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METALLOGENIC STUDIES OF THE TALLY POND BELT, VICTORIA LAKE GROUP: TRACE-ELEMENT GEOCHEMISTRY AND LEAD-ISOTOPE DATA FROM THE EXPLOITS SUBZONE, NEWFOUNDLAND

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ABSTRACT

A new metallogenic study of the Victoria Lake Group in central Newfoundland began in 2000. Initial work concentrated on the Tally Pond volcanics and involved regional rock geochemistry coupled with detailed stratigraphic and radiogenic isotope studies in the Tally Pond area. The Cambro-Ordovician Victoria Lake Group lies within the Exploits Subzone and is a composite and structurally complex assemblage of volcanic, volcaniclastic, and epiclastic rocks that formed in a variety of island-arc, rifted-arc, back-arc and mature-arc settings. The group is dominated by felsic volcanic rocks and by lesser amounts of mafic pillow lava, mafic and felsic pyroclastic rocks, chert, greywacke and shale. The group is divisible into several separate volcanic terranes that include the Tulks belt and Tally Pond belt.

The Tally Pond belt consists of Cambrian island-arc felsic pyroclastic rocks having intercalated mafic volcanic rocks and epiclastic volcanic and sedimentary rocks. In the area of the Duck Pond deposit, these rocks form two structurally juxtaposed sequences, the Upper block and the Mineralized block which form a structural window through an overthrust package of Ordovician sedimentary rocks.

Geochemical analysis indicates that the mafic rocks vary from sub-alkalic basalts to basaltic-andesites, consistently exhibit an arc signature and are depleted arc tholeiites with moderate LREE enrichments. The felsic rocks are rhyolite to rhyodacite and are variably LREE enriched island-arc rocks and are tholeiitic in nature; however, some have transitional to slight calc-alkaline affinities. Subalkalic gabbro and diorite intrusions are transitional and exhibit LREE enrichment relative to the MREE and HREE. The altered footwall felsic rocks that lie beneath the Duck Pond VMS deposit show REE depletions of different magnitudes; Eu being depleted in all of the altered samples to varying degrees. The hanging-wall felsic rocks define a fractionation trend with the mafic varieties and the two sequences may be genetically related. The footwall felsic rocks and mafic intrusions define a weak trend and thus may also be genetically linked.

The geochemical data indicate that the volcanic and intrusive rocks of the Tally Pond belt in the area of the Duck Pond deposit are bimodal, and have geochemical affinities for two tectonic environments. The hanging-wall and footwall volcanic rocks have characteristics typical of island-arc affinities and fall in plate-marginal fields. The mafic intrusive rocks of the Tally Pond belt, exhibit no island-arc affinities and plot in the within plate basalt field.

Lead isotope data from the Tally Pond belt show a very small variation in the $^{206}Pb/^{204}Pb$ and are relatively more radiogenic than other deposits in Newfoundland. Comparision with deposits elsewhere in the Dunnage Zone indicate that there are two general groups of deposits: a primitive group of deposits in the Notre Dame Subzone, and a relatively more radiogenic group represented by deposits in the Exploits Subzone. Deposits in the Notre Dame Subzone were influenced by lead that evolved from the Laurentian margin while those in the Exploits Subzone appear to have been influenced by Gondwanan continental crust.

INTRODUCTION

A new metallogenic study commenced in 2000, as part of a project designed to investigate the nature of volcanogenic massive sulphide mineralization within the Cambro-Ordovician Victoria Lake Group. This project is being undertaken in cooperation with the Geological Survey of Newfoundland and Labrador and the Geological Survey of Canada, as part of the Targeted Geoscience Initiative project ‘Geology of the Iapetus Suture Zone, Red Indian Line, central Newfoundland'. The initial metallogenic work has focused on the Tally Pond volcanics and involved regional rock geochemistry and detailed stratigraphic, structural, geochronological, and radiogenic isotope studies in the Tally Pond area.

LOCATION AND PHYSIOGRAPHY

The Victoria Lake Group occurs in central Newfoundland, and covers portions of NTS map areas 12A/4, 5, 7, 9, 10, 11, 15 and 16 and 2D/13. The study area surrounding Tally Pond is located in the northeast, approximately 20 km south of the community of Millertown. Access to the area is excellent using a series of logging roads that are owned and operated by Abitibi-Consolidated and which cover most of the study area. Outcrops that are exposed along the ridges and in some localities to the south are best reached by helicopter.

The Victoria Lake–Red Indian Lake area of central Newfoundland is characterized by a gently undulating and hummocky, heavily forested landscape having an average elevation of 250 m. The southern part consists of extensive bogs and numerous small rivers and ponds, and a rugged topography dominated by deep glacial valleys and ridges ranging between 300 and 400 m in elevation. To the north, small brooks and ponds are scattered throughout the area where the topography consists of low rolling hills; isolated peaks reach up to 400 m. Extensive areas of glacial till result in generally poor bedrock exposure except along the linear, northeast-trending locally barren ridges.

PREVIOUS WORK

The earliest geological survey in the Red Indian Lake area (Figure 1) of central Newfoundland was conducted by Alexander Murray in 1871 for the Geological Survey of Newfoundland (Murray, 1872). Murray's successor, J.P. Howley, conducted two separate geological expeditions in the area in 1875 and 1888 that focused on exploring the lower Exploits, Lloyds, and Victoria rivers along with parts of Noel Paul's Brook (Howley, 1917). At the beginning of the 20th century much of the land in the Red Indian Lake area was part of a long term charter granted to the Anglo-Newfoundland Development Company (ANDCo.). Prospectors working for the ANDCo. discovered the Buchans River and the Victoria Mine prospects in 1905. In 1926, the ANDCo. entered into a formal agreement with ASARCO to mine the Buchans River orebody, and within six months a number of new orebodies in the Buchans area were discovered. These and later discovered orebodies were mined until 1984, at which time all known ore reserves were exhausted (Thurlow and Swanson, 1981).

The first detailed geological investigations of the present Victoria Lake Group were conducted as part of a series of academic studies sponsored by ASARCO. Brown (1952) mapped the southeastern part of the Lake Ambrose area as part of a M.Sc. thesis at McGill University, and Mullins (1961) mapped the area south of Lake Ambrose to Noel Paul's Steady for a M.Sc. study at Memorial University of Newfoundland.

The Geological Survey of Canada conducted regional (1: 250 000) scale mapping of the Red Indian Lake map area (NTS map area 12/A) in 1965 and 1966 (Williams, 1970). In 1975, the Newfoundland Department of Mines and Energy began a regional geological mapping survey of the Victoria Lake–Red Indian Lake area (Kean, 1977, 1979; Kean and Jayasinghe, 1980, 1982). A regional metallogenic study of the Victoria Lake Group was started in 1984 as part of the Canada–Newfoundland Mineral Development Agreement (Kean, 1985; Evans and Kean, in press). This program consisted of detailed mapping and geochemical sampling (Evans *et al.*, 1990) coupled with an extensive regional gold-sampling program (Evans and Wilson, 1994; Evans, 1996) and detailed deposit-level studies (Evans, 1986; Evans and Wilton, 1995).

In the mid-1970s, Noranda began mineral exploration in the Tally Pond volcanic belt, which led to the discovery of the Burnt Pond Cu–Zn prospect in 1974. This was followed by a five-year period of intense exploration involving the diamond drilling of airborne geophysical anomalies and discovery of numerous geochemical anomalies, massive sulphide float, and outcrops of mineralized felsic volcanic rocks. In 1979, Noranda entered into a joint venture agreement with Abitibi-Price Corp. (later assumed by BP-Selco) who owned the mineral rights to the Tally Pond volcanics to the southeast of Tally Pond.

An extensive series of ground geophysical surveys were followed up by a diamond drilling program which led to the discovery of the Boundary Deposit in 1981. Over the next six years, diamond drilling to the south of the Boundary Deposit intersected abundant pyrite mineralization, altered felsic volcanic rocks, and lithogeochemical anomalies that culminated in the spring of 1987 with the intersection of 55

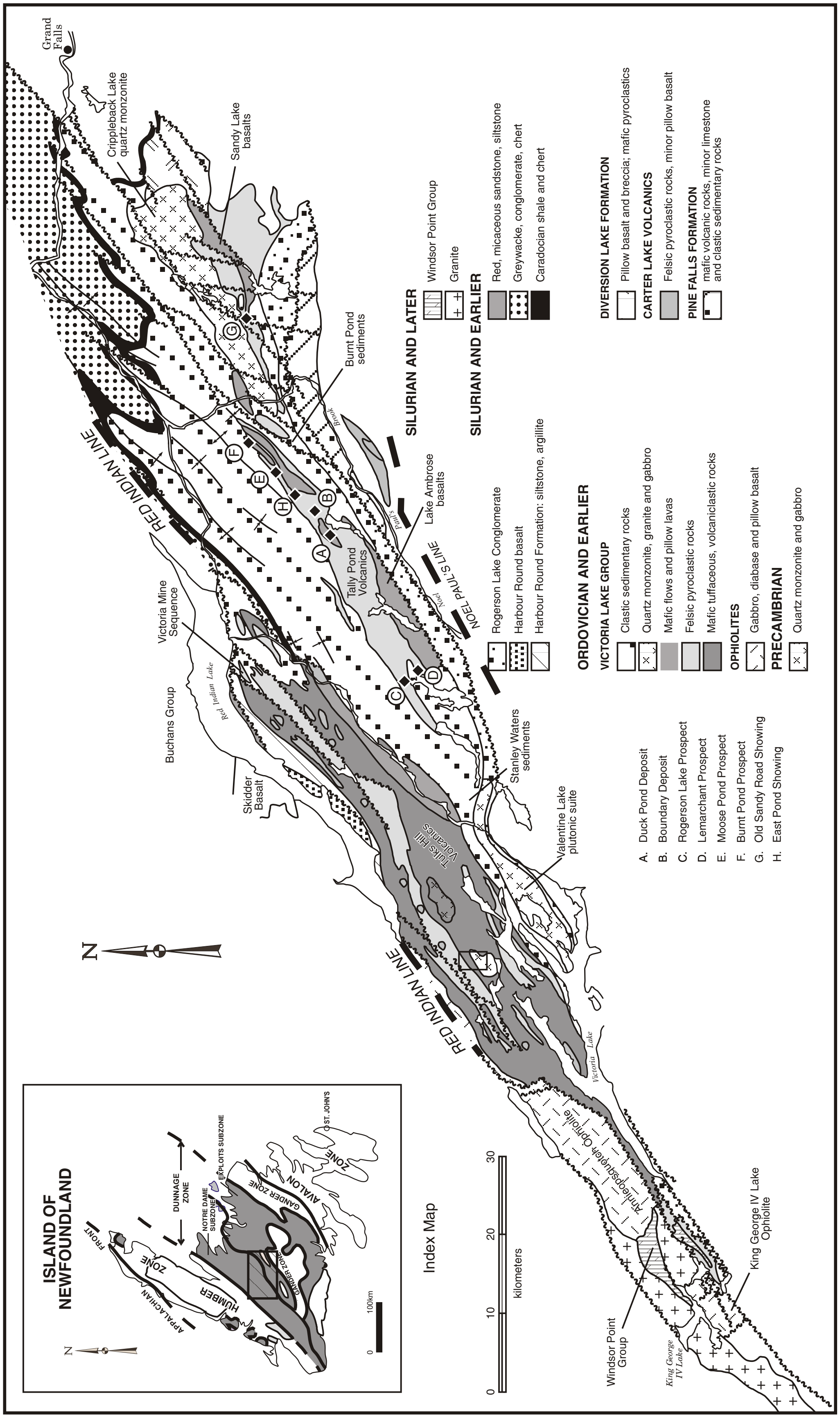

Figure 1. *Geological map of the Victoria Lake Group and adjoining sequences; geology after Kean and Evans (1988).*

