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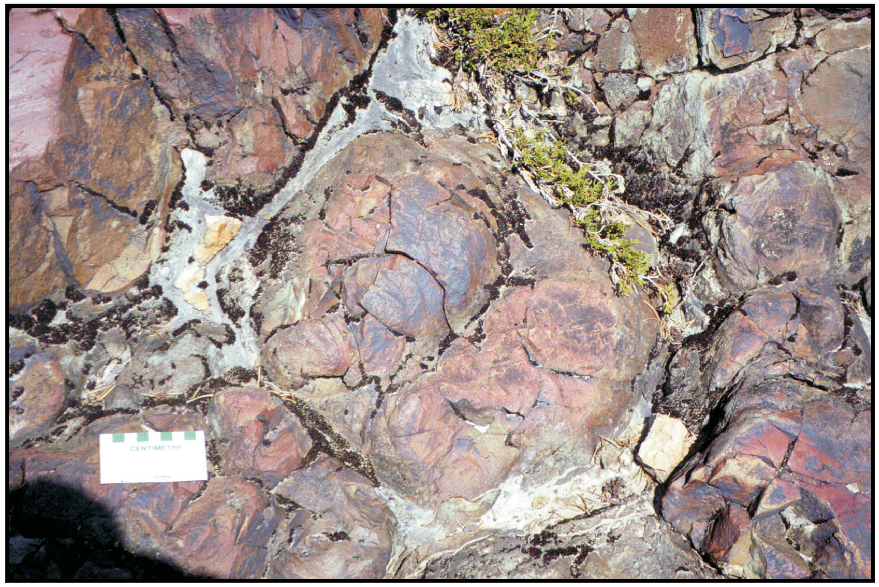
GEOSCIENTIFIC PAPER

Geochemical constraints on the tectonomagmatic evolution of the Fox River Belt, northeastern Manitoba (NTS 53M15 and 16)



By
G. Desharnais, D.C. Peck,
N.M. Halden, R.F.J. Scoates
and L.J. Hulbert

Manitoba

Building for the Future

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by G. Desharnais, D.C. Peck, N.M. Halden, R.F.J. Scoates and L.J. Hulbert
Winnipeg, 2004

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Cover photo: Pillowed komatiitic basalt flow from the Great Falls area on the Fox River

Abstract

The Fox River Belt is one of the best preserved segments of the Circum-Superior Belt. It is a north-facing homoclinal sequence comprising Paleoproterozoic, rift-related, clastic and chemical sedimentary rocks intercalated with thick sequences of komatiitic basalt and intruded at two stratigraphic levels by ultramafic intrusions. Recent mapping, sampling and analyses have resulted in a large geochemical database[1] that is available with this report. The bulk of the samples have been analyzed for a full suite of trace elements, and most of the magmatic samples have high-quality data for Pt, Pd and Au.

Magmatism in the Fox River Belt is tholeiitic and komatiitic in affinity. The Lower and Upper Volcanic formations, which are both subdivided into four members (A to D), are geochemically and volcanologically indistinguishable and could represent a thrust-repeated sequence. The bulk of the volcanic stratigraphy appears to be the product of fractional crystallization of olivine and chromite in a subchamber, possibly represented by the Fox River Sill. The upper section (D Member) of the Lower and Upper Volcanic formations is significantly more evolved than the rest of the sequence, as evidenced by higher Ti concentrations (>1.5%) and lower magnesium number (Mg# < 50). This difference in chemistry could be due to a separate melting event or a shift from fractionation of olivine and chromite to fractionation of plagioclase, clinopyroxene and orthopyroxene, separated by a hiatus in volcanism.

The Fox River Sill, which likely evolved as an open system, is very ultramafic in character: 78% of the sill consists of olivine cumulate. The bulk of the magmatism does not appear to have undergone significant contamination. The exceptions include approximately half of the Lower Intrusions, which appear to be homogeneously contaminated, and the upper and lower contacts of the Fox River Sill. Contamination is shown by elevated light rare earth elements and negative Nb anomalies, and is supported by Sm-Nd and Lu-Hf isotopic compositions. Platinum group element (PGE) depletion is pronounced over a few intervals within the Fox River Sill, as well as within parts of some Lower Intrusions. Several stratigraphic intervals within the sill also have anomalous PGE concentrations. In particular, the Lower Central Layered Zone of the sill has several attributes indicative of PGE prospectivity, yet has never been explored for PGE.

Collectively, the geochemical data for the Fox River Belt support a link to coeval craton-rift assemblages in the Superior Boundary Zone in the Cape Smith Belt of Quebec or the Thompson Nickel Belt of Manitoba. Furthermore, evidence from both the Lower Intrusions and the Fox River Sill suggests that they have incorporated external S and therefore have the potential to host large magmatic sulphide accumulations.

[1] MGS Data Repository Item 2004001, containing the geochemical data used in this report, is provided on the CD-ROM included in the back pocket of the report. It is also available on request from minesinfo@gov.mb.ca or from the Mineral Resources Library, Manitoba Industry, Economic Development and Mines, 360-1395 Ellice Avenue, Winnipeg, MB R3G 3P2, Canada.

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MAP

GP2004-1-1 Geology of the Fox River Sill in the Great Falls area, Fox River Belt, northeastern Manitoba (part of NTS 53M16), scale 1:5000 ....in back pocket

DIGITAL DATA

MGS Data Repository Item 2004001: Major- and trace-element analytical data for whole-rock samples from the Fox River Belt, northeastern Manitoba ....on accompanying CD-ROM in back pocket

Introduction

The Fox River Belt is a Paleoproterozoic volcanic belt that borders the Superior Province in northern Manitoba. It forms a segment of the Circum-Superior Belt, which comprises a series of 2.0–1.8 Ga supracrustal belts with magmatic rocks of komatiitic affinity that overlie and are infolded with the Neoarchean and Mesoarchean gneiss at the margin of the Superior Province (Figure 1; Baragar and Scoates, 1987). The Superior Boundary Zone, the result of early rifting along the present boundary of the Superior Province, now forms the external zone of the Trans-Hudson Orogen. The degree of preservation of these Paleoproterozoic rift-related rocks is dependent on their position during the collisional juxtaposition of the Trans-Hudson rocks with those of the Superior Province (Green et al., 1985; Bleeker, 1990). Other well-studied segments of the Superior Boundary Zone include the Thompson Nickel Belt and the Cape Smith Belt. The Fox River Belt, although poorly exposed, is relatively well preserved and therefore provides a unique opportunity to study these economically important rocks in the context of the geological evolution of the Circum-Superior Belt.

The Fox River Belt is a north-facing homoclinal sequence, comprising clastic and chemical sedimentary rocks, intercalated with thick sequences of komatiitic basalt and intruded at two stratigraphic levels by ultramafic intrusions (Figures 1, 2; Scoates, 1981a; Peck et al., 2002). The lower level of intrusions, the Lower Intrusions, are commonly differentiated into peridotitic bases and gabbroic upper portions. The Lower Volcanic Formation, composed of komatiitic and tholeiitic basalt, has been interpreted as being comagmatic with these intrusions. The second stratigraphic level of intrusion, the Fox River Sill, is one of the largest ultramafic intrusions in the world (Scoates, 1990). The Upper Volcanic Formation is thought to have been tapped from the Fox River Sill and is very similar in composition and physical volcanology to the Lower Volcanic Formation (Scoates, 1981). The grade of metamorphism increases from prehnite-pumpellyite facies in the north to greenschist facies in the south.

Previous work

Merritt (1925) and Quinn (1955) were the first to recognize ultramafic rocks along the Fox River. Potter (1962) delineated the eastern lobe of the Fox River Sill based on ultrabasic rocks he had observed on the Stupart River and from aeromagnetic data. Scoates (1981, 1990) completed a detailed petrographic, petrological and stratigraphic study of the Fox River Sill and the volcanic

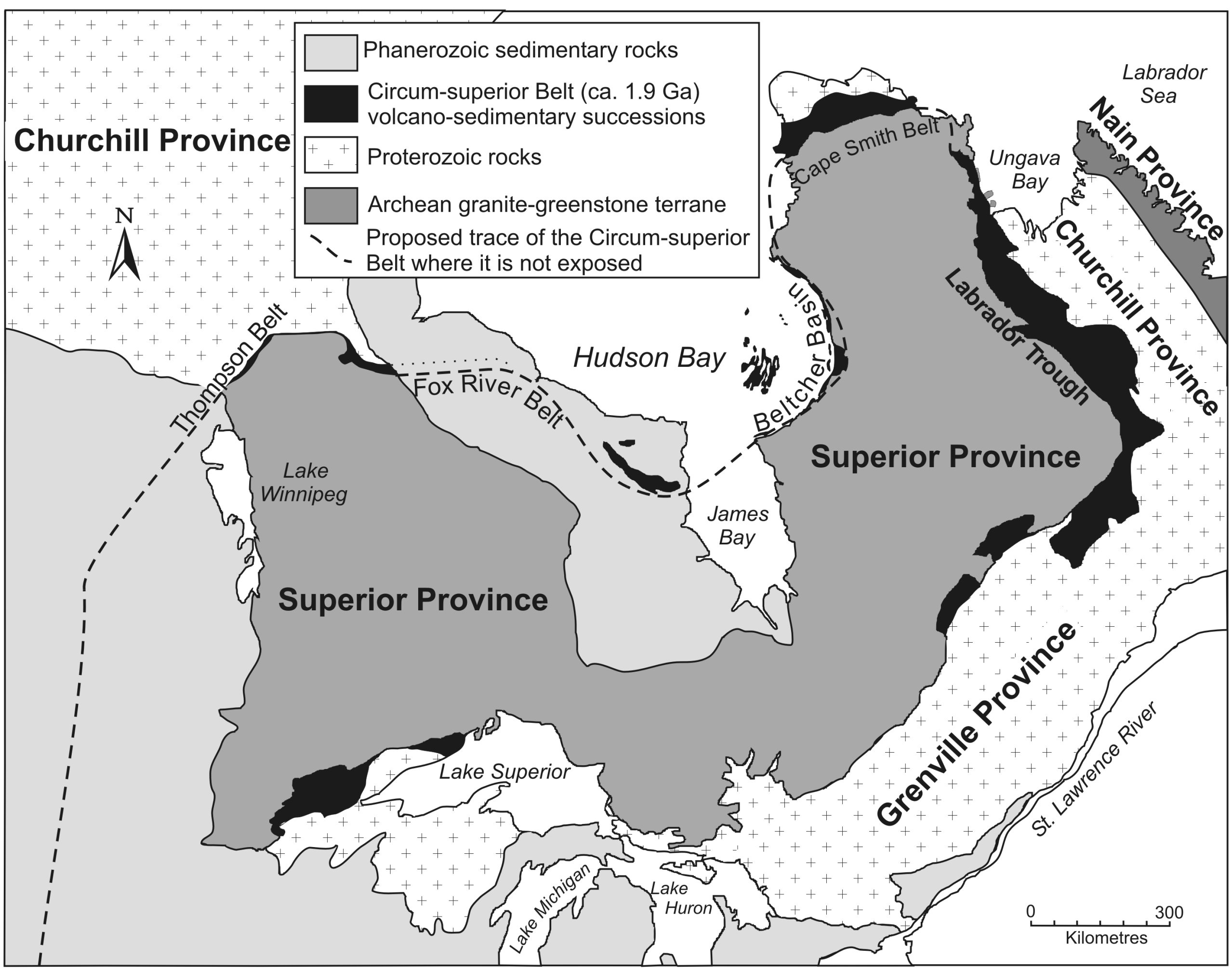

Figure 1: *Geology of east-central Canada, showing the distribution of the Circum-Superior Belt and the location of the Fox River Belt.*

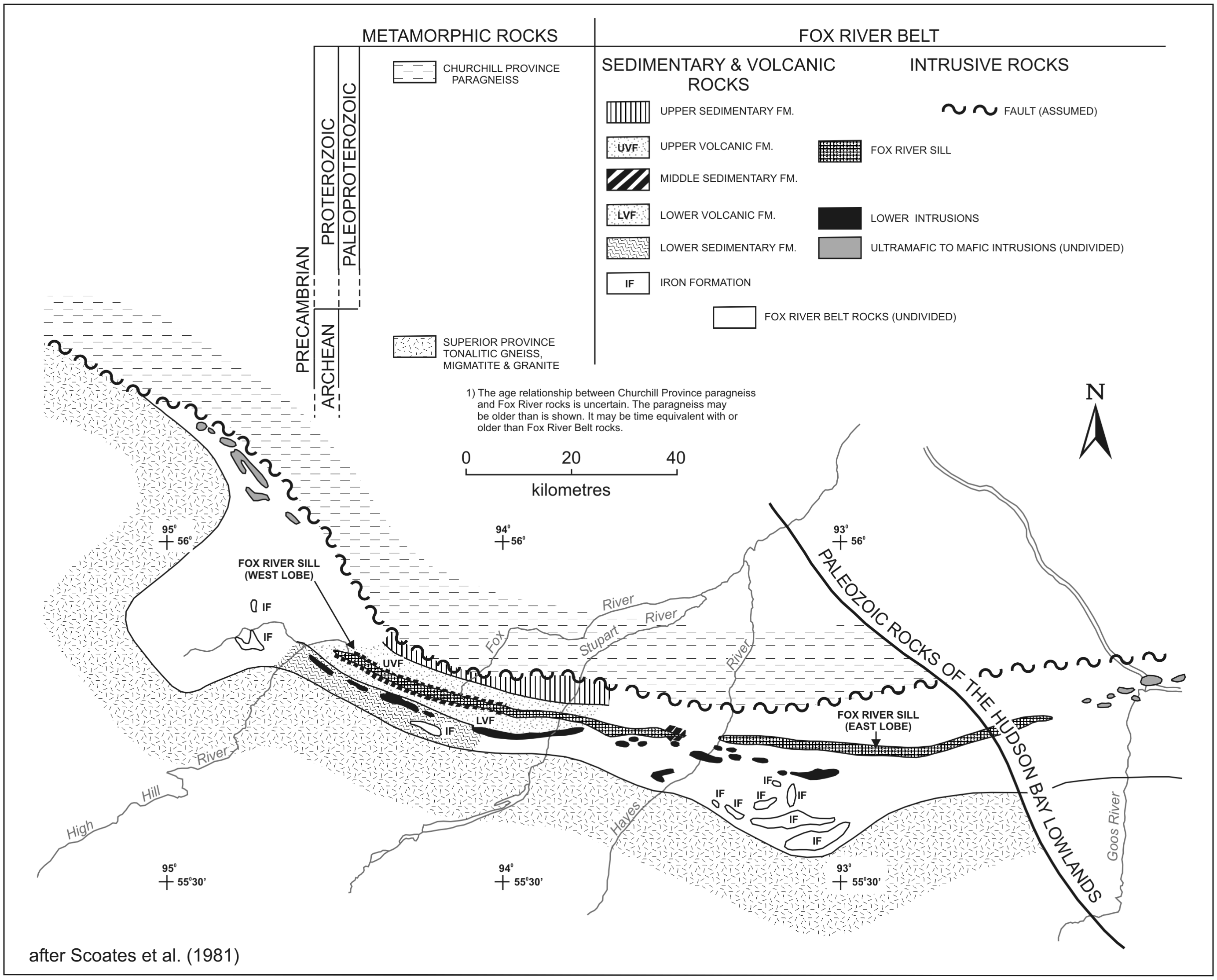

Figure 2: *Geology of part of the Fox River Belt (modified from Scoates et al., 1981).*

rocks of the Fox River Belt. An association between the supracrustal sequences of the Fox River Belt and those of the Cape Smith Belt and Thompson Nickel Belt was first made by Dimroth et al. (1970), Bell (1971) and Gibb and Walcott (1971). Thomas and Gibb (1977) first introduced the term 'Circum-Superior Suture', in reference to the supracrustal rocks that lie between the Superior and Churchill provinces. Scoates (1981) and Baragar and Scoates (1987) introduced the term 'Circum-Superior Belt' to apply to the Paleoproterozoic supracrustal rocks that ring the Superior Province craton. Green et al. (1985) and Bleeker (1990) presented tectonic models for the formation of the Thompson Nickel Belt and Fox River Belt. The term 'Superior Boundary Zone' was introduced by Lucas et al. (1996), and is preferred over the term 'Circum-Superior Belt' in reference to ca. 1.9 Ga mafic-ultramafic magmatism along the margin of the Superior Craton (e.g., Thompson Nickel Belt, Cape Smith Belt and Fox River Belt). Peck et al. (1999, 2002) and Desharnais et al. (2000, 2001, 2002) studied the Fox River Belt, with emphasis on the Marginal Zone of the Fox River Sill and its contained mineralization. Syme et al. (1999) described the physical volcanology of the komatiitic basalt within the Fox River Belt. Much of the current knowledge of the Fox River Belt has been gained from exploration programs conducted by Inco (Canadian Nickel Company Ltd., 1950s–1970s), BP Minerals Canada Ltd. (1980s), WMC Resources Ltd. (1990s) and Falconbridge Limited (1998–present). Dave Peck was responsible for the bulk of the sampling and initial data analysis presented in this report. Funding for this project was provided by Falconbridge Limited, the Natural Sciences and Engineering Research Council of Canada, and Manitoba Industry, Economic Development and Mines.

Geology

Less than 1% of the rocks in the Fox River Belt are exposed at surface. This means that much of the geology (Figures 2, 3) is interpolated between exploration drillholes and inferred from geophysics. Nevertheless, the Great Falls area on the Fox River has substantial outcrop exposure (of the western lobe of the Fox River Sill) and has been mapped at a scale of 1:5000 (Map GP2004-1-1, back pocket; Scoates, 1990; Desharnais et al., 2001).

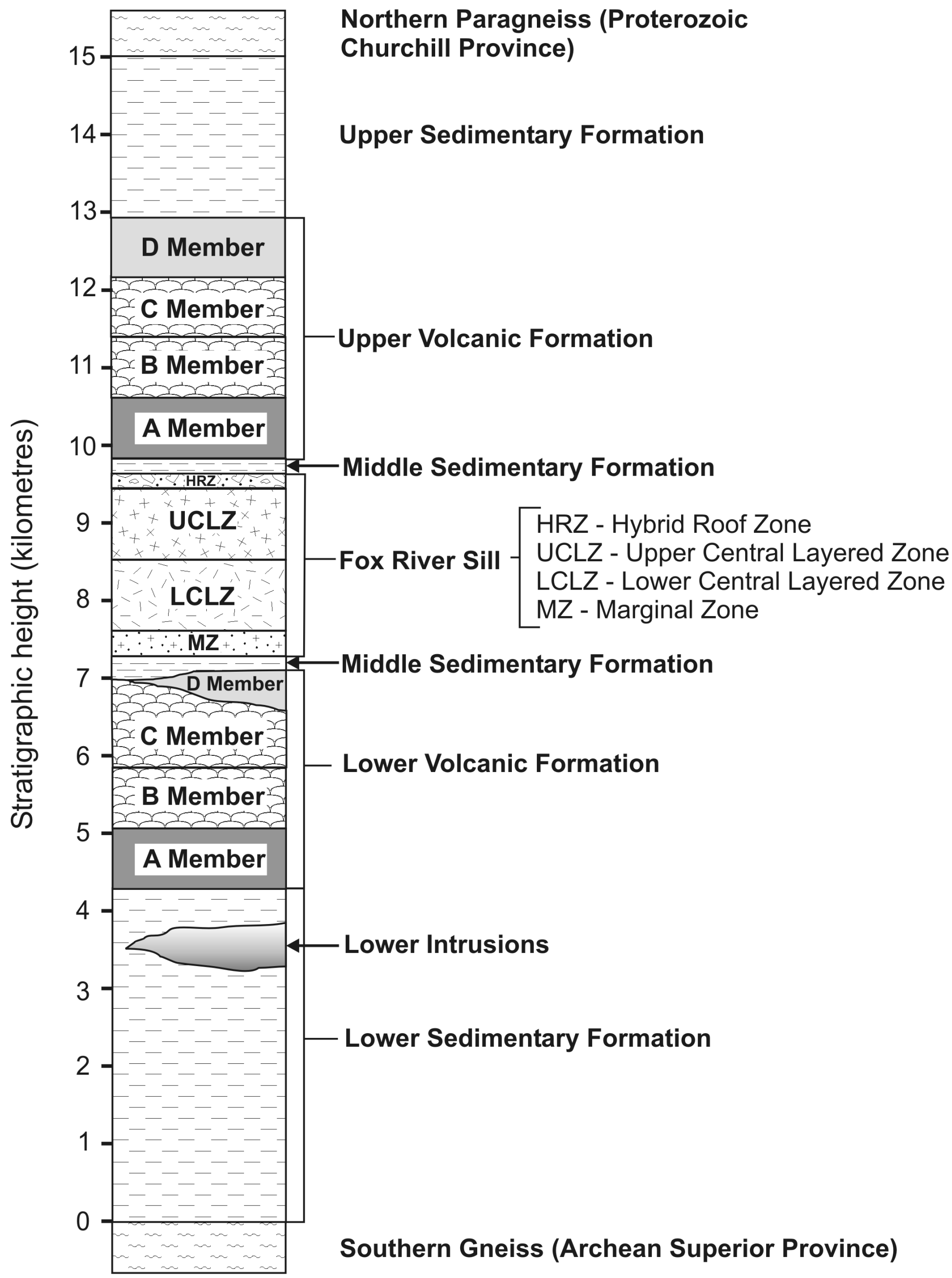

Figure 3: *Stratigraphic section of the Fox River Belt, based on Scoates et al. (1981) and Scoates (1990).*

The Lower Sedimentary Formation (LSF) is composed primarily of fine-grained clastic sedimentary rocks that are finely to coarsely laminated (mudstone, argillite, pyritic argillite, siltstone). There appears to be an increase in the proportion of chemical sedimentary rocks, including carbonate rocks and iron formation, upward in the sequence. Similarities between this formation and the sedimentary rocks of the Thompson Nickel Belt have been noted (Baragar and Scoates, 1987; D. Peck, N. Halden and D. Benson, pers. comm., 2002).

