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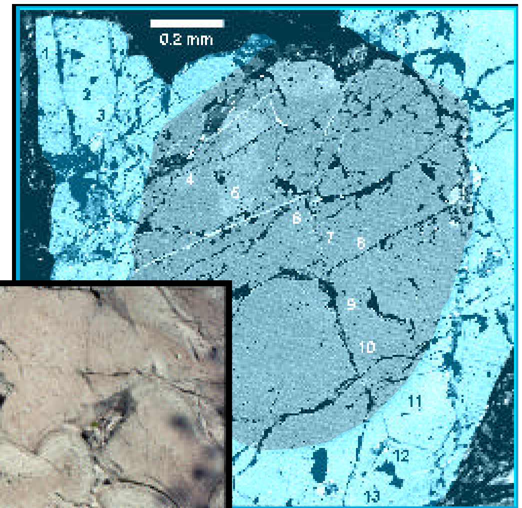

By
A.C. Turnock
and E.C. Syme

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Augite phenocrysts in Paleoproterozoic metavolcanic rocks, Flin Flon, Manitoba

by A.C. Turnock and E.C. Syme
Winnipeg, 2002

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Author address:

A.C. Turnock
Department of Geological Sciences
University of Manitoba
Winnipeg MB R3T 2N2
(204) 474-6911
E-mail: ac_turnock@umanitoba.ca

E.C. Syme
Manitoba Geological Survey
360-1395 Ellice Avenue
Winnipeg MB R3G 3P2
(204) 945-6556
E-mail: rsyme@gov.mb.ca

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Cover photo: Top, concentrically zoned augite phenocryst showing locations of spot microprobe analyses; Bottom, pillowed basalt in the Hook Lake Block, showing exceptional preservation of primary structures.

ABSTRACT

Augite phenocrysts are locally preserved in metabasaltic rocks of the Paleoproterozoic Flin Flon Belt, Manitoba. Microprobe analyses of 73 phenocrysts in 19 rock samples are presented. These phenocrysts contain greater than 90% Ca-Mg-Fe components and less than 10% tschermaks and sodic components. They are diopsidic augites, most of which cluster around Wo_{40} En_{52} Fs_8, corresponding to the Mg-rich primitive end of the Skaergaard trend. Enrichment in Fe parallel to this trend is found in the upper stratigraphic units of the Hook Lake Block, with $Fs<_{16}$ and, in some samples from the Flin Flon Block, $Fs<_{20}$. Concentrically zoned crystals are rare; they are enriched in Fe ($Fs<_{15}$) and Mn in the rims but enriched in Ca, Mg and Al in the cores. The limited range of compositions and calculated zero pressure of origin are characteristics of magma that erupted directly without residence in a magma chamber.

Compositions that scatter beyond the igneous trend have less Ca and more Fe; they are interpreted as having been altered during the prehnite-pumpellyite facies metamorphism that has replaced all primary minerals except the augite phenocrysts.

The augites have low contents of Ti (less than 0.5 wt.% TiO_2), Cr (less than 0.9 wt.% Cr_2O_3), Na (less than 0.2 wt.% Na_2O), and Al^{VI} (less than 0.1 per 4 cations). These contents permit interpretation of the rocks as 'orogenic tholeiitic basalt', consistent with the previous interpretation of whole-rock geochemical data that indicated the rocks were emplaced in an oceanic-arc environment.

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INTRODUCTION

The primary igneous minerals in most Precambrian metavolcanic belts have been replaced by secondary mineral assemblages developed during regional metamorphism. Exceptionally, where very low grade (subgreenschist) domains are present, relict igneous minerals may be preserved (e.g., Jolly, 1974). Such relict pyroxenes are preserved in a portion of the western Flin Flon Belt that has undergone only subgreenschist facies metamorphic conditions (Bailes and Syme, 1989; Digel and Gordon, 1995).

The subgreenschist portion of the Flin Flon Belt was first recognized during mapping of the Flin Flon–White Lake area, when prehnite, pumpellyite and primary pyroxene were documented from the Hook Lake Block (Bailes and Syme, 1989). Subsequent mapping in the adjoining Athapapuskow Lake area extended the known extent of subgreenschist facies mineral assemblages in metavolcanic rocks of the western Flin Flon Belt (Syme, 1988a). The samples in this study were collected during both mapping projects and are identified by Manitoba Geological Survey sample number in Appendix A. Microprobe analysis of primary augite phenocrysts in the basaltic lava flows and volcaniclastic rocks was conducted by the first author in the early 1990s. Subsequently, geochemical studies utilizing precise, inductively couple plasma–mass spectrometry (ICP-MS) analysis provided a comprehensive tectonic framework for the 1.9 Ga supracrustal assemblages (Stern et al., 1995a, b).

The existing whole-rock geochemical data, plus the augite data presented here, provide a unique opportunity to compare independent lines of evidence regarding the origin of these economically important 'greenstones'. Similar to other rocks in Precambrian metavolcanic belts, those in the Flin Flon Belt underwent regional metamorphism that was not necessarily isochemical. Consequently, there is some degree of uncertainty in using whole-rock analyses to assign tectonic affinity. The presence of relict augite phenocrysts in metabasalt provides an independent method of determining tectonic environment, because pyroxenes from different tectonic environments have characteristic compositions (e.g., Leterrier et al., 1982).

Augite phenocrysts that precipitate at near-liquidus temperatures will have compositions that are determined by the composition of the magma plus the temperature and pressure at the time of crystallization. A study of the effects of these variables also permits information about crystallization temperature and pressure to be derived from augite compositions.

