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GEOSCIENTIFIC PAPER

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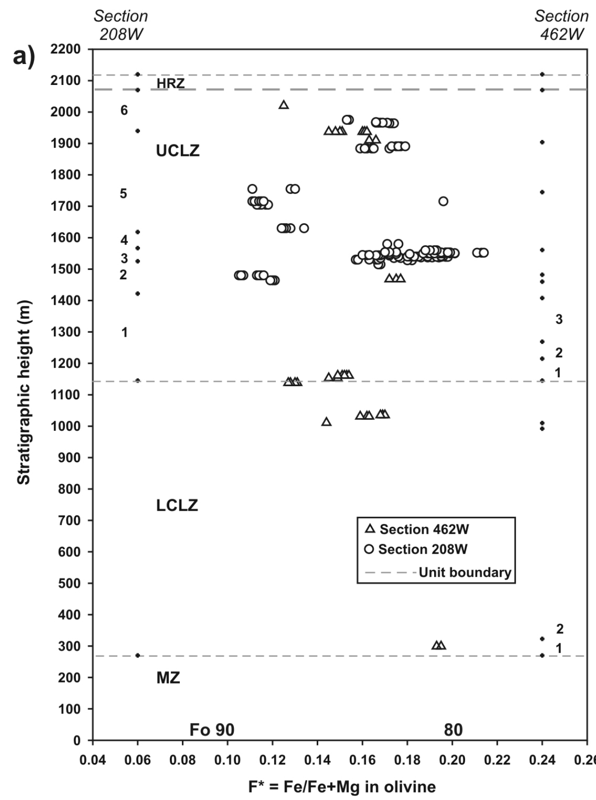

By
A.C. Turnock, M. Raudsepp
and R.F.J. Scoates

Manitoba

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Cover photo: Variation of Fe/(Fe+Mg) in olivine versus stratigraphic height in the Fox River Sill

Abstract

The Fox River Sill, the largest layered ultramafic intrusion in Canada, has been subdivided into four main zones: Marginal Zone (MZ; 10–250 m thick), Lower Central Layered Zone (LCLZ; 800–900 m thick), Upper Central Layered Zone (UCLZ; 900 m thick) and Hybrid Roof Zone (HRZ; 10–100 m thick). This report presents and discusses major-element compositions from electron-microprobe analyses of igneous minerals in 65 polished thin section samples from diamond-drill holes in the western portion of the sill. Two of the diamond-drill holes (38503, 38522) provided samples across the Upper Central Layered Zone (UCLZ) on the 208W section. Five holes (13227, 13327, 13231, 13242, 38523) provided partial sample coverage of both the Lower Central Layered Zone (LCLZ) and the Upper Central Layered Zone (UCLZ) on the 462W section, 3 km east of 208W.

Major-element electron-microprobe analyses show that olivine is rich in Mg and varies in composition (forsterite [Fo] content; Fe/[Fe+Mg]) from Fo_{90} to Fo_{78}. Within this range, olivine displays clusters in composition for each cyclic unit that are distinctly different from those of overlying or underlying units. This variation in olivine composition is irregular with stratigraphic height. Only cyclic unit 3 (section 208W) has enough samples to define Fo variation with stratigraphic height. In this unit, olivine displays three culminations in Fo content but shows no correlation between Fo variation and Ni content. The culminations in Fo content are interpreted to be due to three successive magma pulses. The olivine examined during this study had normal NiO contents (~0.28 wt.%) except in cyclic unit 5 (section 208W), whose depleted NiO (~0.02 wt. %) content is interpreted to result from a sulphide-separation event.

Augite and orthopyroxene are Mg rich and display little compositional variation. Chromite is Cr and Al rich, and plagioclase is Ca rich. Plagioclase and chromite display compositional variation within single samples that is caused by crystal zoning. Compositional variation between units also occurs. Systematic compositional variation between LCLZ and/or UCLZ cyclic units has not been observed, nor are there systematic compositional variations with stratigraphic height.

From these data, it is interpreted that the Fox River Sill was formed by pulses of magma, which were of slightly variable composition, intruded internally into the sill. Variation of composition of minerals by crystal settling and fractionation took place on a small scale.

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[1] Available online to download free of charge at www2.gov.mb.ca/itm-cat/freedownloads.htm, or 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.

Introduction

The Fox River Sill, a stratiform ultramafic-mafic complex, forms an integral part of the Fox River Belt. The Fox River Belt, which is a segment of the Paleoproterozoic Circum-Superior Belt (Baragar and Scoates, 1981), consists of sedimentary rocks, large differentiated sills and ultramafic to mafic volcanic rocks (Scoates et al., 1981). The sill, which is poorly exposed, is 270 km long, and approximately 2 km thick at the present erosional surface. In contrast to the almandine-amphibolite- to granulite-grade gneiss of the Kisseynew Domain to the north and the Superior Province to the south, the Fox River Belt and the contained sill have prehnite-pumpellyite- to lowermost greenschist-facies mineral assemblages (Scoates, 1981, 1990), in which olivine is mostly but not completely serpentinized and pyroxene is only partially hydrated. The sedimentary and volcanic rocks of the belt and the layered sill together form a north-facing homoclinal sequence.

