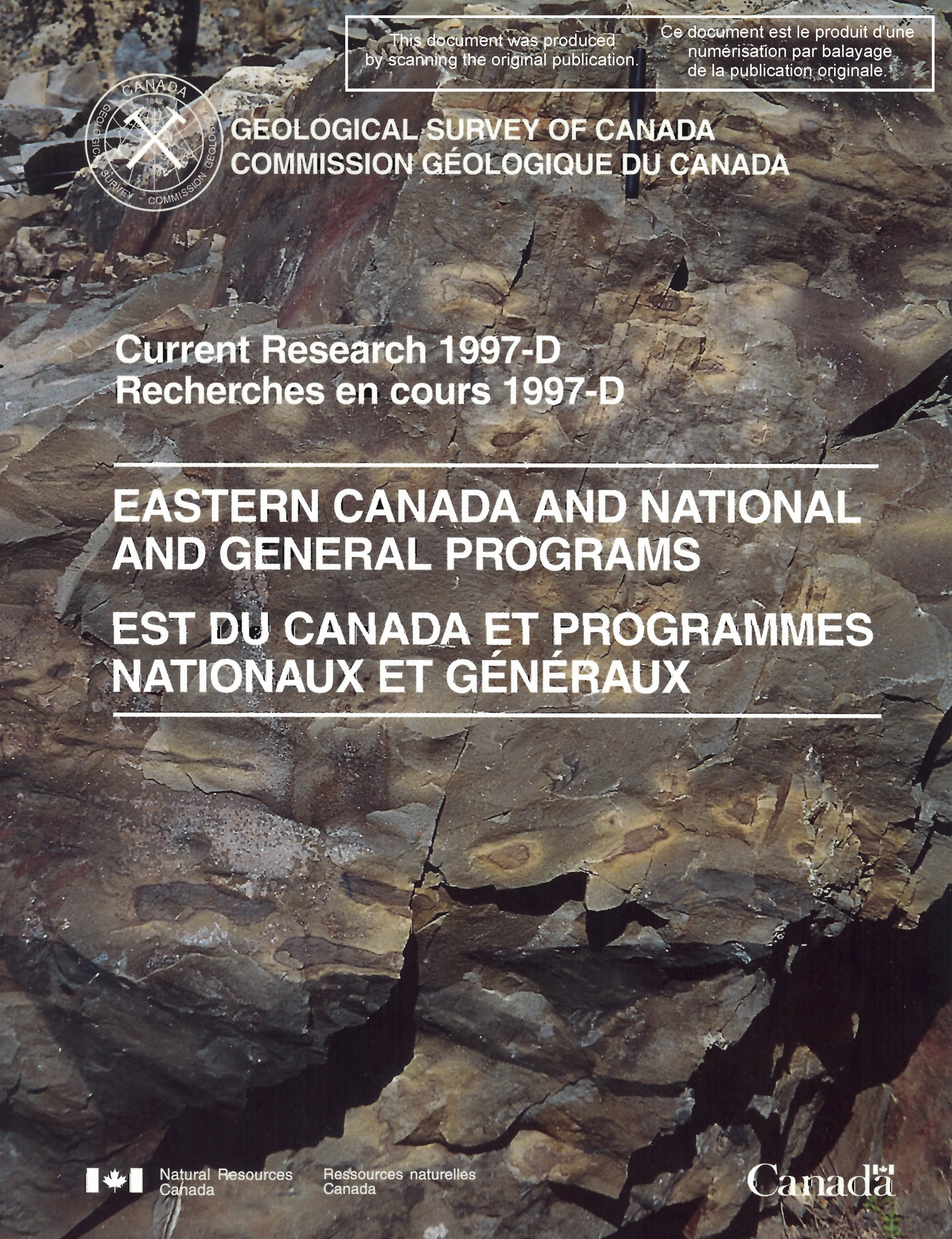

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Cover illustration

Homogenized feldspathic sandstone with fragments of tuff beds (Fogo Harbour Formation, Newfoundland), due to soft-sediment slumping. See paper by Currie, this volume. Photograph by K. Currie. GSC 1996-163

Unité homogène de grès feldspathiques à fragments de lits tufacés (Formation de Fogo Harbour, Terre-Neuve), découlant d'un glissement de sédiments non consolidés. Cette photographie se rapporte à l'article de Currie dans le présent volume. Photo : K. Currie. GSC 1996-163

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CONTENTS

Stratigraphy and deformation of the Humber Zone in Gaspésie, Quebec

Gregory Lynch and Olivier Arsenault

Quebec Geoscience Centre, Sainte-Foy

Lynch, G. and Arsenault, O., 1997: Stratigraphy and deformation of the Humber Zone in Gaspésie, Quebec; in Current Research 1997-D; Geological Survey of Canada, p. 1-8.

Abstract: Cambrian-Ordovician stratigraphy in the Humber Zone of the Grande Vallée area (Gaspésie) can be grouped into three broad packages characterized by (1) rift and continental slope clastic assemblage, (2) upper to lower slope-basin plain carbonate-dominated assemblage, and (3) a thick upper flysch package marking the onset of Taconic deformation. Middle Ordovician deformation features thrust imbrication of Precambrian-Cambrian volcanic units with the stratified Cambrian-Ordovician continental margin deposits, and with the synkinematic Ordovician foreland flysch sediments. New mapping and a cross-section show that units have been telescoped across a relatively short distance due to a steep convex ramp flattening into a décollement towards the foreland. Shortening was accommodated on three principal thrusts, and large north-vergent folds in foreland rocks are interpreted as fault-propagation folds above the tips of blind thrusts.

Résumé : La stratigraphie cambro-ordovicienne de la zone de Humber dans la région de Grande Vallée en Gaspésie peut être groupée en trois grands ensembles caractérisés 1) par un assemblage de roches clastiques de rift et de talus continental, 2) par un assemblage principalement de roches carbonatées de talus supérieur-inférieur et de plaine abyssale, et 3) par un flysch supérieur épais marquant le début de la déformation taconique. La déformation de l'Ordovicien moyen comporte un écaillage par chevauchement des unités volcaniques du Précambrien-Cambrien avec les sédiments stratifiés de marge continentale du Cambrien-Ordovicien, et avec les sédiments de flyschs syncinématiques d'avant-pays de l'Ordovicien. De nouveaux travaux de cartographie et une coupe transversale montrent que les unités ont été télescopées sur une distance relativement courte par suite de l'aplatissement d'une rampe abrupte convexe en un décollement en direction de l'avant-pays. Le raccourcissement a pu se faire sur trois principaux chevauchements, et de grands plis à vergence nord dans les roches d'avant-pays sont interprétés comme des plis de propagation par failles au-dessus des pointes de chevauchements non émergents.

INTRODUCTION

The Humber Zone defines the northwestern limit of the Canadian Appalachians (Williams, 1979). It consists of a thick early Paleozoic succession deposited on the rifted continental margin of Iapetus, and was later thrust towards the continent during the Ordovician Taconic orogeny (St-Julien and Hubert, 1975; St-Julien et al., 1983). In southern Quebec, the Humber Zone has received considerable attention from researchers, with much new geological data now available (e.g. Tremblay and Pinet, 1994; Pinet and Tremblay, 1995). In contrast, the Humber Zone to the north in the Gaspésie region has received much less attention, except for a recent synthesis of Cambrian-Ordovician stratigraphy and structure by Slivitzky et al. (1991). Along strike from northeast to southwest in Quebec, Cambrian-Ordovician stratigraphic groupings show a decent degree of persistence. However, the deformation history changes markedly along strike; two important compressional events have affected the rocks to the

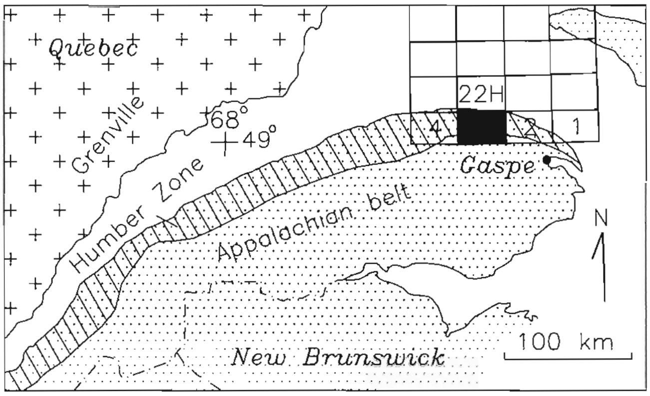

Figure 1. Location map of study area shown as black rectangle (22H/03) within NTS grid 22H, in the northeastern Quebec Appalachians.

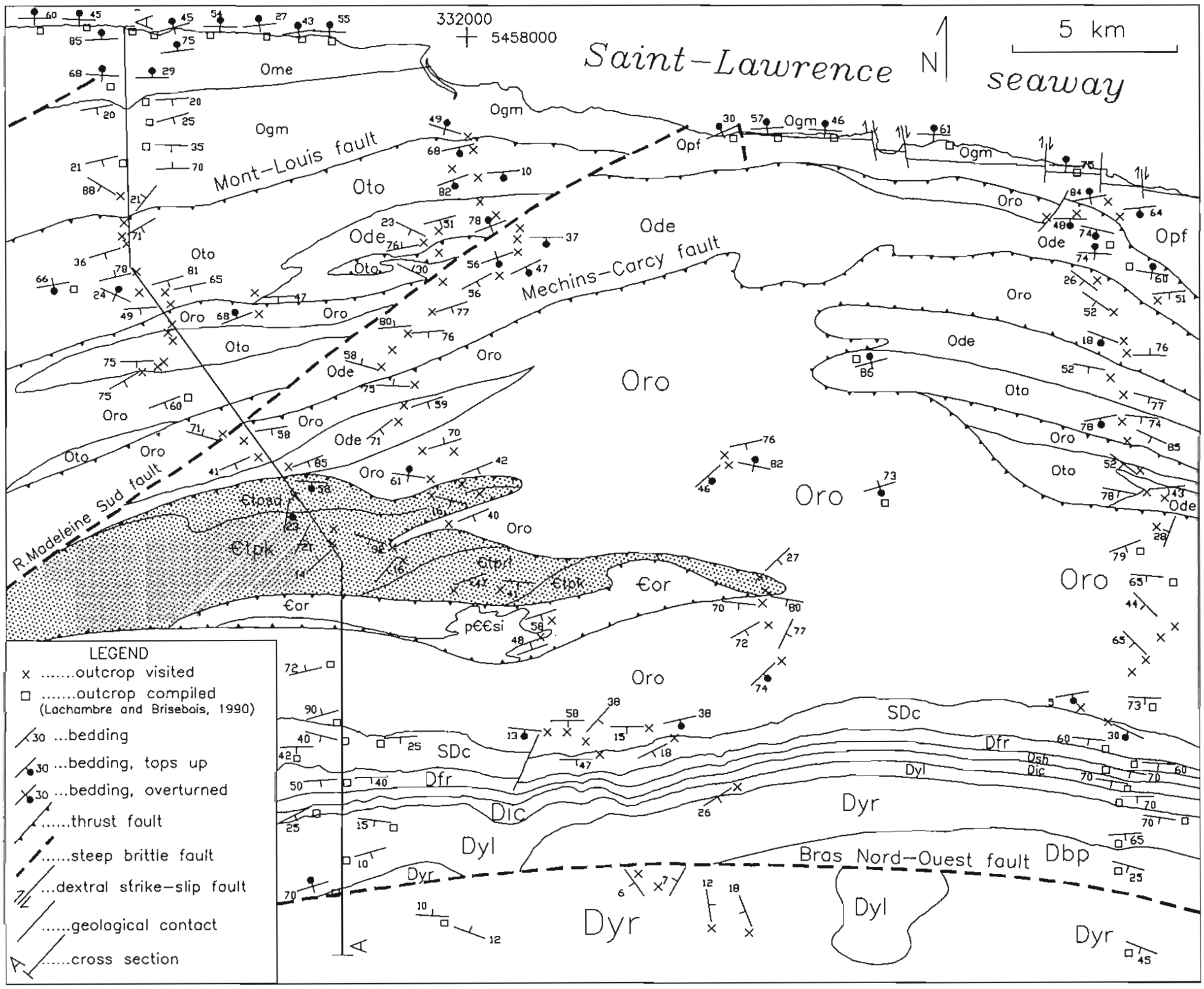

Figure 2. Simplified geology map of Gande Vallée (NTS 22H/03). The x symbol denotes positions of outcrops visited during the course of this study, whereas squares are information taken from compilation of Lachambre and Brisebois (1990). Legend of stratigraphic units is contained in Figure 3.

south during the Ordovician Taconic and Devonian Acadian orogenic events, where metamorphic grades are generally higher; whereas the effects of the Acadian event in the Humber Zone of the Gaspésie region are considered relatively minor, and the rocks show little effects of metamorphism. Silurian-Devonian cover rocks of the Gaspésie-Connecticut Valley Trough overlapping the eastern edge of the Humber Zone, and a pronounced late Silurian angular unconformity (Salinic event) has affected the Quebec Appalachians from north to south. The eastern margin of the Humber Zone also features ophiolite slices derived from the adjacent Dunnage Zone which form an integral part of the thrust assemblages within the central and southern segments of the belt, whereas they are rare to the north where the rocks are apparently further from the suture zone which remains buried beneath the Silurian-Devonian cover in this region.

Mapping in the Humber Zone of the Gaspésie region was conducted sporadically from the early 1950s to early 1980s, with results synthesized by Slivitzky et al. (1991). The geological setting of the Humber Zone in the Gaspésie region has prompted hydrocarbon exploration work, which includes an onshore-offshore Société Québécoise d'Initiatives Pétrolières seismic study from Anticosti Island to the mainland (Rocksandic and Granger, 1981). Otherwise little recent work has been done to characterize the structural style of this region, and no up to date cross-sections are available. This study of the Grande Vallée area (Fig. 1) attempts to improve our understanding of the structure, with the objective of generating cross-sections constructed with new field data. Partial revision of the Grande Vallée map (22H/03) (Fig. 2, 3) and a preliminary cross section (Fig. 4) are presented here. New mapping has resulted in revision of the distribution of stratigraphic units, which in turn has necessitated a reinterpretation of the structure since thrusts are largely defined on a stratigraphic basis. Fold styles are described. Also a qualitative assessment of potential reservoir rocks within the succession is presented.

STRATIGRAPHY

A synthesis of the Cambrian-Ordovician stratigraphy of northeastern Quebec Appalachians is given by Slivitzky et al. (1991). Nomenclature and subdivisions for units are according to Biron (1974) for the upper part of the succession, and from Vallières' (1984) research in the Rivière-du-Loup area, for the lower part of the succession. These studies significantly updated the earlier work of Liard (1972, 1973). Collectively the entire Cambrian-Ordovician succession is known as the Quebec Supergroup, and has a total thickness estimated at approximately 10-12 km, with the sediments ranging in age from Precambrian-Early Cambrian to upper Middle Ordovician. Major units have been traced along strike for over 450 km, from Gaspésie in the northeast to the Rivière-du-Loup region in the southeast. Subdivisions within the supergroup, however, consist mostly of formations which have not

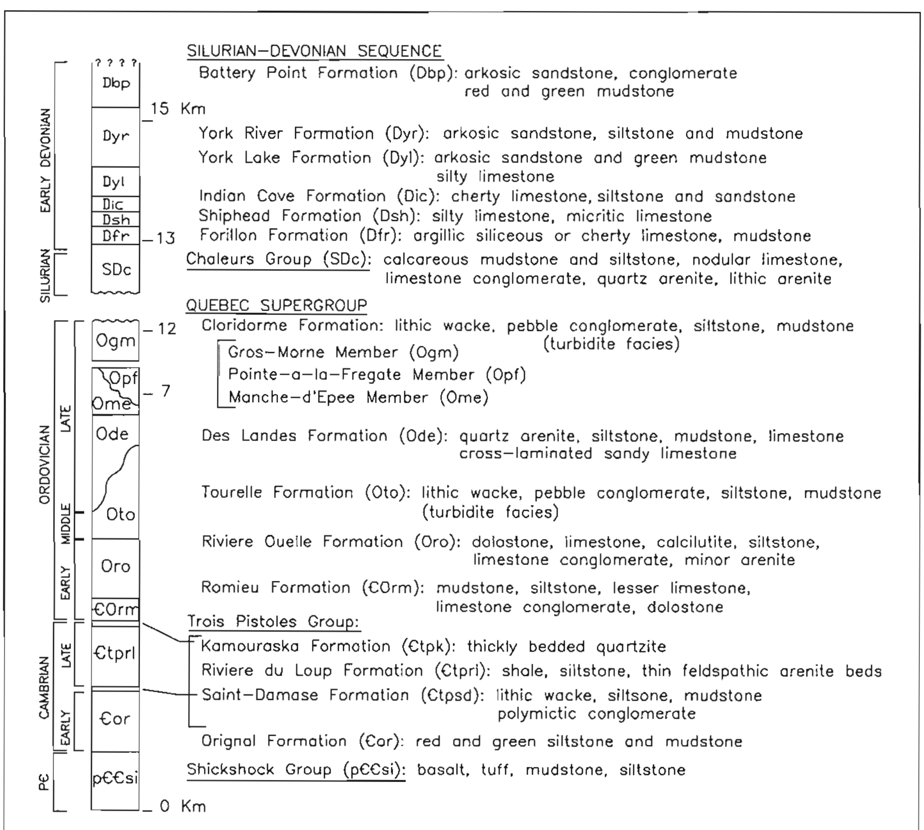

Figure 3. Stratigraphic column for study area and legend to map of Figure 2.

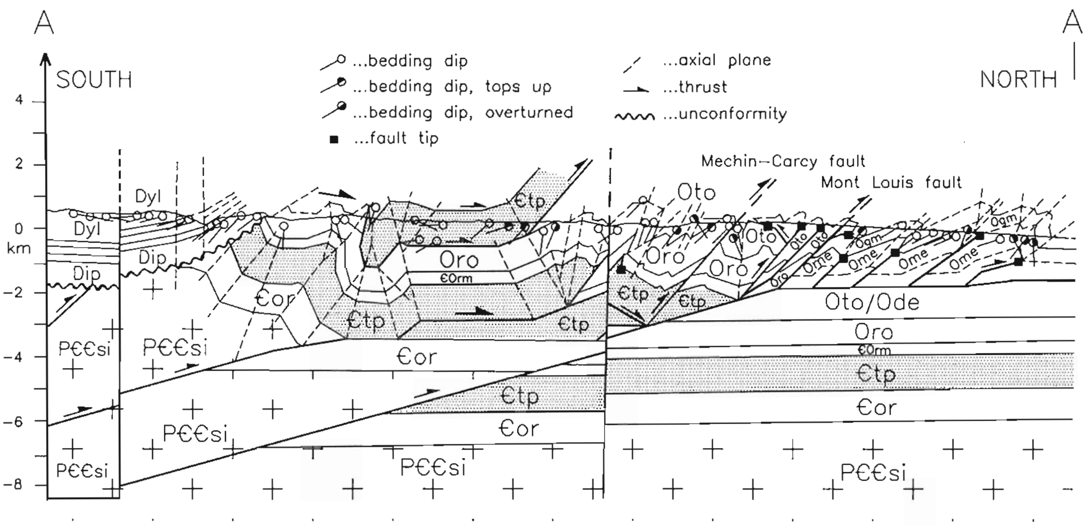

Figure 4. *North-south structural cross-section through the Humber Zone in the Gaspésie region. Position of section (A-A') is shown on the map of Figure 2. Legend of stratigraphic units is contained in Figure 2.*

been assigned to any defined groups. Also a number of members have been identified in the upper part of the supergroup which define large mappable units at 1:50 000 scale, which should be defined as formations even though the actual breakdown relies on biostratigraphy (Slivitzky et al., 1991). Different groupings for Cambrian-Ordovician units are recognized for the Humber Zone of the southern Quebec Appalachians (e.g. Globensky, 1987; Lavoie, 1994). Preliminary regional correlations with Humber Zone rocks of Newfoundland have also been made (Lavoie, 1997).

For practical reasons the Cambrian-Ordovician sedimentary succession covering map area 22H/03 (Fig. 2) can be subdivided into three informal groupings or packages (Fig. 3) according to distinct lithologies and facies assemblages: the lower package features continental slope and basin plain siliciclastic facies including distinct quartzites and conglomerates from the Trois Pistoles Group and hemipelagic muds of the Orignal and Romieu formations; the middle package is dominated by fine- and coarse-grained continental slope and basin plain carbonates featuring ribbon carbonates of the Rivière Ouelle Formation; and the upper package is dominated by turbidite and flysch deposits from the Tourelle, Des Landes, and Cloridorme formations.

Lower package

The oldest units in the study area are from the Shickshock Group and consist of massive porphyritic basalt interbedded with laminated glassy rhyolite tuff and mudstone. Contact relations are not well exposed, and the group resides as an apparent klippe in thrust contact with surrounding units. Basalt from the Shickshock Group is also known to be typically amygdaloidal, vesicular, flow-layered, and locally to display pillow structures. The thickness of the group is not known, but is thought to be greater that 1000 m (Slivitzky et al., 1991). The age for these rocks is only poorly constrained to the Hadrynian-Early Cambrian interval. A regional association of the basalts with arkose and arkosic conglomerates has been interpreted to indicate a rift setting for the Shickshock Group prior to the onset of deep marine sedimentation at the base of the Quebec Supergroup (St-Julien and Hubert, 1975).

The Orignal Formation is apparently the lowermost sedimentary unit in the Quebec Supergroup in the study area, and in the study area occurs adjacent to older volcanic rocks of the Shickshock Group, however the contact between the two units is not exposed. Rocks consist of reddish- and greenish-black mudstone, with minor thin beds of siltstone and arkosic sandstone. In the region Slivitzky et al. (1991) estimate that the formation has a minimum thickness of 1000 m, but this could not be verified due to thrust truncation. Biostratigraphic constraints in the region to the southwest place the Orignal Formation between late Early Cambrian and early Late Cambrian (Vallières, 1984; Lavoie,1997).

In the study area the Trois Pistoles Group was formerly undivided. Fieldwork in the course of this project has resulted in the recognition of the three formations which define the group, namely the Saint-Damase Formation at the base, the Rivière-du-Loup Formation, and the Kamouraska Formation at the top. The Saint-Damase Formation consists of coarse grained to pebbly feldspathic-lithic wacke or arenite, in 5 to 30 cm thick beds with thin siltstone and fine sandstone interbeds. Detrital mica is typically abundant, and black shale clasts are a distinctive feature. Crossbedding is well developed, and although sorting in the sandstones is moderate, they may be quite porous. An isolated brachiopod fossil was collected and has been submitted for identification, however fossils are rare. The unit covers an area previously defined as consisting of the Tourelle and Rivière Ouelle formations (Lachambre and Brisebois, 1990). Here the Saint-Damase Formation is estimated to be approximately 580 m thick, which may be a minimum since the lower contact of the formation is a thrust. Upwards the Saint-Damase Formation passes gradually into the Kamouraska Formation. The

Kamouraska Formation is a distinct, massive, coarse grained, white quartzite unit with poorly defined bedding. Quartz grains are well rounded and well sorted. The clast content is homogeneous with the exception of irregularly dispersed detrital shale flakes, up to 2 cm long, which locally comprise 2-3% of the rock. The discrete alignment of black shale fragments in the white quartzite is in some outcrops the only indication of bedding. The shale clasts persist through the gradual transition from the Saint-Damase to the overlying Kamouraska Formation. In thin section the Kamouraska quartzite displays a minor component of detrital feldspar, and tourmaline, as well as dispersed though large and conspicuous zircon clasts. Also the sandstone is quite porous, with porosity visually estimated at approximately 5-10% in hand sample and in thin section. In the study area the Kamouraska Formation is moderately dipping to flat lying, and the upper contact is not exposed. Consequently the thickness is not known, but from the outcrop distribution is estimated to be at least as thick as the 100 m estimate that Slivitzky et al. (1991) proposed for the formation in the Gaspésie region. The Rivière-du-Loup Formation of the Trois Pistoles Group is dominated by shale and phyllite, locally chloritic, with lesser medium- to fine-grained arkosic sandstone in thin to very thin beds. This formation is not well exposed in the study area, and upper and lower contacts have not been observed. However the unit apparently pinches out laterally between the Saint-Damase and Kamouraska formations, and as such may be intercalated with the Saint-Damase Formation since both contain similar fine grained detrital rocks. In the Gaspésie region the Trois Pistoles Group has not been dated. However the unit can be traced with confidence into the Rivière-du-Loup region where fossil collections have indicated a Late Cambrian to earliest Ordovician age (Vallières, 1984).

Middle package

In this study the Romieu Formation of Slivitzky et al. (1991) and the Rivière Ouelle Formation (Hubert, 1965) have been grouped together because there appears to be little grounds for their distinction on a lithological basis, particularly with regards to the carbonate rocks. It is problematical that a wide variety of lithologies have been included into the definition of the Rivière Ouelle Formation (Slivitzky et al., 1991), lithologies which might be separated as distinct formations in themselves, or which are actually from other known formations which have been incorporated into the Rivière Ouelle. Rocks mapped here as the Rivière Ouelle Formation consist predominantly of interbedded carbonate and shale, featuring thin beds of brown dolostone, limestone (lime mudstone to packstone), calcilutite, as well as minor fine grained arenites. Distinct horizons of carbonate conglomerate and breccia also occur. Detrital carbonate units typically display dynamic sedimentary structures such as well developed crossbedding, load structures at shale-carbonate contacts, and mud rip-up clasts. Slivitzky et al. (1991) consider the Rivière Ouelle Formation to be well dated in the Gaspésie region by virtue of graptolites collected diagnostic of the Early Ordovician. Regionally the unit covers a wide area and has an apparent thickness on the order of 1000 m; however the trace of the unit through the region has been outlined from the work of a number of geologists (e.g. Hubert, 1965; Lajoie, 1972; Liard, 1972; Biron, 1974; St-Julien, 1979, Vallières, 1984; Slivitzky et al., 1991) with neither the top or bottom of the unit clearly defined, while our mapping has significantly modified its distribution (Fig. 2). Further mapping and research is apparently needed for a better definition of the Rivière Ouelle Formation.

Upper package

The Tourelle Formation (McGerrigle, 1954) is the lowermost of the main flysch deposits and is reported to be concordant on the Rivière Ouelle Formation (Vallières, 1984). In the map area the Tourelle Formation has in large part been incorporated into the Rivière Ouelle and Des Landes formations by previous workers (e.g. see "roto" subdivision of Lachambre and Brisebois, 1990). Much of the work here has focused on separating these two formations and better defining their boundaries. The Tourelle Formation now occupies a greater area of the map than previously recognized. The main lithologies consist of thickly bedded lithic wacke, siltstone, and shale often in approximately equal proportions. The base of the coarser beds feature load structures and flute casts, and normal graded bedding is a common feature. Clasts in the wackes range up to pebble size; they include quartz, feldspar, unidentified lithic fragments, chert, carbonate, and detrital mica (mostly biotite). The formation is at least 1500 m thick in areas, but appears to vary significantly in its thickness along strike. Arenigian to Llanvirnian graptolites were collected in the area by Biron (1974) and Slivitzky (1984).

The Des Landes Formation (Slivitzky et al., 1991) features thinly bedded medium- to fine-grained quartz arenite or wacke, with siltstone and shale interbeds. Shale dominated sections may contain thin chert horizons. Thin grey carbonate beds show well developed crosslamination in coarse grained limestones as well as graded bedding. The formation occupies a prominent east-west striking position across the northern sector of the map (22H/03) (Fig. 2). However mapping during the course of this study has established that the Des Landes Formation changes along strike from east to west into coarse, thickly bedded lithic wacke similar to the Tourelle Formation across an apparent facies change. The two formations laterally overlap within the succession, with the Tourelle and Des Landes formations representing proximal and distal turbidite facies, respectively. Graptolites from the Des Landes Formation in the map area indicate a middle Ordovician age (Slivitzky et al., 1991), similar to that for the upper part of the Tourelle Formation. The apparent thickness for the Des Landes Formation is 1000-2000 m.

The Cloridorme Formation (Enos, 1969; Biron, 1971; Slivitzky, 1984; Slivitzky et al., 1991) is a spectacular succession of flysch and turbidite deposits, reaching over 5700 m in thickness (Slivitzky et al. 1991). The unit is well exposed for hundreds of kilometres in coastal sections distributed along the south shore of the St.-Lawrence River. Although Enos (1969) subdivided the Cloridorme Formation into fourteen units, Slivitzky et al., (1991) proposed six principal members with facies changes along strike. Biron (1974) on the other hand suggested that the Cloridorme be defined as a group since he considered the subdivisions of Enos (1969) to be mappable as distinct formations. Although tremendously thick, we found the Cloridorme Formation in the study area (22H/03) to be quite homogeneous and difficult to subdivide in the field without the advantage of biostratigraphy. Consequently better sedimentological criteria are apparently required, at least locally, before the Cloridorme can be raised from formation to group designation. The Cloridorme Formation consists of alternating medium to thickly bedded lithic wacke or arkosic wacke interbedded with siltstone and mudstone. Dispersed 10-40 cm thick beds of brown-weathering micritic limestone are a distinctive feature. Wackes typically show graded bedding with pebbly bases where load structures and flute casts are common. Contorted soft sediment folds are also observed and are contained within thick beds having planar upper boundaries. The Cloridorme Formation is Middle to Late Ordovician (Caradocian) in age (Slivitzky et al., 1991).

STRUCTURE

Structural features associated with thrusting and overturned to recumbent north-verging folds, strike or trend east in the study area (Fig. 5). The structural style is illustrated in the cross-section of Figure 4. Provenance studies of turbidites from the Cloridorme Formation have demonstrated derivation of material from allochthonous Cambrian to lower Ordovician units to the south and east, indicating a synorogenic origin for the formation (Enos, 1969; Slivitzky et al., 1991). This foredeep sedimentation effectively places a Middle Ordovician age on the Taconic thrusting event. Regionally, three tectono-stratigraphic domains have been defined for the Humber Zone; (1) the foreland thrust belt, as well as the (2) external, and (3) internal nappes (St-Julien and Hubert, 1975). The foreland belt is restricted to the Cloridorme Formation and is bound along its southern and eastern side by the Mont-Louis thrust and its hanging wall units, which also defines the "Logan Line" in the study area (St-Julien and Hubert, 1975). The external domain is defined by the zone of imbrication encompassing Cambrian-Ordovician units of the Quebec Supergroup below the Cloridorme Formation. The internal domain is characterized by thrust slices of the Shickshock Group, including exotic ophiolite slices and high grade metamorphic rocks to the southwest. In the study area both the foreland and external domains are exposed. The external domain has been subdivided according to Slivitzky et al. (1991) into the Marsoui River and the Sainte-Anne River nappes, which are separated by the Méchin-Carcy thrust. This thrust essentially separates a hangingwall (Saint-Anne River nappe) of Rivière Ouelle Formation rocks from a footwall (Marsoui River nappe) containing Tourelle and Des Landes formation rocks. Our mapping of this fault and the key stratigraphic units which are juxtaposed across it (Fig. 2) has moved the fault to a new position further south, relative to previous mapping (Lachambre and Brisebois, 1990). Also a large window through the Méchin-Carcy thrust and Saint-Anne River nappe into the underlying Marsoui River nappe has now been defined in the east of 22H/03 (Fig. 2). In outcrop, small scale structural features which relate to the Méchin-Carcy thrust are well preserved through the structural window in Petite Vallée, within the carbonate units of the Rivière Ouelle Formation which occur along the fault. Detached, isoclinal intrafolial folds, bound between planar surfaces of an intensely developed shear fabric, are characteristic of the fault zone (Fig. 6). Asymmetric thrust horses and small scale duplex structures have also been observed. Stretching and segmentation of carbonate beds as boudins between sheared mudstone horizons is also common. The fault dips moderately to the south, and is tens of metres or more wide. Locally open folds and an associated upright northeast-southwest striking spaced cleavage overprint the shear fabric and isoclinal folds in proximity of the Méchin-Carcy thrust, which is a feature reported to be of regional extent (e.g. two phases of deformation in Humber Zone of Slivitzky et al., 1991). In outcrop this cleavage can be linked to fault bend folding where small ramps are observed, and it is proposed that transport of isoclinal folds over such ramps in a forward propagating thrust system is responsible for the two stages of fabrics.

The surface plane of the Mont-Louis thrust is not well exposed in the study area, but can be confidently defined on the basis of juxtaposed stratigraphic units. South-dipping Tourelle and Des Landes formation rocks occur along the south flank of younger south-dipping Cloridorme Formation rocks. Subsidiary thrusts can be observed in the large exposures of folded Cloridorme units (Fig. 7). Tight, small scale

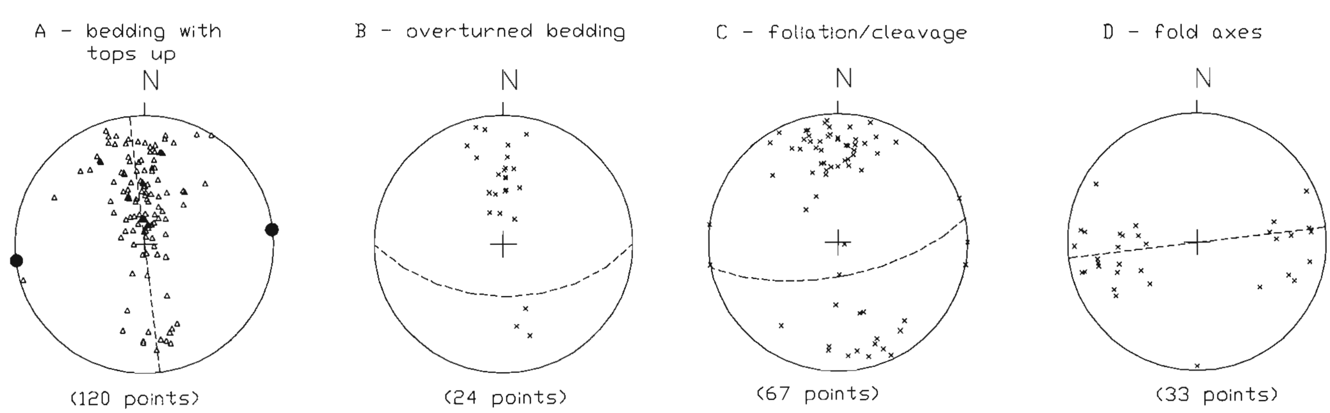

Figure 5. *Lower hemisphere equal area projections of structural data from the study area.*

"drag folds" are truncated along thrusts, which is consistent with a fault propogation origin (e.g. Suppe and Medwedeff, 1990) (Fig. 7) and likely reflects the style of folding for the larger scale features. Also, fault bend folds are well exposed above outcrop-scale ramp and flat thrust structures (Fig. 7), demonstrating that the two modes of fold origin exist. Large amplitude north-verging overturned to recumbent folds are well developed in the Cloridorme Formation in coastal exposures north on the Mont-Louis fault. Although imbrication is restricted to within a single unit, the Cloridorme Formation, overthrusting may still have been significant because of the great thickness of the formation (5700 m). Individual thrusts are difficult to trace, however, because similar units are juxtaposed. Nonetheless the Mont Louis thrust cannot be considered to be the deformation front, and the large overturned folds of the Cloridorme Formation west of the Mont Louis thrust have most likely developed as fault propogation folds above the tips of blind thrusts in the foreland. The strong northward vergence of the folds is reflected in the equal area projections of Figure 5, demonstrating that overturned beds dip mostly to the south.