The Bigstone gabbro comprises gabbronorite bodies of unknown dimensions that intrude the Lower Sedimentary Formation approximately 0.5–1 km above its lower contact (Peck et al., 2000). Similar gabbronorite bodies have been identified along the Sipanigo River, where they are inferred to occur near the middle of the Lower Sedimentary Formation. East-trending mafic dikes, dated at 1900 ±14 Ma (L. Heaman, pers. comm., 2002), have been recognized along the Stupart and Sipanigo rivers, where they intrude Superior Province gneiss. These mafic intrusive rocks may represent a suite of dikes equivalent to the Molson Dikes that intrude the western Superior Province and the Thompson Nickel Belt. The Molson Dikes and the Fox River Sill share an age of 1883 Ma (Heaman et al., 1986).

The Lower Intrusions (LI) are typically very well differentiated, and are composed of a peridotitic base; an overlying, thin, pyroxene-rich layer; and an upper gabbronorite. Some intrusions, however, do not appear to be differentiated. The intrusions range between 50 and 500 m in thickness and appear to extend for tens of kilometres along strike. Trace-element and isotope data show that some of these intrusions are homogeneously contaminated.

The Lower Volcanic Formation (LVF) overlies the Lower Sedimentary Formation and comprises volcanic flows ranging in composition from komatiitic basalt to basalt. The average thickness of the formation is estimated at 2.4 km (Scoates, 1981). The Lower Volcanic Formation consists of three zones: an 1100 m thick lower zone comprising dominantly massive flows; a 700 m thick middle zone comprising mainly pillowed flows; and a 300 m thick upper zone comprising mainly massive flows. Details of the volcanic architecture are described in Syme et al. (1999). Flows of the Lower Volcanic Formation in the Great Falls area do not appear to have undergone significant structural reorganization. This is shown by the relatively unchanging strike and dip of pillow shelves, which are excellent paleohorizontal indicators, and the lack of penetrative fabrics. The composition of the volcanic stratigraphy becomes more evolved upwards (Scoates, 1981).

The Middle Sedimentary Formation (MSF) is less than 100 m thick and is composed of fine-grained sedimentary rocks, dominated by siltstone with variable amounts of pyrite. It is intruded by the Fox River Sill and has been converted to hornfels adjacent to the contact. The margins of the sill in contact with the Middle Sedimentary Formation contain xenoliths of the Middle Sedimentary Formation and have been chemically contaminated (Peck et al., 2000).

The Fox River Sill has been divided into four zones, based on lithology, chemistry and layering (Scoates, 1990); from the base upward, these zones are the Marginal Zone, Lower Central Layered Zone, Upper Central Layered Zone and Hybrid Roof Zone.

In the Great Falls area, the Marginal Zone (MZ) is about 250 m thick and is composed of a Basal Contact Unit, and two cyclic units (Cyclic Units 1 and 2) that evolve from lherzolite to leucogabbro. The Basal Contact Unit is an olivine melagabbro that appears to be reversely differentiated, becoming more ultramafic in composition upward (Peck et al., 1999). The KO Zone, a stratabound zone that commonly contains platinum-group element (PGE)–Cu-Ni mineralization, occurs along an irregular contact at the base of Cyclic Unit 2 (Desharnais et al., 2000). A zircon U-Pb age of 1883 Ma was obtained from a sample of variably textured gabbro at the base of Cyclic Unit 2 in the Great Falls area on the Fox River (Heaman et al., 1986).

The Lower Central Layered Zone (LCLZ) comprises nine or more cyclic units, each of which is composed of a thick olivine-cumulate layer overlain by a thinner clinopyroxene-cumulate layer (1 to 6 m). The rocks commonly contain less than 10% intercumulus material, signifying they are true adcumulates. This zone is about 850 m thick and displays development of plagioclase cumulate only at the top of the zone (Scoates, 1990). Sulphides are relatively rare in this zone, although a few sulphide-bearing samples contain >500 ppb total PGE (Pt+Pd+Au; Smerchanski, 2001). Scoates (1990) interpreted the cyclic units as representing ‘beheaded’ cycles of fractionally crystallized magma, caused by fresh influxes of ultramafic magma.

The Upper Central Layered Zone (UCLZ), which is approximately 900 m thick, differs from the Lower Central Layered Zone in that it has thinner and more complex cyclic units. As well, plagioclase-cumulate rocks cap many of the cyclic units, and orthopyroxene is commonly found as a cumulus phase (Scoates, 1990). Sulphides are also more common than in the Lower Central Layered Zone, with PGE-enriched sulphides occurring near the base of the zone. There are three PGE-enriched zones in the western lobe of the Fox River Sill: the Lower (70 m), Middle (50 m) and Upper (5 m) mineralized units (Schwann, 1989; Schwann et al., 1989; Naldrett et al., 1994). Individual, 1 m long samples from these mineralized units have PGE values ranging from <25 to 980 ppb but generally higher than 100 ppb.

The Hybrid Roof Zone (HRZ) has a wide range of mineral and melt phases, and is characterized by the presence of granophyre and quartz. Its thickness varies widely but averages about 50 m. It is highly contaminated by roof rocks of the Middle Sedimentary Formation, as shown by textures (partially digested xenoliths) and chemistry, including isotopic evidence (Peck et al., 2000; Desharnais et al., 2002).

The Upper Volcanic Formation (UVF), which overlies the Middle Sedimentary Formation, is similar to the Lower Volcanic Formation in terms of chemistry and physical volcanology (Scoates, 1990). In the sections studied by Scoates (1981), the formation can be divided into three zones based on the dominance of certain flow types. The Upper Volcanic Formation is somewhat thicker (2700 m) and has better preservation of primary mineralogy and volcanic textures because of lower metamorphic grade.

Little is known about the Upper Sedimentary Formation (USF) due to lack of exposure. It is inferred to be 2–3 km thick, based on airborne magnetic data and sporadic outcrop and drillhole information (Scoates, 1981).

Geochemistry

Analytical procedure

A total of 1172 whole-rock samples were analyzed for major and trace elements[2]; all analyses were performed at Activation Laboratories Ltd. (Actlabs), Ancaster, Ontario. Samples were dissolved by lithium metaborate-tetraborate fusion and analyzed by inductively coupled plasma–optical emission spectrometry (ICP-OES) and inductively couple plasma–mass spectrometry (ICP-MS). Most of the magmatic samples were analyzed for low-level PGE abundances by fire assay–ICP-MS. Samples that had PGE concentrations at or below the detection limit were reanalyzed using research grade analyses (~0.1 ppb detection limit). This was done to better identify depletion signatures. Any samples that contained visible sulphides were also analyzed by ICP-OES for metals and S, and by ICP-MS for hydrides (including Se).

[2] MGS Data Repository Item 2004001, containing the geochemical data used in this report, is provided on the CD-ROM included in the back pocket of the report. It is also available on request from minesinfo@gov.mb.ca or Mineral Resources Library, Manitoba Industry, Economic Development and Mines, 360-1395 Ellice Avenue, Winnipeg, MB R3G 3P2, Canada.

Data quality

Seven different types of reference materials were inserted about every 10 samples to monitor the data quality. The reference materials were largely internal (not certified) and were chosen to represent the range in composition of the magmatic rocks of the Fox River Belt. A table summarizing the variability of the data obtained from the reference material is included in the geochemical database. Several points can be made from a review of the quality of the data.

The following element concentrations, obtained by ICP-MS, should not be used at all because their relative standard deviation (RSD) is unacceptable[3] for the concentration levels present in the rocks: U, Pb, Tl, W, Ta, Cs, Sb, Sn, In, Ag, Mo, As and Ge.

Several element concentrations, analyzed by ICP-MS, should be used with caution because the error is high for the concentration levels found in the rocks. The error is high for the following elements below the approximate concentrations (in ppm) specified: Hf <5, Nb <10, Zr <25, Rb <5, Zn <150, Cu <80, Ni <500 and Cr <50.

The following elements, analyzed by ICP-OES (Actlabs package 1F), had unacceptable error below the approximate concentrations (in ppm) specified: S <100, Ni <50 and Cu <75.

The following major elements had unacceptable error below the concentrations (in %) specified: P_2O_5 <0.1, K_2O <0.5, Na_2O <1 and MnO <0.15.

Error was acceptable for Pt and Pd at all concentrations. Error was unacceptable[3] for Au at concentrations below 8 ppb.

One significant problem within the dataset is the poor data quality for Ni analyzed by ICP-MS. This appears to be the result of problems in the analytical procedure. Error was unacceptable for concentrations below 500 ppm and the average komatiitic basalt from the Fox River Belt has a Ni concentration of 215 ppm. The use of Ni data in this report is therefore limited to chemostratigraphic plots. Cobalt is used instead of Ni (mainly to show depletion) because these elements show similar behaviour in mafic-ultramafic magmatic systems (Arndt and Jenner, 1986).

Tectonic setting

Scoates (1981) suggested a rift origin for the magmatism in the Fox River Belt and the Thompson Nickel Belt. This idea is supported by the presence of the Molson Dike Swarm, which indicates several kilometres of extension within the Superior Craton at this time. Based on geochemical discrimination diagrams and spider diagrams, Halden (1991) proposed that rocks of the Superior Boundary Zone formed in a marginal-basin environment. The lack of significant fractionation of rare earth elements (REE) and high field-strength elements (HFSE) argues against subduction processes being involved in the generation of these magmas. Additionally, samples from the Lower and Upper Volcanic formations have an average La/Nb ratio of 1.22; according to Rudnick (1995) and Condie (2003), there is likely not a subduction component involved in the production of the magma for rocks with ratios of less than 1.4, such as those in the Fox River Belt. Many consider that the formation of large volumes of komatiitic magma necessitates a mantle-plume source (e.g., Campbell, 2001; Ernst and Buchan, 2001). Ernst and Buchan (2001) suggested that the Molson Dike event, which includes the magmatism within the Fox River Belt, probably occurred due to the arrival of a plume head at the base of the crust.

Recently, the Pickle Crow Dike in northwestern Ontario has been dated at 1876 ±8 Ma. Buchan et al. (2003) suggested that the Molson and Pickle Crow dikes could represent a radiating swarm, emanating from the point of impingement of a plume head with the crust. If this is the case, then the radial dikes could be conduits for the magmatism in the Fox River Belt. The Stupart Dikes, which intrude the Southern Gneiss Belt with a strike of approximately 090º (Peck et al., 2000), could also be part of this swarm, further defining the position of the plume head northeast of Thompson. The Fox River Sill, itself, could represent a magma conduit related to this event. There is clear evidence that dikes with a large lateral flow component will develop into sills when they intersect a sedimentary basin (Fahrig, 1987; Hyndman, 1987). Nevertheless, the plume model, as applied to large igneous provinces in cratonic marginal settings, is highly conjectural.

Fox River Belt magmatism

An extremely large volume of magma intruded and erupted during the formation of the Fox River Belt (~7.5 km of stratigraphic thickness). Scoates (1981, 1990) proposed that the Fox River Sill acted as a staging chamber for the magma of the Upper Volcanic Formation. As the magma in the sill fractionally crystallized, the residual magma that erupted to form the Upper Volcanic Formation became more evolved. A similar relationship was proposed for the Lower Intrusions and Lower Volcanic Formation (Scoates 1981, 1990). It is possible that all of the magmatic products could be modelled from a single initial composition. Initial liquid compositions for the Lower Volcanic and Upper Volcanic formations, estimated using olivine composition, give values of 12–15% MgO for these units. Estimates based on whole-rock analyses from the most primitive units in the Lower Central Layered and Upper Central Layered zones within the Fox River Sill, however, result in an initial magma with an MgO concentration of 19–20% (true komatiite; Osiowy, 2000).

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[3] Unacceptable error for trace elements is defined as an RSD (100*[standard deviation]/[average concentration]) greater than 10% (5% for major elements). This means that more than 10% (5%) of the concentration is needed to describe a 68% confidence interval. Unacceptable error for Pt, Pd and Au is variable because these data are primarily used to define depletion and enrichment. Therefore, an RSD of 100% for concentrations of 1 ppb is acceptable because 2 ppb is still considered depleted.

During certain periods of the Earth's history, magma production was significantly increased. These periods are thought to correspond to superplume events, which produce tremendous amounts of magma. Condie et al. (2001a) defined a superplume as "a relatively short-lived mantle plume event (<100 My) during which several to many large plumes formed and rose to the base of the lithosphere." Piper (1982) and Condie et al. (2000b) have suggested that a superplume and supercontinent formed at 1900 Ma.

Geochemical discrimination diagrams for the determination of magmatic or tectonic affinities should be used with caution, especially when plotting cumulate rocks, because they do not represent liquid compositions. In this section, an emphasis is placed on the volcanic formations, which provide the best estimate of parent liquid composition, even though some of the volcanic rocks may contain cumulus olivine.

The AFM plot in Figure 4a shows that the magmatic rocks from the Fox River Belt have a tholeiitic affinity; conversely, the Jensen diagram in Figure 4b shows that the Fox River Belt magmatic suites are dominantly komatiitic in affinity. It should be noted

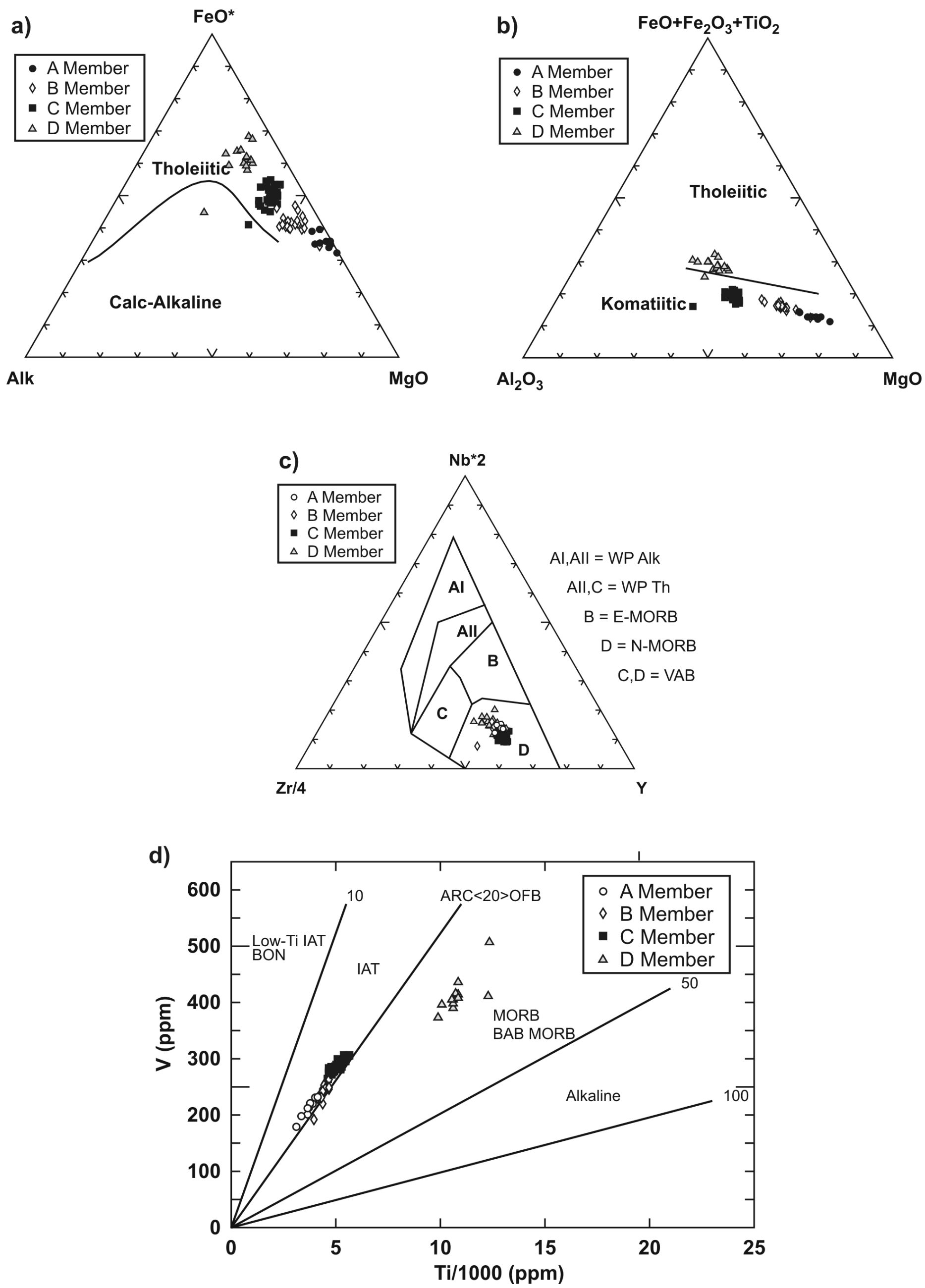


Figure 4: *Discrimination diagrams illustrating the chemistry of magmatic rocks of the A to D members of the Lower and Upper Volcanic formations (see Figure 3) of the Fox River Belt:* ***a)*** *AFM plot;* ***b)*** *Jenson (1976) plot, illustrating dominantly komatiitic affinity;* ***c)*** *Meschede (1986) plot, showing the depleted nature of the system; and* ***d)*** *Shervais (1982) plot, illustrating the oxygen fugacity of the system. Abbreviations: ARC, volcanic arc; BAB, back-arc basin; BON, boninite; E-MORB, enriched mid-ocean ridge basalt; IAT, island-arc tholeiite; N-MORB, normal mid-ocean ridge basalt; OFB, oceanic flood basalt; VAB, volcanic-arc basalt; WP Alk, within-plate alkaline basalt; WP Th, within-plate tholeiite.*

that the volcanic samples that plot in the tholeiitic field are all from D Member, which represents the uppermost zone of both the Lower Volcanic and Upper Volcanic formations (discussed in detail later). The discrimination diagram (Meschede, 1986) in Figure 4c shows that the Fox River Belt magma came from a depleted-mantle source. This is consistent with recent Hf and Nd isotopic compositions, and from REE plots (Desharnais et al., 2002). The Ti versus V discrimination plot (Shervais, 1982) in Figure 4d shows clearly that the bulk of the magmatism was under oxygen fugacity conditions similar to those of arc-tholeiite. The notable exceptions, again, are the D Member volcanic rocks, which fall well within the normal mid-ocean ridge basalt (N-MORB) field. A possible explanation for this is that V is depleted (relative to Ti) in these rocks due to the fractional crystallization of a mineral phase containing V within the subchamber (such as primary magnetite). It is possible that the D Member volcanic rocks represent a separate melting event; this will be further discussed in the 'Lower and Upper Volcanic formations' section.