GEOLOGICAL SETTING

The GSC-Manitoba-Saskatchewan NATMAP Shield Margin Project and LITHOPROBE Trans-Hudson Orogen Transect built on an extensive existing geological database to generate a much-improved understanding of the components and evolution of the southeastern Reindeer Zone, including the Flin Flon Belt (e.g., Lucas et al., 1996). These investigations have shown that, on the scale of the crust, the Flin Flon 'greenstone' belt is only one of three components in a northeast-dipping stack, juxtaposed during 1.84–1.80 Ga collisional deformation (Lucas et al., 1997) in the following order:

1) at the lowest structural level (exposed in the Pelican window): metaplutonic rocks and paragneiss (3.20–2.40 Ga) of the 'Sask craton'
2) at intermediate structural levels: Flin Flon Belt (1.92–1.87 Ga, now defined to include the Attitti Block and Paleoproterozoic rocks in the Hanson Lake Block) and Glennie Domain (together comprising the 'Flin Flon–Glennie Complex' [FFGC]; Lucas et al., 1997)
3) at the highest structural level: marine turbidite (Burntwood Group; 1.85–1.84 Ga) and distal facies of alluvial-fluvial sandstone (Missi Group) in the Kisseynew Domain

The Flin Flon Belt, despite its location within a crustal-scale thrust stack, contains a well-preserved record of its earlier magmatic and tectonic history. The range in lithological and geochemical associations, Sm-Nd isotopic signatures and U-Pb zircon ages has allowed subdivision of the 'greenstones' into a series of 1.92–1.87 Ga arc and ocean-floor assemblages (Syme and Bailes, 1993; Stern et al., 1995a, b; Lucas et al., 1996; Stern et al., 1999). These contrasting volcanic assemblages are separated by early high-strain zones and are stitched by crosscutting plutons (1.88–1.84 Ga), suggesting that they were accreted to form a tectonic collage at 1.88–1.87 Ga ('Amisk collage' of Lucas et al., 1996), shown in Figure 1. The Flin Flon Belt tectonostratigraphic assemblages include juvenile-arc rocks (~68% of the exposed Flin Flon Belt), juvenile ocean-floor–back-arc rocks (~20%), and minor (totalling ~3%) oceanic plateau, ocean-island basalt and 'evolved' plutonic-arc rocks (~9% are undivided; Syme et al., 1999).

Arc-assemblage rocks in the Flin Flon Belt

The Flin Flon arc assemblages comprise arc-related volcanic, volcaniclastic and intrusive rocks, as well as subordinate turbidite and arc-rift basalt (Bailes and Syme, 1989; Syme and Bailes, 1993; Stern et al., 1995a; Lucas et al., 1996). These assemblages are bimodal, dominantly basalt–basaltic andesite and rhyolite-dacite; intermediate compositions are rare. Tholeiitic arc suites tend to be older (1.90–1.89 Ga) than calc-alkaline (1.89–1.88 Ga) and shoshonitic (1.885 Ga) suites; boninite (>1.892 Ga) occurs only in the Snow Lake arc assemblage (Stern et al., 1995a; Stern et al., 1999). The majority of arc rocks contain primary structures indicating that they were deposited in a subaqueous environment. However, there is clear morphological evidence (e.g., presence of bubble wall shards, pumice) that some resedimented pyroclastic rocks may have been erupted in a very shallow marine or subaerial setting, principally in the younger calc-alkaline and shoshonitic sequences (Bailes and Syme, 1989; Syme and Bailes, 1993). Deposits emplaced in subaerial and littoral environments, although locally preserved (Ayres et al., 1991),