Figure 6. *Tight to isoclinal intrafolial folds between planar shear surfaces, within Rivière Ouelle Formation limestone in immediate hanging wall of the Méchin-Carcy thrust, south of Petite Vallée on east side of map 22H/03.*

Figure 7. *Photograph from Cloridorme Formation in coastal exposure southwest of map area 22H/03, view looking east. Picture shows the two prominent types of folding associated with Taconic thrusting in the foreland sediments. Discrete thrust plane breaks through the limb of a fault propagation fold on the lower right hand side of the picture, leaving behind a fragment of the overturned syncline in its footwall; whereas ramping of the thrust on the left side of the photograph has kinked the hangingwall strata into an open syncline, through the mechanism of fault bend folding. Photograph of cliff face is approximately 20 m from top to bottom.*

To the south, in the external domain, in the western portion of the study area, an unnamed thrust which may have accomodated a significant amount of transport occurs at the base of the Trois Pistoles and Shickshock groups which appear as a klippe above the Rivière Ouelle and Des Landes formations. The trace of the thrust is based largely on stratigraphy, however an outcrop along the thrust features tectonic mélange and breccia several metres thick with brown dolostone clasts from the Rivière Ouelle Formation wrapped in shallow-dipping gouge with a strong planar fabric.

The Rivière Madeleine fault is a northeast trending, regional scale, late fault structure, which obliquely transects map 22H/03 (Fig. 2). Offset of older thrusts and stratigraphic units in the study area show an apparent dextral and/or normal (down to the northwest) sense of displacement (Fig. 2).

Previous maps of the area have drawn the trace of the east trending Shickshock Sud fault through the local area (Lachambre and Brisebois, 1990; Slivitzky et al., 1991). However outcrops visited where the fault is supposed to occur show no signs of shearing. Furthermore there is no apparent stratigraphic evidence for the fault; the Rivière Ouelle Formation occurs across the fault along much of its trace. However a better understanding of the Riviere Ouelle and Romieu formations is needed. Due to these features we have removed the fault, but more information is needed to fully resolve the issue.

DISCUSSION AND SUMMARY

The stratigraphic framework for the Humber Zone in the northern Quebec Appalachians has been established from a number of studies conducted over several years. However, in detail further work to establish groupings and define formations seems waranted. In particular, mapping in 22H/03 has resulted in the modification of the distribution of the Rivière Ouelle Formation. Consequently the position of the Méchin-Carcy thrust has been adjusted since it is largely defined on the basis of stratigraphy, and position of the Rivière Ouelle Formation. Also, the distribution of the Tourelle and Des Landes Formations has been modified, and lateral facies changes indicate that these two formations may have been contemporaneous in part. Furthermore the style of sedimentation for these two formations is in many ways similar to that of the Cloridorme Formation, which may be interpreted to indicate that thrusting began prior to the Cloridorme Formation if they are included in the foredeep assemblage of the upper package.

Structurally, units of the Quebec Supergroup (10-12 km thick) are telescoped across a short width (15-20 km at surface). A north-south cross-section (Fig. 4) illustrates that a relatively steep ramp below a tapering wedge is required to accommodate the imbrication (e.g. Boyer, 1995), with the hinterland in the south unconformably covered by the Silurian-Devonian Chaleurs Group. In the foreland to the north, fold geometries suggest that blind thrusts exist at depth north of the Mont Louis thrust rooted in a flat décollement within the Cloridorme Formation. It seems apparent that the foreland underwent relatively limited structural thickening or burial. As such the Mont Louis thrust does not represent the northern limit of Taconic deformation. Also, the structural segregation of the Cloridorme Formation into the foreland, from the Tourelle and Des Landes formations in the external nappe is arbitrary and structural compartmentalization should be revised.

Future work will focus on the construction of cross-sections through the northern Humber Zone in this region, providing insight into the structural style and possibly bringing insight into hydrocarbon potential and resource evaluation. The great thickness of shale and mudstone may be considered as potential source material for hydrocarbons (work in progress). Also, within the imbricate stack, thick porous quartzite of the Cambrian Trois Pistoles Group is a candidate as a reservoir rock for hydrocarbons, although more research is necessary for its assessment. Possible traps consist of Taconic fold closures or areas where the Trois Pistoles Group may reside directly beneath the Late Silurian unconformity. Furthermore, the structural model predicts a sharp gradient in the maturation level across the imbricate system, with lowest levels expected in the north.

ACKNOWLEDGMENTS

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Cambrian-Ordovician slope conglomerates in the Humber Zone, Quebec Reentrant, Quebec

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Abstract Cambrian-Ordovician deep-water sediments in the Humber Zone of the Quebec Reentrant occur in thrust complexes in eastern Quebec. The lithostratigraphy is complex because of the use of locally defined units. Limestone conglomerates are used to refine this framework. Lower Cambrian conglomerates consist of oligomict and polymict varieties with slope- and platform-derived clasts in a quartzose matrix. Upper Cambrian polymict conglomerates differ in their composition and characteristics, conglomerates form decametre-thick fining-upward units. Clasts include shallow water limestones and siliciclastics, slope-derived siliciclastic rafts, and abundant basement fragments. Ordovician conglomerates are finer grained (except in the southern area) and occur in thin successions. They consist of platformal and slope material with lime mudstone as the dominant clast type.

Résumé : Les sédiments cambro-ordoviciens d'eau profonde de la zone de Humber du rentrant de Québec se rencontrent dans des complexes de chevauchement dans l'est du Québec. La lithostratigraphie est complexe de part l'utilisation d'unités à définition locale. Des conglomérats à fragments de calcaire sont utilisés pour raffiner ce schéma. Les conglomérats du Cambrien inférieur sont des conglomérats oligogéniques et polygéniques qui contiennent des fragments dérivés de la plate-forme et du talus continentaux dans une matrice quartzeuse. Les conglomérats polygéniques du Cambrien supérieur ont des compositions et des caractéristiques variées et forment des unités décamétriques à granulométrie décroissante vers le haut. Les clastes comprennent des fragments de calcaire et de roches silicoclastiques d'eau peu profonde, des débris silicoclastiques dérivés du talus continental et des fragments abondants provenant du socle. Les conglomérats de l'Ordovicien ont une granulométrie plus fine (sauf dans le secteur sud) et forment de minces successions. Ils se composent de fragments provenant de la plate-forme et du talus continentaux, dont le type prédominant est du mudstone calcaire.

INTRODUCTION

Cambrian - Ordovician continental slope sediments in the Humber Zone of the Quebec Reentrant outcrop for some 600 km along the south shore of the St. Lawrence River in eastern Québec (Fig. 1). Besides a small inlier of Cambrian shallow marine facies in the Percé area (Fig. 1), they are the only record of a Cambrian passive margin in the Quebec Reentrant, the coeval shallow platform being buried beneath the Appalachians (Hubert et al., 1970; Davies and Walker, 1974; Hendry, 1978; Lajoie, 1979; Hein and Walker, 1982; Slivitzky et al., 1991; Bernstein et al., 1992; among others). The succession consists of siliciclastic-dominated Cambrian, and mixed siliciclastic/carbonate Ordovician strata. The current lithostratigraphy is complex because of the use of locally defined units (Table 1) that even if fine local sedimentological, paleontological and biostratigraphic analyses are available (see above). The regional significance of these rocks, their along-strike correlations within the Humber Zone and with the coeval unexposed shallow marine platform, and their thermal history are unknown. Furthermore, the most recent structural synthesis of the area (Slivitzky et al., 1991) relied heavily on the classical interpretation of St-Julien and Hubert (1975) which in the light of current tectonic concepts in the Appalachians, needs to be revised (Lynch and Arsenault, 1997).

This continental slope succession is quite similar to the Cow Head Group in western Newfoundland (James and Stevens, 1986) at the St. Lawrence Promontory (Fig. 1). There, correlations between the slope and shallow platform sedimentary records are well established and led to the proposition of a coherent paleogeographic scenario (James et al., 1989). The integration of the regional paleogeographic picture with detailed tectonic studies (Waldron and Stockmal, 1994; Stockmal et al., 1995) was instrumental in the discovery of oil reservoirs in western Newfoundland.

In the light of recent interest for hydrocarbon potential of eastern Canadian Paleozoic basins and in particular for the Cambrian-Ordovician tectonostratigraphic Humber Zone (Williams, 1979), an integrated stratigraphic, sedimentological, maturation, and structural study of the Humber Zone in the Quebec Reentrant has been initiated. The goal of this project is to propose up-to-date paleogeographic, thermal, and tectonic synthesis for this largely unknown area stretching from Québec City to Gaspésie.

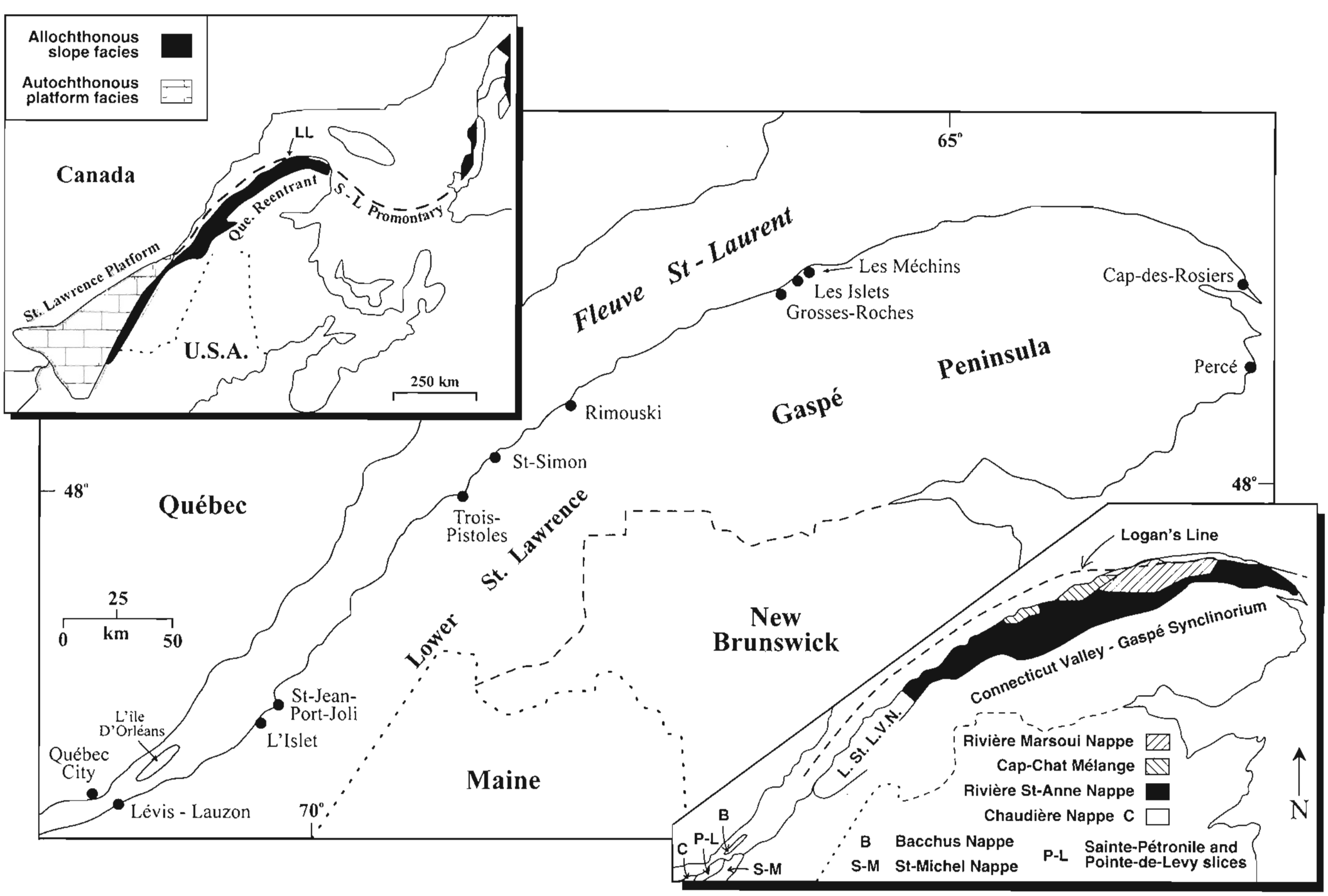

Figure 1. Location map for eastern Quebec with inset map showing distribution of Cambro-Ordovician allochthonous slope sediments and autochthonous platform sediments for the Quebec Reentrant and St. Lawrence Promontory. L.L. is for Logan's Line. Modified from Bernstein et al. (1992).

Table 1. Stratigraphic nomenclature for Cambrian to Ordovician continental slope deposits of the Humber Zone in the Quebec Reentrant. F is for faulted contact and R-D-L is for Rivière du Loup. All units are formations unless otherwise stated. Localities are shown on Figure 1.

Slivitzky St.-Julien (1987)	Hubert (1973)	Vallières (1984) Slivitzky et al. (1991)	Hubert et al. (1970)	Bersntein et al. (1992)	This paper
Québec City	L'Islet	R-D-L / Gaspésie	Rimouski / Trois-Pistoles	Grosses-Roches Les Méchins	Eastern Quebec
Ville de Québec		Tourelle F		Tourelle F	Taconian Flysch F
Lévis	Rivière-Ouelle	Rivière-Ouelle	Ladrière	Anse du Crapaud	Package 4
		Romieu			
Lauzon or Sillery Gp.	Kamouraska St. Damase	Kamouraska R-D-L St. Damase	Cap Enragé	Grosses-Roches	3 Packages 2
Ile D'Orléans Gp Sillery Gp.	St. Roch	Orignal	Orignal	Orignal	Package 1

This paper describes field characteristics of Cambrian-Ordovician continental slope conglomerates exposed in eastern Quebec (Fig. 1). This first phase of the research aims to correlate these conglomerates to produce a regionally coherent stratigraphic framework upon which ongoing studies are based.

GEOLOGICAL SETTING

Cambrian-Ordovician continental slope deposits in the Humber Zone of the Quebec Reentrant are part of the ca. 5 km-thick Québec Supergroup outcropping from Quebec City to Gaspésie (Fig. 1). These predominantly fine-grained, poorly fossiliferous, and locally poorly exposed sedimentary rocks are preserved in southeasterly-dipping thrust slices of the external tectonic domain as defined by St-Julien and Hubert (1975). These slices were emplaced over the Cambrian-Ordovician shelf during the Middle Ordovician Taconian orogeny (St-Julien and Hubert, 1975; St-Julien et al., 1983). Acadian-related transcurrent displacement of the slices has also been demonstrated (Slivitzky et al., 1991; Malo et al., 1992).

STRATIGRAPHY

The lack of a coherent stratigraphic framework for the Humber Zone in eastern Quebec largely lies in its structural complexity, but also on the limited number of biostratigraphic data and on the dominance of fine-grained sediments with few marker beds. The present stratigraphy (Table 1) is based on large-scale mapping (e.g., Béland, 1957; Hubert, 1973; Biron, 1971, 1974; Liard, 1973; Lajoie, 1972, 1974; Vallières, 1984; Slivitsky and St-Julien, 1987; Slivitzky et al., 1991; among others) and has proven to be inadequate at more detailed scales (Bernstein et al., 1992). The age of these units is loosely defined; local paleontological studies have revealed the presence of graptolites (Erdtmann, 1967; Riva, 1972; Landing et al., 1986; Slivitzky et al., 1991; Maletz, 1992), trilobites and brachiopods (Landing and Ludvigsen, 1984), chitinozoans (Achab, 1980, 1982, 1989) and conodonts (Uyeno and Barnes, 1970; Barnes, 1984). Moreover, the age of the slope conglomerates is mostly constrained by the youngest fossils in limestone clasts (Rasetti, 1943, 1944, 1945a, b, 1946a, b, 1948a, b).

Regionally, the succession can be divided into broad stratigraphic packages consisting of fine-grained sediments separated by or interbedded with coarse-grained units (Fig. 2). These packages will serve as a basis for a workable stratigraphic framework to be used for regional correlations as well as for event stratigraphy. The lower package consists of Lower Cambrian siliciclastic rocks capped by conglomerate units. The overlying package is defined by Middle Cambrian fine-grained siliciclastic rocks capped by lowest Upper Cambrian conglomerates. The third package consists of Upper Cambrian mixed siliciclastic and limestone conglomerates, sandstones, and shales capped by a conglomerate unit. Finally, a last package is represented by Lower to Middle Ordovician fine-grained successions of siliciclastic rocks and limestones locally punctuated by conglomerates.

The continental slope conglomerate units within or capping these packages offer field characteristics (sedimentary structures, thickness, stratal cycles, composition of clasts and matrix) that are fairly consistent along strike within the Humber Zone of the Quebec Reentrant. Most of these conglomerates bear exotic (platform- and basement-derived) clasts. The presence of these fragments suggest significant episodes of sea-level lowstands resulting in erosion of the shallow marine passive margin, the conglomerates can thus be used as a proxy for sea-level history and for documenting facies present on the currently unknown platform.

LOWER CAMBRIAN CONGLOMERATES

The best exposures of the Lower Cambrian conglomerates (part of package 1; Fig. 2) are in the foreshore flats of the Saint-Jean-Port-Joli and l'Islet areas (Fig. 1). These conglomerates were included in the Saint-Roch Formation although elsewhere, they were included in the Sillery and Ile D'Orléans groups and in the Orignal Formation (Table 1). The conglomerates are part of a predominantly fine-grained hemipelagite and turbidite succession and have been extensively studied for their sedimentology (Hubert et al., 1970; Hubert, 1973; Lajoie and Chagnon, 1973; Rocheleau and Lajoie, 1974; Strong and Walker, 1981), although little is known about the composition of embedded clasts and their significance for sea-level history.

Middle Lower Cambrian conglomerates

Conglomerate beds reaching 10 to 90 cm in thickness are found near the base of the section at Saint-Jean-Port-Joli (Fig. 1). The conglomerates occur as lenticular units filling decimetre-sized channels in hemipelagites; crossbedded sandstones commonly cap the conglomerates. Locally, gradings and clast imbrications occur (Fig. 3a). The conglomerates are clast supported, with fine quartzose sandy matrix representing about 15% of the rock volume. Most of the conglomerates are oligomictic (Fig. 3b); clasts include: limestone (90%), phosphate (7%), shale (3%), and minor quartz. Most of the fragments are sub-rounded and granulometric sorting is poor to fair. Most of the limestone clasts are represented by cross- and parallel-laminated calcisiltite (Fig. 3c) whereas few cyanobacterial micrite (thrombolite) clasts are present.

The calcisiltite clasts are similar to the ribbon limestones found at a few other places within the succession, and are most likely derived from these slope facies. However, the presence of thrombolite clasts argue for a shallow marine origin for some of the fragments and point to the presence of shallow marine carbonate production in Early Cambrian time. This is also supported by the slope-restricted ribbon limestones for which the source of carbonate muds can only be ascribed to shallow marine production.

Uppermost Lower - lowermost Middle Cambrian conglomerates

These conglomerates are best exposed near the wharf at l'Islet (Fig. 1) and have been the subject of detailed sedimentological studies. Three conglomerate units fill metre-sized deep channels with a few tens of metres of lateral extent (Fig. 4a). The channels truncate an underlying turbidite succession, and the conglomerates are interbedded with pebbly and crossbedded arkosic sandstones. The conglomerates are graded and crude bedding is seen at the top of individual units which reach between 3 to at least 10 m in thickness. The conglomerates are clast-supported and a quartzose sandy matrix forms about 10% of rock volume. These conglomerates are polymictic (Fig. 4b); clasts include: limestone (60%), quartz (15%), turbiditic siltstone rafts (15%), dolomite (5%), sandstone/quartzite (5%) with minor phosphate and shale fragments. The carbonate fragments are rounded to sub-rounded whereas siliciclastic ones are either angular or sub-rounded. The base of conglomerate units is poorly sorted (Fig. 4c), large siliciclastic clasts (up to 25 cm) are surrounded by millimetre-sized limestone fragments; sorting increases near the top of individual units. Limestone clasts are typified by a wide spectrum of facies (Fig. 4d), these include: slope-derived calcisiltites and platform-derived thrombolites, locally sandy bioclastic (brachiopod, trilobite, archaeocyathid) packstones, grainstones and wackestones, peloidal wackestones and oolitic grainstones.

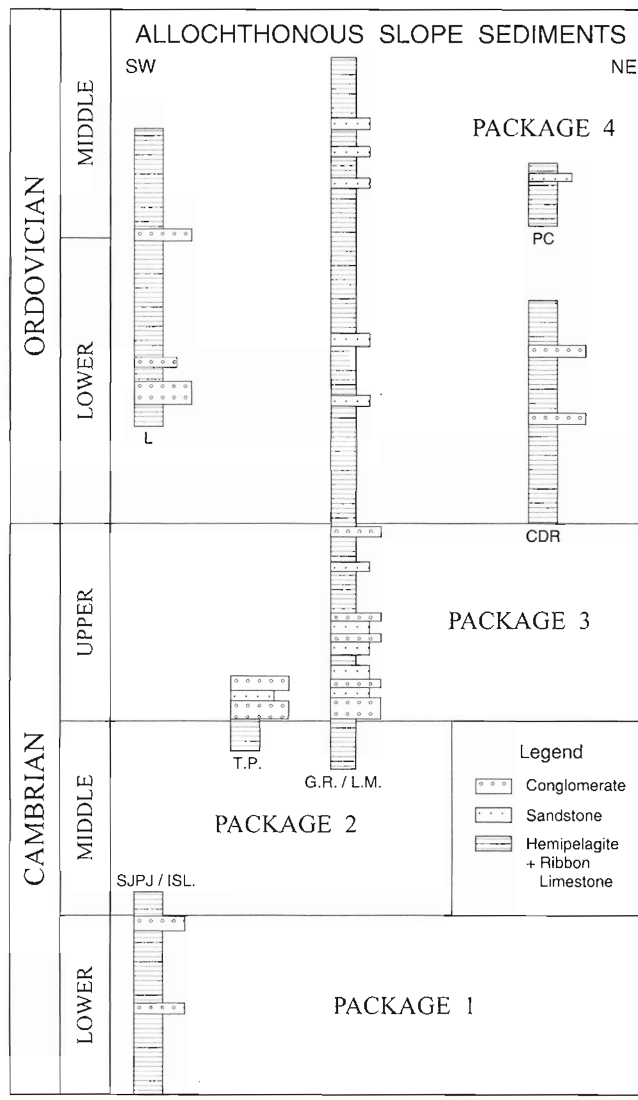

Figure 2. *Cambro-Ordovician lithostratigraphic packages proposed for the Humber Zone continental slope deposits in eastern Quebec. SJPJ – ISL is for Saint-Jean-Port-Joli-Islets, L is for Lévis, T.P. is for Trois-Pistoles, G.R. / L.M. is for Grosses-Roches / Les Méchins, CDR is for Cap-des-Rosiers, PC is for Pointe Carse.*

The nature of fragments suggest that a diversified and widespread shallow marine setting was eroded during a major latest Early Cambrian sea-level lowstand. The presence of abundant exotic siliciclastic fragments (coarse quartz, quartzites and sandstones) and the number of quartz-rich limestone facies suggest that the carbonate setting was likely bordering a siliciclastic shelf, a situation recorded in coeval successions (Forteau Formation) in western Newfoundland (James et al., 1989).

UPPER CAMBRIAN CONGLOMERATES

Upper Cambrian conglomerates (package 3, Fig. 2) are well exposed at many localities along the south shore of the St. Lawrence River. Excellent exposures are found in the Trois-Pistoles – Saint-Simon – Bic and in the Grosses-Roches – Les Méchins areas (Fig. 1). These thick conglomeratic successions have been the subject of detailed sedimentology studies (Hubert et al., 1970; Davies and Walker, 1974; Lajoie, 1974; Hendry, 1978, 1979; Hein, 1982; Hein and Walker, 1982; Bernstein et al., 1992). These conglomerates are part of

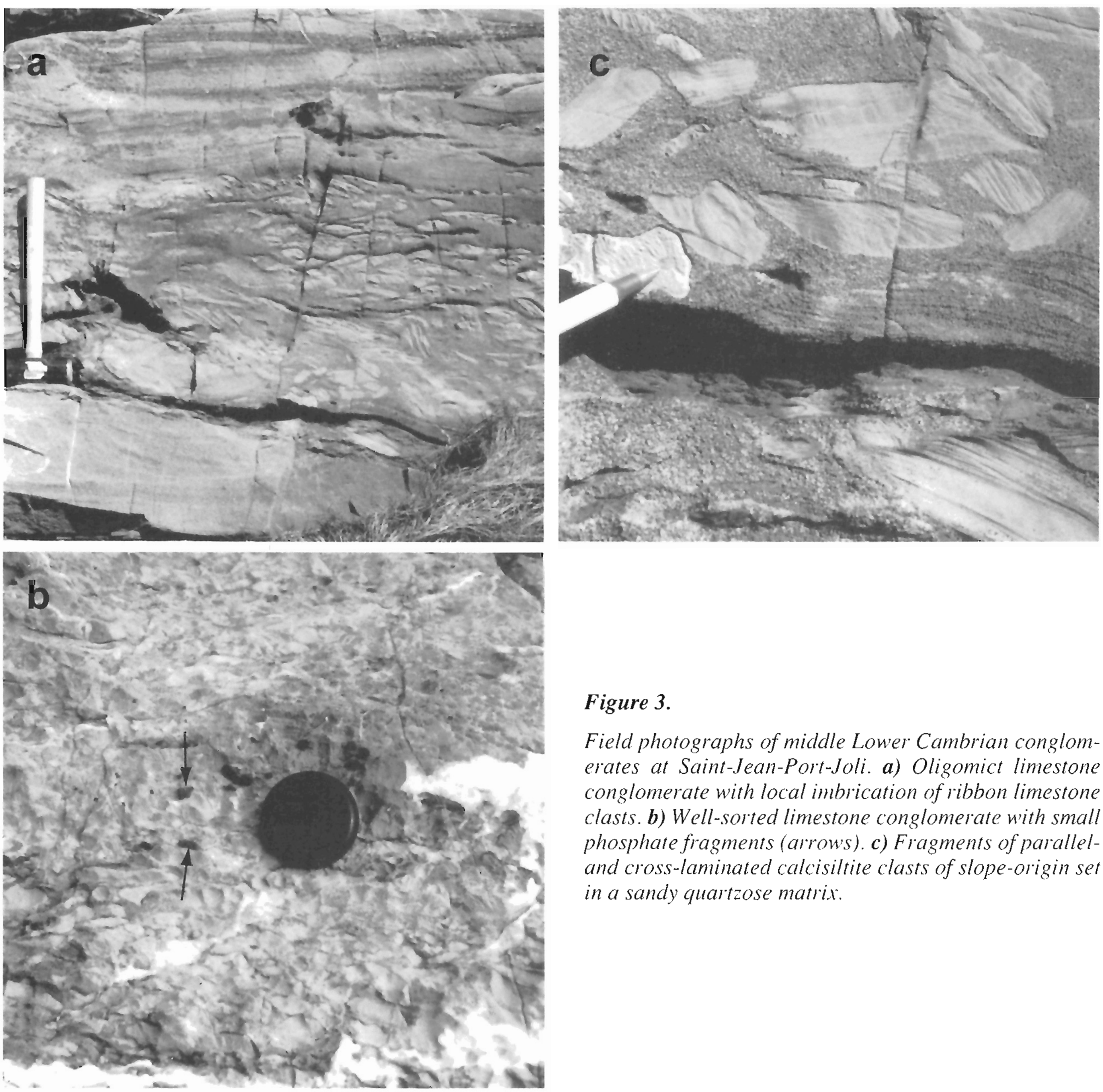

Figure 3.

Field photographs of middle Lower Cambrian conglomerates at Saint-Jean-Port-Joli. ***a)*** *Oligomict limestone conglomerate with local imbrication of ribbon limestone clasts.* ***b)*** *Well-sorted limestone conglomerate with small phosphate fragments (arrows).* ***c)*** *Fragments of parallel- and cross-laminated calcisiltite clasts of slope-origin set in a sandy quartzose matrix.*

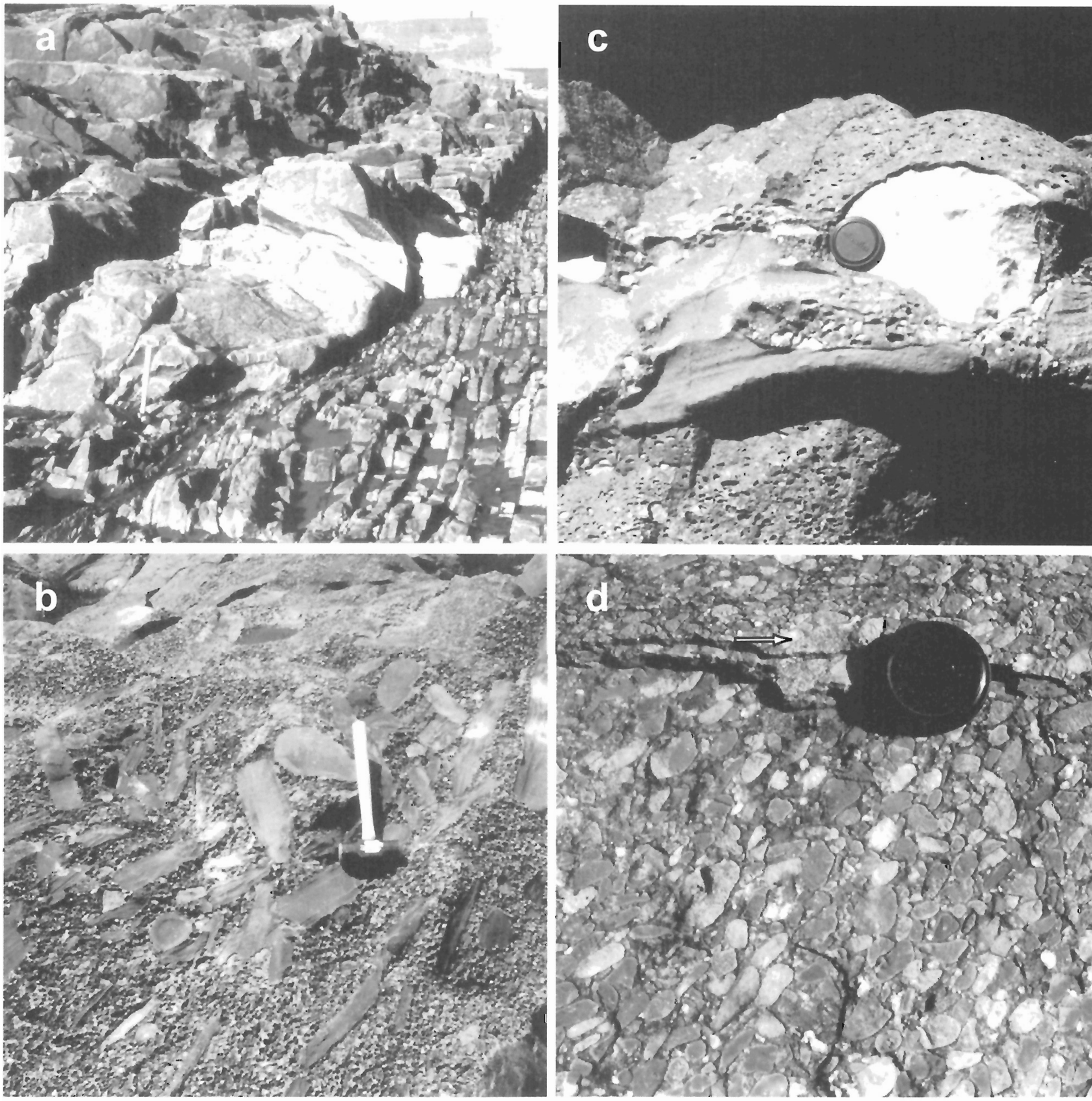

Figure 4. *Field photographs of uppermost Lower Cambrian conglomerates at l'Islet.* ***a)*** *Channel-fill conglomerates cutting through well-bedded turbiditic dolosiltite.* ***b)*** *Polymict limestone conglomerate with large siliciclastic rafts embedded in a finer-grained quartzose limestone conglomerate.* ***c)*** *Unsorted polymict conglomerate with siliciclastic rafts and large fragments of thrombolite (under lens cap).* ***d)*** *Diversified small limestone clasts including slope-derived calcilutite, cyanobacterial micrite and bioclastic grainstone (arrow) with abundant well rounded white quartz fragments.*

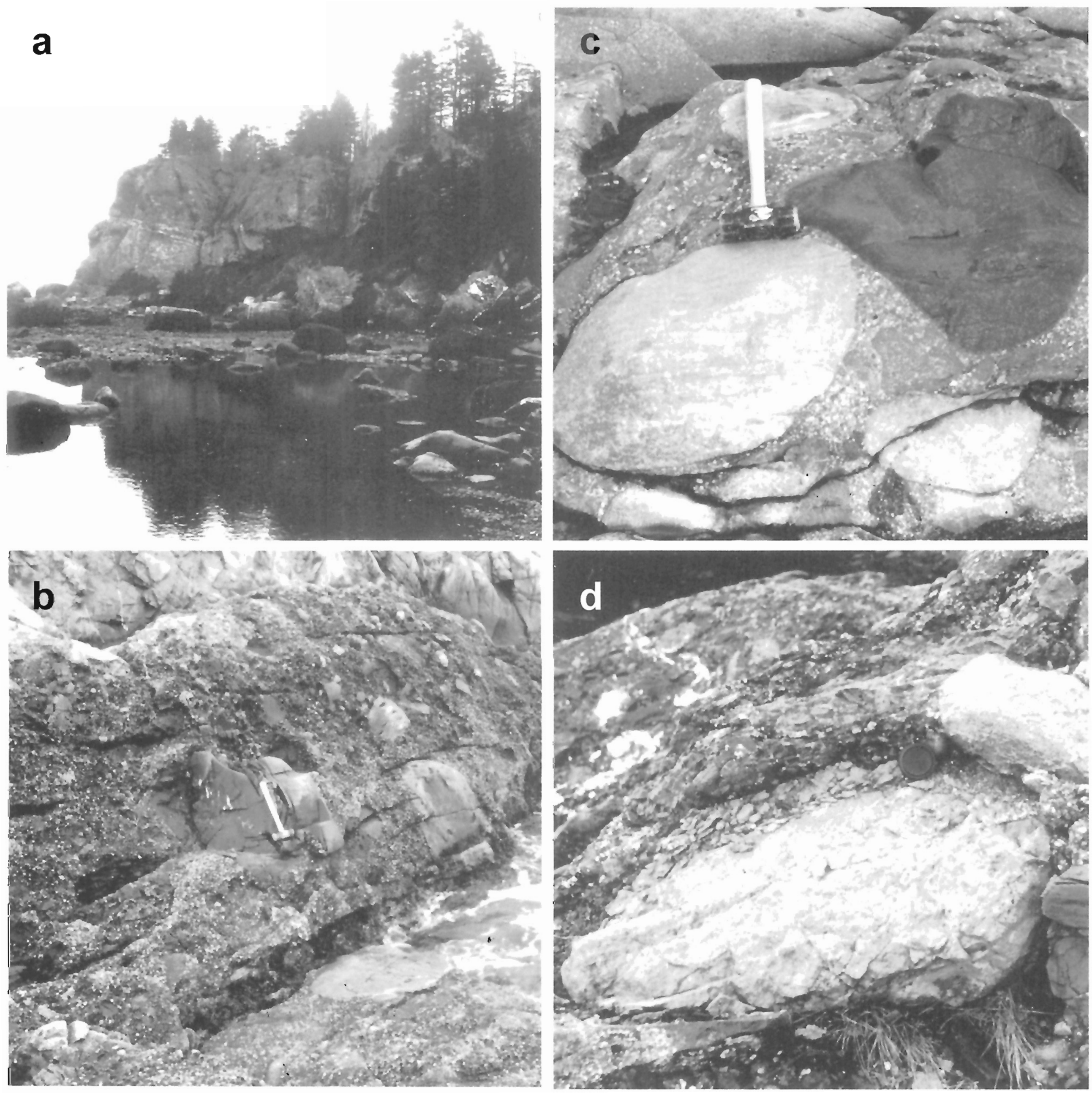

Figure 5. *Field photographs of lowermost Upper Cambrian conglomerates.* ***a)*** *Large channel fills by conglomerate cutting through Middle Cambrian hemipelagite. Grosses-Roches section.* ***b)*** *Unsorted and chaotic nature of lower part of channel-fill conglomerate. Large diversified clasts are embodied in quartz-rich finer-grained polymict limestone conglomerate. Trois-Pistoles section.* ***c)*** *Large well-rounded basement clasts (black: diabase; grey: orthoquartzite) set in quartz-rich polymict conglomerate. Trois-Pistoles section.* ***d)*** *Two large fragments of cyanobacterial micrite (thrombolite) surrounded by sandy polymict limestone conglomerate dominated by slope-derived limestone clasts. Grosses-Roches section.*

the Kamouraska and Saint-Damase formations (Trois-Pistoles Group) of some previous workers (Vallières, 1984; Slivitzky et al., 1991), and have been included in the newly defined Grosses-Roches Formation by Bernstein et al. (1992) (Table 1). Their significance for the paleogeography and sea-level history of the passive margin are mostly unknown.