The Fox River Sill has been divided into four zones (Scoates, 1990): 1) the Marginal Zone (MZ; 0–280 m), distinguished by an abundance of postcumulus minerals; 2) the Lower Central Layered Zone (LCLZ; 280–1145 m), characterized by densely packed, adcumulate olivine layers; 3) the Upper Central Layered Zone (UCLZ; 1145–2070 m), displaying more plagioclase and orthopyroxene and disseminated sulphides; and 4) the Hybrid Roof Zone (HRZ; 2070–2120 m), marked by the presence of quartz and granophyre. Thicknesses were determined from different areas using outcrop and drillhole data. Each zone is characterized by distinctive lithological units and, except for the HRZ, by distinctive cyclic arrangement of units.

Layers in the Sill have been grouped into cyclic units (Scoates, 1990), based on a model of magmatic fractional crystallization (i.e., a complete cycle for a pulse of magma has a basal layer of olivine cumulate, overlain by pyroxene cumulate, plagioclase cumulate and gabbro). Also present are incomplete cycles, in which one or more of the top layers are not present. This study also identified cryptic layering, which also shows chemical evidence of fractional crystallization, and terminated cycles. Each termination is interpreted to represent a flush and intrusion of a new pulse of magma.

Previous work on Fox River Sill mineral compositions

Osiowy (2000) reported mineral analyses from three UCLZ samples in the western part of the sill, two MZ samples from the central part of the sill, two Lower Volcanic Formation samples (footwall of sill) and four samples from the Lower Differentiated Intrusions (mafic rocks intruded into the Lower Sedimentary Formation and Lower Volcanic Formation). He reported 44 analyses of olivine, 40 analyses of pyroxenes and 34 analyses of chromite; the mineral compositions are similar to those reported here.

Smerchanski (2002) reported bulk chemical and mineral analyses from 39 samples of the lower eight cyclic units of the LCLZ from the Great Falls area (11 km east of the 462W section). Compositions of olivine, pyroxene and chromite are similar to those presented here.

Sample locations and stratigraphic height

Figure 1 shows the locations of the drillholes in the western lobe of the sill (Scoates, 1990). The sill is exposed in cross-section, with major layers topping and dipping steeply to the north. The heavy lines in Figure 1 mark the locations of sections 208W and 462W, along which drillholes that were sampled are aligned. Sample numbers used in this report indicate the depth in the hole in feet.

Stratigraphic height (SH), the distance in metres above the base of the sill, provides the stratigraphic location of the samples. This was measured by scale on cross-section plots of the drillholes (as presented by Scoates, 1990), with reference to the top of the UCLZ at 2070 m, the UCLZ-LCLZ boundary at 1145 m or the base of the LCLZ at 280 m.

Mineral compositions

The compositions of olivine, augite, orthopyroxene, chromite and plagioclase were determined by electron-microprobe analysis (EMPA). Details of the analytical method are given in Appendix 1 and formula calculations are given in Appendix 2. The analytical results are available as Excel spreadsheets in Data Repository item (DRI) 2005001.[2]

Olivine

Olivine compositions, as determined by EMPA, are listed in Data Repository item (DRI) 2005001, Table 1 (190 point analyses from 43 samples). The olivine crystals have been altered along fractures to serpentine, so the EMPA points are on segments of relict olivine crystals. The overall compositional range is Fo_{90} to Fo_{78} ($Fo_{90}Fa_{10}$–$Fo_{78}Fa_{22}$, or F* = Fe/[Fe+Mg] = 0.10–0.22). Olivine compositional variations are plotted against stratigraphic height (SH) in Figures 2a and b. For any given sample, the analytical results for several points are mostly similar, with variation being less than 2%; for example, sample SH1937 from hole 38523 has eight point analyses that range in composition from Fo_{86} to Fo_{84}. In sample SH1716 from hole 38522, there are eight point analyses that range from Fo_{89} to Fo_{80}. This large range could be the result of compositional zoning in the crystals and/or analytical error. Compositional zoning can develop during crystal growth, due to crystallization-differentiation of the magma, especially during late adcumulus growth. Analytical error in EMPA may result if the area of excitation of the beam crosses a boundary into an adjacent grain.

Individual cyclic units possess olivine compositions that are different from those of other units in the stratigraphic

[2] MGS Data Repository item 2005001, containing the data or other information sources used to compile this report, is available online to download free of charge at www2.gov.mb.ca/itm-cat/freedownloads.htm, or 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.