Rock types found within the Fox River Sill can be grouped using the MgO versus Al_2O_3 diagram (Figure 5a). Samples that are contaminated or that contain Fe-Ti oxides plot to the right of the gabbro field (examples of the latter case are represented by samples from the Upper Central Layered Zone, as well as one Marginal Zone sample). Two relationships emerge when the samples from the Lower Intrusions are overlain on the plot (Figure 5b): 1) the Lower Intrusions are similar in composition to the Marginal Zone of the Fox River Sill; and 2) a considerable cluster of data points falls on the contaminated side of the 'gabbro limit line', which is defined by the compositions of augite and plagioclase. All samples that fall on the 'contaminated' side of the gabbro limit line are from Lower Intrusions identified as contaminated from REE plots (further discussed in the 'Lower Intrusions' section below). Exceptions to this are samples from Lower Intrusions FX-01-10 and FX-01-11. Comparison of data from the Lower and Upper Volcanic formations shows that many of the samples do not overlap with the Fox River Sill samples, since the magma that formed the volcanic formations represents an evolved liquid rather than a cumulus rock (Figure 5c). Therefore, the trend is interpreted to reflect the effects of fractional crystallization within subchambers that fed the volcanic units. It is possible that Lower Intrusions FX-01-10 and FX-01-11 represent either thick layered flows or intrusions that are comagmatic with the Lower Volcanic Formation.

The Marginal Zone follows a different evolutionary path than the Lower Central Layered and Upper Central Layered zones (Figure 6). The shallower evolutionary trend of the Marginal Zone samples is probably related to the presence of orthopyroxene that crystallized from intercumulus liquid (Figure 6a). This could be a function of faster cooling due to its proximity to country rocks. The Upper Central Layered Zone also has a somewhat shallower evolutionary trend; again, this is probably due to minor amounts of orthopyroxene (Figure 6b). It is apparent that the Lower Intrusions are closer in terms of mineralogy to the Marginal Zone than to the rest of the Fox River Sill, even though there is some true dunite, as shown by the high Mg and negligible Ca (Figure 6c). The similarity to the Marginal Zone is likely due to trapped intercumulus liquid that crystallized orthopyroxene, a logical deduction considering the relative size of the Lower Intrusions and the relatively rapid cooling of such systems (Marsh, 1996). The thin pyroxene-rich layers are represented as a cluster at 18% CaO and 19% MgO. The gabbroic portion of the intrusion has a steeply declining CaO trend. This is due, in part, to the fact that augite has more Ca than plagioclase and, as the amount of augite decreases, the rock becomes less Ca rich. Also, plagioclase becomes more sodic as the magma becomes more evolved. Two broad trends can be seen for rocks of the Lower Volcanic and Upper Volcanic formations in Figure 6d, the first being a decrease in MgO with a concurrent increase in CaO. This could be a function of segregation of olivine in a subchamber, depleting the erupting magma in Mg and leaving the residual liquid increasingly enriched in Ca. The second arrow, showing decreasing Ca and Mg concentrations, could represent plagioclase and augite fractionation in a subchamber, thereby depleting the erupting magma in Mg and Ca. The production of evolving magma compositions by fractional crystallization will be explored in a paper that will be submitted to *Precambrian Research* by September 2004, and will not be dealt with here.

Only a small number of samples was used in the analysis of trace-element ratios, as many samples had concentrations below or close to the detection limits. Samples that contained Nb concentrations of less than 1 ppm were removed from the dataset. This sorting process introduced an element of bias by preferentially excluding samples that have not been contaminated with country rocks (rich in trace elements). This being said, there are 49 samples from the Lower and Upper Volcanic formations that are considered to be uncontaminated and have Nb concentrations above 1 ppm. It is assumed here that the volcanic formations most closely represent the original trace-element ratios of the parent magma.

Niobium and titanium are useful in identifying a magmatic source region because these elements are not significantly enriched in the crust compared to the mantle (Figure 7). Therefore, the plot of Nb/Yb vs. Ti/Yb (Figure 7a) is less sensitive to contamination than those plots that use trace-element ratios with REE or other HFSE. The volcanic rocks have a signature similar to N-MORB (depleted mantle), or primitive mantle (relatively undepleted; Taylor and McLennan, 1995; Sun and MacDonough, 1989; Stolz et al., 1990). This represents a depleted source for the magma, a conclusion that is corroborated by the Nd and Hf isotope data (Desharnais et al., 2002). Contamination is detected using Nb/La, which measures the negative Nb anomaly, and La/Sm, which measures light rare earth element (LREE) enrichment (Figure 7b). There is significant variation of these ratios for the sedimentary and magmatic rocks. Despite the scatter, the limits of which are shown, the samples of sedimentary rocks largely cluster around the average value. Contamination of magma with sedimentary rocks of different composition could result in different vectors and different degrees of contamination. The volcanic rocks cluster close to the origin, suggesting that they have a composition similar to that of the present-day mantle. The Lower Intrusions have a cluster in the lower right quadrant, toward the possible contaminants (sedimentary rock and gneiss). This is likely a function of these intrusions being variably contaminated with sedimentary rock or gneiss. Uncontaminated examples of the Lower Intrusions are underrepresented because they have lower trace-element concentrations and were therefore preferentially removed from the dataset. A few examples do exist and plot in the

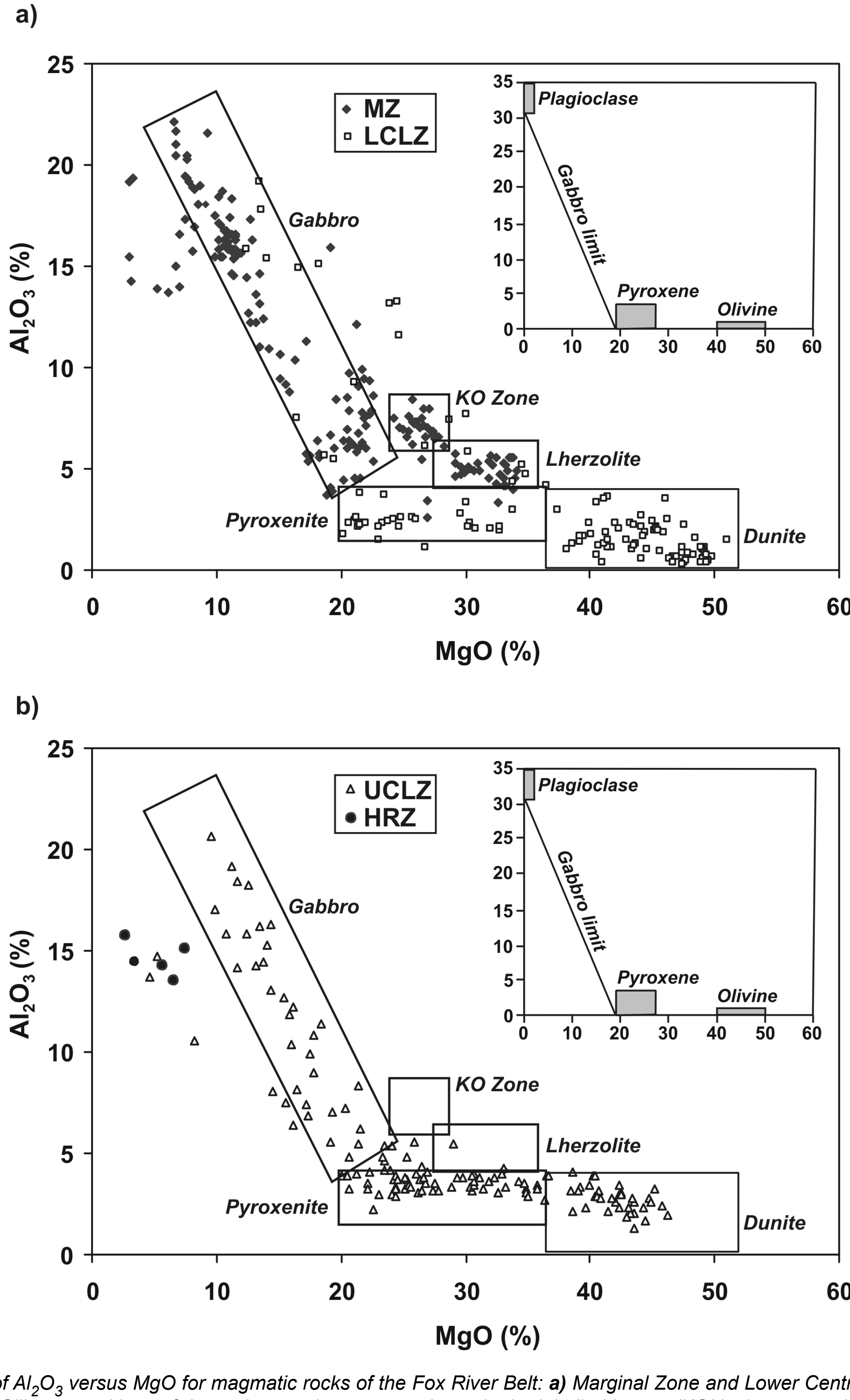
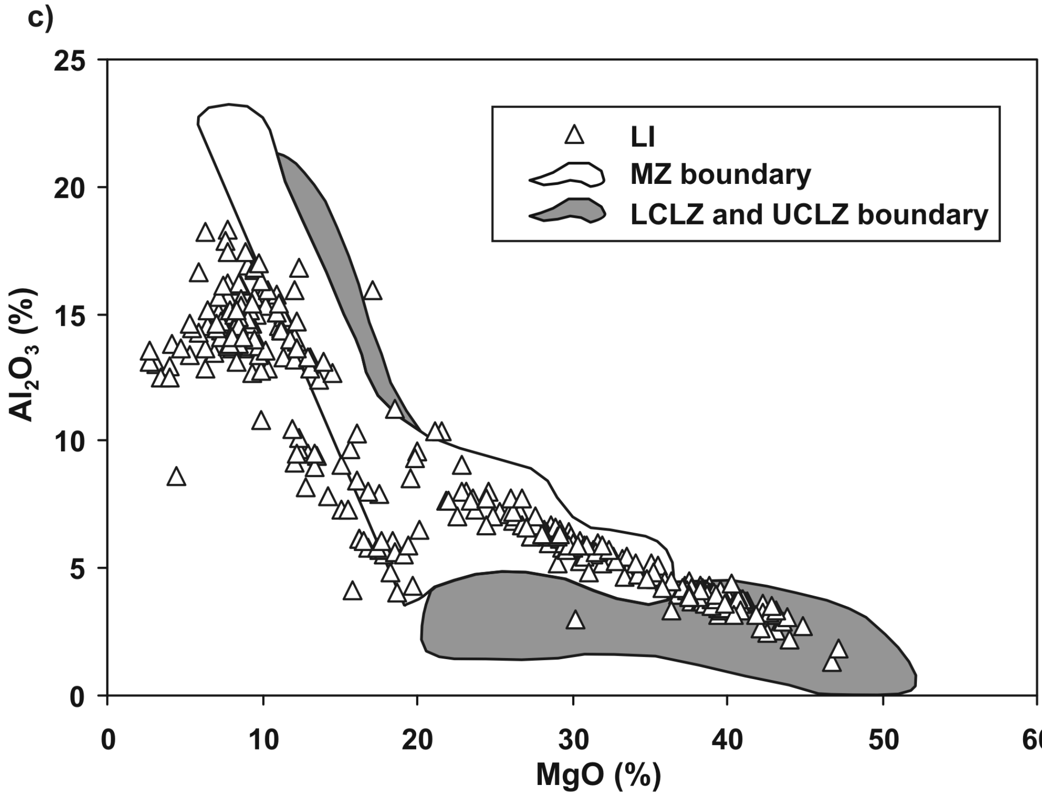


Figure 5: *Plots of Al_2O_3 versus MgO for magmatic rocks of the Fox River Belt:* ***a)*** *Marginal Zone and Lower Central Layered Zone of the Fox River Sill; compositions of the various rock types are shown in the labelled boxes; 'KO' is the composition of the olivine websterite of the KO Zone within the Marginal Zone; inset diagram shows the range in compositions of the main rock-forming minerals (pyroxene composition field includes the compositions of orthopyroxene and clinopyroxene within the belt);* ***b)*** *Upper Central Layered Zone and Hybrid Roof Zone of the Fox River Sill;* ***c)*** *data for Lower Intrusions overlain on Fox River Sill data for comparison; and* ***d)*** *data for Lower and Upper Volcanic formations overlain on Fox River Sill data for comparison. Abbreviations: HRZ, Hybrid Roof Zone; LI, Lower Intrusions; LCLZ, Lower Central Layered Zone; LVF, Lower Volcanic Formation; MZ, Marginal Zone; UCLZ, Upper Central Layered Zone; UVF, Upper Volcanic Formation.* *(continued on next page)*



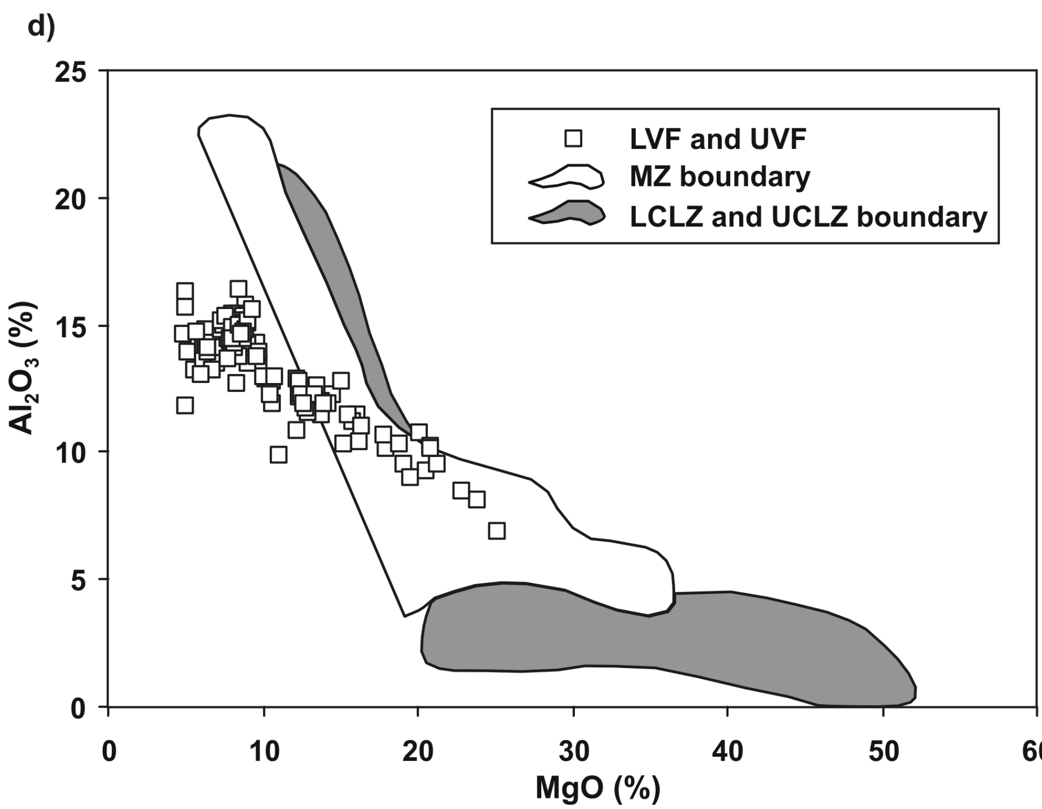
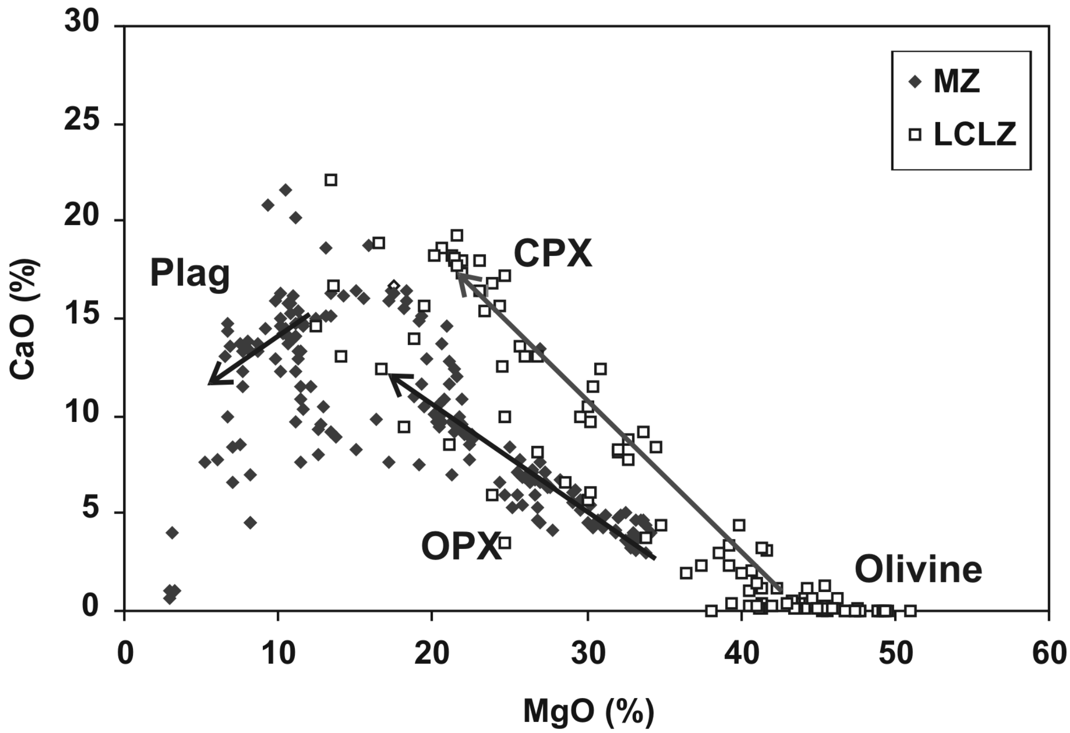


Figure 5 (continued): *Plots of Al_2O_3 versus MgO for magmatic rocks of the Fox River Belt:* ***a)*** *Marginal Zone and Lower Central Layered Zone of the Fox River Sill; compositions of the various rock types are shown in the labelled boxes; 'KO' is the composition of the olivine websterite of the KO Zone within the Marginal Zone; inset diagram shows the range in compositions of the main rock-forming minerals (pyroxene composition field includes the compositions of orthopyroxene and clinopyroxene within the belt);* ***b)*** *Upper Central Layered Zone and Hybrid Roof Zone of the Fox River Sill;* ***c)*** *data for Lower Intrusions overlain on Fox River Sill data for comparison; and* ***d)*** *data for Lower and Upper Volcanic formations overlain on Fox River Sill data for comparison. Abbreviations: HRZ, Hybrid Roof Zone; LI, Lower Intrusions; LCLZ, Lower Central Layered Zone; LVF, Lower Volcanic Formation; MZ, Marginal Zone; UCLZ, Upper Central Layered Zone; UVF, Upper Volcanic Formation.*

a)