Lowermost Upper Cambrian conglomerates

These conglomerates form 10 to 100 m-thick successions and the contact with the underlying Orignal Formation is marked by channels which are tens of metres wide and deep (Fig. 5a). The conglomerates (and associated coarse-grained sandstones) occur in metre- to decametre-thick thinning- and fining-upward successions previously interpreted as representative of channel fills in slope to basin plain settings (Hendry, 1978; Hein and Walker, 1982)..

The conglomerates are typified by a highly disorganized and unsorted lower interval where metre-sized clasts are surrounded by millimetre-sized fragments (Fig. 5b). Sorting and bedding are developed near the top of individual fining- and thinning-upward successions. As a whole, these conglomerates are clast-supported with the matrix averaging about 20% of the rock volume. This matrix consists of coarse-grained quartzose sand with well rounded quartz grains. The conglomerates are polymictic; clasts include: limestone (50%), quartz (20%), dolomite (10%), dolomitic siltstone and sandstone rafts (10%), various basement rocks (igneous, volcanic and metamorphic) (10%), and rare shale fragments.

Figure 6. *Field photograph of uppermost Cambrian conglomerates. Intraformational conglomerate consisting of locally-derived sandstone, siltstone and hemipelagite angular fragments set in a fine-grained siliciclastic matrix. Grosses-Roches section.*

Carbonate fragments, ranging from a few millimetres up to 1 m in size, are commonly rounded, although irregularly broken clasts occur at the base of the conglomerate successions. Basement clasts are locally huge (up to 2 m; Fig. 5c), and almost invariably well rounded suggesting significant remobilization prior to deposition. Conversely, siliciclastic clasts are either well rounded or angular depending on their origin (exotic or slope-derived, respectively). Limestone fragments are made up of various facies (Fig. 5d) including siliciclastic-free platform-derived lithologies: lime mudstones, bioclastic (brachiopod, trilobite, crinoid), oolitic and peloidal grainstones, packstones and wackestones, cyanobacterial limestones (thrombolite and stromatolite), uncommon resedimented limestone conglomerate fragments, and calcite cement clasts. The slope-derived carbonates consist of cross-laminated calcisiltites and calcilutites.

The regional distribution of these conglomerates suggest a major sea-level lowstand at the onset of the Late Cambrian, an event recognized in coeval facies (Port au Port and Cow Head groups) from Newfoundland (James et al., 1989). The nature of limestone fragments suggests that a diversified carbonate platform acted as a source for the clasts. Lithologies ranging from platform margin to intertidal facies are recognized in these fragments. The presence of quartzite fragments, similar to the Upper Cambrian Potsdam quartzite at the base of the St. Lawrence Lowlands succession, suggests that a siliciclastic nearshore setting was present. The various Precambrian basement fragments argue for deep incision on the shelf. This earliest Late Cambrian lowstand deposition ended at the onset of the following sea-level rise and highstand conditions recorded in the overlying mudstone-shale succession.

Upper Cambrian conglomerates

Above a thick succession of hemipelagites overlying the lowermost Upper Cambrian conglomerates, an interval dominated by quartzites with interbedded quartzose polymictic conglomerates, hemipelagites, turbidites and minor ribbon limestones is present. The conglomerates are thinner and finer grained, and they are similar to the ones at the base of the Upper Cambrian succession although basement clasts are nearly absent. This suggest that highstand and lowstand events are present but lowstand conditions were not as pronounced as in earliest Late Cambrian time.

The Late Cambrian – Early Ordovician transition is marked by a last conglomerate unit represented by intraformational conglomerate beds consisting of angular fragments of slope-derived sandstone, siltstone, and hemipelagite (Fig. 6). Locally, sandy polymict limestone conglomerates are seen. The succession likely records some minor lowstands in a more general sea-level rise that culminated in the sedimentation of the fine-grained Lower Ordovician deposits.

LOWER ORDOVICIAN CONGLOMERATES

The Lower Ordovician sediments (package 4, Fig. 2) are well exposed from Lévis to Cap-des-Rosiers (Fig. 1). These successions have yielded some prolific fossil localities (see stratigraphy) and direct correlations can be made with the platform in the St. Lawrence Lowlands. Terminology for Lower to Middle Ordovician deep marine strata is complex (Table 1) and is based on local definitions; this reflects the local nature of previous works as well as the proximal versus distal nature of the sediment packages.

Lower Ordovician facies are mostly dominated by variously coloured hemipelagites and slope limestones with subordinate calciturbidites and conglomerates locally arranged in cyclic succession described as "Logan cycles" (Landing and Benus, 1985).

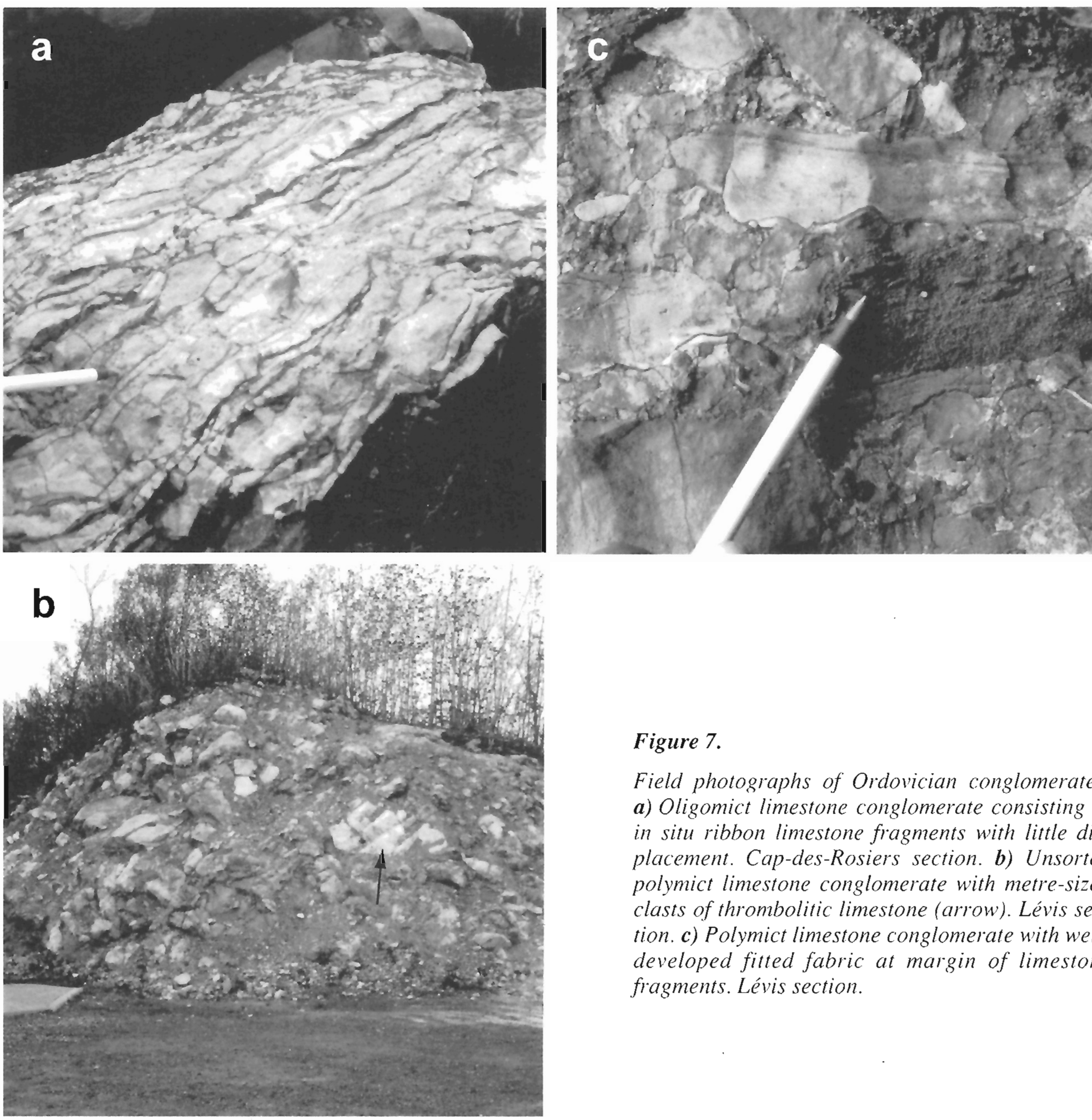

Figure 7.

Field photographs of Ordovician conglomerates. ***a)*** *Oligomict limestone conglomerate consisting of in situ ribbon limestone fragments with little displacement. Cap-des-Rosiers section.* ***b)*** *Unsorted polymict limestone conglomerate with metre-sized clasts of thrombolitic limestone (arrow). Lévis section.* ***c)*** *Polymict limestone conglomerate with well-developed fitted fabric at margin of limestone fragments. Lévis section.*

The conglomerates are commonly oligomict (Fig. 7a) consisting of in situ slope-derived fine-grained limestone fragments; they occur in thick successions of ribbon and parted limestones. These conglomerates, forming decimetre- to metre-thick units, are clast supported, and have little matrix; the fragments are commonly imbricated with little evidence for remobilization; fitted fabrics are routinely observed. Locally, some exotic clasts (oolitic grainstones, bioclastic packstones) are noted.

Thick sandy polymictic conglomerates (Fig. 7b) are restricted to the Levis area (Paquette, 1985), at the southern end of the study region (Fig. 1). These conglomerates ranging from 2 to 15 m in thickness, are late Tremadoc; they are clast-supported with a sandy dolomitic matrix counting for about 20% of the rock volume. The conglomerates are chaotic with no internal structure. Locally metre-sized clasts are derived from platformal facies (Fig. 7b) and include oolitic grainstones, thrombolite and stromatolite limestones, bioclastic grainstones, packstones and wackestones, and lime mudstones.

The presence of this conglomerate suggests some significant erosion on the shallow marine setting at the end of the Tremadoc, its absence in coeval successions farther northeast could be related either to the preservation of more distal facies for those localities or to a tectonic event affecting the southwestern segment of the Early Ordovician platform. If eustatic, the sea-level lowstand recorded by this conglomerate would be of lesser magnitude compared to the previously described Cambrian events.

MIDDLE ORDOVICIAN CONGLOMERATES

Middle Ordovician (late Arenig to Llandeilo) deep marine sediments (package 4, Fig. 2) are known at few localities (Lévis – Les Méchins – Pointe Carse; Fig. 1). The sediment is dominated by hemipelagites with subordinate sandstones, peloidal and phosphate-rich calciturbidites, ribbon limestones, and rare conglomerates. A coarse-grained interval typifies the Arenig – Llanvirn boundary possibly recording a relative sea-level fall on the shelf. This event could be related to the passage of the Taconian peripheral bulge marking the transition from passive margin to foreland basin in the Appalachians (Knight et al., 1991).

The conglomerates occur in a metre-thick succession embedded in variously coloured hemipelagites. Oligomict and some polymict varieties are present although limestone clasts are dominated by slope-derived silty calcilutite fragments. Platform-derived clasts consist of bioclastic wackestones and packstones, and lime mudstones. These conglomerates are fairly well sorted with local clast imbrications and grading (Fig. 7c).

The few occurrences of conglomerates at the transition from passive to convergent margin points to a relative minor or short-lived sub-aerial exposure on the platform. This is indeed the case observed for the Beekmantown Group in southern Quebec where major erosion is local (Bernstein, 1992) in contrast to what is known for coeval succession at the St. Lawrence Promontory where major erosion on the platform and coarse-grained slope deposits are reported (James and Stevens, 1986; Knight et al., 1991). This fact underlines the importance of the continental margin morphology (reentrant *vs* promontory) for their tectono-stratigraphic evolution (Lavoie, 1994).

Finally, Llandeilo slope deposits are tectonically overlain by Taconian-derived flyschs (e.g. Tourelle Formation). The record of continental slope deposition is then lost.

CONCLUSION

Limestone conglomerates from Cambrian-Ordovician continental slope deposits in the Humber Zone of the Quebec Reentrant are a key feature in defining a regionally coherent stratigraphic framework for the succession, upon which detailed sedimentological, biostratigraphic, maturation, and structural studies will rely.

Lower Cambrian conglomerates are typified by minor platform-derived siliciclastic-rich carbonates with a significant number of siliciclastic fragments. Upper Cambrian conglomerates consist of thick units of polymict limestone conglomerates arranged in fining- and thinning-upward successions. Limestone fragments are diversified and huge basement clasts are common. The Upper Ordovician conglomerates record the most pronounced sea-level lowstand that affected the Cambrian-Ordovician passive margin in the Quebec Reentrant. Uppermost Cambrian conglomerates are represented by intraformational conglomerates. Finally, Ordovician conglomerates are represented by relatively thin and fine-grained oligomict varieties with slope-derived limestones as typical clast; coarse-grained polymict cases are known in the southernmost part of the study area.

The conglomerates are used to define four stratigraphic packages (Lower Cambrian-Middle Cambrian-Upper Cambrian - Ordovician) that serve as the base for ongoing and future work.

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Geological Survey of Canada Project 960012 ZH

Chemostratigraphic analysis of the volcanic and sedimentary rocks in the Heath Steele B-B5 zone area, Bathurst camp, New Brunswick: stratigraphic and structural implications[1]

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Lentz, D.R. and Wilson, R.A., 1997: Chemostratigraphic analysis of the volcanic and sedimentary rocks in the Heath Steele B-B5 zone area, Bathurst camp, New Brunswick: stratigraphic and structural implications; in Current Research 1997-D; Geological Survey of Canada, p. 21-33.

Abstract: Geochemical differences between footwall and hanging wall volcanic and sedimentary rocks hosting the Heath Steele B-B5 zone massive-sulphide deposits indicate that revision of previous stratigraphic and structural interpretations is necessary. The lower footwall sedimentary rocks have high transition metal contents (Cr > 40 ppm) compared to upper footwall sedimentary rocks (Cr < 30 ppm); the former are chemically similar to the Miramichi Group, whereas the latter resemble tuffaceous rocks of the Tetagouche Group. There are also immobile trace-element differences between the stratigraphic footwall and hanging wall crystal tuffs/tuffites; the hanging wall crystal tuffs have Zr/TiO_2 ratios greater than 0.05, whereas the footwall crystal tuffites have lower values. Furthermore, Y and Th contents are higher in the hanging wall than the footwall crystal tuffites, although the continuum for Y and Th indicates that the felsic volcanic units are related.

Résumé : Les différences géochimiques entre les roches volcaniques et sédimentaires des épontes supérieure et inférieure dans lesquelles logent les gisements de sulfures massifs de la zone Heath Steele B-B5 mettent en évidence la nécessité de réviser les interprétations stratigraphiques et structurales antérieures. Les roches sédimentaires de la base de l'éponte inférieure ont une forte teneur en métaux de transition (Cr > 40 ppm) comparativement aux roches sédimentaires de la portion supérieure de l'éponte supérieure (Cr < 30 ppm); les premières sont de composition chimique semblable aux roches du Groupe de Miramichi tandis que les dernières ressemblent aux roches tufacées du Groupe de Tetagouche. On observe également des différences dans les éléments traces immobiles entre les tufs/tuffites cristallins des épontes stratigraphiquement inférieure et supérieure, car les tufs cristallins de l'éponte supérieure présentent des rapports Zr/TiO_2 plus élevés que 0,05 alors que les tuffites cristallines de l'éponte inférieure ont des valeurs plus faibles. De plus, les teneurs en Y et Th sont plus élevées dans l'éponte supérieure que dans les tuffites cristallines de l'éponte inférieure bien que le continuum de Y et Th révèle que les unités volcaniques felsiques sont apparentées.

[1] Contribution to the 1994-1999 Bathurst Mining Camp, Canada-New Brunswick Exploration Science and Technology (EXTECH II) Initiative

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INTRODUCTION

Heath Steele is one of the largest Zn-Pb-Cu-Ag massive-sulphide deposits in the Bathurst camp and, thus far, has produced 17. 9 Mt of 1.73% Pb, 4.67% Zn, 0.96% Cu, and 63 g/t Ag with additional ore reserves of 3.9 Mt (Hamilton et al., 1993). The six massive-sulphide deposits (A to F, Fig. 1) within the Heath Steele belt are hosted by crystal-rich felsic volcaniclastic rocks and associated tuffaceous sedimentary rocks of the Nepisiguit Falls Formation, which represents the base of the Middle Ordovician Tetagouche Group in this area (van Staal and Fyffe, 1991; Wilson, 1993). The geology in the Heath Steele area is complicated by 1) polyphase deformation, including local areas of intense strain, 2) variable degrees of syngenetic hydrothermal alteration, and 3) syndeformational metasomatism and metamorphic recrystallization. Although the geology, particularly the structural geology, of the area has been described in considerable detail by previous workers (McBride, 1976; Moreton and Williams, 1986; de Roo et al., 1990, 1991, 1992; Moreton, 1994), most of the structural interpretations were based on the assumption that the crystal tuff-sedimentary rock contacts constitute a single marker horizon. In a detailed orientation study through the lower part of the B zone deposit, Lentz et al. (in press) identified immobile-element geochemical differences between the footwall and hanging wall crystal tuffs, and between the lower footwall and upper footwall sedimentary sequences. These chemostratigraphic data do not support structural interpretations that equate these units as F_1 fold repetitions, and indicate that the ore horizon is restricted to only certain sedimentary rock-crystal tuff contacts, which is consistent with the field evidence (Fig. 2).

This study expands the areal extent of the earlier orientation study (Lentz et al., in press) using 15 samples from surface outcrops and 73 samples from seven drillholes in the B-B5 zone area (Fig. 3). These data are used to test the significance of the earlier study, to possibly reveal other key chemostratigraphic features, and, most importantly, to aid in the correlation of units in the B-B5 zone and elsewhere in the Heath Steele Belt. As a result of recent chemostratigraphic studies (Lentz et al., in press), a revised stratigraphic column is proposed based on the geochemical similarity of the lower sedimentary rocks to the Miramichi Group (Fig. 2). Although this suggests that the lower and upper footwall sedimentary rocks are not a single unit repeated by isoclinal F1 folding, there is no doubt of the importance of the F1 folds in controlling some of the distribution of the rock units at Heath Steele; however, their significance needs re-assessment in light of these revelations.

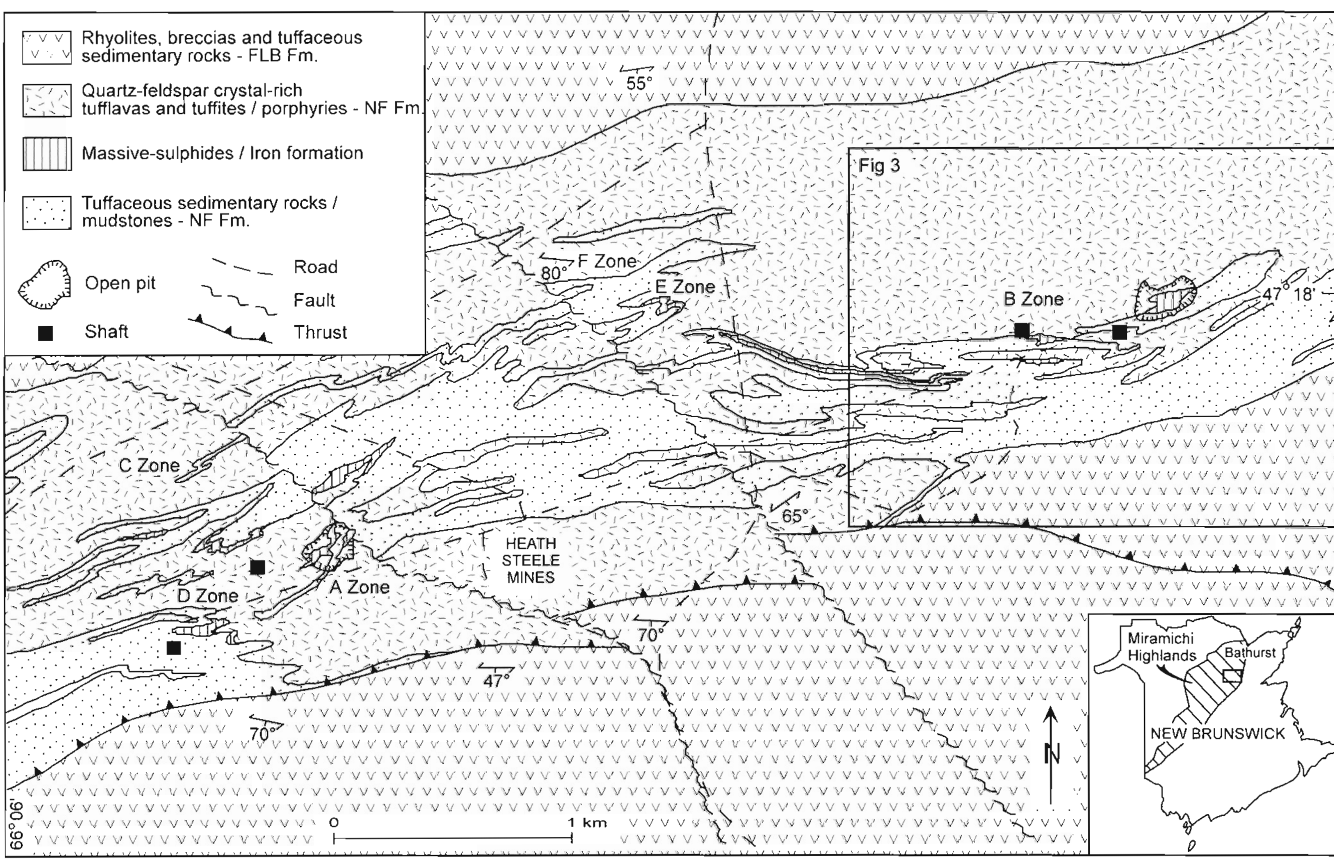

Figure 1. Location of the Heath Steele A, B, C, D, E, and F zone massive-sulphide deposits (after Hamilton et al., 1993) with Figure 3 located (inset). NF Fm. – Nepisiguit Falls Formation; FLB Fm. – Flat Landing Brook Formation.

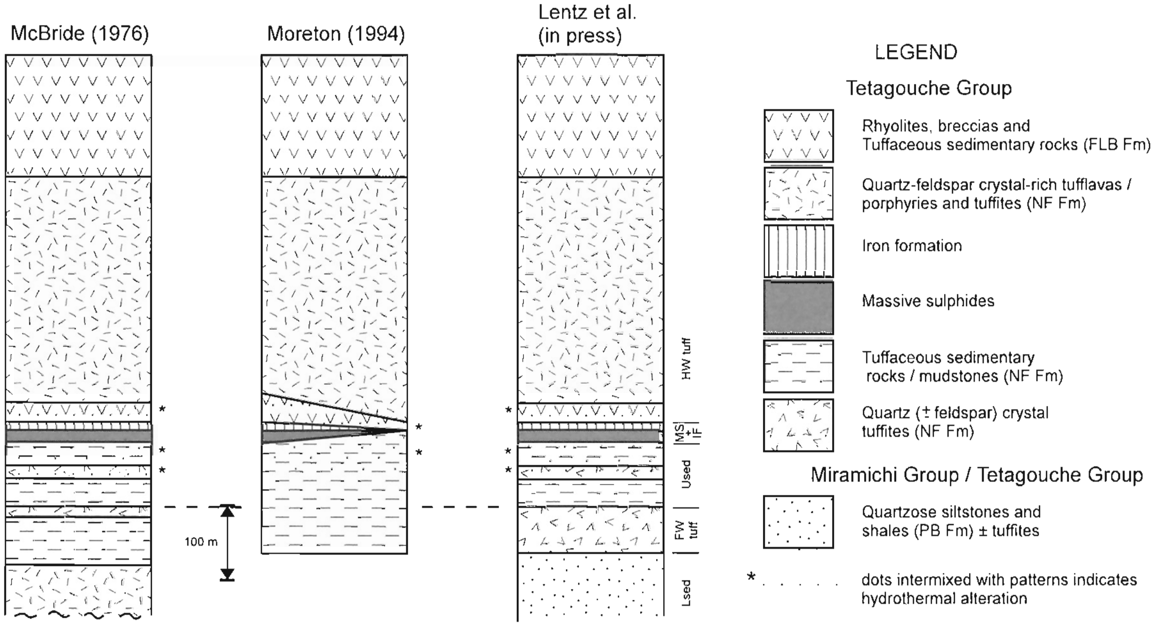

Figure 2. *Schematic stratigraphic columns of the Heath Steele area showing two previous interpretations of the mine stratigraphy (McBride, 1976; Moreton and Williams, 1986; de Roo et al., 1991; Moreton, 1994) compared to that proposed in this study. Lsed – lower footwall sedimentary rock, FW tuff – footwall crystal tuffites, Used – upper footwall sedimentary rock, HW tuff – hanging wall crystal tuff, tufflava/porphyry, NF Fm – Nepisiguit Falls Formation, FLB Fm – Flat Landing Brook Formation.*

GEOLOGICAL SETTING

The Bathurst mining camp is underlain by a sequence of sedimentary and bimodal volcanic rocks that were intruded by synvolcanic mafic and felsic intrusions of Middle to Late Ordovician age (Skinner, 1974). The oldest rocks at Heath Steele Mines are quartz wackes and carbonaceous shales typical of those in the upper part of the Miramichi Group, although locally they contain fine-grained crystal tuffite horizons and are, therefore, included in the Tetagouche Group (Nepisiguit Falls Formation). The Nepisiguit Falls Formation consists of volcanic, volcaniclastic, and sedimentary rocks that host the deposits, and is overlain by rhyolite and hyalotuff of the Flat Landing Brook Formation (Fig. 1, 2; van Staal and Fyffe, 1991; Wilson, 1993). Up to five generations of folds have been identified, beginning with Late Ordovician (Ashgillian) D_1 thrusting and tight recumbent folding accompanied by upper greenschist metamorphism, and culminating in the Devonian Acadian Orogeny (van Staal, 1985, 1987; deRoo et al., 1990, 1991; van Staal and Fyffe, 1991; van Staal et al., 1992).

The Heath Steele belt is bounded to the south by the east-west Heath Steele Fault (Fig. 1, 3), which juxtaposes the Nepisiguit Falls Formation against massive rhyolite and coarse pyroclastic rocks of the Flat Landing Brook Formation. Wilson (1993) proposed that at least part of the contact between the crystal tuffs (Nepisiguit Falls Formation) and rhyolites (Flat Landing Brook) in the quarry south of the B zone (Fig. 3) is depositional in nature, although affected by layer-parallel shear (see also Moreton, 1994). To the north, Flat Landing Brook rocks similar to those south of the Heath Steele fault appear to conformably overlie the Nepisiguit Falls Formation. The regional structure of the Heath Steele area was first described as a broad antiform by Dechow (1960), although de Roo et al. (1990) and Moreton (1994) suggested that the entire sequence is in thrust contact with the rhyolites to the south. In the B zone area, Dechow (1960) incorrectly interpreted the sequence as south-younging, whereas the position of the iron-formation (hanging wall) and intense hydrothermal alteration (footwall) indicates a north-younging sequence at the deposit (McMillian, 1969; Whitehead, 1973; McBride, 1976; Owsiacki, 1979; Owsiacki and McAllister, 1979). The mine stratigraphy was reinterpreted by McBride (1976) and Moreton and Williams (1986), and revised by de Roo et al. (1991) and Moreton (1994) (Fig. 2) based on structural observations.

The stratigraphic position of the crystal-rich tuff in the structural footwall at the B zone has not been determined with certainty. McBride (1976) suggested that it represents a stratigraphic footwall unit, whereas de Roo et al. (1991) suggested that it represents stratigraphic hanging wall crystal tuff infolded into the structural footwall, which would imply the repetition of the ore horizon. All of their sedimentary rocks were considered to belong to a single unit. Moreton (1994) employed lithogeochemistry to investigate the possibility of multiple units but stratigraphic correlation was generally unsuccessful, apparently because of the limited extent of his sampling in the hanging wall crystal tuffs. Although it was noted that the sedimentary rocks have higher Cr, V, and Zr than the felsic volcanic rocks, there was no attempt to chemostratigraphically identify the sedimentary packages.

GEOCHEMISTRY

Introduction

To test the validity of the previous chemostratigraphic study (Lentz et al., in press), outcrops and drill core from the B zone area were sampled to obtain a representative suite from each stratigraphic interval (see Fig. 3 for location). Although hydrothermal alteration is manifested in all rock types, sampling was restricted to rocks with weak to moderate alteration in order to study primary compositions and, therefore, does not record, in a representative way, the alteration in the area. The main objective was to obtain immobile-element data suitable for chemostratigraphic interpretation of the volcanic and sedimentary rocks in the B zone area.

High-field-strength elements (HFSE) have high ionic potentials (charge/radius) and, as a result, usually have low solubilities, therefore, are relatively immobile in volcanic and sedimentary rocks. Those elements applicable to this study include Al, Ti, Zr, Y, rare-earth elements (REE), Th, and possibly Nb (see Taylor and McLennan, 1985; Rollinson, 1993; Lentz, 1996a,b). In addition to Ti, the transition elements, such as Cr, Ni, Sc, and V, are also relatively immobile in most seawater settings (Jenner, 1996). Furthermore, calculating a ratio of an incompatible element such as Zr, against a compatible one, like TiO_2 (i.e. Zr/TiO_2), enhances the differences between rock types, particularly for the evolved felsic volcanic rocks (Winchester and Floyd, 1977; Floyd and Winchester, 1978). In addition, immobile-element ratios (i.e. Zr/TiO_2) are generally insensitive to the mass change effects typically associated with moderate to intense hydrothermal alteration systems (MacLean and Barrett, 1993; Barrett and MacLean, 1994; Lentz, 1996a).

In the detailed study of the Brunswick No. 12 deposit, there was no discernable variation in the high-field-strength and transition elements with respect to alteration (Lentz and

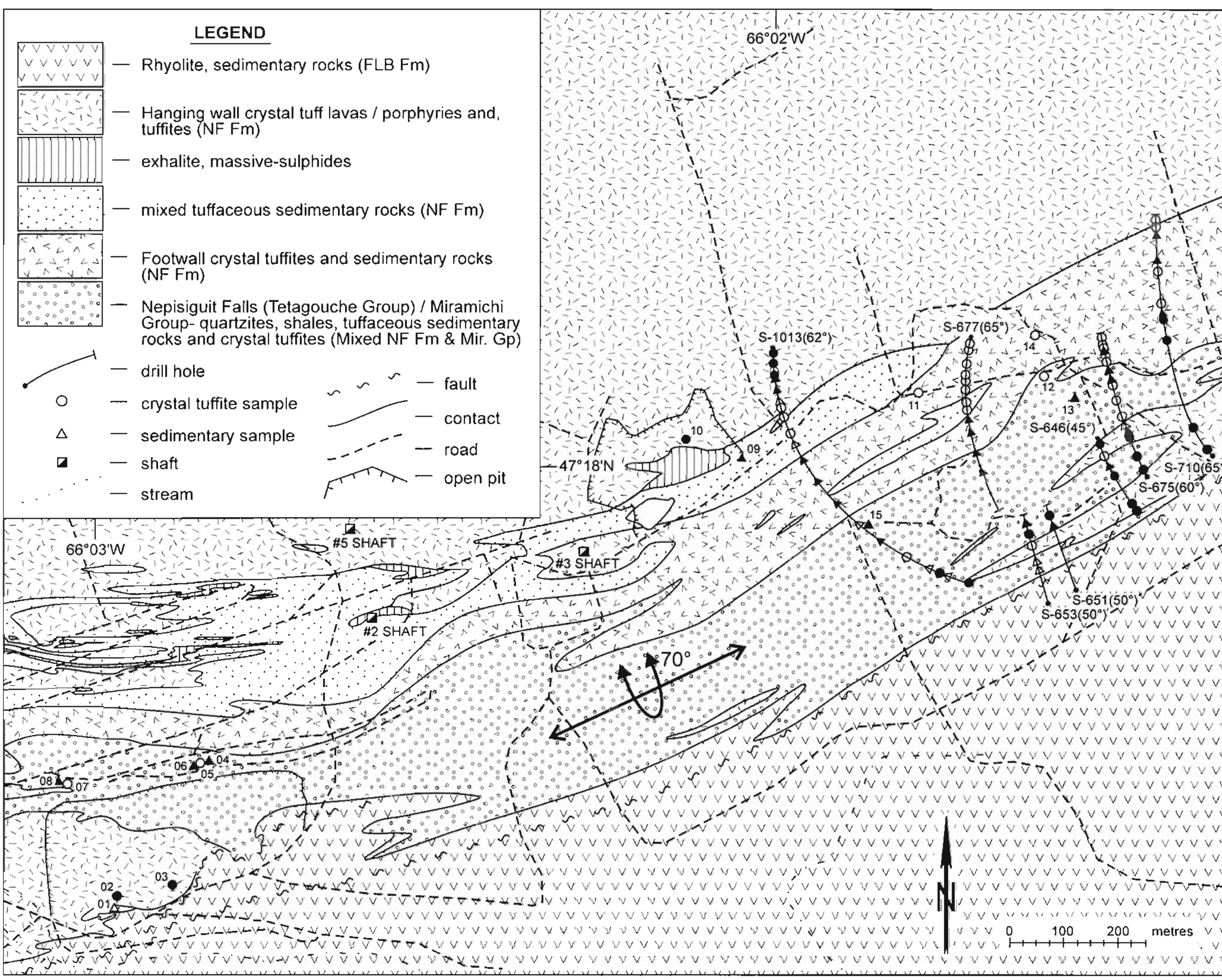

Figure 3. Detailed geology of the area of the B-B5 zone massive-sulphide deposits, Heath Steele belt, Bathurst camp (courtesy of Noranda Exploration Limited). The drillholes sampled are vertically projected and, therefore, do not directly correspond to the surface geology.

Goodfellow 1993, 1994a), although these elements were somewhat mobile in the most altered silicified chloritic stockwork zone (Lentz and Goodfellow, 1996). Also, transition-element (Ti, Cr, V, Sc, and Ni) systematics are used to distinguish between altered Miramichi Group sedimentary rocks and Nepisiguit Falls tuffaceous sedimentary rocks, as was previously demonstrated for the complexly folded and altered FAB mineralized zone located between the Brunswick No. 6 and 12 deposits (Lentz and Goodfellow, 1994b).