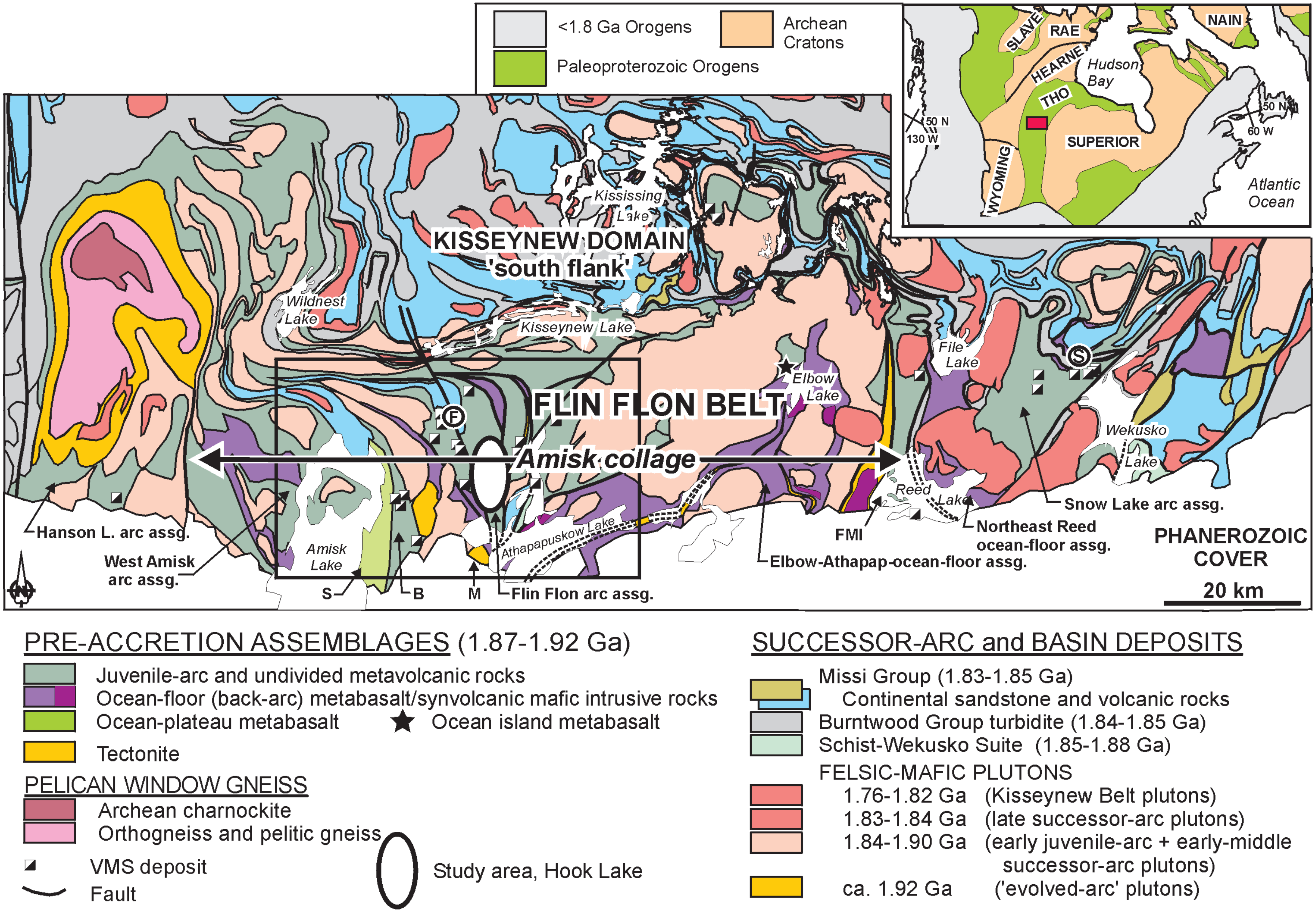

Figure 1: Tectonic assemblages in the exposed portion of the Flin Flon Belt, based on NATMAP Shield Margin compilation maps (NATMAP Shield Margin Working Group, 1998). Abbreviations: S, Sandy Bay ocean-plateau assemblage; B, Birch Lake arc assemblage; M, Mystic Lake evolved-arc assemblage; FMI, Fourmile Island arc assemblage; S (circled), Snow Lake; F (circled), Flin Flon. Inset map shows the location of Flin Flon Belt (box) in the Trans-Hudson Orogen (THO).

are rare. Arc sequences commonly represent a proximal facies with respect to source vents, comprising abundant pillowed and massive flows, coarse volcaniclastic debris flow deposits and rare sedimentary interbeds. Synvolcanic intrusions form a calcic gabbro–diorite–quartz diorite–tonalite series (Whalen et al., 1999) and occur as high-level, discrete sills, dikes and plutons (Bailes and Syme, 1989). Stratigraphic sequences are complex and typically display a wide variety of rock types with interfingering relationships, lenticular units and abrupt facies variations.

Neodymium isotopic and trace-element data indicate that the Flin Flon arc-assemblage volcanic and plutonic rocks are predominantly juvenile (i.e., positive initial ε_{Nd} values of +2 to +5, similar to the contemporaneous depleted mantle; Stern et al., 1995a, b) and show only limited contributions from older crustal sources. Stern et al. (1995a) suggested that the contributions from older crustal sources were best explained by recycling of small amounts (<10%) of Archean and/or older Proterozoic crust via sediment subduction or possibly intracrustal contamination.

The Flin Flon arc-assemblage rocks are geochemically similar to modern island-arc tholeiite. Contents of high-field-strength elements (HFSE) and rare earth elements (REE) are low relative to mid-ocean ridge basalt (MORB). Chondrite-normalized light REE (LREE) patterns show depletion to slight enrichment (Syme, 1990; Stern et al., 1995a). The calc-alkaline andesite-rhyolite and rare shoshonite are more strongly enriched in LREE and have comparatively higher abundances of HFSE. These calc-alkaline– and alkaline-series rocks have trace-element signatures (high Th/Nb, La/Nb) that are almost identical to those forming in modern intra-oceanic arcs (Stern et al., 1995a). The extreme extent of the HFSE depletion exhibited by arc tholeiite at Flin Flon is observed in the island-arc tholeiite of the Tonga-Kermadec arc (e.g., Ewart and Hawkesworth, 1987) and Fiji (Gill, 1987). This is consistent with the arc tholeiite representing primitive arc segments built on oceanic lithosphere.

Local setting

A collage of fault-bounded blocks (Fig. 2) marks the western part of the Flin Flon Belt. Flin Flon arc-assemblage stratigraphic sequences within fault blocks differ widely in thickness, lithology and environment of deposition (Bailes and Syme, 1989). Each block has a more or less intact, definable stratigraphy that is unique to that block alone; correlation of sequences or individual units across block-bounding faults is impossible.

Volcanic rocks that have been affected by very low grade (prehnite-pumpellyite facies) metamorphism occur predominantly within the Hook Lake and Flin Flon blocks (Bailes and Syme, 1989; Digel and Gordon, 1995). These rocks, which contain primary pyroxene phenocrysts, were sampled and their pyroxene phenocrysts analyzed. The sampled rock types include massive and pillowed flows, tuff and breccia, all of which are interpreted to have been deposited in a subaqueous environment.

Although structure within the Hook Lake Block is complex, a composite stratigraphic section, approximately 7.5 km thick, has been constructed for the northern Hook Lake Block (Fig. 3), making it the thickest complete section in the Flin Flon area (Syme, 1988a, b; Bailes and Syme, 1989). Basalt, basaltic andesite and rare andesite, in the form of subaqueous lava flows (79% of the sequence), pillow-fragment breccia (14%) and scoriaceous tuff and breccia (7%), compose the Hook Lake stratigraphic sequence. The mafic flows occur in mappable units, 120 to 1000 m thick, with units defined by the presence and abundance of plagioclase and pyroxene phenocrysts. Pillow-fragment breccia units up to 820 m thick can similarly be distinguished on the basis of their phenocryst content.

Mafic volcaniclastic rocks in the southern part of the Hook Lake Block form a thickness of almost 3 km of pyroclastic material, in a diverse assemblage of breccia, lapilli-tuff and tuff (Syme, 1988a). The breccia is composed of subrounded to rounded, porphyritic scoria fragments and angular nonscoriaceous accessory fragments supported by a matrix of scoria granules, plagioclase crystal fragments and recrystallized ash. These redeposited, subaqueous pyroclastic rocks are correlated with unit H in Figure 3. Pyroxene samples 279, 287 and 313 were collected from scoria-rich breccia that forms a unit more than 800 m thick, directly overlying plagioclase-phyric mafic flows.

PYROXENE PHENOCRYSTS

Clinopyroxene phenocrysts are common in these mafic metavolcanic rocks (Bailes and Syme, 1989). They are colourless in thin section, subhedral and vary in length from 0.3 to 2 mm (no megacrysts). Synneusis (clustering) is common. Incipient to complete alteration of the pyroxene phenocrysts is common and includes crosscutting veinlets of carbonate, colourless chlorite developed along fractures and cleavages, and overgrowths of pale green, fibrous tremolite-actinolite. As described below, this alteration may cause anomalous compositions in microprobe analyses.

