the unit's regional extent.

With data collected over the course of this study, several revisions were made to the interpretation of the regional geology of the Grand Falls-Windsor-Badger area. The main changes are as follows:

1) New outcrop localities led to revisions in the distribution of Lawrence Harbour Formation shale and identification of the mappable extent of underlying bioturbated chert.
2) Repositioning of several northeast-southwest trending faults, again aided by information from new outcrop localities. These faults also define regional fault-bound packages of Ordovician and Silurian sediments.

3) At Sandy Brook (east-central region of map) turbidites previously identified as Point Leamington Formation are assigned to the Victoria Lake Group based on preliminary graptolite identification and previously unmapped shale outcrop in the area.
4) The Crippleback Lake Quartz Monzonite was dated at 565 +4/-2 Ma (Evans et al., 1990) making its contact with the overlying volcanic and sedimentary rocks unconformable. Past geological maps have shown mid-Paleozoic structures cross-cutting the Precambrian unit without acknowledging the unconformity. The geological map accompanying this thesis defines the faulted edges of this excised basement rock as well as the unconformable contact with overlying strata.

Besides these changes, there were a number of problematic areas that were difficult to interpret. At several locations there appear to be exposures of interbedded Lawrence Harbour and Point Leamington formations. Rather than a complete section of shale, the Lawrence Harbour Formation in these areas is interpreted as being predominantly black shale with several turbidite interbeds in the uppermost layers. This trend was not noted everywhere across the region. As mentioned previously in Chapter 2, the base of the Point Leamington Formation has been defined as being diachronous. H. Williams et al. (1995) also noted that sediment input was approximately from the northwest. Therefore, in the northwestern regions of the map area, Point Leamington Formation turbidites may have prograded overtop Lawrence Harbour Formation shales earlier than in the southwest, producing the observed map patterns. At Red Indian Falls, several imbricate packages of these two sediment types were also observed. These fault-derived repetitions may have also contributed to the observed outcrop distributions.

Although the majority of mesoscopic northwest-dipping faults exhibit northwest block up (i.e. reverse) motion sense, the regional cross-section appears to illustrate an opposite sense suggestive of apparent normal faulting. Considering that compressional fold and steepened thrust fault structures are frequently observed in outcrop, and overturned beds and fold hinge zones are observed on a regional scale, it is unlikely that the apparent normal faulting is actually real. The regional map shows an apparent bi-directional strike slip motion sense between regional fault-bound packages. With an average plunge of 15 degrees to the northeast for regional F_2 folds, strike slip motion along these faults would reposition folded lithologies such that an apparent northwest block down normal fault sense would be observed. Therefore the implications of this interpretation are i) that concentric F_2 regional folding with an average fold axis plunge of 15 degrees northeast cross cut by these strike slip faults produces an apparent northwest block down motion sense, and ii) that there was a later stage of strike slip faulting along some of the regional fault planes.

3.4 Regional Structural Elements

Using evidence from the detailed structural maps, combined with regional structural data collected throughout the Grand Falls-Windsor-Badger region, several deformational stages were identified. In addition to the main phases listed above, there appears to be a later D_4 stage of strike-slip faulting and a D_5 related to the Hodges Hill Granite intrusion. A sub-horizontal crenulation cleavage was also observed within Victoria Lake Group sediments. It was observed at one locality only in the southwestern-

<u>Figure 3.10:</u> **Photograph of F_1 fold in siliceous black shale with associated blocky axial planar cleavage. Field of view approximately 2 metres across, looking north in cross section.**

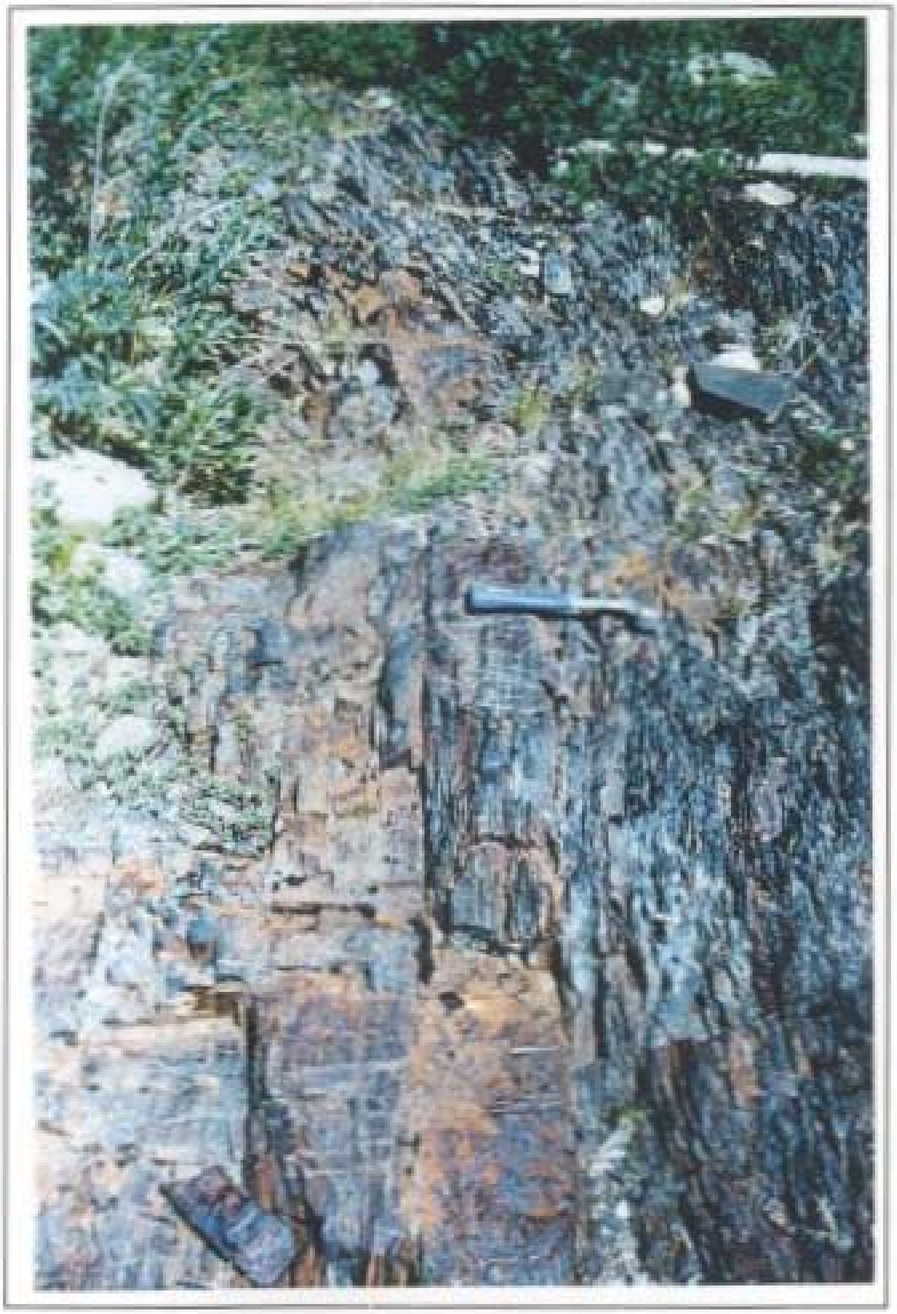


Figure 3.11: Photograph of fissile black shale beds where bedding and cleavage are near parallel. Hammer approximately 30 centimetres in length, view is to northeast..

most extent of the map area, and its regional extent is not known. Stereonet plots in this section are of two types: equal area stereonets were used for contoured values whereas equal angle stereonets were employed to determine angular relationships between planar and linear elements.

3.4.1 D_0 Deformation

Bedding (S_0) is defined by primary sedimentary layering, with graded bedding found within the overlying siltstone turbidites and possibly in underlying grey-green chert beds. Within shales, bedding is usually observed as laterally continuous horizons with well defined top and bottom contacts and a cleavage nearly parallel to bedding (Figure 3.11), although there are several shale outcrops that appear as massive and highly cleaved. Rip up clasts occur at the tops of some graded units (Figure 3.12). Layer thickness within the Lawrence Harbour Formation ranges from several millimetres to ten's of centimetres. Bedding throughout the Grand Falls-Windsor-Badger-Millertown region has a dominant northeast-southwest trend and dips steeply, predominantly to the northwest, except within fold hinge zones where strike and dip vary. A contoured stereonet plot of poles to bedding is provided in Figure 3.13a. Note that the highest population of poles to bedding is derived from a predominantly northeast-southwest striking, steeply northwest-dipping set of beds. A subsidiary maximum defines beds also with a northeast-southwest strike, but dipping to the southeast. These data represent measurements taken on the shorter limbs of regional asymmetric folds. In several cases bedding was recognised in outcrop as being overturned, with dips predominantly to the

Figure 3.12: Sedimentary structures used in determining younging direction, such as the shale rip-up clasts and graded bedding pictured above. Map view profile, with pen knife approximately 11 centimetres in length.

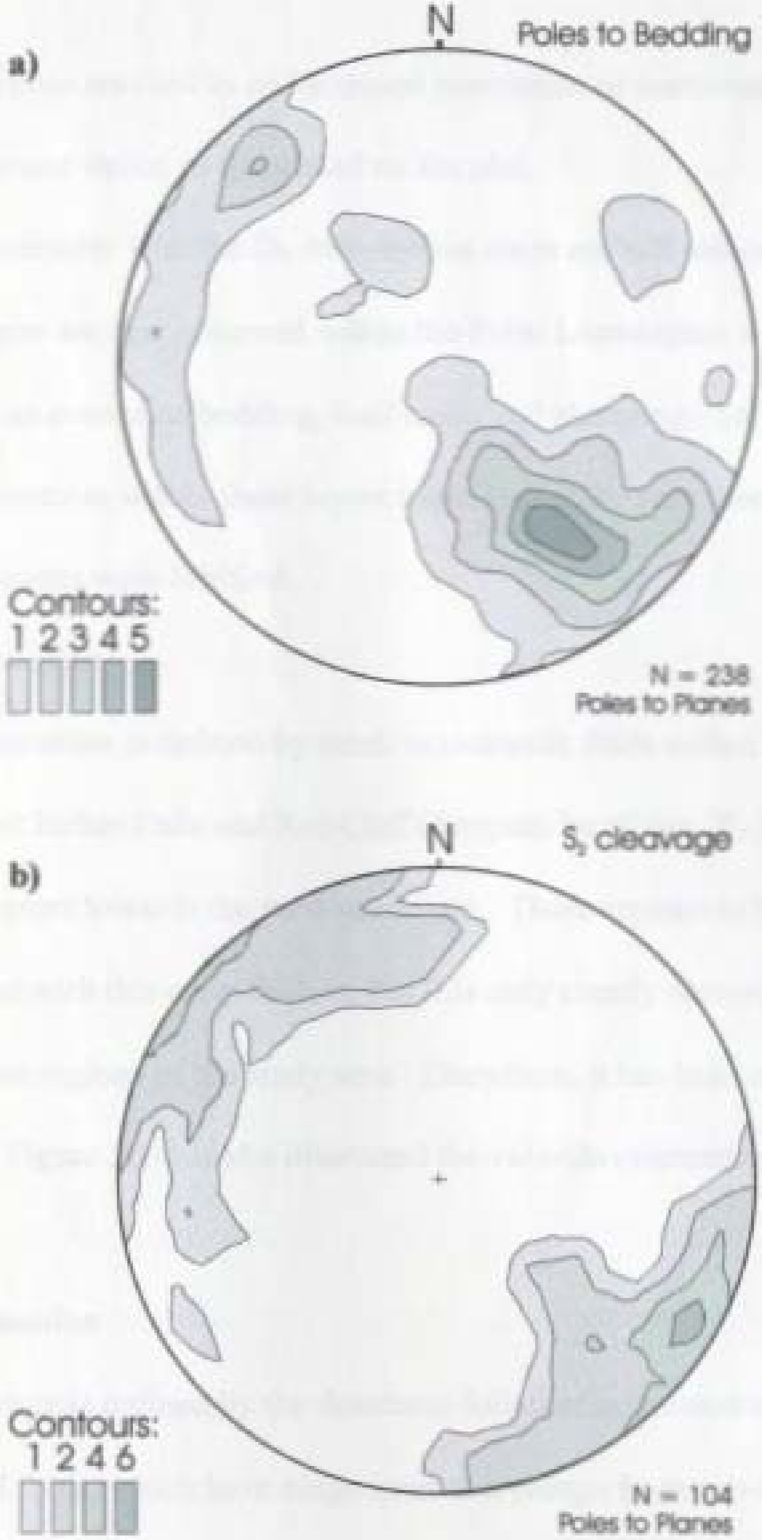


Figure 3.13: a) Contoured equal area stereonet plot of poles to bedding planes, b) Contoured equal area stereonet plot of poles to S_1 cleavage planes. Contour intervals per 1% area shown.

northwest. This has resulted in an increased population of northwest dipping beds with northeast-southwest strike, as illustrated on the plot.

Also associated with the D_0 deformation stage are soft sediment deformation structures. These are best observed within the Point Leamington turbidites and include structures such as convolute bedding, load casts, and slumping. Soft sediment deformation structures within these layers indicate that the area was tectonically active before the sediments were lithified.

3.4.2 D_1 Deformation

D_1 deformation is defined by small asymmetric folds within black shales occurring at Red Indian Falls and Red Cliff Overpass localities. F_1 fold axes plunge at about 30-45 degrees towards the west-northwest. There appears to be an associated fabric developed with this early folding, but it is only clearly observed predominantly in the western-most regions of the study area. Elsewhere, it has been overprinted by D_2 and D_3 structures. Figure 3.14b and c illustrated the variable orientations of L^1_0 and F_1 fold axes.

3.4.3 D_2 Deformation

S_2-cleavage is defined by the dominant foliation associated with F_2 open to close, steeply inclined folds, which have hinge lines that plunge from sub-horizontal to steeply northeast plunging. Figure 3.4 illustrates what at first glance appears to be cleavage refraction between black shale and grey, bioturbated chert. However considering the low angle that S_2 cleavage makes with bedding in the shales, and the implied very large angle of cleavage refraction (~110°) between the shale and chert beds, the cleavage refraction hypothesis seems unlikely. As explained earlier, a more plausible explanation lies in the contrasting competency of the units during subsequent extension, although this interpretation cannot be unequivocally proven with the available data.

S_2 foliations trend predominantly northeast-southwest and vary in dip depending on their location relative to fold limbs. The contoured stereonet plot of poles to S_2 cleavage (Figure 3.13b) illustrates the dominantly northeast-southwest strike, and shows that dips of S_2 tends to be steeper than bedding planes. The population straddles the primitive in both the southeast and northwest quadrants, illustrating dip changes as cleavage fans from one fold limb to the other. Also note that bedding-cleavage relations observed at the Exploits River fold (location B on 1:50000 map) are illustrated in cross-section as fanning and axial planar.

Bedding-cleavage intersection lineations (L^2_0) are shown in Figure 3.14b. Lineations plotting with shallow plunge to the northeast and southwest approximate the majority of F_2 fold axis orientations (Figure 3.14c). Figure 3.10 illustrates an F_2 fold with a weak axial planar cleavage within basal siliceous black shales. F_2 folds tend to have northeast-southwest, steeply inclined axial planes with fold axes that are subhorizontal or plunge gently to the northeast. Vergence in asymmetric folds, as defined by McClay (1987), is the horizontal direction of movement of the upper component of a fold as observed in a profile plane. By this definition, vergence of folds in the Grand Falls-Windsor-Badger region is to the southeast. A minority of fold axes was measured plunging shallowly to the southwest. On a regional scale, larger folds are recognised by variation in younging direction based on graded bedding and load cast observations

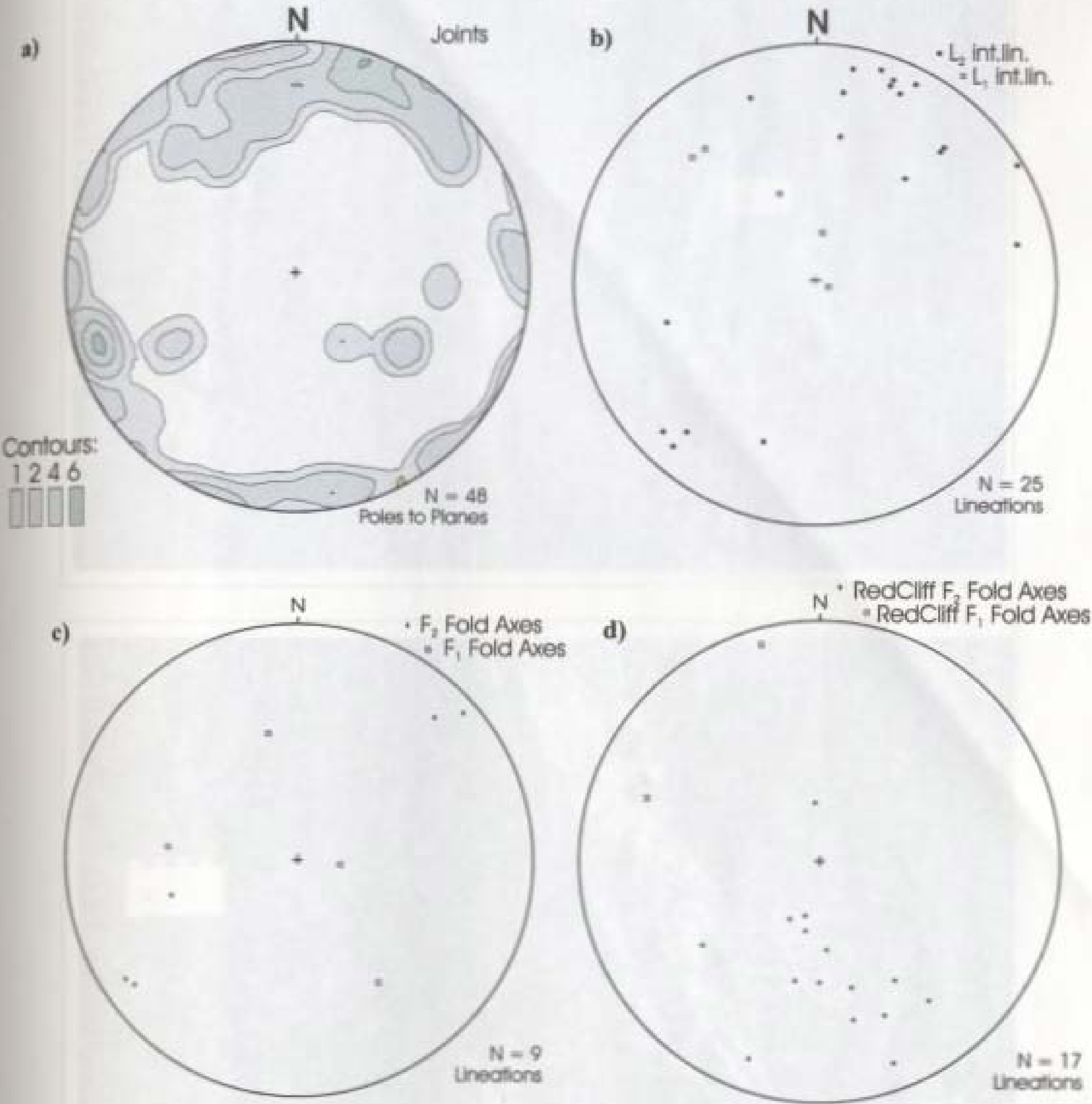
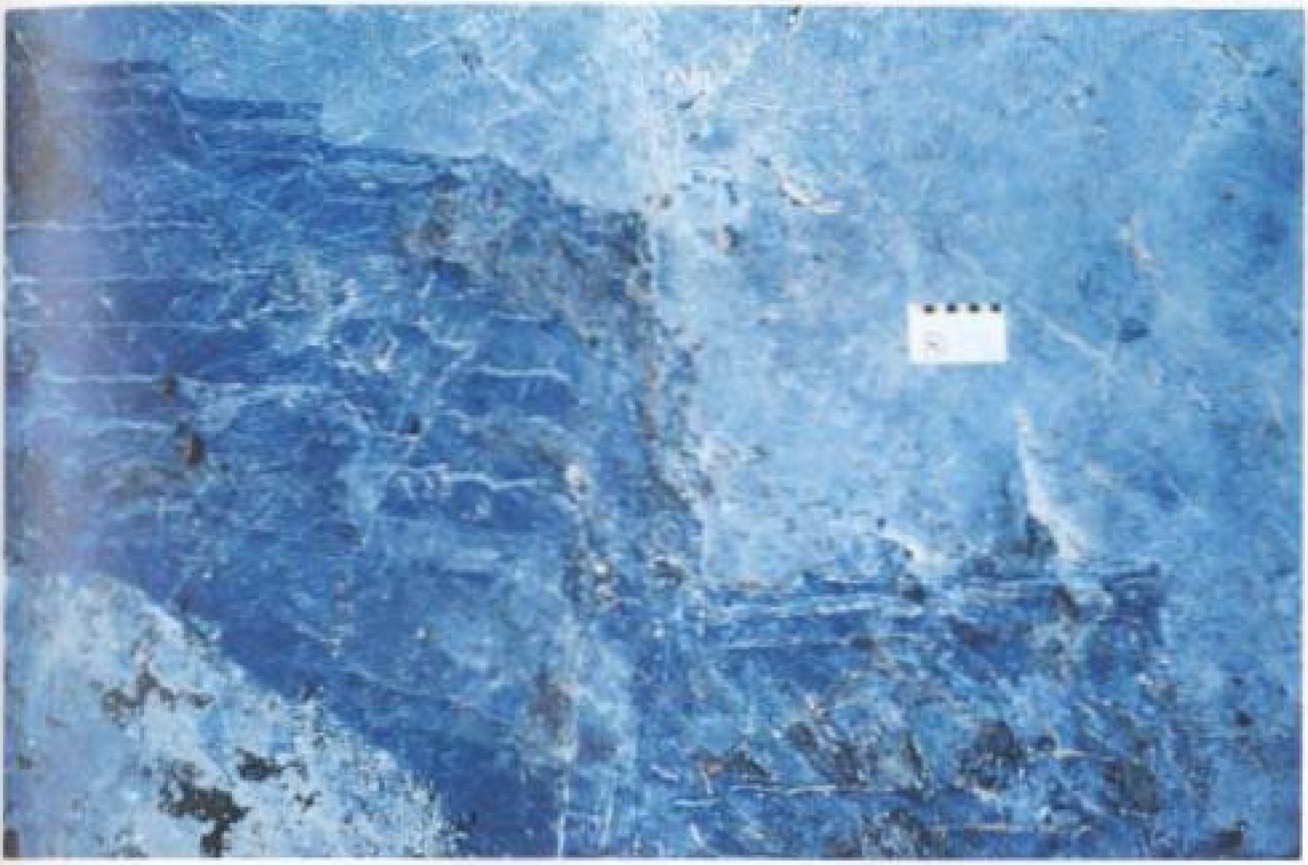


Figure 3.14: **a) Contoured equal area stereonet plot of poles to joint planes, b) Stereonet plot of L^2_0 and L^1_0 intersection lineations, c) Stereonet plot of F_2 and F_1 fold axes, and d) Stereonet plot of F_2 and F_1 fold axes measured at Red Cliff overpass, west of Grand Falls-Windsor.**