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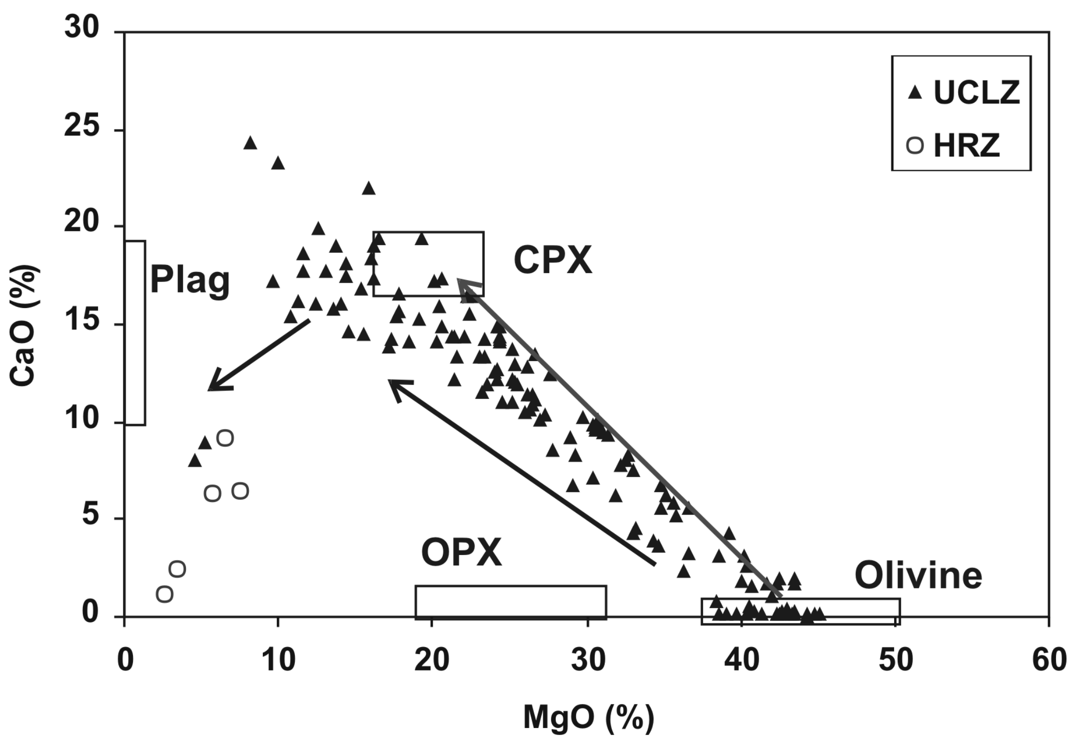

Figure 6: *Plots of CaO versus MgO for magmatic rocks of the Fox River Belt (arrows show main evolution pathways):* ***a)*** *evolution of the Marginal Zone (black arrows) and Lower Central Layered Zone (grey arrows) of the Fox River Sill; fields for the mineral compositions are illustrated;* ***b)*** *compositional variation for the Upper Central Layered Zone (grey arrow) and Hybrid Roof Zone;* ***c)*** *compositional variation of the Lower Intrusions; the Lower and Upper Central Layered zones are represented in the dark grey field and the Marginal Zone by the light grey field; and* ***d)*** *Lower and Upper Volcanic formations. Abbreviations: CPX, clinopyroxene; HRZ, Hybrid Roof Zone; LI, Lower Intrusions; LCLZ, Lower Central Layered Zone; LVF, Lower Volcanic Formation; MZ, Marginal Zone; OPX, orthopyroxene; PLAG, plagioclase; UCLZ, Upper Central Layered Zone; UVF, Upper Volcanic Formation.*
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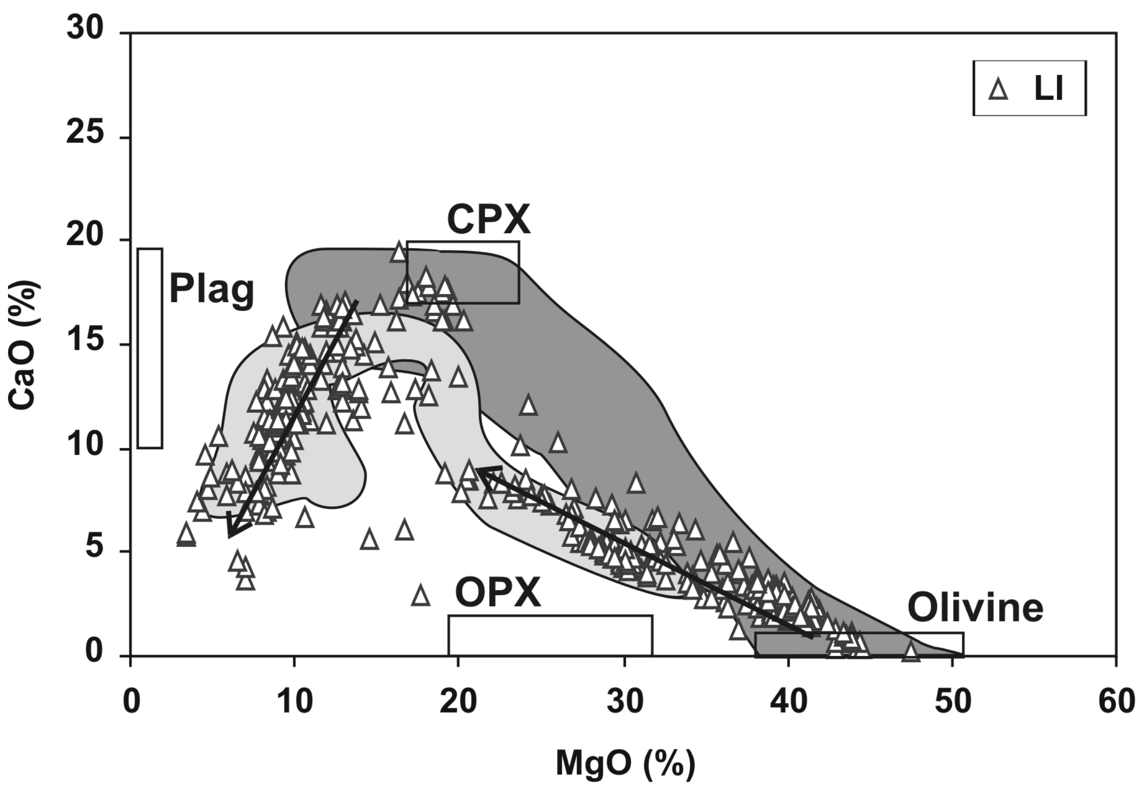
c)



d)

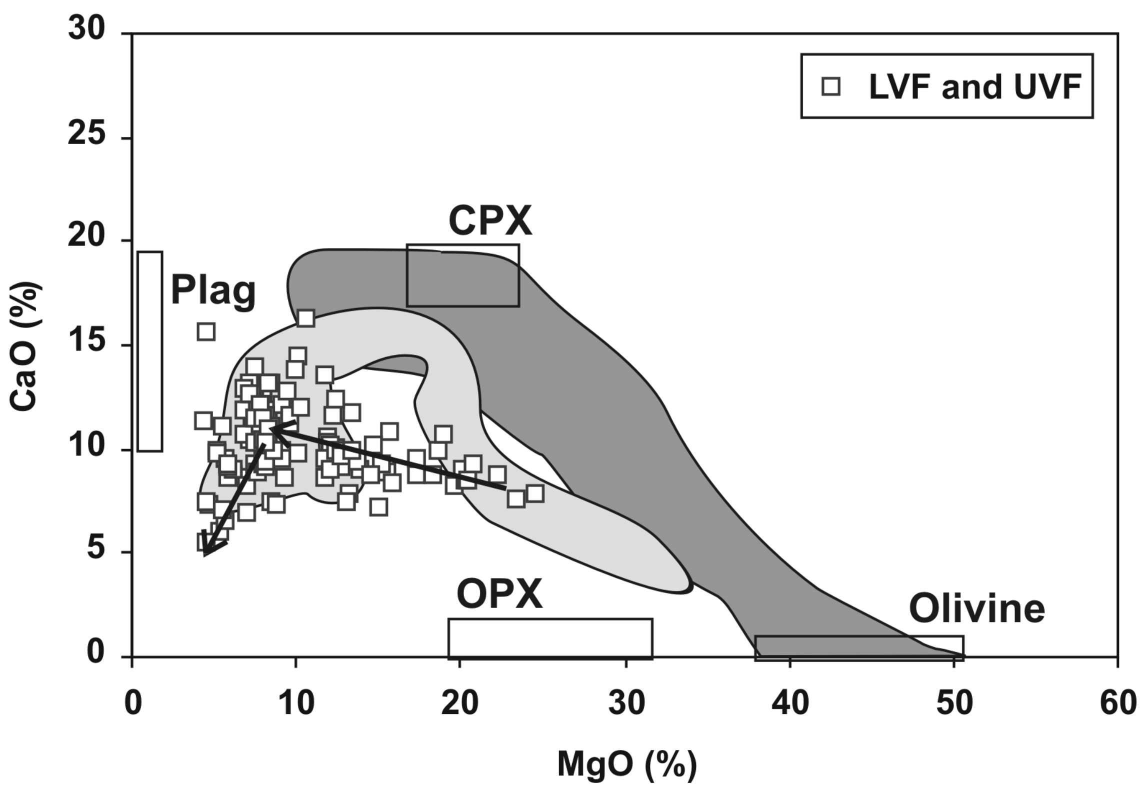


Figure 6 (continued): *Plots of CaO versus MgO for magmatic rocks of the Fox River Belt (arrows show main evolution pathways):* ***a)*** *evolution of the Marginal Zone (black arrows) and Lower Central Layered Zone (grey arrows) of the Fox River Sill; fields for the mineral compositions are illustrated;* ***b)*** *compositional variation for the Upper Central Layered Zone (grey arrow) and Hybrid Roof Zone;* ***c)*** *compositional variation of the Lower Intrusions; the Lower and Upper Central Layered zones are represented in the dark grey field and the Marginal Zone by the light grey field; and* ***d)*** *Lower and Upper Volcanic formations. Abbreviations: CPX, clinopyroxene; HRZ, Hybrid Roof Zone; LI, Lower Intrusions; LCLZ, Lower Central Layered Zone; LVF, Lower Volcanic Formation; MZ, Marginal Zone; OPX, orthopyroxene; PLAG, plagioclase; UCLZ, Upper Central Layered Zone; UVF, Upper Volcanic Formation.*

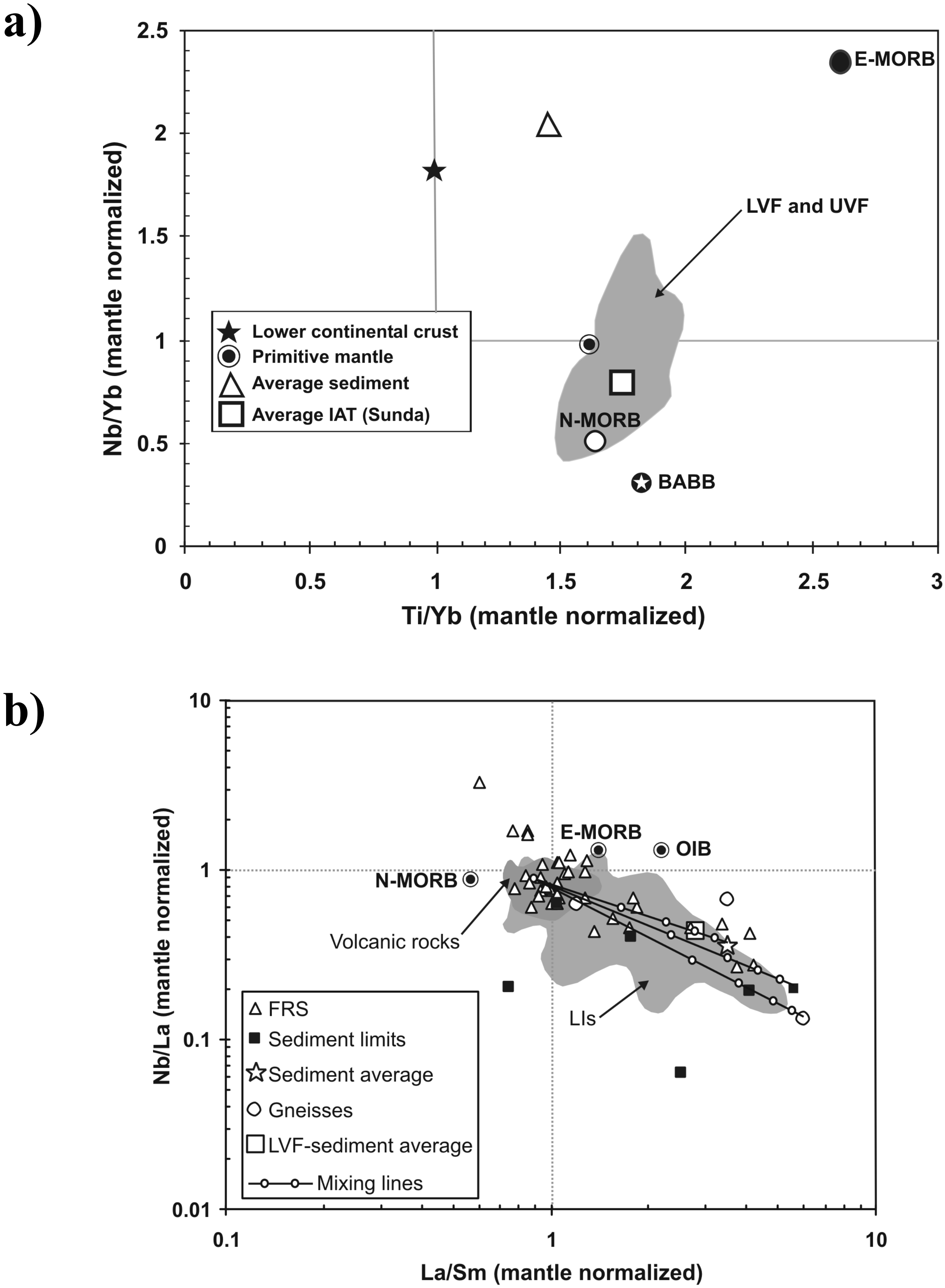


***Figure 7:** Mantle-normalized trace-element ratio plots meant to convey **a)** source characteristics, and **b)** contamination effects. The dotted line within the Lower Intrusions field represents the location of the bulk of the 'contaminated intrusions'. The samples from the Fox River Sill that are illustrated are only the extreme examples (mostly from the Hybrid Roof Zone). Nodes on the mixing line indicate 20% intervals. Lower continental crust data are from Taylor and McLennan (1995); primitive mantle, N-MORB (depleted normal mid-ocean ridge basalt), E-MORB (enriched mid-ocean ridge basalt) and OIB (ccean island basalt) data are from Sun and MacDonough (1989); BABB (back-arc basin basalt) data are from Ewart et al. (1994). Other abbreviations: FRS, Fox River Sill; IAT, island-arc tholeiite; LI, Lower Intrusions; LVF, Lower Volcanic Formation; UVF, Upper Volcanic Formation.*

volcanic rocks field. The rocks from the Fox River Sill (dominantly represented by the Marginal Zone here) show the greatest spread. A few samples plot in the upper left quadrant of the diagram, while some Hybrid Roof Zone (HRZ) samples plot close to the sedimentary rock. This is consistent with the idea that the HRZ includes a large component of assimilated sedimentary rock. The degree of contamination can be modelled by using two end points; in this case, the average volcanic rock and three possible contaminants were chosen. The amount of contamination required to produce the observed compositions is variable and depends on the contaminant chosen. The bulk of the contaminated Lower Intrusions can be modelled as having incorporated 12–14% of 'average sediment', 5–18% of 'enriched sediment' (samples having more extreme LREE enrichment and Nb anomalies), or 2.5–10% of enriched gneiss.

Lower Intrusions

The current understanding of the Lower Intrusions is derived from limited drillcore information, as these bodies are not exposed at the surface. Recent drilling by WMC International and Falconbridge Limited has delineated several new Lower Intrusions, and provided new insight on the types and occurrence of these sills. It should be noted that it is very difficult to differentiate between the thick, layered flows at the base of the Lower Volcanic Formation and the Lower Intrusions. Nevertheless, detailed magnetic-survey data indicate that most of the Lower Intrusions are locally discordant to stratigraphy, whereas the volcanic units appear to be conformable to stratigraphic layering and lack the high magnetic intensity. The Lower Intrusions are designated according to the drillhole that interested them.

Titanium is a relatively incompatible element throughout the evolution of these intrusions (Figure 8a). Two intrusions appear to have evolved to much more Ti-rich final compositions (FX-01-10 and FXR 006/010). The anomalous Ti concentrations are likely related to late magma, which crystallized Fe-Ti oxides. Late system closure could produce such Ti-rich compositions; therefore, it cannot be inferred that the intrusions developed under closed-system conditions since initiation. Wide sample spacing does not preclude the possibility that other intrusions contain similar rock types. Chromium has a very close relationship with Mg# (here expressed as molar 100 x Mg/[Mg+Fe^{2+}], where total Fe has been corrected to Fe^{2+} (Figure 8b). This relationship is a function of the cotectic crystallization of chromite and olivine in the Lower Intrusions. Most samples have PGE (Pt+Pd) concentrations between 10 and 40 ppb (Figure 8c). Individual Lower Intrusions have very different PGE behaviour. Some Lower Intrusions have PGE concentrations that vary little throughout the intrusion (e.g., FX-01-10), whereas others have trends of increasing PGE concentrations with decreasing Mg# (FX-01-15 and FX-01-11). Intrusion FX-01-15 has four samples containing >100 ppb PGE, an anomalous enrichment. Intrusion FXR 006/010 has two distinct groups, one with normal concentrations and the other being depleted. The implications of these observations will be discussed further in the 'Chemostratigraphy' section.

Rare earth element variation

Some Lower Intrusions (13203, 13207, 13236, 38576, FX-01-07, FX-01-10, FX-01-11, FXR 001) display flat to slightly depleted REE patterns approximately two to nine times chondrite (Figure 9a). Some intrusions (38530, FXR005, FXR 006/010, FXR007) display enrichment in the LREE, coupled with elevated concentrations in all trace elements (Figure 9b). Commonly, this is interpreted as contamination of the magma by country rocks (Arndt and Jenner, 1986; Lesher and Burnham, 2001b). Candidates for possible contaminants in the Fox River Belt are the lower crust, the gneissic rocks of the Superior Province, or the sedimentary rocks from the Lower and Middle Sedimentary formations (Figure 9c). Some of the Lower Intrusions (FX-01-10, FX-01-14, FX-01-15, 13214) display both types of trends: a flat uncontaminated trend and an LREE-enriched trend (Figure 9d). Where both patterns are present, the LREE-enriched samples are found at the contacts with sedimentary rocks. This is more prevalent at the upper contacts, thus supporting the idea that enriched patterns are due to contamination. It is also possible that the LREE-enriched intrusions have a different source than those with flat REE patterns. Nevertheless, the coherence between separate intrusions in terms of major-element geochemistry suggests that these intrusions had a similar parent magma.

Chemostratigraphy

Only three of the largest and most systematically sampled intrusions will be described in this section. Intrusion FXR 001 is about 150 m thick and has a Mg# ranging from 93 at its core to 65 at the top (Figure 10a). The Mg # trend has an asymmetric bow shape, with the base being more Mg-rich than the top. The increasing upward trend in Mg# and Ni that can be observed at the very base of the intrusion reflects an increase in the proportion of cumulus olivine (Figures 10a, b). This apparent reverse differentiation trend is likely due to an increase in the proportion of trapped liquid toward the base of the intrusions caused by more efficient heat loss through this part of the intrusion. The peridotitic portion of the intrusion is 100 m thick, clearly illustrated by the Ni concentrations (Figure 10b). Intrusion FXR 001, an example of an uncontaminated intrusion as shown by relatively flat REE patterns, has mantle-normalized Ce/Yb ratios close to one (Figure 10c). The appearance and dominance of plagioclase and clinopyroxene as crystallizing phases is sudden, as shown by the abrupt increase in Ca and Sc concentrations (Figures 10d, e). There are a few metres of pyroxenite between the peridotite and the gabbro, illustrated by the spike in Sc values (Sc is compatible within augite). This typical feature is observed in most of the Lower Intrusions. Two samples with elevated Cu concentrations (>200 ppm) occur just above the contact between peridotite and pyroxenite (Figure 10f), although there is no associated PGE enrichment.