Pyroxenes are the only primary minerals that have survived the pervasive alteration of low-grade metamorphism (with one exception: in sample 4518 from the Flin Flon Block, unaltered microphenocrysts of plagioclase are clustered with the augite). Primary plagioclase phenocrysts are mostly replaced by pseudomorphs of albite and variable amounts of epidote, sericite and carbonate; minor amounts of chlorite, tremolite-actinolite and pumpellyite occur in some pseudomorphs. The groundmass of mafic flows is composed of albite pseudomorphs after primary calcic plagioclase microlites, and interstitial mafic minerals that have been replaced by chlorite, epidote and local pale green tremolite-actinolite, plus prehnite, pumpellyite, carbonate and leucoxene. Prehnite and pumpellyite are also common in amygdules.

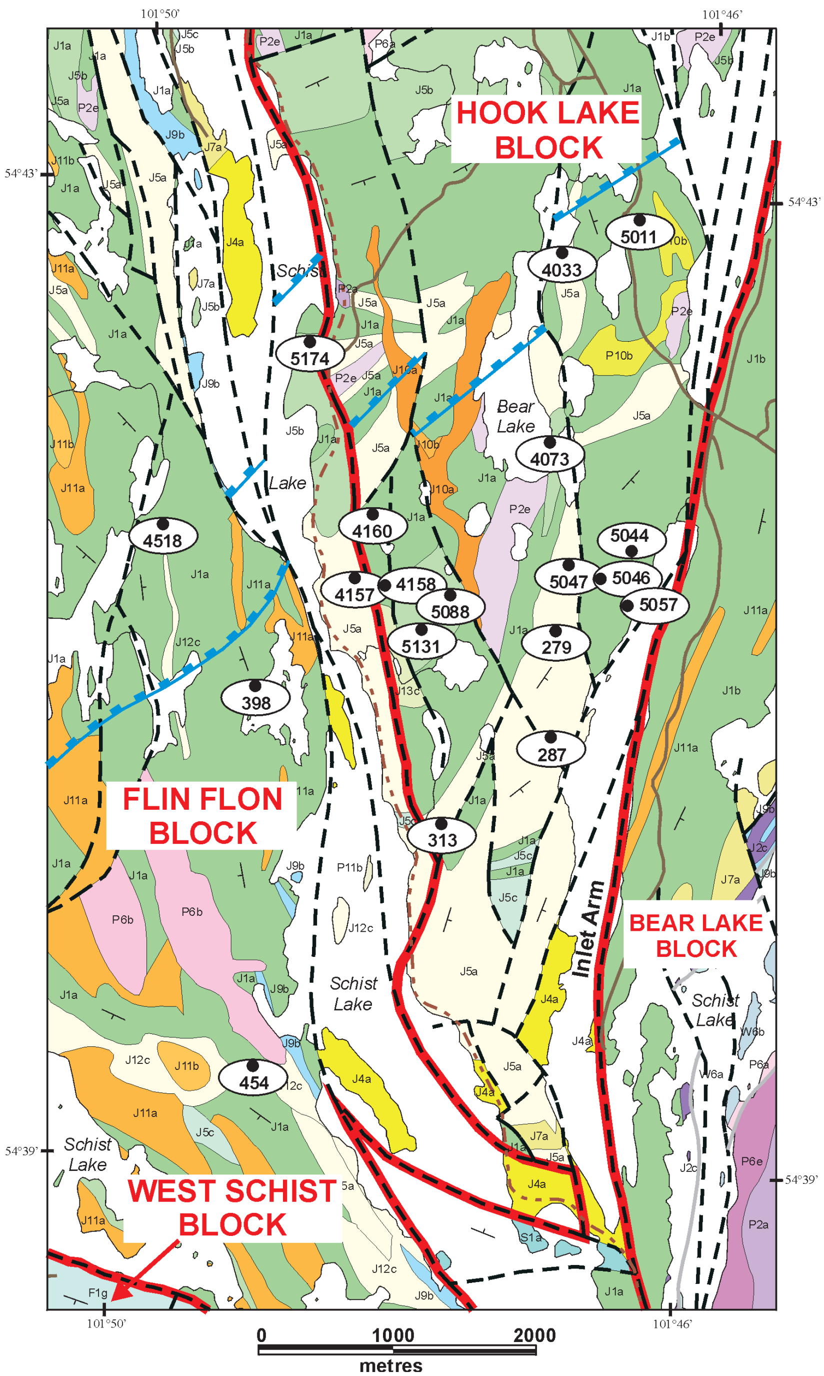

Figure 2: Geology of the Schist Lake area, showing sample locations.

PYROXENE PHENOCRYST COMPOSITION

Nineteen rock samples of the Flin Flon arc-assemblage volcanic rocks containing augite phenocrysts were studied: 14 are from the Hook Lake Block and 5 from the Flin Flon Block. In each of the 19 samples, 1 to 5 crystals were analyzed by electron microprobe (EMPA) for a total of 289 spot analyses in 73 crystals. The analyses are listed in Appendix A, notes on methods are given in Appendix B, and stoichiometry calculations are given in Appendix C.

These augites have compositions that are characteristic of subalkaline rocks (i.e., lower values of Ti and Al than those of alkaline rocks; LeBas, 1962; Garcia, 1978; Leterrier et al., 1982). Also, LeBas (1962) and Dal Negro et al. (1989) showed that alkaline rocks had greater contents of Ca+Na, plotted against Mg+Fe, than subalkaline rocks. The line 'L' in Figures 4, 5, 6 and 7 is a projection of a discrimination line of LeBas (1962) onto the pyroxene quad; these augites plot in the field of '**subalkaline**' rocks, which is on the low-Ca side of the line.

In the Ti vs. Al diagram (Fig. 8b), the low values of Ti in the Flin Flon augites place them in the '**tholeiitic basalt**' field (discriminated from calc-alkali basalt; Leterrier et al. 1982).