Analytical Method

Samples were crushed in a steel jaw crusher and a portion was pulverized in an agate swing mill. Fused disks were prepared and analyzed on a Philips PW2400 X-ray Fluorescence Spectrometer in the geochemical laboratory at the University of Ottawa (see Table 1). The accuracy and precision were determined by repeated analyzes on two standards 94-RHY and 94-GS (Lentz, 1995) submitted as blanks. Based on the analysed standards, the error in major elements is less than 2% and in most trace elements is less than 5%, except for low abundance minor- and trace-elements like TiO_2 (< 15%), Cr (< 9%), Ni (< 10%), Zn (< 10%), Nb (< 10%), Ba (< 8%), La (< 3%), Ce (< 11%), Nd (< 8%), and Th (< 15%). However, the precision of all the analyses is within 2%.

Sedimentary Chemostratigraphy

The geochemical data reveals a bimodal distribution of Cr, Ni, TiO_2, and V contents in the sedimentary rocks supporting the results of the orientation study (Lentz et al., in press). These key transition elements are plotted in profile (Fig. 4a, b, c) in order to illustrate the chemostratigraphic significance of their distribution. The population with high transition metal contents (e.g., Cr > 40 ppm) covaries strongly with Al_2O_3, reflecting a mature provenance. The positive covariation of Cr, Ni, TiO_2, and V with Al_2O_3 in the Miramichi-like sedimentary rocks is a function of the quartz to mica mixing ratio in these rocks, i.e. the trace-element contents are generally associated with the clay/mica components (see Lentz et al., 1996). The tightness of the mixing array indicates a simple mica/clay-quartz mixing relationship, which is consistent with a related provenance.

The second population (Cr < 30 ppm) generally has compositions more similar to the felsic volcaniclastic rocks of the Nepisiguit Falls Formation in the region (Lentz, 1996a). Lentz et al. (in press) found that the composition of the lower footwall sedimentary rocks, which are dominantly quartzose siltstones, slates, and wackes, generally have higher TiO_2 (1.04 ± 0.08 wt.%), Cr (80 ± 18 ppm), V (134 ± 24 ppm), Ni (44 ± 8 ppm), and Sc (19.4 ± 4.3) compared to the TiO_2 (0.55 ± 0.11 wt.%), Cr (27 ± 18 ppm), V (55 ± 20 ppm), Ni (15 ± 9 ppm), and Sc (9.4 ± 3.5) contents of the upper footwall sedimentary unit. Lentz et al. (in press) pointed out that the lower footwall sedimentary unit has compositions similar to the mature passive margin sedimentary sequence (Miramichi Group) that underlies the Tetagouche Group (see Lentz et al., 1996). This follow-up study has confirmed that the lower footwall sedimentary rocks are compositionally akin to the sedimentary rocks forming the upper part of the Miramichi Group, i.e. the Patrick Brook and Knight's Brook formations (Fig. 5). However, the presence of thin interbeds of crystal tuff/tuffite suggests that these rocks are more appropriately included in the Nepisiguit Falls Formation (Tetagouche Group), unless they represent schistose dykes.

The upper footwall sedimentary unit is interpreted as dominantly a sequence of reworked tuffaceous sedimentary rocks derived from Nepisiguit Falls felsic volcaniclastic rocks, because of local textural and compositional similarities. Although the composition of the upper sedimentary rocks is somewhat dissimilar to the felsic volcanic rocks at Heath Steele, they are not unlike the approximately contemporary felsic volcanic and sedimentary rocks towards the northeast around the Brunswick deposits (see Lentz and Goodfellow, 1992; Langton and McCutcheon, 1993; Lentz, 1996a). It is also possible that some of the upper footwall sedimentary unit represents a mixture of tuffaceous sedimentary and mature sedimentary (clay + quartz) components, producing a mixed compositional product reflecting the relative proportions of these two sources. The uppermost part of the upper sedimentary unit located just beneath the ore horizon, for example, has high transition element (Cr, Ni, V, Ti) contents comparable to the lower footwall sedimentary unit (see also Lentz et al., in press). This may reflect either an increase in pelagic or a decrease in tuffaceous sedimentation preceding ore deposition, but must in any case be considered during chemostratigraphic assessment of the sedimentary units.

In summary, the composition of the lower footwall sedimentary unit resembles mature sedimentary rocks of the Miramichi Group, whereas the upper sedimentary unit is compositionally similar to immature tuffaceous sedimentary rocks with a possible mature sedimentary component. The significant point is that there are two units, not one unit that is structurally repeated as was interpreted by de Roo et al. (1991, 1992) and Moreton (1994).

Volcanic chemostratigraphy

Immobile trace element differences between the footwall and hanging wall tuff units, which were documented by Lentz et al. (in press), are confirmed in this study. Between these two units absolute contents of Zr partially overlap, whereas the TiO_2 contents seem indistinguishable (Fig. 6, 7a). However, the Zr/TiO_2 ratios are distinct (Fig. 6, 7), with Zr/TiO_2 greater than 0.05 in the hanging wall unit and less than 0.05 in the footwall unit (Fig. 4). In addition to this, Y is higher in the hanging wall than the footwall (Fig. 4b, 5b). Th contents also are higher in the hanging wall unit (> 14 ppm Th) compared to the footwall tuff unit (< 13 ppm, Fig. 5c). These geochemical features have helped to assign some crystal tuff/tuffite units to the hanging wall sequence, e.g. the crystal tuffs at the B5 zone and south of the waste rock quarry (samples 2 and 3; Fig. 3).

Although there is a difference in the Zr/TiO_2 ratios of the hanging wall and footwall tuff units, there is a compositional continuum for Zr, Y, and Th, as well as other petrogenetically important trace elements, indicating that these units are probably related by progressive fractional crystallization.

Table 1. Major- and trace-element geochemical data from the B-B5 zone area, Heath Steele area, Bathurst camp

Location	m	Unit	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	SUM	V	Cr	Co	Ni	Zn	Rb	Sr	Y	Zr	Nb	Ba	Th	U	La	Ce	Nd	Zr/TiO_2
field (1)	0	sed	62.1	0.908	14.42	8.64	0.160	2.95	1.85	3.13	2.09	0.28	3.6	100.3	56	15	7	4	186	81	66	41	446	27	372	6	0	43	85	43	0.049
field (2)	0	Nct	74.1	0.269	13.29	1.99	0.037	0.63	0.57	3.04	3.97	0.13	1.3	99.5	16	13	1	7	38	147	47	40	150	11	504	15	7	37	85	36	0.055
field (3)	0	Nct	74.1	0.303	13.80	2.16	0.054	1.03	0.16	2.52	3.09	0.11	1.9	99.4	14	7	3	11	166	167	45	40	163	13	542	15	4	20	53	28	0.05
field (4)	0	sed	76.5	0.801	10.75	5.26	0.047	1.16	0.08	0.87	2.21	0.07	2.2	100.1	77	53	6	23	153	108	24	30	331	19	259	9	2	36	61	26	0.041
field (5)	0	Nct	73.1	0.277	14.64	2.84	0.017	0.81	0.15	1.83	3.49	0.14	2.4	99.8	21	8	3	12	148	183	56	25	130	12	365	11	7	17	61	24	0.046
field (6)	0	sed	71.1	0.898	13.79	6.08	0.060	1.28	0.07	1.32	2.86	0.07	2.4	100.1	92	56	5	32	165	141	33	31	276	19	300	10	5	27	61	12	0.030
field (7)	0	Nct	75.1	0.273	12.99	2.66	0.029	0.79	0.64	2.29	2.51	0.15	1.9	99.5	21	14	3	8	68	129	73	28	121	10	286	10	6	20	55	26	0.044
field (8)	0	sed	72.8	0.89	12.80	6.02	0.027	1.42	0.06	0.99	2.45	0.06	2.5	100.5	91	64	3	31	120	124	29	30	296	20	267	7	1	42	71	38	0.033
field (9)	0	sed	68.2	0.801	14.87	8.33	0.058	1.44	0.07	0.05	3.37	0.10	2.8	100.3	79	67	6	20	94	156	10	27	167	16	391	7	4	46	44	25	0.021
field (10)	0	Nct	71.9	0.288	14.09	2.50	0.041	1.99	0.13	1.62	3.96	0.13	2.3	99.2	19	7	0	8	139	204	43	39	158	13	779	17	5	27	78	36	0.055
field (11)	0	Nct	72.1	0.301	13.81	3.58	0.090	1.51	0.04	0.06	4.86	0.12	2.7	99.4	19	7	1	4	67	248	13	25	131	13	686	15	0	24	64	23	0.044
field (12)	0	Nct	73.7	0.366	13.47	3.36	0.021	1.10	0.11	2.25	2.98	0.11	1.9	99.4	24	18	2	11	42	134	66	22	151	11	326	10	5	27	59	34	0.041
field (13)	0	sed	65.8	1.079	16.10	6.62	0.061	1.90	0.09	0.61	4.21	0.12	3.0	99.8	117	73	9	27	81	207	20	35	268	22	395	10	1	46	107	42	0.025
field (14)	0	Nct	78.1	0.247	11.25	2.27	0.023	1.37	0.12	0.00	3.81	0.11	2.0	99.4	20	5	1	8	46	188	9	25	103	8	370	9	5	9	60	35	0.042
field (15)	0	Ns	74.0	0.785	11.07	8.13	0.037	1.18	0.07	0.04	2.21	0.09	2.5	100.3	81	64	2	16	59	96	21	32	608	27	298	7	2	54	90	36	0.077
s675	15.8	Nct	74.3	0.268	13.37	1.88	0.034	1.12	0.22	2.03	4.20	0.13	1.4	99.1	20	1	2	7	247	171	45	45	151	12	780	15	7	18	76	31	0.056
s675	57.0	Nct	72.2	0.274	13.60	2.43	0.055	1.86	0.24	2.24	4.32	0.12	1.6	99.1	13	12	3	4	169	195	42	41	158	12	491	15	7	36	60	27	0.058
s675	107.6	Nct	74.0	0.258	12.96	1.96	0.072	1.84	0.38	1.71	4.08	0.12	1.8	99.4	14	3	2	5	305	164	47	41	145	11	510	16	7	17	77	35	0.056
s675	128.9	sed	71.5	0.828	13.14	5.54	0.071	1.57	0.17	0.37	3.91	0.06	1.9	99.2	89	59	10	20	184	175	16	25	232	17	327	7	0	43	95	39	0.028
s675	145.7	mfc	55.8	2.837	13.36	13.69	0.203	4.07	1.95	2.81	0.55	0.37	4.7	100.5	271	16	26	13	230	27	73	38	264	30	103	6	0	36	87	26	0.009
s675	162.2	Nct	73.5	0.292	13.67	2.98	0.046	1.17	0.28	2.51	3.15	0.14	1.6	99.4	25	11	5	10	95	139	45	29	122	10	442	10	4	14	43	21	0.042
s675	211.8	Nct	75.5	0.245	13.04	2.00	0.031	0.74	0.22	1.88	4.00	0.13	1.5	99.4	16	10	5	7	244	188	46	31	111	9	370	10	6	29	56	20	0.045
s675	268.8	Nct	74.7	0.248	12.91	2.42	0.054	0.85	0.56	2.48	3.39	0.12	1.5	99.3	13	14	4	9	122	187	54	31	113	10	356	8	4	29	47	18	0.046
s675	274.9	sed	70.1	0.772	14.14	5.60	0.043	1.42	0.34	1.31	3.35	0.09	2.3	99.7	87	50	13	30	152	159	30	30	220	17	335	11	4	32	83	31	0.028
s675	307.5	sed	59.3	1.176	19.32	7.80	0.049	2.28	0.18	0.34	5.31	0.08	3.8	99.8	142	92	18	45	184	234	34	35	223	22	570	14	2	37	108	35	0.019
s675	323.1	Nct	72.7	0.242	13.28	3.64	0.027	2.17	0.47	1.31	3.32	0.13	2.3	99.7	18	13	4	8	92	155	22	32	117	10	437	11	5	24	65	23	0.048
s675	349.3	Nct	73.2	0.246	13.09	3.12	0.030	1.39	0.37	1.56	3.89	0.14	2.0	99.3	24	11	5	8	123	177	25	32	115	10	1566	8	3	20	62	25	0.047
s675	367.0	sed	76.0	0.753	10.04	6.41	0.039	1.91	0.08	0.00	2.53	0.05	2.3	100.2	67	47	14	31	102	104	8	29	275	18	239	5	3	20	85	34	0.037
s675	389.2	Nct	73.1	0.228	12.22	5.46	0.025	1.83	0.21	0.01	3.99	0.13	2.1	99.3	19	1	10	10	108	182	9	30	109	11	431	9	3	14	51	23	0.048
s675	392.3	Nct	71.2	0.258	13.63	5.00	0.019	1.97	0.25	0.01	4.71	0.13	2.5	99.8	19	11	6	8	79	220	12	35	123	12	478	12	5	25	54	21	0.048
s675	413.9	Nct	72.1	0.262	14.20	3.14	0.014	1.28	0.31	2.58	3.73	0.14	1.7	99.6	17	11	4	10	78	169	47	33	125	10	468	10	7	22	56	23	0.048
S651	170.1	sed	60.6	0.872	14.42	12.14	0.440	3.63	0.45	0.00	3.85	0.32	3.3	100.2	112	84	19	48	183	146	21	39	214	20	638	15	5	64	87	33	0.025
S651	194.2	Nct	74.6	0.266	12.92	2.01	0.070	0.84	0.39	2.74	3.41	0.12	1.9	99.5	20	8	1	7	202	142	43	39	145	11	1031	15	6	24	93	35	0.055
S646	7.3	Nct	76.0	0.191	12.46	1.42	0.017	0.55	0.14	1.86	4.70	0.13	1.4	99.1	13	12	8	5	745	178	68	31	98	8	362	15	7	35	61	23	0.051
S646	39.6	Nct	70.9	0.3	14.61	3.12	0.047	1.34	0.11	0.88	5.63	0.10	2.2	99.5	23	12	9	10	461	217	46	24	127	10	669	15	4	15	49	26	0.042
S646	93.0	Nct	73.2	0.272	13.58	2.19	0.107	0.72	0.26	3.13	3.52	0.13	1.8	99.1	18	7	3	6	199	155	59	33	146	9	688	20	6	29	70	28	0.054
S646	68.6	sed	64.3	1.023	16.65	6.99	0.061	1.81	0.19	0.09	4.86	0.11	3.4	99.7	118	80	17	37	240	227	27	29	212	20	441	16	4	56	88	32	0.021
S646	175.0	Nct	74.0	0.27	13.13	2.01	0.034	1.08	0.29	2.04	4.71	0.13	1.3	99.2	15	1	2	6	95	169	42	37	151	10	713	20	8	15	82	30	0.056
S646	197.5	Nct	73.3	0.286	13.40	2.21	0.096	0.80	1.02	2.86	3.22	0.15	1.9	99.0	22	1	3	6	94	146	46	37	150	10	861	22	7	31	78	22	0.052
S653	106.1	FLBs	64.7	0.475	12.58	6.35	0.184	1.25	3.71	1.42	3.42	0.12	5.2	99.5	37	13	4	6	144	135	77	36	218	16	395	16	3	34	84	35	0.046
S653	81.4	FLBs	67.1	0.506	13.31	4.99	0.074	1.29	2.36	2.45	3.74	0.13	3.4	99.5	34	26	4	7	107	133	65	31	233	16	467	15	3	57	71	33	0.046
S653	155.4	Nct	63.3	0.936	14.13	9.22	0.285	3.34	0.61	3.40	1.82	0.31	2.6	100.1	76	17	9	6	223	62	47	35	212	17	408	10	2	31	77	20	0.023
S653	179.8	Nct	69.7	0.258	12.79	8.88	0.076	1.05	0.18	0.09	3.79	0.12	3.5	100.9	13	8	8	12	2797	159	10	36	138	11	926	16	7	25	47	15	0.054
S653	219.5	sed	66.2	0.713	14.66	10.24	0.078	1.39	0.19	0.05	3.39	0.13	2.9	100.3	78	47	33	24	132	159	18	31	166	16	551	18	5	35	85	28	0.023
S710	87.8	Nct	74.4	0.246	12.72	1.96	0.028	0.79	0.55	1.87	4.81	0.12	1.4	99.0	11	9	2	7	68	158	45	34	137	9	551	15	8	22	27	16	0.056
S710	14.3	Nct	73.0	0.270	13.31	2.17	0.050	0.84	0.60	2.40	4.73	0.13	1.7	99.4	17	2	3	5	222	158	44	37	149	11	632	17	8	15	66	29	0.055

Location	m	Unit	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	SUM	V	Cr	Co	Ni	Zn	Rb	Sr	Y	Zr	Nb	Ba	Th	U	La	Ce	Nd	Zr/TiO_2
S710	311.8	Nct	72.9	0.265	13.07	2.69	0.027	1.03	0.20	0.51	6.70	0.12	1.2	98.9	18	6	2	5	98	223	36	40	143	11	1063	15	7	26	49	30	0.054
S710	391.7	Nct	73.9	0.251	12.48	4.10	0.034	2.16	0.19	0.01	3.96	0.12	2.3	99.6	13	7	3	7	63	146	10	36	138	11	518	16	6	24	59	28	0.055
S710	406.6	sed	65.4	0.518	12.49	10.85	0.077	4.44	0.20	0.01	2.39	0.12	3.6	100.3	47	79	18	8	176	98	7	31	217	15	352	11	3	46	75	32	0.042
S710	422.1	Nct	73.6	0.255	13.33	2.90	0.061	1.21	0.32	1.34	3.92	0.13	2.3	99.5	11	2	5	7	124	207	19	29	114	8	371	11	6	7	59	29	0.045
S710	525.2	Nct	73.5	0.253	13.37	2.53	0.056	1.27	0.39	2.34	3.65	0.13	2.0	99.6	20	1	3	6	106	179	41	30	115	9	351	10	5	10	50	18	0.045
S710	565.4	sed	72.0	0.207	12.22	7.05	0.043	1.88	0.20	0.01	3.43	0.13	2.9	100.2	12	12	14	13	80	170	7	33	103	9	387	11	6	29	53	18	0.050
S710	621.2	sed	61.8	1.068	18.33	7.52	0.071	2.23	0.15	0.64	4.83	0.11	3.3	100.2	125	89	17	45	145	216	20	34	200	20	434	15	6	46	83	37	0.019
S710	636.1	Nct	75.9	0.219	12.07	3.18	0.021	1.17	0.25	0.73	3.78	0.12	1.9	99.5	13	10	5	8	60	167	22	28	104	8	436	10	4	31	36	16	0.047
S710	659.9	Nct	75.2	0.230	12.75	2.23	0.017	1.05	0.31	1.71	4.24	0.13	1.7	99.6	12	3	3	8	70	176	36	28	108	8	360	12	5	19	45	25	0.047
S677	10.1	Nct	72.4	0.267	14.61	1.71	0.060	1.14	0.13	1.59	5.20	0.13	2.1	99.5	15	8	1	4	173	279	40	32	123	10	410	12	5	21	20	14	0.046
S677	36.6	Nct	74.5	0.283	13.08	2.48	0.101	1.42	0.15	1.43	3.69	0.11	2.0	99.4	22	12	2	9	224	216	35	30	102	8	372	11	6	21	58	6	0.036
S677	13.1	sed	77.7	0.252	10.84	2.42	0.155	1.03	0.20	1.67	3.34	0.12	1.7	99.4	16	9	9	7	294	200	29	27	100	9	209	10	4	16	37	13	0.040
S677	44.5	Nct	75.4	0.250	12.00	3.77	0.069	1.57	0.18	0.00	4.00	0.12	2.0	99.5	18	8	7	4	537	220	9	29	110	10	438	10	3	15	49	18	0.044
S677	71.3	Nct	76.6	0.265	12.16	1.99	0.026	1.22	0.21	1.93	3.11	0.14	1.6	99.4	17	5	0	6	138	169	40	30	115	9	413	10	5	11	50	12	0.043
S677	84.7	Nct	74.1	0.284	13.16	2.48	0.038	1.09	0.22	1.59	4.29	0.14	1.9	99.4	17	9	2	6	172	196	48	34	119	9	415	11	5	19	67	25	0.042
S677	108.2	Nct	77.8	0.259	11.59	1.48	0.041	0.75	0.20	2.81	2.83	0.12	1.3	99.3	17	11	2	5	130	120	64	27	109	8	277	10	7	21	66	30	0.042
S677	128.3	Nct	72.2	0.277	13.74	2.98	0.069	1.41	0.25	2.71	3.24	0.16	2.2	99.4	17	17	10	9	335	147	61	30	122	9	321	11	7	21	24	9	0.044
S677	157.6	sed	67.1	0.765	14.20	7.28	0.064	3.02	0.16	2.71	1.86	0.10	2.6	100.0	62	54	17	31	232	81	58	33	267	19	261	11	3	36	109	42	0.035
S677	185.6	sed	73.0	0.866	11.56	5.97	0.054	1.58	0.10	0.65	2.61	0.07	2.2	99.8	80	52	13	32	177	120	20	30	353	20	247	8	5	30	70	26	0.041
S677	231.3	sed	76.8	0.802	10.11	5.84	0.035	1.38	0.14	0.13	2.29	0.10	2.3	100.1	73	46	11	23	191	114	19	27	325	19	252	8	2	21	86	24	0.041
S677	265.2	sed	66.5	1.024	15.69	7.32	0.045	1.81	0.17	1.20	3.23	0.10	2.7	99.9	113	66	18	39	134	160	38	33	247	20	363	14	4	37	76	30	0.024
S1013	19.7	Nct	73.7	0.258	12.69	2.27	0.012	1.51	0.18	1.57	5.64	0.12	1.2	99.4	11	9	3	5	164	209	24	35	142	11	713	15	4	25	29	18	0.055
S1013	52.4	Nct	73.5	0.239	12.35	2.40	0.024	1.84	0.50	1.96	5.06	0.12	1.3	99.5	15	3	3	7	39	199	26	33	134	10	580	16	5	15	58	21	0.056
S1013	97.8	Nct	71.6	0.261	12.86	3.64	0.034	2.30	0.37	1.48	4.99	0.12	1.5	99.3	18	10	2	5	32	225	38	37	141	12	687	17	6	30	51	14	0.054
S1013	102	Nct	71.5	0.248	12.51	4.42	0.057	3.30	0.47	2.26	2.53	0.12	2.3	99.8	17	8	3	6	66	123	34	36	137	11	358	15	5	25	67	24	0.055
S1013	105	sed	75.7	0.754	9.62	5.82	0.060	1.90	0.13	0.00	3.02	0.09	2.8	100.0	74	53	13	13	45	134	7	26	380	18	342	8	2	33	78	26	0.050
S1013	160	sed	68.6	1.012	14.76	6.39	0.065	1.75	0.13	1.54	2.94	0.08	2.7	100.1	101	62	15	29	103	142	26	30	290	21	315	13	3	37	101	51	0.029
S1013	198.8	sed	66.2	0.430	13.56	11.19	0.067	2.52	0.14	0.29	2.80	0.09	2.9	100.3	14	15	17	7	33	124	13	41	265	20	364	13	3	43	102	40	0.062
S1013	220.2	Nct	74.7	0.269	9.91	7.32	0.067	2.66	0.14	0.00	2.29	0.09	2.3	99.8	16	14	13	10	47	101	7	23	98	8	274	10	5	23	13	5	0.036
S1013	249.8	Nct	73.5	0.252	13.46	2.55	0.096	1.39	0.26	1.78	4.26	0.11	1.4	99.2	12	11	4	8	25	196	42	28	111	10	483	12	6	27	43	22	0.044
S1013	301.7	Nct	71.2	0.272	13.73	5.49	0.163	1.85	0.20	0.03	3.79	0.14	2.2	99.4	23	9	4	4	1312	165	12	28	119	11	267	16	1	17	62	20	0.044
S1013	351.5	sed	80.9	0.571	6.33	7.49	0.056	1.57	0.10	0.00	0.92	0.06	1.7	99.7	37	21	10	17	37	47	5	20	313	15	87	8	1	21	50	24	0.055
S1013	397.4	sed	78.6	0.729	8.51	6.91	0.072	1.23	0.12	0.00	1.74	0.08	1.9	100.0	64	42	10	30	58	83	9	29	474	21	175	8	2	29	78	37	0.065
S1013	506	sed	71.7	0.924	12.90	5.76	0.016	1.87	0.13	0.03	3.89	0.09	2.3	99.8	90	63	12	35	16	176	21	33	336	21	487	11	3	45	93	40	0.036
S1013	600	sed	78.7	0.682	8.74	5.76	0.024	1.60	0.16	0.00	1.94	0.08	2.0	99.8	60	47	14	23	12	91	16	27	345	19	297	9	3	39	85	36	0.051
S1013	698.8	mfc	53.2	2.570	14.95	13.54	0.104	5.83	2.24	3.40	0.04	0.52	3.6	100.2	245	17	30	13	84	5	43	60	683	38	27	3	1	41	115	41	0.027
S1013	798	sed	62.0	1.083	18.38	7.60	0.044	2.07	0.23	0.98	4.22	0.13	5.5	102.4	131	82	20	44	107	202	41	37	204	21	473	16	4	41	93	39	0.019
S1013	896	Nct	75.3	0.236	12.61	2.18	0.040	0.90	0.32	1.68	4.52	0.12	1.3	99.3	13	16	3	8	67	177	68	29	109	8	358	9	6	30	41	16	0.046
S1013	1000	sed	67.2	0.508	13.43	8.79	0.077	3.17	0.32	0.04	3.43	0.13	3.0	100.2	32	7	13	6	39	137	13	37	234	18	554	13	4	37	79	36	0.046
S1013	1022	Nct	76.2	0.228	11.44	2.65	0.043	1.47	0.26	1.08	4.33	0.11	1.4	99.4	10	9	2	4	46	136	65	32	125	10	965	13	4	26	24	15	0.055
S1013	1045	mfc	62.0	1.282	13.91	8.75	0.217	4.72	0.57	3.13	2.96	0.33	2.0	100.0	182	12	13	5	171	128	45	30	170	15	314	10	2	46	55	23	0.013
S1013	1139.5	Nct	74.2	0.257	12.60	2.44	0.053	1.46	0.23	1.39	5.18	0.12	1.4	99.6	20	5	1	5	254	160	49	37	138	10	968	16	6	33	71	26	0.054
Lower FW sed. (n=3)			58.6	1.04	19.73	8.89	0.07	2.25	0.25	2.10	3.58	0.10			134	80	19	44	122	160	97	37	180	17	496	14	4.5	48.7	94.3	42	0.017
Upper FW sed. (n=5)			61.0	0.55	9.35	20.16	0.07	2.24	0.18	0.47	0.75	0.09			55	27	153	15	96	37	21	28	192	13	134	8	2.2	35.2	68.8	31.4	0.035
FW crystal tuff (n=9)			73.2	0.31	13.10	3.87	0.12	1.20	0.41	0.89	4.51	0.13			25	10	3.5	6	504	182	56	34	130	11	659	10	4	23.8	48.6	22.7	0.042
HW crystal tuff (n=8)			73.4	0.25	13.03	2.55	0.03	1.52	0.41	1.31	5.00	0.13			15	8	2	3.6	592	179	61	43	146	14	1350	14	5	28.1	57.1	26.1	0.058

NOTES: Location includes field samples and diamond drill hole samples. Unit: FLB - rhyolitic sedimentary rock, Nct - Nepisiguit Falls crystal tuff, sed. - sedimentary rock of unknown parentage, mfc - mafic sediment/volcanic or dyke (?). Averages of Lower sed., Upper sed., footwall (FW) crystal tuff, and hanging wall (HW) crystal tuff are from Lentz et al. (in press).

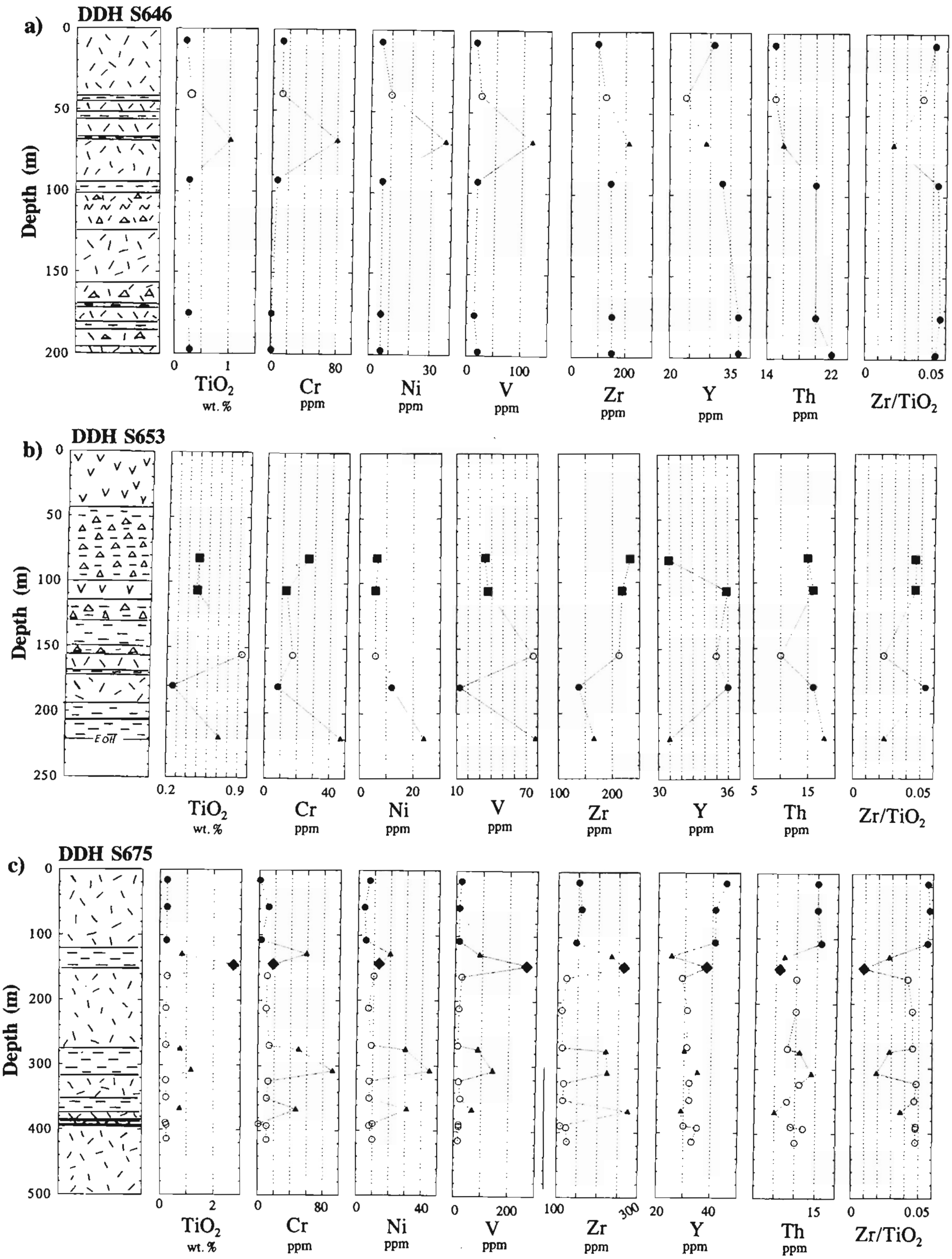

*Figure 4. Diamond-drill hole (DDH) profiles for **a)** S646, **b)** S653, **c)** S675, **d)** S677, **e)** S710, and **f)** S1013 illustrating TiO_2, Cr, Ni, and V variations that are particularly important for discriminating the lower and upper (footwall) sedimentary rocks, and Zr, Y, Th, and Zr/TiO_2 contents that are important in identifying hanging wall and footwall crystal tuffs. Interpreted lower footwall sedimentary rocks (Miramichi Group- like) (▲), and upper footwall sedimentary rocks (Nepisiguit Falls Formation) (△), footwall crystal tuffs/tuffites (○), hanging wall crystal tuff (●), and mafic volcanic/dike (◆).*

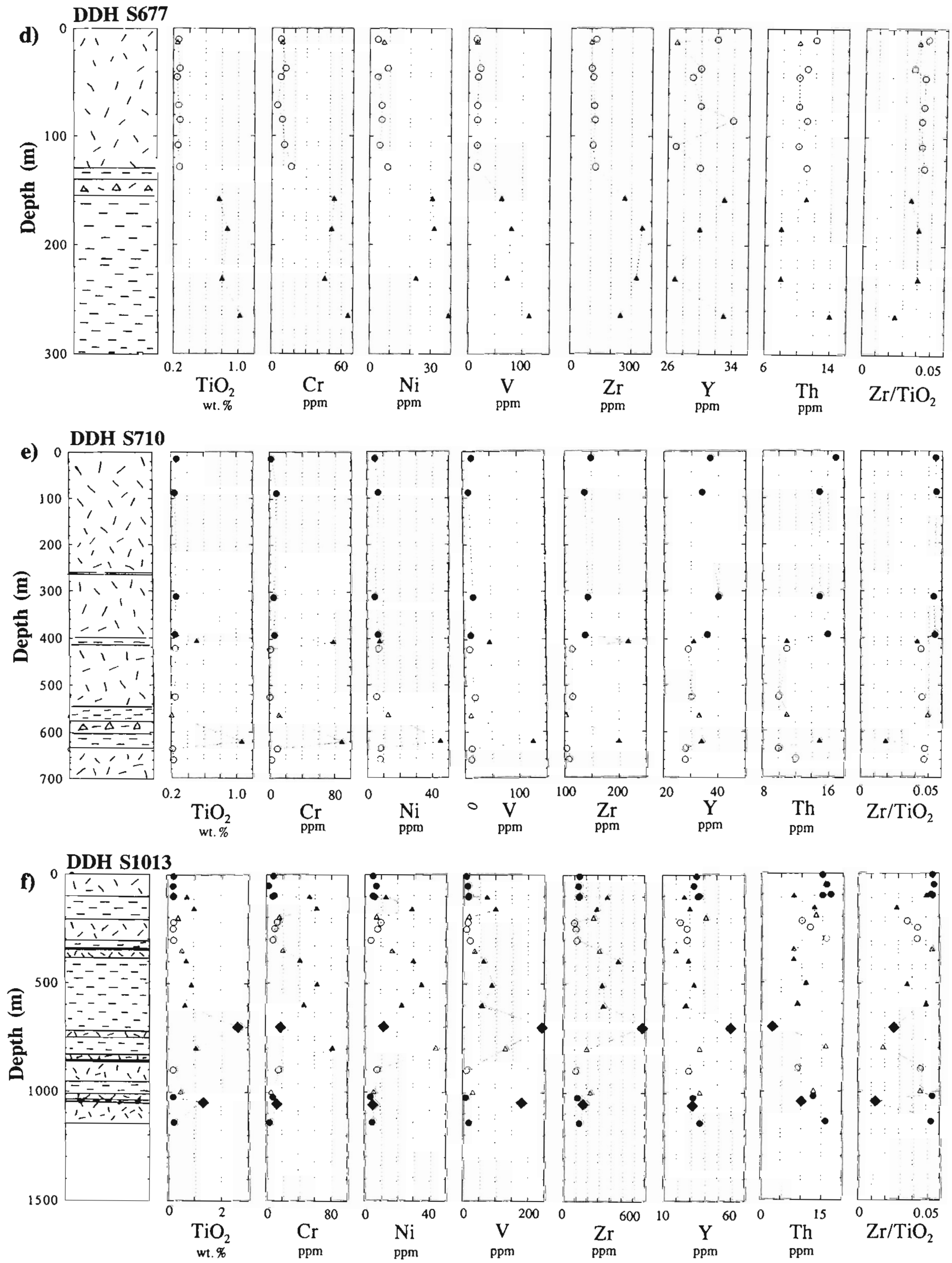

Figure 4. *(cont.)*

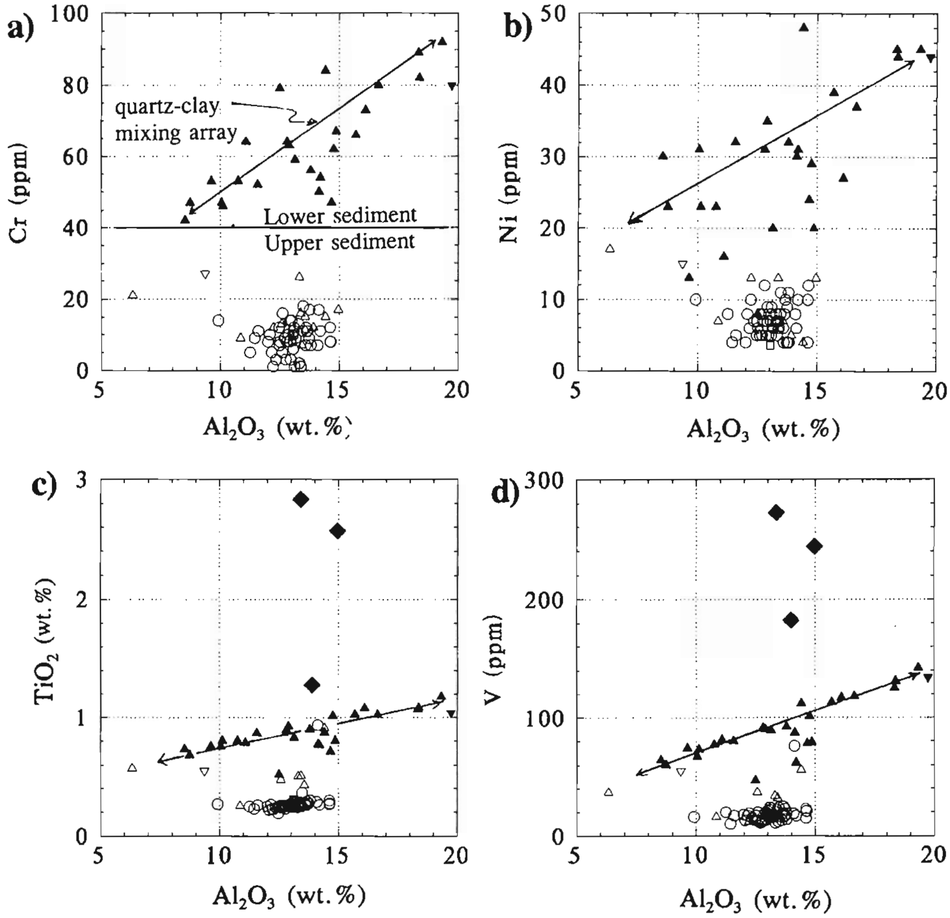

*Figure 5. Al_2O_3 versus **a)** Cr, **b)** Ni, **c)** TiO_2, and **d)** V variation diagrams illustrating the compositional ranges of the sedimentary rocks (▵) and crystal tuffs (○) sampled in the Heath Steele B-B5 zone area (see Table 1). The bimodal Cr distribution of sedimentary rocks is inferred to indicate a Miramichi Group compositional affinity for Cr greater than 40 ppm (▲) and a tuffaceous affinity, Nepisiguit Falls, Tetagouche Group, for Cr values less than 30 ppm (▵), footwall and hanging wall crystal tuffs/ tuffites (○), mafic volcanic/dyke (◆), and Flat Landing Brook rhyolitic sedimentary rocks (■). ▼ – average Miramichi-like sedimentary rocks and ▿ – average Nepisiguit Falls tuffaceous sedimentary rocks (Lentz et al., in press).*

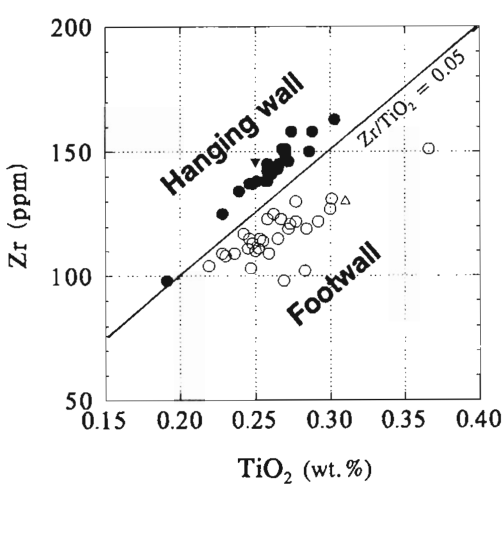

Figure 6.