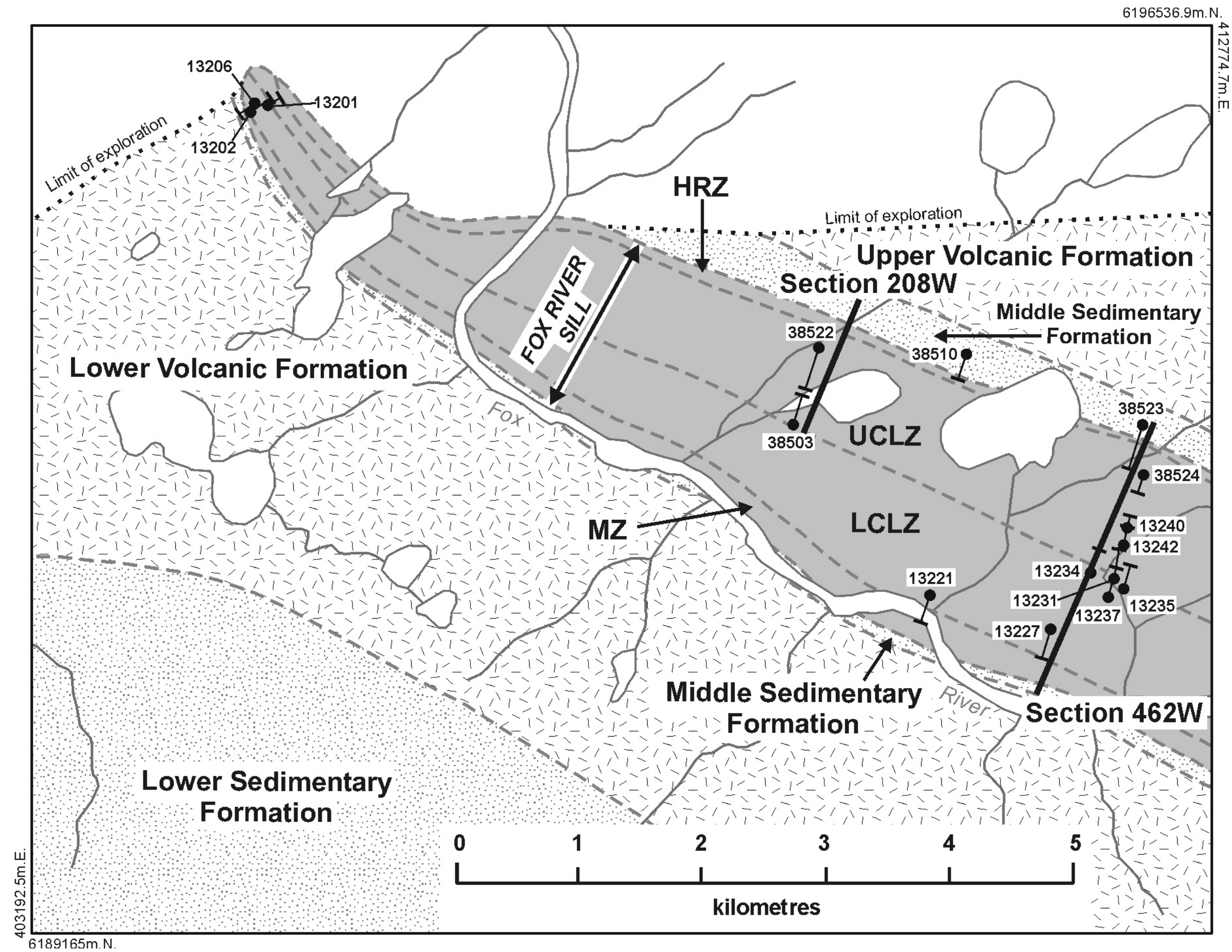

Figure 1: *Part of Manitoba Department of Energy and Mines Map GR81-1-1 (Scoates et al., 1981), showing the locations of drillholes in the Fox River Sill from which samples were collected.*

section. Olivine in UCLZ cyclic unit 2 (section 208W) ranges from Fo_{88} to $Fo_{90,}$ whereas cyclic units 3 and 6 are more Fe rich (cyclic unit 3, $Fo_{79-84;}$ cyclic unit 6, Fo_{83-85}).

Some individual cyclic units display regular variations with stratigraphic height (Figures 2a, b). The unnumbered LCLZ upper cyclic unit (section 462W) shows a small enrichment of Fe with height, from Fo_{83} to Fo_{84} (hole 13237, samples SH1031 and SH1035). A similar range and trend are shown in UCLZ cyclic unit 1 (section 462W; hole 13231, samples SH1153 and SH1161). For UCLZ cyclic unit 3 (section 208W; Fo_{84}–Fo_{79}), there is a slight and noisy positive slope (Figure 2b). A positive slope (increase in Fe content of olivine with height) is the expected igneous crystallization trend, and here there are three such trends, each of which is terminated by a nonlinear (noisy) return to a lower Fe content (more Mg-rich compositions). Cyclic unit 3 is interpreted to have formed from three pulses of magma, each of which terminated the previous cycle of fractional crystallization and initiated a new cycle.

The highest Ni contents (Figure 3; DRI 2005001, Table 1), 0.24–0.36 wt.% NiO, are similar to those found in Mg-rich (Fo_{90-80}) olivine in other ultramafic rocks (Duke and Naldrett 1978), so the lower Ni contents found in upper parts of the sill are considered to represent 'Ni depletion'. Low Ni contents (0.05–0.10 wt.%) in UCLZ cyclic unit 3 occur near the base of the unit (hole 38522, sample SH1537). Other low Ni contents in UCLZ cyclic unit 3 occur in samples SH1540 (0.06–0.12wt.%), SH1553 (0.10–0.12 wt.%) and SH1560 (0.12–0.14 wt.%). High Ni contents (0.24–0.36 wt.%; samples SH1630–SH1755) occur in the lower part of UCLZ cyclic unit 5 (section 208W), whereas lower Ni contents (0.01–0.03 wt.%; samples SH1880–SH1891) occur near the top of the unit. In cyclic unit 6, lower Ni contents (0.14 wt.%) occur in the middle of the unit (sample SH1964) and higher Ni contents (0.24–0.27 wt.%) occur toward the top of the unit (sample SH1975). Large and irregular variations in Ni versus stratigraphic height occur within and between cyclic units (Figure 3a), but these are not correlated with variations of the Fe/(Fe+Mg) ratio (forsterite [Fo] content; *see* Figure 2a). In Figure 3b, variations in the Ni contents of UCLZ cyclic unit 3 (section 208W) olivine and the Fe/(Fe+Mg) ratio (Fo content) show that variations in Ni content are not controlled by the same process that gives rise to the Fe/(Fe+Mg)