Concentric compositional zoning was found in one sample (4158), where it occurs in four out of eight crystals. Zoning was not observed optically, but is apparent in backscattered electron (BSE) images. The best-zoned crystal is 4158C (Appendix A, #6, crystal C); Figure 4a shows the well-defined core and rim in a BSE image. In Figure 4b, the traverse of analyses shows that the

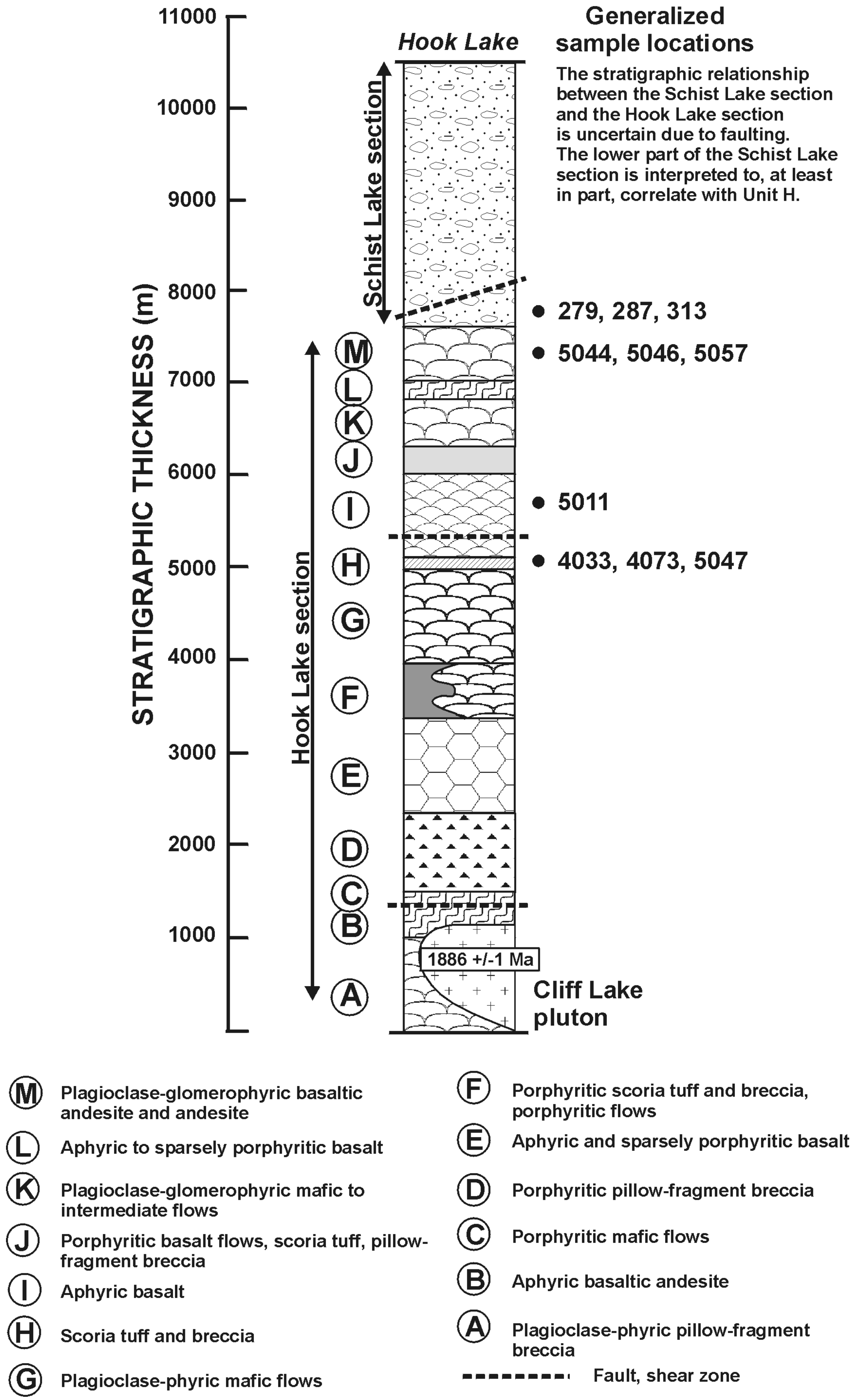

Figure 3: Composite stratigraphic section of the Hook Lake Block, showing sample locations (after Bailes and Syme, 1989).