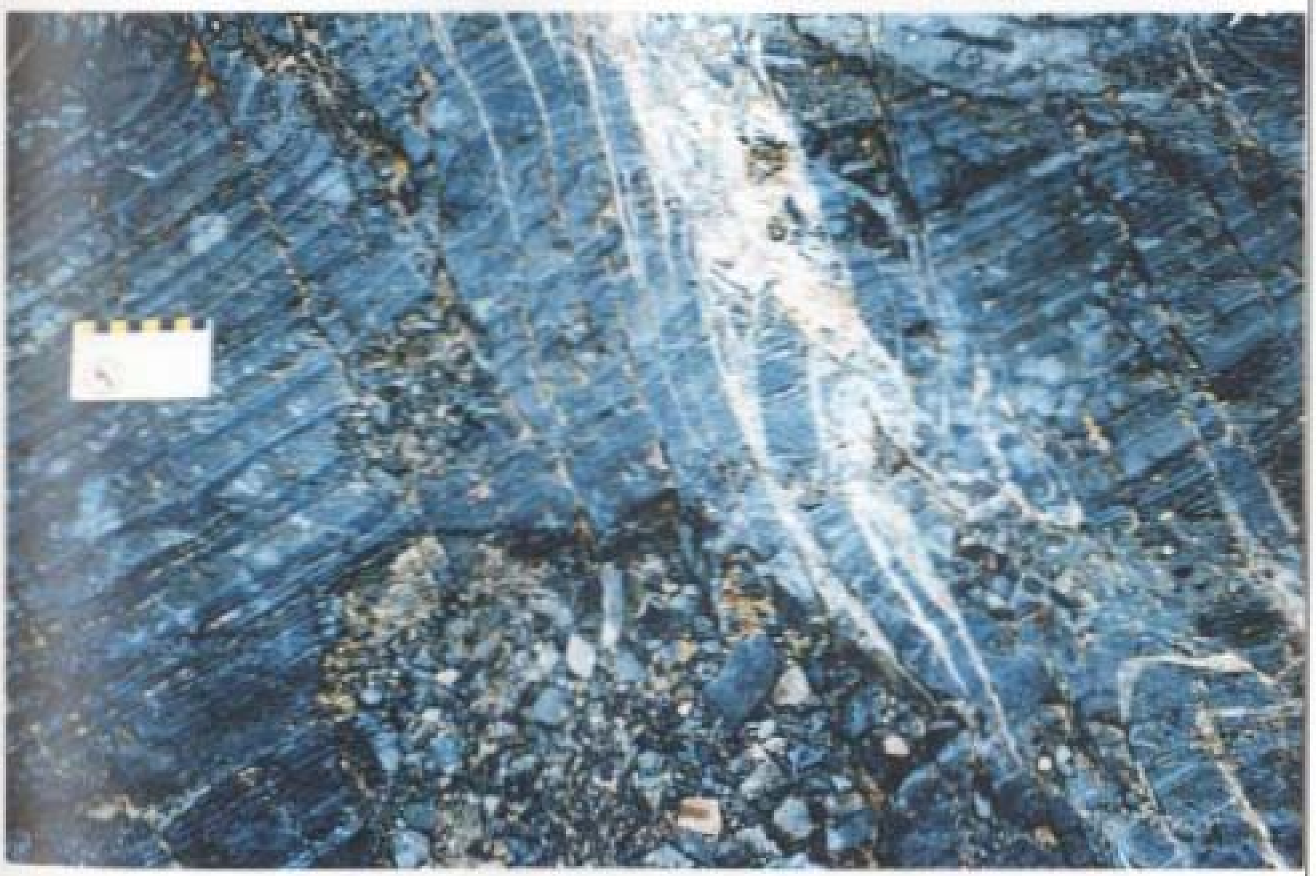


Figure 3.15: Upper: Photograph of centimetre scale brittle shears with dextral offset. Lower: Photograph of small scale kink folding cut by later tension gashes. Both are map or plan view profiles.

within Point Leamington turbidites (Figure 3.12). On a mesoscopic scale, folds occur as parasitic open to close folds with interlimb angles of about 100-60 degrees. As mentioned earlier, in the case of central Newfoundland, the Lawrence Harbour shales have undergone flexural flow folding while chert and sandstone layers have undergone flexural flow. The most commonly observed evidence of this is found as slickenside lineations along bedding planes that lie perpendicular to fold axial planes.

Figure 3.14d illustrates F_2 fold axes measured in shales outcropping at Red Cliff overpass. These exposures occur less than 500 metres from the Hodges Hill Granite and reflect a re-orientation of F_2 fold axes by this mid-Paleozoic intrusion.

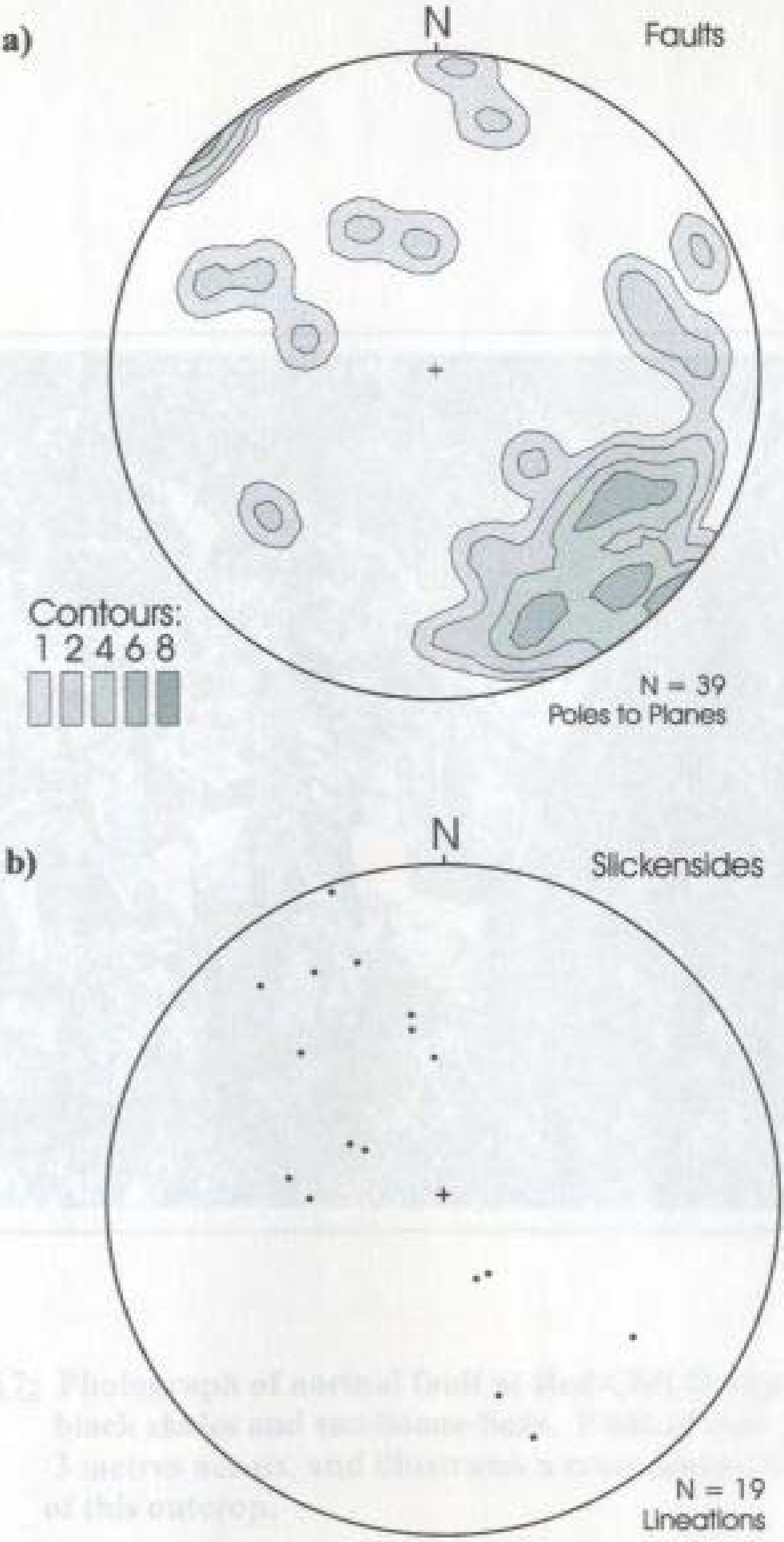
Many joint planes were also measured over the course of this study. Figure 3.14a illustrates a contoured stereonet plot of these measurements. Although this pole to plane plot appears to consist of many random fractures, there is some order to the measurements. The two maxima on the contour represent poles to planes that dip steeply and intersect at an angle of about 45 degrees. These represent a conjugate set of fracture joints that developed with folding. Poles to joint planes lying in the southeast and northwest quadrants represent joints that developed parallel to cleavage planes, again associated with folding.

Thrust faulting, producing imbricate and intermingled packages of Point Leamington sandstone and Lawrence Harbour shale beds, is also associated with the D_2 phase of deformation. These faults are best observed within the uppermost shale lithologies at Red Cliff Overpass and Red Indian Falls, as well as in outcrop distribution patterns at a macroscopic scale.

Figure 3.15 illustrates small, centimetre scale brittle shears with dextral offset of shale and sandstone interbeds within the Point Leamington Formation. These late stage shears consistently trend approximately northwest-southeast and are steeply dipping. Offset of these shears varies from centimetres (as in Figure 3.15) to about one metre as a maximum. The lower photograph in Figure 3.15 illustrates a pair of shears with conjugate geometry consisting of an older sinistral ductile (kink banding) component and a younger dextral semi-brittle (tension gashes) component. The dextral component (northwest-southeast striking) is the more dominant of the two, with kinematic indicators like en echelon tension gashes providing motion sense. Sinistral, approximately east-west striking shears appear to be less common and are only locally observed.

3.4.4 D_3 Deformation

Sometime after initiation and formation of F_2 folds and associated S_2 cleavage, thrust faulting, with a minor component of normal faulting, occurred. Examples of these faults are presented in Figures 3.5 and 3.17. The majority of these faults strike northeast-southwest (Figure 3.16a), commonly occurring along overturned, southeast facing fold limbs. Thrust repetition occurs on a metre scale within less competent shales, whereas in more competent chert and sandstone layers faulting tends to be spaced out over several ten's of metres and fold limbs are locally preserved rather than being faulted away. Slickenside lineations (Figure 3.16b) associated with faulting indicate a motion sense of northwest-block up and to the southeast, or southeast directed thrusting. Smaller splay faults that branch of the main fault plane and dip steeply to the southeast are locally associated with these thrust faults.



<u>Figure 3.16:</u> a) Equal area contoured stereonet plot of poles to fault planes, b) Stereonet plot of slickenside lineations.

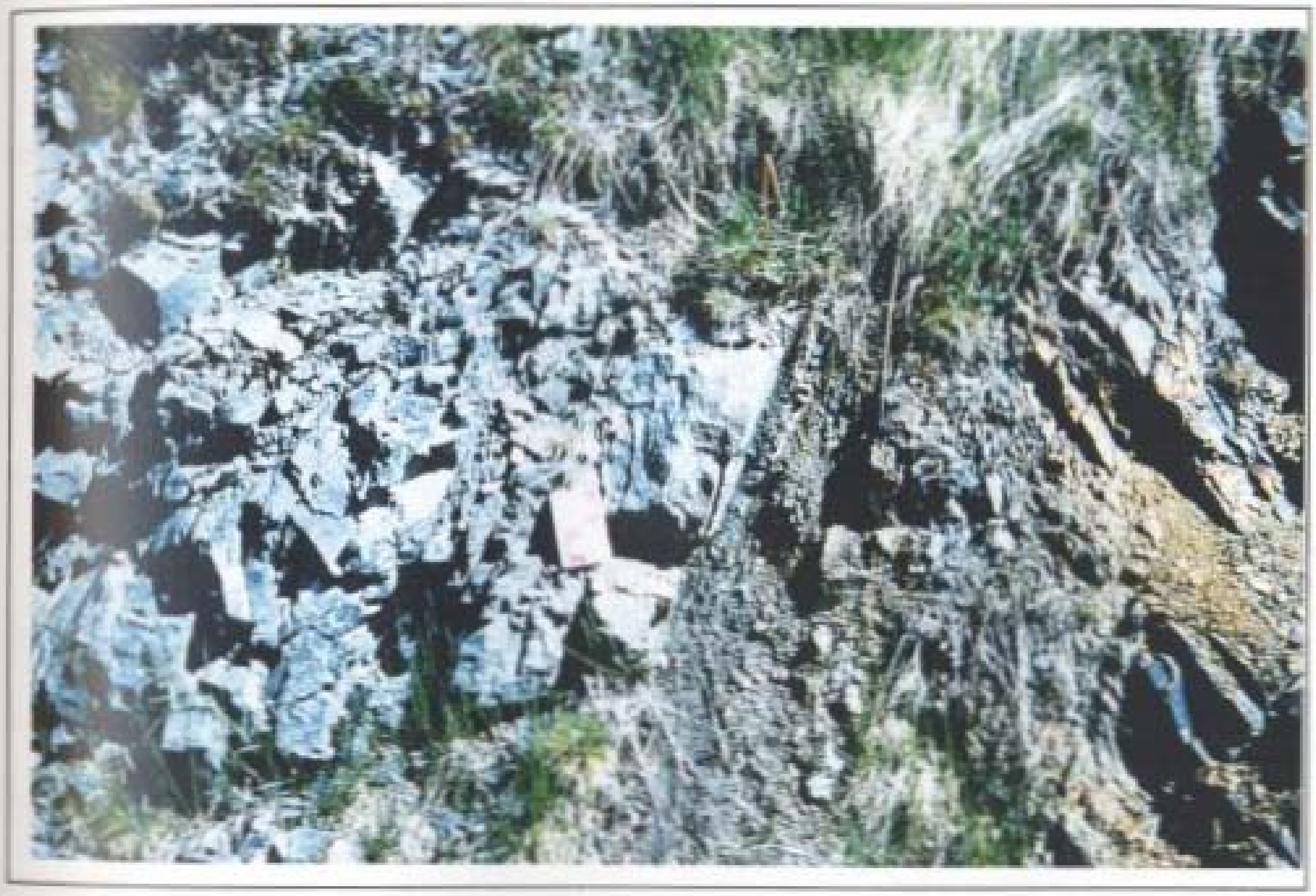


Figure 3.17: Photograph of normal fault at Red Cliff Overpass between black shales and sandstone beds. Field of view is approximately 3 metres across, and illustrates a cross section through part of this outcrop.

3.4.6 D_4 Deformation

Apparent bi-directional strike slip faulting striking northeast-southwest occurs on a regional scale representing the D_4 deformation. These faults separate the regional stratigraphy into fault bound packages usually composed of a F_2 syncline and anticline pair. Faults assigned to this deformation stage are found along overturned or excised southeast-facing limbs of the anticline-syncline pairs. Since on both a mesoscopic scale and regional scale steepened thrust faults occur in the same orientation, it is thought that initially these structures were associated with D_3 thrust faulting and were later remobilized through strike slip faulting.

3.4.7 D_5 Deformation

The mid-Devonian intrusion of the Hodges Hill Granite has produced a late stage deformation that re-orientates all other structures. It occurs on a local scale in the northeastern-most portion of the study area, near Red Cliff Overpass. D_5 is characterised by minor uplift nearest to the intrusive boundary and normal faulting offsetting earlier structures. Gentle warping of F_2 folds and re-orientation of F_2 axes in the area is noted and thought to be due to a monocline which parallels the intrusive margin resulting in a south-southwest F_2 plunge. Normal faulting is commonly observed cross-cutting the regional northeast-southwest trending structures. Locally, S_2 fabrics are also re-oriented, but they remain axial planar to F_2 folds.

3.5 Structural Evolution of the Grand Falls-Windsor-Badger Area

Table 3.1 summarises the deformation history of the Grand Falls-Windsor-Badger region based on observations from this study, with all deformation stages described below in terms of structural evolution. Note that deformation events described below are not intended to represent separate and/or distinct tectonic events, but are representative of relative relations between observed structures.

Initially, sedimentation during the Upper Ordovician produced the conformable stratigraphic packages observed in the Grand Falls-Windsor-Badger region. In the uppermost Ordovician, sedimentation was coeval with tectonic activity, leading to the observed debris flows and synsedimentary deformation structures within the Point Leamington Formation. This was followed by an early phase of northeast-southwest compression that produced the northwest trending F_1 folds. Although only a small population of D_1 structures was observed, several at Red Indian Falls suggest a sinistral shear sense to this deformation stage through their asymmetric shape. It is important to note that these D_1 structures are mainly observed in the western regions of the study area. O'Brien (1993) described several structural zones with northwest-trending elements as being related to D_1 and D_4 deformation events. One such zone lies northwest of the study area in Badger Group sediments (B. O'Brien, per. com). Therefore, it would appear that in the northwest portion of the map area, remnant structures associated with the northwest trending domain have been partially overprinted by younger events. Either the overprinting has almost completely obliterated the D_1 structures in central and eastern areas of the Grand Falls-Windsor-Badger region, or did not fully develop there. The

Table 3.1: Summary of Deformation Events and Associated Structures.

Deformation Stage	Structural Element	Characteristics
D_0	S_0	Bedding planes, predominantly striking NE-SW. Soft sediment deformation structures.
D_1	F_1	Mesoscopic asymmetric folding observed in black shales at Red Indian Falls.
	S_1	NW-SE striking cleavage associated with F_1 folding.
D_2	S_2	Well developed regional axial planar cleavage.
	F_2	Open to close folds with associated cleavage. Axial planes near vertical to NW dipping, and striking NE-SW. Fold Axes doubly plunging gently to NE or SW, overall on average of 15° NE at macroscopic scales.
	Faulting	Thrust faulting, related to folding, leading to imbrication in uppermost shales.
	L^2_0	Bedding-cleavage intersection lineation. Approximately parallel to F_2-fold axes.
	J_2	Conjugate joint sets associated with D_2 folding event.
	Shearing	Conjugate sets of E-W and NW-SE brittle/ductile shears. Both dextral and sinistral offset observed.
D_3	Faulting	SE-directed reverse (steepened thrusts) and minor normal faulting usually associated with southeast-facing fold limbs.
	L_m	Slickenside fibre lineations along thrust fault planes.
D_4	Faulting	Regional strike slip faulting.
D_5 Hodges Hill Granite Intrusion	Faulting	Localised to Red Cliff Overpass Region. Normal faults, motion sense unknown. Strike is approximately north-south, variable to southwest and southeast, and steeply dipping. Localised re-orientation of older structures.

origin of D_1 deformation is unknown; however O'Brien (1993) related these northwest-trending structures to collision involving southwestward tectonic transport.

Next, the dominant northeast-southwest structures of the area were produced through northwest-southeast compression. This event formed the regional northeast trending open to close F_2 folds and their associated axial planar cleavage, as well as a conjugate set of joints associated with folding and minor thrust faulting that imbricated uppermost Lawrence Harbour and Point Leamington formation beds. The D_2 phase was followed by a D_3 stage of reverse and minor normal faulting, resulting in structures that strike parallel to D_2 structures in a northeast-southwest orientation. Slickenside lineation data along a majority of D_3 fault planes indicate northwest block up motion, and dips of these reverse faults range from 50 to 78 degrees to the northwest. Reverse faults of this nature have been described as steepened thrust faults by O'Brien (1993), which in the Badger area are indicative of southeast-directed thrusting. Due to the nature of D_3 faults (southeast-directed thrusting, with strikes parallel to F_2 axial planes) these structures may be related to the progression of northwest-southeast compression during D_2. They have been separated out in this study because the faults cross-cut D_2 related folds, but it is likely that the thrust faults and F_2 folds are related to different stages of the same deformation event. Both D_2 and D_3 structures are cross-cut by a set of compressional shears with conjugate geometry. These small shear zones commonly show both dextral and sinistral offset over 1 to 10 centimetres. The second and third deformation events are likely due to Salinic and Acadian orogenies during mid-Silurian to mid-Devonian times.

D_4 deformation was defined through regional mapping as apparent strike slip faulting (both sinistral and dextral offset) with large strike separation, recognised through identification of offset regional anticline-syncline pairs. Many authors (e.g., Blewett and Pickering, 1988; Lafrance and Williams, 1992; and O'Brien, 1993) describe regional late stage strike-slip faulting in the Exploits Subzone, adding support to this interpretation. Their role with respect to the polyphase deformation history is unclear, but they may have resulted in the development of new structures, F_2 folding and faulting, or have caused remobilization of D_3 faults. The remobilization hypothesis appears most likely, however because all of these regional faults (D_4) lie along structural zones of weakness associated with overturned F_2 fold limbs, thus suggestive of a relation to earlier (D_2 or D_3) structures. The F_2 and strike slip faulting situation also seems problematic due to the lack of observed mesoscopic faults that record evidence of strike slip motion. Since orientations and dips of the regional strike slip faults appear to parallel the orientation of mesoscopic steepened thrust faults, it seems likely that these D_4 faults record later strike slip movement along initial regional thrusts associated with D_3 deformation.

A final D_5 stage of deformation involved intrusion of the Hodges Hill Granite in the northeast portion of the study area. This mid-Devonian intrusion re-oriented D_2, D_3, and possibly D_4 structures. Intrusion of large batholiths, such as the Hodges Hill pluton, are though to mark the end of the Acadian orogeny (Kusky, 1985).

Chapter 4

Geochemistry

4.1 Introduction

Deposition of the Lawrence Harbour Formation represents the establishment of deep marine, anoxic conditions and subsequent burial by basin infill sediments related to a major, early Caradoc transgression. A subject of debate with respect to the evolution of central Newfoundland terranes during the Ordovician concerns whether one large, or several small basins were present (H. Williams, 1995a). As a marker unit, the Upper Ordovician shales appear to occur throughout the Exploits Subzone. With this in mind, shale samples were collected in an attempt to fingerprint signature variations on a vertical and lateral scale, and thus identify possible changes in basin characteristics.

Geochemical compositions of shale are influenced by several first order processes. These include weathering, source rock composition, sorting, and diagenesis, which are themselves further influenced by tectonic setting of source regions, transportation systems, and depositional environment (Johnsson, 1993). Even though these processes operate together in affecting the geochemical characteristics of sediment, correlations between sediment composition and tectonic setting are often observed (e.g., McLennan et al, 1990; André et al., 1986). The use of rare earth element (REE) data in determining provenance and tectonic setting has been well documented in recent geochemical studies on sediments. Much of this work has involved the use of sand and mud fractions of deep-sea turbidites (e.g., T.M. Williams et al., 1996; McLennan et al., 1990). In the past, fine-grained sediments were rarely used in petrographic studies. More traditional applications of widespread shale horizons involved use of the units, particularly when fossiliferous, as stratigraphic marker horizons (e.g., S.H. Williams, 1991b). With increasing focus on geochemical studies of sediments, use of shales as possible provenance and tectonic indicators has become more appealing. André et al. (1986) and McLennan et al. (1993) have shown that shales are reliable indicators of provenance and tectonic setting provided that there is some component of fine-grained terrigenous sediment present (i.e., the sediment is not entirely pelagic in origin).

4.2 Diagenetic Considerations

Geochemical signatures of fine-grained argillaceous rocks are commonly influenced by several primary factors, as discussed above. Of these processes, none have as profound an effect as diagenesis. In shales there are several stages of diagenetic reactions that convert siliceous muds to layered authigenic clays, all of which involve dewatering and removal of Si, Al, Fe, Ca, Na, Mg, and K ions from rock into pore waters.