m of massive sulphide. This intersection included over 20 m of ore grade sulphide that contained over 2% Cu and 10% Zn, in what was to be called the Upper Duck lens. Further drilling led to the discovery of the Lower Duck and Sleeper lenses, which were collectively called the Duck Pond Deposit. In 1998, Thundermin Resources Inc. entered into an agreement with Noranda to acquire a 100 percent interest in the Duck Pond/Boundary base-metal property. Thundermin Resources Inc. subsequently formed a 50/50 joint venture with Queenston Mining Corp. and undertook a diamond-drilling program aimed at delineating portions of the Duck Pond and Boundary deposits as a possible precursor to mine development.

REGIONAL GEOLOGICAL SETTING

The Newfoundland Dunnage (tectonostratigraphic) Zone is separated on the basis of geochemical, metallogenic, geochronological, paleontological and geophysical parameters into two large subzones, the Notre Dame and Exploits subzones (Williams *et al.*, 1988). The Victoria Lake Group lies within the Exploits Subzone of the Dunnage Zone (Figure 1). These subzones are separated by an extensive fault system, the Red Indian Line that can be traced across Newfoundland. It has been suggested that the two subzones were developed on opposite sides of the Iapetus Ocean (Hall *et al.*, 1998) and were not linked until the late Llanvirn–early Llandelio.

The Victoria Lake Group is a composite and structurally complex collection of volcanic, volcaniclastic, and epiclastic rocks of varying ages, geochemical groupings and tectonic environments. It consists of mafic pillow lava, mafic and felsic pyroclastic rocks, chert greywacke and shale that formed in a variety of island-arc, rifted-arc, back-arc and mature-arc settings. The group encompasses all the pre-Caradocian rocks between Grand Falls in the northeast to King George IV Lake in the southwest, and from Red Indian Lake in the north to Noel Paul's Brook in the south (Kean, 1977).

In the northeast, the Victoria Lake Group is conformably overlain by Llandelio–Caradocian black shales and cherts, which in turn are conformably overlain by Middle Ordovician to Early Silurian flysch, argillite and conglomerate (Evans and Kean, 1987). Along its southeastern contact, the Victoria Lake Group is unconformably overlain by the Rogerson Lake Conglomerate, although this contact is generally sheared and faulted. The linear, narrow outcrop pattern of the conglomerate and local clast provenance suggest that it is a fault-scarp, molasse-type deposit (Kean and Evans, 1988).

Rocks of the Victoria Lake Group occupy a regional northeast-trending anticlinorium, termed the Victoria Anticlinorium (Kean, 1985). Regionally, the sequence youngs northwesterly on the north limb and southeasterly on the south limb; however, there are numerous smaller scale, first-order and second-order folds that result in variable facing directions. The lack of outcrop in the area has precluded detailed structural interpretation (Kean and Evans, 1988).

The Victoria Lake Group contains an inhomogeneously developed, regional penetrative foliation defined by chlorite, sericite, flattened clasts and crystal augen, that increases in intensity to the northwest, toward the Red Indian Line. This foliation is subparallel to bedding and axial planar to tight to isoclinal folds. Rocks of the Victoria Lake Group have been metamorphosed to lower greenschist-facies, however, middle greenschist- to lower amphibolite-facies rocks are present along the southern margin (Evans *et al.*, 1990).

Regionally, the Victoria Lake Group has been divided into two major lithofacies (Kean and Jayasinghe, 1980, 1982): 1) volcanic rocks comprising two linear belts, the Tally Pond belt in the northeast and the Tulks belt in the southwest; and 2) a laterally equivalent, volcanically derived sedimentary belt in the northeast.

The Tally Pond belt refers to the sequence of volcanic, volcaniclastic and sedimentary rocks that extend from Victoria Lake northeastward to the Diversion Lake area (Kean and Jayasinghe, 1980). The sequence contains volcanic rocks of the Tally Pond volcanics and Diversion Lake Formation, which are intercalated by epiclastic volcanic and sedimentary rocks of the Burnt Pond and Stanley Waters sediments. The Tally Pond belt also contains the Valentine Lake plutonic suite and the Crippleback Lake quartz monzonite.

The Tally Pond volcanics are exposed in a linear belt that consists of dominantly felsic pyroclastic rocks having intercalated mafic volcanic rocks comprised of vesicular and amygdaloidal, generally pillowed, flows and mafic to andesitic tuff, agglomerate and breccia. The pillows are generally small and have minor interpillow material that consists of mafic tuff and green chert (Plate 1). Most of the breccias consist of mafic volcanic rock fragments; some contain pillow fragments. The mafic volcanic rocks within the Tally Pond volcanics form two distinct volcanic sequences that are referred to as the Lake Ambrose basalts and the Sandy Lake basalts (Dunning *et al.*, 1991).

The felsic rocks are composed of felsic breccia, lapilli tuffs (Plate 2), quartz porphyry, crystal tuff, and flow-banded rhyolite, rhyodacite, and rhyolite breccia. The breccias contain angular felsic volcanic fragments ranging from 5 to 50 cm in length within fine- to medium-grained tuffaceous

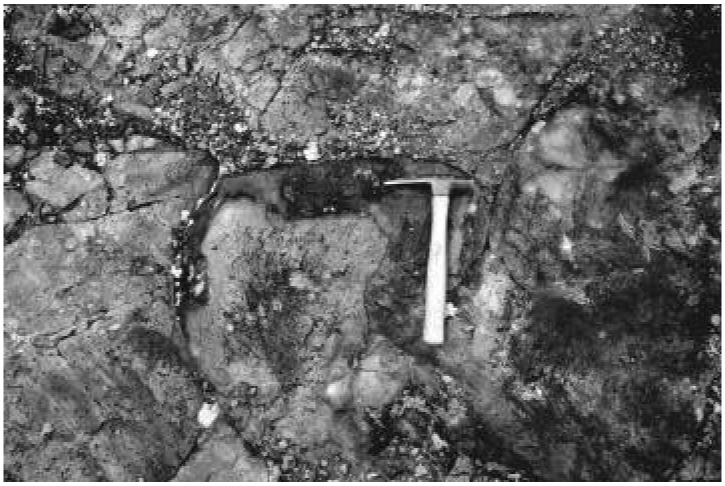

Plate 1. *Weakly mineralized pillow lava of the Lake Ambrose volcanic belt.*

Plate 2. *Felsic lappili tuff with minor sulphide staining, Tally Pond volcanics, located at the mouth of Boundary Brook.*

matrices. Tuffisitic gas breccias are present and consist of flow-aligned, in situ brecciated clasts in an aphanitic to vitric, siliceous matrix (Kean, 1985). The lapilli tuff consists of dacite and rhyolite clasts, locally flow banded, in a fine grained to locally vitric tuffaceous matrix. The rhyolite is generally a thick sequence of massive to locally flow banded, aphyric to quartz and/or feldspar porphyritic, frequently autobrecciated flows that locally grade into dacitic compositions. Zircons derived from rhyolite in the area northeast of Tally Pond have yielded a U/Pb age of 513 ± 2 Ma (Dunning *et al.,* 1991) making the Tally Pond volcanics the oldest well-dated Iapetan island-arc sequence in the Appalachian Orogen.

The Victoria Lake Group hosts about 30 significant VMS deposits, prospects, and showings. The Tally Pond volcanics hosts two major deposits (Duck Pond and Boundary), four prospects (Rogerson Lake, Lemarchant, Moose Pond and Burnt Pond) and two significant showings (Old Sandy Road and East Pond). The mineralization is mostly restricted to the felsic volcanic belts and comprises disseminated, stockwork, massive, and transported sulphides, that is generally coeval with the enclosing felsic volcanic rocks. The Duck Pond and Boundary deposits, the largest known VMS occurrences in the Victoria Lake Group, contain a combined resource of 6 350 000 tonnes of 6.3% Zn, 3.29% Cu, 1.0% Pb, 63.5 g/t Ag and 0.82 g/t Au (Squires *et al.,* 2000).

LOCAL GEOLOGICAL SETTING

The Tally Pond area is underlain by Cambrian submarine felsic and mafic volcanic, volcaniclastic and sedimentary rocks of the Tally Pond volcanics (Figure 2). In the area of the Duck Pond deposit these rocks form two structurally juxtaposed sequences, informally named the Upper block and the Mineralized block (Figure 3), which form a structural window through an overthrust package of Ordovician sedimentary rocks (Squires *et al.*, 1990). A series of moderate to steep dipping thrust and wrench faults complicate the stratigraphy, with displacements ranging from 500 m to 2 km.

The Upper block is in excess of 1000 m thick and comprises cycles of shallow-dipping, deep submarine, massive to pillowed (Plate 3) and brecciated mafic and felsic flows and pyroclastic rocks intercalated locally with graphitic sediments and reworked tuffs (Squires *et al.,* 2000). Gabbroic (Plate 4) and porphyritic dykes and sills (Plate 5) have intruded the sequence along a number of reverse faults. Alteration and mineralization within the block are rare. The base of the block is delineated by the 45° south-dipping Duck Pond thrust, which is marked by zones of mylonite and fault gouge, that juxtapose the Upper block upon the Mineralized block. Essentially, the Upper block represents structural hanging-wall material to VMS mineralization and the Mineralized block represents the original stratigraphic footwall.