Intrusion FX-01-15 is approximately 120 m thick and ranges in Mg# from 48 to 90 (Figure 11a). The Mg# and TiO_2 patterns

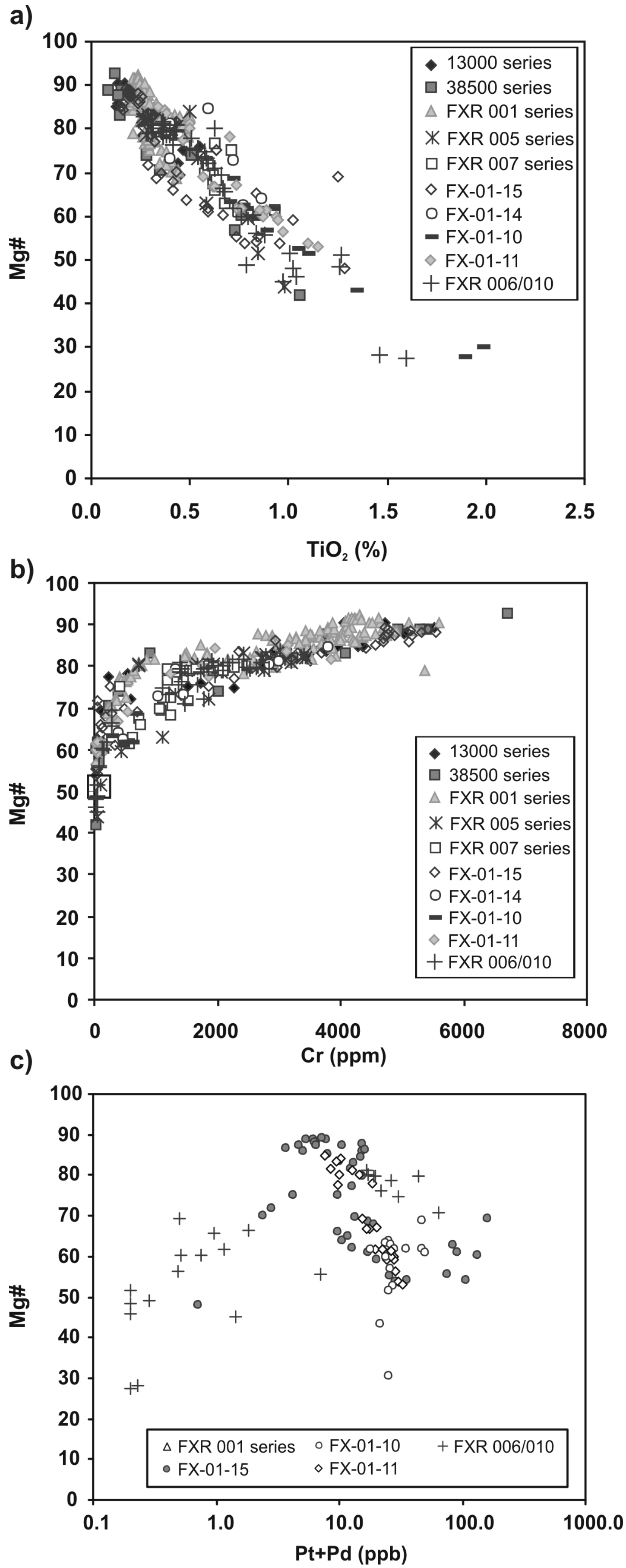


Figure 8: *Harker diagrams for rocks of the Lower Intrusions:* ***a)*** *Mg# versus TiO_2,* ***b)*** *Mg# versus Cr, and* ***c)*** *Mg# versus PGE (Pt+Pd).*

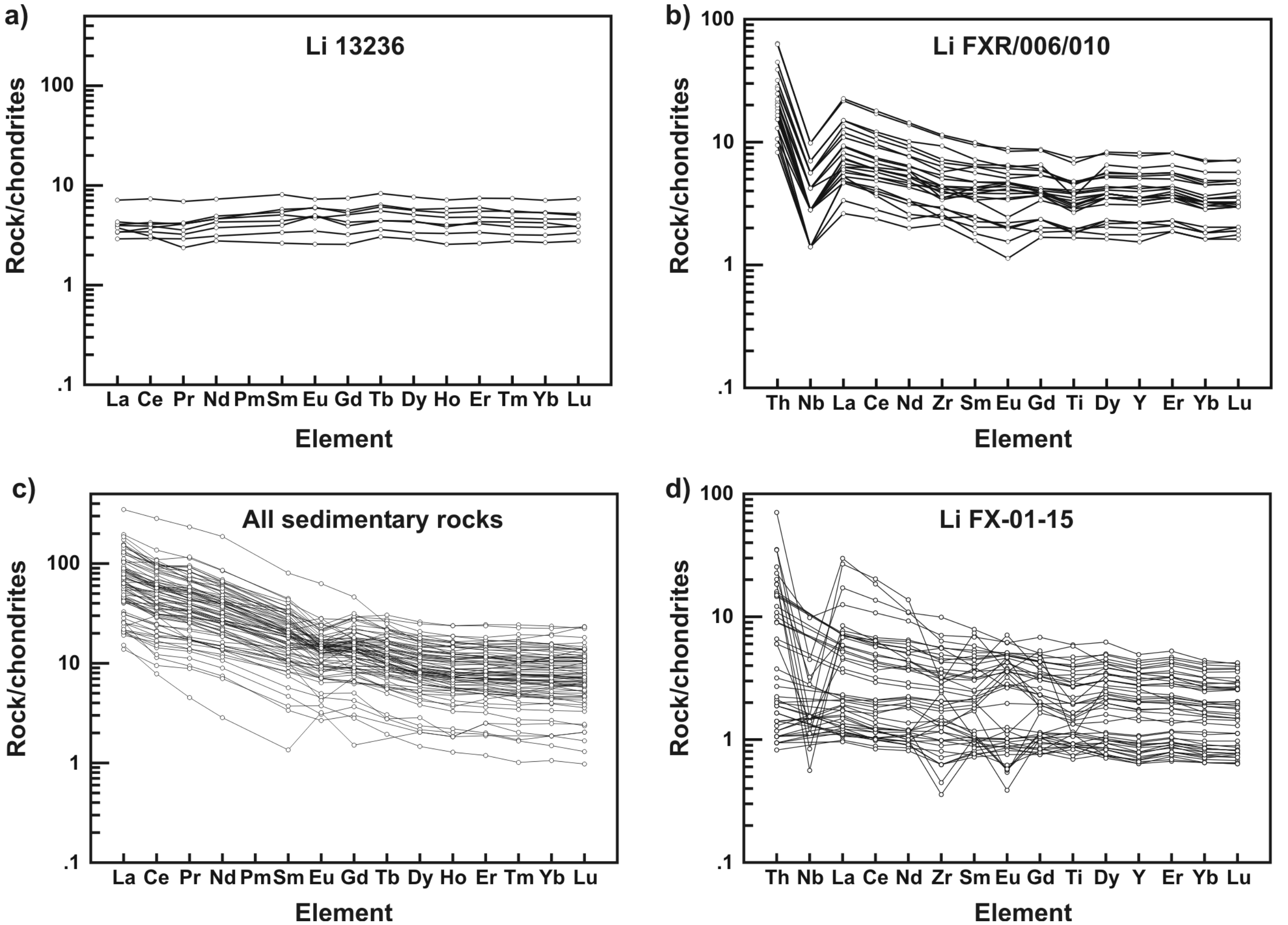


***Figure 9:** Rare earth element plots for rocks of the Fox River Belt: **a)** example of an uncontaminated Lower Intrusion (13236); **b)** example of a contaminated intrusion (FXR 006/010); **c)** all of the sedimentary rocks sampled within the belt (possible contaminants); and **d)** example of a Lower Intrusion that is variably contaminated; samples with enriched patterns are from the top of the intrusion (FX-01-15). Results were normalized using the chondrite data from Sun and MacDonough (1995).*

illustrate that the peridotite portion of the intrusion is about 60 m thick, or half of the intrusion, compared to two-thirds for FXR 001 (Figures 11a, b). The reversals in Mg# and TiO_2 at the very top of the intrusion are likely due to significant interaction of the Lower Intrusion with dolomitic host rock. Chlorite and carbonate alteration become more pervasive at the top of the intrusion, where chalcopyrite and pyrrhotite occur as blebs and veins. The addition of Mg from the dolomite and the dilution of Ti in the magma by the bulk addition of sedimentary rock could produce the observed chemostratigraphic pattern. The contamination signature can also be seen in the Ce/Yb ratio, which increases sharply at the top (up to 6.4). Chromium has a sympathetic relationship with Mg#. The slight increase in Cr concentrations at the top of the Lower Intrusion suggests that the interaction of magma with the sedimentary rock occurred early in the evolution of the chamber (i.e., before the magma became depleted in this element due to crystallization of chromite within the peridotitic portion of the intrusion). One sample at the top of the intrusion shows significant enrichment in Ni and PGE (Figures 11e, f). This sample, which occurs within a chaotic reaction zone between the overlying dolomite and the intrusion, contains 1.7% S, 4.5 ppm Se, 1910 ppm Cu and 3610 ppm As. The chlorite and carbonate alteration appears to suggest that the mineralization formed, at least in part, through a process of localized hydrothermal activity. Five samples at about 100 m in stratigraphic height have Pt+Pd concentrations in excess of 75 ppb. Drillcore over this section contained 0.5–1% pyrrhotite and chalcopyrite.

Drillholes FXR 006 and FXR 010 intersect the same 95 m thick intrusion and together form a continuous section through the intrusion. The Mg# ranges from 28 to 82, and the peridotitic portion of the intrusion is only 30 m thick, or one-third of the total intrusion (Figures 12a, b). Two samples (at 70 and 80 m) have extremely low Mg#, high TiO_2 concentrations, and Ni concentrations below the detection limit of 20 ppm. This interval could represent a 'sandwich zone', where final crystallization occurred and incompatible elements became concentrated (Figures 12a–c). As with intrusion FXR 001, there is a thin interval of pyroxenite between the peridotite and gabbro (Figure 12d). Figure 12e illustrates the LREE enrichment in FXR 006/010; the whole of the intrusion appears to be contaminated (average ratio of 1.9). Above the peridotite, the ratio increases upward from 1.6 to a maximum of 2.4 within the 'sandwich zone'. Figure 12f illustrates extreme depletion of Pt and Pd (average <1.2 ppb) in the gabbro. The pyroxenite layer occurring between the gabbro and the peridotite contains up to 1% blebs of pyrrhotite and chalcopyrite, yet shows only slight enrichment in Pt+Pd (up to 65 ppb). The PGE depletion is good evidence that a process has

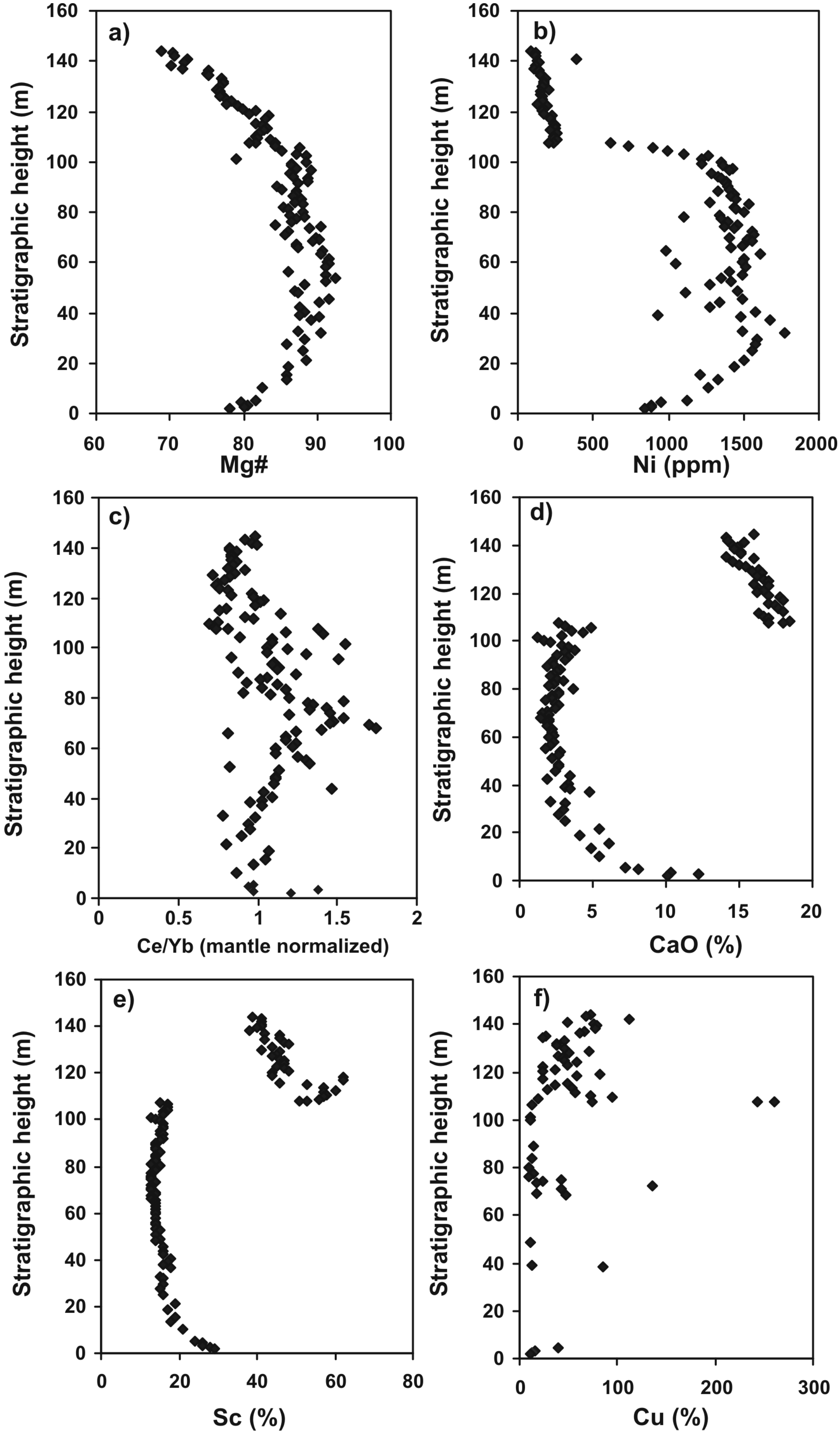


***Figure 10:** Chemostratigraphic plots for Lower Intrusion FXR 001: **a)** Mg#, **b)** Ni, **c)** Ce/Yb (mantle normalized), **d)** CaO, **e)** Sc, and **f)** Cu.*

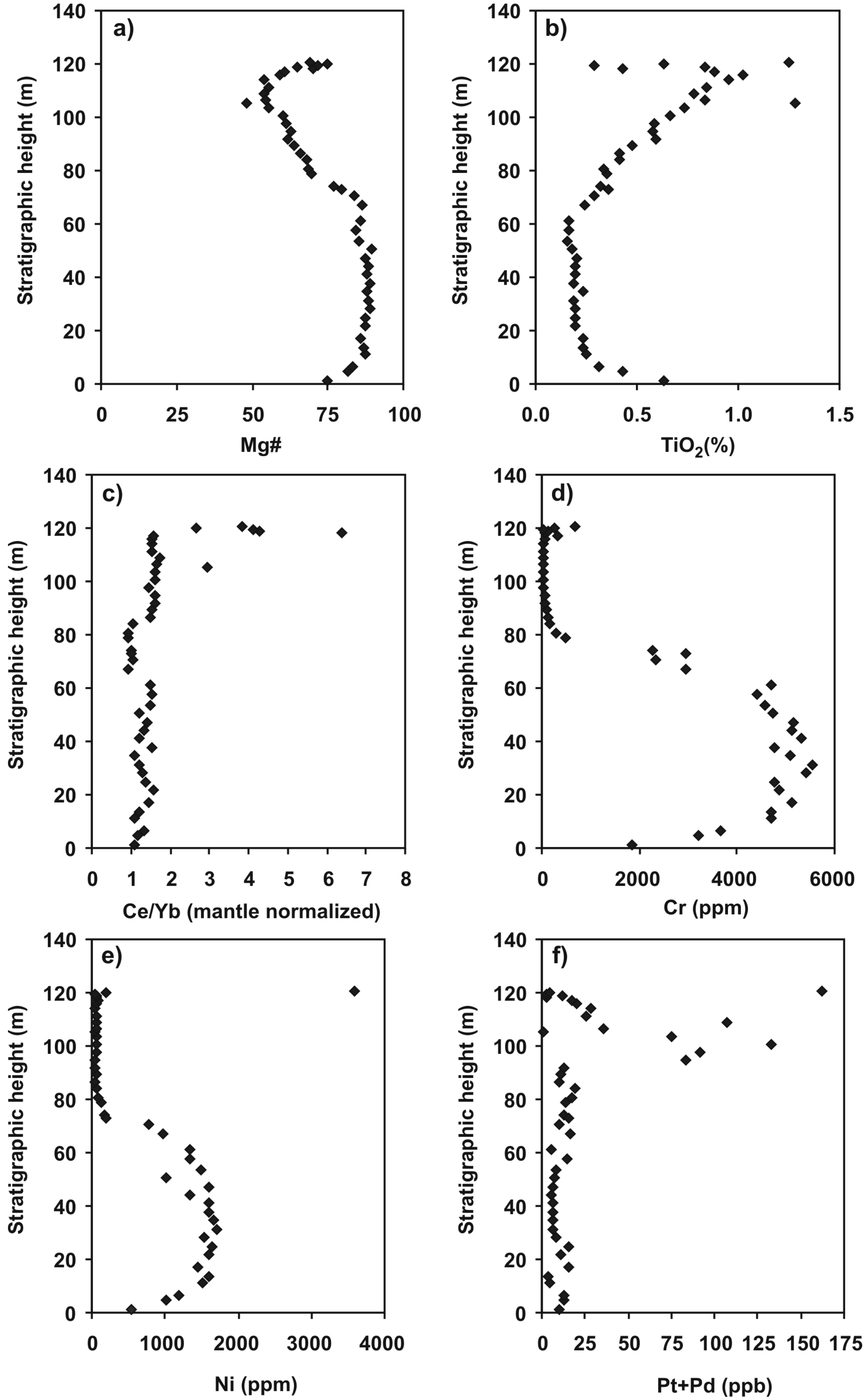


Figure 11: *Chemostratigraphic plots for Lower Intrusion FX-01-15:* ***a)*** *Mg#,* ***b)*** *TiO_2,* ***c)*** *Ce/Yb (mantle normalized),* ***d)*** *Cr,* ***e)*** *Ni, and* ***f)*** *Pt+Pd.*

effectively scavenged the PGE from the magma. Sulphide saturation may have occurred after crystallization of the peridotite. The pyroxenite layer was recently resampled, but no significant PGE enrichment was found.

Lower and Upper Volcanic formations

A thorough description of the volcanology, petrography and chemistry of the Lower and Upper Volcanic formations can be found in Scoates (1981a). Additionally, Syme et al. (1999) produced several detailed volcanological sections through the volcanic formations along the Fox and Stupart rivers. Distinguishing between Lower Intrusions and volcanic sequences in drillcore can be difficult, especially at the top of the Lower Sedimentary Formation. This is because thick flows can differentiate and produce grain sizes that are comparable to those of the Lower Intrusions. Distinguishing between these flows and intrusions was done primarily by observing contact relationships with country rocks, as well as identifying the hostrocks. Interflow sedimentary rocks tend to be less than 5 m thick, and are composed of laminated sulphidic argillite (up to 20% S). For the most part, interflow sedimentary rocks constitute <5% of the volcanic pile (both LVF and UVF), suggesting rapid effusion rates for the Fox River Belt volcanic sequences, similar to that inferred for flood basalt.