Although geochemical signatures of argillaceous rocks have been used by others to infer source terranes and tectonic histories, it is not yet an exact method. Element mobility during diagenesis and metamorphism is still not fully. As a result, one must infer that mobility has affected all rocks equally and thus signatures are not completely reflective of their source terranes. It has been shown, however, that trace- and REE geochemistry can be used successfully in studies of provenance and basin evolution (e.g. T.M. Williams et al., 1996). Furthermore, SEM analyses of Lawrence Harbour Formation shales illustrates about 75% of primary sediment (quartz) constituent with a maximum of 25% of composition being diagenetic clays suggesting only minor amounts of diagenetic alteration for these rocks.

Element ratio plots of 'mobile' versus 'immobile' components can also be used to establish diagenetic effects. Certain ratios should remain similar if the shale samples were originally homogenous. A scattering of the ratios can be taken as an indicator of element mobility. In the case of major elements, samples of the Lawrence Harbour Formation produced a somewhat scattered plot suggestive of a minor amount of mobility, whereas trace and REE appear to suggest immobilty with both linear and tightly clustered plots. Finally, it is unlikely that all samples experienced similar degrees of diagenetic mobility across the entire region. As a result, the homogenous signatures of the tracer and REE data described below for the Lawrence Harbour shales suggest that the elements were immobile.

In this study data obtained from analyses of Lawrence Harbour Formation samples are therefore considered to be indicative of original geochemical signatures with regard to trace- and rare earth elements. Major elements are considered to have undergone modification and hence to be unreliable. Any further insight toward the diagenetic mobility/immobility problem could be derived from an X-ray diffraction study of diagenetic clay elemental composition within shale samples. However, due to time constraints, this was not conducted over the course of the present study.

4.3 Approach

A total of 39 shale samples were collected from the Lawrence Harbour and equivalent formations. Samples collected from several regions (Dunnage melange, Conne River, and Glenkiln Burn) were included for comparative purposes. Geographic locations of samples were recorded by Global Positioning System (in UTM co-ordinates) and biostratigraphic levels determined where possible. Sample density decreases away from the main region of study in the Grand Falls-Windsor-Badger-Millertown area.

Shale outcrops with penetrative slaty cleavage commonly occurs in friable and weathered exposures. Furthermore, a minor number of shale outcrops located stratigraphically in the basal portions of the LHF, are highly siliceous. Care was taken to collecting representative samples so that weathered and siliceous outcrop was either avoided entirely, or samples were removed below weathering levels.

All samples were analysed for trace- (Pb, U, Th, Rb, Sr, Y, Zr, Nb, Ga, Zn, Cu, Ni, La, Ti, Ba, V, Ce, and Cr) and rare earth elements (REE's), as well as major oxides. Analytical procedures and data tables are listed in Appendices C and D. Elements chosen for extended REE and ternary plots were selected due to immobility during diagenesis, their ability to reflect sedimentary processes, and the geochemical signature of the source terrane. All samples have been normalised against primitive mantle values (cf. Rollinson, 1994). Normalisation is done to compensate for the Oddo-Harkins rule, where natural abundances of even atomic numbered elements is enriched relative to odd atomic numbered elements. There are several accepted normalisation data sets and all of which are valid for this data set, however, the primitive mantle values are commonly used in sediment provenance studies and will be used for the purposes of this study.

4.4 Trace and REE Variation in the Lawrence Harbour Formation

Extended REE and trace element plots are commonly used to discriminate between differing provenance and geochemical signatures. The Lawrence Harbour shales were subdivided into two groups based on these plots. The first group is characterised by strong Zr, Hf, Ti depletion, a negative Eu anomaly, and light REE (LREE) enrichment relative to the remainder of REE's (figure 4.1a). For the most part, this group consists of samples from the *C. bicornis* graptolite Zone, with a few samples from the lowermost *D. clingani* Zone. Lithologically, this corresponds to siliceous, very fine-grained black shale, with or without secondary pyrite. Element concentrations appear to vary inversely with quartz content, indicating a quartz dilution effect, but all samples appear to exhibit similar patterns. A few samples show minor negative Y anomalies. Sample jc0026, has negative Ce and Nd anomalies but otherwise follows a trend similar to the others. A single sample of Dunnage Melange matrix shale was also included on this plot due to the similarity of its extended REE signature to those of Group 1 shales from the Lawrence Harbour Formation. The Dunnage Melange formed as a major slump unit composed of clastic and mafic volcanic rocks within a shale matrix (H. Williams, 1995), that is overlain by Upper Ordovician shales in the northwestern Exploits Subzone (Horne, 1969). There have been several ages provided for blocks within the melange (e.g., Kay and Eldredge, 1968; Hibbard et al., 1977; H. Williams, 1995) but the source of the matrix shales is unclear. Recent isotopic dating of the Coaker Porphyry (an intrusion contemporaneous with melange emplacement) suggests an Early to Middle Ordovician time of formation (H. Williams, 1995). The shale melange matrix analysed in this study exhibits a signature similar to that of Lawrence Harbour shale (Figure 4.1a). Similarity of REE patterns suggests that further geochemical study may prove to be an asset in further studies of the Dunnage Melange Matrix, and whether it is related to the Lawrence Harbour Formation.

A second group of samples with similar trends reflects a geochemical signature related to a silty shale lithology that spans the lower *D. clingani* to *P. linearis* zones. It is defined by a minor depletion (or rare enrichment) of Zr, Hf, Ti , a negative Eu anomaly and a minor LREE enrichment over HREE's (figure 4.1b). Sample jc0025, which is listed as early *C. bicornis* Zone, falls within this population even though on the basis of age it should be found within the first grouping. This may be the result of a misidentification of graptolites or a change in lithology in the region sampled. Note that the youngest specimen, taken from silty shale near the contact between the Point Leamington and Lawrence Harbour formations exhibits strong Zr and Hf enrichment relative to the REE's which may reflect a more terrestrial source.

Several samples taken from the Baie D'Espoir region, southern Newfoundland,

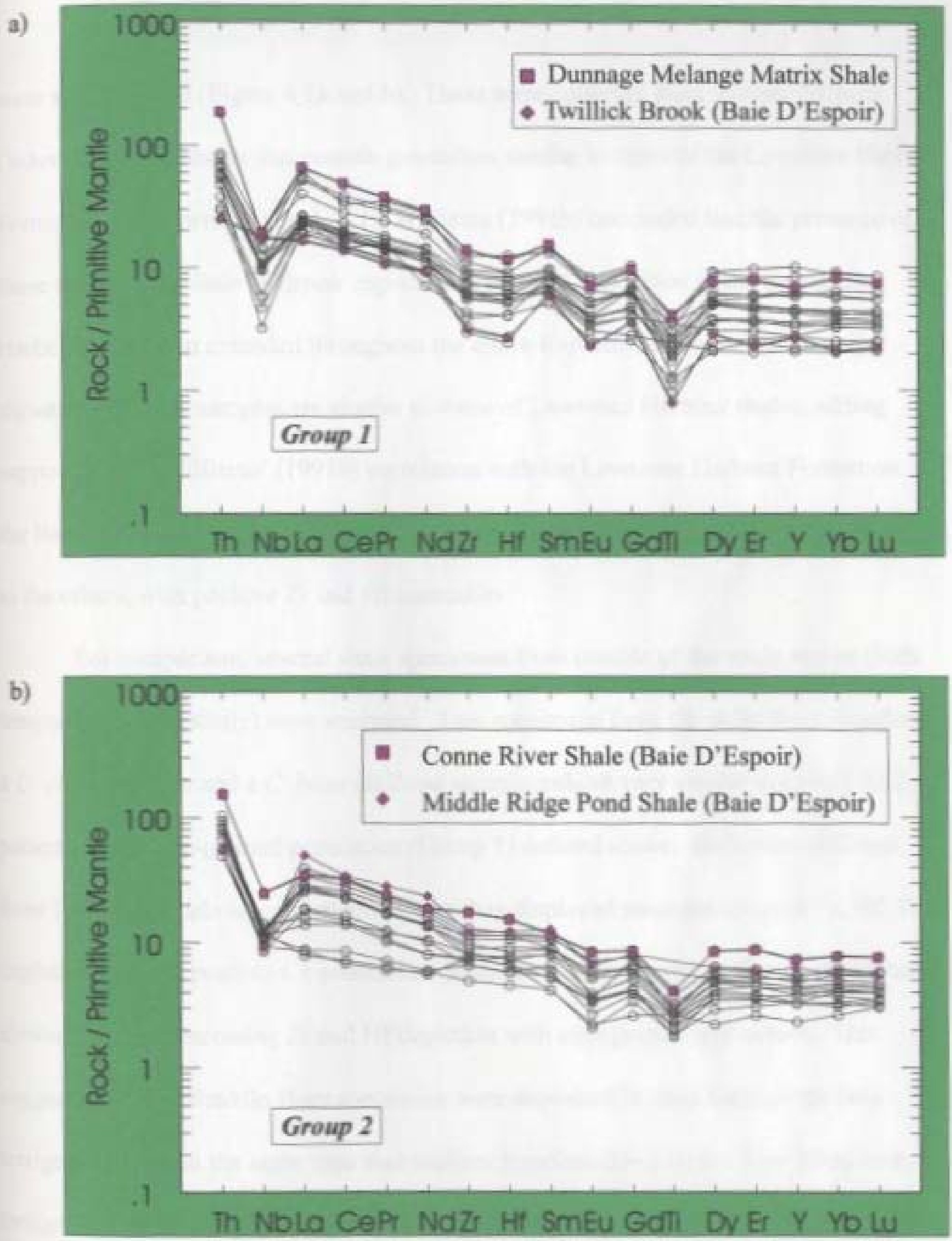
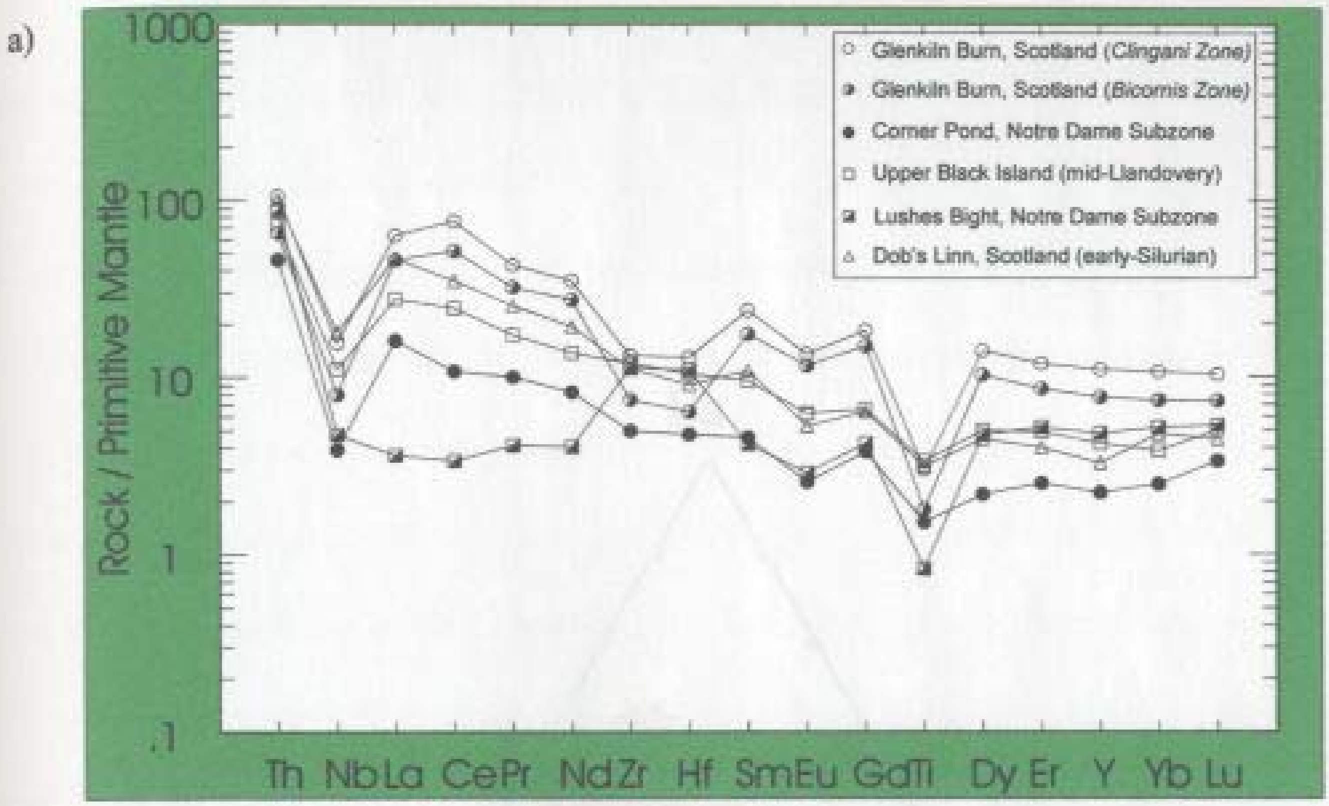


Figure 4.1: a) Group 1 extended REE plot, and b) Group 2 extended REE plot. Individually listed samples were collected from outside the study region.

were also analysed (Figure 4.1a and b). These were collected from unnamed Upper Ordovician black shales that contain graptolites similar to those of the Lawrence Harbour Formation of the present study. S.H. Williams (1991b) concluded that the presence of these shales in the Baie D'Espoir region indicated that deposition of the Lawrence Harbour Formation extended throughout the entire Exploits Subzone. Geochemical signatures of these samples are similar to those of Lawrence Harbour shales, adding support to S.H. Williams' (1991b) correlation with the Lawrence Harbour Formation. Of the Baie D'Espoir samples, the Conne River specimen exhibits a slightly different pattern to the others, with positive Zr and Hf anomalies.

For comparison, several shale specimens from outside of the study region (both temporally and spatially) were analysed. Two specimens from Glenkiln Burn (Scotland), a *D. clingani* Zone and a *C. bicornis* Zone sample, exhibit very similar trace and REE patterns to the fine-grained population (Group 1) defined above. Both were different from Lawrence Harbour equivalents in that they displayed more pronounced Zr, Hf, Ti depletion and had positive Ce anomalies. It can be shown, however, (Figure 4.2a) that a similar trend of decreasing Zr and Hf depletion with stratigraphic age occurs. This suggests that the Glenkiln Burn specimens were deposited in deep basins with little terrigenous input at the same time that shallow Newfoundland basins were filled with terrigenous material. This is supported by T.M. Williams et al. (1996) and Colman-Sadd et al. (1992a), who have suggested that black shale deposition in both Newfoundland and Scotland began in the Upper Ordovician, but continuing well into Early-



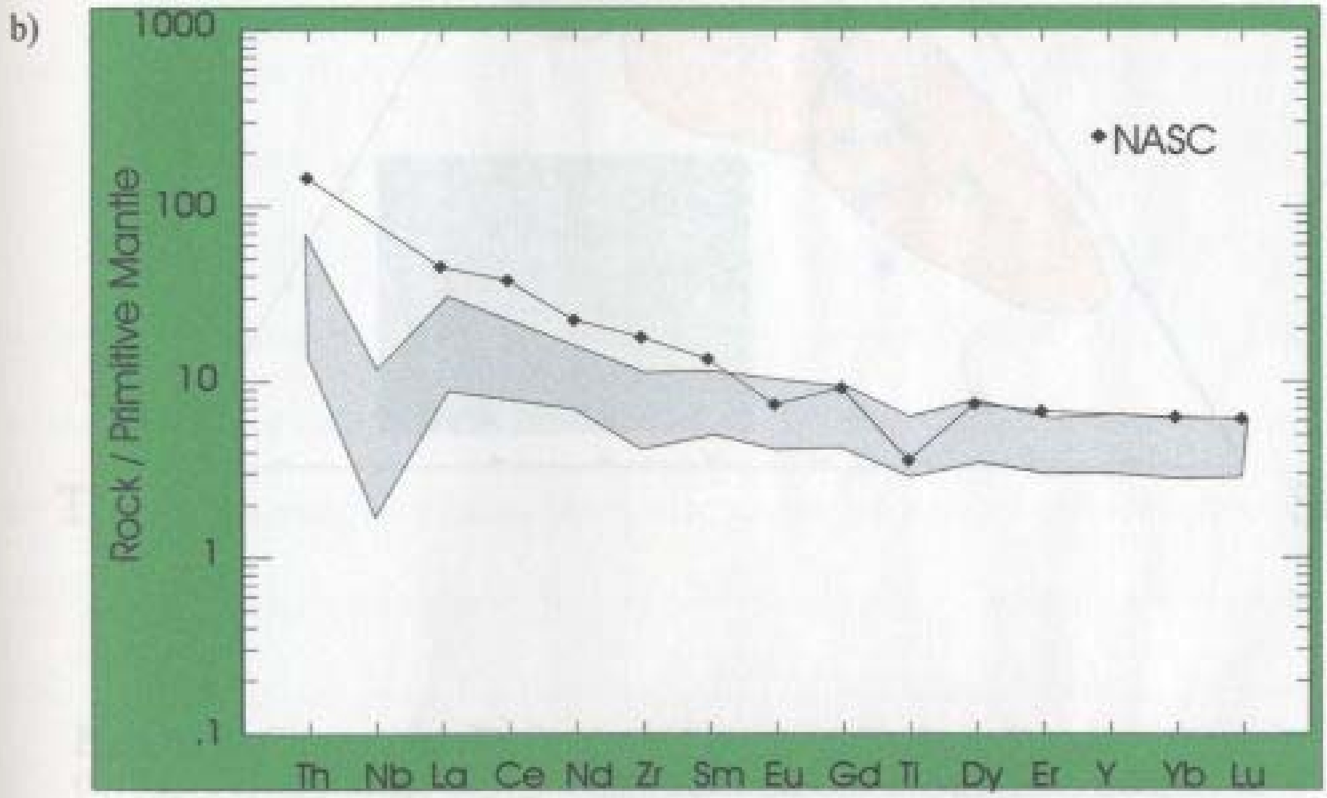


Figure 4.2: **a) Extended REE plots of comparative samples including Scottish equivalents of the Lawrence Harbour shales, and b) Average extended REE plot values of Dunnage Zone volcanic rocks (grey) plotted with North American Shale Composite (NASC; Gromet et al, 1984) values (After Carter et al, 1997).**

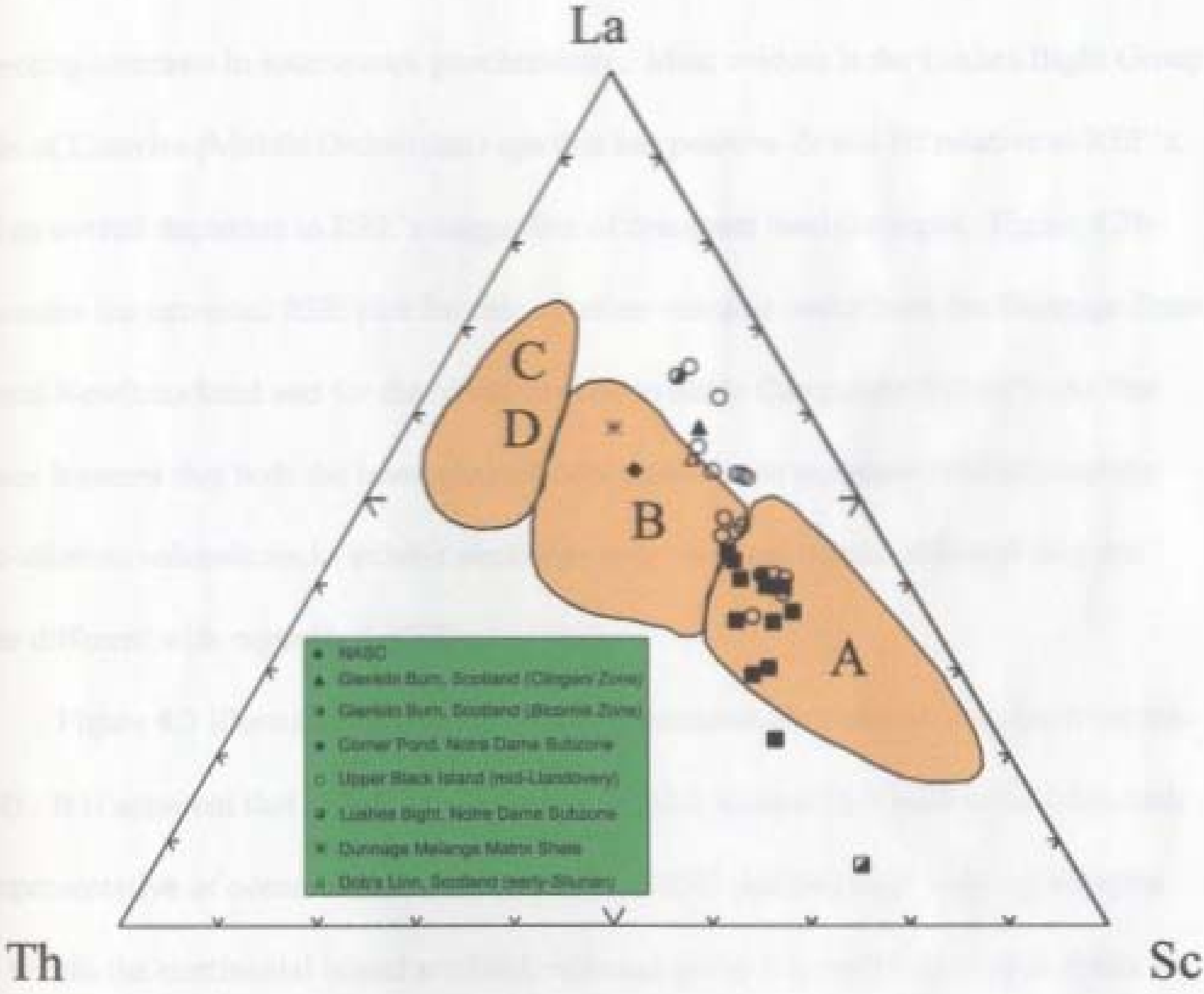


Figure 4.3: Ternary La-Th-Sc plot of Lawrence Harbour Formation samples (Group 1 open circles, Group 2 solid squares) and comparative samples of figure 4.2a. fields are A-oceanic island-arc; B-continental island-arc; C-active continental margin; D-passive margin (after Rollinson, 1993).

Middle Silurian in Scotland while Newfoundland deposition ended in Uppermost Ordovician-Early Silurian times.

The remaining samples chosen for comparison are plotted in Figure 4.2a. They show that different extended REE patterns occur in shales from different localities, thus reflecting contrasts in source rock geochemistry. Most evident is the Lushes Bight Group shale of Llanvirn (Middle Ordovician) age that has positive Zr and Hf relative to REE's, and an overall depletion in REE's suggestive of dominant boninite input. Figure 4.2b illustrates the extended REE plot for calc-alkaline volcanic rocks from the Dunnage Zone, central Newfoundland and for the North American Shale Composite (NASC). At first glance it seems that both the homogenised continental crust signature (NASC) and the calc-alkaline volcanic rocks exhibit similar to near identical trends, although they are quite different with regard to LREE's.

Figure 4.3 illustrates a La-Sc-Th ternary discrimination plot of samples from this study. It is apparent that silty shales of group 2 (solid squares) fall within field A which is representative of oceanic island arc sources. NASC and Dunnage melange samples fall within the continental island arc field, whereas group 1 samples fall within fields A and B and also outside all fields (open circles). This appears to reflect a gradual change from very fine-grained hemipelagic black shale to a more terrestrially-derived shale-silty shale lithology (group 2) with a volcanic oceanic island arc volcanic terrane.