The Mineralized block comprises a greater than 900-m-thick sequence of highly altered and deformed, flat-lying aphyric felsic flows and autobreccias (Plate 6), lesser mafic flows and mafic and felsic dykes and minor deep-water graphitic argillite muds that locally contain base-metal bearing sulphide debris-flow beds. The block is interpreted to be wedge-shaped due to the convergence of its bounding faults. Alteration is variable and comprises chloritization, sericitization, silicification, carbonitization (Plate 7) and pervasive pyrite (Squires *et al.,* 1990). Deformation within the block is

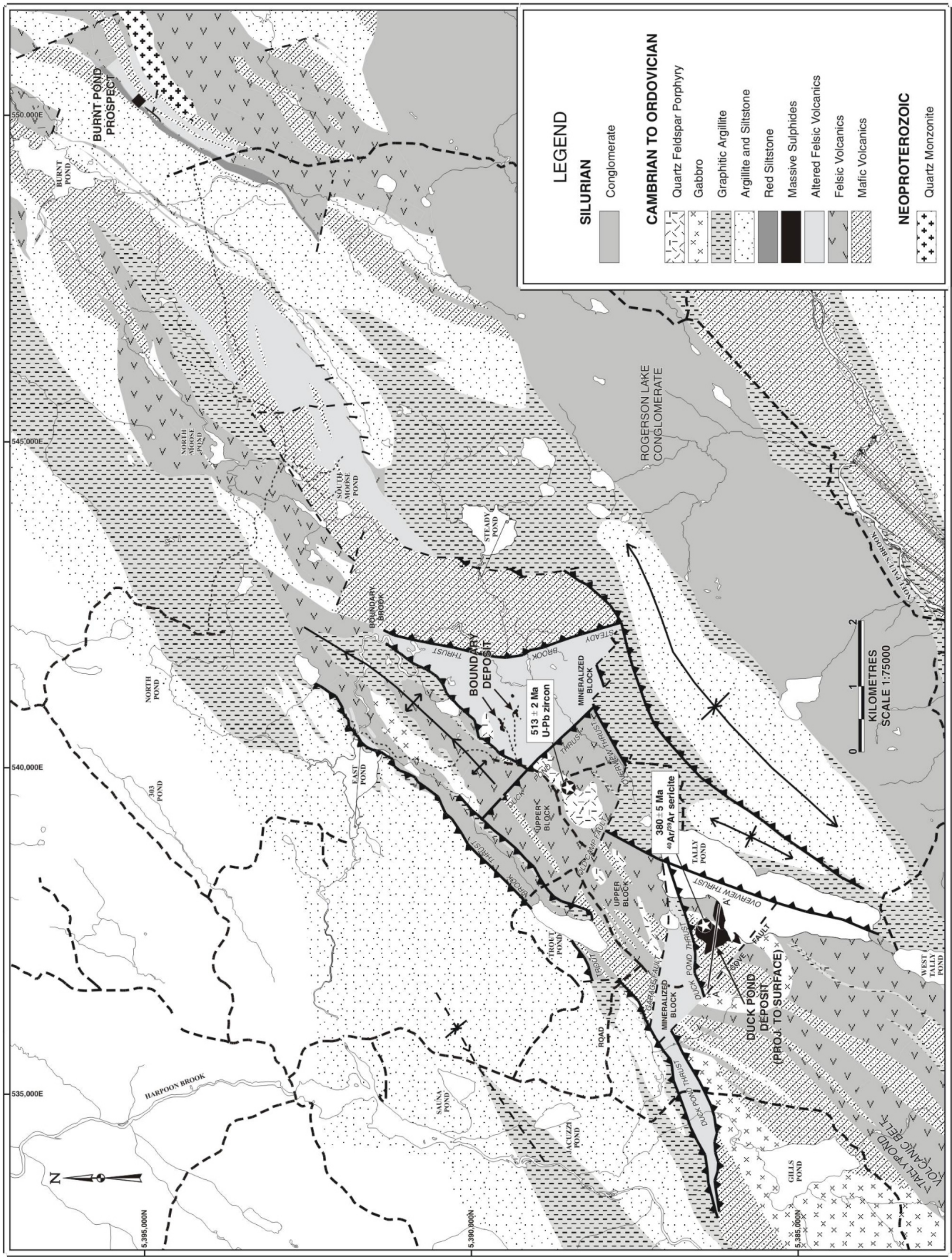

Figure 2. *Geological map of the Tally Pond belt in the Tally Pond–Burnt Pond area; modified from Squires et al. (2000).*

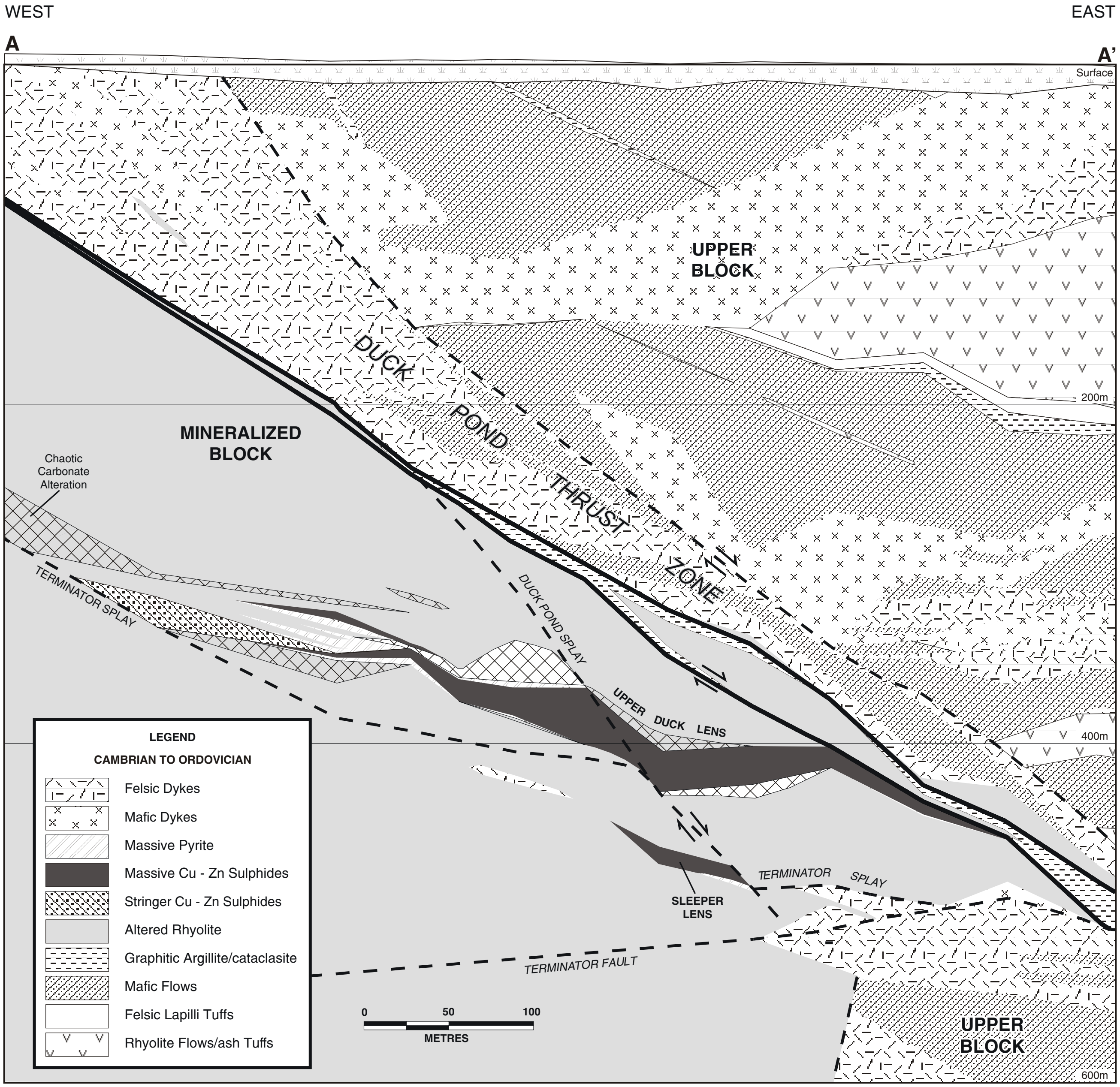

Figure 3. *Geological cross-section along line A-A'; modified from Squires* et al. *(2000).*

pervasive and is dominated by moderately south-dipping, sub-parallel thrust faults that disrupt both the stratigraphy and mineralization.

The two juxtaposed blocks were subsequently disrupted by an episode of southwest-directed thrusting along the north-dipping Terminator thrust. This thrust cuts the Duck Pond deposit and is interpreted to be responsible for the offset between the Upper and Lower Duck zones. A series of northwest–southeast-trending wrench faults termed the Cove, Garage and Old Camp, faults offset the stratigraphy of the two blocks both vertically and laterally by up to 2 km (Squires *et al.*, 1990).

GEOCHEMISTRY

Twenty-nine samples, including outcrop and drillcore, were collected during the 2000 field season from the Tally Pond area for geochemical analysis. The samples were submitted for whole-rock XRF analysis at the Department of Earth Sciences, Memorial University of Newfoundland (MUN), following the procedures of Longerich (1995). The samples were from the area surrounding the Duck Pond and Boundary deposits and their selection was based on the need to provide a wide geochemical coverage for the various rock units in the Tally Pond area. Where possible, samples were collected from the interior of pillows and high-level intru-

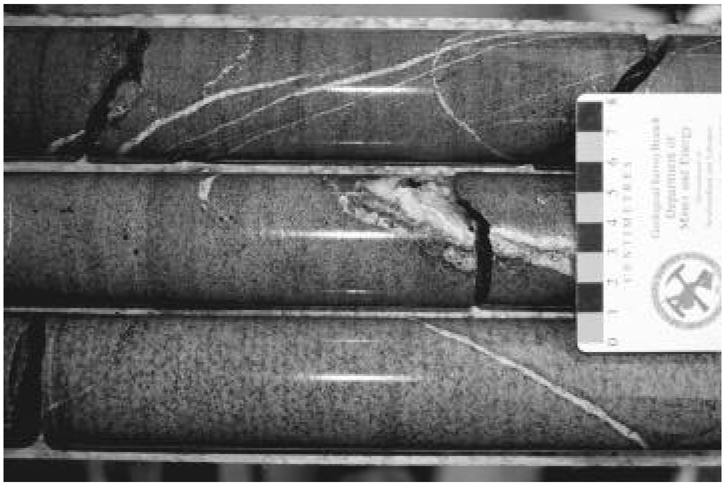

Plate 3. *Calcite amygdaloidal, pillowed mafic flows from the Upper block. Note chlorite alteration along pillow margins.*