TiO_2 versus Zr diagrams illustrating the compositional ranges of the crystal tuffs sampled in the Heath Steele B-B5 zone area (see Table 1). Samples with Zr/TiO_2 less than 0.05 are typical of the stratigraphic footwall (FW) crystal tuffs (○) and those with Zr/TiO_2 greater than 0.5 are typical of hanging wall (HW) crystal tuffs (●). ▼ – average hanging wall tuffs and ▵ – average footwall tuffs (Lentz et al., in press).

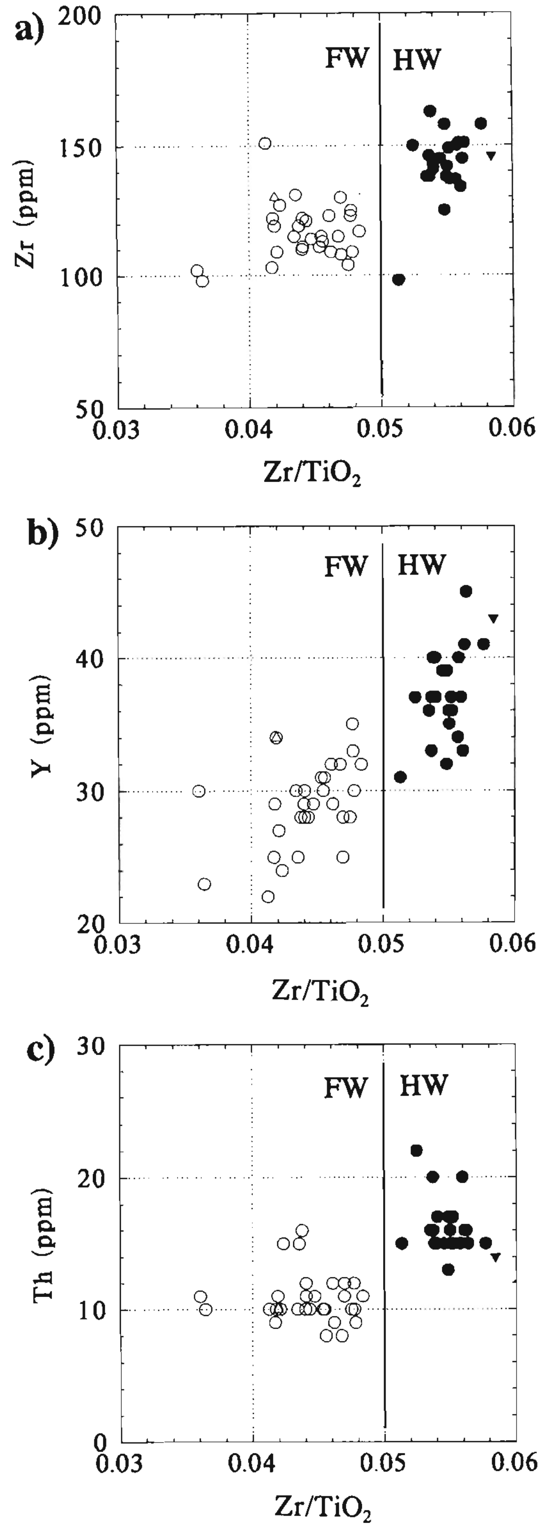

Figure 7. *Zr/TiO_2 versus **a)** Zr, **b)** Y, and **c)** Th diagrams illustrating the compositional ranges of the crystal tuffs sampled in the Heath Steele B-B5 zone area (see Table 1). Stratigraphic footwall (FW) crystal tuffs (○) and hanging wall (HW) crystal tuffs (●). ▾ – average hanging wall tuffs and ▵ – average footwall tuffs (Lentz et al., in press).*

Lentz (1996b) showed that the Zr/TiO_2 ratio is one of the most effective indices for geochemical differentiation of the principle felsic volcanic units in the Bathurst camp.

Several schistose mafic volcanic (?) rocks or dykes were sampled as they resembled chloritic sedimentary rocks. However, they have very high Ti and V contents (Fig. 5), which are similar to some of the within-plate basalts of the Heath Steele area (Winchester et al., 1992; Wilson, 1993), therefore where not dealt with in detail here.

DISCUSSION

The geological and geochemical data indicate that there are separate and distinct footwall and hanging wall crystal tuff units within the Nepisiguit Falls Formation in the vicinity of the Heath Steele B zone deposit (Fig. 6). Mature sedimentary rocks (Miramichi-like) are located at the base of the section, whereas dominantly tuffaceous sedimentary rocks are situated in the footwall of the deposit, although some Miramichi-like sediments were also deposited immediately before the ore mineralization. The occurrence of stratigraphic hanging wall crystal tuffs ($Zr/TiO_2 > 0.05$) above the B5 zone deposit and in the south quarry (samples 2 and 3) indicates that the lower crystal tuff and upper sedimentary rocks are absent along the southern limb of the regional-scale Heath Steele fold (Fig. 3). This stratigraphic interpretation is virtually identical to that of McBride (1976), which was based solely on underground mapping and detailed drill core logging. However, in contrast to the previous interpretations, the ore horizon trends northeasterly to the east of the B zone pit, and then continues eastward. This is consistent with the occurrence of altered footwall sedimentary rocks (upper corner of Fig. 3) at the inferred footwall crystal tuff-hanging wall crystal tuff contact. This has been confirmed by recent Noranda drilling along this eastern extension of the B zone (Reg Felix, pers. comm.).

In addition to the obvious exploration significance, this study demonstrates that the B zone deposit occurs near the base of the Nepisiguit Falls Formation (see also Wilson, 1993; McCutcheon et al., 1993). The footwall tuffaceous sedimentary rocks appear to thin significantly towards east, where no sulphide bodies have been encountered. This suggests that the sulphides accumulated in basins and is consistent with detailed observations of base-metal zoning and footwall sediment thickness at the B zone (see Lusk, 1969, 1992).

Further studies should be conducted to the west to help resolve some of the stratigraphic and structural complexities in the C and C-north zones, to determine whether the chemostratigraphic framework remains intact, and to establish further the correlations between deposits throughout the Heath Steele Belt. In a detailed lithogeochemical study of the Heath Steele Belt, Wahl (1978) analyzed crystal tuffs and sedimentary rocks from the hanging wall and footwall sequence for many elements including Cr, Ni, V, and TiO_2 using a HF-based multi-acid technique. It is possible that some of these data could be used to further enhance the stratigraphic understanding of the area.

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The Canfield Creek copper deposit, Nova Scotia – a late Carboniferous cupriferous bog deposit: implications for exploration for redbed copper in Carboniferous clastics in Nova Scotia and New Brunswick[1, 2]

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Abstract: On the flank of a salt dome that cuts the Westphalian C-D Malagash Formation near Pugwash, Nova Scotia, chalcocite nodules have replaced diagenetic pyrite nodules at the base of a grey fluvial channel sandstone. Pyrite and organic matter occur throughout the grey bed and redox fronts separating it from over- and underlying red floodplain mudstones are concordant with its base and top. Regional presence of green sandstones in overlying formations argues against large scale oxidation from above during Permian unroofing. There is no macroscopic evidence that the salt dome was involved in the mineralization. Rather than forming a roll front, cupriferous ore solution probably migrated as syngenetic to early diagenetic groundwater from underlying red floodplain mudstones. An unusually high content of plant debris and of pyrite nodules in the mineralized bed might be linked to a local overlying grey-black, laminated mudstone of probable swamp origin.

Résumé : Dans le flanc d'un dôme salifère qui découpe la Formation de Malagash du Westphalien C-D près de Pugwash (Nouvelle-Écosse), des nodules de chalcocite ont remplacé des nodules de pyrite diagénétique à la base d'un grès gris de chenal fluvial. De la pyrite et des matières organiques sont présentes dans toute la couche grise, et les fronts d'oxydoréduction qui la séparent des mudstones rouges sus-jacentes et sous-jacentes de plaine d'inondation sont concordants avec sa base et son sommet. La présence régionale de grès verts dans les formations sus-jacentes témoigne contre une oxydation à grande échelle à partir de couches supérieures au cours de l'érosion au Permien. Il n'existe pas d'indications macroscopiques de la participation du dôme salifère à la minéralisation. Plutôt que de former un gisement de type «roll,», la solution cuprifère a probablement migré sous forme d'eau souterraine syngénétique ou de diagenèse précoce à partir des mudstones rouges sous-jacents de plaine d'inondation. La concentration inhabituellement élevée de débris végétaux et de nodules de pyrite dans la couche minéralisée pourrait être associée à un mudstone laminé gris-noir local sus-jacent, probablement issu d'un milieu marécageux.

[1] Contribution to Canada-Nova Scotia Cooperation Agreement on Mineral Development (1992-1995), a subsidiary agreement under the Canada-Nova Scotia Economic and Regional Development Agreement.
[2] Contribution to the Magdalen Basin NATMAP Project

INTRODUCTION

Sediment-hosted copper occurrences in the Carboniferous sedimentary rocks of Nova Scotia and New Brunswick lie at three main stratigraphic horizons. Subeconomic occurrences are scattered along a regional redox boundary between red alluvial sandstones of the Tournaisian Horton Group and the overlying, regionally distributed, Macumber Formation, a Kupferschiefer-like laminated marine limestone at the base of the Visean Windsor Group (Ryan et al., 1989). The style of mineralization is similar to the well known Kupferschiefer deposits (Kirkham, 1989).

In New Brunswick the Dorchester Copper deposit, mined between 1898 and 1916 (McLeod and Ruitenberg, 1978) lies at a similarly widespread redox boundary between redbeds of the Namurian Enrage Formation and drab pyritic fluvial sandstone of the overlying, early Westphalian Boss Point Formation. The Boss Point Formation is also marked by occurrences of lead mineralization where it overlies granitic conglomerate of the Claremont Formation near New Glasgow. Also the slightly younger and lithologically similar Westphalian A Silvermines Formation hosts the Yava zinc-lead deposit where it overlies a Pb-rich granite (Sangster and Vaillancourt, 1990). Where shale occurs at the base of the Boss Point Formation this type of mineralization was likened to Kupferschiefer mineralization (Ryan and Boehner, 1994), but because the Boss Point Formation is dominated by fluvial sandstone, the comparison is misleading. Nevertheless the widespread early Westphalian A sandstones in New Brunswick and Nova Scotia constitute a host rock of some significance for sediment-hosted base metal mineralization.

A third type of sediment-hosted copper mineralization occurs as numerous showings in grey, pyritic sandstone and shale units, interbedded with red shales in the late Westphalian fluvial sandstones of the Malagash and Balfron formations (Ryan et al., 1989; Ryan and Boehner, 1994). They commonly occur, close to redox boundaries, in grey shale or at the base of grey upward-fining fluvial sandstone sequences, where coalified plant material is concentrated in channel lags (Dunsmore, 1977; Ryan and Boehner, 1994). The main copper mineral is chalcocite that has replaced pyrite (Papenfus, 1931; Shumway, 1951). However, so far none has proved economic. The most promising of these occurrences is the Canfield Creek deposit, which contains about 300 000 t of 1.2% Cu. In 1980-1981 Esso Minerals Ltd. drilled 24 holes over the deposit (O'Sullivan, 1981), but it has not been tested below 120 m and is open in at least two directions (Ryan and Boehner, 1994). It lies in a grey sandstone unit of the Malagash Formation, that dips about 30° northeast on the northeast flank of the Canfield salt dome, south of Pugwash Bay, Nova Scotia (Fig. 1, 2) that rose after deposition of the host rocks (Ryan, 1986). From a genetic point of view, the salt dome is a potential source of chloride and carbonate for mobilizing copper as complexes (Ryan et al., 1989; Ryan and Boehner, 1994), and of sulphur (Kirkham, 1989) for fixing the metals as sulphides. Undisturbed unimodal fluvial

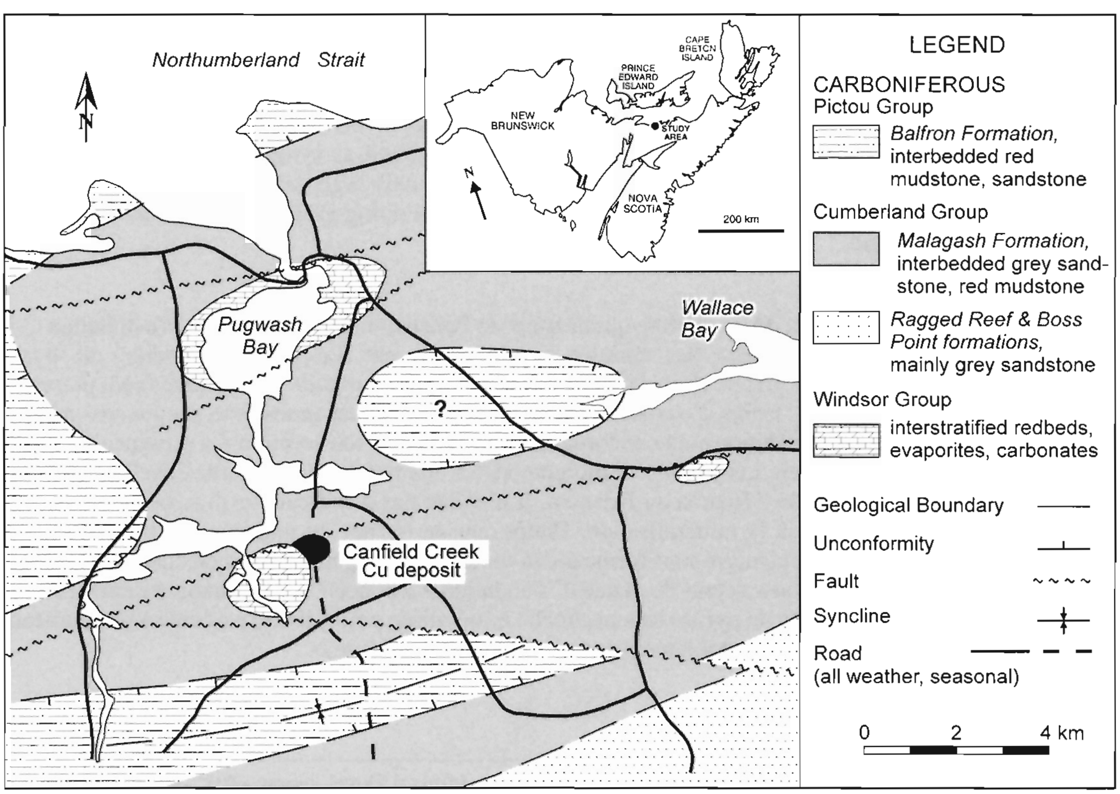

Figure 1. *Geological map to show the geological context of the Canfield Creek deposit, after Ryan et al. (1990).*

paleocurrents in the Malagash Formation in the Canfield Creek area indicate that the Canfield Creek salt diapir was not present during deposition of the host rocks. Of interest is that the Dorchester deposit, mentioned above, also lies 2 km northeast of a salt dome (McLeod and Ruitenberg, 1978) – one of a number of similar Windsor salt diapirs rising through late Carboniferous fluvial strata of the Maritimes. Thus, understanding the genesis of the Canfield Creek deposit is important in assessing the potential of late Carboniferous sandstones of the Canadian Maritimes as a host environment for redbed copper deposits.

Sedimentary copper deposits occur where oxidized cupriferous solutions meet reduced, often pyritic facies. At such redox boundaries sulphide minerals are deposited in a well documented series across the redox interface away from the redbeds, generally summarized as chalcocite-bornite-chalcopyrite-pyrite (Brown, 1993), with the pyrite zone is commonly interpreted as pre-ore diagenetic pyrite, a source of sulphur for the copper sulphides (Rose, 1989). Therefore, the arrangement of redox boundaries and direction of sulphide mineral zoning are important in determining the flow direction of the ore fluid, a factor important in modelling the genesis of, and in exploration for sedimentary copper deposits.

As a simple field study, the macroscopic distribution of chalcocite versus pyrite nodules in drill core from a number of Esso Minerals Ltd.'s diamond-drill holes (O'Sullivan, 1981) and the distribution of reduced versus redbed facies were studied in core and outcrop, as a measure of the transport direction of the ore fluid.

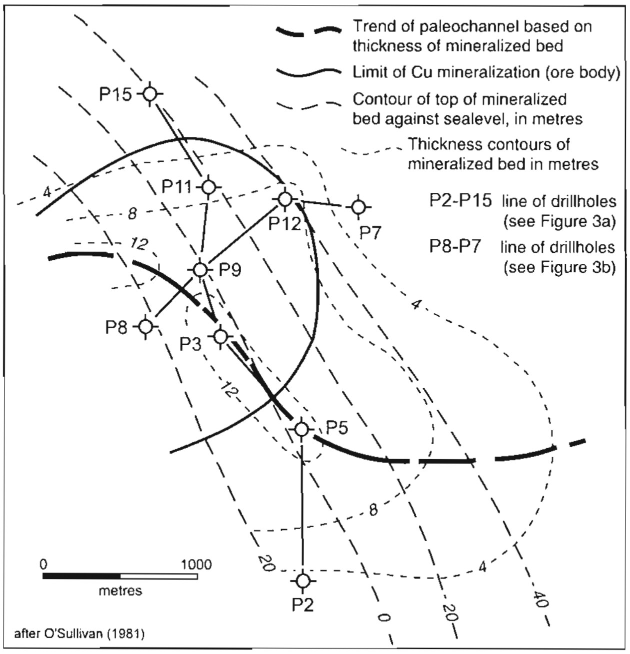

Figure 2. Plan of selected diamond drill holes (P) across the Canfield Creek Deposit, after O'Sullivan (1981).

REGIONAL GEOLOGY OF THE MALAGASH FORMATION

The Malagash Formation of northern Nova Scotia (Ryan et al., 1991), and its stratigraphic equivalent in southeastern New Brunswick, the Richibucto Formation (Johnson, 1995), are part of a clastic, alluvial molasse sequence deposited in equatorial latitudes, on the northern flank of the Appalachian-Mauretanides Orogen (Ziegler, 1989).

Field and drill core studies east of the Canfield Creek deposit (Nova Scotia Department of Mines and Energy, DDH P-58, 1986, UTM 5057200 N, 530900 E; Aquagold Resources Inc., DDH P-88-1, 1988, UTM 5073340 N, 536860 E; Malagash Point, UTM 5072000, 482000 E) show the 450 m thick Malagash Formation to consist of two interbedded dominant facies, grey or green arkosic channel sandstone and red floodplain mudstone-siltstone. In some cases a third grey, rippled siltstone facies overlies the channel sandstone.

The author's studies show that channel sands are coarse- to fine-grained and can be stacked in units up to 60 m thick. They contain varied amounts of coalified plant fragments, which are up to 5 m long, and pyrite, especially in channel lag pebble conglomerate. Locally, copper stains occur on pyritized plant fragments in outcrop. Floodplain deposits are generally composed of mudstone and siltstone and contain the following units: thin (<30 cm) coals; thin (<2 m), generally red, sandstone units; local thin (<45 cm) lacustrine carbonate units; incipient nodular calcrete and rhizoliths. Also red soils with darker tops, marked by slickensides, calcrete, rhizoconcretions, and root traces are common and probably represent vertisols. These features of the floodplain deposits are evidence of a strongly seasonal tropical climate with a marked dry season.

GEOLOGY OF THE HOST ROCKS AT CANFIELD CREEK

There is very little exposure in the vicinity of the Canfield Creek deposit, consequently host rock data come from drill core targeted at the mineralized horizon (Fig. 3). The mineralized unit is a grey, northeast-dipping channel sandstone 2-25 m thick and unusually organic rich and pyritic for the Malagash Formation. It lies between red floodplain deposits, those above including some thick sandstone. At the base of the grey bed, a thin reduced zone, similar to that seen in exposure at Malagash Point (below), may have either the characteristics of a synsedimentary reduction zone or a soil top. Where mineralized by chalcocite nodules the grey unit is capped by a unit of laminated, fissile, black to grey mudstone up to 4 m thick. The mudstone may be pyritized and contains abundant disarticulated plant remains, including leaves, oriented in the bedding plane. The thickest part of the laminated mudstone seems to coincide with the thickest part of the mineralized grey unit (Fig. 3) and is thinner or absent where the grey unit does not contain copper minerals. The mudstone or its oxidized equivalent was not seen overlying red sandstone units in the Canfield Creek core.

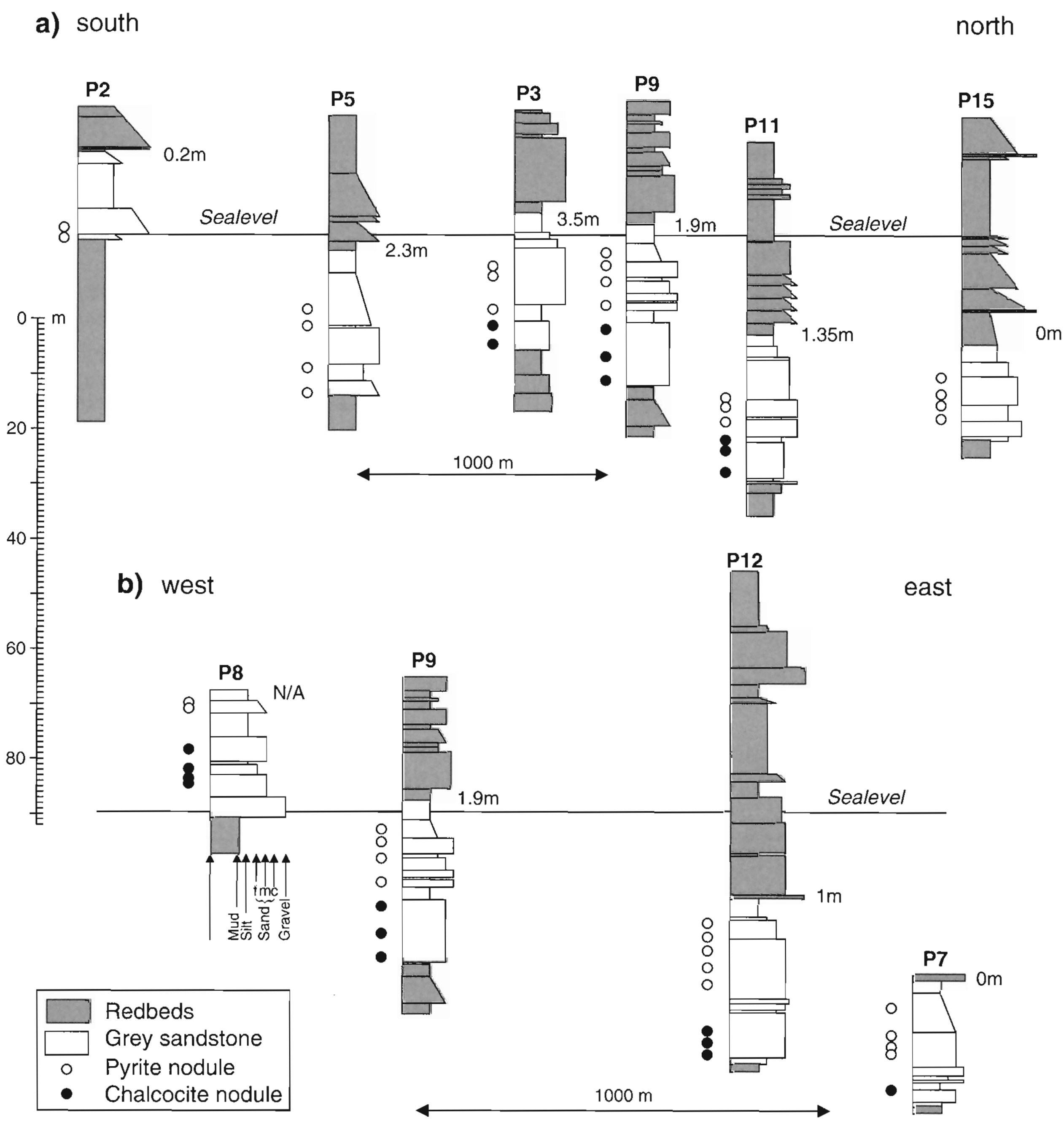

Figure 3. *Redox boundaries and sulphide zoning in the Canfield Creek Deposit, derived from drill core. Thicknesses in metres refer to laminated grey mudstone that overlies mineralized grey sandstone unit. For locations of drill holes (P), see Figure 2.*

Viewed regionally, channel sandstone units of the Malagash Formation contain scattered coalified plant fragments with associated pyrite, and lie between red floodplain mudstone sequences, both up to tens of metres thick. Where not overlain by the grey, rippled siltstone facies, the upper part of the channel sandstone units may be oxidized, a feature well demonstrated in several 7.6 to 20 m thick channel sandstone units at the type section of the formation at Malagash Point 33.5 km east (UTM 5072000N, 482000 E). At Malagash Point, the channel sandstones consist of a lower green part, a middle mottled part, and an upper red part. The colour boundaries are conformable with the base and top of the channel sandstone units. In the middle mottled part, green patches isolated in a red background suggest superimposition of reddening on the originally green sandstone by penetration along crossbed foresets and set boundaries. In exposure, at the base of the lower green part, the upper part of the underlying red mudstones may be reduced over a thickness of 2-50 cm. Presence of red remnants in the green mudstone suggests reduction of the top of the originally red mudstone. The colour boundaries discussed above, are conformable with the upper and lower boundaries of the channel sandstones.

SEDIMENTARY COPPER DEPOSITS

Kupferschiefer copper deposits

Sedimentary copper deposits are divided into a paralic marine (or lacustrine) Kupferschiefer type and the less important, continental, redbed type (Kirkham, 1989). The former, also named the stratiform copper deposits (SCD), commonly have the following genetic characteristics. An underlying source of redbeds, other cupriferous rocks or deep magmatic fluids releases metals to a warm or hot brine as chloride complexes which collect in an oxidized aquifer (footwall redbeds). The metalliferous brine then circulates across a redox boundary associated with an extensive fine grained, reducing, S-rich rock. A continental rift setting (extensional tectonics) may provide a heat source to drive basin-scale circulation. In general, laterally broad, subvertical, upward Cu>Pb>Zn>Cd zonation suggests fluid entry from below. The mineralization overprints pre-ore pyrite or, pre-existing sulphates. The metal trap is commonly a basin-wide transgressive pyritic mudstone or carbonate. Common association of sedimentary copper deposits with evaporite suggests formation of host rocks in hot dry climates within 30° of the equator (Jowett, 1986; Brown, 1993).

Redbed copper deposits

This type is mainly found in Carboniferous fluvial sequences with red floodplain deposits, sometimes containing calcrete, and channel sands that contain wood trash and early diagenetic pyrite. Metalliferous fluids emanating from the redbed react with the wood trash and pyrite to deposit copper minerals at mobile redox fronts. Less common processes include reaction of a reduced sulphur-bearing fluid with an oxidized metalliferous fluid as in Dzhezkazgan (see below), or leaching of metals from redbeds by brines derived from evaporites. Many major sedimentary copper deposits are early rather than late diagenetic (Kirkham, 1989). Redbed-type copper deposits have been split into a number of submodels as follows.

The Permian Dzhezkazgan Cu-Pb deposit, in Kazakhstan, is believed to have formed when cupriferous brines, squeezed from surrounding redbeds, migrated up dip along the redbed Dzhezkazgan Formation, to meet H_2S and methane-bearing water rising along a fault system. The ore was deposited at discordant redox boundaries in the Dzhezkazgan Formation (Baskov, 1987).

A common setting of uranium mineralization is at roll fronts (Selley, 1988, Fig. 2.11) in Permian to Tertiary, fluvial sandstones of the western U.S.A. Uranium roll fronts are believed to form by downward percolation of oxidized water along porous, inclined organic-rich fluvial sandstone units during weathering. Mineralization occurs at the oxidation boundary between the oxidized percolating fluid and the plant debris-bearing host rock (Selley, 1988). Genetically similar redbed chalcocite-Ag deposits have also been reported at roll fronts in fluvial channel sandstones in the Permian Wellington Formation as at Paoli, Oklahoma (Shockey et al., 1974).

In the Nacimiento model, chalcocite mineralization replaces fossil logs and locally pyrite, in the lower part of a 13 m thick alluvial flood cycle at the base of the Triassic Agua Zarca Formation in the Sierra Nacimiento of New Mexico. The Agua Zarca is under- and overlain by redbeds. Absence of mineralization in a drab unit containing plant debris, lying 100 m conformably above the Agua Zarca, suggested that the mineralization preceded deposition of the overlying unit. The mineralization is interpreted to have occurred when ore solutions migrating through the channel complex encountered plant debris (Woodward et al., 1974). The mineralized unit is white to buff and earlier pyrite has not been recorded from higher in the channel complex. Absence of iron sulphides, likely to be early diagenetic, suggests that this type of mineralization was deposited by the roll front mechanism, but that the roll fronts have passed on, leaving copper minerals behind in concentrations of woody material in channel-fill conglomerates.

Recent cupriferous bogs are common especially where abundant peaty material is preserved in low-lying, poorly drained areas and appear to be associated with pre-existing copper mineralization. Decayed wood and cupriferous muck in a cupriferous swamp in New Brunswick have concentrated copper, the muck having a general range of 2-6% Cu (Boyle, 1977).

CANFIELD CREEK DEPOSIT

The above attributes of Kupferschiefer and redbed type copper deposits indicate that the Canfield Creek deposit, with its compressive, as opposed to rifting, tectonic setting (Keppie, 1993) belongs to latter class. The redbed copper deposits of Nova Scotia and New Brunswick have been explained with a number of submodels. For example Papenfus (1931) interpreted them as supergene because ascending hot magmatic solutions would have destroyed the associated organic matter and its cell structure. Also, Brummer (1958) reported subeconomic copper-uranium mineralization to be widespread in the Pictou Formation (now the Malagash Formation and overlying Pictou Group; Ryan et al., 1991) of northern Nova Scotia, associated with chalcocitized plant fragments in stream channel sandstones, overlying red mudstones. The copper minerals were reported as mainly nodular chalcocite, replacing pyrite or coaly material and as disseminations with, or replacing coaly material. Surface examination of nine prospects and drill core indicated that the mineralization did not extend "more than a few tens of feet downdip", leading to the suggestion that it is of supergene origin (Brummer, 1958). But Ryan and Boehner (1986) observed chalcocite in drill core at a depth of 440 m, thereby challenging a simple supergene model.

Fission track (Ryan et al., 1992) and preliminary paleomagnetic data (Morris, 1987) indicated to Ryan et al. (1989) late Permian erosion and downward penetration of oxidized surface water under desert conditions in northern Nova Scotia. The oxidized groundwater was suggested (Ryan et al., 1989) as the ore solution for the mineralization at Canfield Creek, implying a late diagenetic mineralization. A simple top-down oxidation (Van de Poll and Ryan, 1985) is considered unlikely because of this author's observations of significant numbers of green and grey sandstones within the red floodplain deposits in the three formations of the Pictou Group that overlie the host formation of the Canfield Creek deposit. Furthermore, work in progress 70 km to the east near New Glasgow, on the early Westphalian New Glasgow Formation, suggests that locally at least diagenetic paleomagnetic remanence is early Kiaman (late Carboniferous) and that a late diagenetic (end Permian) remanence may not be pervasive (K.A. Buchan pers. comm., 1996).