4.5 Summary

Contents of Zr, Hf, Ti, and Nb in shales of the Lawrence Harbour Formation change with stratigraphic height in the unit, which is most likely associated with fractionation of detrital heavy mineral grains (zircon for Zr and Hf; magnetite for Ti) in progressively coarser grained shale specimens. This signature, however, is also related to island-arc magmatism, which may contribute to observed trends. However, irrespective of whether this trend is primarily a result of sedimentary or volcanic processes, it is likely that sedimentary sorting would have affected element concentrations. Therefore, major trends observed in signatures of the Lawrence Harbour Formation are interpreted to be caused by grainsize and sediment sorting effects. Overall, samples exhibit homogeneous chemical signatures with LREE enrichment relative to HREE's and Zr, Hf, Eu, and Ti anomalies. The negative Eu anomalies observed in most samples are due to fractionation of plagioclase feldspar into coarser sediment. This pattern is typical of average continental crust values (NASC) and of calc-alkaline volcanic terranes of the Dunnage Zone, as Figure 4.2b indicates. This result therefore suggests that even though samples of the Lawrence Harbour Formation exhibit consistent geochemical signatures, their derivation, whether from a calc-alkaline volcanic source terrane or from homogenised continental crust cannot be determined. Thus, although trends for Upper Ordovician shales are somewhat unique, there does appear to be a consistent correlation in geochemical signatures of the shales with grain size.

The shales of the Lawrence Harbour Formation can be subdivided into two distinct groups that correlate with stratigraphic height in the formation. Group 1, as described above, comprises older, finer-grained shales of the Lawrence Harbour Formation. These are commonly, but not always, associated with the *N. gracilis* to *C. bicornis* zones. Group 2 comprises a population of increasing grainsize, silty shales that, for a majority of samples, lies within the *D. clingani* to *P. linearis* zones. Figure 4.3 further illustrates the division of Groups 1 and 2. A majority of group 2 samples plot within the island arc volcanics field, supporting a calc-alkaline geochemical signature for the shales. Group 1 samples on the other hand, plot outside of the given descriminant fields. This two-fold division of samples may be indicative of a homogenised continental signature for Group 1 samples, which grades into a calc-alkaline arc signature for coarser-grained Group 2 samples. Overlapping with both Group 1 and Group 2 are samples from shales thought to be equivalent to the Lawrence Harbour Formation based on biostratigraphy (see Appendix C, Carter et al. 1997 for sample localities). The extended REE plots illustrate marked similarities between these units, and there is no strong evidence of local influence from other potential volcanic source terranes.

Lateral variation of samples in the Lawrence Harbour Formation is no more pronounced than in samples obtained from Glenkiln Burn in Scotland. Both of these samples exhibit the Group 1 trend even though they were taken from different biostratigraphic levels. This can also be observed on a limited scale with some of the Lawrence Harbour Formation samples. The results therefore suggest that relatively coarse clastic sediment input reached portions of the basin earlier in some regions than others, while fine-grained hemipelagic sedimentation dominated elsewhere. This implies some degree of lateral variation in sedimentation rates occurring both across and over the life of the basin in which these shales were deposited. Furthermore, Scottish samples illustrate existence of extended deep marine sedimentation into latest Early-Middle Silurian time, while in central Newfoundland coeval sedimentation involved deposition of turbidites.

Since samples were taken from across the Exploits Subzone and geochemical signatures appear fairly homogeneous, it suggests that there may have been only a single basin over this (Upper Ordovician) timespan. This basin was infilled by Late Ordovician times in Newfoundland, but shale deposition continued until Middle Silurian in Scotland.

Chapter 5

Discussion

5.1 Introduction

This chapter combines the results outlined in the previous chapters to refine tectonic models for the evolution of the Lawrence Harbour Formation. It is clear that new ideas related to stratigraphy, geochemistry, and structure have been obtained over the course of this project. The model presented here is consistent with the evidence presented, but other possible scenarios are briefly explored.

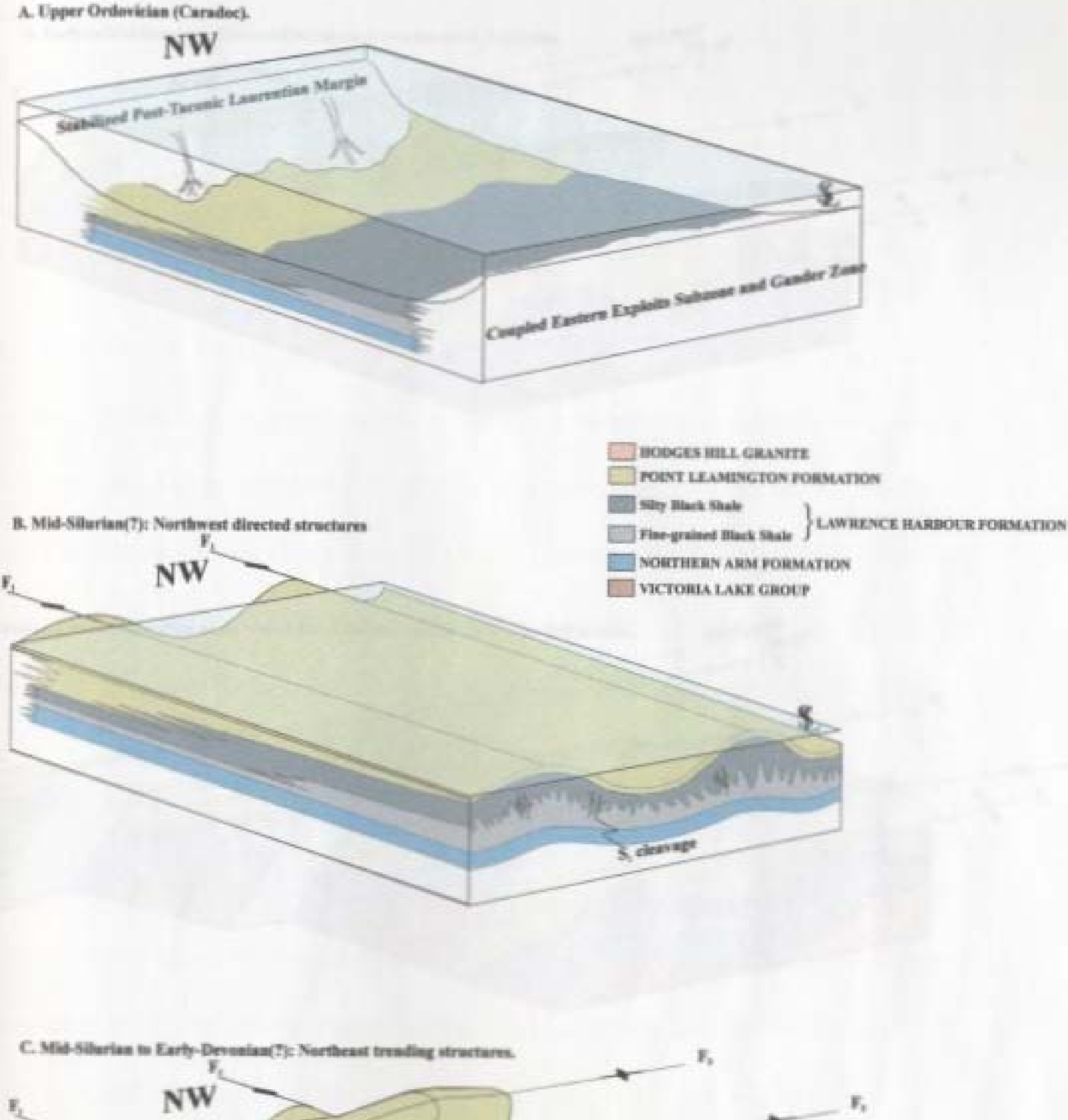
5.2 Depositional and Structural History of the Lawrence Harbour Formation

The Lawrence Harbour Formation consists of black shales and is bound by the Northern Arm Formation at its base and Point Leamington Formation at its top. Past work on these Upper Ordovician shales has led some authors to name and separate biostratigraphically equivalent shales within the Exploits Subzone. Geochemical analyses suggest that these are all equivalent units, with the upper silty shale and possibly also the lower fine-grained black shale lithologies, having been derived from a calc-alkaline source terrane in a back-arc setting within a closing Iapetus Ocean. This interpretation for the Lawrence Harbour Formation is also applicable from Notre Dame Bay to Baie D'Espoir, suggesting that the shales were deposited within a single, or several interconnected, basins that experienced no major changes in source terrane during the Upper Ordovician (Figure 5.1A).

At some time around 458 Ma, the relatively well-oxygenated bottom water conditions ceased and conditions became anoxic, as defined by the lowermost black shale horizon of the Lawrence Harbour Formation. This was part of a global Upper Ordovician anoxic event that has been interpreted by some to be a result of eustatic sea level rise with the black shales being deep marine in origin. Deposition of black shales over chert may also be related to decreased circulation within an isolated basin close to the continental margin, but the overlying turbidites of the Point Leamington Formation support the former explanation of deep marine sedimentation.

The Lawrence Harbour Formation experienced uninterrupted deposition until late Caradoc/early Ashgill times, with turbidites continuing to prograde southeastwards over top of the shales (Figure 5.1B). Geochemical and SEM analyses have shown that vertical changes in lithology are due primarily to increasing grainsize, indicating that the uppermost silty shales are likely the most distal expression of these prograding submarine fans. Furthermore, there is an indication that Lawrence Harbour Formation shales of the *C. bicornis* Zone in the west are of coarser-grained lithology than those in the east. This is suggestive of diachroneity within the coarsening upward sequence defined in the shales. If this is the case, it would suggest that sediment was being input from the west or northwest; this is similar to trends for overlying turbidites of the Badger Group (H. Williams et al., 1995; Kusky, 1985). The implications of this are twofold. First, it would imply that the same graptolite zones would occur in lithologies varying from siliceous black shale through dark grey silty shale. Second, it would imply an uninterupted coarsening upward sequence that begins in the Lawrence Harbour Formation and proceeds through to the overlying Point Leamington Formation flysch sequence. This connection between Upper Ordovician shales and the overlying sediments leads this author to believe that the Lawrence Harbour Formation should be included within the Badger Group, even though it was excluded by H.Williams et al. (1995) from the group in its original definition.

In mid-Ordovician times, an island arc complex collided with the eastern North American continental margin in what is known as the Taconic orogeny (Kusky, 1985). Post-Taconic convergence is manifest in the mid-Silurian to mid-Devonian Salinic and Acadian orogenies (Figure 5.1C and D). It is these two later orogenies that produced the dominant structures observed, with previously undeformed Exploits Subzone rocks compressed against the (stabilised) Notre Dame Subzone which records evidence of the Taconic orogeny (H.Williams et al., 1995). H. Williams et al. (1995) also suggested that the Caradoc marine basin was not open to the southeast, but was bound by a margin consisting of coupled eastern Dunnage and Gander zones. The southeast polarity of thrusting observed within sedimentary rocks of the Grand Falls-Windsor-Badger region may have been controlled by the infringing Gander terrane, which is described by H. Williams et al. (1995) as underthrusting rocks of the Exploits Subzone. Strike slip faulting is defined in the Grand Falls-Windsor-Badger region by significant apparent strike separation of F_2 folded lithologies (Figure 5.1E). Timing of strike slip faulting is


A. Upper Ordovician (Caradoc).
NW
Stabilized Post-Taconic Laurentian Margin
Coupled Eastern Exploits Subzone and Gander Zone
HODGES HILL GRANITE
POINT LEAMINGTON FORMATION
Silty Black Shale
Fine-grained Black Shale
LAWRENCE HARBOUR FORMATION
NORTHERN ARM FORMATION
VICTORIA LAKE GROUP
B. Mid-Silurian(?): Northwest directed structures
NW
F_1
F_1
S_1 cleavage
C. Mid-Silurian to Early-Devonian(?): Northeast trending structures.
NW
F_1
F_1
F_2
F_2
F_2
S_2 cleavage

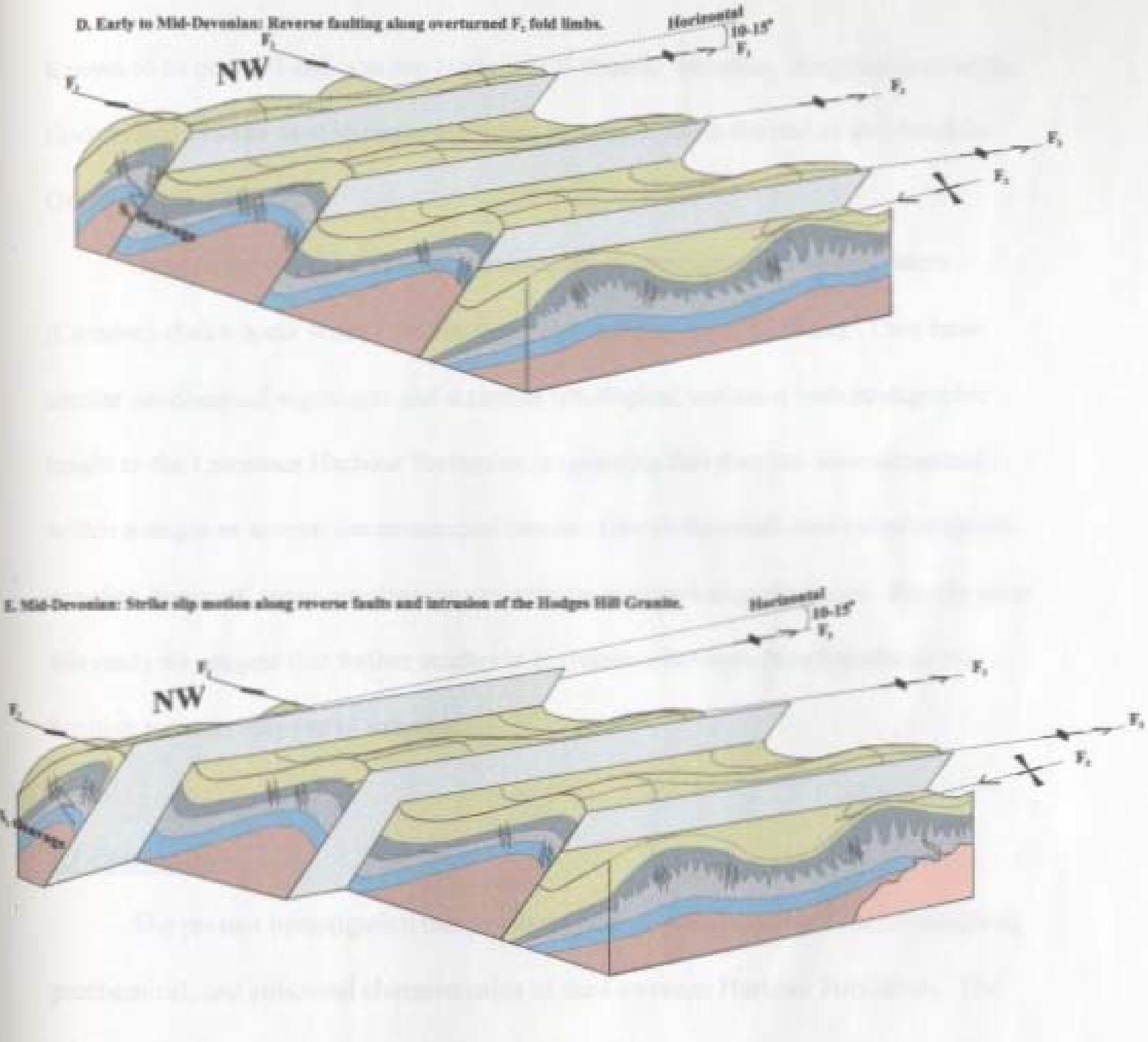


Figure 5.1: Schematic illustration of the evolution of Upper Ordovician geology in central Newfoundland.

Known to be post-D3 and was pre-Hodges Hill Granite intrusion. Emplacement of the Hodges Hill Granite in mid-Devonian times appears to mark the end of the Acadian Orogeny in this region.

Outside the central Newfoundland region, biostratigraphically equivalent (Caradoc) shales occur within the Southern Uplands region of Scotland. They have similar geochemical signatures and a similar lithological variation with stratigraphic height to the Lawrence Harbour Formation, suggesting that they too were deposited within a single or several interconnected basins. Due to the small number of analysed samples, however, these conclusions can only be regarded as preliminary. Results from this study do suggest that further studies in correlation between Newfoundland and Scottish terranes may prove valuable.

5.3 Conclusions

The present investigation has produced new information about the lithological, geochemical, and structural characteristics of the Lawrence Harbour Formation. The main conclusions are summarised below.

1) Vertical change in lithology observed in outcrop is due primarily to grainsize increase from the base to the top of the Lawrence Harbour Formation. This is evident in both the geochemical signatures of the shales, and in SEM analyses of clay floccule size variation. Vertical variations in geochemical trends are characterised by Zr, Hf, and Ti depletion in finer-grained basal black shales with progressively no depletion of

these elements in coarser black silty-shale lithologies.

2) The defined coarsening upward sequence within the Lawrence Harbour Formation, combined with possible indications of diachroneity within the shales, suggests a close association to the coarsening upward Point Leamington Formation. As a result, the Lawrence Harbour Formation should be included within the Badger Group as conformably underlying the Point Leamington Formation.

3) The basal grey bioturbated chert has been identified as a regional marker and mapped as such. Stratotype and parastratotype localities are given as Northern Arm and Red Indian Falls/Black Duck Brook respectively. Its basal contact consists of a sharp, conformable contact with underlying red chert. The upper contact consists of one to two metres of gradation with siliceous black shale of the *N. gracilis* Zone. It has been elevated to formational status and given the name Northern Arm Formation.

4) Results of detailed structural mapping indicate that the dominant deformation features in the area are open to close F_2 folds that are cross-cut by later steepened D_3 thrust faults. This D_2/D_3 deformation overprints earlier D_0 (soft sediment) and D_1 structures. The folding and thrust faulting leads to complex mesoscopic and macroscopic structural patterns for lithological packages in the Grand Falls-Windsor-Badger region.

5) Mesoscopic and regional structural trends parallel those of other Exploits Subzone terranes in that both northwest and northeast trending structures were formed over the course of the Salinic and Acadian orogenies; intensities and the level of overprinting

do, however, vary by region.

6) Geochemical signatures of Lawrence Harbour Formation shales have similar trends to samples from Baie D'Espoir in the south and to Notre Dame Bay in the north. This suggests that there was a similar sediment source for the basin, and that the shales were deposited in one large basin, or several interconnected basins. The geochemical trends reflect a calc-alkaline volcanic source.

7) Scottish shales of equivalent age showed similar geochemical trends and further work may lead to improved correlation between Upper Ordovician terranes in Newfoundland and Scotland.

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Appendix A:

Scanning Electron Microscopy Sample Preparation and Procedure

A.1 Scanning Electron Microscope Sample Preparation and Procedure

Several representative shale samples were selected and polished thin sections were made and coated with a thin film of carbon. Carbon coating involved vaporizing a graphite road within a vacuum chamber that contained the polished sections. Once vaporized, the carbon settled upon the rotating samples forming a thin carbon layer. Coating of the samples is done in order to make them electrically conductive so that while being analysed, they do not build up a charge and damage the SEM.

Once coated, the samples were placed on a metal mount and inserted within the SEM. Thin sections were examined with a Hitachi S570 SEM with an accelerating voltage of 20 kV. It was equipped with a GW Electronics Type 113 Solid State Backscattered Electron Detector and a Tracor Northern 5500 ED (Energy Dispersive) X-ray Analyser with a Microtrace silicon X-ray spectrometer Model 70152. The intensities of x-ray spectra were measured and the abundances of the elements were computed based on comparisons with reference samples. Elemental compositions of minerals in the thin sections were determined to within approximately 2% through Standardless Quantitative Analyses (Tracor Northern Software) utilizing a stored library of element references and matching peak intensities from the samples with the stored reference values. Under the scanning mode, the electron microscope was used at a voltage of .5 to 30 kV to produce high resolution images for photographing the shale samples. Photographs were taken as back scattered electron images and were recorded on Polaroid type 665 positive/negative film.

Appendix B:

Geochemical Data

B.1 Trace- and REE Analyses of Shales

Trace- and REE analyses of shale samples from the Lawrence Harbour Formation, and equivalent units, used in this study are presented in this appendix. Major oxides are in wt% and all others are ppm.

Sample #	Location	Location	Graptolite Biozone	Easting	Northing	Lithology
jc0001	Central NF	Grand Falls-Windsor				shale
jc0002	Central NF	Grand Falls-Windsor		569875	5415233	shale
jc0003	Central NF			563726	5417141	graphitic shale
jc0004	central NF			559550	5415450	shale
jc0005	central NF			586250	5422800	shale
jc0011	central NF	Grand Falls-Windsor	Gracilis (?)	564000	5416413	shale
jc0009	central NF	Grand Falls-Windsor		557450	5410100	shale
jc0013	Central NF	Grand Falls-Windsor	Bicornis	562250	5410600	shale
jc0015	Exploits Subzone	Grand Falls-Windsor	Clingani or Later	564995	5413100	shale
jc0014	Exploits Subzone	Grand Falls-Windsor		563833	5410774	shale
jc0018	Exploits Subzone	Grand Falls-Windsor		569319	5416580	shale
jc0017	Exploits Subzone	Grand Falls-Windsor	Lower Clingani	569656	5415330	
jc0008	central nfld			561345	5414606	graphitic shale
jc0036	Exploits Subzone	Grand Falls-Windsor				shale
jc0035	Exploits Subzone	Grand Falls-Windsor				shale
jc0032	Exploits Subzone	Grand Falls-Windsor				shale
jc0028	Exploits Subzone	Grand Falls-Windsor	Later Clingani	560200	5415550	shale
jc0027b	Exploits Subzone	Grand Falls-Windsor				shale
jc0027a	Exploits Subzone	Grand Falls-Windsor		554400	5410755	shale
jc0026	Exploits Subzone	Grand Falls-Windsor	Clingani	584750	5422355	shale
jc0025	Exploits Subzone	Grand Falls-Windsor	Early Bicornis	584550	5422155	shale
jc0021	Exploits Subzone	Grand Falls-Windsor		580092	5772262	shale
jc0020	Exploits Subzone	Grand Falls-Windsor	Later Bicornis to Clingani	584759	5413495	shale
jc0019	Exploits Subzone	Grand Falls-Windsor	Later Clingani	572594	5415216	shale
M10129G	Red Indian Falls	bicornis zone LR14	Bicornis	556700	5412750	shale
M10130L	Red Cliff	bicornis zone RC3	Bicornis	588850	5421900	shale
M10131B	Twillick Brook	14/7/90-L8 LHEQUIVA				shale
M10132R	Lushes Bight	Notre Dame LB1				shale
M10133H	Red Cliff	clingani zone RC6	Clingani	588850	5421900	shale
M10134Y	Red Indian Falls	clingani zone LR23	Clingani	556700	5412750	shale
M10135O	Lawrence Harb. Pit	bicornis zone LHP1	Bicornis			shale
M10136E	Upper Black Island	12/6/90-4.1 control				shale
M10137U	Glenkiln Burn, Scot.	clingani zone 1M	Clingani			shale
M10138K	Glenkiln Burn, Scot.	bicornis zone 1B	Bicornis			shale
M10139A	Comer Pond					shale
M10140Z	Dob's Linn. Scot.	LBT5.05-5.15 test				shale
M10141Y	Middle Ridge Pond	MRP1b LHEQUIV.				shale metamorph?
M10142Y	Dunnage Melange	control 1/6/76DM				shale
M10143Y	Above Conne River					shale/ phyllite?