The Lower and Upper Volcanic formations are chemically and volcanologically very similar. Figures 13a–c illustrate how these volcanic piles overlap completely and are likely comagmatic. They might, in fact, represent the same sequence that has been structurally repeated. Additionally, the LVF and UVF are almost identical in terms of chemostratigraphic relationships, and will therefore be treated together in this section. Figures 12a and b show that there are two very distinct groups. The group with high TiO_2 and Yb is from the D Member, whereas the rest belong to the A, B and C members; these are all described in more detail below.

Chemostratigraphy

The Lower Volcanic Formation (LVF) is represented in the chemostratigraphic plots of Figure 14 by samples from the Great Falls area only (the very base of the volcanic section is not represented). All of the samples from the Upper Volcanic Formation (UVF) were used to construct the plots in Figure 14; all but one of these samples were collected along the Fox and Stupart rivers. The very base, the very top and a large section in the middle of the stratigraphy were not sampled due to lack of outcrop. The chemostratigraphies of the two volcanic formations are a close match, even though the UVF is thicker. The datum upon which the two datasets were hung was based on Cr concentrations at the transition between Cr >500 ppm and Cr <500 ppm (Figure 14a). This was done by setting the thickness of the missing stratigraphy of the Lower Volcanic Formation (south of Great Falls) at 450 m. This is 300 m less than suggested on the map by Scoates (1981), but the location of the base of the LVF is poorly constrained due to the lack of available geological information. The gaps in the sampling in the LVF and UVF do not preclude the possibility that the stratigraphy in the UVF is a dilated version of the LVF or that specific units are thicker in the UVF (e.g., the C or D Member of the UVF could be in excess of 1000 m thick). Furthermore, it is possible that parts of the stratigraphy are structurally repeated, although there is no direct evidence to support this idea. Unfortunately, it is impossible to prove or disprove any of these suppositions without more exposure or diamond-drill core. Regardless, it is useful to show the LVF and UVF together on these stratigraphic plots because they are very similar in composition and physical volcanology. The major and trace-element chemostratigraphic plots suggest there are four distinct zones that essentially correspond to volcanology and phenocryst populations described by Scoates (1981).

The lowermost zone extends from 0 to 430 m; the A Member may correspond to the Lower Massive Zone of the LVF, but this is based on only one sample (Scoates, 1981). The A Member appears to correspond to the Lower Zone of the UVF, described as layered komatiitic basalt flows and olivine clinopyroxenite flows. It is characterized by high Mg and Cr owing to its ultramafic composition, which is also reflected by the presence of olivine and chromite phenocrysts (Figures 14a, b). Low Sc and Al_2O_3 concentrations reflect the ultramafic character of the magma (Figures 14c, d).

The B Member (430–910 m) corresponds to the base of the Middle Pillowed Zone of the LVF, which is composed of pillowed flows of plagioclase-bearing olivine clinopyroxenite. It also corresponds to the Middle Zone of the UVF (similar lithology to that described above; Scoates, 1981). The B Member has Cr concentrations of 600–1400 ppm and MgO concentrations of 10–16%. This zone is therefore more mafic in composition, likely due to fractional crystallization of olivine and chromite within a subchamber. Increased Sc and Al concentrations reflect the relative incompatibility of these elements in olivine and chromite.

The C Member (910–1640 m) corresponds to the top of the Middle Pillowed Zone of the LVF, which comprises basalt with pyroxene and plagioclase phenocrysts. It also corresponds to the base of the Upper Zone of the UVF (similar lithology to the LVF, plus rare olivine; Scoates, 1981). The C Member is characterized by limited variation in MgO (8–9.5%) and Cr (250–300 ppm). The Sc and Al_2O_3 concentrations are still higher than in the A and B members. Again, this is consistent with cotectic crystallization of olivine and chromite in a subchamber. There is a gap between the concentrations of all these elements and those of the B Member. This may be a function of sample spacing, a hiatus in volcanism, or the volcanic architecture.

The D Member (1640–2500 m) corresponds to the Upper Massive Zone of the LVF and consists of plagioclase-phyric basalt. It also corresponds to the Upper Zone of the UVF, which comprises pyroxene-plagioclase-phyric basalt (Scoates, 1981). The D Member has considerably lower MgO (5–7%) and Cr (80–150 ppm) than the other zones. Scandium concentrations appear to be slightly lower than those of the C Member, with the exception of three samples (not shown) that have concentrations in excess

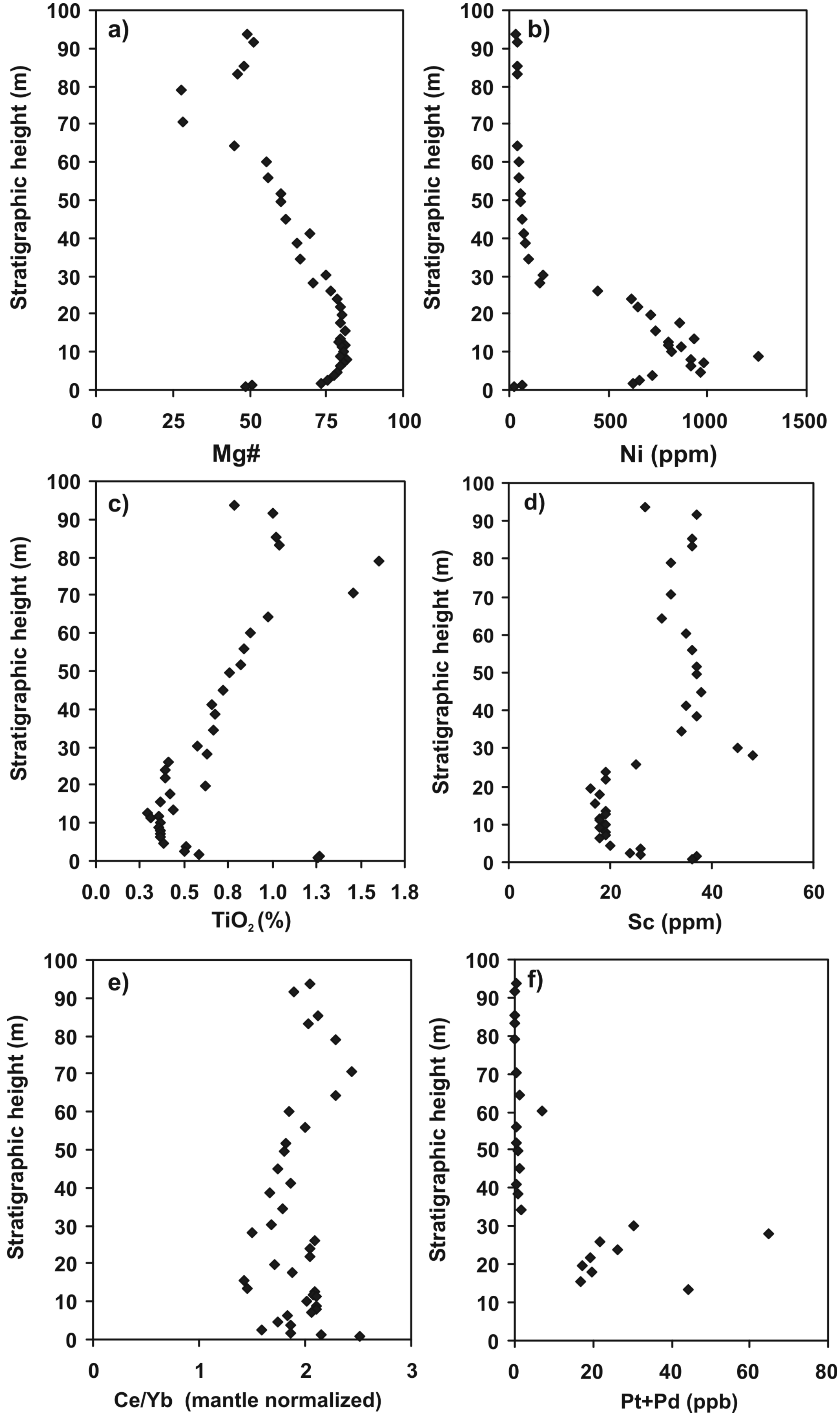


Figure 12: *Chemostratigraphic plots for Lower Intrusion FXR 006/010:* ***a)*** *Mg#,* ***b)*** *Ni,* ***c)*** *TiO_2,* ***d)*** *Sc,* ***e)*** *Ce/Yb (mantle normalized), and* ***f)*** *Pt+Pd.*

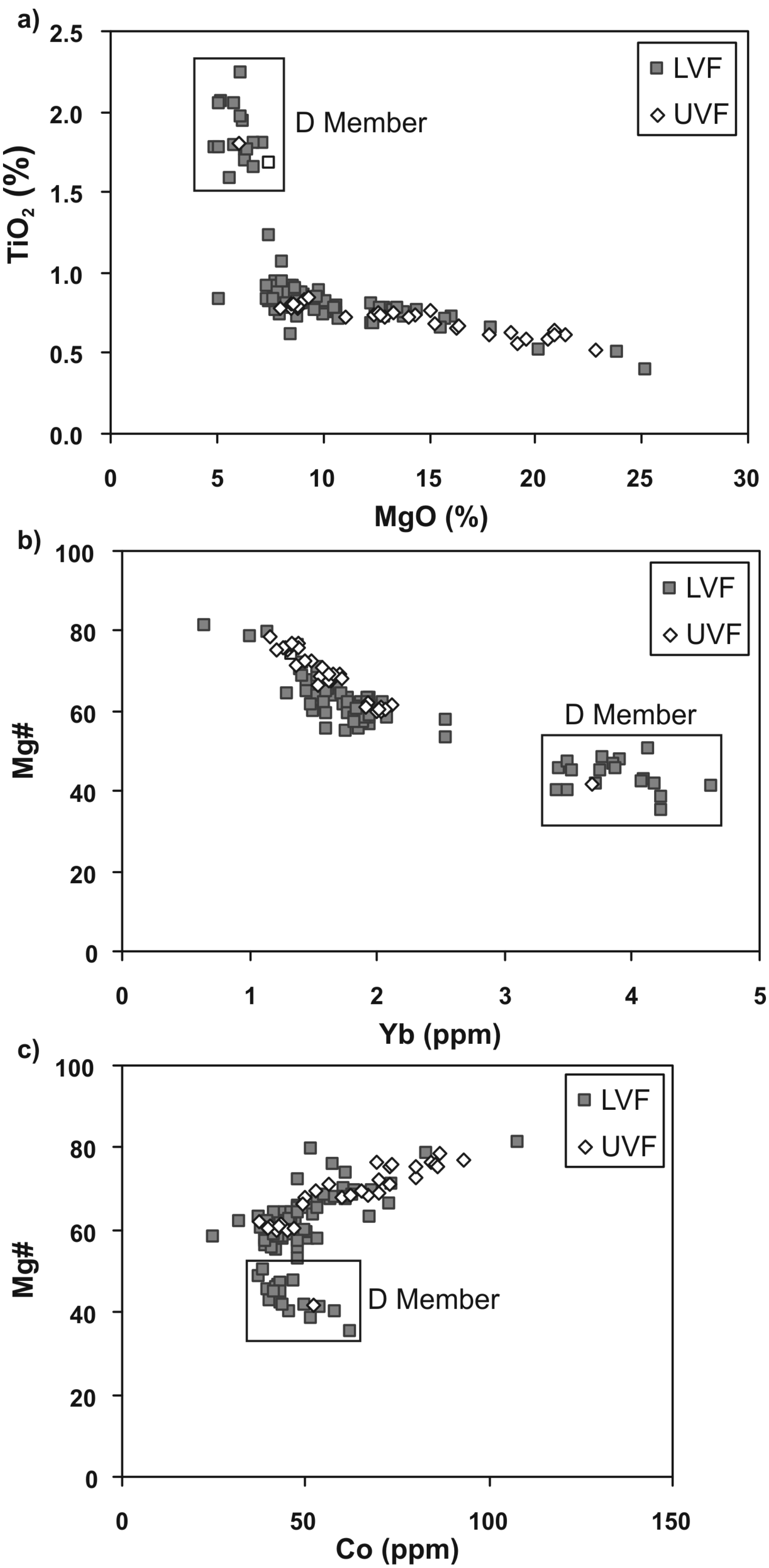


Figure 13: *Harker diagrams of the Lower and Upper Volcanic formations:* ***a)*** *TiO_2 versus MgO,* ***b)*** *Mg# versus Yb, and* ***c)*** *Mg# versus Co. Abbreviations: LVF, Lower Volcanic Formation; UVF, Upper Volcanic Formation.*

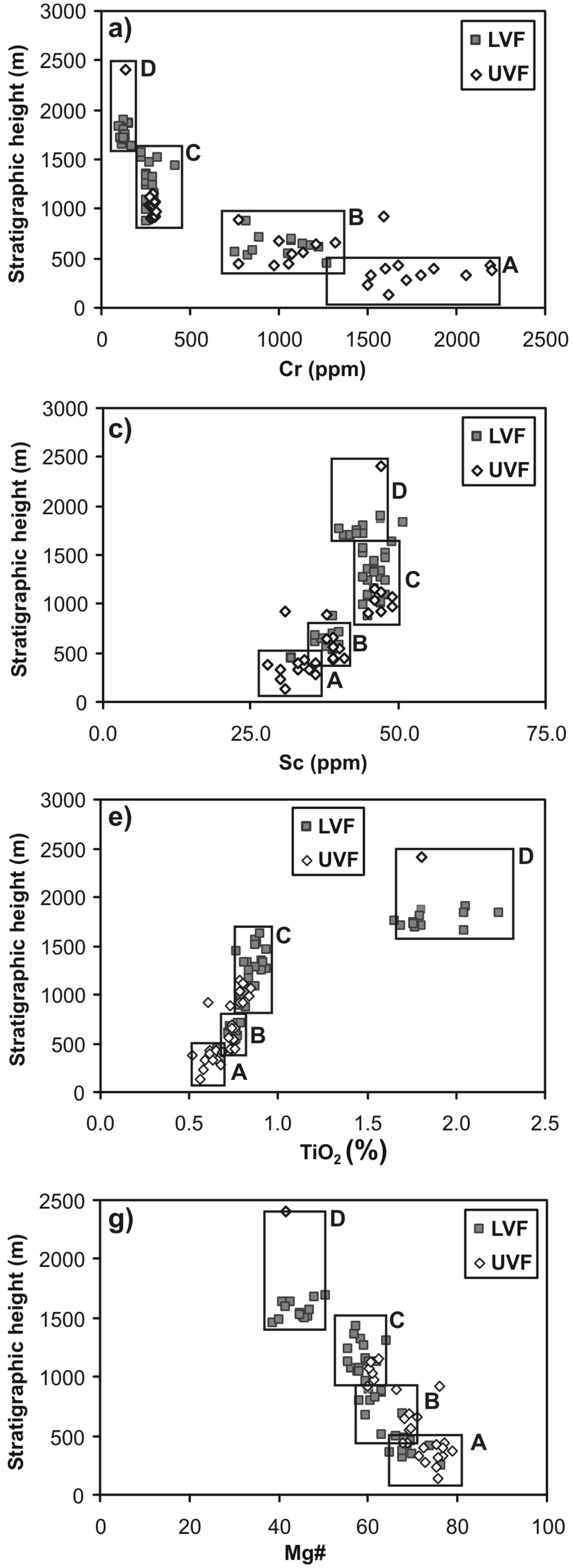


Figure 14: Chemostratigraphic plots of the Lower and Upper Volcanic formations: ***a)*** *Cr,* ***b)*** *MgO,* ***c)*** *Sc,* ***d)*** *Al_2O_3,* ***e)*** *TiO_2,* ***f)*** *Yb,* ***g)*** *Mg#, and* ***h)*** *Ce/Yb (mantle normalized). Upper-case letters indicate member names. Abbreviations: LVF, Lower Volcanic Formation; UVF, Upper Volcanic Formation.*

of 80 ppm. These values are higher than those of the olivine pyroxenite within the Lower Central Layered Zone of the Fox River Sill (where the highest values would be expected); therefore, it seems likely that these high concentrations are due to addition of Sc through possible alteration. The Al_2O_3 concentrations appear to be lower than in the C Member samples. The reduced concentrations of Al_2O_3 and Sc could represent a change in the mineralogy crystallizing from the magma in a subchamber. The arrival of plagioclase and augite on the liquidus would mean relative compatibility of Al and Sc and their retention in a subchamber. High TiO_2 and Yb concentrations set the D Member apart from the rest of the zones (Figures 14e, f). These concentrations are similar to those found in the 'sandwich zone' within Lower Intrusion FXR 006/010. The D Member may represent late eruption of the magma after a subchamber evolved into closed systems (temporarily). A hiatus in volcanism in the LVF and UVF would also account for the jump seen in the levels of Cr, MgO, and Mg# (Figures 14a, b, g).

The Ce/Yb ratio illustrates slight LREE enrichment, which appears to have affected the base and the top of the section (Figure 14h). This LREE enrichment can be achieved through one of three processes: mixing with an enriched magma or country rock; a separate enriched source; or, in extreme cases, crystallization and fractionation of a large amount of olivine and clinopyroxene. The D Member has the highest trace-element concentrations (Yb) and exhibits slight LREE enrichment (Figure 15). This may reflect a process of assimilation and fractional crystallization (AFC). Fractional crystallization could account for the higher overall trace-element content, and concurrent assimilation could account for the LREE enrichment. If a fractional crystallization process was occurring to form the volcanic rocks of the D Member, then plagioclase and pyroxene are likely to be fractionating phases, as shown by the negative Al and Sc anomalies in Figure 15 (Al and Sc are compatible in plagioclase and pyroxene, respectively). A large volume of crystals would have to fractionate to account for the observed compositions, as shown by the doubling of the Yb concentrations between the C and D members. This means that approximately half the volume of the remaining magma would have to crystallize to produce the observed Yb concentrations.