Kirkham (1989) suggested a variant of the Dzhezkazgan model, in which sour gas was localized on the flanks of salt domes to explain the Canfield Creek deposit, though he does not mention it by name. Although two faults are shown to occur near the Canfield Creek deposit (Fig. 1), there is no evidence that reduced fluids ascended along them as at Dzhezkazgan. As mentioned above (see also Ryan and Boehner, 1994), there is no evidence that the grey unit at Canfield Creek was originally a redbed unit.

Ryan et al. (1989) adopted the Paoli roll front model to explain the copper occurrences of northern Nova Scotia. Both ascending brine from the salt dome, which would have enhanced copper solubility, and descending oxygenated groundwater may have reached the bed via faults. Copper and silver were leached during the passage of oxidized water along the sandstone units during the end-Permian diagenetic reddening event (Ryan and Boehner, 1994). Copper was deposited on encountering coalified material "presumably" at the interface between the (oxygen bearing) groundwater and reducing basinal fluids (Ryan et al., 1989). Ryan and Boehner (1994) also noted similarities between the Canfield Creek deposit and the Dzhezkazgan and Nacimiento types of deposit, proposing a combined model (also Ryan et al., 1989). Basinal brine, rising up faults, met oxidized solutions that descended along the same faults. This mixed solution migrated along pyritic sandstone beds, depositing Cu on meeting organic material and pyrite.

Drilling at Canfield Creek showed more conclusively than possible at Malagash Point that redox boundaries at the base and top of the grey unit are concordant. Although searched for, roll front-type or other discordant redox boundaries were not seen. The reduced, sulphidized state of the host fluvial channel sand was maintained along both traverses (Fig. 2, 3) well to the north, east, and south of the ore body. Erosion of the top of the east-dipping grey horizon DDH P 8 and to the west, prevented assessing the redox and sulphidation state of the host unit west of the ore body (Fig. 2).

In all drill cores shown on Figure 3, crossbed and ripple laminae in the grey channel sands are picked out by finely divided coaly material. Nodules of pyrite, up to 1.5 cm across, have grown within and around these laminae, both within and outside the ore body. Within the ore body, pyrite nodules at the base of the channel sands appear to have been replaced by nodules of chalcocite (Fig. 3). Sulphide zoning is concordant with the bedding of the host rocks and associated redox boundaries. There is no sign of discordant sulphide zoning except that the thinner channel sand, outside the ore body, in some cases has a low organic content and pyrite is the only sulphide mineral. Thus, there is no evidence of roll front processes at Canfield Creek. On the contrary, concordant redox boundaries at Malagash Point and at Canfield Creek argue against such a process. Also, absence of secondary reduction of the grey beds (also Ryan and Boehner, 1994) argues against a Dzhezkazgan model.

Field relations at Malagash Point suggest that reduction of red floodplain mudstone at bases of reduced channel sandstones was likely synsedimentary. It is probably significant that channel sandstone units do not have reddened tops where they are overlain by grey siltstone units. This could be explained by protection of the channel sands from diagenetic oxidation, but there is no evidence of downward oxidation of the grey siltstone units. Also this model would have to explain the absence of upward reddening at the base of channel sandstone units. The grey siltstone units could be the results of glacioeustatic flooding (A. Archer, pers. comm., 1994). Spore evidence (G. Dolby, pers. comm., 1986) suggests that the grey laminated siltstone unit at Canfield Creek is a fresh water swamp deposit. If either of these explanations is correct, the channel sandstones were probably protected from oxidation by a high water table and may have formed in depressed areas of the floodplain. Conversely, channel sands with oxidized tops that are not overlain by grey siltstone units may have been exposed to low water tables in higher parts of the floodplain. Presence of vertisols containing incipient calcrete in the red floodplain deposits of the Malagash Formation argue for a strongly seasonal tropical climate with a pronounced dry season. Therefore this reddening could be early diagenetic and related to lowering of the water table either annually or over short term synsedimentary climate fluctuations.

CONCLUSIONS

The Canfield Creek copper deposit was formed in postcollisional transpressive tectonic environment. The climate prevailing during deposition of the host rocks of the Canfield Creek deposit was tropical and strongly seasonal (Chandler et al., 1994; Chandler, 1995), with a pronounced dry season. There is no evidence that the nearby salt dome or associated faults played a role in formation of the deposit.

Concordant redox boundaries and sulphide zoning at Canfield Creek argue against roll fronts. Presence of plant material and lack of evidence of secondary reduction of the grey bed preclude a Dzhezkazgan model. Lack of oxidation of the mineralized bed renders a Nacimiento model unlikely. Simple upward sulphide zoning throughout the deposit, concordance of a redox boundary at the base of the grey unit and preliminary paleomagnetic data, indicate that the ore fluid moved upward from underlying red floodplain deposits soon after sedimentation.

Plant debris-bearing, pyritic, fluvial channel sandstones of the Malagash Formation are interbedded with red floodplain deposits. Some have been subjected to apparently early diagenetic, top-down oxidation. Others, separated from the overlying redbeds by grey-black mudstones and siltstone have not been so affected. One example of the latter at Canfield Creek may be a late Carboniferous analogue of a cupriferous swamp in which a sandstone unit directly underlying the swamp muck has trapped copper introduced by upward-moving groundwater. Thus, a new guide to extensive redbed copper deposits in Carboniferous alluvial formations with red floodplain deposits might be extensive swamp deposits overlying reduced channel sandstones. Modern cupriferous swamps lie close to pre-existing copper mineralization (Boyle, 1977). This implies that there may be a preexisting copper deposit beneath the Canfield Creek deposit, perhaps associated with the Boss Point Formation or the contact between the Horton and Windsor groups.

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Geology of Fogo Island, Newfoundland – a study of the form and emplacement of igneous intrusions

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Abstract: The Siluro-Devonian Fogo Batholith forms a density-stratified, sill-like body within the Silurian Fogo Harbour Formation. Passive emplacement of composite gabbro-rhyolite dykes and rhyolite sills preceded and facilitated emplacement of the main batholith, which was accompanied by eruption of extensive rhyolite ignimbrites of the Brimstone Head Formation. Composite dykes, synplutonic dykes, and sequences of non-intrusive sheets of contrasting composition and texture demonstrate that mafic and salic components of the batholith coexisted as magmas. Complex mafic-salic relationships and local agmatization probably resulted from convection during emplacement. Extreme scarcity of pegmatites, quartz veins, and alteration indicate relatively dry magma, greatly reducing the economic potential of the batholith, except as a possible source of dimension stone. Emplacement preceded final juxtaposition of the Botwood and Indian Islands belts along the Dog a Line and occurred during late folding of the Botwood Belt.

Résumé : Le Batholite de Fogo du Silurien-Dévonien constitue un amas en forme de filon-couche à stratification par densité au sein de la Formation de Fogo Harbour du Silurien. La mise en place passive de dykes de gabbro-rhyolite et de filons-couches de rhyolite a précédé et facilité l'emplacement du batholite principal, ce qui a été accompagné de l'éruption d'ignimbrites rhyolitiques de grande étendue de la Formation de Brimstone Head. La présence de dykes composites, de dykes synplutoniques et de séquences de nappes non intrusives de composition et de texture contrastantes indique que les composantes mafiques et saliques du batholite ont coexisté comme magmas. Les liens mafiques-saliques complexes et l'agmatitisation locale sont probablement le résultat de la convection durant la mise en place du batholite. L'extrême rareté des pegmatites, des filons de quartz et de l'altération indique que le magma était relativement sec, ce qui réduit grandement le potentiel économique du batholite, sauf comme source possible de pierre de taille. La mise en place du batholite a précédé la juxtaposition finale des ceintures de Botwood et d'Indian Islands le long du linéament de Dog Bay et ce, durant le plissement tardif de la ceinture de Botwood.

INTRODUCTION

Fogo Island, at the the northeast termination of the Appalachian Orogen in North America, consists mainly of epizonal salic and mafic igneous rocks of the Siluro-Devonian Fogo Batholith (Baird, 1958). Previous investigations of the batholith (Baird, 1958; Cawthorn, 1978; Aydin et al., 1994; Sandeman and Malpas, 1995) paid little attention to the form and mechanism of emplacement of the igneous rocks. Current remapping suggests that these factors are a key to understanding the relation of the igneous components to each other, to the supracrustal rocks, and to the rest of the Botwood Belt (Williams, 1995) and the Appalachian Orogen in general.

DESCRIPTION OF UNITS

Figure 1 is a geological map of Fogo Island (2E/9), revised and corrected from the map of Baird (1958). The island consists of the Fogo Batholith, which includes granitic, intermediate and mafic rocks, and host clastic and volcanic rocks of the Silurian Botwood Group (Williams, 1964). Excellent exposures on the seacoast and rocky barrens in the northern part of the island, can be easily reached via highway and boat. A thin cover of southerly derived rocky till is present throughout the island. Numerous string and peat bogs, patchy boreal forest, and thickets of dwarf spruce and birch ("tuckamore") obscure bedrock in the southern part of the island.

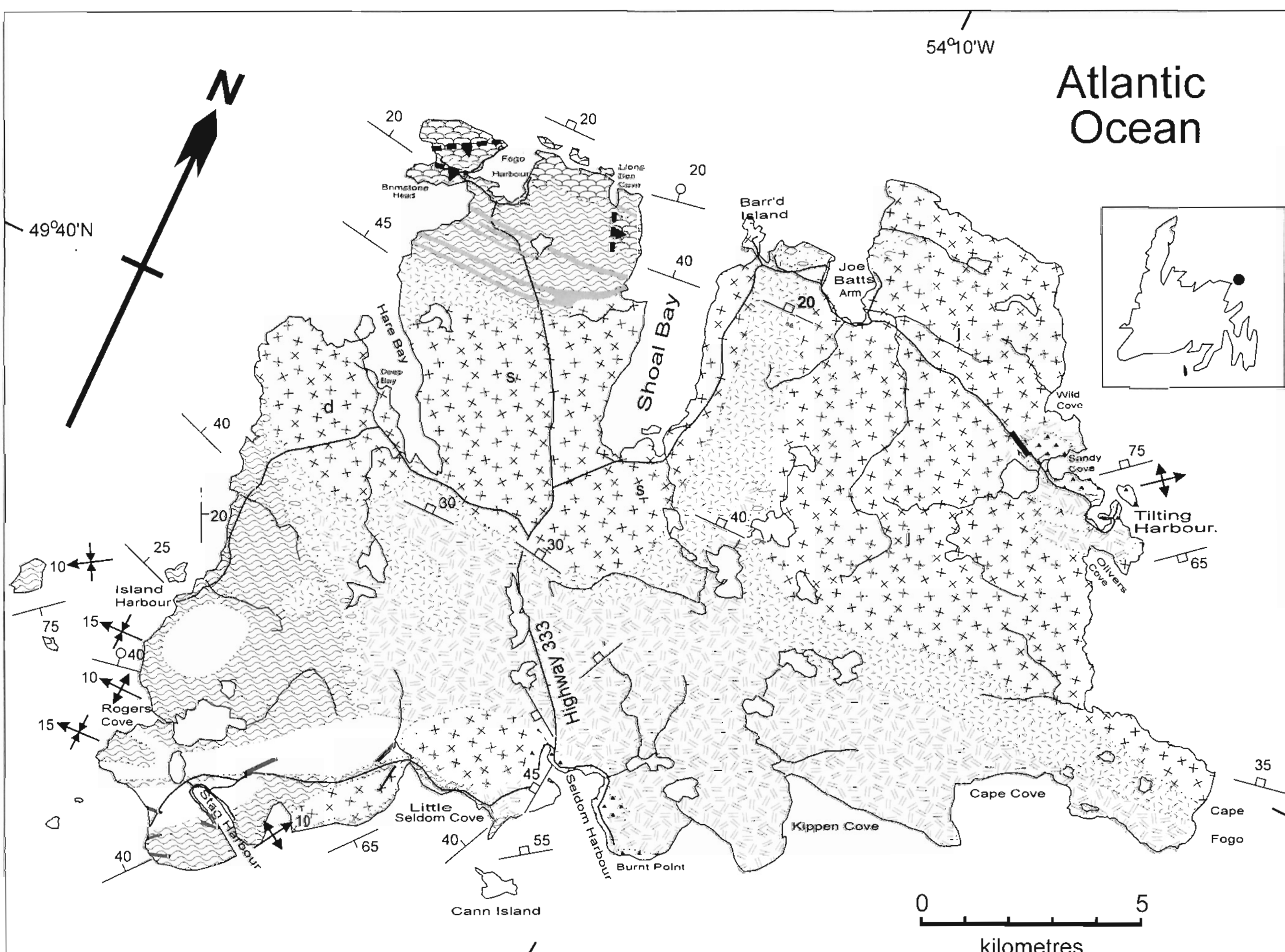

Figure 1. Geological map of Fogo Island, Newfoundland. (after Baird, 1958, as revised by K.L. Currie, 1996). The inset map shows the position of Fogo Island relative to the main island of Newfoundland.

Botwood Group

The Botwood Group on Fogo Island comprises siltstone, sandstone, and matrix-supported conglomerate of the Fogo Harbour Formation, and overlying rhyolite ignimbrites, rhyolitic tuff, and rare tuffaceous sandstone of the Brimstone Head Formation.

Fogo Harbour Formation

Outcrops of Fogo Harbour Formation, defined by Baird (1958), occur throughout the western half of the island, but a substantial thickness of the formation is found only around Rogers Cove, Stag Harbour, and Fogo Harbour (Fig.1). The formation consists mainly of pale green and brown siltstone and quartz-rich buff sandstone with subordinate amounts of tuffaceous rocks and conglomerate. South of Fogo Harbour a monoclinal succession suggests a thickness of at least 1300 m for the formation, with the base unexposed. The base of the formation may be exposed on Cann Island where thinly laminated siltstone is intercalated with basalt and rhyolite tuff of the Lawrenceton Formation of the Botwood Group. The top of the formation is well exposed at Brimstone Head, where it is conformably overlain by rhyolite ignimbrite of the Brimstone Head Formation. Much of the Fogo Harbour Formation consists of monotonous grey-green siltstone and sandstone with beds from 5 to 30 mm thick which locally are ripple marked, channeled, and crossbedded. Rare, conglomerate beds 1 to 2 m thick contain up to 20 volume per cent of centimetre to metre-scale sedimentary fragments in an almost massive, pale olive sandstone matrix. These beds occupy metre-scale erosive channels in underlying strata, suggesting formation by slumping and homogenization of thinner-bedded sections. Around Fogo Harbour and Rogers Cove, tuffaceous siltstone beds contain felsic lapilli and feldspar debris. All exposures of the Fogo Harbour Formation have been hornfelsed to some degree. Intense hornfelsing can be recognized by orange to pink weathering colour. Strata commonly dip north at 15 to 45°, but open folds without axial plane cleavage are common.

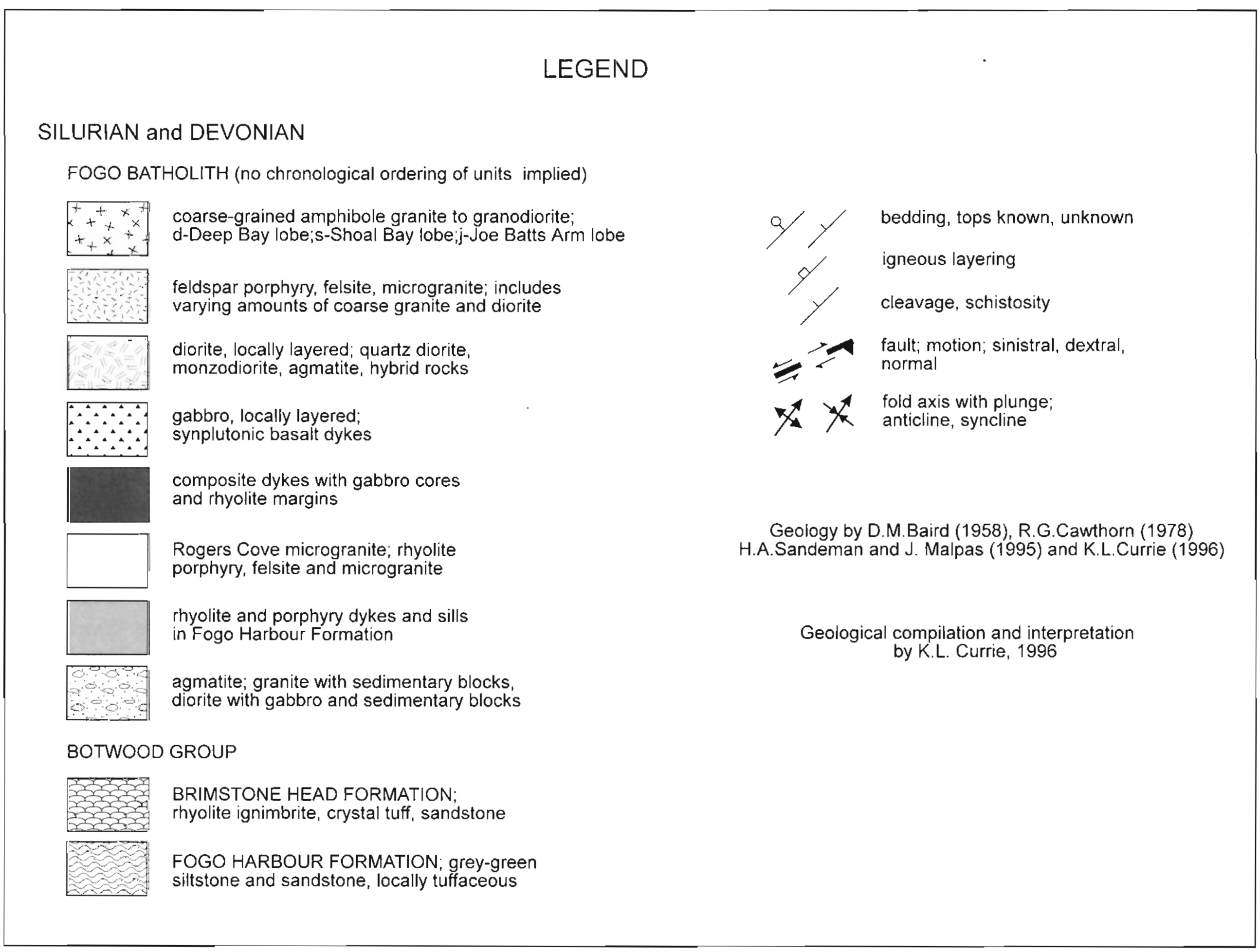

Figure 1. *Legend*

Brimstone Head Formation

The Brimstone Head Formation (Baird, 1958) conformably overlies the Fogo Harbour Formation, forming a narrow belt across the northern part of Fogo Harbour. All of the smaller islands from Fogo northeast to Little Fogo also consist of Brimstone Head Formation. The thickness of the formation is uncertain because the top is unknown, and the rocks may be openly folded like the underlying Fogo Harbour Formation. However, the formation outcrops across a belt at least 10 km wide with consistent northerly dips around 30°. On Fogo Island the rocks consist almost entirely of rhyolite ignimbrite sheets, with minor amounts of coarse felsic tuff, tuff breccia, and tuffaceous sandstone. Elongate pale streaks (up to 2 to 3 cm in length by several millimetres wide) of less welded material (fiamme) define layering in the ignimbrite sheets. West of Lions Den Cove three sheets can be defined by colour and texture variation. The central parts of the sheets are very densely welded, essentially massive and featureless rhyolite, whereas the margins contain thin, discontinuous zones of tuff and tuff breccia. The rhyolite exhibits strong vertical jointing, similar to that in rhyolite dykes and sills in the Fogo Harbour Formation. Moderately welded crystal tuffs and tuff breccias occur at the entrance to Fogo Harbour, and on the offshore islands to the north. Sedimentary rocks occur at the north foot of Brimstone Head, where a few metres of strongly feldspathic green sandstone are interbedded on centimetre scale with coarsely fragmental pink, salic tuff beds, and on offshore islands where a few thin lenses of red sandstone are present. East-northeast- trending faults with south-side-down offsets control outcrop of the formation in the Brimstone Head area.

Fogo batholith

The Fogo Batholith underlies 80 per cent of Fogo Island (about 250 km^2), and underlies two small islands about 8 km offshore to the east and southeast. The eastern termination is unknown. The batholith comprises eight mappable lithologies: (1) agmatite containing sedimentary blocks in an igneous matrix, (2) rhyolite dykes and sills in the Fogo Harbour Formation, (3) a distinctive rhyolite porphyry and microgranite (Rogers Cove porphyry), (4) composite dykes with gabbro cores and rhyolite margins, (5) gabbro with synplutonic mafic dykes, (6) a diorite complex, including monzodiorite, quartz diorite, agmatite and hybrid rocks, (7) microgranite, feldspar porphyry and felsite, and (8) medium- to coarse-grained amphibole granite. Field relations demonstrate that these units overlap in age. Fryer etal. (1992) reported a Rb-Sr isotopic age of 412 Ma for the Fogo Batholith.

Agmatite

North and east of Island Harbour, across the mouth of Joe Batts Arm, east of the southern part of Shoal Bay, and around Little Seldom, agmatite consists of 50 to 75 per cent hornfelsed blocks of Fogo Harbour Formation in a medium- to coarse-grained granitic matrix. The blocks become larger and more coherent with distance from the granite contact, and agmatite passes into irregularly folded sedimentary rocks with a few granite dykes and veins. Within 50 m of the granite contact, centimetre-scale beds are broken up in a surrounding homogeneous, aphanitic host which appears to be an in situ partial melt. Despite intense hornfelsing, and possibly local partial melting, new mineral growth in the hornfels is extremely rare. In a few places, notably the Anglican cemetery in Barr'd Island, some fine-grained biotite is present in siliceous metasediments, but this is the only known example of neoblastesis, suggesting that heating and cooling took place rapidly enough that equilibrium was not attained. The marginal agmatite zone at Little Seldom is one of the few localities on Fogo Island where there is a clear, crosscutting contact. The agmatite zone cuts bedding at an angle of about 40°.

Rhyolite dykes and sills in the Fogo Harbour Formation

Rhyolite dykes and sills abound on the Fogo Peninsula. All strike sub-parallel to the host rocks, but the sills are concordant whereas the dykes tend to dip perpendicular to bedding. The dykes and sills consist of very fine-grained pink to green rhyolite with sparse feldspar phenocrysts. At least four porphyry dykes, 10 to 50 m in width, pass into sills. A fine example occurs in the Anglican cemetery south of Fogo, where both intrusive dike contacts are exposed on the south side, and the upper conformable sill contact is exposed on the north side of the cemetery. The dike-sill transition, which can be mapped because the dykes form prominent rock ridges, may be preserved due to thickening of the erosionally resistant igneous body at this point. Sandeman and Malpas (1995) interpreted the sills as ignimbrites, but their intrusive nature is indicated by: (i) equal and intense hornfelsing of the host on both sides of the sill, and (ii) presence of laminated siltstone on both sides with no increase of tuffaceous material.

Rogers Cove microgranite and porphyry

The Rogers Cove microgranite (Sandeman and Malpas, 1995) forms sills and dykes of pink quartz-feldspar porphyry in the Fogo Harbour Formation around Rogers Cove. Some bodies are large enough to map separately, but many smaller bodies occur in the same region. Pink feldspar and quartz phenocrysts up to a millimetre across occur in a fine-grained to aphantic matrix which is locally spherulitic and flow-banded. Mafic minerals (amphibole, minor biotite) are commonly sparse and small, but in a few cases form thin seams, or clots up to a centimeter in diameter.

Composite gabbro-porphyry dykes

Composite dykes up to 60 m thick occur in quarries and on the shore from Little Seldom Cove to Stag Harbour. These dykes comprise a gabbro core up to 30 m wide with rims of quartz-feldspar porphyry up to 20 m wide. Many dykes strike parallel to the host rock, but dip perpendicularly. Gabbro exhibits a narrow chilled margin against the porphyry, rarely more than 10 cm wide, and the core of the gabbro has crystals up to 3 mm long. The gabbro, commonly plagioclase-porphyritic, may contain zones of pink potassium feldspar as fragments or rounded masses resembling ocelli (Aydin et al., 1994), and commonly exhibits visible development of epidote and chlorite. Porphyry rims have a sharp, planar contact against the central gabbro, but vein and stope sedimentary host rocks, against which they display chilled, aphanitic rims up to a metre thick. In a quarry 2 km northeast of Stag Harbour, a composite dike passes into a sill of porphyry. The gabbro core ends in blunt fingers.

Gabbro

Mafic and intermediate plutonic rocks occur as a large crescentic mass occupying much of the southeast shore of the island, and as a separate mass around Tilting Harbour. Both consist of relatively small cores of gabbro, locally layered and commonly foliated, surrounded by thick shells of "diorite" which can vary from leucogabbro through diorite and quartz diorite to monzodiorite. Mafic dykes, most of them visibly boudined and altered, form a significant component of diorite and gabbro phases east of Seldom Harbour.

Gabbro occurs as small ovoid masses around Tilting and Seldom harbours. The larger of two masses at Tilting Harbour is about 1.5 km long by 0.8 km wide. (Cawthorn (1978) incorrectly showed this body as much larger, including the surrounding shell of diorite as part of the gabbro). The smaller body is about 500 m by 200 m in size. Both consist of ortho- and clinopyroxene, variably overgrown by hornblende, plagioclase, and either minor olivine or magnetite plus quartz. Ubiquitous mineral alignment foliation, commonly striking about 080° and dipping 75° to the northwest, is overprinted by large poikilitic pyroxene, variably converted to amphibole, giving the rock a characteristic blotchy appearance. Cawthorn (1978) studied well-developed sequences of decimetre to metre-scale layers with sharp, non-intrusive contacts ranging from basal pyroxene-rich gabbro (websterite) through gabbro to hornblende-plagioclase pegmatite. Gabbro grades into coarse-grained, unfoliated hornblende-plagioclase rocks which in turn grade to other lithologies of the diorite complex. Around Seldom Harbour, a well exposed gabbro body at Burnt Point contains about 10 per cent mafic dyke fragments up to 2 m wide and 5 m long. The gabbro is abruptly truncated at the Burnt Point light by a north-trending leucodiorite dyke at least 50 m thick. Gabbro pods are exposed on the road near the Anglican church and near the turnoff from Highway 333. The latter occurrence, several hundred metres in width, exhibits lithological variation from leucogabbro on the south to pyroxene-rich rocks on the north. Individual gabbro outcrops were noted within the diorite complex, but due to poor outcrop, it is uncertain whether they represent sizable pods, or large blocks within agmatite. Gabbro consistently contains a low tenor of disseminated pyrrhotite, of the order of 2 to 5 per cent.

Gabbroic compositions are common within dykes and in a complex of mafic sheets exposed along Little Seldom Cove. Dykes and sheets comprise both plagioclase-porphyritic and aphyric varieties. Some plagioclase-porphyritic dykes and sheets strikingly resemble both the gabbroic portion of composite gabbro-rhyolite dykes, and gabbroic lithologies exposed within pods at Seldom Harbour. Gabbroic lithologies, including distinctive plagioclase-porphyritic varieties also occur as synplutonic dykes and boudins within the coarse-grained granites.

Diorite

The diorite complex is the most variable unit of the Fogo Batholith on both large and small scale. Some dioritic rocks have coarse, massive textures comparable to those of the gabbro and granite, but large exposures invariably include patchy, inequigranular textures, streaks of one lithology in another, and schlieren and blocks of more mafic lithologies. Agmatite containing approximately equal amounts of mafic blocks in a more salic matrix forms a major part of the diorite complex. In coastal exposures at Tilting Harbour and from Cape Fogo to Kippen Cove, the massive, homogeneous matrix and some mafic blocks exhibit intimate amoeboid interfingering, and pillow-like masses of one within the other, strongly suggestive of coexisting magmas. The matrix of agmatites appears to be consistently more potassic and coarse-grained than surrounding homogeneous rocks. The dioritic complex includes compositions from gabbroic through hornblende-plagioclase rocks to quartz diorite and varieties rich in potassium feldspar ranging from monzodiorite to syenite. Rocks geographically close to gabbro tend to be more mafic, whereas those close to granite tend to be more salic. Changes are, in general, gradational, although indistinct streaks and schlieren of contrasting lithologies are common. Rocks rich in potassium feldspar commonly have a patchy, inequigranular texture with polycrystalline areas of feldspar up to a centimetre across surrounded by coarse, altered amphibole, in turn surrounded by a finer-grained, more dioritic matrix. Some dioritic rocks show excellent layering, particularly in the Seldom-Little Seldom area where the layering defines a syncline-anticline pair. Much of the interior part of the diorite complex comprises locally homogeneous, fine- to medium-grained, granoblastic, hornblende-plagioclase rocks with variable but minor amounts of clinopyroxene, quartz, and potassium feldspar. Many of these rocks exhibit traces of epidote-rich healed fractures. Near the diorite-granite contact, diorite and granite are typically observed in alternate outcrops, or in small adjacent areas with few visible contact relations. Baird (1958) and Sandeman and Malpas (1995) concluded that the granite cuts the diorite. However granite and diorite form well-exposed, conformable, non-intrusive sheets at Hare Bay, in a large quarry on Highway 333, and at Cape Fogo and Cape Cove. Agmatite is typical of the diorite complex, not of the diorite-granite contact. In the examples mapped by Baird (1958) at Wild Cove, Cape Fogo, Kippen Cove and Little Seldom Cove, the matrix is leucodioritic, not granitic as shown by Baird (1958). These relations suggest a generally non-intrusive, essentially gradational or interlayered granite-diorite contact. This conclusion simplifies the map pattern, since small areas of "granite" (which commonly also include dioritic lithologies) shown by Baird (1958) can be grouped with the diorite complex.

Felsite and porphyry

Felsite and porphyry occur in a continuous zone stretching from Cape Fogo to the west side of the island, with two apophyses near Barr'd Islands and Hare Bay separating coarse-grained granite into distinct lobes. The felsite-porphyry zone contains about 65 per cent felsite, with the rest composed of coarse-grained granite, diorite, and large sedimentary agmatite enclaves. Felsite and porphyry occur as lenses up to 100 m wide and 1.5 km long which trend 110° (i.e. at an angle of about 70° to the trend of the apophyses of the zone) and have abruptly gradational contacts over less than a centimetre into coarse-grained granite. Felsite typically is buff to pink, fine-grained, and uniform, without obvious phenocrysts, but contains centimetre-scale, roughly equant, aggregations of fine-grained amphibole which may form 2 to 5 per cent of the volume. Similar aggregations occur as joint fillings. Sandeman and Malpas (1995) ascribed these phenomena in the Rogers Cove microgranite to late deuteric processes in a fluid-rich magma. Amphibole masses are associated with ilmenite-hematite aggregations and rarely titanite and zircon, according to Sandeman and Malpas (1995). North of Hare Bay a curving, kilometre-thick zone of felsite is in sharp contact with Fogo Harbour Formation, with virtually no dyking of the sedimentary section and few inclusions of sedimentary rocks in the felsite. Along Hare Bay the proportion of medium- and coarse-grained granite gradually increases southward as nebulous patches of brown-weathering amphibole leucogranite (Sandeman and Malpas, 1995). Most of the contact between the felsite zone and the diorite complex is poorly exposed, but quarry exposures and natural exposures on Cape Fogo show that felsite and diorite sheets occur in coarse-grained granite without obvious intrusive contacts. Felsite forms irregular lenses within granite along the granite-agmatite contact north of Island Harbour.

Amphibole granite and granodiorite

Coarse-grained granite of the Fogo Batholith occurs in three distinct lobes, here termed the Deep Bay, Shoal Bay, and Joe Batts Arm lobes. All consist of medium- to coarse-grained amphibole granite with minor biotite. The Shoal Bay lobe is feldspar-porphyritic, and contains 1 to 2 per cent of mafic inclusions up to 5 cm across. The Deep Bay and Joe Batts Arm lobes are more equigranular, approaching granoblastic texture, and mafic inclusions are rare. None of the lobes contains significant pegmatites or quartz veining. The Deep Bay lobe weathers to a reddish brown or olive shade, while the Shoal Bay lobe weathers grey to pale buff, and the Joe Batts Arm lobe tends to pink or grey shades and shows more colour variation than the other lobes. All three lobes are locally very homogeneous, but become more potassium feldspar-rich and leucocratic to the northwest. Normally this change is gradational, but at the southeast corner of Shoal Bay, a pink leucocratic phase intrudes a grey, slightly more mafic-rich phase as veins up to 20 cm wide. All three lobes contain synplutonic mafic dyke segments with chilled margins, commonly 1 to 2 m wide and 5 to 10 m long, including plagioclase-porphyritic varieties typical of the composite rhyolite-gabbro dykes. In some cases a chain of boudins, separated by a few metres of granite, marks the former course of the dike. Only the Shoal Arm lobe is in direct contact with supracrustal rocks. The sedimentary rocks are strongly hornfelsed, but neither agmatite nor granitic veining is present. The granite does not display a chill zone, and contains few sedimentary inclusions. East of Highway 333, the granite cuts both sedimentary rocks and a complex of rhyolite dykes and sheets. At the contact, granite displays slightly finer grain size, contains nebulous inclusions of rhyolite, and exhibits a crude sheeting parallel to the attitude of the supracrustal rocks. The Shoal Bay lobe displays prominent southeast-trending, joints spaced 10 to 20 m apart, which locally parallel a mineral alignment foliation. The southern boundary of the Shoal Bay lobe against the felsite zone and diorite complex, displayed in a large quarry on Highway 333, consists of east-trending, north-dipping sheets of felsite, granite and diorite up to 20 m thick across a zone about 300 m wide. The proportion of diorite increases to the south. Contacts in this zone are sharp, but not intrusive. The Deep Bay and Joe Batts Arm lobes have sharp, non-intrusive contacts with agmatite. The coarse-grained lobes contact one another within the felsite zone, but the contacts cannot be recognized on the ground, and are therefore assumed to be gradational. No contact relations were observed between granite and gabbro because diorite consistently separates the two lithologies. A few centimetre-scale veins or pods of alaskite cut the gabbro, but these bodies appear unrelated to the major granite. Granite is in contact with gabbro along a small fault exposed in the ditch of the road to Tilting. The granite is sheared and reddened with development of minor white mica and a low tenor of pyrite mineralization. This occurrence and a similar one along a rhyolite dyke in the Fogo Peninsula, are the only known examples of hydrothermal alteration on Fogo Island.

ECONOMIC GEOLOGY

Extreme rarity of pegmatites and quartz veins, and alteration restricted to minor development of epidote and chlorite suggest that the Fogo Batholith was an exceptionally dry body. Minor sulphide mineralization occurs in gabbro and diorite, and in shears in granite and rhyolite on the north contact of the batholith. Local residents pointed out pits sunk for copper exploration near Stag Harbour and Lions Den Cove. There is no visible mineralization in these areas now. The Fogo Batholith, particularly the Shoal Bay lobe, offers possibilities for quarrying dimension stone from large volumes of homogeneous rock with a range of colours from black and grey through buff to rose. The felsites are favoured by the Department of Transportation for road metal because close jointing produces small fragments suitable for gravel.

FORM OF THE FOGO BATHOLITH

The Fogo Batholith is sill-like in form, exhibiting bed-parallel contacts against the same host on both northern and southern margins. Where the batholith exhibits layering, it is generally conformable with bedding in nearby sedimentary rocks. Small scale related intrusions, such as the Rogers Cove microgranite and the complex of sheets along Little Seldom

Cove are also sills. Assuming an average dip of 30°, as suggested by layering and attitudes of bedding, the mafic part of the batholith would be about 2 km thick, while the salic part would be 4-6 km thick, giving a total thickness for the batholith of 6-8 km.