Geochemical data

Sample #	Anhyd Coeff	SiO2	TiO2	Al2O3	Fe2O3	MnO	MgO
jc0001	11302	57.59	1	18.19	10.51	0.16	5.55
jc0002	1.04102	66.63	0.65	15.15	7.38	0.09	5.3
jc0003	1.02338	79.86	0.41	10.06	4.24	0.02	2.61
jc0004	1.01698	80.14	0.42	9.21	5.17	0.02	2.45
jc0005	1.05086	72.23	0.64	11.68	6.11	0.02	3.42
jc0011	1.01874	73.4	0.56	11.7	7.03	0.05	3.13
jc0009	0.97485	81.47	0.76	12.02	0.92		1.56
jc0013	0.99344	78.73	0.67	12.96	1.88		1.49
jc0015	1.05809	64.22	0.69	16.49	7.27	0.1	4.95
jc0014	1.06078	71.06	0.55	13.93	5.47	0.06	4.13
jc0018	1.04921	69.75	0.63	13.78	4.7	0.06	3.49
jc0017	1.01276	75.31	0.45	12.53	4.44	0.04	3.46
jc0008	0.97588	78.33	0.52	12.53	2.22	0.02	2.17
jc0036	1.00898	90.25	0.21	4.9	2.98		0.37
jc0035	1.06123	59.11	0.83	17.14	9.89	0.12	6.18
jc0032	1.02124	86.31	0.45	8.12	2.04		1.45
jc0028	1.01317	80.95	0.37	9.56	4.28	0.02	2.4
jc0027b	0.97656	80.59	0.48	10.63	3.25	0.02	2.19
jc0027a	0.98804	90.42	0.27	6.26	0.64		0.66
jc0026	0.92954	84.29	0.28	7.84	3.29	0.02	1.85
jc0025	0.99631	87.3	0.4	7.31	1.86	0.01	0.91
jc0021	0.98097	82.49	0.58	11.54	1.31		0.84
jc0020	1.0098	83.82	0.38	9.08	3.12	0.01	0.98
jc0019	0.98241	81.75	0.54	11.01	1.36	0.01	1.64
M10129G		79.84	0.41	9.7	6.02	0.01	1.62
M10130L		73.69	0.83	16.28	1.8		1.47
M10131B		97.5	0.18	4.79	1.08		0.41
M10132R		79.62	0.18	15.49	1.64		0.99
M10133H		76.5	0.47	12.73	4.45	0.04	4.09
M10134Y		72.79	0.55	14.07	6.19	0.03	2.33
M10135O		90.1	0.52	8.15	1.24		0.82
M10136E		61.5	0.73	15.45	8.22	0.1	6.31
M10137U		63.74	0.65	12.85	10.51	0.06	2.81
M10138K		79.97	0.39	8.53	5.74	0.01	1.65
M10139A		92.93	0.33	7	2.77	0.01	1.8
M10140Z		69.73	0.68	13.08	6.98	0.02	3.71
M10141Y		84.25	0.58	11.88	0.52	0.01	1.73
M10142Y		62.76	0.87	16.06	7.63	0.05	3.13
M10143Y		66.43	0.9	22.48	3.37	0.05	2.42

Sample #	CaO	Na2O	K2O	P2O5	LOI	Mg #	Cr	Ni
jc0001	1.44	1.48	3.98	0.1	4.18	51.14	122	45
jc0002	0.62	1.34	2.78	0.07	4.3	58.71	93	26
jc0003	0.06	0.97	1.72	0.04	4.54	54.95	72	38
jc0004	0.07	0.65	1.82	0.05	4.75	48.44	66	51
jc0005	2.84	1.23	1.75	0.09		52.56	117	30
jc0011	0.68	1.17	2.22	0.06	5.48	46.84	83	74
jc0009	0.03	0.23	3	0.01	6.95	77.12	134	12
jc0013	0.03	1.86	2.36	0.02	6.13	61.12	183	
jc0015	1.58	2.32	2.32	0.08		57.43	93	24
jc0014	0.54	1.44	2.76	0.05	5.12	59.89	99	68
jc0018	3.8	1.58	2.12	0.08	4.84	59.55	88	55
jc0017	0.26	0.88	2.59	0.04	4.23	60.73	78	19
jc0008	0.35	1.23	2.6	0.03	4.53	65.85	77	5
jc0036	0.07	0.04	1.13	0.04	4.45	19.9	70	16
jc0035	1.4	1.69	3.57	0.08	3.69	55.29	97	37
jc0032	0.06	0.09	1.42	0.06	4.99	58.44	52	22
jc0028	0.07	0.91	1.38	0.05	5.33	52.66	64	40
jc0027b	0.05	0.76	1.99	0.04	4.63	57.12	63	18
jc0027a	0.03	0.43	1.27	0.01	4.22	67.12	48	
jc0026	0.28	0.41	0.69	0.06	3.7	52.68	125	28
jc0025	0.1	0.32	1.76	0.03	6.06	49.08	65	22
jc0021	0.04	1.01	2.17	0.02	4.99	55.97	62	
jc0020	0.14	0.79	1.66	0.02	6.13	38.34	64	15
jc0019	0.38	1.08	2.2	0.03	3.74	70.56	74	
M10129G	0.08	0.69	1.86	0.05	7.3	34.77	108	93
M10130L	0.04	1.37	1.86	0.03	8.39	61.79	226	23
M10131B	0.02	0.37	0.9	0.01	6.21	42.92	484	142
M10132R	0.23	1.23	3.25	0.14	4.63	54.45	94	10
M10133H	0.14	0.99	2.48	0.06	5.58	64.54	96	57
M10134Y	0.09	1.27	2.55	0.05	6.67	42.71	115	57
M10135O	0.02	0.63	1.42	0.02	6.45	56.7	150	65
M10136E	0.89	2.67	2.7	0.1	3.17	60.32	271	94
M10137U	0.34	1.44	2.46	0.08	12.06	34.62	332	251
M10138K	0.08	0.56	1.81	0.05	7.23	36.28	260	146
M10139A	0.07	0.24	1.2	0.06	4.78	56.27	289	106
M10140Z	0.04	0.69	2.8	0.04	6.85	51.28	104	52
M10141Y	0.02	0.06	2.86	0.01	7.19	86.82	245	28
M10142Y	0.12	0.83	4.66	0.07	14.28	44.82	169	158
M10143Y	0.1	0.81	5.03	0.02	5.5	58.71	215	8

Sample #	Sc	V	Cu	Pb	Zn	S	As	Rb	Ba
jc0001	36	233	59	27	96	973.89	15.58	152	525
jc0002	25	166	32	22	77	9077.66	6.25	97	456
jc0003	19	363	32	20	28	11258.25	9.21	84	1046
jc0004	13	141	26	21	13	20377.3	28.48	62	426
jc0005	23	184	42	22	51	15607.4	26.27	60	824
jc0011	14	154	51	31	35	33674.61	38.71	79	431
jc0009	19	1370	13	11		571.26	15.6	95	1721
jc0013	16	396	11	54		3893.3	35.76	93	2155
jc0015	20	146	39	21	66	8794.84	17.99	76	483
jc0014	18	309	30	21	118	13513.32	32.88	98	442
jc0018	18	145	35	23	19	13249.4		73	378
jc0017	15	195	22	17	17	7488.35	14.18	88	437
jc0008	18	357	23	28	5	370.83	24.4	93	685
jc0036		216	38	31	10	21927.15	46.41	49	546
jc0035	29	181	68	20	99	10637.8		126	476
jc0032	9	575	23	13	20	8979.78	45.96	46	1381
jc0028		189	29	14	23	12555.22	18.24	54	1160
jc0027b	11	236	25	29	10	9825.2	38.09	63	361
jc0027a		167		19		2351.55		46	935
jc0026	11	204	64	8	50	15682.28		55	550
jc0025		903	44	13	6	12689.05	52.8	57	1004
jc0021	12	198	7	18		5498.33	30.41	71	453
jc0020	17	122	39	14	8	18271.23	26.25	57	369
jc0019	14	379	17	14		2505.16	15.72	75	492
M10129G	15	276	53	24	31	32018	111	70	1047
M10130L	26	2017	28	46	11	3879	33	120	1841
M10131B		165	12	21		5898	33	32	1233
M10132R	25	216	8	46		6284	38	100	1734
M10133H	16	155	39	8		20180		88	656
M10134Y	21	158	42	27		21344	25	90	1224
M10135O	10	733	8	21		6989		52	1305
M10136E	21	150	41	15	65	2329		72	505
M10137U	22	355	177	162	95	49415	108	97	296
M10138K	12	745	119	86		28832	61	72	296
M10139A	12	626	76	20		6393	51	41	212
M10140Z	18	137	63	23		36143	34	100	343
M10141Y	17	1053		22		2288		92	880
M10142Y	16	1047	74	81	21	29470	105	165	898
M10143Y	30	333	20	20		157		226	6726

Sample #	*Sr*	*Ga*	*Ta*	*Nb*	*Hf*	*Zr*	*Y*	*Th*	*U*
jc0001	126	24	0.68	8.7	4.07	160	27	9.8	4.45
jc0002	79	20	0.67	6.6	2.93	103	21	8.33	7.51
jc0003	132	11	0.95	7.2	1.6	64	13	5.1	6.14
jc0004	32	11	1.11	7.4	1.64	69	15	4.55	9.15
jc0005	223	16	1.65	9.3	3.23	118	23	6.94	
jc0011	82	14	0.74	9	2.4	97	20	5.71	10.19
jc0009	11	13	1.04	12.5	253	101	27	5.67	13.65
jc0013	41	15	1	10.4	2.79	107	46	6.04	
jc0015	200	17	1	7.4	3.53	127	22	7.99	
jc0014	68	17	0.74	10	2.23	92	20	6.87	7.43
jc0018	122	17	0.98	8.8	2.58	108	19	7.45	9.44
jc0017	44	16	0.98	8.2	1.79	74	15	6.26	7.09
jc0008	51	16	0.89	9	2.03	84	21	6.83	4.88
jc0036	44	7	0.95	4.2	0.75	33	12	2.6	5.04
jc0035	217	22	0.77	8.1	3.49	130	25	8.07	5.31
jc0032	24	10	0.86	6.9	2.19	81	26	4.01	12.25
jc0028	22	12	0.87	6.8	1.64	63	16	4.96	8.11
jc0027b	41	13	1.17	7.6	1.84	67	16	4.56	11.72
jc0027a	11	8	1.03	3.4	1.26	44	9	2.47	7.9
jc0026	58	8	0.84	4.2	1.25	48	19	3.21	3.72
jc0025	25	10	1.08	6.7	1.4	55	15	4.16	17.93
jc0021	90	13	0.99	6.1	2.01	84	11	4.78	12.75
jc0020	86	13	0.81	7.8	1.76	73	17	4.68	13.13
jc0019	90	15	1.15	8.6	2.04	84	15	5.65	10.81
M10129G	17	10	0.5	7.5	1.82	71	21	5.55	8
M10130L	90	22	0.89	14.2	2.8	125	38	7.16	25
M10131B	70	5	0.98	13.1	0.88	37	13	2.24	8
M10132R	150	16	0.58	3.4	3.37	127	22	7.5	7
M10133H	67	15	0.59	8	2.31	81	15	6.92	7
M10134Y	27	16	0.54	8.7	2.38	87	17	6.8	5
M10135O	45	11	0.4	2.3	1.9	66	10	4	10
M10136E	139	16	0.68	7.9	3.22	135	19	6.2	
M10137U	76	19	0.52	11.1	3.99	149	50	9.01	6
M10138K	53	13	0.43	5.7	1.98	84	35	5.56	16
M10139A	18	9	0.36	2.8	1.47	56	10	3.94	5
M10140Z	40	18	0.75	12.9	2.8	125	15	8.63	10
M10141Y	7	14	0.53	6.8	3.87	139	29	4.79	8
M10142Y	60	23	1.2	13.3	3.48	153	30	15.49	27
M10143Y	96	24	1.52	18	4.77	196	34	13.31	12

Sample #	*La*	*Ce*	*Pr*	*Nd*	*Sm*	*Eu*	*Gd*	*Tb*
jc0001	29.83	60.9	7.12	27.74	5.49	1.25	5.31	0.82
jc0002	18.36	41.93	4.99	19.19	4.18	0.95	4.03	0.61
jc0003	16.85	33.69	4.06	16.69	2.95	0.6	2.41	0.39
jc0004	15.61	33.07	3.93	15.18	3.28	0.66	2.8	0.45
jc0005	19.74	45.84	5.38	21.55	4.56	0.6	4.35	0.64
jc0011	18.22	40.94	4.95	19.5	4.14	0.89	3.87	0.61
jc0009	27.12	49.3	6.55	25.37	4.29	0.89	3.8	0.51
jc0013	41.47	57.89	9.6	37.8	6.47	1.4	6.17	1.02
jc0015	19.18	39.71	4.68	19.05	3.98	0.99	3.7	0.6
jcG314	10.76	25.02	3.34	14.04	3.61	0.88	3.37	0.54
jc0018	19.67	41.68	4.78	18	3.91	0.99	3.58	0.55
jc0017	5.98	15.16	1.97	8.04	2.39	0.57	2.52	0.4
jc0008	13.84	29.2	3.88	16.48	3.8	1.09	3.51	0.6
jc0036	17.64	35.49	4.07	16.43	2.83	0.55	2.38	0.31
jc0035	23.37	50.37	5.96	23.6	4.85	1.2	4.63	0.72
jc0032	16.84	35.01	4.68	18.89	3.79	0.66	3.9	0.65
jc0028	15.84	31.66	3.85	15.09	3.2	0.63	2.87	0.44
jc0027b	12.86	27.04	3.28	12.66	2.87	0.66	2.68	0.44
jc0027a	13.09	26.3	3.19	12.43	2.26	0.43	1.51	0.24
jc0026	16.04	25.53	4.33	9.59	3.83	0.78	4.01	0.61
jc0025	5.84	12.11	1.67	7.84	1.86	0.35	2.02	0.32
jc0021	12.34	26.55	2.93	10.84	1.85	0.37	1.55	0.26
jc0020	12.7	28.74	3.38	13.64	2.91	0.59	2.53	0.44
jc0019	5.41	12.79	1.76	7.49	2.32	0.56	2.46	0.41
M10129G	17.57	34.18	4.28	17.2	3.82	0.87	3.7	0.59
M10130L	36.58	67.75	8.53	33.82	6.29	1.3	5.83	1
M10131B	11.95	25.77	3.09	13.13	2.74	0.4	2.23	0.43
M10132R	2.49	6	1.14	5.46	1.86	0.49	2.53	0.5
M10133H	9.53	24.8	2.79	10.77	2.6	0.45	2.32	0.38
M10134Y	18.36	39.8	4.65	18.21	3.53	0.66	3.06	0.48
M10135O	15.93	30.64	3.8	15.13	2.69	0.51	1.67	0.23
M10136E	18.93	43.79	4.78	18.61	4.24	1.05	3.94	0.57
M10137U	43.41	134.7	11.86	47.31	10.53	2.26	10.93	1.77
M10138K	31.65	91.73	8.86	36.87	7.76	1.94	8.93	1.36
M10139A	11.07	19.16	2.77	11.17	2.02	0.43	2.26	0.26
M10140Z	32.23	62.24	6.98	26.17	4.83	0.89	3.82	0.56
M10141Y	35.28	62.32	8.01	32.67	5.83	1.15	4.86	0.71
M10142Y	44.14	84.03	10.13	38.69	6.7	1.15	5.56	0.86
M10143Y	24.1	58.28	6.68	25.4	5.24	1.42	5.18	0.98

Sample #	*Dy*	*Ho*	*Er*	*Tm*	*Yb*	*Lu*	*Density*
jc0001	5.18	1.08	3.25	0.48	3.38	0.47	2.45
jc0002	3.91	0.84	2.38	0.36	2.44	0.34	2.41
jc0003	2.31	0.5	1.49	0.24	1.64	0.24	2.34
jc0004	2.7	0.55	1.76	0.24	1.72	0.25	2.34
jc0005	4.11	0.86	2.48	0.37	2.45	0.35	2.39
jc0011	3.7	0.8	2.25	0.32	2.13	0.3	2.37
jc0009	3.88	0.85	2.73	0.4	2.88	0.41	2.31
jc0013	6.81	1.53	4.66	0.68	4.34	0.63	2.32
jc0015	3.96	0.9	2.61	0.39	2.75	0.41	2.42
jc0014	3.61	0.76	2.3	0.33	2.19	0.32	2.38
jc0018	3.53	0.73	2.12	0.28	1.96	0.29	2.4
jc0017	2.59	0.54	1.71	0.24	1.52	0.25	2.36
jc0008	3.79	0.79	2.36	0.34	2.21	0.33	2.33
jc0036	1.81	0.4	1.25	0.18	1.25	0.19	2.29
jc0035	4.73	1.02	2.86	0.44	2.91	0.43	2.46
jc0032	4.3	0.95	2.88	0.44	3.14	0.46	2.3
jc0028	2.79	0.59	1.82	0.25	1.84	0.26	2.33
jc0027b	2.77	0.58	1.7	0.26	1.64	0.24	2.33
jc0027a	1.53	0.33	0.97	0.15	1	0.15	2.28
jc0026	3.63	0.75	2.14	0.3	1.92	0.28	2.32
jc0025	2.14	0.48	1.49	0.23	1.6	0.23	2.29
jc0021	1.63	0.38	1.25	0.19	1.3	0.23	2.31
jc0020	2.8	0.61	1.78	0.26	1.82	0.26	2.31
jc0019	2.59	0.55	1.67	0.24	1.63	0.26	2.32
M10129G	3.86	0.85	2.33	0.31	2.03	0.32	2.79
M10130L	6.68	1.24	3.97	0.64	4.53	0.63	2.71
M10131B	2.21	0.43	1.15	0.15	1.08	0.17	2.69
M10132R	3.47	0.75	2.48	0.38	2.56	0.4	2.63
M10133H	3.01	0.6	1.85	0.26	2.01	0.3	2.8
M10134Y	3.09	0.67	2.15	0.29	2.12	0.29	2.76
M10135O	1.56	0.36	1.18	0.15	1.15	0.18	2.7
M10136E	3.67	0.8	2.35	0.35	1.89	0.37	2.84
M10137U	10.32	2.18	5.71	0.89	5.28	0.77	2.82
M10138K	7.57	1.49	4.11	0.59	3.65	0.54	2.8
M10139A	1.61	0.4	1.21	0.23	1.23	0.25	2.81
M10140Z	3.29	0.71	1.92	0.3	2.35	0.33	2.81
M10141Y	4.55	1.08	2.82	0.45	2.78	0.4	2.69
M10142Y	5.53	1.19	3.72	0.57	3.98	0.54	2.75
M10143Y	6.35	1.32	4.26	0.6	3.88	0.57	

Appendix C:

Analytical Techniques

Analytical Techniques

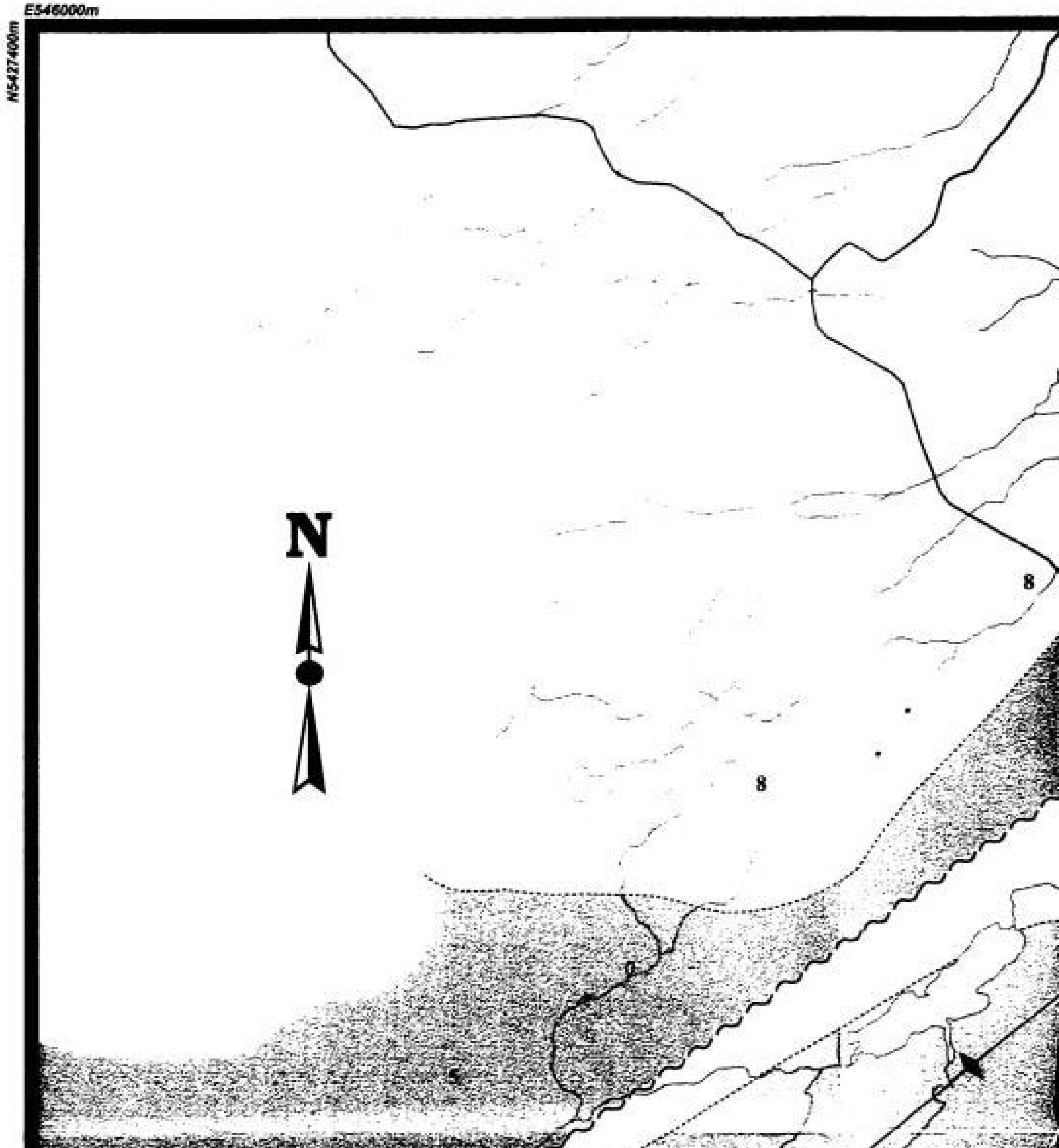
C.1 Trace element analyses

Concentrations of trace elements were determined using a Fisons/ARL model 8420+ sequential wavelength-dispersive X-ray spectrometer with a rhodium anode end-window x-ray tube. Pellets were produced from 5 grams of powdered shale samples and 0.70 grams of BRP-5933 Bakelite phenolic resin as a binding medium. A jar, in which these two powders were placed, was left on a roller mixer for ten minutes prior to insertion of two stainless steel ball bearings. The mixed powder was then placed in a pellet press (29 mm diameter mould) and pressed for approximately 5 seconds at a pressure of 20 tons. Samples were then baked at 200 degrees centigrade for 15 minutes, making them ready for XRF analysis.