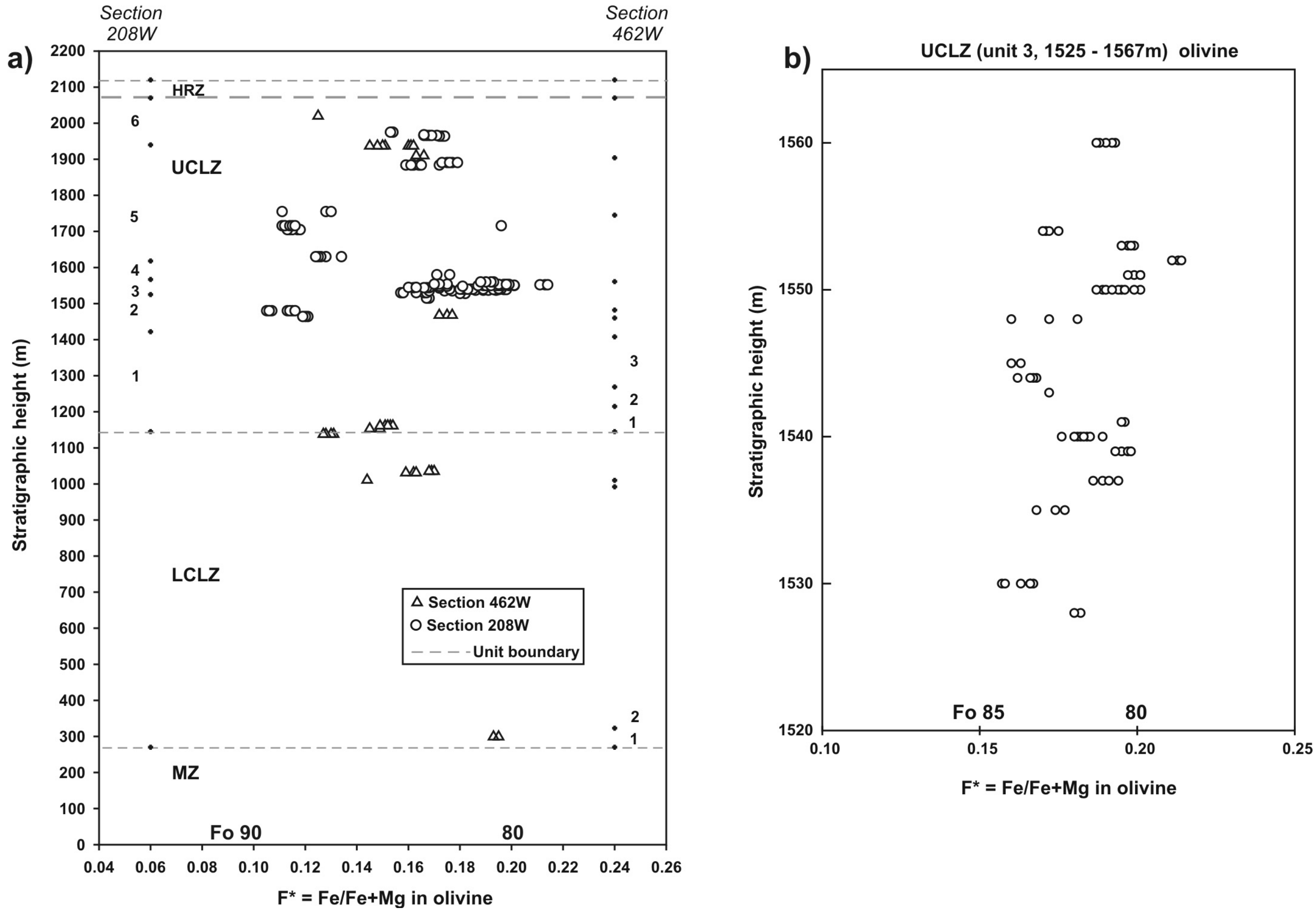

Figure 2: *Variation of Fe/(Fe+Mg) in olivine versus stratigraphic height in* ***a)*** *the entire Fox River Sill, and* ***b)*** *unit 3, section 208W (enlarged portion of part a).*

variations. Low Ni concentrations in olivine are interpreted to indicate Ni depletion, possibly related to the formation of sulphides in the magma (Duke and Naldrett, 1978). The possibility of sulphide saturation during late stages of fractional crystallization of magma has been confirmed by studies of sulphide mineralization in the Marginal Zone of the Fox River Sill by Desharnais et al. (2004).

Pyroxenes

Pyroxene compositions (DRI 2005001, Tables 2 and 3) are plotted in Figures 3 and 4, in terms of the major components En-Fs-Wo ($MgSiO_3$-$FeSiO_3$-$CaSiO_3$). There are 154 analytical points for augite (it is most resistant to hydrothermal alteration). In contrast, most orthopyroxene crystals are altered, so there are only 47 analyses. Pseudomorphs after orthopyroxene (chlorite, serpentine, talc) retain the poikilitic texture of late crystallization. The limited data for section 462W (Figure 4d) illustrate that augite has compositions of about En_{57}–Fs_5–Wo_{38}; two points are anomalously enriched in Wo (= Ca). This apparent enrichment may be caused by the inclusion of Ca-rich alteration minerals in the beam excitation volume during EPMA. Data for section 208W (Figure 4a–c) show that augite compositions are centred around En_{55}–Fs_7–Wo_{38}, with small compositional variations between and within units. Iron enrichment, typical of the igneous differentiation trend, is not found.