Layering in gabbro and diorite sills around Little Seldom and Seldom defines an open anticline-syncline pair which reflects structure in the Fogo Harbour Formation, and, in subdued form, regional-scale cylindrical folds of the Botwood Belt (Currie, 1995). Field and chemical evidence (Malpas and Sandeman, 1995) strongly suggest that the top of the batholith was erupted as ignimbrite sheets of the Brimstone Head Formation. Since this formation is clearly involved in regional folding, both internal structure of the batholith and relations with its host suggest emplacement during regional folding.

The Dog Bay Line (Williams et al., 1994), a Silurian terrane boundary which truncates both Botwood Group and regional folds south of Fogo Island, must therefore be younger than the Fogo Batholith, and the observation of Williams et al. (1989) that Fogo-type complexes are confined to the Exploits Subzone receives a natural explanation. This conclusion suggests that the Dog Bay Line passes through the Wadham Islands, about 10 km south-southeast of Cape Fogo where Copper Island is an extension of the mafic rocks of the Fogo Batholith, while the adjoining White Island is megacrystic granite typical of the Indian Islands Subzone.

The batholith shows strong differentiation, with mafic rocks at the structural base, and salic rocks at the top. (The isolated occurrence of mafic rocks at Tilting Harbour can be explained as a local antiformal upwarp.) Field relations clearly show that salic and mafic components of the batholith were simultaneously mobile. The stratified character must therefore represent a feature preserved or created during intrusion. The orientation of the mafic-salic relations strongly suggest density layering.

MECHANISM OF EMPLACEMENT

The Fogo Harbour Formation displays remarkably constant, systematic dips, and clearly did not founder into the underlying magma. Dykes consistently dip perpendicular to the trend of bedding, even where dykes form 25-50% of the section. Although the sedimentary rocks are hornfelsed, they have not developed metamorphic minerals. These data indicate a passive yet rapid mode of emplacement for sills and dykes in the Fogo Harbour Formation. The roof must have been constantly supported, yet rapidly stretched to form and extend tensile fractures sufficient to accomodate the dykes. Given the rapid cooling indicated by hornfelsing without major new mineral growth, and the lack of rotation of sedimentary blocks, emplacement of the sills probably occurred by lifting of the roof. The common occurrence of composite sills of microgranite and gabbro south of the batholith strongly suggests that much of the thermal energy for intrusion derived from the mafic rocks. The lack of mafic material north of the batholith can be ascribed to a higher position in the sedimentary section, such that dense mafic magma could not rise to this level. Coarse-grained granite cuts rhyolitic dykes and sheets both north and sorth of the batholith. Dyking and sheet emplacement therefore represent an early phase of emplacement, which established both a style of emplacement and a zone sufficiently heated to allow emplacement of a large body. This preliminary process probably culminated in eruption of the Brimstone Head Formation.

The main batholith forms a density stratified body, reflecting some combination of gravitational settling and crustal anatexis above a mafic mantle-derived magma. Settling clearly formed layers in the gabbro, but cannot account for the complex mafic-salic relations. Hot mafic rocks at the base of a layered body should produce convective overturn in the overlying salic fraction, which could account for the development of sheeted, hybrid and agmatitic rocks at the junction of mafic and salic portions, and also for the separation of the granitic phase into lobes. On this model the felsite zones separating the lobes represent sinking, chilled material on the margins of convection cells, a speculation supported by the common presence of large sedimentary rafts in these zones. In a slightly different context, convection could also account for the presence of basal agmatite zones, where relatively rapidly moving hot magma was brought directly in contact with the sedimentary host, providing sufficient mechanical and thermal energy for large scale breakup of beds.

DISCUSSION

The conclusions of this study conflict with a recent paper by Sandeman and Malpas (1995), which assumed that the batholith was post-tectonic, that salic, water-rich phases intruded mafic ones, and that the Fogo Batholith could not be directly compared to the bimodal Mount Peyton complex because some of the granitic rocks of the Fogo Batholith have A-type affinities. As documented above, field observations clearly indicate that emplacement of the batholith preceded final juxtaposition of the Botwood and Indian Islands belts along the Dog Bay Line and probably occurred during late folding of the Botwood Belt. Composite dykes, synplutonic dykes, and layered, non-intrusive contacts between salic and mafic fractions refute the assumption, introduced by Baird (1958), that the salic components generally intrude the mafic ones. The relatively dry character of the Fogo Batholith is amply attested by the almost total lack of pegmatites, quartz veins, and hydrothermal alteration, as well as lack of miarolitic cavities and explosive volcanism. A-type granites can be generated by partial melting of a crust from which an orogenic granite has been previously extracted (Whalen et al., 1987), a probable situation in the Botwood Belt, as noted by Currie (1995), or directly from mantle melts. The value, or lack of it, of comparison of the Fogo Batholith with the Mount Peyton complex is therefore independent of the presence of such rocks within the batholith.

ACKNOWLEDGMENTS

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Geological Survey of Canada Project 730044

A note on the geology of Change Islands, Newfoundland

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Currie, K.L., 1997: A note on the geology of Change Islands, Newfoundland; in Current Research 1997-D; Geological Survey of Canada, p. 51-55.

Abstract: Change Islands provide a cross-section through an asymmetric anticline involving the Botwood and Badger groups of the Botwood Belt. Rhyolite, probably correlative to the upper Caradoc Baytona Formation, forms the core of the anticline, overlain by turbidites of the upper Ordovician-lower Silurian Badger Group ("Sansom greywacke"), which are in turn unconformably overlain by bimodal volcanic rocks of the Llandovery Lawrenceton Formation. The upper part of these volcanic rocks is interlayered with and grades into cross-bedded sandstone of the Fogo Harbour Formation, which in turn grades by increase in proportion of rhyolite debris and sheets into the latest Silurian Brimstone Head Formation. The anticline is disrupted by dextral normal faulting parallel to the main east-northeast-trending, south-dipping cleavage, and by sinistral normal faulting on a subordinate north-northeast-trending cleavage. These late normal faults probably represent relaxation after folding and thrusting.

Résumé : Les îles Change comportent une coupe au travers d'un anticlinal asymétrique touchant les groupes de Botwood et de Badger de la ceinture de Botwood. Une rhyolite, que l'on peut vraisemblablement mettre en corrélation avec la Formation de Baytona du Caradocien tardif, forme le noyau de l'anticlinal, sur lequel reposent des turbidites du Groupe de Badger de l'Ordovicien tardif-Silurien précoce («grauwacke de Sansom»), qui sont à leur tour recouvertes en discordance de roches volcaniques bimodales de la Formation de Lawrenceton du Llandovérien. La partie supérieure de ces roches volcaniques est interstratifiée de grès à stratification oblique de la Formation de Fogo Harbour et y fait place. La Formation de Fogo Harbour passe à son tour par proportion croissante de débris et de nappes de rhyolite à la Formation de Brimstone Head du Silurien terminal. L'anticlinal est perturbé par des failles normales dextres parallèles au clivage principal à inclinaison sud et à direction est-nord-est, et par des failles normales senestres sur un clivage subordonné à direction nord-nord-est. Ces failles normales tardives représenteraient un relâchement qui a suivi le plissement et le chevauchement.

INTRODUCTION

The Change Islands (2E/9) comprise a north-trending archipelago of two major and numerous minor islands lying about 4 km east-northeast of the main island of Newfoundland (Fig.1). Together with the Dog Bay Islands to the south, they comprise an almost complete cross-section across the Botwood Belt of northeast Newfoundland (Williams et al., 1995) from the Dog Bay Line (Williams et al., 1994) to the Reach Fault. Since other parts of this belt are not well exposed, and stratigraphic relations between the Botwood Belt and the adjacent Badger Belt (Williams et al., 1995) are not completely defined, this cross-section is important for understanding upper Ordovician and lower Silurian stratigraphy in northeast Newfoundland.

The Change Islands were systematically mapped by Baird (1958), whose work was converted into contemporary stratigraphic nomenclature by Williams (1964). The islands were the subject of a detailed study by Eastler (1969), and were briefly examined by Williams (1993). The islands were remapped in 1996 to complete systematic remapping of the east half of NTS 2E map area (Currie, 1995).

Williams (1993) pointed out that the Change Islands represent a section across a major anticline which contains typical distal turbidites of the Badger Group ("Sansom greywacke") in its core. These turbidites provide a stratigraphic link to New World Island across the Reach Fault. The present work, while generally confirming the conclusions of Williams (1993), shows that the anticlinal structure is more complex than he envisaged, and that rocks older than the Badger Group are exposed.

DESCRIPTION OF UNITS

The strata of the Change Islands can be assigned to five middle Ordovician to late Silurian units; the middle Ordovician Baytona Formation (Currie, 1994), the upper Ordovician-lower Silurian Badger Group (Williams et al., 1995), and three formations of the Silurian Botwood Group, namely the Lawrenceton, Fogo Harbour, and Brimstone Head formations.

Baytona Formation

The oldest rocks, found in the core of the anticline around Red Rock Cove, comprise homogeneous rhyolite or porphyry consisting of pink weathering, grey-green salic rock in which rare, minute flakes of biotite can be distinguished in an unresolvable salic matrix. On weathered surface some specimens appear to have smeared, nebulous, millimetre-scale feldspar phenocrysts, but on fresh surface no crystals can be seen, possibly due to pervasive fine saussuritization. Eastler (1969) and Williams (1993) considered these rocks to form an intrusion younger than the Badger Group. However an exposure on the south shore of Red Rock Cove, about 200 m west of the highway near NTS grid reference 687950,5501910, displays north-facing turbidites resting on and facing away from the rhyolite, with fragments of rhyolite in the turbidites. No dykes or hornfels have been identified around the rhyolite, and despite the size of the body (almost 5 km^2), there is no variation in grain size. These data demonstrate that the Red Rock Cove body is older than the Badger Group, and strongly suggest that it is extrusive rather than intrusive. Farther southwest in the Botwood Belt, at Loon Bay, the unit underlying Badger Group is the Baytona Formation (Currie, 1994) consisting of rhyolite and chert capped by fossiliferous, mid- to upper Caradoc black shale and chert. The rhyolite at Red Rock Cove is therefore correlated with the Baytona Formation. The black shale portion of this formation appears to be included within the basal part of the Badger Group on Change Islands, as discussed below.

Badger Group

The rocks overlying the Baytona Formation consist of coarsening-upward, medial to distal turbidites. The base of the unit comprises siltstone and black shale laminated on a centimetre scale. Some of the shale is graphitic, reminiscent of the upper part of the Baytona Formation and the Dark Hole Formation of New World Island. However this material grades over about 10 m into turbidite beds 10-40 cm thick with graded brownish-green greywacke bases and thinly laminated, pale grey-green siltstone or shale tops, typical of material loosely termed "Sansom greywacke" by previous writers, but now assigned to the Badger Group of upper Ordovician to lower Silurian age (Williams, 1995). Eastler (1969) reported a Llandovery fauna from fossiliferous limestone boulders in Badger conglomerate on Change Islands. The bases of the turbidite units are both feldspathic and lithic, with a network of quartz gash veins. The beds, remarkably regular, face away from the Red Rock Cove rhyolite. Basaltic dykes and sills cut the beds, but there are no salic dykes or sills.

Botwood Group

Lawrenceton Formation

Bimodal volcanic rocks of the Lawrenceton Formation overlie the Badger Group. The contact is commonly faulted with most of the brecciation in the volcanic rocks, but near grid reference 686890, 5500210 about 10 m of the contact is preserved in the hanging wall of a fault. A conglomerate beneath the volcanic rocks contains blocks of both volcanic and sedimentary rocks in a matrix of disrupted and homogenized greywacke. Bedding in greywacke in the footwall of the fault strikes at an angle of about 20° to the fault, whereas in the volcanic rocks bedding is parallel to the fault. The other known exposure of this contact, at Port Albert about 10 km to the southwest (Williams, 1993), exhibits a frozen stratigraphic contact with bedding parallel above and below the contact.

The volcanic section consists of basaltic flows, breccia, agglomerate, and tuff as well as rhyolitic flows, agglomerate, conglomerate, and tuff, and lenses of laminated siltstone. Amygdaloidal, feldspar-porphyritic basalt flows with brecciated bases, and reddened, slaggy tops commonly form the basal part of the section. South of Red Rock Cove at least three flows can be distinguished. East of Red Rock Cove,

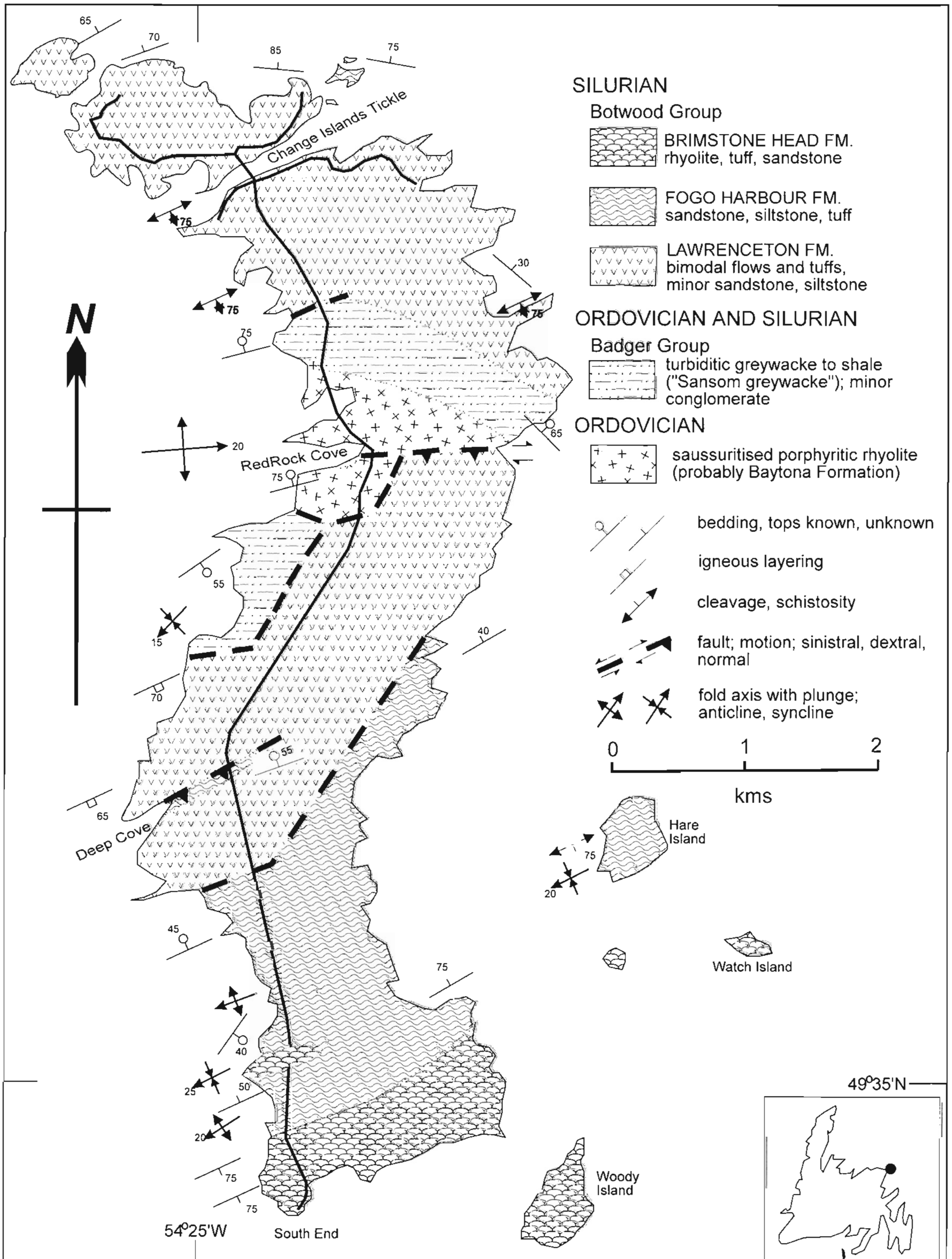

Figure 1. Geological map of Change Islands, Newfoundland (revised from Baird, 1958 and Eastler, 1969). The inset map shows the position of Change Islands relative to the main island of Newfoundland.

rhyolite may be in contact with the Badger Group, but exposure is poor due to widespread bog in this region. On the west side of the islands the volcanic section north of the Badger Group, estimated to be more than 3500 m thick, consists almost entirely of basalt. Flows can be identified along Change Islands Tickle, but much of the northern island consists of homogeneous basaltic tuff. South of Red Rock Cove and along the east side of the island salic volcanic rocks predominate, particularly spectacular red crystal tuff, tuff breccia, agglomerate, and conglomerate. Facing directions can locally be determined in this sequence from grading in tuffs. The conglomerate comprises angular blocks of rhyolite up to 50 cm in largest dimension in a red sandstone matrix, locally passing to lenses of red sandstone up to 10 m thick and 100 m long. In addition to the red sandstone, lenses of grey-green, finely laminated siltstone up to 10 m thick and 200 m long occur within the volcanic section south of Red Rock Cove. These lenses are lithologically identical to the Fogo Harbour Formation (Baird, 1958) as seen on Fogo Island (Currie, 1997), and contain no obvious volcanic material except a few pink ellipsoids up to 3 mm across.

The Lawrenceton Formation of the Botwood Group (Williams, 1964, 1972) overlies the Badger Group throughout the Botwood Belt. On the basis of fossil evidence collected 60 km southwest of Change Islands, the Lawrenceton Formation is considered to be of Llandovery age (Williams, 1972). On Change Islands the thickness of the formation approaches or excedes 3500 m, which greatly exceeds the thickness on the Port Albert Peninsula to the west or on islands south of Change Islands (Williams, 1993), suggesting that the Change Islands must be close to a vent area for the Lawrenceton Formation.

Fogo Harbour Formation

The Fogo Harbour Formation overlies the Lawrenceton Formation, apparently conformably although no exposed contact was found. The formation consists of intervals of crossbedded brown sandstone up to 10 m thick intercalated with intervals of similar thickness of grey-green siltstone bedded on centimetre scale. Similar thin-bedded siltstone forms intervals up to 10 m thick in the Lawrenceton Formation near Deep Cove, and forms much of the Fogo Harbour Formation on Fogo Island (Currie, 1997). Distinctive clast-poor, unsorted, matrix-supported conglomerate beds up to 2 m thick form about 5 per cent of the section. Similar beds occur in the formation on Fogo Island. Much of Fogo Harbour Formation contains no obvious volcanic material, but tuffaceous material in the form of millimetre-scale pink ellipsoids and larger clasts of rhyolite appears sporadically in individual beds throughout the formation. Such beds become more abundant and thicker toward the toward the top of the formation, producing a gradation to the overlying Brimstone Head Formation.

The Fogo Harbour Formation is younger than the underlying Llandovery Lawrenceton Formation and older than the overlying Brimstone Head Formation, thought to be of latest Silurian or earliest Devonian age (Currie, 1997). The Fogo Harbour Formation appears to be equivalent, in part, to the Llandovery Wigwam Formation (Williams, 1972) in the southwest part of the Botwood Belt.

Brimstone Head Formation

The Brimstone Head Formation conformably overlies the Fogo Island Formation. On Fogo Island the formation boundary is defined by appearance of thick, densely welded, rhyolite ignimbrite sheets. On Change Islands these sheets are either absent or thin and location of the boundary is difficult to establish. In this work the boundary is defined to be at the base of the lowest rhyolite sill. This definition is consistent with that used on the Port Albert Peninsula to the southwest (Currie, 1995), and also with that on Fogo Island if some of the "sills" turn out to be ignimbrite sheets.

The Brimstone Head Formation on Change Islands consists of tuffaceous sedimentary rocks and a complex of rhyolite dykes and sills occupying the southern tip of the islands. The bulk of the formation consists of tuffaceous brownish siltstone and sandstone containing abundant rhyolite fragments up to 30 cm across. Complexes of sills, dykes and possibly ignimbrite sheets occur in three places. In each case several (3 to 6) metre-scale sills are present over a width of about 20 m. Most rhyolite bodies have cross-cutting apophyses or are connected to crosscutting dykes, and hence are clearly intrusive. However some seem to be completely concordant and do not hornfels the surroundings. They could be distal ends of the thick ignimbrite sheets seen on Fogo Island. All of the igneous rocks consist of feldspar-porphyritic rhyolite with 5 to 10 per cent of millimetre-scale phenocrysts and sparse hornblende crystals in a deep pink, very fine-grained matrix. The Brimstone Head Formation is deduced to be the same age as the Fogo Batholith (412 Ma, Sandeman and Malpas, 1995), that is of latest Silurian or earliest Devonian age.

STRUCTURE

Change Islands provide a cross-section across a kilometre-scale, near-cylindrical asymmetric anticline plunging about 10-15° to the east, as noted by Eastler (1969) and Williams (1993). Dips and facings indicate that the structure is tight to almost isoclinal, and slightly overturned to the north. North of Red Rock Cove the structure appears to be simple and little disturbed, although minor folds with amplitudes of several tens of metres are present, and local presence of brittle shattering and minor dextral SC fabric indicates small-scale faulting. A well-developed cleavage strikes about 080° and dips 70-80° to the south. Eastler (1969) and Karlstrom et al. (1982) pointed out that although this cleavage is approximately parallel to the axial plane of the major fold, detailed cleavage-bedding relationships indicate that it crosscuts the fold, and must be younger. South of Red Rock Cove a number of smaller-scale open folds occur with limb dips of 20-50° and variable but gentle plunges, as first mapped by Baird (1958). The style of these folds resembles those on Fogo Island (Currie, 1997), but is quite different from the tight to isoclinal, asymmetric character of the major anticline. The reasons for this discrepancy are uncertain, but may be linked to presence of the competent Fogo Batholith a few kilometres to the east. Most of these folds trend more northeasterly than the major fold, and a steeply dipping cleavage with this trend is locally present.

A fault in Red Rock Cove oriented parallel to the main cleavage has a dextral offset of about 500 m, and the presence of a small patch of north-dipping and facing Badger Group on the south side of the fault indicates a south-side-down movement of at least this much. A small sliver of north-facing and north-dipping Fogo Harbour Formation juxtaposed against south-facing volcanic rocks in Deep Cove indicates a large south-side-down offset on a fault roughly parallel to that in Red Rock Cove, and local SC fabric indicates some dextral movement on this fault as well. To the south of the Red Rock Cove fault, the Badger Group is truncated by a fault trending north-northeast. Shearing and slickensides associated with this fault indicate that it dips steeply to the east, and involved late oblique east-side-down sinistral motion. The net result of these faults was to uplift the anticlinal core of Badger Group and underlying rhyolite.

DISCUSSION

As pointed out by Williams (1993), the presence of the Badger Group on Change Islands provides a stratigraphic link to New World Island, demonstrating that late faults such as the Reach Fault only locally disrupt the stratigraphy, rather than representing a terrane boundary. The presence of salic volcanic rocks beneath black shale of the Badger Group on Change Islands confirms the continuity of stratigraphy along the Botwood Belt, and suggests parallels with stratigraphy in the adjoining Badger Belt where the Badger Group is underlain by black shale (Dark Hole Formation) and by volcanic rocks of the Summerford Group (Currie, 1995; Williams et al., 1995). Southwest of Change Islands, the Reach Fault truncates the Botwood Group by slicing across kilometre-scale cylindrical folds at a low angle (Currie and Williams, 1995), but on Change Islands the Botwood Group forms S-folds which provide a large sinistral offset of the east-northeast-trending strata without faulting. Since these folds affect the uppermost Silurian Brimstone Head Formation, they must be late features, possibly related to the Reach Fault. These data suggest that the late sinistral deformation noted by Piasecki (1992) to the southeast also affects the Botwood Belt.

Faulting on Change Islands involves a large element of normal motion, an unusual condition in a region where faulting commonly involves dominantly thrust and transcurrent motions. As noted above, these normal motions occurred late in the tectonic history. They may represent relaxation after compression. Relaxation after orogeny has been little studied in this part of the orogen, but these features suggest that there may be a significant relaxation history.

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Geological Survey of Canada Project 730044

Application of laser microprobe inductively coupled plasma mass spectrometry for trace metal fingerprinting of native gold[1]

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Chen, Z., Doherty, W., Gregoire, D.C., and Harris, D., 1997: Application of laser microprobe inductively coupled plasma mass spectrometry for race metal fingerprinting of native gold; in Current Research 1997-D; Geological Survey of Canada, p. 57-62.

Abstract: Major, minor and trace elements in 60 native Au samples from across Canada were analyzed directly by laser ablation microprobe inductively coupled plasma-mass spectrometry (LAM-ICP-MS). Diameters of laser ablation craters ranged from 100 to 150 µm defining the smallest sample size determinable. The Au signal was used as an internal standard to correct for differences in ablation yields, matrix effects and signal drift during analysis. Analytical results obtained over a period of seven months for the synthetic Au alloy standard 501 demonstrated the long-term reproducibility of the method. The elemental signatures obtained from individual specimens have proven to be unique and reproducible, yielding data that can be used for matching "unknowns" with their source location.

Résumé : En combinant spectrométrie de masse, plasma à couplage inductif et microsonde d'ablation au laser, on a analysé la teneur en éléments majeurs, mineurs et traces de 60 échantillons d'or natif provenant de toutes les régions du Canada. Le diamètre des cratères d'ablation au laser variait entre 100 et 150 µm, définissant la taille du plus petit échantillon déterminable. Le signal de l'or a servi d'étalon interne pour corriger les différences dans les rendements d'ablation, les effets de la matrice et la dérive du signal durant l'analyse. Les résultats d'analyse obtenus pendant une période de sept mois pour l'étalon d'alliage d'or synthétique 501 ont mis en évidence la reproductibilité à long terme de la méthode. Les signatures élémentaires produites par les éprouvettes individuelles se sont avérées uniques, reproductibles et livrant des renseignements que l'on peut utiliser pour apparier les «inconnus» avec leur lieu d'origine.

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INTRODUCTION

Since the first report of Gray in 1985, the laser ablation microprobe has steadily gained in popularity as a technique for the direct sample introduction of solids into the inductively coupled plasma mass spectrometer (see balance of references). Sample introduction by laser ablation offers several advantages over conventional pneumatic nebulization including: fewer sample preparation steps involving the use of reagents and glassware; better control of sources of contamination; application to dissolution-resistant minerals; and elimination of some polyatomic interferences due to the presence of solvents. The laser sampling technique also provides for the spatial analysis of small selected areas on sample surfaces. Laser ablation microprobe inductively coupled plasma-moss spectrometry (ICP-MS) has been used for the direct solid sampling of a wide variety of materials including geological (Jackson et al., 1993; Chenery and Cook, 1993; Jarvis and Williams, 1993), metallic (Evans et al., 1994), biological (Kogan et al., 1994, Wang et al., 1994), nuclear (Crain and Gallmore, 1992) plastic (Marshall et al., 1991), environmental (Perkins et al., 1991), and glass (Denoyer, 1992), samples. More recently, Watling et al. (1994) applied laser ablation ICP-MS to the characterization of the trace element composition or "fingerprint", of selected Au samples from Western Australia and South Africa. This work, however, was primarily applied to the analysis of Au bullion samples. Also, major elements in the Au samples were not determined because signal intensities for these elements were beyond the range of the detector and drift, matrix effects, and changes in laser ablation yields were not accounted for in their report.

In this study approximately 60 Au ore samples from gold mines across Canada (obtained from the Geological Survey of Canada's National Mineral Collection) were analyzed directly by LAM-ICP-MS. The elemental fingerprint of a Au sample consists of the relative measured abundances of 61 major, minor, and trace elements which were monitored during the ICP-MS measurement. Our objective is to establish a database of elemental fingerprints of native Au samples and to develop methodology that could potentially be used to provide legal evidence in court cases involving mining claims, tracing Au samples, or to mineral exploration studies.

EXPERIMENTAL

Instrumentation

A Perkin-Elmer SCIEX Model 320 Laser Sampler was used in conjunction with the Perkin-Elmer ELAN Model 5000 ICP-MS. A Nd:YAG laser was operated in Q-switched mode with a fundamental wavelength of 1064 nm. Both the sample stage and the laser with its floor-mounted power supply were controlled by a personal computer. Optimization of plasma and mass spectrometer conditions was accomplished using solution nebulization sample introduction and aqueous standards. The signal intensity was optimized using NIST 610 glass. For each analytical run, the nebulizer gas flow was adjusted to 1.10 l min-1, using NIST 610 glass containing about 450 μg^{-1} of trace elements, so that: (1) $ThO^+/Th^+ < 0.5\%$; (2) sensitivity of La >40 (counts $sec^{-1}/\mu g^{-1}$), and (3) sensitivity of Th > 30 (counts $sec^{-1}/\mu g^{-1}$). ICP-MS and laser operating conditions are shown in Table 1.

Samples

Samples analyzed included Au ores, mineral mounts, thin sections, and slabs obtained from the National Mineral Collection and from several Au deposits under active study at the GSC. These samples were ablated directly, as received, without any further preparation prior to analysis.

Data Acquisition and Reduction

Analyte isotopes monitored and corresponding OmniRange settings used during data acquisition for the analysis of all samples and the synthetic Au alloy standard 501 (Squair and student, 1965; 80% Au, 20% Ag) are given in Table 2. The OmniRange facility on the ELAN 5000 ICP mass spectrometer essentially reduces the sensitivity of the mass spectrometer system by changing voltages applied to the quadrupole system. This feature allows for measurement of signal within the linear range of the detection system for elements contained in the sample at up to % levels. The synthetic Au alloy standard

Table 1. ICP-MS operating conditions and data acquisition parameters.

Inductively coupled plasma:	
Plasma gas	Argon
Forward power	1000 W
Gas flows:	
Plasma (outer) gas flow-rate	15.0 l min^{-1}
Auxiliary (intermediate) gas flow-rate	0.9 l min^{-1}
Nebulizer (inner) gas flow-rate	0.9 l min^{-1}
Ion lens settings:	
B lens	11.3 V
P lens	-45.6 V
E-1 lens	4.8 V
S-2 lens	0 V
Data acquisition parameters:	
measurement mode	multichannel
Dwell time	17 ms
Sweeps/replicate	4
Number of replicates	30
Points across peak	1
Resolution	Normal
Laser	
Laser Type:	Nd:YAG
Wavelength:	1064 nm
Pulse Mode:	Q-switched
Repetition Rate:	10 Hz
Laser Energy:	200-250 mJ/pulse
Laser Duration:	40 seconds
Carrier Gas Flow:	1.10 l min^{-1}

501 was analyzed daily as a quality control monitor. Sample was pre-ablated for a few seconds to remove any surface contamination. Three replicate analyses for each of three spots were completed for each sample. Background levels for each element were established by acquiring data for approximately 50 seconds prior to commencing ablation. The laser was fired for 40 seconds in order to obtain steady-state signals such as those shown in Figure 1. Count rates were collected using the ELAN software. Data files were processed using a compiled, in-house written, Microsoft Basic program which translated the data into a Lotus formatted spread sheet file. All subsequent data manipulation was done off-line using commercial spread sheet software on a personal computer. Scanning electron microscopy of the laser ablation craters revealed that the diameters of the craters ranged from 100 to 150 μm.

Table 2. Analyte masses and OmniRange settings.

Element	m/z	OmniRange	Element	m/z	OmniRange
Sc	24	0	Cs	133	0
Si	29	0	Ba	138	0
Sc	45	0	La	139	0
Ti	48	0	Ce	140	0
V	51	0	Pr	141	0
Cr	52	0	Nd	143	0
Mn	55	0	Sm	149	0
Fe	56	20 (10)*	Eu	153	0
Ni	60	0	Gd	157	0
Co	59	0	Tb	159	0
Cu	63	10	Dy	163	0
Zn	66	0	Ho	165	0
Ga	69	0	Er	166	0
Ge	72	0	Tm	169	0
As	75	0	Yb	173	0
Se	77	0	Lu	175	0
Rb	85	0	Hf	178	0
Sr	88	0	Ta	181	0
Y	89	0	W	182	0
Zr	90	0	Re	185	0
Nb	93	0	Os	192	0
Mo	95	0	Ir	193	0
Ru	101	0	Pt	195	0
Rh	103	0	Au	197	25
Pd	105	0	Hg	202	5
Ag	107	20	Tl	205	0
Cd	111	0	Pb	208	25 (15)
In	115	0	Bi	209	30 (5)
Sn	120	0	Th	232	0
Sb	121	0	U	238	0
Te	128	20			

*The numbers in brackets are OmniRange settings for synthetic gold alloy standard 501.

RESULTS AND DISCUSSION

Processing of Elemental Patterns

As has been shown by Watling et al. (1994), the fingerprinting of Au for trace elements does not rely on producing classical quantitative data but on the presence, association or lack of association, of specific suites of analyte elements. In this study, the sample intensity for each element was calculated as the mean count-rate obtained during the ablation period. The Au signal was used as an internal standard to correct for differences in ablation yields, matrix effects, and signal drift during the ICP-MS analysis. All element intensities were normalized to the intensity of Au in the same ablation period. To facilitate the comparison between the samples, a gold normalized intensity (GNI) was calculated as follows:

$$GNI = Log(I_e/I_g \cdot 10000)/4 \cdot 100\%$$

Where I_e is the signal intensity for an element, and I_g is the signal intensity for Au. The count rate for native Au was about $1 \cdot 10^5$ count per second. The detection limit is defined here as 3 times the standard deviation of the background count rate (n=5). For most elements, the detection limits were less than 10 counts per second. If the concentration of an element is below the detection limit, the GNI for the element is negative and will not be shown in the elemental pattern. Some examples of elemental patterns are shown in Figures 2 and 3.

Long-Term Reproducibility

The synthetic Au alloy standard 501 was analyzed over several months, and typical analytical data are presented in Figure 2. For the sake of brevity, not all analytical results are shown. These mass spectra, used as a quality control monitor illustrates that the trace element distribution patterns obtained over an extended period were stable providing evidence of the long-term reproducibility of the technique.