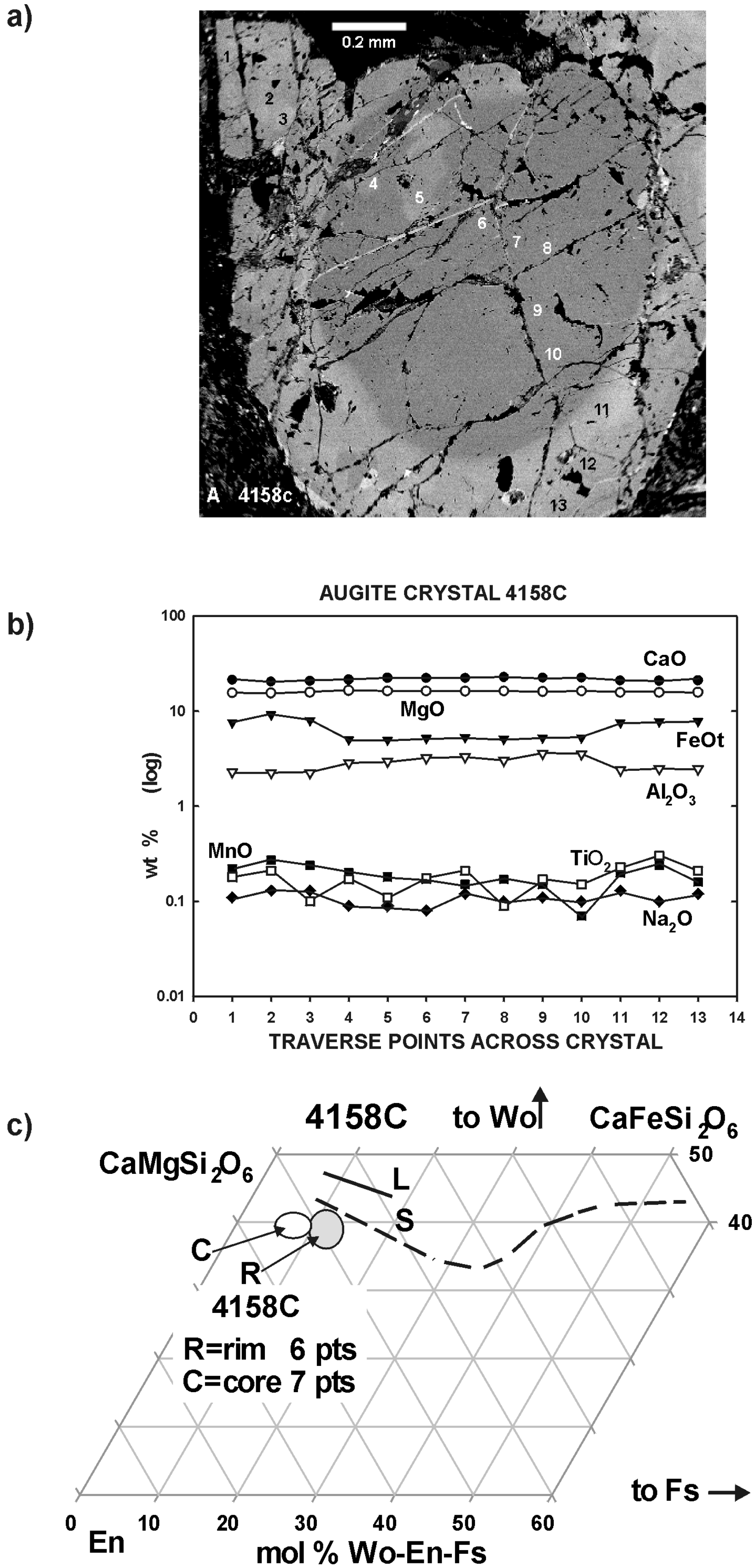

Figure 4: Concentric zoning in crystal 'C', sample 4158, Hook Lake Block, Schist Lake sub-block: a) backscattered electron (BSE) image, with numbers showing the EPMA points on a traverse across the crystal; b) variation of composition of elements (listed in Appendix A6) along the traverse of points, rim-core-rim; c) plots of the mol ratios of the major components Wo-En-Fs (the 'pyroxene quad'); this and the same diagram in Figures 5, 6 and 7 include lines for the the Skaergaard trend (S; Brown, 1957) and the projection of the subalkaline-alkaline field boundary (L; LeBas, 1962).

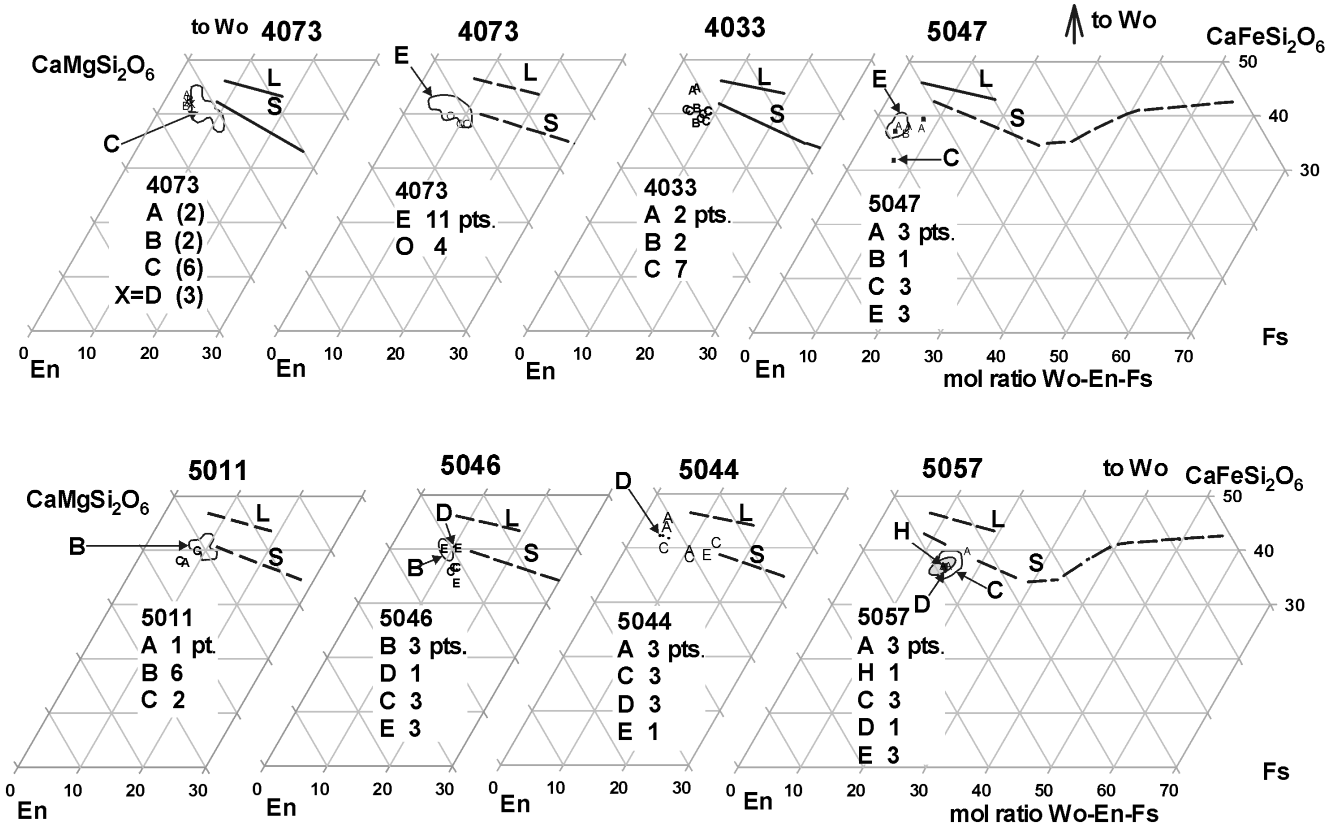

Figure 5: Pyroxene quad plots of augites in samples 4033, 4073, 5047, 5011, 5044, 5046 and 5057, Hook Lake section (data in Appendix A).