Chromite

Chromite compositions are provided in Table 4 of DRI 2005001 (74 point analyses). Analyses marked 'c' (for cumulus) are orthogonal in shape and interpreted to be of cumulus origin. Analyses marked 'i' are irregular in shape and interpreted to be interstitial. The two types are not different in composition. Figure 5, a plot of the ratios of the trivalent cations, shows an elongation of the cluster. The elongation is the result of variation in $Fe^{3+}/(Fe^{3+}+Al+Cr)$, whereas $Cr/(Cr+Al+Fe^{3+})$ is less variable. Such variation may result from late igneous activity (deuteric alteration) or later metamorphic recrystallization. Figure 6 shows that atomic ratios (F* = Fe/[Fe+Mg]) in chromite range between 0.48 and 0.83, and there is no trend with stratigraphic height. The amount of Cr_2O_3 in chromite ranges from 25 to 45 wt.%, with a cluster in the range 38 to 42 wt.%. There is a weak positive correlation of C (= Cr/[Cr+Al]) versus F (= Fe/[Fe+Mg]).

Plagioclase

Plagioclase compositions (n = 37) were obtained from the top of cyclic unit 3 and the lower portion of cyclic unit 4 (Figure 7; DRI 2005001, Table 5). They are Ca rich, ranging from An_{85} to An_{95}. Individual samples have some compositional variation (hole 38522, sample SH1562; 11 analyses, $An_{86–91}$); this is interpreted as zoning in the crystals. The range in UCLZ

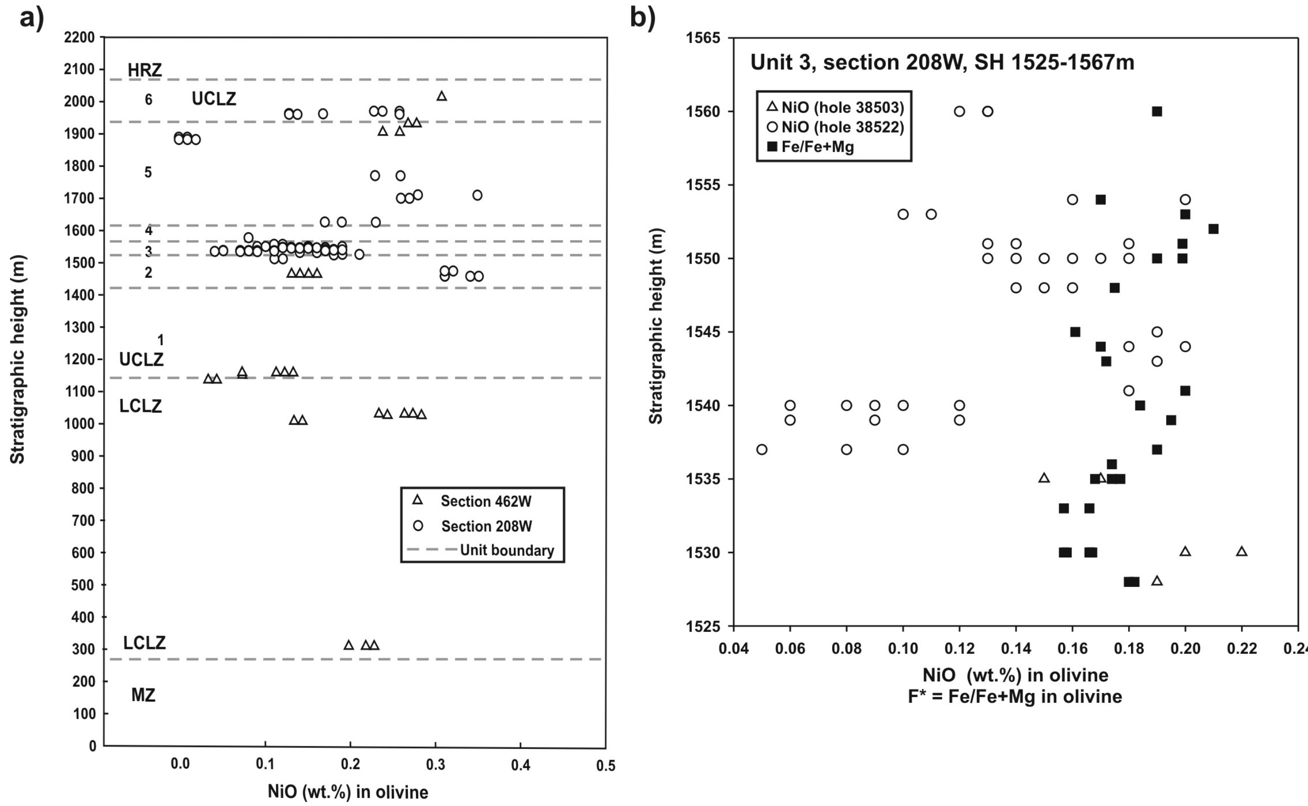

***Figure 3:** Variation of NiO in olivine versus stratigraphic height for **a)** the entire Fox River Sill (n = 159), and **b)** unit 3, UCLZ, section 208W (plus data for Fe/[Fe+Mg]).*