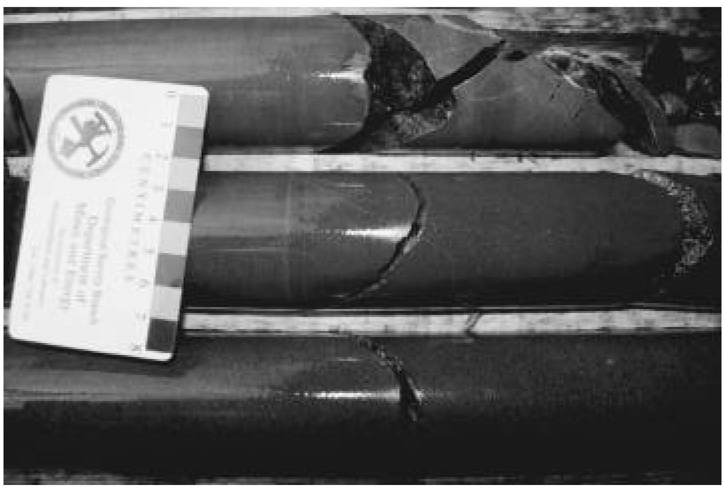

Plate 4. *Fine- to medium-grained diorite-gabbroic dyke, Upper block.*

Plate 5. *Weakly chlorite altered feldspar-quartz porphyritic rhyolite dyke from the Upper block.*

sions; samples showing excessive alteration, veining, or weathering were discarded. The 29 samples include five mafic flows and pillow lavas, four gabbroic to dioritic intrusions, seven rhyodacites from the Upper block, nine rhyodacites from the Mineralized block, two quartz porphyritic rhyolite intrusions and two mafic dykes. The results are presented in Table 1.

The rocks in the Tally Pond area are weakly metamorphosed to lower greenschist-facies, and have undergone periods of intense hydrothermal alteration; therefore, only those elements considered to be immobile with respect to alteration are considered in the following discussion concerning the nature and tectonic setting of the rocks. Trace elements considered to be immobile in typical water–rock reactions are the high field strength elements (HFSE): Ti, Zr, Hf, Nb, Ta, Y and P; the low-field strength elements (LFSE): Th; and the rare-earth elements (REE): La to Lu (Jenner, 1996).

TRACE-ELEMENT DISCRIMINATION DIAGRAMS

The mafic volcanic rocks within the Tally Pond area are classified as either subalkalic basalts or basaltic-andesites. On a discrimination plot (Figure 4a) of Nb/Y vs. Zr/TiO_2 (Winchester and Floyd, 1977) the "structural" hanging-wall mafic rocks plot as two distinct groups. Pillow basalts have Zr/TiO_2 ratios of 0.003 to 0.1 and Nb/Y ratios of 0.1-0.2; gabbros and diorites have approximately the same Zr/TiO_2 ratios but exhibit higher Nb/Y ratios of 0.3 to 0.5 (Figure 4a). Further screening by the ternary Zr–Ti–Y plot (Figure 4b) indicates a similar bimodal subdivision with the pillow basalts restricted to the field of island-arc tholeiites and the gabbroic and dioritic rocks in the field defined by within-plate basalts with some overlap into the calc-alkalic basalt field.

A diagram of Ti–V indicates a similar subdivision for these mafic rocks of the Tally Pond area (Figure 4c). The majority of pillow lava samples show a minimal Ti spread with varying amounts of V and plot in the field for island-arc tholeiites. The exception to this is the one sample that contains greater amounts of Ti and plots between the arc volcanic and MORB fields. The gabbros and diorites exhibit a slight V spread but display a large variation in Ti contents. They also exhibit continental flood basalt characteristics with two samples having an ocean-island alkali-basalt signature. The large variation in Ti/Y ratios of the gabbroic–dioritic rocks is considered to be the result of a Ti-bearing alteration phase, possibly leucoxene and/or rutile.

Plate 6. *Flow-banded, hydrobrecciated rhyodacite, Mineralized block.*

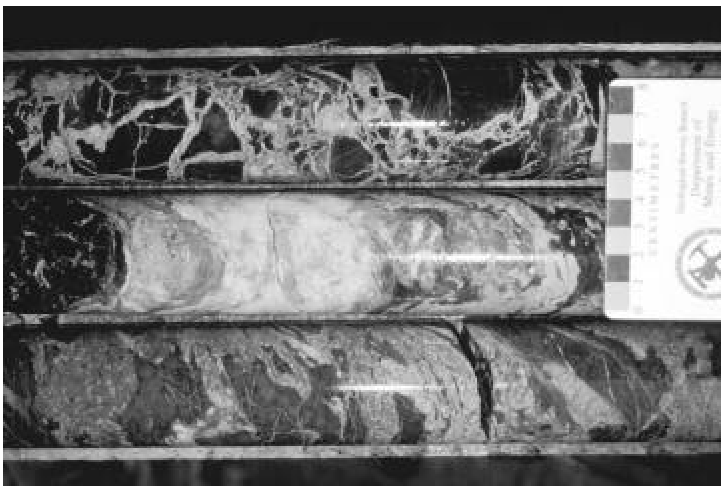

Plate 7. *Intense chlorite and chaotic carbonate altered rhyodacite, Mineralized block.*

A Zr–Zr/Y diagram (Figure 4d) was used to subdivide the mafic rocks of the Tally Pond volcanics into those belonging to oceanic arcs, where only oceanic crust is used in arc construction, and arcs developed at continental margins. The pillow basalts lie in the island-arc field and exhibit an oceanic source, whereas the gabbros and diorites plot with higher Zr/Y and higher Zr, indicating a geochemical behaviour consistent with continental arcs.

Using the same discrimination diagram as for the mafic rocks (Figure 4a), the felsic rocks of the Tally Pond volcanics are classified as mainly rhyodacite to dacite with three samples falling in the rhyolite field. Using a bivariate plot of Nb–Y (Figure 5), the felsic rocks plot as two groups that both lie in the volcanic-arc granite/syn-collisional granite field. One sample from the "structural" hanging-wall displays an ocean ridge granite signature. The seven samples from the hanging-wall show a moderate Nb spread (3 to 10 ppm) and a large variation in Y (9 to 40 ppm), while the nine samples from the footwall have a minimal variation in Nb (6 to 7 ppm) with a slightly larger disparity in Y (25 to 50 ppm). It is interesting to note that the two samples of the quartz porphyritic rhyolite that occur in the hanging-wall plot with the samples from the footwall.

The volcanic rocks are plotted on a Zr–Y diagram (Figure 6) of Barrett and MacLean (1994) to subdivide them on the basis of volcanic affinity. The fields on the diagram are separated on the basis of the Zr/Y ratio where rocks having a Zr/Y ratio of <4.5 are tholeiitic, those with ratios >7 are calc-alkaline, and rocks with intermediate ratios are considered to be transitional. The data from the Tally Pond volcanics plot as two distinct trends. The hanging-wall pillow lavas and rhyolites define a linear trend with the tholeiitic Zr/Y ratio of 4.3. This trend implies that the hanging-wall mafic and felsic rocks may be genetically linked and that they may have had a common magmatic source. The lower trend represents the rhyodacite from the footwall and the porphyritic rhyolites from the hanging-wall and gabbro–diorite dykes from both the footwall and hanging-wall. This group has a Zr/Y ratio of 6.1 and plots in the transition field, indicating that the rocks have both tholeitic and calc-alkaline affinities. This separate trend may be due to a number of factors that include a change in the nature of magmatism or a change in the source that produced the melt material.

RARE-EARTH-ELEMENT GEOCHEMISTRY

After initial examination of the XRF data, 12 of the 29 samples were submitted for analysis by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at the Department of Earth Sciences, MUN, following the sodium peroxide sinter digestion method of Jenner *et al.* (1990). The samples were analyzed for the HFSE: Y, Zr, Nb, Hf, Ta and Ti; the LFSE: Th and Ba; and the REE: La, Ce, Pr, Nd, Sm, Eu, Tb, Dy, Gd, Ho, Er, Tm, Yb and Lu. The geochemical data are listed in Table 2 and presented graphically (Figures 7 and 8) as primitive mantle normalized extended rare-earth-element plots, normalized to Wood *et al.*'s (1979) primitive mantle values.

Mafic pillow lavas of the Tally Pond volcanics plot as depleted island-arc tholeiites and are characterized by moderate LREE enrichment having slightly concave upward extended REE patterns. (Figure 7a). The two samples range between 2 to 11x primitive mantle values for the LREE and 4 to 5x for the HREE. They display prominent negative Nb

Table 1. Major- and trace-element analysis of volcanic rocks of the Tally Pond belt determined by XRF

Sample		DP-89-127	DP-99-202	JP-00-176	JP-00-177	JP-00-178	JP-00-180	JP-00-182	JP-00-185	JP-00-188
Na2O	wt%	3.02%	1.14%	2.21%	4.51%	3.00%	3.24%	2.11%	0.34%	0.30%
MgO	wt%	0.71%	1.64%	5.37%	2.48%	3.71%	9.87%	4.17%	1.12%	5.60%
Al2O3	wt%	13.39%	17.26%	10.79%	14.83%	16.78%	13.91%	16.02%	21.54%	17.56%
SiO2	wt%	65.14%	62.65%	40.88%	70.51%	63.93%	40.86%	66.84%	59.42%	42.93%
P2O5	wt%	0.02%	0.02%	0.28%	0.01%	0.02%	0.38%	0.01%	0.01%	0.04%
K2O	wt%	1.96%	4.14%	0.57%	1.64%	3.46%	0.18%	3.13%	5.19%	3.82%
CaO	wt%	1.12%	3.75%	7.24%	0.31%	0.34%	3.74%	0.23%	0.06%	12.49%
TiO2	wt%	0.18%	0.18%	3.56%	0.16%	0.22%	1.39%	0.18%	0.14%	0.75%
Fe2O3T	wt%	0.73%	1.19%	19.14%	2.61%	4.42%	15.91%	2.30%	9.69%	11.52%
MnO	wt%	0.02%	0.07%	0.22%	0.02%	0.06%	0.21%	0.02%	-0.00%	0.29%
Total	wt%	86.68%	93.20%	90.84%	97.22%	96.84%	90.07%	95.38%	112.82%	98.15%
V	ppm	6	17	451	1	12	389	9	3	398
Cr	ppm	24	15	-8	3	14	51	1	14	15
S	ppm	913	3469	1497	54	3175	1045	328	60134	10413
Cl	ppm	77	161	58	40	32	56	13	9	46
Sc	ppm	7	10	45	19	24	46	11	18	46
Ni	ppm	-12.26	-10.99	-4.22	-8.25	-7.24	3.39	-10.47	505.69	2.17
Cu	ppm	-3.58	0.07	64.76	-3.22	-1.31	18.02	-2.11	14.74	54.90
Zn	ppm	-5.48	-11.90	115.47	28.66	54.33	64.26	14.90	1.30	328.33
Ga	ppm	12.89	16.22	21.65	15.21	22.56	23.39	13.42	20.92	17.06
As	ppm	6.46	36.84	32.92	-0.09	3.71	21.38	2.88	145.39	70.19
Rb	ppm	26.16	58.41	17.13	24.53	54.61	2.20	47.56	67.72	46.02
Sr	ppm	53.37	82.39	224.82	61.76	58.09	98.93	15.30	18.20	280.09
Y	ppm	24.15	22.50	33.08	43.47	42.94	20.61	37.97	29.51	10.00
Zr	ppm	182.57	132.25	210.06	187.91	198.77	48.25	160.69	195.23	35.41
Nb	ppm	7.33	6.25	18.11	6.29	7.07	2.79	7.94	7.73	2.05
Ba	ppm	850.74	2003.21	161.38	429.96	427.62	15.10	2022.33	1281.22	665.36
Ce	ppm	43.47	52.06	-28.99	49.55	45.03	-23.77	35.58	14.24	-34.62
Pb	ppm	-5.87	-0.69	8.87	-5.91	3.55	-8.91	-9.82	81.81	10.34
Th	ppm	5.36	3.09	2.35	7.47	6.57	2.94	5.47	7.90	0.94
U	ppm	2.55	3.79	0.10	0.56	1.09	1.31	1.45	0.20	-2.43