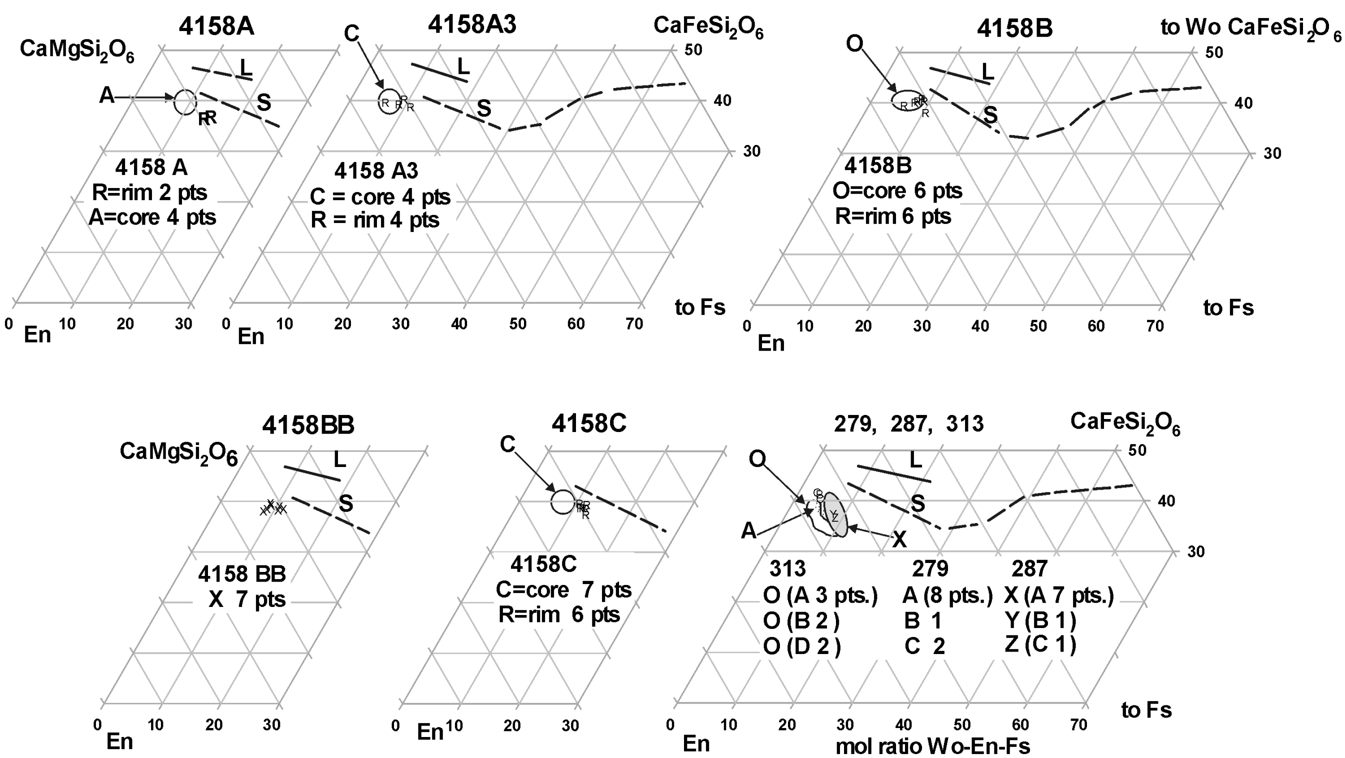

Figure 6: Pyroxene quad plots of augites in samples 279, 287 and 313 from the pyroclastic rocks of the Hook Lake Block, plus sample 4158 from the Schist Lake sub-block of the Hook Lake Block.