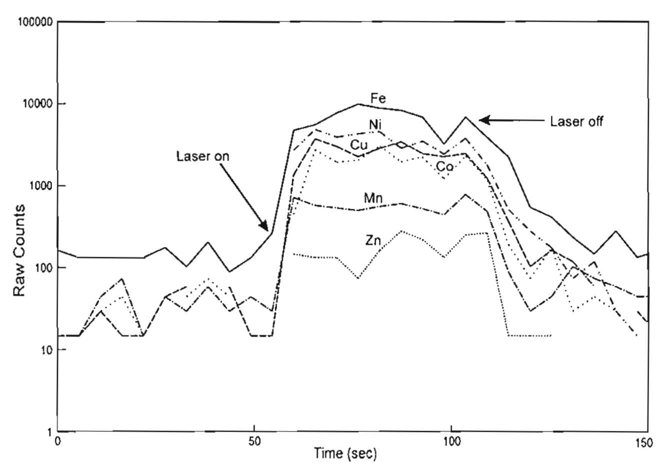

Figure 1. *Time variation of the ICP-MS signal (counts per second) of selected elements in a native AU sample. The intensity for each element was calculated as the mean count-rate during ablation.*

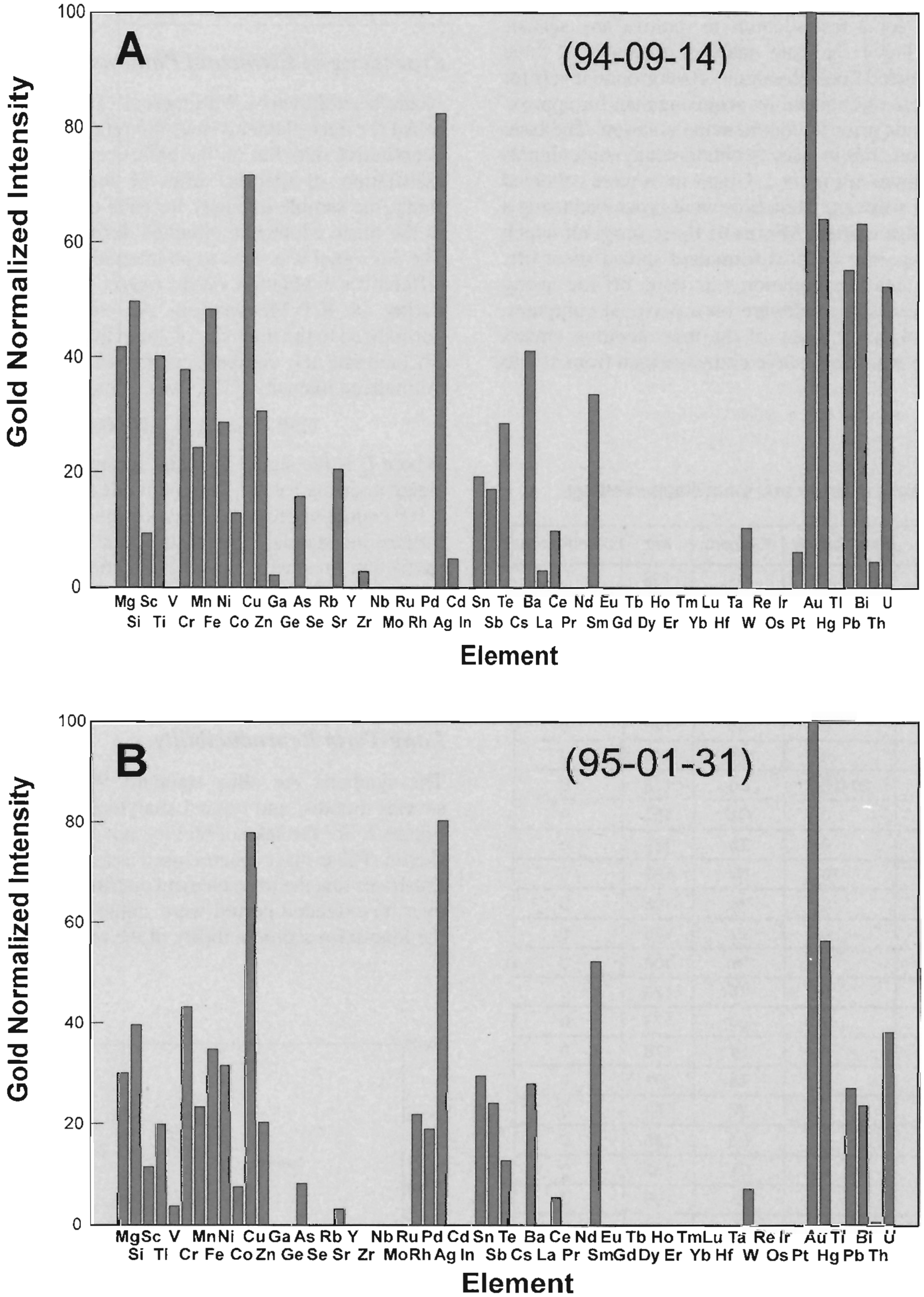

***Figure 2.** Elemental pattern callculated as Au normalized intensity from the synthetic Au alloy standard 501. The numbers in the brackets show the date of analysis.*

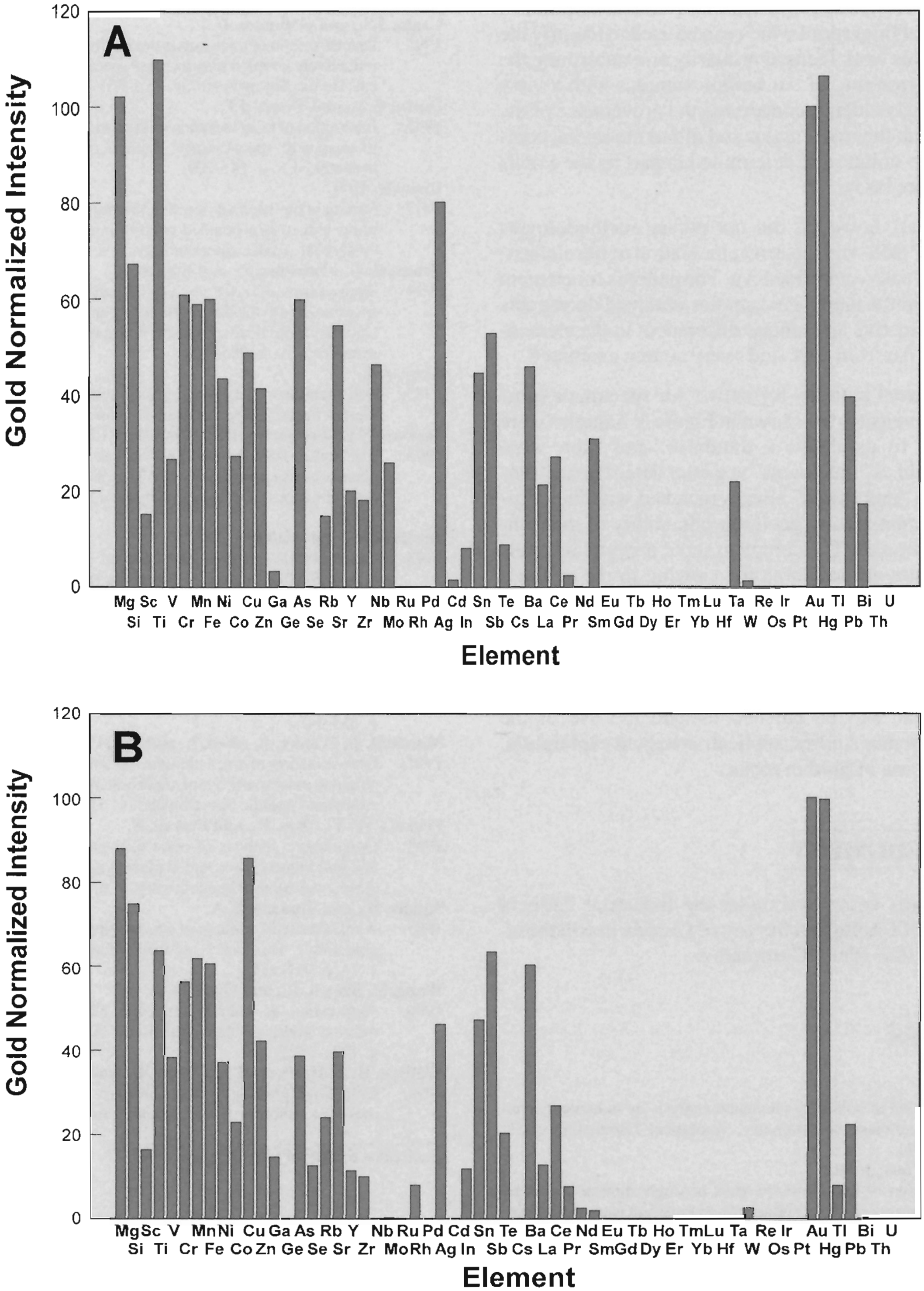

Figure 3. *Elemental patterns calculated as Au normalized intensity from the National Mineral Collection. Sample locations:* ***A)*** *Goldenville, Nova Scotia;* ***B)*** *Malartic gold fields, Quebec.*

Gold Fingerprinting

Watling et al. (1994) first reported that processed Au has a unique elemental fingerprint which can be used to identify the source of Au. This work focused primarily on establishing the elemental fingerprinting of Au bullion samples with a view to providing legal evidence concerning the provenance of the Au, implying that the trace, major and minor elemental composition of Au is unique and determined in part by the events producing the ore body.

Watling et al., however, did not pursue methodologies using LAM-ICP-MS which permit elucidation of the elemental signatures of native unrefined Au. The patterns for element concentrations in the native Au samples obtained during this study show distinctive and unique differences in the elemental signature of Au from each and every source examined.

Some elemental patterns for native Au specimens (normalized to Au intensity) are shown in Figure 3. Samples were first analyzed to establish a database, and then were re-analyzed again as "unknowns" at a later date. The patterns obtained for the "unknowns" always matched with the original patterns, demonstrating good reproducibility of the technique for real samples. The complete set of analytical results for all 60 samples are available for viewing in the author's laboratory.

Further work is currently underway to provide a means of not only identifying trace element patterns, but also to accurately determine the absolute concentration of each element. Applications that will be pursued include the use of the technique for forensic studies, application to gold exploration, and in-situ analysis of gold in rocks.

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Geological Survey of Canada Project 380077

Aeromagnetic survey program of the Geological Survey of Canada, 1996-1997

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Dumont, R., Kiss, F., Stone, P.E., and Tod, J., 1997: Aeromagnetic survey program of the Geological Survey Canada, 1996-1997; in Current Research 1997-D; Geological Survey of Canada, p. 63-65.

Abstract: In 1996, three high-resolution, regional aeromagnetic surveys totalling 138 663 line kilometres were flown over Victoria Island, Northwest Territories, Baffin Island, Northwest Territories and southwest Saskatchewan. Each survey was supported by a cost-sharing agreement with industry partners. A detailed, helicopter-borne electromagnetic/magnetic/gamma-ray spectrometric survey totalling 1648 line kilometres was flown to complete a project commenced in 1995 in British Columbia; this survey was funded by the Province of British Columbia. Two detailed, multi-parameter electromagnetic/magnetic/gamma-ray spectrometric helicopter-borne surveys flown in British Columbia and in New Brunswick have been compiled and published in 1996. An aeromagnetic survey flown in 1995-1996 in the area bordering British Columbia/Yukon Territories/Northwest Territories is being compiled and will be completed in 1997. The program to level the Canadian aeromagnetic profile data set, for the elimination of survey boundary effects, is continuing with drape computation and levelling of surveys flown at constant altitude in British Columbia.

Résumé : En 1996, trois levés aéromagnétiques régionaux á haute résolution totalisant 138 663 kilomètres linéaires ont été réalisés dans l'île Victoria et l'île de Baffin, dans les Territoires du Nord-Ouest, et dans le sud-ouest de la Saskatchewan. Chaque levé a bénéficié d'un financement par le biais d'une entente à frais partagés avec des partenaires de l'industrie. Pour compléter un projet entrepris en 1995 en Colombie-Britannique, on a effectué un levé électromagnétique-magnétique-spectrométrique (gamma) héliporté totalisant 1 648 kilomètres linéaires; ce levé a été financé par la Colombie-Britannique. En 1996, on a compilé et publié les données de deux levés multiparamétriques électromagnétiques-magnétiques-spectrométriques (gamma) détaillés héliportés entrepris en Colombie-Britannique et au Nouveau-Brunswick. La compilation de données tirées d'un levé aéromagnétique réalisé en 1995-1996 dans la région frontalière de la Colombie-Britannique, du Yukon et des Territoires du Nord-Ouest est en cours et se terminera en 1997. Le programme de nivellement de l'ensemble de données des profils aéromagnétiques canadiens, pour l'élimination des effets dus aux limites des levés, se poursuit. Il est combiné à un calcul simulant un levé à hauteur constante et à un nivellement de levés enregistrés à une altitude constante en Colombie-Britannique.

INTRODUCTION

In 1996-1997, the GSC aeromagnetic survey program included two regional aeromagnetic projects in the Northwest Territories and one in Saskatchewan. One target survey was completed in British Columbia. Locations of the 1996 projects are shown in Figure 1 and details are summarized in Table 1.

BRITISH COLUMBIA/YUKON/ NORTHWEST TERRITORIES

An aeromagnetic survey totalling 108 153 line kilometres was initiated in 1995 by a consortium of three oil companies and the Geological Survey of Canada on a cost-shared basis (Fig.1, Table 1). Data within British Columbia will be released in 1997, while the Yukon and Northwest Territories data will be made public in 1999. These data support geological mapping and future exploration programs.

A helicopter-borne, electromagnetic/magnetic/VLF-EM/gamma-ray spectrometric survey totalling 1648 line kilometres over the Purcell supergroup rocks in the Creston area, has been flown and compiled for publication in 1997. Funding for this survey was provided by the Province of British Columbia. The survey objectives are to search for new deposits similar to the Sullivan ore body, assist in the search for other types of mineralization and to map basement structure relevant to base metal exploration. Draping (continuation of constant elevation data to a topographic surface) of the aeromagnetic surveys over the Rocky Mountains was tested and a reference grid generated. This grid will be used to level the profile data to a common datum in order to eliminate survey boundary effects.

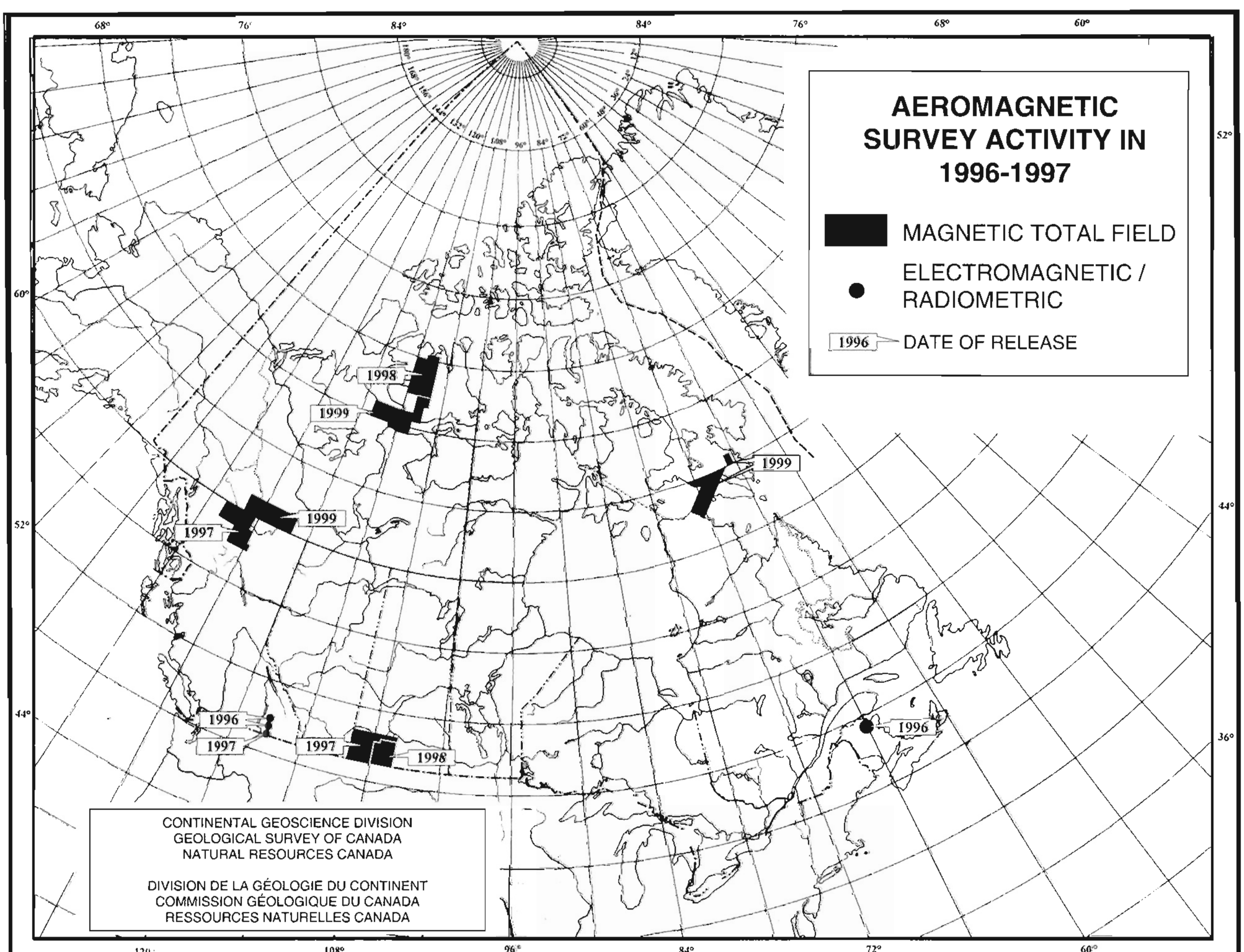

Figure 1. Aeromagnetic survey activity in 1996-1997.

Table 1. Aeromagnetic survey activity in 1996-97.

Survey	Type	Line km	Line spacing	Altitude	Year of publication
Saskatchewan Phase VII (Swift Current) 1996-97	Aeromagnetic Total Field	34 735	800 m	150 m MTC	1998
Victoria Island, N.W.T. Phase II 1996-97	Aeromagnetic Total Field	54 640 4 700	800 m 1600 m	200 m MTC	1999
British Columbia 1996-97 (Creston)	Aeromagnetic Frequency Domain EM Spectrometric	1 648	400 m	60 m MTC	1996
Baffin Island, N.W.T. 1996-97	Aeromagnetic Total Field	9 000 29 588 6 000	400 m 800 m 2 400 m	150 m MTC	1999

SASKATCHEWAN

The seventh phase of a multi-year program to acquire the regional aeromagnetic coverage was undertaken in southern Saskatchewan (Fig., Table 1). The current project, comprising 34 735 line kilometres, is being funded by the Geological Survey of Canada, Saskatchewan Energy and Mines (SEM), and one industry partner. Survey results will be useful for hydrocarbon and kimberlite exploration, as well as for detailed mapping of the sub-Phanerozoic basement. Consortium members receive one year exclusive use of the data, prior to release to the public.

NEW BRUNSWICK

Compilation of the helicopter-borne/electromagnetic/magnetic/VLF-EM/gamma-ray spectrometric survey of 22 235 line kilometres covering the entire Bathurst mining camp in New Brunswick is in progress. Maps and gridded digital data were published in 1996. An atlas of airborne geophysical responses over known deposits, is currently being compiled. Funding for this survey was provided by the Canada-New Brunswick Cooperation Agreement on Economic Diversification (1994-1998) and is a component of the GSC's 1994-1999 Bathurst mining camp, Canada-New Brunswick Exploration Science and Technology (EXTECH II) Initiative.

VICTORIA ISLAND, NORTHWEST TERRITORIES

A total field magnetic survey totalling 59 340 line kilometres was flown over an area covering the southern part of Victoria Island, part of the Coronation Gulf and the mainland west of Coppermine (Fig. 1, Table 1). These data will support detailed geological mapping and base metal exploration programs. One industry partner participated in a cost-sharing agreement with GSC to acquire the data. The survey results are to be released to the public in 1999.

BAFFIN ISLAND, NORTHWEST TERRITORIES

A total field magnetic survey totalling 44 588 line kilometres was flown over an area extending southwest from Iqaluit, Northwest Territories to the Quebec coast. A second block located to the northeast of Iqaluit was also surveyed. (Fig. 1, Table 1). These data will support detailed and regional geological mapping and base metal exploration programs. Two industry partners shared the cost of data acquisition with the GSC and the results will be released to the public in 1999.

Geological Survey of Canada Projects 930002, 910019, 940001, 940015, 950028, 960010.

National Gravity Program of the Geodetic Survey of Canada, 1996-1997

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Gibb, R.A. and Hearty, D.B., 1997: National Gravity Program of the Geodetic Survey of Canada, 1996-1997; in Current Research 1997-D; Geological Survey of Canada, p. 67-70.

Abstract: The National Gravity Program has been refocused to meet the needs of the Geodetic Survey Division for a refined geoid model for Canada and the integration of spatial and gravity networks and databases. During 1996, seven gravity surveys were completed: two were reconnaissance surveys of Arctic channels, one located in Nares Strait and the other in Dolphin and Union Strait; and five were detailed surveys of geological targets including the Oak Ridges Moraine, Ontario, the Steen River crater, Alberta, Alberta LITHOPROBE transects, the Western Superior LITHOPROBE transect, and phase 1 of a marine survey of the seaward extension of the Chicxulub crater, Mexico. Totals of 4548 new gravity stations and 3809 line kilometres of marine gravity data were collected during these surveys. The absolute gravity field program was reduced to only six measurements by October 1996 due to instrumentation problems. A three-year plan to develop a refined geoid model for Canada was distributed to stakeholders.

Résumé : Le Programme gravimétrique national a été réaménagé pour répondre aux besoins de la Division des levés géodésiques et ainsi affiner le modèle du géoïde du Canada et intégrer les réseaux et les bases de données spatiales et gravimétriques. En 1996, on a réalisé sept levés gravimétriques dont deux étaient des levés de reconnaissance dans l'archipel Arctique, soit un dans le détroit de Nares et un autre dans le détroit de Dolphin and Union, et cinq étaient des levés détaillés de cibles géologiques dont la Moraine d'Oak Ridges en Ontario et le cratère de Steen River en Alberta, les transects du LITHOPROBE en Alberta, le transect du LITHOPROBE dans la partie ouest de la Province du lac Supérieur et la première phase d'un levé marin du prolongement océanique du cratère Chicxulub au Mexique. Au cours de ces levés, on a établi 4 548 nouvelles stations gravimétriques et enregistré des données gravimétriques prélevées en mer sur 3 809 kilomètres linéaires. Le programme du champ gravimétrique absolu a été réduit à six mesures seulement avant octobre 1996 à cause de problèmes d'instrumentation. Un plan triennal pour affiner le modèle du géoïde pour le Canada a été distribué aux intervenants.

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INTRODUCTION

The National Gravity Program (NGP) is undergoing a fundamental reorientation to meet the needs of the program of the Geodetic Survey Division (GSD). The main thrusts of the new strategic direction of the NGP are as follows:

1) The gravity survey program will focus on the enhanced gravity coverage requirements for an improved geoid model for Canada while remaining responsive to the needs of the Geological Survey of Canada (GSC) for target surveys and the US National Imagery and Mapping Agency for densification surveys.
2) The gravity standards and applications program will focus on the readjustment of the Canadian Gravity Standardization Net (CGSN), on integration of absolute gravity control stations of the CGSN with the Canadian Base Network (CBN), a high precision terrestrial network of geodetic monuments designed to link together the national horizontal and vertical control networks, the Canadian Active Control System and tide guage stations, and on applications research e.g. marine tide modelling, while continuing to support the Canadian Superconducting Gravimeter Installation (CSGI) and alliances with Canadian industry to build improved airborne gravity systems.
3) The absolute gravity program will focus on the provision of additional absolute measurements to meet the requirements of CGSN, the Canadian Active Control System (CACS), the integration of CGSN with CBN, collaboration with the Geodynamics Program, GSC, and international commercial opportunities in partnership with Canadian industry.
4) Improved geoid determination will be a major focus of the NGP with a new Canadian Gravimetric Geoid 2000 (CGG2000) as the ultimate goal of an ambitious three-year plan (outlined below) that will involve important input from the universities, provinces, industry, and the United States National Geodetic Survey.
5) The National Gravity Database (NGDB) will be fully integrated into the Canadian Geodetic Information System by March 1997 with internet access to gravity data an immediate goal.
6) A variety of commercial services (e.g. establishment of absolute gravity datum and scale, international gravity ties, geoid computation, and training in gravity data processing and geoid computation) offered by the NGP will provide real opportunities to enhance program resources and to increase national and international recognition of the program.

GRAVITY SURVEYS

In 1996-1997, the gravity survey program comprised two reconnaissance surveys, one sponsored by the Division and one by the US National Imagery and Mapping Agency (NIMA), and five detailed surveys over geological targets sponsored by GSC and other agencies.

Nares Strait

An on-ice gravity and bathymetry survey, sponsored by NIMA, was conducted between April 17 and May 7 to complete a void in the systematic coverage of Nares Strait that resulted from open water conditions in 1995. The survey was conducted from a base camp at the RCMP facilities at Alexander Fiord in cooperation with the Canadian Hydrographic Service and the Mapping and Charting Establishment (MCE), Department of National Defence (DND) with logistic support from the Polar Continental Shelf Project and funding support from NIMA. A total of 125 gravity and bathymetry measurements was observed at 10 km intervals on the sea-ice using a damped LaCoste and Romberg gravimeter. Positioning was provided by differential GPS using Ashtech XII receivers supplied by MCE. This survey completes the regional gravity coverage of Nares Strait between Ellesmere Island and Greenland from Smith Sound to the Lincoln Sea. Preliminary data have been passed to the National Survey and Cadastre of Denmark for inclusion in the computation of a local geoid model for the area. Following final data processing, the digital data will be made available through the national gravity database in 1997.

Dolphin and Union Strait

An on-ice gravity survey of Dolphin and Union Strait was completed in the period February 25 to March 21. The survey formed part of a long-term program of combined bathymetric and gravity surveys of the Canadian Arctic channels carried out in cooperation with the Canadian Hydrographic Service (CHS) and the Polar Continental Shelf Project on an annual basis. From a base camp established by CHS northwest of Coppermine at Bernard Harbour, a total of 291 gravity and bathymetry observations were made at 6 km intervals on the sea-ice using a helicopter for transportation. Gravity observations were made by hydrographers trained by GSD using a damped LaCoste and Romberg gravimeter. Motorola GPS receivers with radio links provided real-time differential positioning for all stations and eliminated the requirement for post-survey GPS processing. The data will be included in the national gravity database when final processing is completed in 1997.

Oak Ridges Moraine

A gravity survey, sponsored by GSC's Terrain Sciences Division, was conducted over the Oak Ridges Moraine in southern Ontario in two parts. In the first part, a gravity profile was observed along the shoreline of Toronto harbour; in the other, gravity was observed on a network of secondary roads in the area west of Lake Simcoe and north of Barrie to Georgian Bay to extend the coverage of surveys completed in the two previous years. These surveys form part of the Oak Ridges Moraine Hydrogeology Project in the Bolton area north of Toronto and their objective is to evaluate the use of gravity for mapping the bedrock surface beneath the moraine in a cost-effective way.

Gravity measurements were made along the shoreline of Lake Ontario by a GSC student observer using a Scintrex CG-3 AUTOGRAV gravimeter. A total of 336 new gravity stations was established at 50 to 100 m intervals along roadways or trails adjacent to the lakeshore. Coordinates were scaled from a 1:10 000 map published by the City of Toronto and elevations were derived from altimeter measurements tied to the lake level. A GSD field crew established 718 new gravity stations at approximately 1 km intervals along secondary roads on three 1:50 000 NTS map areas (Barrie, Collingwood and Elmvale). Gravity measurements were made using a Scintrex CG-3 gravimeter and repeat measurements were made at every tenth station using a LaCoste and Romberg gravimeter. Horizontal positioning and elevations were derived from differential GPS measurements using portable Sokkia GPS receivers. Preliminary field processing indicated that elevations and coordinates to two metre accuracy were obtained. Station locations were accurately located on 1:50 000 maps to check for any gross errors in positions derived from the GPS processing. Final processing will be completed by January 1997 and digital data will be included in the national gravity database.

Steen River Crater

A GSC sponsored gravity survey was conducted in northern Alberta, in collaboration with the Continental Geoscience Division (CGD), as a pilot project to establish the magnitude and character of the gravity signature previously identified in the regional gravity field over the Steen River crater. Between January 11 and January 24, 1996, under extreme arctic weather conditions (-40° C), 231 gravity stations were established at 100 m intervals along three radial profiles corresponding to previously surveyed seismic reflection lines across the structure. LaCoste and Romberg gravimeters were used for the gravity observations and vertical and horizontal positions were established using TurboRogue GPS receivers in differential mode. Preliminary data processing was completed in the field. Post-survey analysis of the GPS data is in progress. The data will be corrected for terrain effects and integrated with data collected during a second gravity survey conducted by a private contractor in the area; the combined data set will be added to the national gravity database.

Alberta LITHOPROBE Transects

At the request of the GSC's Calgary office, a gravity survey was organized by GSD and conducted by the Mapping and Charting Establishment (MCE), in northern and southern Alberta between November 15, 1995 and February 16, 1996. MCE personnel, working in two crews, experienced extreme cold and record snowfall conditions during December and January. Captain Philip Maye and Warrant Officer Robert Smith shared responsibility for field operations and logistics. A total of 2632 stations and 250 repeat measurements was collected at 500 m intervals along 20 seismic lines on the Peace River Arch and Southern Alberta LITHOPROBE transects. The survey started west of Dawson Creek in November and continued east of Edmonton before moving south towards the Lethbridge area. One Scintrex CG-3 gravimeter and three LaCoste and Romberg gravimeters were used on the survey. Two GPS base stations were established and two mobile Ashtec XII GPS receivers were deployed each day to collect differential horizontal and vertical positions at each observation point. Ellipsoidal heights on the World Geodetic System 1984 (WGS84) datum were used in preliminary field processing to check data integrity. Closure errors on daily traverses, repeat measurements, and results of preliminary processing indicate that survey specifications of ±0.05 mGal for gravity, ±5.0 m horizontal and ±1.0 m vertical were achieved. Conversion from ellipsoidal to orthometric heights using the GEOID95 model and from WGS84 to the North American Datum 1927 (NAD27) using the national transformation software will be completed during final data processing. Data will be made available to the user community through the national gravity database.

Western Superior LITHOPROBE Transect

At the request of GSC's Continental Geoscience Division (CGD), a gravity survey was conducted on a LITHOPROBE seismic refraction line along the CN railway and adjacent roadways from Nakina to Highway 595 just north of Kenora in western Ontario. Transportation along the tracks was provided by CN inspection vehicles and personnel. Phase I of this survey was conducted between July 16 and July 28 in collaboration with CGD, during the deployment of seismometers along the CN railway from Sioux Lookout to Armstrong. Phase II was conducted between August 16 and 28. A total of 205 gravity and GPS stations was established at 1.3 km intervals coincident with seismometer locations. Gravity observations were made at each site with a Scintrex CG-3 gravimeter and repeat measurements were made at every tenth station using a LaCoste and Romberg gravimeter. Horizontal and vertical positions were obtained from differential GPS observations using TurboRogue GPS receivers. Altimeter and temperature measurements were also made at each site with ties to geodetic bench marks along the track where possible as a back-up for derived elevations from GPS processing.

Chicxulub Crater

The deep-water phase of a gravity survey of the seaward extension of the Chicxulub crater, Yucatan Peninsula, Mexico was completed in October as part of a multi-parameter marine geophysical survey sponsored by the GSC's Continental Geoscience Division, the British Institutions Seismic Reflection Profiling Syndicate, the University of Texas, the Universidad Nacional Autonoma de Mexico, the National Science Foundation, the Pan American Institute of Geography and History and the National Geographic Society. A total of 3809 line kilometres of gravity data was collected. The gravimeter was transferred to a smaller vessel for the near-shore phase of the survey which is currently (October 1996) in progress.

ABSOLUTE GRAVIMETRY

A series of four absolute gravity stations were observed during the latter part of May and early June in Quebec. The stations were located at La Pocatière, Charlevoix, Schefferville, and Lauzon. The last station located near Quebec City is one of several new stations that will be established on piers constructed by the Canadian Coast Guard. The Charlevoix and La Pocatière stations are situated in a seismically active region of Quebec, whereas the Schefferville site is one of three Canadian stations forming part of the International Absolute Gravity Base Station Network (IAGBN). Measurements were made also at Yellowknife and at Pinawa in October.

GEOID

A three-year plan entitled "Towards a Refined Gravimetric Geoid for Canada 1996-1999" (Pagiatakis et al., internal report, Geomatics Canada, 1996) was distributed to stakeholders in August. One of the key goals of the Geodetic Survey Division is to develop a new high resolution geoid model to meet the needs of clients and to maintain and enhance the Canadian Spatial Reference System (CSRS), thus providing ties between GPS positioning and traditional survey networks. It is one of the Division's primary responsibilities to ensure that the CSRS is widely available to serve as the basis upon which all surveys in Canada rest. The Division will play a leading role by contributing to and supporting the required research and development and by coordinating the joint efforts and expertise of many agencies and institutions. The University of Calgary and the University of New Brunswick will collaborate during the three-year period to improve the infrastructure of data sets needed for the project and to contribute to the solution of outstanding theoretical problems. The Division will organize three-day workshops to present and discuss results and progress each year. Attendance at these workshops will be open to clients and other stakeholders and participation from collaborating agencies, provincial agencies, clients in the private sector, American counterparts, and graduate students will be encouraged.

The plan is comprehensive and covers the following topics (Pagiatakis et al., 1996):

1. **International Commitments** - 1.1 Global Geopotential Models, 1.2 Towards a North American Geoid;
2. **Technical Issues** - 2.1 Documentation of GSD95 Geoid Model, 2.2 Data Collection, 2.3 Re-adjustment of the Levelling Network, 2.4 Data Assessment and Integrity, 2.5 National Gravity Database;
3. **Theoretical Issues** - 3.1 Synthetic Gravity Field, 3.2 Data Reduction Algorithms, 3.3 Gravity Data Accuracy and Distribution, 3.4 DEM and TMDD Accuracy and Distribution, 3.5 Global Geopotential Models and Long Wavelength Geoid, 3.6 Analysis and Assessment of Computational Methods, 3.7 Heterogeneous Data Evaluation and Integration.

A major goal of the plan is an improved Canadian geoid model - CGG2000 - by the year 2000.

GRAVITY SYSTEMS DEVELOPMENT

Funding support from GSC's Industrial Partners Program (IPP) for the development of a new airborne gravity technology ended in March 1996 but GSD continued to support this cooperative effort of private industry, universities, and government agencies as it nears completion. Flight testing of the new gravity sensor is scheduled for November/December 1996 following bench and road testing. Funding support, also under the GSC's IPP, for the development by Scintrex Ltd. of Heligrav, a system that uses a helicopter and a self-levelling, remotely operated gravimeter for cost-effective regional gravity surveys, also ended in March. GSD has continued to support this project in 1996. Following two series of ground tests in June and September, Scintrex plans to undertake initial flight tests of the system in 1997.

AUTHOR INDEX

NOTE TO CONTRIBUTORS

Submissions to the Discussion section of Current Research are welcome from both the staff of the Geological Survey of Canada and from the public. Discussions are limited to 6 double-spaced typewritten pages (about 1500 words) and are subject to review by the Chief Scientific Editor. Discussions are restricted to the scientific content of Geological Survey reports. General discussions concerning sector or government policy will not be accepted. All manuscripts must be computer word-processed on an IBM compatible system and must be submitted with a diskette using WordPerfect. Illustrations will be accepted only if, in the opinion of the editor, they are considered essential. In any case no redrafting will be undertaken and reproducible copy must accompany the original submissions. Discussion is limited to recent reports (not more than 2 years old) and may be in either English or French. Every effort is made to include both Discussion and Reply in the same issue. Current Research is published in January and July. Submissions should be sent to the Chief Scientific Editor, Geological Survey of Canada, 601 Booth Street, Ottawa K1A 0E8 Canada.

AVIS AUX AUTEURS D'ARTICLES

Nous encourageons tant le personnel de la Commission géologique que le grand public à nous faire parvenir des articles destinés à la section discussion de la publication Recherches en cours. Le texte doit comprendre au plus six pages dactylographiées à double interligne (environ 1500 mots), texte qui peut faire l'objet d'un réexamen par le rédacteur scientifique en chef. Les discussions doivent se limiter au contenu scientifique des rapports de la Commission géologique. Les discussions générales sur le Secteur ou les politiques gouvernementales ne seront pas acceptées. Le texte doit être soumis à un traitement de texte informatisé par un système IBM compatible et enregistré sur disquette WordPerfect. Les illustrations ne seront acceptées que dans la mesure où, selon l'opinion du rédacteur, elles seront considérées comme essentielles. Aucune retouche ne sera faite au texte et dans tous les cas, une copie qui puisse être reproduite doit accompagner le texte original. Les discussions en français ou en anglais doivent se limiter aux rapports récents (au plus de 2 ans). On s'efforcera de faire coïncider les articles destinés aux rubriques discussions et réponses dans le même numéro. La publication Recherches en cours paraît en janvier et en juillet. Les articles doivent être envoyés au rédacteur en chef scientifique, Commission géologique du Canada, 601, rue Booth, Ottawa K1A 0E8 Canada.