Table 1. (*Continued*)

Sample		JP-00-193	JP-00-194	JP-00-195	JP-00-199	JP-00-202	JP-00-207	JP-00-208	JP-00-209	JP-00-210
Na2O	wt%	6.91%	2.36%	2.27%	0.97%	1.29%	2.28%	6.29%	4.24%	2.86%
MgO	wt%	0.34%	11.07%	5.21%	1.01%	5.45%	1.39%	2.23%	7.88%	6.60%
Al2O3	wt%	12.44%	13.71%	10.81%	12.92%	16.46%	15.16%	13.67%	14.02%	11.91%
SiO2	wt%	73.37%	41.54%	40.85%	77.55%	70.17%	67.71%	60.78%	43.05%	42.41%
P2O5	wt%	0.01%	0.06%	0.37%	0.02%	0.01%	0.02%	0.05%	0.04%	0.16%
K2O	wt%	0.14%	1.79%	1.30%	2.67%	1.76%	2.54%	0.54%	0.57%	0.68%
CaO	wt%	0.59%	7.13%	9.21%	1.20%	0.07%	1.60%	1.91%	4.58%	6.87%
TiO2	wt%	0.15%	0.77%	2.48%	0.13%	0.14%	0.17%	0.25%	0.67%	1.38%
Fe2O3T	wt%	0.42%	11.11%	17.35%	1.03%	2.90%	2.28%	3.39%	12.75%	17.10%
MnO	wt%	0.01%	0.15%	0.22%	0.04%	0.01%	0.04%	0.04%	0.19%	0.27%
Total	wt%	94.67%	89.97%	90.87%	97.94%	101.77%	94.65%	89.24%	88.66%	90.64%
V	ppm	5	268	285	18	40	8	14	360	299
Cr	ppm	-1	269	-1	11	-0	5	9	176	31
S	ppm	950	122	2525	1260	13480	5085	65	1928	838
Cl	ppm	64	40	80	42	18	26	46	21	18
Sc	ppm	28	29	28	14	20	13	12	52	37
Ni	ppm	-9.32	91.59	0.89	-9.02	-9.78	-11.09	-8.10	73.13	25.74
Cu	ppm	-2.54	34.49	47.13	3.82	-2.40	-2.34	-3.67	57.56	62.83
Zn	ppm	-20.16	29.50	81.92	-0.41	9.04	26.76	27.80	101.57	73.19
Ga	ppm	6.98	13.95	23.15	11.99	15.75	12.80	18.32	16.46	21.13
As	ppm	2.50	2.06	-5.41	26.42	74.80	39.47	-7.79	60.84	14.19
Rb	ppm	1.74	26.71	46.31	31.50	27.70	35.75	6.35	5.65	8.55
Sr	ppm	81.56	210.27	303.35	26.34	68.41	39.39	83.91	64.21	299.89
Y	ppm	35.55	17.16	33.87	35.42	32.90	37.99	40.87	18.37	33.88
Zr	ppm	195.21	48.38	223.92	131.83	155.51	168.88	248.46	61.57	201.05
Nb	ppm	9.60	1.88	18.51	5.79	5.90	7.72	7.17	3.37	16.77
Ba	ppm	30.70	779.75	199.56	351.10	870.73	1185.86	151.00	137.45	339.51
Ce	ppm	27.41	1.43	28.01	45.92	24.29	32.60	16.20	14.05	5.28
Pb	ppm	-9.41	-9.59	-3.75	44.43	-2.49	-12.55	-6.38	8.11	-7.63
Th	ppm	7.76	0.86	2.85	5.81	4.47	6.93	7.41	0.23	2.05
U	ppm	0.70	-2.41	-1.68	1.88	2.24	0.82	2.90	4.48	-1.75

Table 1. (*Continued*)

Sample		JP-00-212	JP-00-215	JP-00-275	JP-00-276	JP-00-277	JP-00-279	JP-00-284	JP-00-288	JP-00-201
Na2O	wt%	0.71%	2.11%	3.69%	3.38%	2.53%	4.49%	3.37%	0.50%	0.79%
MgO	wt%	1.17%	0.38%	1.34%	8.17%	6.84%	0.38%	6.63%	2.36%	14.92%
Al2O3	wt%	18.78%	14.91%	12.25%	12.15%	12.23%	13.53%	23.43%	8.76%	18.71%
SiO2	wt%	67.67%	70.19%	66.89%	41.19%	43.23%	71.76%	36.43%	73.96%	48.85%
P2O5	wt%	0.00%	0.02%	0.02%	0.05%	0.34%	0.02%	0.14%	0.00%	0.25%
K2O	wt%	3.66%	3.75%	1.35%	0.83%	0.88%	2.46%	1.50%	1.44%	2.05%
CaO	wt%	0.08%	0.48%	2.34%	11.27%	7.83%	1.95%	13.87%	2.40%	1.40%
TiO2	wt%	0.13%	0.18%	0.23%	0.62%	2.07%	0.14%	1.85%	0.09%	3.31%
Fe2O3T	wt%	2.20%	2.14%	3.12%	9.01%	16.36%	1.36%	4.54%	3.91%	5.75%
MnO	wt%	0.00%	0.05%	0.11%	0.18%	0.21%	0.05%	0.20%	0.02%	0.11%
Total	wt%	97.70%	94.46%	91.67%	87.32%	92.78%	96.27%	92.48%	102.20%	96.65%
V	ppm	5	2	-0	331	254	-5	284	19	388
Cr	ppm	2	15	28	390	38	8	177	41	9
S	ppm	12404	348	894	817	218	123	298	30682	649
Cl	ppm	18	19	25	28	75	46	31	-1	20
Sc	ppm	15	14	4	42	19	23	37	1	56
Ni	ppm	-10.51	-15.73	-10.55	83.45	29.93	-10.67	15.09	-18.38	0.01
Cu	ppm	4.33	-2.00	6.60	45.31	87.78	-1.56	0.99	2064.05	1.58
Zn	ppm	-14.52	30.49	30.28	14.32	79.54	-13.39	37.62	2156.09	95.13
Ga	ppm	16.91	17.48	13.70	8.78	19.04	13.83	19.50	13.88	24.70
As	ppm	49.32	37.19	9.26	36.71	8.12	2.73	113.66	162.20	34.06
Rb	ppm	56.26	54.96	22.08	8.07	10.28	23.32	23.73	22.53	39.54
Sr	ppm	23.00	37.62	276.21	222.51	404.68	56.03	297.96	24.30	55.73
Y	ppm	18.82	43.42	37.01	11.90	36.59	55.54	22.17	8.08	42.50
Zr	ppm	154.50	200.56	160.82	31.87	230.84	174.39	130.06	73.79	258.60
Nb	ppm	5.64	7.55	6.19	2.13	16.80	6.83	12.92	3.69	23.75
Ba	ppm	1382.70	960.89	198.02	592.28	387.03	537.41	2508.41	1798.36	1616.20
Ce	ppm	-3.75	14.28	-16.11	-7.80	56.73	40.17	-9.84	75.61	49.29
Pb	ppm	-1.34	-7.48	-4.81	-9.36	-3.03	-12.12	-8.92	2896.91	-10.10
Th	ppm	6.86	7.37	3.00	6.14	7.99	4.33	6.76	19.72	5.57
U	ppm	1.69	-0.17	-0.61	-0.58	1.45	0.39	-0.32	2.11	0.56

and Ta anomalies and positive Th anomalies with respect to La and Ce, which is typical of island-arc, subduction related lavas (Swinden *et al.,* 1989). Both samples also have prominent negative Zr and Hf anomalies and less obvious negative Ti and Y anomalies of varying magnitude.

The gabbroic–dioritic rocks are enriched in the incompatible elements and are characterized by steep, relatively flat extended REE patterns (Figure 7b). Both samples are depleted in Nd, Sm and Y and enriched in Zr, Nf, Ti and Er. The prominent negative Ta anomaly in sample 284 is due to incomplete dissolution during the sodium peroxide sinter digestion method used to analyse the sample, and does not represent an actual depletion in Ta. The internal check of Zr and Hf analyzed by ICP-MS and XRF indicates that there are no further dissolution problems with the REE.

The extended REE extended plot for the felsic volcanic rocks from the hanging-wall is characterized by enrichment of the LREE relative to the HREE and slightly concave upward patterns consistent with depletion of the MREE and HREE. Two samples of flow-banded rhyolite (Figure 8a) and two samples of porphyritic rhyolite (Figure 8b) contain obvious negative Ti and Eu anomalies, and positive Th, and negative Ta, Nb anomalies. All four samples are slightly depleted in Y and Nb and enriched in Hf. One of the porphyritic rhyolite samples (212) shows a relative depletion in the LREE when compared to the other samples. This sample contains a network of chlorite veins and has undergone at least one episode of alteration that is considered to have been responsible for the depletion of the LREE.