C.2 Rare earth element analyses

Concentrations of REE's were determined using a Sciex Elan model 250 ICP-MS. Sample solutions were produced using the Na_2O_2 dissolution procedure. 0.2 grams of sample were accurately weighed into a clean nickel crucible. After adding and mixing 0.8 grams of Na_2O_2, samples were placed into a muffle furnace at 500 °C and left to sinter for 1.5 hours. Once the sample had cooled, 10 ml of distilled water was then poured into a centrifuge tube, with additional distilled water added to make a final volume of 30ml. After 15 minutes in the centrifuge, the tube was removed, extraneous liquid was poured off, and the remaining residue was rinsed with 25 ml of distilled water. The mixture was placed in the centifuge for an additional 15 minutes.

Next, residue remaining at the base of the centrifuge tube was dissolved in 2.5 ml of 8N HNO_3 and 4 ml of oxalic acid. Subsequent addition of 4 ml of 0.113M HF/ 0.453M boric acid solution to the tube was done, and the entire mixture was left to sit overnight. Finally, in a clean jar, the solution was brought up to 50g with distilled water. Then 2g of sample was diluted with 8g of HNO_3, completing preparation for ICP-MS analysis. Each run of samples for Na_2O_2 sinter analysis consists of 21 samples, 3 procedure duplicates, two standards (DNC-1, MRG-1), and 2 SiO_2 blanks.



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Election Pond
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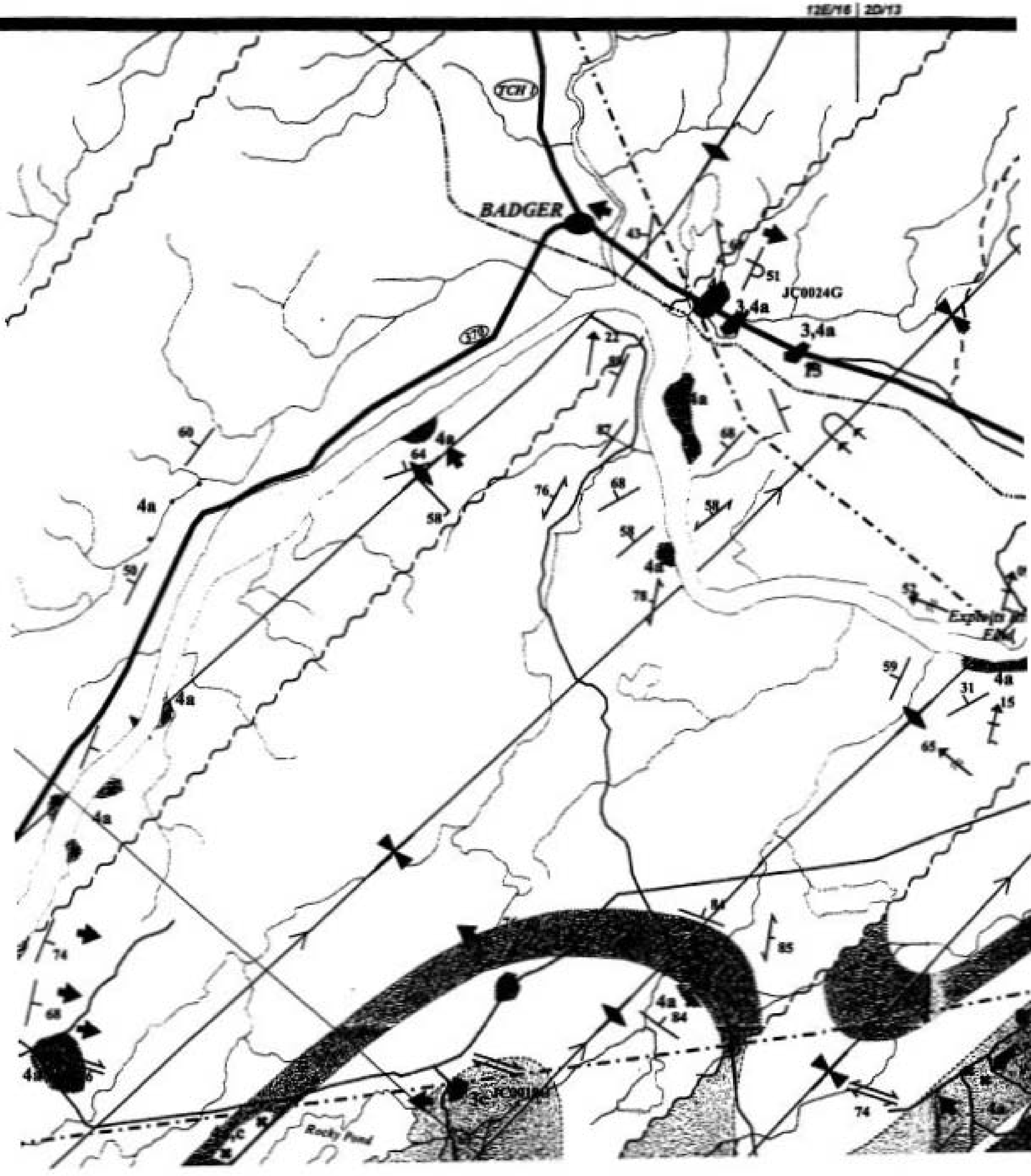
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Rocky Pond


EXPLOITS
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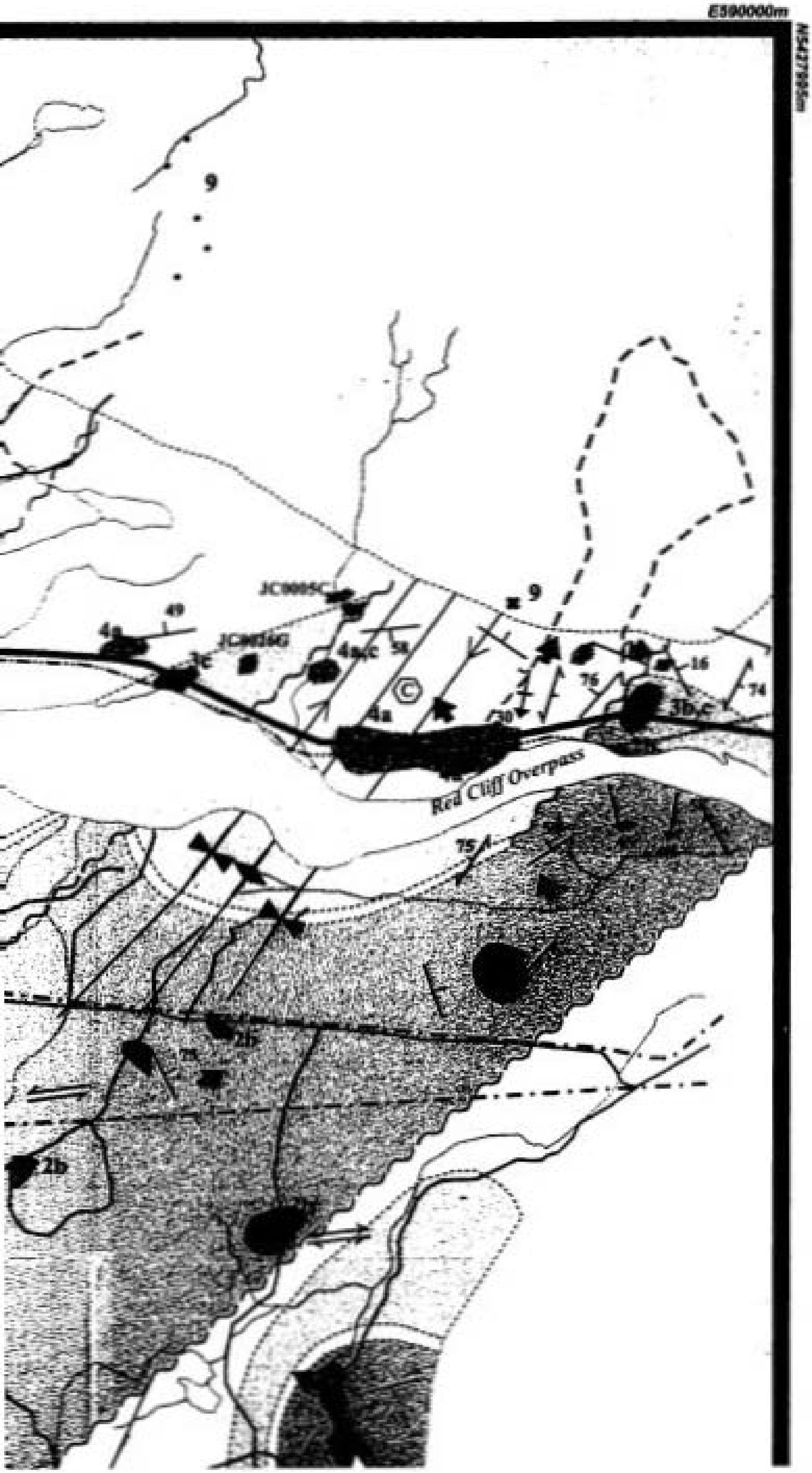

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8	Skull Hill Quartz Syenite. and quartz monzonite.

Geology
Grand Falls-Windsor-Badger Area

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Hodges Hill Granite. medium- to coarse-grained pink and white, equigranular, homogeneous hornblende-biotite granite.

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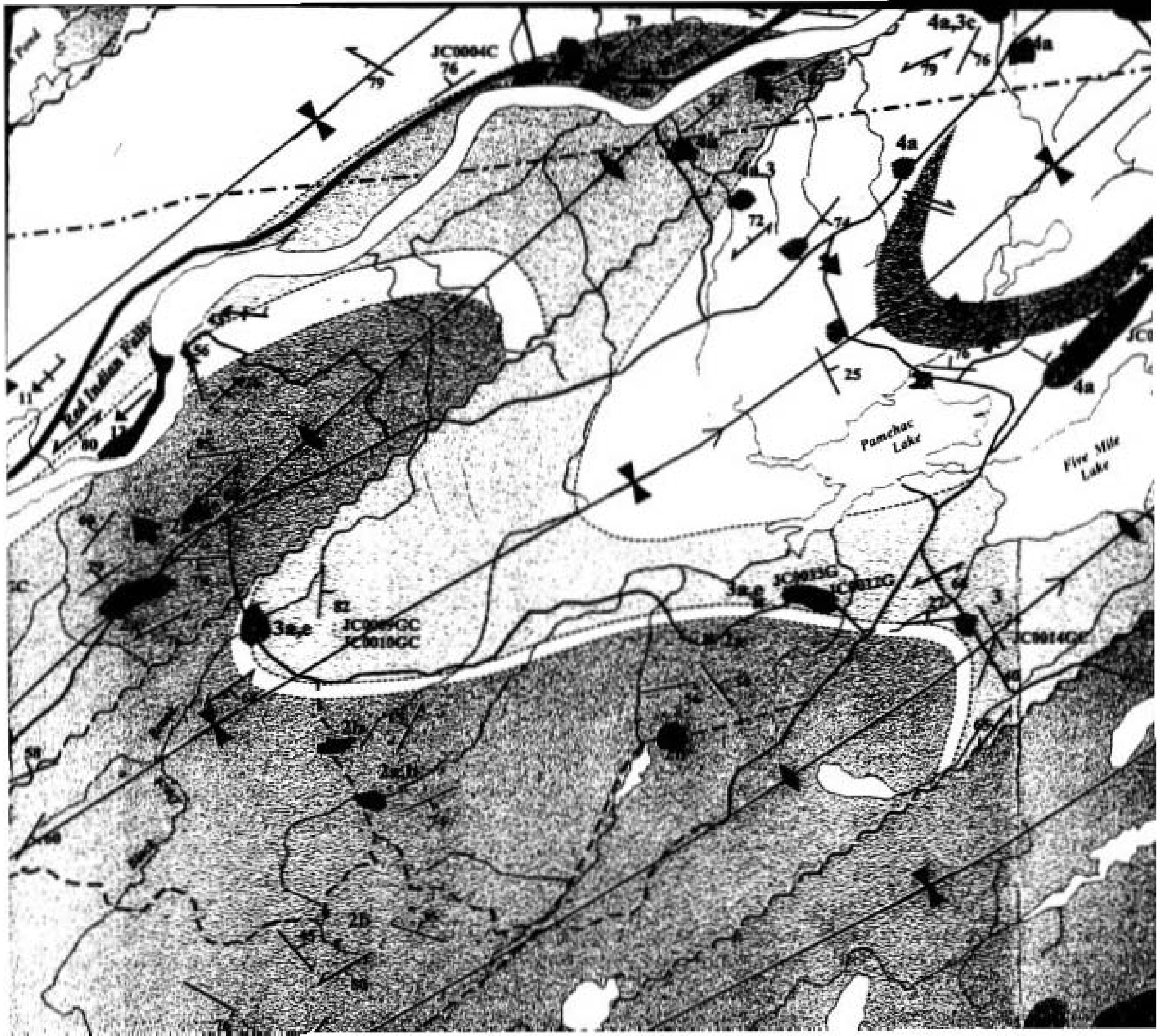
Point Leamington Formation


Red Indian Fault
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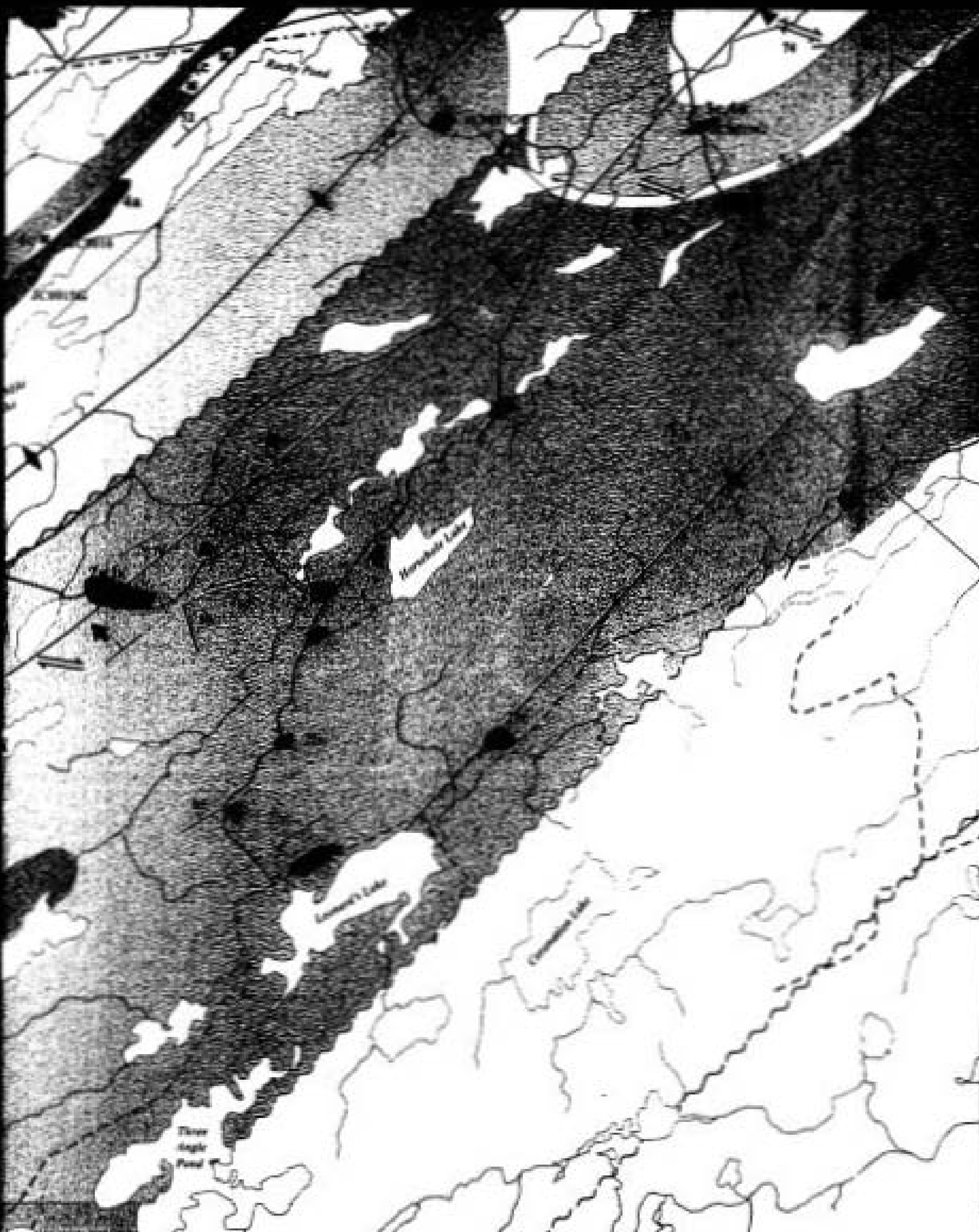
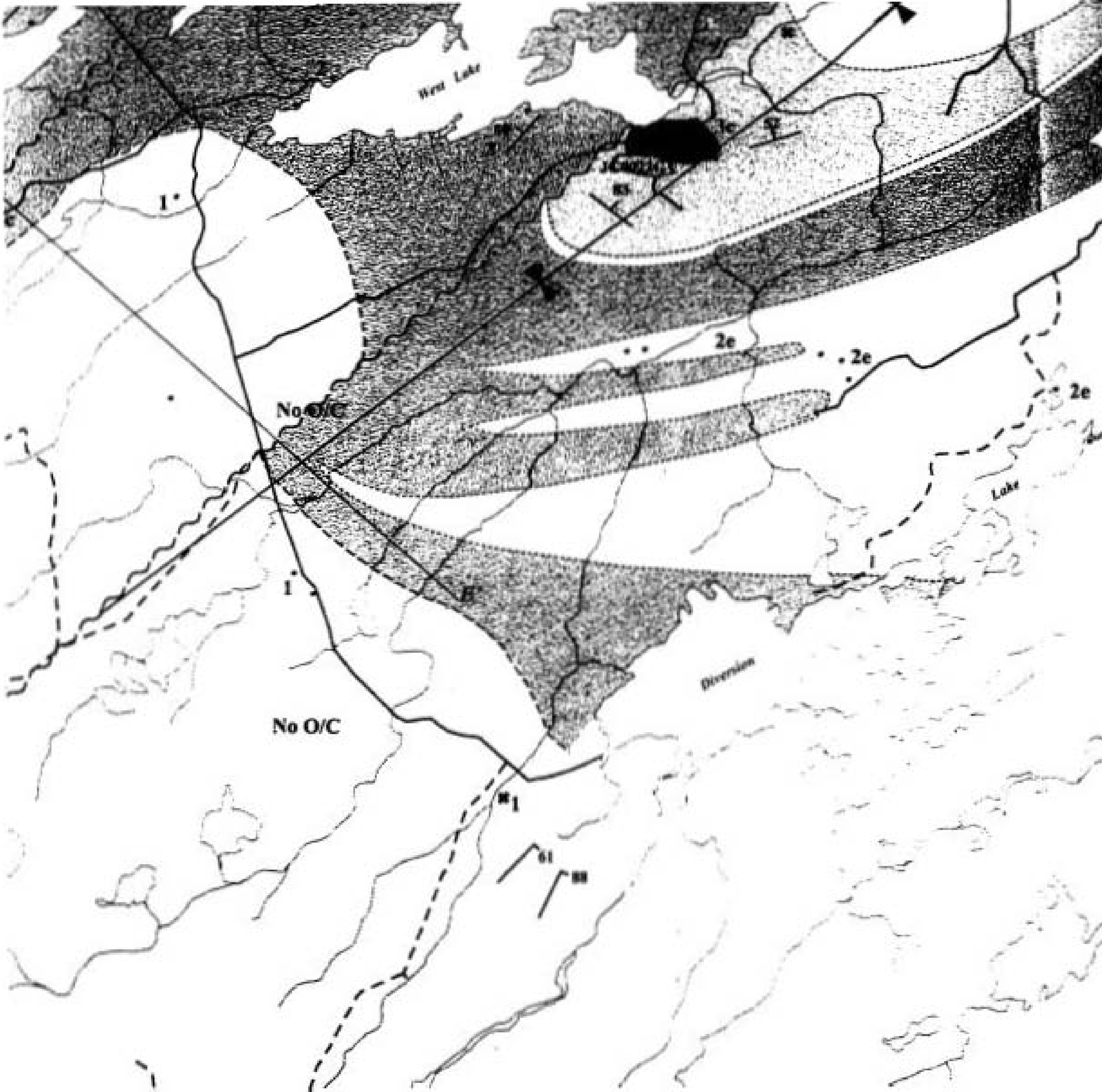
Five Mile Lake
JC0004C

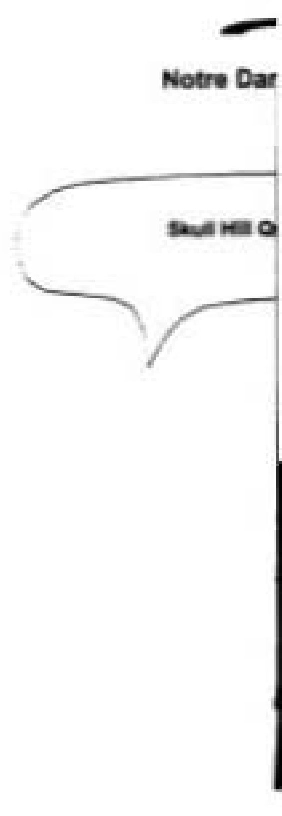

Three Angle Pond



West Lake
1
No O/C
2e
2e
2e
No O/C
1
B'
Lake
Diversion
1
61
88

Buchans Group

undivided mafic-felsic volcani rocks.



Silurian and Ordovician

roup

afic-felsic volcanic rocks and minor sedimentary

Point Leamington Formation

sandstone, conglomerate, siltstone, and shale; **4a**,turbidites consisting of coarse-, medium-, and fine-grained sandstone (locally calcareous), minor silty shale interbeds; **4b**, debris flow; **4c**, pebble to boulder polymictic conglomerate..

Upper Ordovician

Lawrence Harbour Formation

fine-grained, locally graphitic, graptolite-bearing black shale; **3a**, basal siliceous black shale, orange-yellow-green weathering **3b**, fine-grained black to black silty shale; **3c**, black to dark grey silty shale.

Northern Arm Formation

fine-grained, microcrystalline, grey-green bioturbated chert, white weathering.