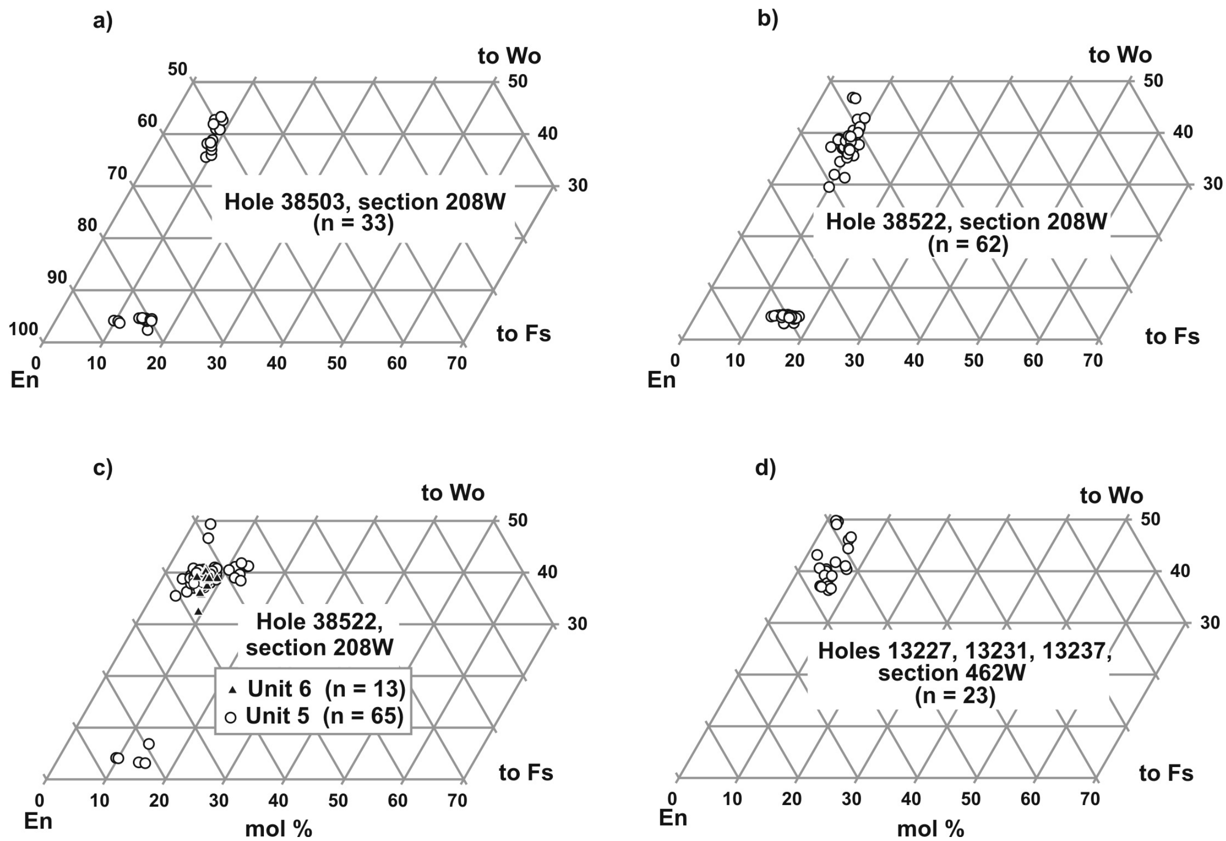

***Figure 4:** Compositions of pyroxenes (Wo-En-Fs) in samples of the Fox River Sill from **a)** hole 38503, section 208W (units 2 and 3, lower UCLZ); **b)** hole 38522, section 208W (units 3 and 4, UCLZ); **c)** hole 38522, section 208W (units 5 and 6, UCLZ); and **d)** holes 13227, 13231 and 13237, section 462W (LCLZ).*