Four samples of rhyodacitic flows from the footwall are the most LREE enriched felsic rocks (Figure 8c). They have steep negatively sloping REE patterns and all have distinctive negative Ti, Eu, Ta and Nb anomalies and positive Th anomalies. All of the samples contain negative Y anomalies with respect to adjacent REE. Sample 288 is overall less enriched compared to the remaining three and displays a marked negative Nd anomaly along with severe depletion in the LREE relative to the MREE and HREE. This sample is a highly altered and weakly mineralized rhyodacite that occurs immediately beneath the Duck Pond deposit. There appears to be a minor amount of mass gain in the rock and the alteration seems to have preferentially stripped the rock of the LREE-La, Ce and Nd.

LEAD-ISOTOPE GEOCHEMISTRY

A total of 13 galena separates from the Tally Pond belt were analyzed for their lead isotope ratios. Galena was collected from the shallow and deep sections of the Upper

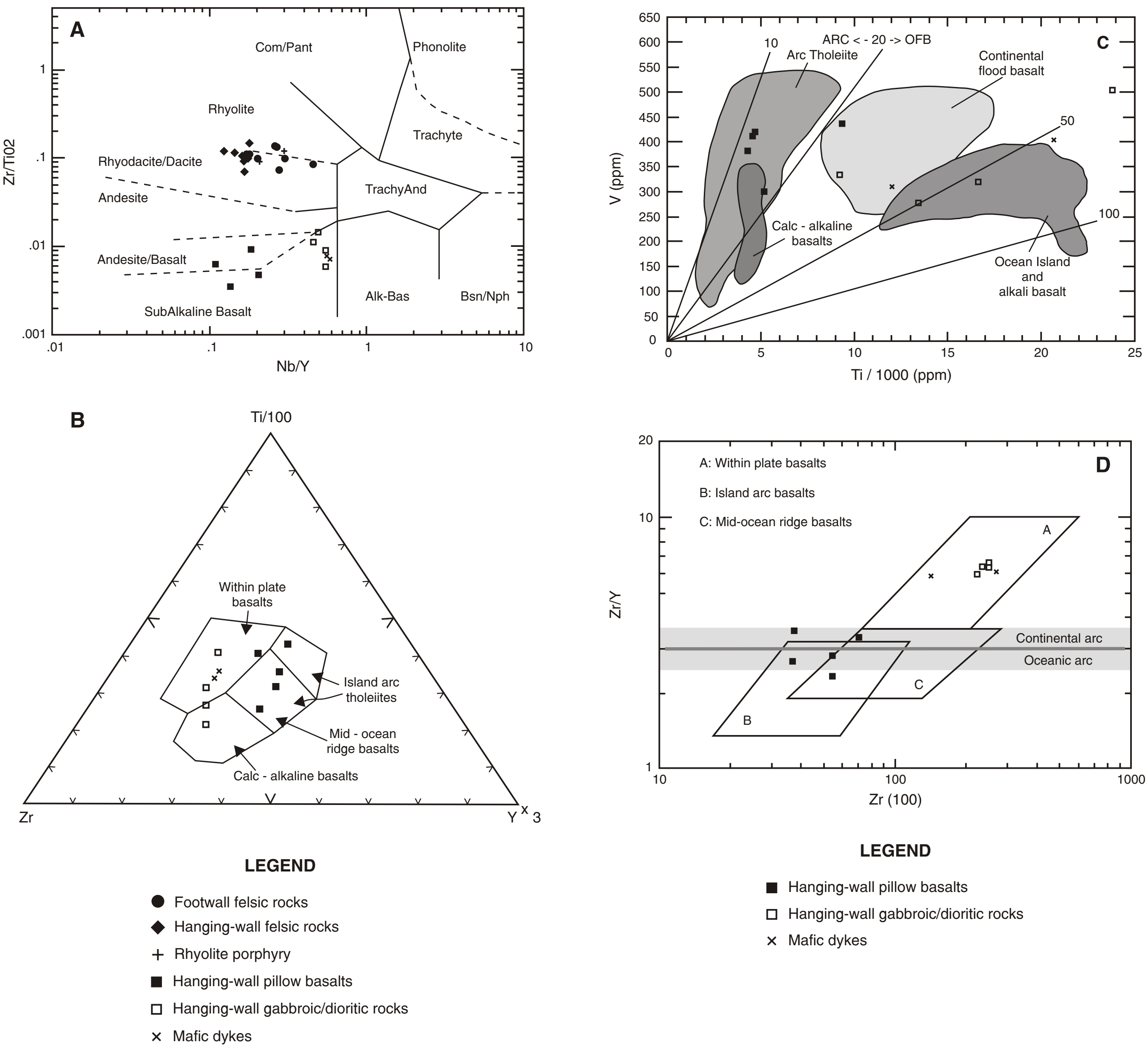

Figure 4. *Immobile trace-element discrimination diagrams for volcanic rocks for the Tally Pond belt a) Nb/Y vs. Zr/TiO_2; b) Zr–Ti–Y, fields after Pearce and Cann (1973); c) Ti–V, fields after Shervais (1982); and d) Zr–Zr/Y, the shaded area is the field of overlap between the two arc types; fields after Pearce and Norry (1979).*

Duck lens of the Duck Pond Deposit, the South Moose Pond zone, and the Lemarchant prospect. Analyses were carried out at the GEOTOP Laboratory, Université du Québec á Montréal (UQAM). Data are reported as $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{206}Pb$ with an analytical uncertainty of 0.05% amu-1 at the 1 σ level (Moritz and Malo, 1996).

The lead-isotope data for the Tally Pond belt are listed in Table 3 and shown in Figure 9. The data indicate that all samples from the Tally Pond belt show a very small variation in the $^{206}Pb/^{204}Pb$ ratio bound on the lower end by the Lemarchant prospect and the high end by the samples from the deep sections of the Upper Duck lens. The $^{207}Pb/^{204}Pb$ ratios are highly variable between all of the samples and indicate that the lead isotopes for the Tally Pond belt define three groups, 1) a primitive group represented by galena from the Lemarchant prospect, 2) a slightly more radiogenic group that includes the higher levels (<350m) of the Upper Duck lens and South Moose zones, and 3) a relatively radiogenic group that represents the deep sections (>400m) of the Upper Duck lens.

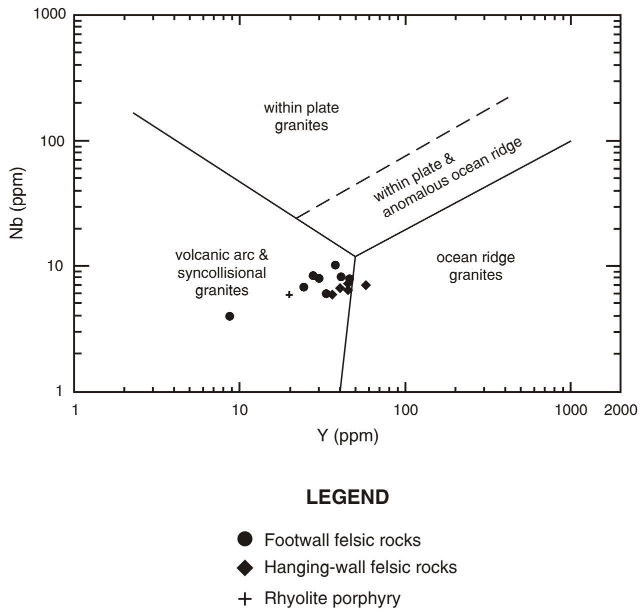

Figure 5. *Bivariate plot of Nb–Y for felsic volcanic rocks; fields after Pearce* et al. *(1984).*

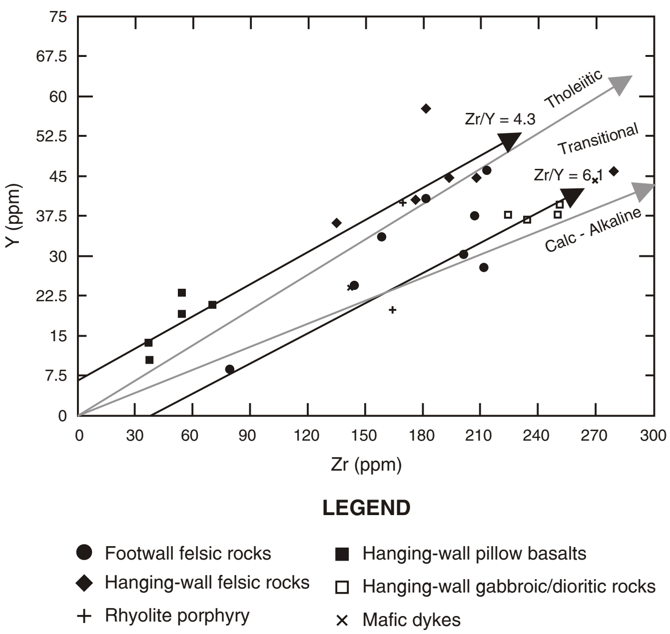

Figure 6. *Zr–Y diagram used to subdivide felsic volcanic rocks based on volcanic affinity.*

The variation in the lead isotope signatures between the deep and shallow sections of the Upper Duck lens may be due to one of a couple of different factors. Lead in the deeper sections of the Upper Duck lens is more radiogenic than the structurally higher levels of the Upper Duck lens suggesting derivation from a source with more continental crust. Such a scenario may indicate that the entire deposit has been structurally inverted since its time of formation. This scenario seems unlikely as sulphide-bearing debris-flow beds are fining upward sequences, and the large chlorite alteration feeder pipes are presently located beneath the massive sulphide bodies. The more likely scenario is that the lead from the deep sections of the Upper Duck lens is a mixture of both continental and mantle derived lead as the steep, linear trend between the Duck Pond samples is interpreted as a mixing line. The relatively more radiogenic lead ratios in the deep Upper Duck lens may indicate the influence of a continental lead source in the hydrothermal system followed by introduction of more mantle-derived lead when the ore-bearing system became more intense. The high levels of the Upper Duck lens consist of a less radiogenic end member and is almost certainly derived from a mantle source. The variation in the lead isotope ranges for the Duck Pond deposit, probably reflects the lead isotope variation present when the deposit formed rather than a distribution due to past ore deformation and metamorphism (Bjerkgård *et al.*, 2000).

Previous workers (Swinden, 1987; Hall *et al.*, 1998; Williams *et al.*, 1988; Evans, 1996) have suggested that the lead isotopic signatures in volcanogenic massive sulphide deposits of the Notre Dame Subzone contrast with those of the Exploits Subzone. Analysis of the lead isotope data from other deposits in the Victoria Lake Group and elsewhere in the Newfoundland Dunnage Zone (Figure 9) indicate that a contrast does exist in the lead isotopic signatures between the two subzones. The Skidder, Connel, Buchans, and Mary March deposits (Cumming and Krstic, 1987), located in the Notre Dame Subzone, display a larger variation in the $^{206}Pb/^{204}Pb$ than the $^{207}Pb/^{204}Pb$ ratio and are the most primative in terms of their U/Pb evolution. Three other deposits from the Notre Dame Subzone, the Bull Road, Pilleys Island and Shamrock, lie in the same field as those of the Buchans area, with the Pilleys Island sample being the most primitive.