Platinum group element (PGE) data are not available for most samples from the UVF and parts of the LVF. The average concentration of Pt+Pd within the D Member of the LVF, excluding samples with unusually high concentrations (>50 ppb), is 5 ppb (14 samples). The average PGE concentrations for the C Member (27 samples) and the A Member (12 samples), calculated in the same way, are ~25 ppb and ~17.5 ppb, respectively (Figure 16). The lower arrow illustrates the comparable relative increases in abundance of Yb and Pt+Pd between zones A and C (~50% increase). This suggests that the PGE largely behaved as incompatible elements in the subchamber during this stage of evolution, and implies that sulphide saturation was not reached in the subchamber during the olivine-chromite fractional crystallization stage. The upper arrow in Figure 16 illustrates what happens

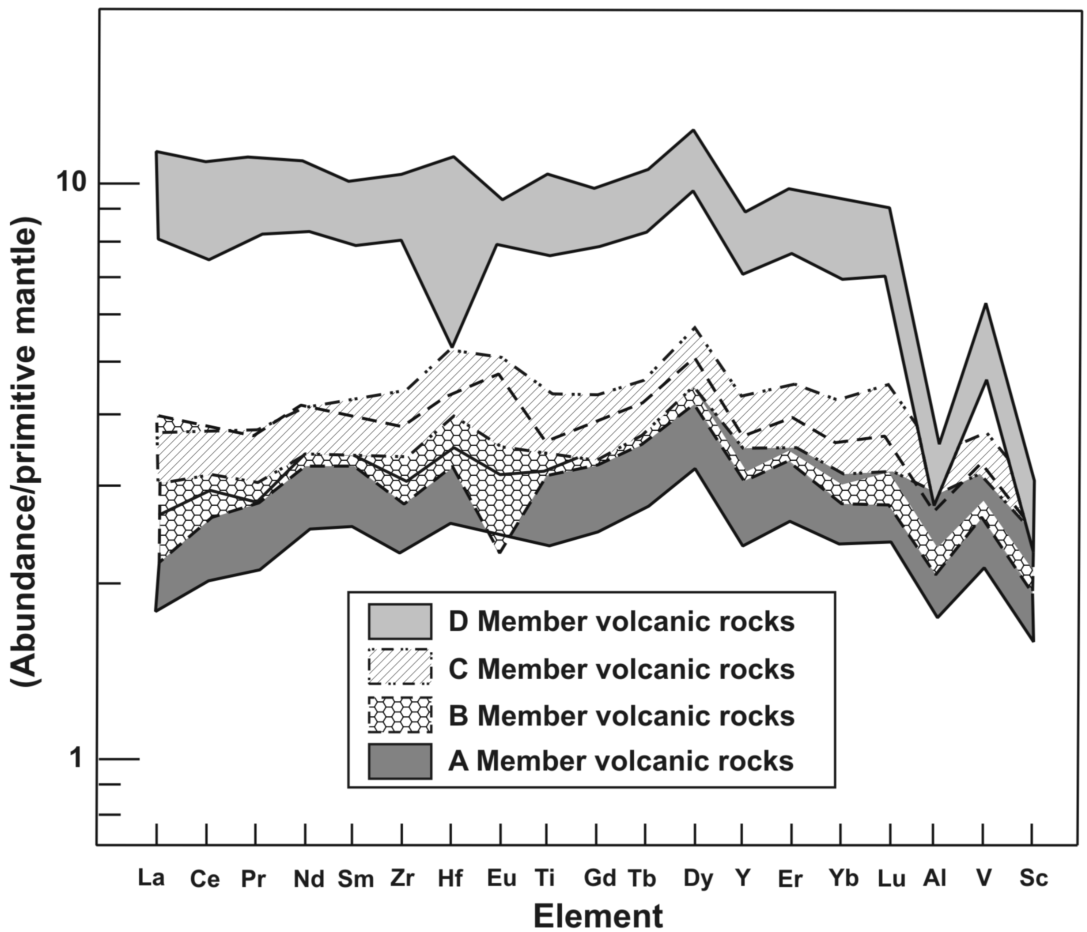


Figure 15: *Primitive-mantle–normalized spider diagram of the Lower and Upper Volcanic formations. Primitive-mantle values for normalization from Sun and MacDonough (1989).*

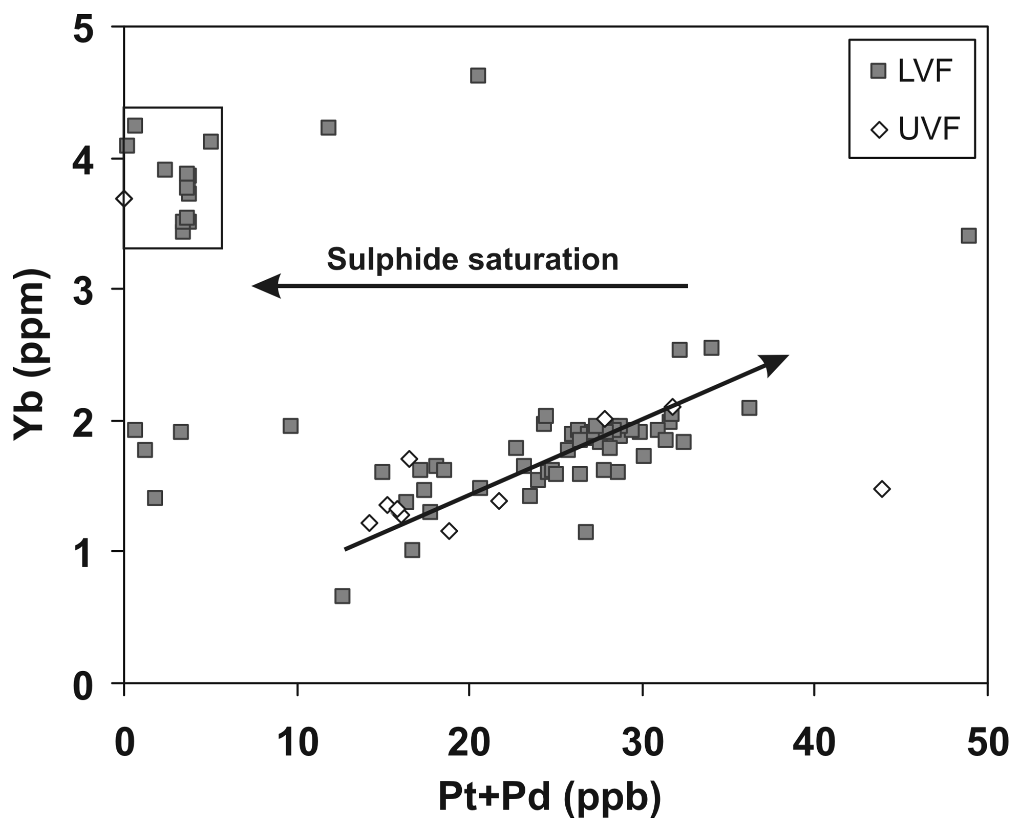


Figure 16: *Plot of Yb versus Pt+Pd, illustrating the incompatible behaviour of PGE for the bulk of the fractional crystallization history of the magma (see text for discussion). The grey box encompasses 14 samples from the D Member that contain less than 5 ppb Pt+Pd (relative depletion). Abbreviations: LVF, Lower Volcanic Formation; UVF, Upper Volcanic Formation.*

when sulphide saturation occurs in the magma, effectively scavenging the PGE from the remaining magma. This could be an indication that a PGE-rich sulphide horizon was present within a subchamber associated with the extrusive rocks. Another possible explanation is that the magma that formed the D Member was produced from a low degree of partial melting of the mantle. During melting in the mantle, high degrees of partial melting are needed to mobilize all of the sulphides; if any sulphide remains in the melt region, then most of the PGE are retained in the mantle (Hamlyn and Keays, 1986; Rehkämper et al., 1999). A low degree of partial melting would also cause higher overall concentrations of incompatible elements (e.g., Ti), and lower concentrations of Mg and Cr would be expected (MORB-like magma). Resolving the origin of the D Member volcanic rocks is essential in understanding the magmatic history of the belt and also has important economic implications.

Nickel is commonly used to track olivine fractionation, as well as sulphide saturation, within magmatic systems (Naldrett 1999). Unfortunately, the Ni data are of relatively poor quality, so Co is used instead. Cobalt changes its behaviour between the C and D members (Figure 13c). Assuming that the magma evolved in one or several subchambers, then the trend of decreasing Co with decreasing Mg# should represent relative compatibility of Co within a cumulate phase in the intrusion (probably olivine). The opposite trend seen in the D Member represents the relatively incompatible behaviour of Co within the subchamber due to a change in the main cumulus phase (olivine no longer on the liquidus). This is consistent with the interpretation that the transition between the C and D members represents a change in the main crystallization phases in the subchamber from olivine and chromite to plagioclase and clinopyroxene. Several samples fall off the main trend toward lower Co in Figure 13c (mostly ultramafic samples from FX-01-11). These samples could represent Co (and Ni) depletion caused by the formation of immiscible sulphides that would have scavenged Ni and Co, leaving the magma depleted in these elements (e.g., Maier et al., 1998; Naldrett, 1999).

Fox River Sill

The Fox River Sill is dominated by olivine-chromite cumulate rocks and can therefore be called an ultramafic intrusion. The highest Mg# values are found in the Lower Central Layered Zone and peak at 95 (Figure 17a). The Mg# increases upward toward the middle stratigraphic levels and then drops off above the contact between the Lower and Upper Central Layered zones to values below 90. Cyclic Unit 1 within the Marginal Zone shows significant variation in Mg#, ranging from 85 at the base to 67 at the top; this suggests a process of fractional crystallization in a closed system. Cyclic Unit 2 has much more limited variation in Mg#, from 69 to 63. This limited Mg# variation, coupled with decreasing Ti and Zr concentrations toward the top of this cyclic unit, suggest that the system became open during the crystallization of Cyclic Unit 2 (i.e., magma influx diluting the concentrations of incompatible elements; Figures 17b, c). The Marginal Zone, as a whole, has high Ti concentrations compared with the rest of the Fox River Sill. It is unlikely that this is from contamination by the Middle Sedimentary Formation, as these rocks only

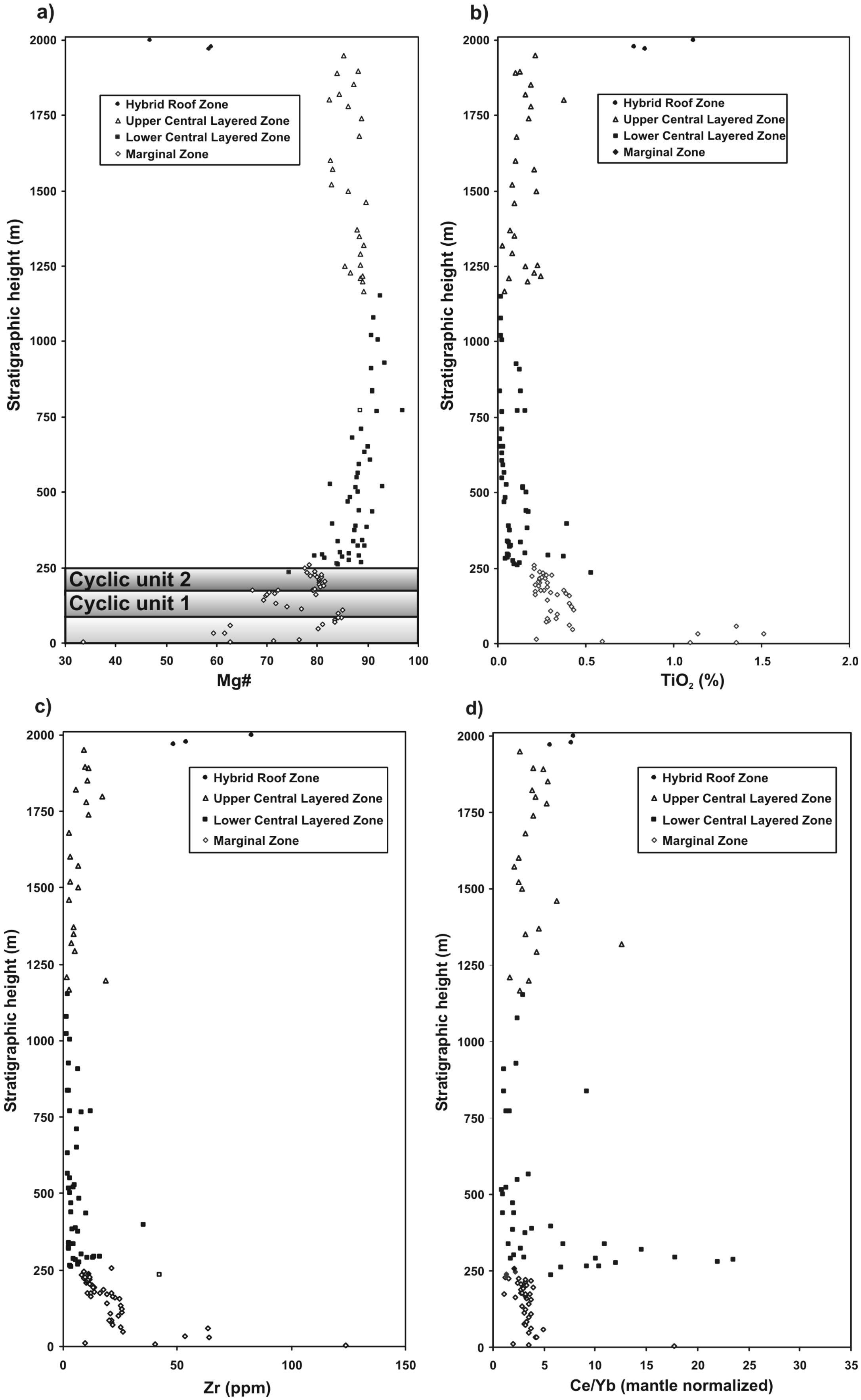


Figure 17: *Chemostratigraphic plots for the Fox River Sill:* ***a)*** *Mg#,* ***b)*** *TiO_2,* ***c)*** *Zr,* ***d)*** *Ce/Yb (mantle normalized), and* ***e)*** *Pt+Pd. Samples in (e) with PGE concentrations below the detection limits were given a value of 0.2 ppb. Abbreviations: LMU, lower mineralized unit; MMU, middle mineralized unit; UMU, upper mineralized unit.* *(continued on next page)*

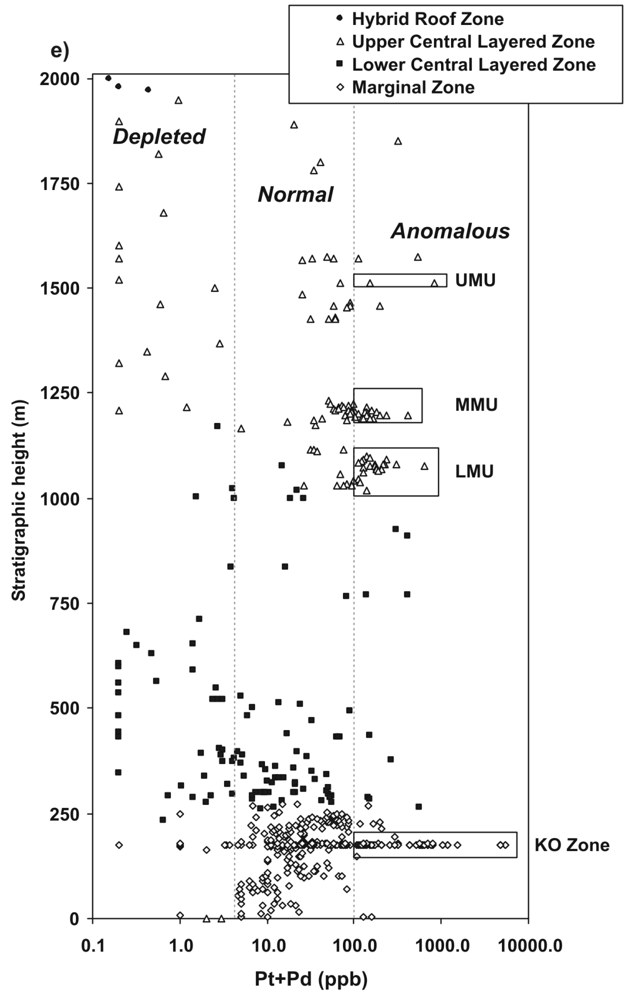


Figure 17 (continued): *Chemostratigraphic plots for the Fox River Sill:* ***a)*** *Mg#,* ***b)*** *TiO_2,* ***c)*** *Zr,* ***d)*** *Ce/Yb (mantle normalized), and* ***e)*** *Pt+Pd. Samples in (e) with PGE concentrations below the detection limits were given a value of 0.2 ppb. Abbreviations: LMU, lower mineralized unit; MMU, middle mineralized unit; UMU, upper mineralized unit.*

contain an average of 0.5% TiO_2.

The bow-shaped pattern that is apparent in Figures 17a–c is due, in part, to the fact that both the Hybrid Roof Zone and the Basal Contact Unit of the Marginal Zone are variably contaminated. This is supported by the Ce/Yb ratios, which are higher at the contact (Figure 17d). Low ε_{Hf} and ε_{Nd} values for these rock types also support this idea (Desharnais et al., 2002). There is a major deviation in the Ce/Yb ratio at the base of the Lower Central Layered Zone. This pattern was noticed by Smerchanski (2001) and was attributed to alteration because of the extensive hydration of these samples and their association with apparently nonmagmatic PGE mineralization. The samples between 600 and 750 m have REE concentrations below the detection limit.

Platinum-group elements

Several stratigraphic intervals within the Fox River Sill have anomalous PGE concentrations, both enrichments and depletions (Figure 17e). There is some overlap between the different zones on this plot because of their varying thicknesses (e.g., the Lower Central Layered Zone is thicker in the Great Falls area than in the western section). Sampling was quite sparse in some parts of the intrusion, so it is difficult to ascertain whether PGE depletion occurs in these areas. There are a few samples within the KO Zone horizon that show depletion, but this is likely a function of the extremely high density of samples in this area. Previously recognized intervals that show PGE mineralization, from bottom to top, are the KO Zone, the Lower Mineralized Unit, the Middle Mineralized Unit, and the Upper Mineralized Unit (Scoates and Eckstrand, 1986; Schwann, 1989).

Marginal Zone

Detailed mapping of bush and river outcrops of the Marginal Zone along the Fox River has delineated a heterogeneous sequence of mineralized (PGE-Cu-Ni) ultramafic and mafic rocks, several metres thick, referred to as the KO Zone (Figure 18; Peck et al., 1999; Desharnais et al., 2000). The base of the KO Zone is represented by an irregular, commonly scalloped and undulating contact between gabbroic to anorthositic rocks of the LG1 subunit and coarse-grained actinolite-bearing olivine

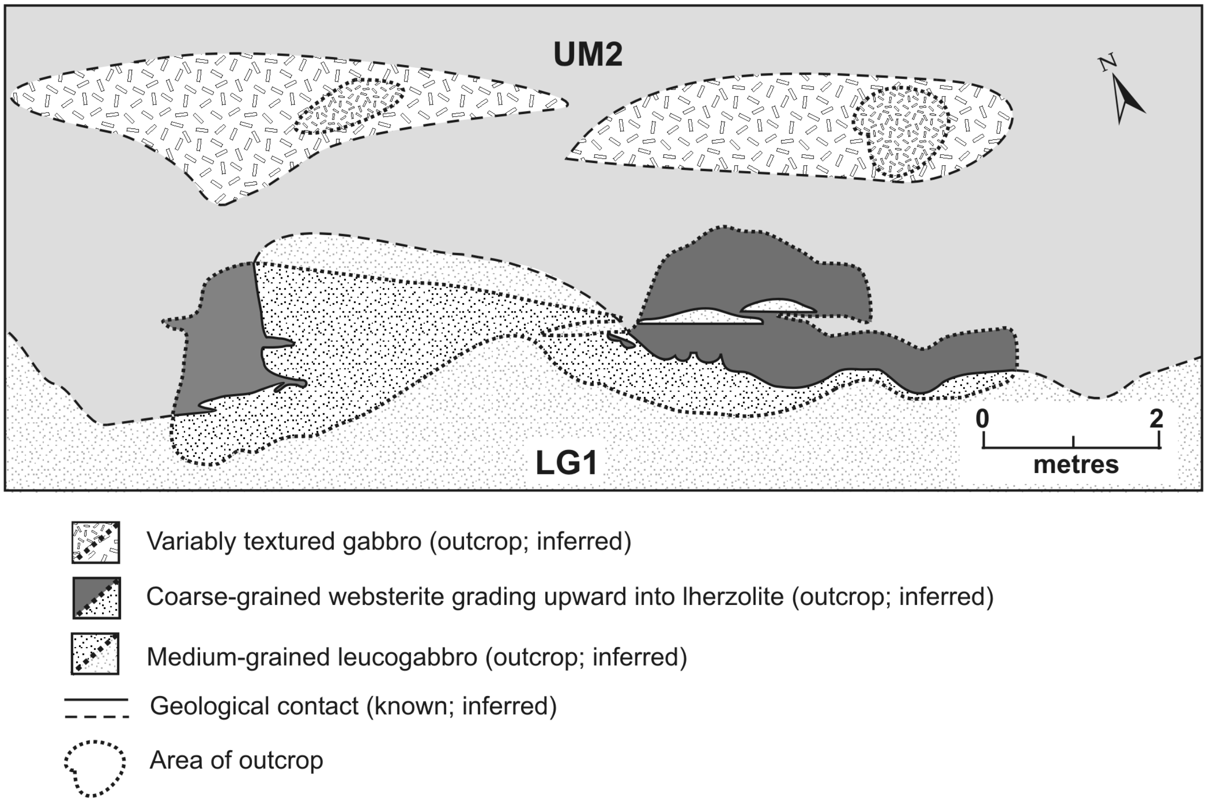


***Figure 18:** Outcrop-scale map of the KO Zone, showing the irregular contact between Cyclic Units 1 and 2 (modified from Desharnais et al., 2000).*

websterite of the KO Zone (base of Cyclic Unit 2). The websterite layer ranges from <1 to 3 m in thickness. It commonly contains net-textured, blebby and disseminated sulphides that are concentrated within decimetre- to metre-scale trough structures along the irregular LG1-UM2 contact. The mineralized websterite is typically 1 m thick and both grain size (ranging from 2 to <0.5 cm) and sulphide content (ranging from 15 to <1%) decrease upward (Desharnais et al., 2000). There is an apparent decreasing-upward trend in the PGE concentrations within the mineralized portion of the KO Zone. The PGE are associated with sulphides, and have a relatively good correlation with Cu and Ni (Desharnais et al., 2000; Peck et al., 2002). Sulphides tend to be barren of precious metals where the websterite layer is less developed or absent. Hand samples have a maximum grade of 2.1% Cu, 0.9% Ni, and 5 g/t combined Pd+Pt+Au. Metal concentrations recalculated to 100% sulphide are as high as 27% Cu, 4% Ni and 110 g/t combined Pd+Pt+Au. Locally, crescent-shaped pods and discontinuous, metre-size layers of variably textured gabbro, diorite, leucogabbro and leucodiorite occur within weakly mineralized lherzolite in the upper part of the KO Zone. These pods are locally mineralized and can display size (coarsest at the base) and compositional (least evolved at the base) grading of sulphide and silicate components (Peck et al., 1999; Huminicki, 2000). The pods are thought to reflect rheomorphic segregations derived from the underlying, gabbroic, upper part of Cyclic Unit 1 (LG1) that ascended into the lower part of Cyclic Unit 2 (Desharnais et al., 2000). The Pt and Pd occur in nearly equal concentrations in weakly mineralized samples, whereas the richest samples typically have three times more Pd than Pt.