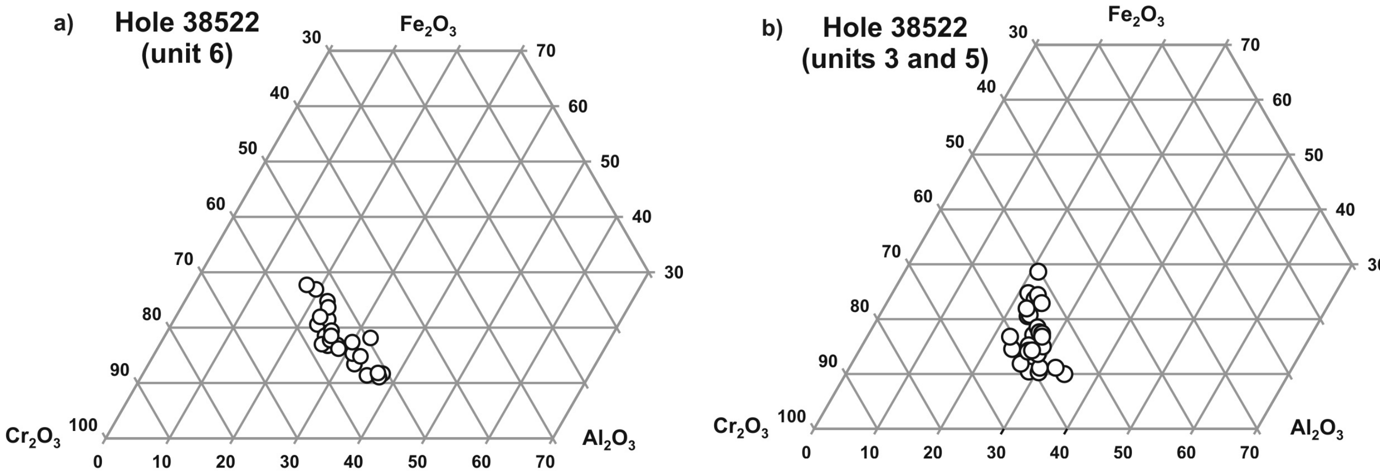

Figure 5: *Compositions of chromites (mol ratios of Cr, Al and Fe^{3+}) from the upper part of the UCLZ, Fox River Sill (hole 38522, section 208W):* ***a)*** *unit 6,* ***b)*** *units 3 and 5.*

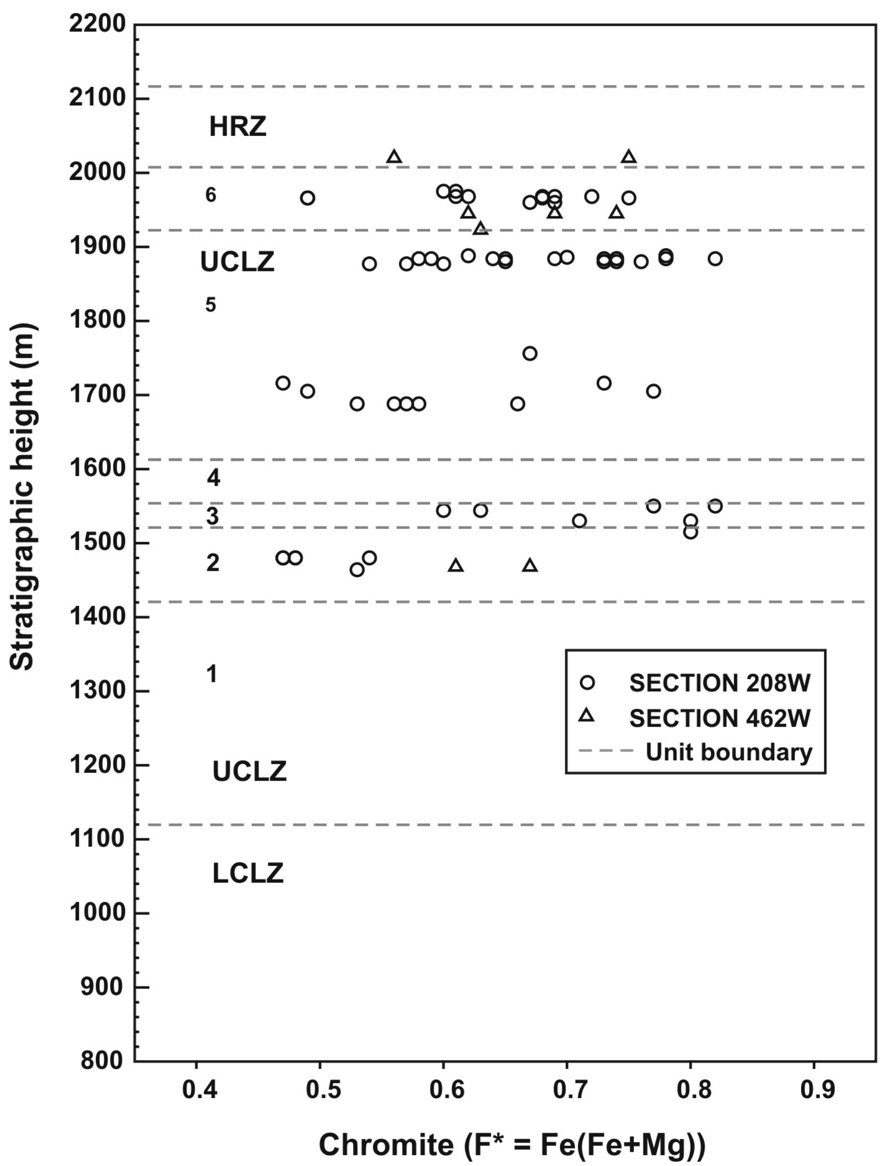

Figure 6: *Compositions of chromites (Fe/[Fe+Mg]) versus stratigraphic height, Fox River Sill.*