Samples from the Exploits Subzone include the 13 samples collected for this study from the Duck Pond Deposit and Lemarchant prospect of the Tally Pond belt, along with the Tulks East, Tulks Hill, and Victoria Mine prospect from elsewhere in the Victoria Lake Group (Cumming and Krstic, 1987). The lead isotope signatures of each of these deposits are much more radiogenic than those of the Notre Dame Subzone and have a larger variations in the $^{207}Pb/^{204}Pb$ than the $^{206}Pb/^{204}Pb$ ratio; this is opposite to that of the Notre Dame Subzone and indicates that the material may have been derived from sources with slightly different U/Pb ratios. The Strickland deposit (Swinden and Thorpe, 1984), located in the southwest Exploits Subzone, has a high $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ ratio, is relatively more radiogenic and lies in the field defined by the Exploits Subzone. Galena from the Handcamp occurrence has the same $^{206}Pb/^{204}Pb$ ratio as deposits in the Exploits Subzone, however, the $^{207}Pb/^{204}Pb$

Table 2. Trace-element analysis of volcanic rocks of the Tally Pond belt determined by ICP-MS

Sample		DP-99-202	JP-00-193	JP-00-288	JP-00-215	JP-00-208	JP-00-275	JP-00-284	JP-00-176
Y	ppm	26.123	31.200	18.706	37.459	37.911	34.024	21.061	31.267
Zr	ppm	122.929	150.470	63.627	151.388	224.103	124.214	120.012	213.208
Nb	ppm	4.462	7.227	3.344	7.064	6.144	4.789	4.071	16.642
Ba	ppm	1339.450	41.102	1301.043	739.399	131.932	172.494	1398.130	168.496
La	ppm	19.297	17.124	3.450	19.313	20.026	15.336	7.301	15.549
Ce	ppm	40.571	34.708	6.723	40.748	45.713	33.641	17.244	37.197
Pr	ppm	4.787	4.029	0.764	4.842	5.685	4.196	2.348	5.052
Nd	ppm	19.556	16.159	3.101	20.021	23.609	17.808	10.862	22.993
Sm	ppm	4.282	3.289	1.037	5.255	5.892	4.710	3.481	6.217
Eu	ppm	0.994	0.664	0.259	1.183	1.229	1.172	1.226	2.032
Gd	ppm	4.751	3.990	2.089	5.903	6.222	5.312	4.281	6.726
Tb	ppm	0.764	0.750	0.511	1.000	1.079	0.918	0.704	1.063
Dy	ppm	5.065	5.600	3.870	6.674	7.369	6.206	4.390	6.533
Ho	ppm	1.106	1.299	0.806	1.456	1.570	1.350	0.869	1.300
Er	ppm	3.646	4.369	2.367	4.844	5.326	4.424	2.615	3.879
Tm	ppm	0.507	0.616	0.295	0.693	0.778	0.620	0.345	0.513
Yb	ppm	3.205	4.088	1.737	4.654	5.214	4.104	2.097	3.163
Lu	ppm	0.432	0.554	0.237	0.728	0.811	0.649	0.308	0.469
Hf	ppm	3.848	3.948	1.781	4.338	6.477	3.553	3.446	5.803
Ta	ppm	0.377	0.517	0.334	0.517	0.443	0.344	0.330	1.187
Th	ppm	6.003	6.552	2.746	6.773	5.706	4.278	1.916	2.565

Table 2. (*Continued*)

Sample		JP-00-212	JP-00-182	JP-00-194	JP-00-180	JP-00-182*	JP-00-212*	DP-99-202*
Y	ppm	30.898	34.179	15.797	19.482	33.767	16.656	18.644
Zr	ppm	125.012	142.641	43.487	45.697	138.302	120.351	120.019
Nb	ppm	3.910	4.403	1.334	1.992	6.230	5.394	2.172
Ba	ppm	825.347	1344.596	623.923	34.013	1334.671	862.079	1418.825
La	ppm	7.064	16.835	3.915	3.876	17.002	7.255	19.029
Ce	ppm	14.423	35.546	9.570	10.782	35.577	14.376	40.435
Pr	ppm	1.696	4.217	1.328	1.692	4.215	1.736	4.772
Nd	ppm	6.959	17.130	6.330	8.700	17.102	6.965	19.417
Sm	ppm	2.135	4.407	2.012	2.854	4.356	1.743	4.153
Eu	ppm	0.558	0.769	0.745	1.164	0.771	0.403	0.909
Gd	ppm	3.713	4.918	2.494	3.546	4.845	1.997	3.965
Tb	ppm	0.756	0.869	0.425	0.567	0.854	0.374	0.573
Dy	ppm	5.317	5.899	2.913	3.713	5.706	2.668	3.693
Ho	ppm	1.173	1.311	0.627	0.787	1.260	0.647	0.810
Er	ppm	3.905	4.476	2.006	2.454	4.328	2.404	2.706
Tm	ppm	0.555	0.651	0.267	0.323	0.634	0.379	0.391
Yb	ppm	3.627	4.395	1.716	2.037	4.268	2.765	2.609
Lu	ppm	0.571	0.701	0.266	0.317	0.688	0.463	0.364
Hf	ppm	3.780	4.615	1.362	1.445	4.271	3.558	3.798
Ta	ppm	0.364	0.412	0.097	0.152	0.457	0.391	0.215
Th	ppm	4.751	6.012	0.939	1.439	5.915	4.791	5.771

ratio is slightly less indicating that the Handcamp occurrence is less radiogenic than the deposits in the Victoria Lake Group.

The Neoproterozoic Winter Hill deposit from the Avalon Zone is included in this study for comparative purposes. Five samples from the deposit (Sears and Wilton, 1996) have significantly lower $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios and are therefore much older than deposits in the Dunnage Zone. The lead isotopes are more radiogenic than those of the Notre Dame Subzone, and suggest that the Gondwanan continental crust contained a higher U/Pb amount, or μ value, than the Laurentian crust.

Stacey and Kramers' (1975) model ages calculated from the $^{207}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ data are listed in Table 3. Model

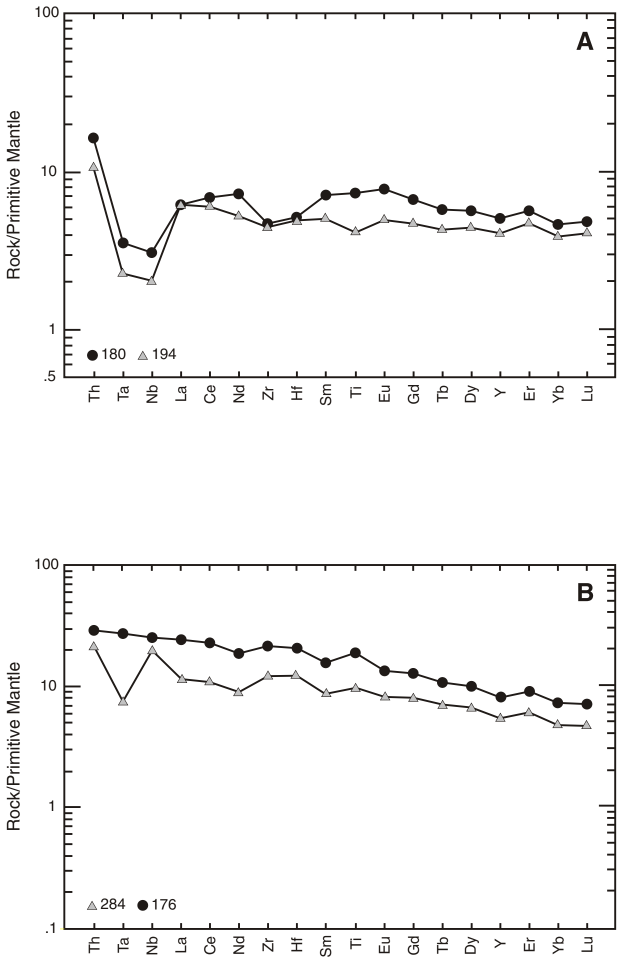

Figure 7. *Primitive mantle normalized-extended rare-earth-element plots of mafic rocks a) pillow lavas and b) gabbro–diorite.*

lead ages from Paleozoic VMS deposits should be used with caution, as these ages are only accurate if both U and Pb remained closed to external disturbance during radioactive decay in the source material and were then separated into the ore deposit. These rigid conditions are seldom realized in nature and one must assume that the U and Pb isotopes have been disturbed. The model ages for the 13 analyses from the Tally Pond belt range from a high of 589 Ma to a low of 295 Ma. Six samples from the top section of the Upper Duck lens, 2 samples from the South Moose Pond zone, and 2 samples from the Lemarchant prospect yield model ages that range from 327 to 299 Ma, which are significantly younger than the model ages for the 3 samples from the deep section of the Upper Duck lens, calculated at 396, 425 and 589 Ma. All of these ages (except sample 342) are much younger than the minimum age of the Tally Pond belt, which has been precisely determined by U/Pb zircon geochronology as 513 ± 2 Ma (Dunning *et al.*, 1991). These model ages