Middle Ordovician and Older

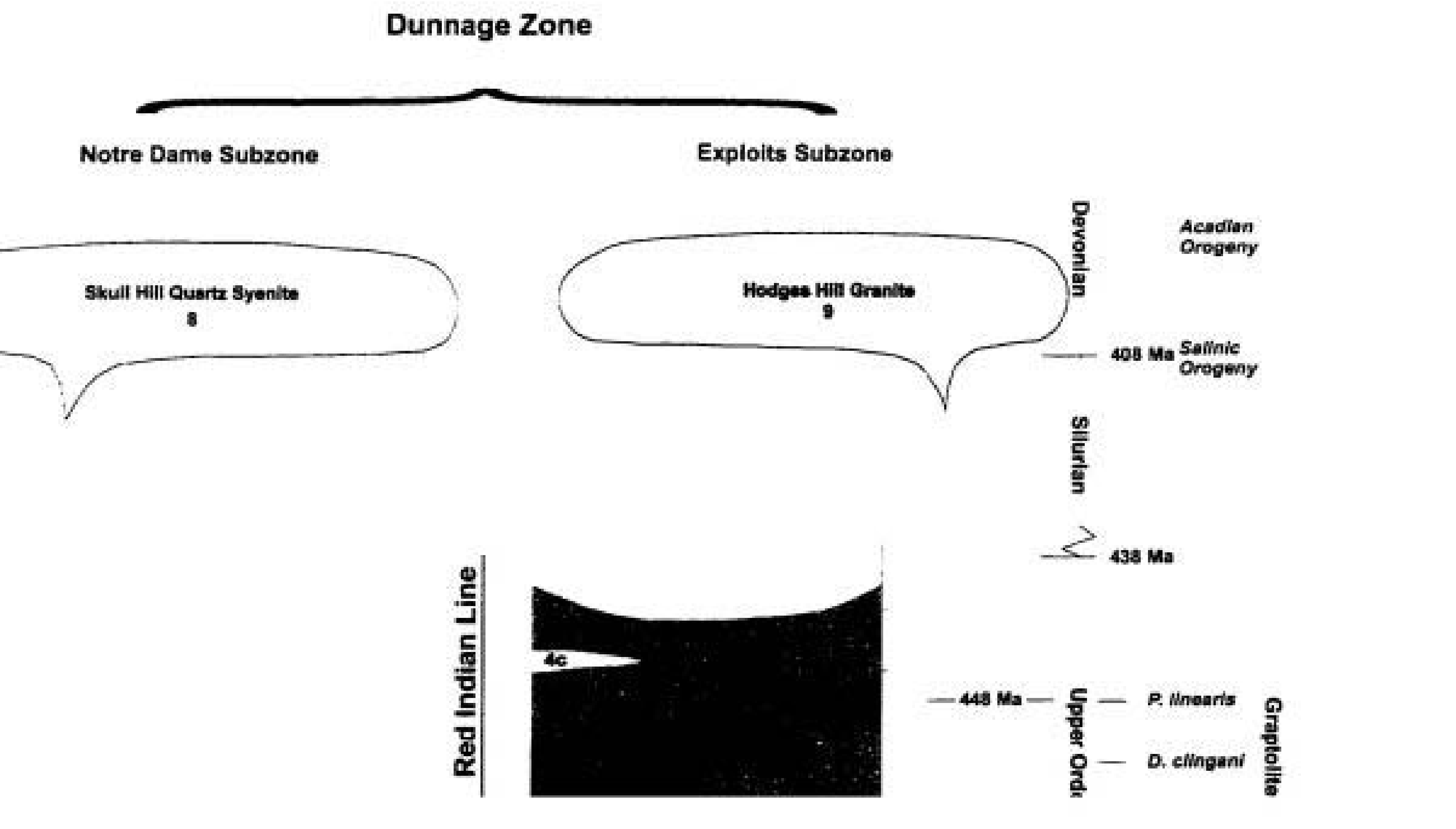
Victoria Lake Group

2a, green and red chert with no black shale interbeds, without bioturbation, minor preservation of primary sedimentary structures; **2b**, sandstone turbidites, coarse-, medium-, and fine-grained, with siltstone or dominant siltstone beds; **2d**, mafic volcanic flows.

2e — Tally Pond Volcanic Rocks. green, mafic to intermediate pillow lava, pillow breccia, lapilli tuff and tuff.

Precambrian

1 — Crippleback Lake Quartz Monzonite. medium-grained quartz monzonite and granodiorite.



medium-grained gabbro and diabase.

eamington Formation

ne, conglomerate, siltstone, and shale; **4a**, turbidites
ng of coarse-, medium-, and fine-grained sandstone
calcareous), minor silty shale interbeds; **4b**, debris flow;
ole to boulder polymictic conglomerate.

ian

ce Harbour Formation

ined, locally graphitic, graptolite-bearing black shale;
al siliceous black shale, orange-yellow-green weathering;
-grained black to black silty shale; **3c**, black to dark grey
ale.

m Arm Formation

ined, microcrystalline, grey-green bioturbated chert,
eathering.

ian and Older

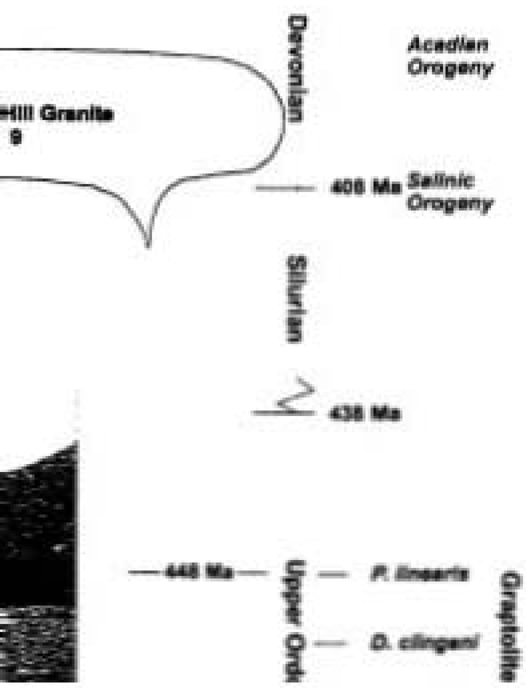
Lake Group

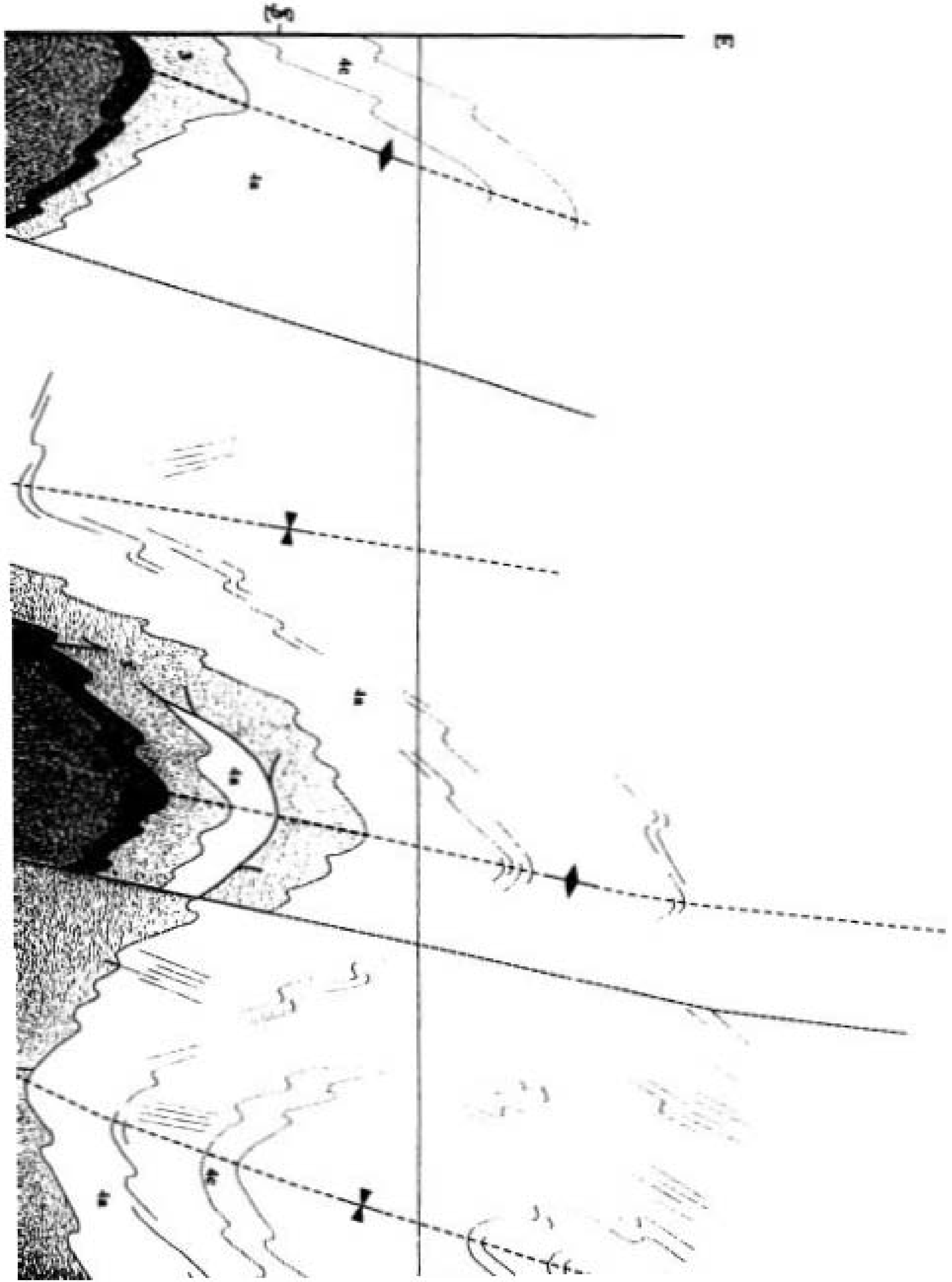
en and red chert with no black shale interbeds,
bioturbation, minor preservation of primary sedimentary
es; **2b**, sandstone turbidites, coarse-, medium-, and
ined, with siltstone or dominant siltstone beds; **2d**,
lcanic flows.

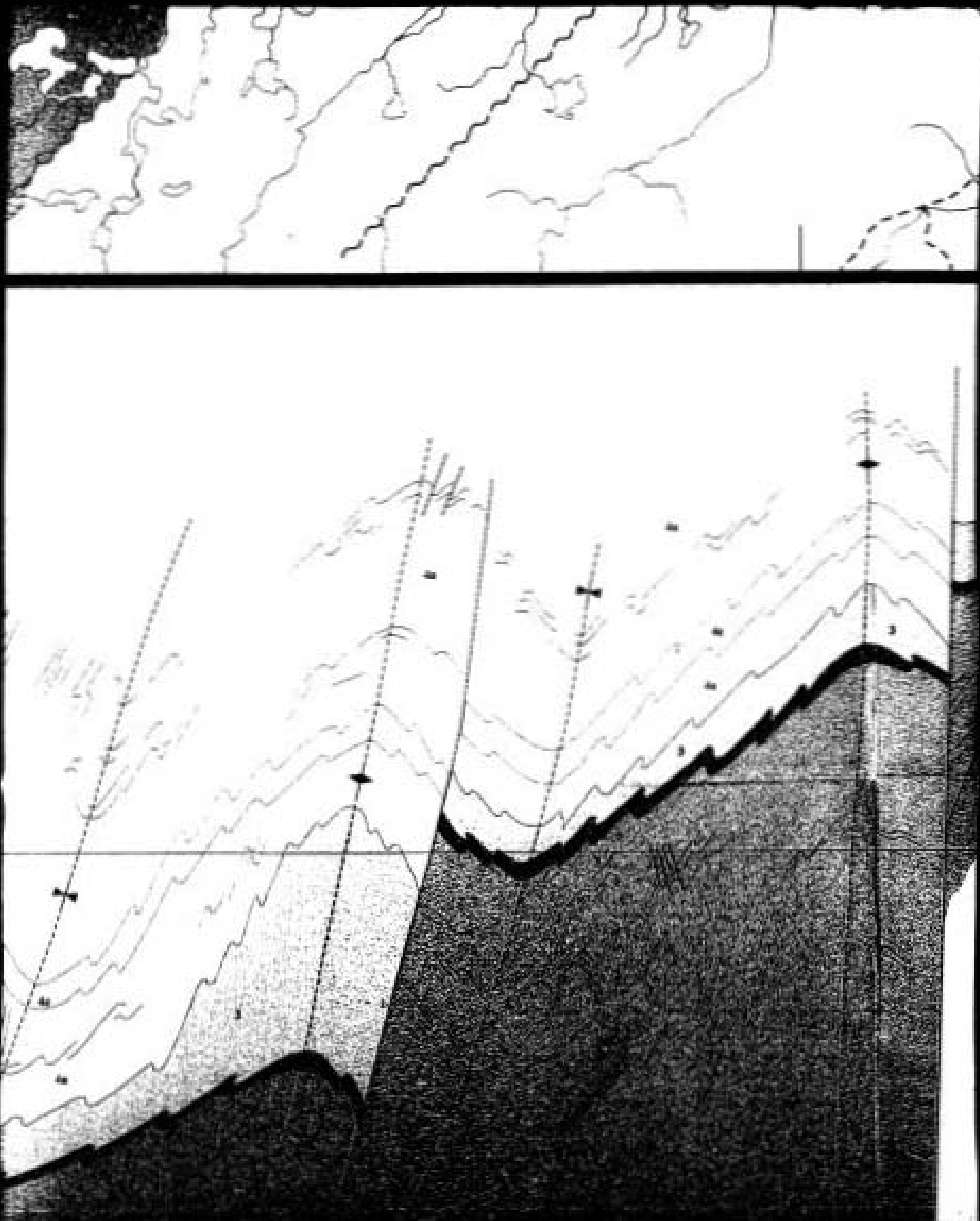
nd Volcanic Rocks, green, mafic to intermediate pillow
low breccia, lapilli tuff and tuff.

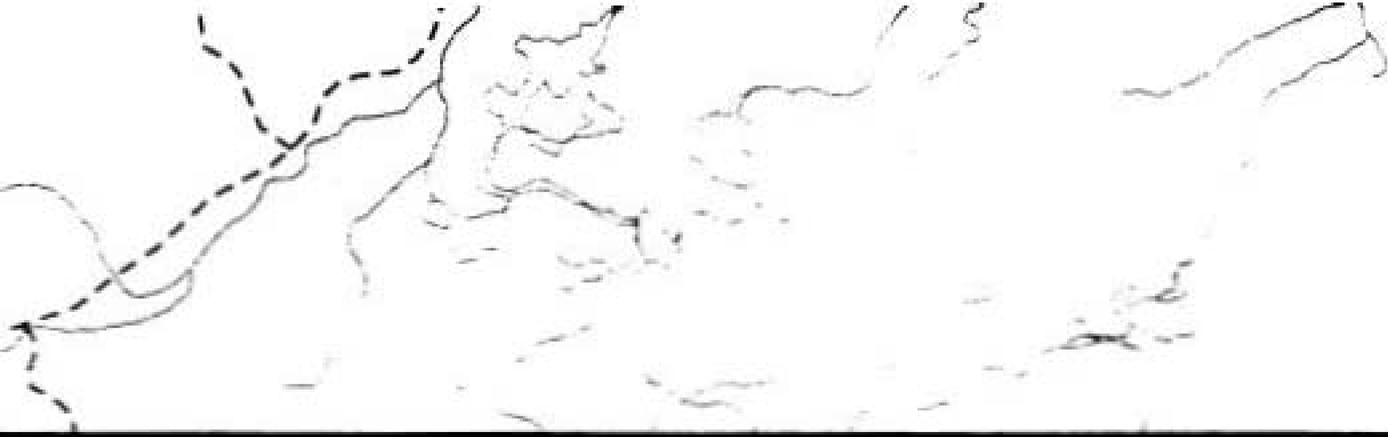
ack Lake Quartz Monzonite, medium-grained quartz
ite and granodiorite.

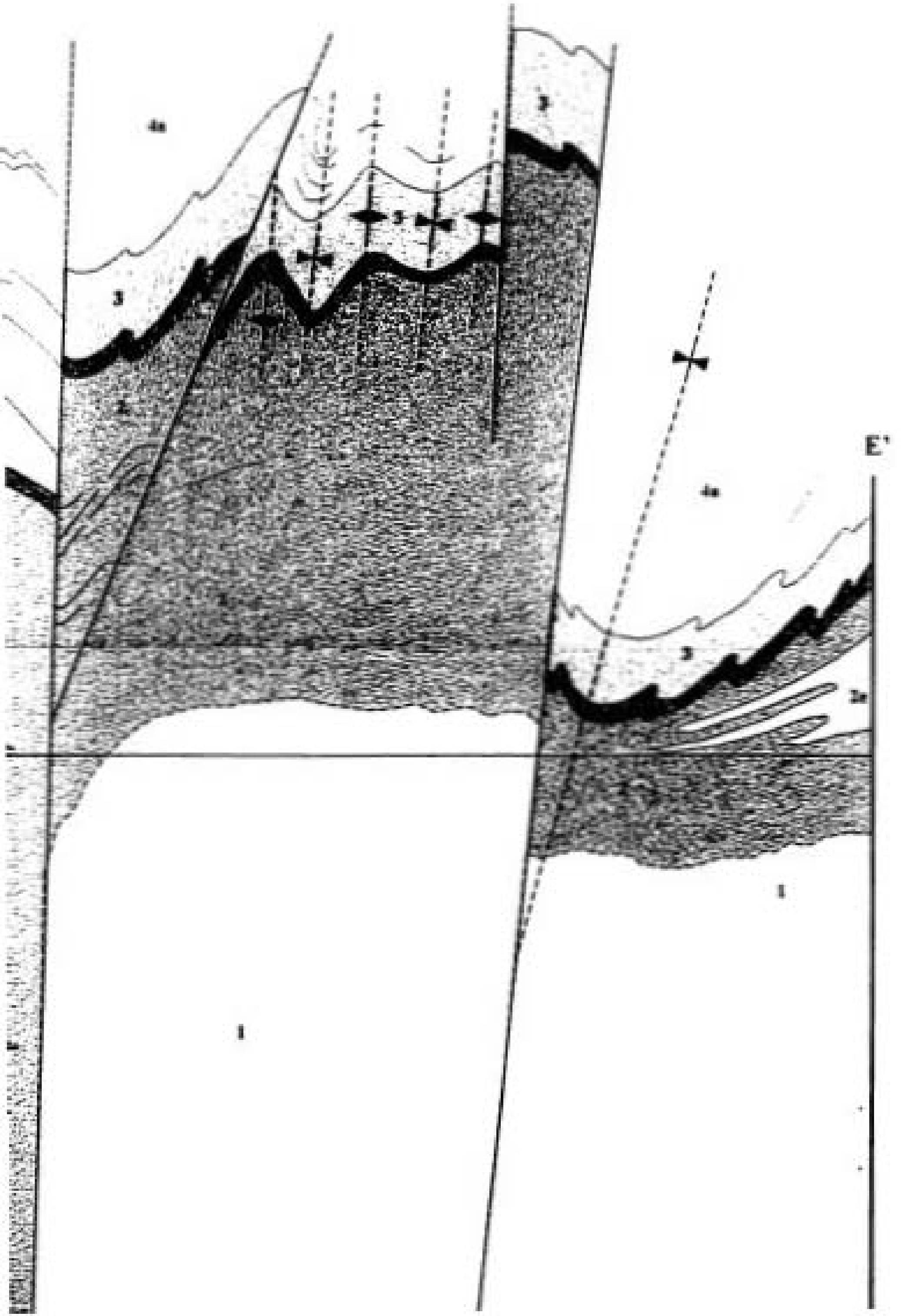
bzone

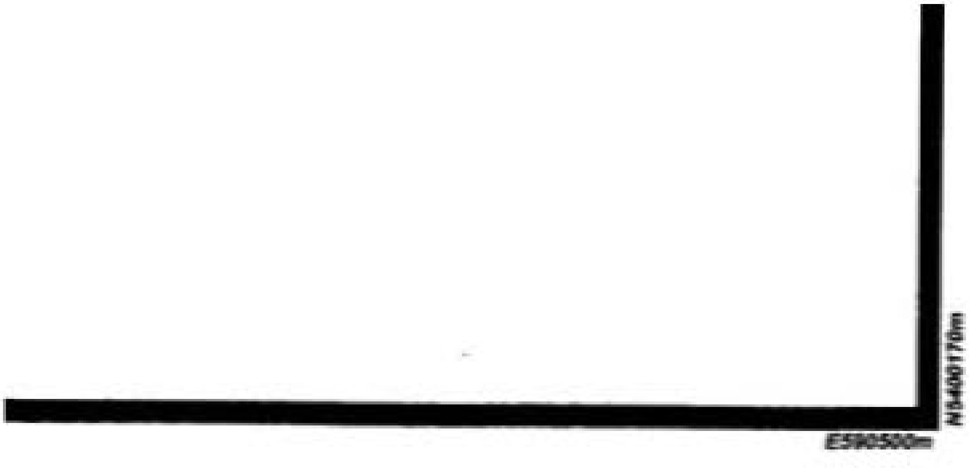


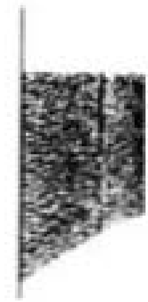







4a
3
3
5
2
E'
4a
3
2a
1
1





* see notes.

Sym

data point from Kean and Mercer (1981
Jayasinghe (1982)..

bedding (Map: dip known, overturned,

foliation (Map: S_2, S_1,S_2 vertical; Sectior

intersection lineation (L^2_1, L^1_2)..................

F_1 fold axis..

slickenside lineation....................................

contact (inferred, gradational, sharp, un

fault (Map: inferred, known; Section: inf

younging direction......................................

F_2 anticline..

F_2 syncline, overturned...............................

Outcrop (extensive, point)..............................

brittle-ductile shear zone (motion sense

Sample locality (G-graptolite; C-geoche

power line..

highway, gravel road, forest track or trai

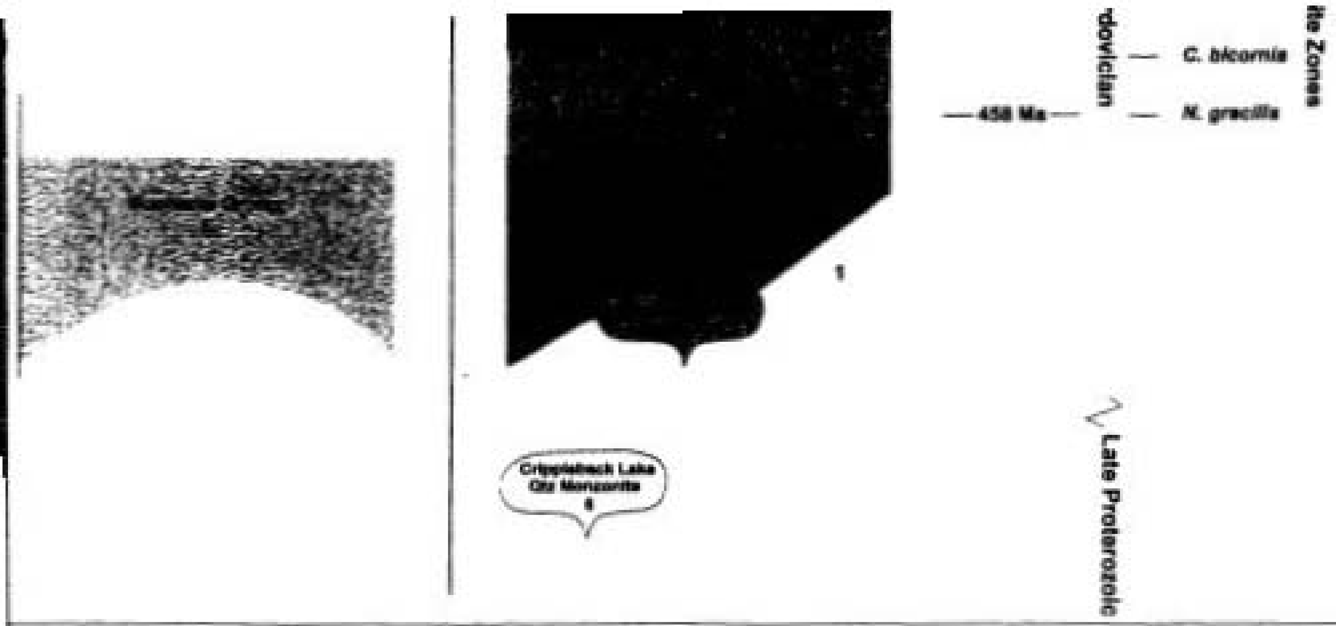
UTM reference co-ordinates.........................

unconformity..