The MZ2 subzone, which occurs within the gabbro of Cyclic Unit 2, is an erratically disseminated sulphide zone. Sulphide concentrations are mainly less than 1% but may be as high as 15% in metre-sized areas within variably textured patches (Peck et al., 1999). In most places, the sulphides are dominated by pyrrhotite and tend to be barren. The few examples that contain chalcopyrite tend to have anomalous PGE concentrations (up to 210 ppb). The average concentration of PGE in the Marginal Zone is 18 ppb when samples with concentrations greater than 50 ppb are excluded.

Lower Central Layered Zone mineralization

The average PGE concentration within the Lower and Upper Central Layered zones is 11 ppb (excluding samples with concentrations >50 ppb). This is lower than the average in the Marginal Zone (18 ppb) and the A Member of the Lower and Upper Volcanic formations (16 ppb). A possible explanation is that the rock in these zones is largely adcumulate, meaning that there was very little interstitial melt between cumulus grains. Platinum-group elements are incompatible in silicate minerals and are concentrated in the interstitial melt (and the late phases that crystallize from that melt).

Enrichment of PGE was previously unrecognized in the Lower Central Layered Zone. Of the ten samples that have anomalous PGE concentrations (>100 ppb), eight are olivine pyroxenite or wehrlite. Most of the samples contain negligible sulphides, with the exception of 38536-405.3, which contains 3.9 % S. Only two of the samples have Cu anomalies (>500 ppm) and none of them has significant Ni or Cr anomalies. The Pt/(Pt+Pd) ratio ranges from 0.23 to 0.6. A process of hydrothermal alteration is interpreted to have enriched sample GMD-01-048-10 (566 ppb total PGE; Smerchanski, 2001). In the Great Falls area, four of five samples from the olivine pyroxenite of Cyclic Unit 3 have PGE concentrations exceeding 65 ppb (one sample has 149 ppb total PGE). All of the nine samples above this olivine pyroxenite (from 500 to 750 m) have concentrations less than 7 ppb; this is low relative to the average concentration within the sill. Four of these samples were taken from olivine pyroxenite layers and five were from dunite layers (i.e., this anomaly is not due to preferential sampling of dunite). In the Great Falls area, the olivine pyroxenite from the sixth and seventh cyclic units contain anomalous PGE concentrations (85–421 ppb total PGE).

Upper Central Layered Zone mineralization

Three mineralized units were discovered in the Upper Central Layered Zone during drilling by BP Minerals Canada Ltd. The sulphides, consisting mainly of pyrrhotite, pentlandite, chalcopyrite, cubanite and mackinawite, rarely exceed 3% by volume (Scoates and Eckstrand, 1986). The three mineralized units are the Lower Mineralized Unit (80 m thick), Middle Mineralized Unit (50 m thick) and Upper Mineralized Unit (5 m thick; Schwann, 1989). The maximum PGE concentrations within the Upper Central Layered Zone tend to occur at the base of pyroxenite units and generally do not exceed 1 ppm. The Pt/(Pd+Pt) ratios increase upward between mineralized intervals, as well as within individual intervals (Schwann, 1989; Schwann et al., 1989). The most anomalously PGE-rich samples have Pt/(Pd+Pt) ratios as high as 0.91, whereas most samples in the mineralized units are dominated by Pd.

Sulphur isotopes

Sulphur-isotope data are derived from samples analyzed during this project, as well as samples from earlier studies conducted by Eckstrand et al. (1989) and Schwann (1989); the 88 samples are plotted by stratigraphic unit in Figure 19. Samples from this study were analyzed by Ed Ripley at Indiana University. Sulphides were drilled out using a dentist drill and heated to 1070°C, and the SO_2 gas was cryogenically separated and aspirated into a Thermo Electron Corporation Finnigan MAT 252 mass spectrometer. There are limited samples from certain parts of the Fox River Belt: there was only one sample from the Lower Central Layered Zone and none from the Lower Volcanic Formation; samples from the Lower Intrusions were solely from those interpreted to be contaminated; and samples from the Lower Sedimentary Formation were taken from three drillholes only. Some conclusions that can be drawn from this dataset are:

- Most of the Fox River Sill has heavy S contents (mean $\delta^{34}S$ = 8.4‰, range = 3.6–12.3‰; mantle derived S is 0).
- The Hybrid Roof Zone contains much heavier S than the rest of the Fox River Sill (15.7‰ and 20.7‰).
- The Middle Sedimentary Formation has very heavy S (mean $\delta^{34}S$ = 14.3‰, range = 5.8–25.9‰).
- The S from the Lower Sedimentary Formation (mean $\delta^{34}S$ = 7.8‰, range = 4.5–11.9‰) is light relative to that of the Middle Sedimentary Formation.

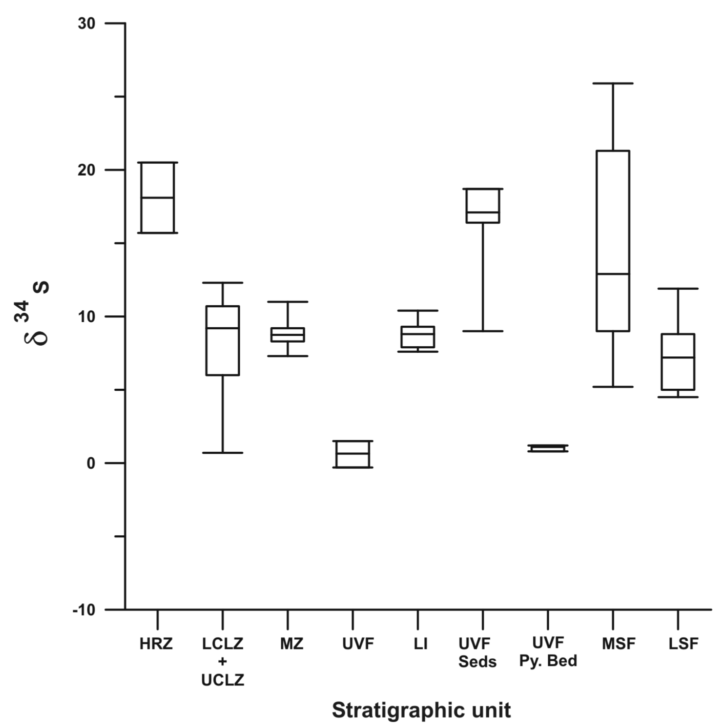


Figure 19: *Box and whisker plot illustrating variations in S-isotope compostions of rocks from the Fox River Belt.*

- The ‘contaminated’ Lower Intrusions have S-isotope signatures that are the same as those of the Fox River Sill (mean $\delta^{34}S$ = 8.7‰, range = 7.6–10.4‰).
- Sulphur from the Upper Volcanic Formation has a mantle signature (mean $\delta^{34}S$ = 0.6‰, range = -0.3–1.5‰];
- The S from a pyrite bed within the Upper Volcanic Formation has a mantle signature (mean $\delta^{34}S$ = 1‰).

It appears that the Fox River Sill and the ‘contaminated’ Lower Intrusions have a $\delta^{34}S$ composition that differs with that of the mantle ($\delta^{34}S \approx 9$). The heavy S in these intrusions was likely incorporated from the host sedimentary rocks. The Middle Sedimentary Formation has a large spread in $\delta^{34}S$ and is generally heavier than the Fox River Sill. The heavy S in the Fox River Sill was likely derived from the Middle Sedimentary Formation, although most Fox River Sill samples do not show contamination (LREE enrichment). A possible explanation for this is that the S was derived from the country rocks without wholesale melting (i.e., decoupling).

Conclusions

In considering the formation of the Fox River Belt, it is possible that all magmatic rocks of the Belt evolved from a single initial magma, and that the observed variation in composition is a function of fractional crystallization. Olivine compositions seem to suggest that the initial magma had an MgO content of 12–20%. Such a magma must have formed from high degrees of partial melting, as is also shown by the relatively high Cr and Ni contents and the high background concentrations of PGE (15–20 ppb; Rehkämper et al., 1999). The source would have been depleted, as shown by LREE depletion and positive ε_{Nd} and ε_{Hf} values (Desharnais et al., 2002). A mantle-plume source is suspected, based on high degrees of partial melting, the large volumes of magma (>10000 km^3), the association with a mafic dike swarm (Molson Dikes), and the proximity to a proposed plume head at 1883 Ma (Ernst and Buchan, 2001; Buchan et al., 2003). Trace-element variations are thought to be primarily a function of local contamination of the magma. Approximately half of the Lower Intrusions sampled have a distinct LREE enrichment, suggesting that the magma incorporated some country rock. In most cases, the entire intrusion shows LREE enrichment; in some examples, the lower and upper contacts are the only parts to show significant contamination. The latter is the case with the Fox River Sill, where significant contamination is shown only by the Hybrid Roof Zone and the base of the Marginal Zone, and perhaps the base of the Lower Central Layered Zone in the Great Falls area on the Fox River.

There is significant variability in the thickness of the peridotite portions of the Lower Intrusions, as well as in the composition of the most evolved rocks of these intrusions. This is likely a function of size and timing of the system opening and closing. Some of the intrusions must have behaved as open systems for at least part of their history. This is illustrated by the bulk composition of some of these intrusions, which is much too ultramafic to be representative of an initial magma.

The Lower and Upper Volcanic formations are geochemically indistinguishable. Stratigraphically, they consist of four distinct geochemical zones, each of which becomes more evolved upward. The chemostratigraphic patterns are distinctively stepwise, suggesting that the subchambers were affected by sudden changes in chemistry. Alternatively, the gaps could be the result of gaps in eruption, allowing magma compositions to change considerably between eruptions. Also, given the relatively poor exposure, incomplete sampling could have contributed to the stepwise pattern. The uppermost division, the D Member, shows a significant increase in incompatible elements (e.g., TiO_2 and REE) and records the transition from cotectic crystallization of olivine and chromite to crystallization of pyroxene and plagioclase. The relatively small volume of the D Member within the Lower Volcanic Formation suggests that most of the volcanism occurred during a period when crystallization of olivine and chromite (dunite) was dominant. Due to the apparently small volumes of olivine-chromite cumulate within the Lower Intrusions, it is unlikely that these intrusions represent good candidates for subchambers to volcanism of the Lower Volcanic Formation. The Fox River Sill may be a better candidate because of its size and the fact that it consists largely of olivine-chromite cumulate.

The broadly similar successions of sedimentary, volcanic and intrusive rocks that constitute the Fox River Belt have led to the speculation that they could be explained by tectonic repetition (i.e., thrusting; Scoates et al., 1981). Harker diagrams and chemostratigraphic plots of the Lower and Upper Volcanic formations further illustrate their close geochemical affinity. Evidence of faulting is rare, although this could be due to, in part, to lack of exposure and the difficulty in identifying faults in drillcore. There are examples of strongly foliated and brecciated rock near the base of the Fox River Sill in three drillholes (FX-01-25, 38528 and 38541). There are four other drillholes, however, that do not show evidence of faulting. If the volcanic formations are fault repeated, then this would have several important implications, including the possibility that the Lower Intrusions represent apophyses of the Fox River Sill. Another implication of the thrust theory is that the Lower and Middle Sedimentary formations would be stratigraphic equivalents. This is supported by the identification of very distinctive sedimentary rocks (carbonaceous shale with quartz spheres 2–5 cm in diameter) as rafts within the Fox River Sill and within the Lower Sedimentary Formation. Therefore, the Fox River Sill may have been intruded into the Lower Sedimentary Formation, and later physically separated from the rest of the sedimentary package by a thrust fault.

Scoates (1981) found a higher metamorphic grade within the top of the Lower Volcanic Formation that was interpreted as representing a thermal aureole related to the intrusion of the Fox River Sill. This argues against the possibility that the Lower and Upper Volcanic formations are structurally repeated sequences. The question of structural repetition remains unresolved.

Contamination of the volcanic rocks appears to be minor (samples with the highest Ce/Yb ratios are within the range of what is considered uncontaminated). The lack of contamination is corroborated by positive ε_{Hf} and ε_{Nd} values, and $\delta^{34}S$ values near zero. It should be noted that the bases of both volcanic piles, which have the highest prospectivity for magmatic nickel deposits (stratigraphic position analogous to mineralized Raglan horizon within the Cape Smith Belt), are unexposed and unsampled.

The chemistry of the Marginal Zone is appreciably different than the rest of the Fox River Sill, more closely resembling that of the Lower Intrusions. This is most likely a function of more rapid cooling, which resulted in more trapped interstitial liquid between cumulus minerals. The Marginal Zone appears to have crystallized as a closed system, with the exception of the top of Cyclic Unit 2, which appears to have evolved under open-system conditions. The ultramafic character of the Lower and Upper Central Layered zones supports the idea that the Fox River Sill acted as a subchamber for the Upper Volcanic Formation. Chemically, it is difficult to distinguish between the Lower and Upper Central Layered zones because they are so similar. One could use a cutoff Mg# value of 90 because the top third of the Lower Central Layered Zone has higher Mg# values and the base of the Upper Central Layered Zone has values that drop sharply below 90 at the contact.

The evolution of the magma that erupted to form the Lower and Upper Volcanic formations would have taken place largely in the ultramafic portion of this plumbing system (Fox River Sill), as shown by the high proportion of volcanic rocks whose chemistry was primarily controlled by the cotectic crystallization of olivine and chromite in the subchamber (A, B and C members).

Heavy S signatures within the Fox River Sill and Lower Intrusions indicate that these intrusions have acquired S from an external source. This may be attributed to assimilation of sedimentary rock, or volatile absorption from sedimentary rock into the intrusions. The fact that the Upper Volcanic Formation has a lighter S-isotope signature than its proposed subchamber, the Fox River Sill, is puzzling.

Economic geology

The following features of the Fox River Belt suggest that it has high potential for the formation of economic Ni-Cu-PGE deposits:

- It is located within the Superior Boundary Zone between two world-class nickel mining camps (Thompson Nickel Belt, Cape Smith Belt).
- All of the magmatic rocks have a mafic-ultramafic character.
- The magma was undersaturated in S when it reached crustal levels, as shown by the high background PGE concentrations.
- Sulphur-rich sedimentary rock represents an excellent candidate for a source of external S.
- Magmatic bodies and volcanic rocks were emplaced into and flowed onto these S-rich sedimentary rocks.
- Minor magmatic sulphide mineralization is present within the Fox River Sill.

Ultramafic magmas, by their very nature, are sulphide undersaturated; therefore, a change in the dynamics of the system is usually invoked to account for sulphide saturation (Lesher et al., 2001). The most commonly used trigger for driving a magmatic system to sulphide saturation is the addition of S, either by physical incorporation of a S-rich country rock or through absorption of S as a volatile phase (Naldrett, 1999; Lesher and Burnham, 2001a). The added S can induce sulphide saturation and cause exsolution of immiscible sulphide droplets. The PGE, Cu and Ni have high partition coefficients for sulphide liquid and will partition preferentially into the sulphide phase. A turbulent flow environment is favoured because it forces the sulphide droplets to interact with large volumes of magma and should therefore increase the metal tenor of the sulphides (high R-factor).

The Raglan horizon in the Cape Smith Belt hosts more than a hundred small lenses of Ni-Cu-PGE mineralization at the base of an ultramafic flow-sill complex (Barnes, 1990). The base of the Lower and Upper Volcanic formations could represent equivalents of the Raglan horizon. Lack of exposure makes exploration along these horizons much more difficult than it is in northern Quebec. The base of the Lower Intrusions could also represent good targets for massive Ni-Cu-PGE deposits, similar to those of the Thompson Nickel Belt or the Noril'sk region. Exploration should be concentrated within the contaminated intrusions, because contaminated magmas have more potential for attaining sulphide saturation (e.g., FXR 006/010). Most hostrocks for nickel deposits worldwide are associated with dynamic, open systems that allow significant interaction between sulphides and magma (Naldrett, 1999).

In some of the drillholes in the Fox River Sill, the Marginal Zone is absent (i.e., dunite from the Lower Central Layered Zone is in contact with the Middle Sedimentary Formation). These areas, where ultramafic magma is in contact with sulphide-rich sedimentary rock, represent good targets for Ni-Cu-PGE mineralization.

Several features of the Fox River Sill make it a good exploration target for PGE deposits:

- The Fox River Sill is one of the largest intrusions in the world.
- The background PGE values are high (10–30 ppb).
- Anomalous values of PGE are found at several levels within the sill.
- Samples depleted in PGE are found at several intervals within the sill.
- The Fox River Sill, especially the Lower Central Layered Zone, is relatively unexplored for PGE.

If the Fox River Sill indeed represents the subchamber for both the Lower and Upper Volcanic formations, then PGE depletion in the D Member of the volcanic succession should correspond to a PGE mineralization event within the Fox River Sill. If this is the case, then the onset of plagioclase crystallization can be used as a marker for locating this mineralization. This would correspond to the base of the Upper Central Layered Zone, where PGE mineralization has already been identified (Scoates and Eckstrand, 1986; Schwann, 1989). The lithological units at or just above the contact between ultramafic and mafic portions of large layered intrusions commonly contain PGE mineralization; these include the JM Reef in the Stillwater Complex and the Merensky Reef in the Bushveld Complex (e.g., Campbell et al., 1983). At this time, the Lower Intrusions are not considered to represent very good targets for PGE deposits because of their smaller size (magma volumes limit PGE enrichment of sulphides), even though PGE depletion has been recognized within the upper portion of FXR 006/010.

Scoates (1990) emphasized the high potential for chromite deposits within the Fox River Sill. There are several millimetre-scale layers with chromite concentrations of 5–25% within the Lower and Upper Central Layered zones. Unfortunately, chromite compositions in the Fox River Sill appear to be somewhat aluminous (Scoates, 1990; Osiowy, 2000; Smerchanski, 2001). Additionally, chromite is almost ubiquitous within the dunite of the Fox River Sill, which means that the magma was constantly being depleted in Cr as it evolved (Scoates, 1990). This reduces the likelihood of formation of thick, metallurgical-grade chromitite layers.

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