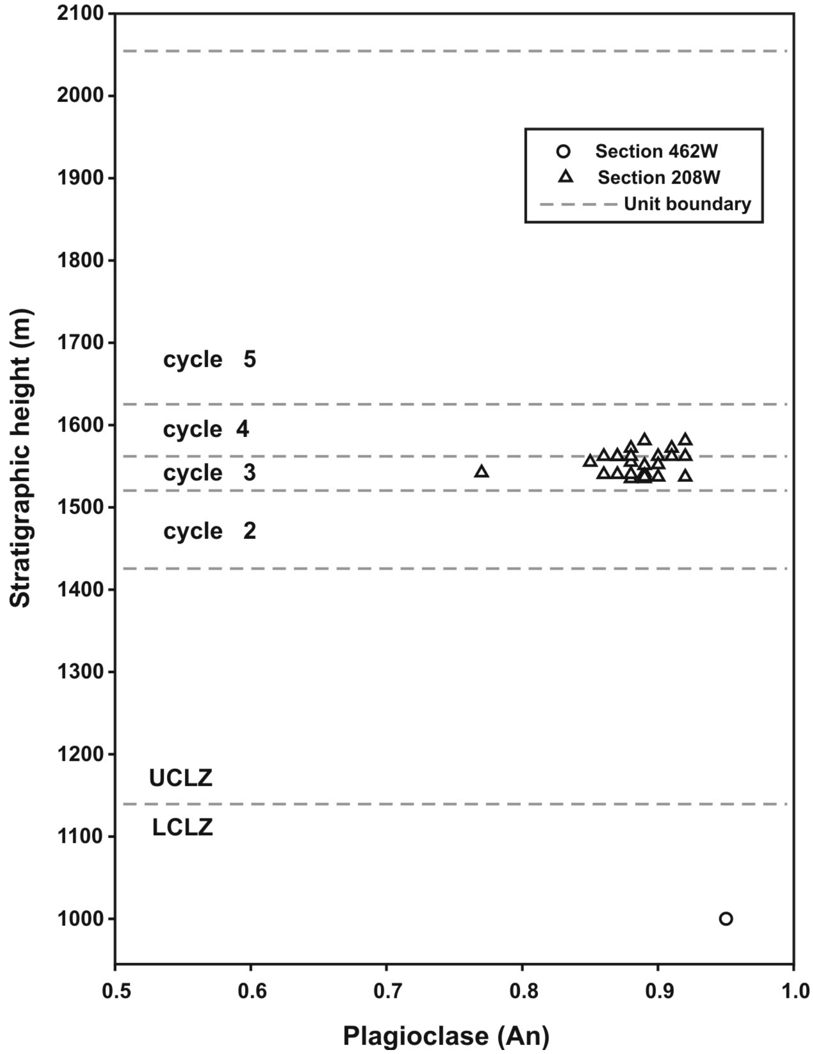

Figure 7: *Compositions of plagioclase (An = 100Ca/[Ca+Na]) versus stratigraphic height, Fox River Sill.*

cyclic unit 4 is similar to that of cyclic unit 3, and there is no sign of systematic variation with stratigraphic height in either cyclic unit.

Conclusions

Cumulus minerals of the Fox River Sill are Mg-rich olivine and pyroxene, Cr-rich chromite and Ca-rich plagioclase. They have some variation in composition, but the compositional range is small compared with that found in other layered mafic intrusions. This argues against their crystallization in one large closed system of a single-magma-pulse intrusion; in that situation, continuous trends of fractional crystallization and the production of more evolved compositions would be expected. Distinct differences are found in the composition of olivine and chromite between different cyclic units, which supports the interpretation that each cyclic unit was formed by a separate pulse of magma. In the case of cyclic unit 3 (section 208W), the data from this study show three Fe-enrichment trends in olivine; this unit could be subdivided into three units, each of which represents a pulse of magma. The Fox River Sill is a composite sill, built up by the intrusion of at least 15 pulses of magma, each of slightly different composition.

The variation in composition of olivine and chromite within a cyclic unit is complex. These compositional variations are interpreted as resulting from zone development of chemical concentration in crystals and/or small-scale igneous differentiation trends or, in the case of the Ni content of olivine, by the magma becoming saturated in sulphide. Zoning is developed by continued growth (adcumulate growth) of crystals in a changing igneous chemical environment.

Abnormal compositions were found for a few samples, some of which may be explained by the chemical alteration of the minerals. Augite with abnormal contents of $CaSiO_3$ is interpreted to be the result of some epidote alteration of the crystal. In chromite, the trivalent cations Cr^{3+}, Al^{3+} and Fe^{3+} are distributed with an extension of the cluster toward Fe^{3+}. This pattern was explained by Smerchanski (2002) when he showed that chromite grains had alteration textures of magnetite replacement incursive into chromite. This is interpreted as postmagmatic oxidation alteration because mafic magma (and rocks) have, by their large content of ferrous iron and small content of water, a buffering capacity that would limit oxidation. Regional large-scale serpentinization would contribute to the enrichment of Fe^{3+} in chromite.

Acknowledgments

Ronald Chapman made the analyses possible by maintenance of the electron microprobe and calibration from international standards. Sergio Mejia enabled computer graphics and their transmission. Norm Halden is thanked for editorial assistance. Funding for microprobe analyses was provided by the 1984–1989 Canada-Manitoba Mineral Development Agreement.

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Appendix 1 – EMPA analytical methods

Analyses were done on the microprobe MAC-5 at the University of Manitoba by M. Raudsepp and A.C. Turnock. Conditions: filament voltage 15 kv, current 10 na, spot size of about 4 μm by 4 μm on the surface of the sample, 20 s count time. A standard fayalite was analyzed every hour to permit drift corrections on the electron beam flux. The characteristic X-rays were counted by a Kevex 7000 EDS, and ZAF corrections made by the MAGIC V program. Fayalite, jadeite, augite and other international standards were used.

Appendix 2 – Assignment of cations

For olivine, the atomic ratio Mg/Mg+Fe was calculated with the assumption that all iron was ferrous. For augite and orthopyroxene, the computer program of Cebria (1990) was used to calculate Wo-En-Fs by the system of Lindsley and Andersen (1983). For chromite, ferric iron was calculated by charge balance, using ‘Formula’ by Scott Ircit. For plagioclases, An = Ca/Ca+Na.