Refe

Colman-Sadd, S.P., Hayes, J.P.
of the Island of Newfound
Branch, Newfoundland De

Kean, B.F., and Jayasinghe, N.F
Map Area (12A/16). New



Symbols

ercer (1981); Kean and

....

verturned, vertical; Section: trace)

cal; Section: trace).....................

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....

....

, sharp, unconformable)..........

Section: inferred)....................

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tion sense unknown, known).

C-geochemistry)..................... JC0021GC

....

ack or trail, railway...............

.... NS400170m

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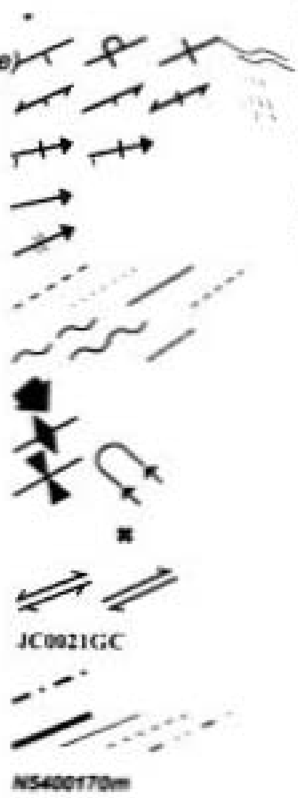

References

ayes, J.P., and Knight, I., 1990. Geology
Newfoundland: Map 90-1. Geological Survey
ndland Department of Mines and Energy.

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/16), Newfoundland. Mineral Development
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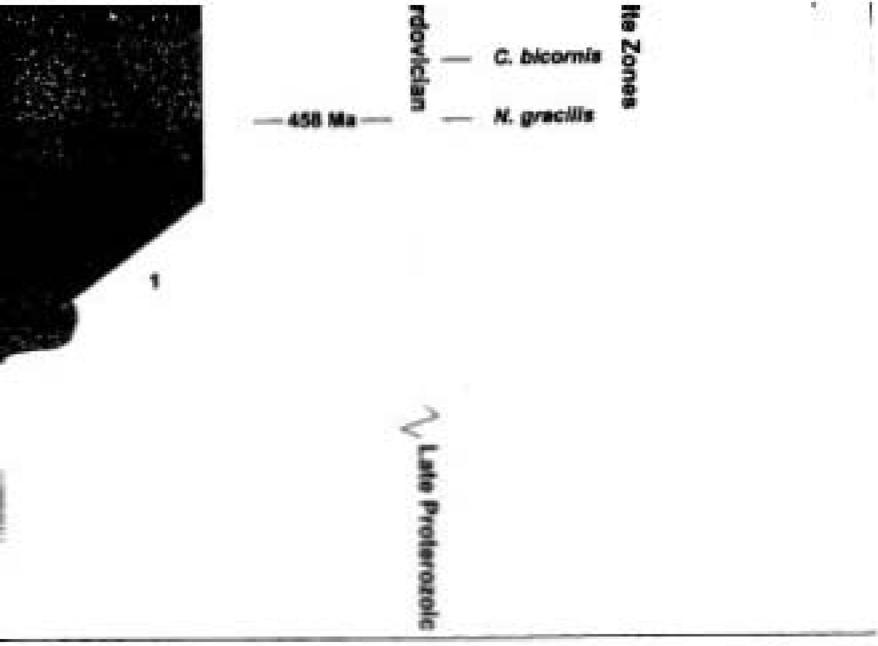
Index Map



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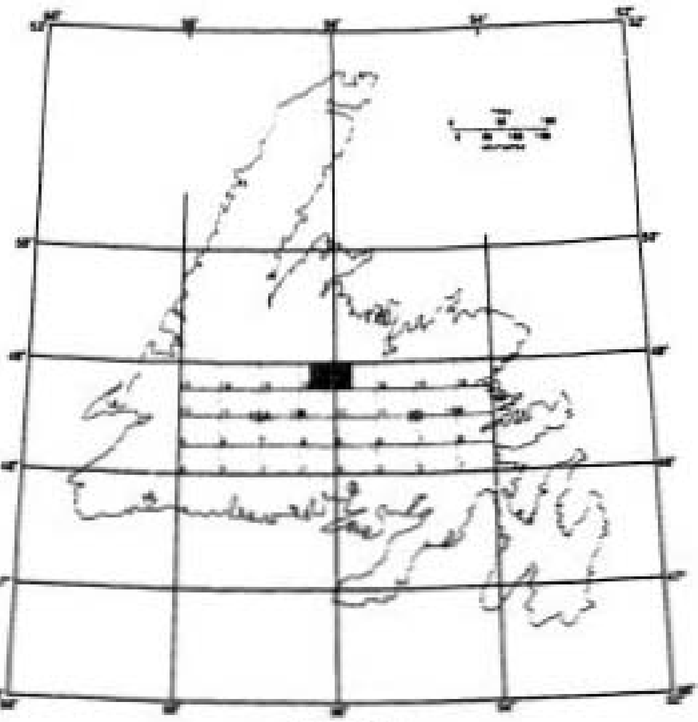
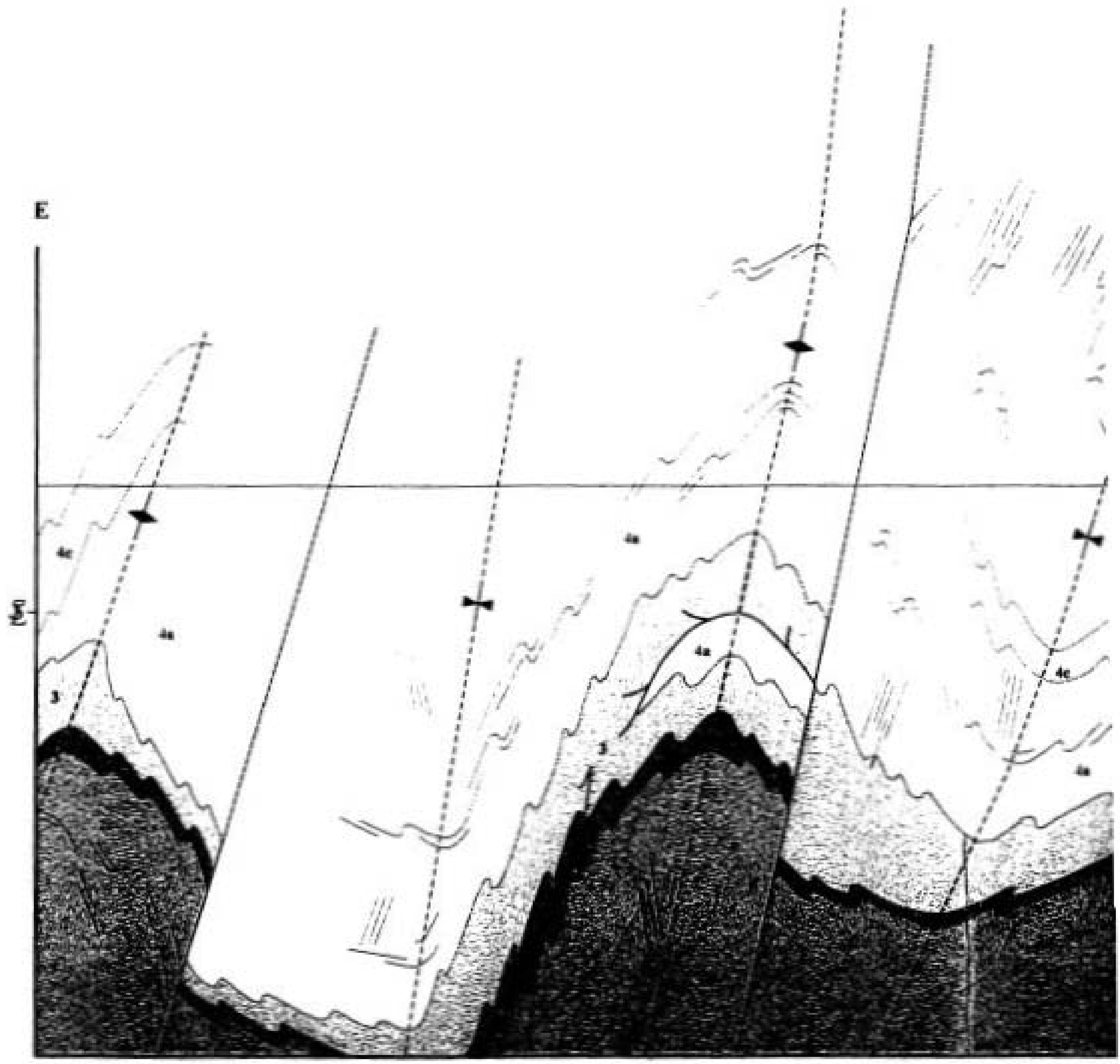
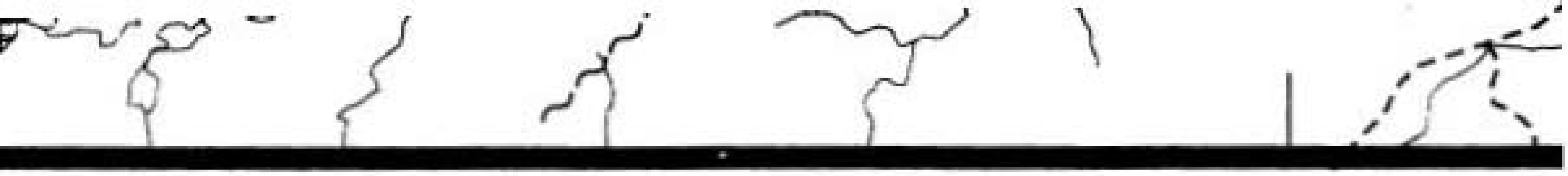
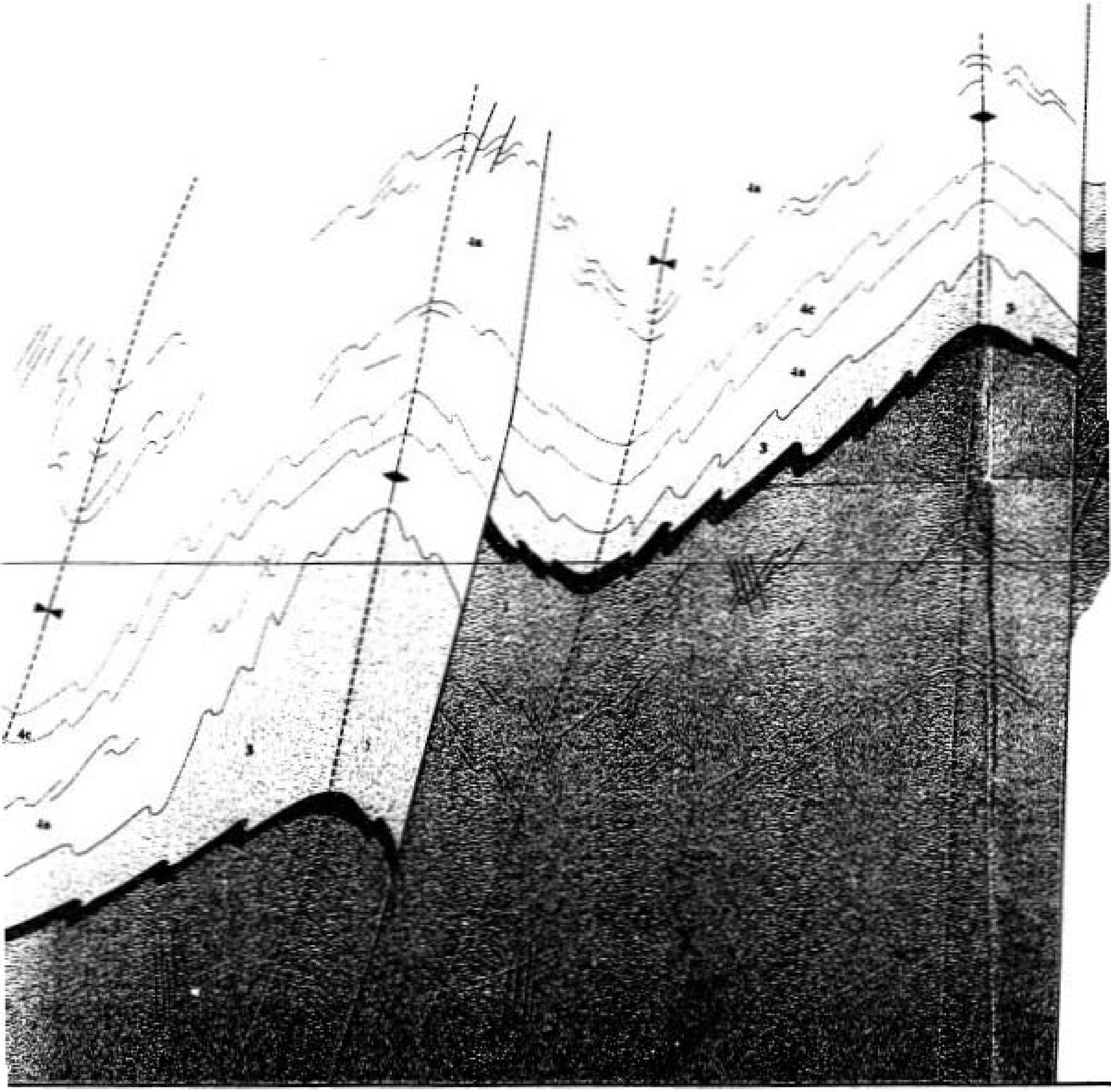


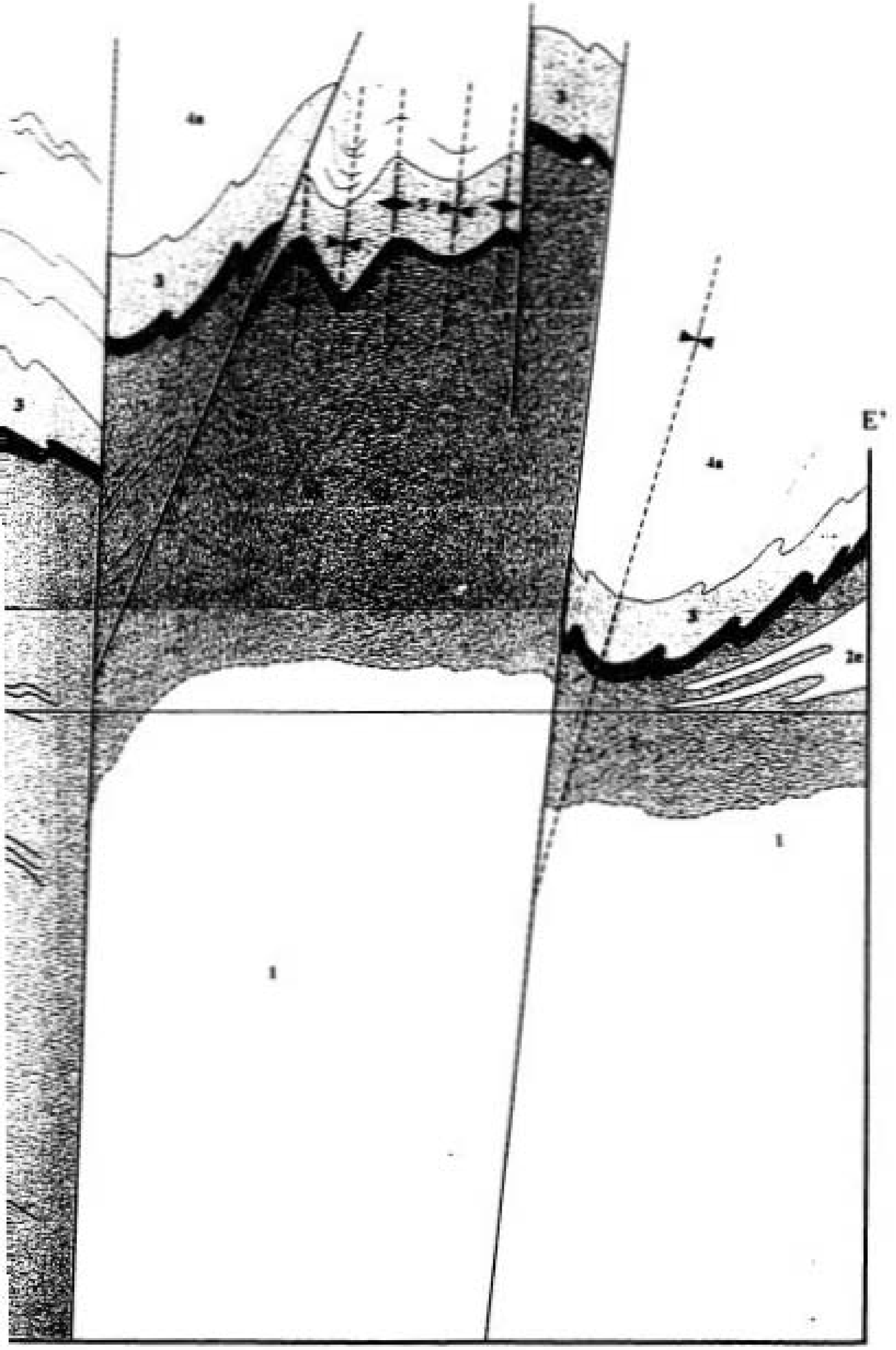
Index Map

Geology and compilation by J.E. Carter, 1998


E
4c
4a
3
4a
3
4a
4c
4a
4c






E'
4a
3
2a
1

N5400170m

E590500m

* see notes.

Sym

data point from Kean and Mercer (1981
Jayasinghe (1982)........................

bedding (Map: dip known, overturned,

foliation (Map: S_2, S_1-S_3 vertical; Section

intersection lineation (L^2_0, L^1_0)...............

F_1 fold axis...

slickenside lineation.....................................

contact (inferred, gradational, sharp, un

fault (Map: inferred, known; Section: infe

younging direction...

F_1 anticline..

F_1 syncline, overturned.................................

Outcrop (extensive, point)...............................

brittle-ductile shear zone (motion sense

Sample locality (G-graptolite; C-geocher

power line...

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unconformity...

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Kean, B.F., and Jayasinghe, N.R
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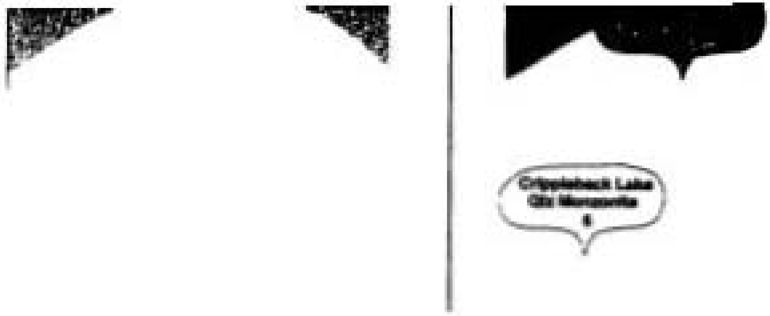
Division, Newfoundland D
Report 81-2, 37p.

Kean, B.F., and Mercer, N.L., 198
Map 81-99 (2D/13). Mine
Newfoundland Departmen



Late Proterozoic

Symbols

a Kean and Mercer (1981); Kean and
982)

dip known, overturned, vertical; Section: trace)

$S_?$, $S_?S_?$ vertical; Section: trace)

eation ($L^1_?$, $L^1_?$)

ation

d, gradational, sharp, unconformable)

rred, known; Section: inferred)

tion

rturned

sive, point)

hear zone (motion sense unknown, known).

(G-graptolite; C-geochemistry) JC0021GC

' road, forest track or trail, railway

co-ordinates N5400170m

References

-Sadd, S.P., Hayes, J.P., and Knight, I., 1990. Geology f the Island of Newfoundland: Map 90-1. Geological Survey ranch, Newfoundland Department of Mines and Energy.

.F., and Jayasinghe, N.R., 1982. Geology of the Badger Map Area (12A/16), Newfoundland. Mineral Development Division, Newfoundland Department of Mines and Energy. Report 81-2, 37p.

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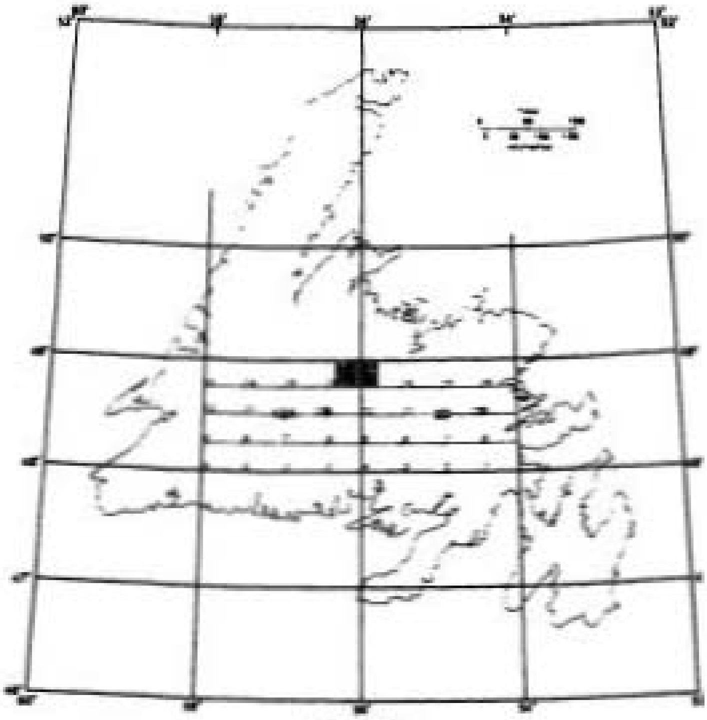

Index Map

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1

Late Proterozoic

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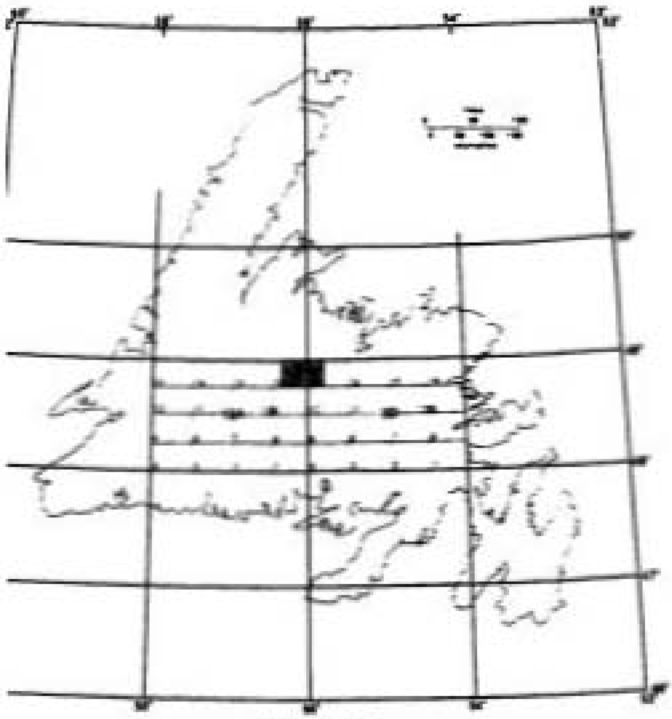
...The space-time legend concept, and ages for the fine- to ...-grained gabbro were obtained from Colman-Sadd ...990).



Index Map

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