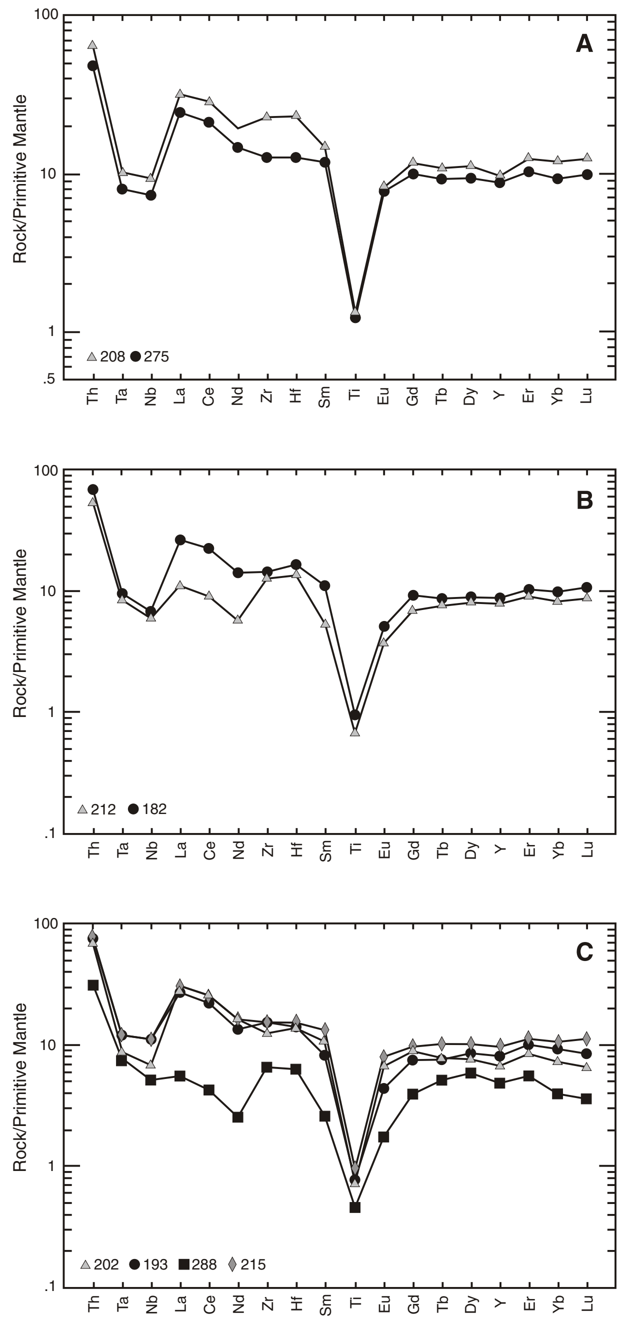

Figure 8. *Primitive mantle normalized-extended rare-earth-element plots of felsic rocks a) hanging-wall rhyolite, b) porphyritic rhyolite and c) footwall rhyodacite.*

suggest that the U and/or Pb in the source material were disturbed at one or possibly many times before the Pb was segregated into the ore. The anomalously high 589 Ma model age may be in part due to a remobilization from an earlier Pb accumulation.

Table 3. Lead-isotope ratios for 13 samples in the Tally Pond area, and 3 other deposits in the Newfoundland Dunnage Zone.

Sample	Deposit	206Pb/204Pb	207Pb/204Pb	208Pb/204Pb	207Pb/206Pb	208Pb/206Pb	Model Age	µ
JP-00-03	Lemarchant	18.098	15.555	37.762	0.8595	2.0866	305	9.557
JP-00-34	South Moose Pond	18.159	15.584	37.872	0.8582	2.0855	319	9.67
JP-00-44	South Moose Pond	18.17	15.586	37.872	0.8577	2.0842	314	9.676
JP-00-90	Lemarchant	18.119	15.576	37.821	0.8597	2.0874	332	9.645
JP-00-322	Upper Duck	18.16	15.579	37.84	0.8578	2.0834	307	9.647
JP-00-336	Upper Duck	18.189	15.599	37.892	0.8576	2.0832	327	9.729
JP-00-337	Upper Duck	18.144	15.567	37.809	0.8579	2.0838	295	9.598
JP-00-338	Upper Duck	18.172	15.586	37.858	0.8577	2.0834	313	9.675
JP-00-339	Upper Duck	18.149	15.571	37.822	0.8579	2.0839	299	9.614
JP-00-340	Upper Duck	18.15	15.575	37.829	0.8582	2.0844	307	9.632
JP-00-341	Lower-Upper Duck	18.276	15.681	38.081	0.8579	2.0834	425	10.07
JP-00-342	Lower-Upper Duck	18.311	15.783	38.484	0.8614	2.1014	589	10.53
JP-00-343	Lower-Upper Duck	18.209	15.641	37.95	0.8577	2.0834	396	9.912
W-97-18	Pilleys Island	17.831	15.417				217	9.013
W-97-19	Bull Road	17.931	15.498				315	9.347
W-95-38	Handcamp	18.096	15.54				275	9.49

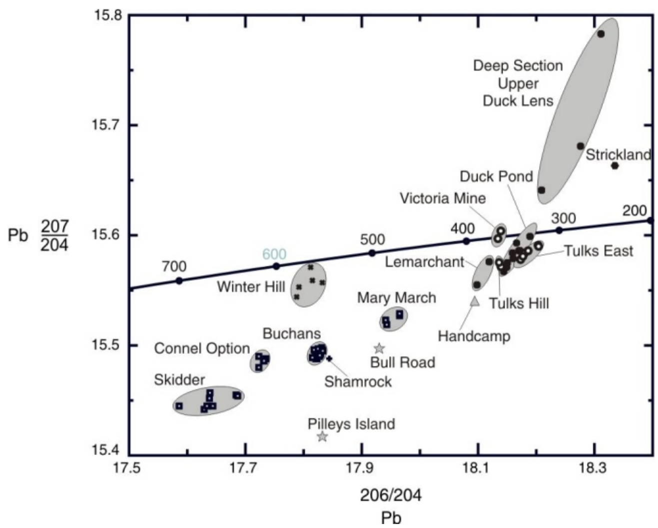

Figure 9. *$^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ data for analyses in the Tally Pond belt and other deposits in central Newfoundland. The solid line is Stacey and Kramers' (1975) average crust growth curve; ages by marks are in Ma.*

CONCLUSIONS

The Tally Pond belt comprises a mixed volcanic assemblage dominated by felsic pyroclastic rocks containing minor mafic flows and intrusions. The assemblage ranges from depleted arc-tholeiitic basalt to moderately LREE enriched rhyolites having tholeiitic affinities and transitional to slightly calc-alkaline, variably LREE enriched rhyodacites. The basaltic rocks consistently exhibit an arc signature based on their Zr–Zr/Y ratios and high V contents relative to Ti. They are depleted arc tholeiites with moderate LREE enrichments. The felsic rocks range from rhyolite to rhyodacite and display a volcanic arc signature due to their high Y/Nb ratios. These rocks are variably LREE enriched island-arc volcanic rocks that are mainly tholeiitic whereas samples from the footwall have transitional to slight calc-alkaline affinities. Gabbro and diorite intrusions into the mafic and felsic rocks are subalkalic basalt in composition, transitional, and exhibit LREE enrichment relative to the MREE and HREE. The altered footwall felsic rocks that lie beneath the Duck Pond VMS deposit show REE depletions of different magnitudes. Europium is depleted in all of the samples to varying degrees and the most heavily altered and weakly mineralized samples have the largest negative Eu anomalies in addition to severe depletion in the LREE–La, Ce, and Nd. The depletion of the LREE and Eu in these samples is due to the destruction of feldspar during periods of intense alteration.

From this evidence, the felsic volcanic rocks of the hanging-wall and footwall show some slight differences. The two rock groups have the same general Nb–Y ratios but differ in the variation of each element; hanging-wall rocks contain a large variation in Y and moderate variations in Nb whereas the footwall rocks exhibit minor variations in both elements. Zr–Y ratios demonstrate that the hanging-wall volcanic rocks exhibit tholeiitic affitinities, whereas the felsic rocks from the footwall are transtional to almost calc-alkaline. Comparison of the HFSE and REE elements from the hanging-wall and footwall also illustrate that there are minor differences in the two rocks groups. Both rocks groups have concave-upward patterns and are depleted in the MREE and HREE. All of the rocks exhibit prominent negative Ta, Nb and Ti anomalies. The differencs in the hanging-wall and footwall felsic volcanic rocks is in the degree of LREE enrichment; the footwall rocks are slightly more enriched in the LREE than those of the hanging-wall.

The variations in REE patterns between the mafic and felsic volcanic rocks is interpreted to be the result fractionation differences between the mafic and felsic rocks. The mafic volcanic and intrusive rocks are depleted to moderately LREE enriched whereas the felsic rocks are 5 to 8 times more enriched in the LREE. This variability results from the LREE being the most incompatible of the REE and therefore will remain in the melt phase until the final stages of fractionation. The slightly concave-upward extended REE patterns exhibited by the felsic rocks results from the relative depletion of the MREE with respect to the LREE and HREE. The MREE are more compatible than the LREE and the depletion in the felsic rocks is due to fractionation from an amphibole-bearing magma.

The hanging-wall felsic rocks define a fractionation trend with the mafic varieties based on their Zr–Y ratios. A similar case can be made for the footwall felsic rocks and mafic intrusions; these groups define a weak trend and thus may be genetically related. Volcanic-arc environments are notoriously (geochemically) complex and the disparity in the trace-element abundances between the various rocks types may possibly reflect variations in the source characteristics coupled with differences in the degree of partial melting.

The geochemical data indicate that the volcanic and intrusive rocks of the Tally Pond belt in the area of the Duck Pond deposit are viewed as broadly bimodal, with geochemical affitities to two tectonic environments. The mafic and felsic volcanic rocks of the hanging-wall and footwall have characteristics of island-arc magmatism in their HFSE and REE elements and plot in plate marginal fields on the Ti–Zr–Y diagram. All of the rocks exhibit distinctive positive Th and negative Ta and Nb anomalies which indicates that magmatism was influenced by a subducting slab (Swinden *et al.*, 1989). The mafic intrusive rocks of the Tally Pond belt, exhibit no island-arc affinities on the extended REE diagrams and plot in the within plate basalt field on the Ti–Zr–Y diagram. These rocks are considered to have been produced in a setting influenced by continental crust. The distinctively high Ti/V and Zr/Ti ratios exhibited by these rocks indicate that they were contaminated by melting from a deep crustal source.

Lead isotope ratios for volcanogenic massive sulphide deposits in the Newfoundland Dunnage Zone indicate that there are two general groups of deposits. A primitive group, which consists of the Buchans, Skidder, Mary March, and Connel deposits of the Notre Dame Subzone and a relatively more radiogenic group comprising the deposits of the Victoria Lake Group and the Strickland occurrence of the Exploits Subzone. The variations in these lead isotope ratios suggest that the deposits of the Exploits subzone contain a greater influence of continental crust material.

Previous studies (Cumming and Krstic, 1987; Winter, 2000) have shown that there is a consistency in the lead isotope ratios of all data from the Buchans area and that these deposits evolved in a region of relatively low U/Pb. This feature is also a characteristic of lead deposits in the Grenville Province (Farquhar and Fletcher, 1980) and suggests that the Buchans deposits and other deposits in the Notre Dame Subzone evolved under the influence of Laurentian continental crust.

The lead-isotope data from the Victora Lake Group and other deposits indicate that the Exploits Subzone evolved in a region of higher U/Pb relative to the Notre Dame Subzone. The Exploits Subzone appears to have been influenced not by the Laurentian crust but rather by Gondwanan continental crust. This hypothesis seems reasonable as data from the Avalon Zone, namely the Winter Hill deposit, indicate that the Avalonian continental margin includes a considerable amount of crustal material that evolved with large amounts of U relative to Pb.

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