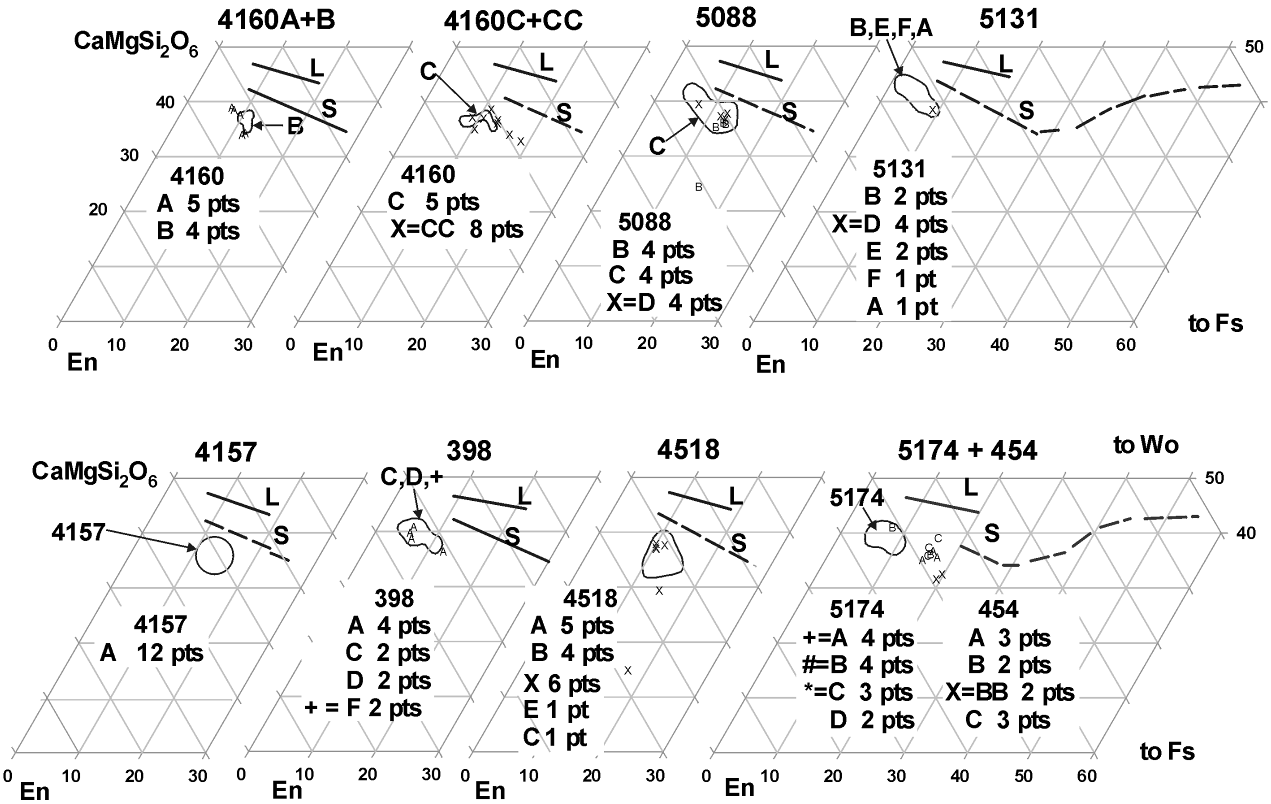

Figure 7: Pyroxene quad plots of augites. Top-row samples 4160, 5088 and 5131 are from the Hook Lake Block, Schist Lake sub-block. Bottom-row samples 4157, 398, 4518, 5174 and 454 are from the Flin Flon Block.

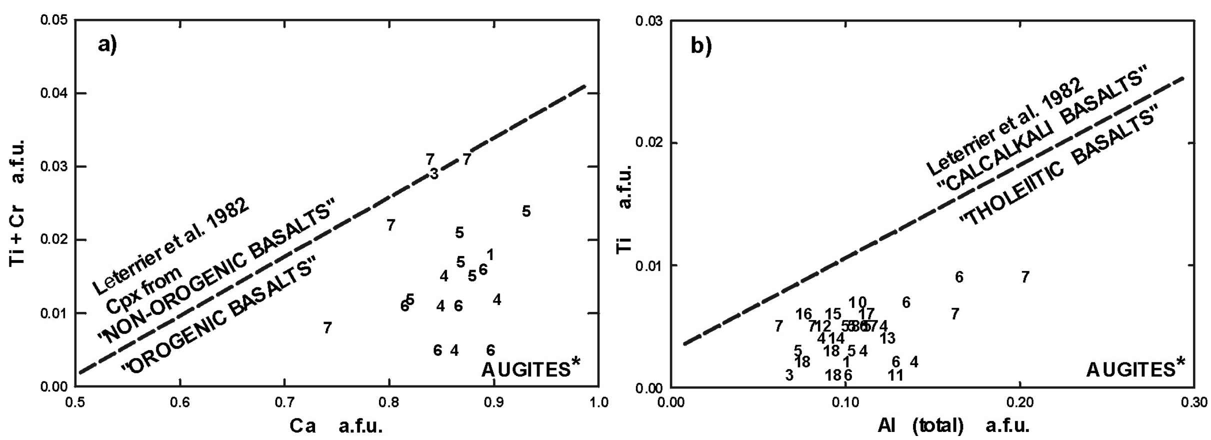

Figure 8: Discrimination diagrams of Leterrier et al. (1982) for augites from Flin Flon arc-assemblage basalt: a) Ti + Cr vs. Ca, which discriminates nonorogenic from orogenic; and b) Ti vs. Al, which discriminates calc-alkali from tholeiitic.The symbols 1, 2, 3, etc. are the sample numbers from Appendix A. Maximum and minimum values points are given for numbers 4 to 7; numbers 1, 3 and 8 to 18 are average values. Abbreviation: a.f.u., atoms per formula unit.

rim is enriched in Fe and Mn, whereas the core is enriched in Ca, Mg and Al. The Na content does not show a trend in either zone. Titanium shows irregular variation with a hint of enrichment in the crystal rims. The quad plot (major components Wo-En-Fs) in Figure 4c shows distinct clusters for core and rim due to the Fe-enrichment (Fs component) of the rims. Similarly, the Fe-rich rims in crystals 4158A, A3 and B are distinct in Figure 6. This iron enrichment, albeit minor, is aligned parallel to the Skaergaard trend (line 'S'), and indicates a small amount of iron enrichment in the magma as the crystals were growing.

Most crystals were not concentrically zoned. In sample 4073 (Appendix A, #5), both crystals E (11 analytical points) and C (6 points) did not show zoning in the BSE image, nor in a plot of analyses on a traverse across the crystal. In the quad plot (Fig. 5), however, the points are strung out in the Fe-enrichment trend line with a distribution similar to that of the core plus rim compositions of 4158C. Crystal 4157A, one of the largest crystals (at 2 x 0.5 mm), has small variations that do not correspond with concentric zoning (13 analytical points, Appendix A, #17; Fig. 7).

Major-element variation in the pyroxenes from seven rocks of the upper units of the Hook Lake Block is shown in Figure 5.

The augites from stratigraphic unit 'H' (*see* Fig. 3), samples 4073, 4033 and 5047, are rich in Mg and Ca, low in Fe, and comparable to the primitive early pyroxenes in the Skaergaard trend. The pyroxenes of sample 5011, from stratigraphic unit 'I', are similar. The pyroxenes of samples 5044, 5046 and 5057, from stratigraphic unit 'M' at the top of the section, are more enriched in Fe, with compositions up to Fs_{14} in the top sample (5057).

The major-element variation of the augites from samples 279, 287 and 313 is shown in Figure 6. These samples of pyroclastic breccia from southern Hook Lake Block were correlated during mapping with stratigraphic unit 'H' (Fig. 3). This interpretation is supported by the pyroxene compositions in the unit, which are similar to those of unit 'H' (4033, 4073 and 5047, Fig. 5).

A small trend to lower Ca contents is observed in the clusters of points for samples 313 and 287 (Fig. 6). Similar scatter is observed in the cluster for sample 5047-C in Figure 5, and for samples 4160-A, 5088-B and 4518-X in Figure 7. This trend could reflect incipient alteration through leaching of Ca, or it could be the "metastable trend of crystallization produced by rapid cooling" described by Smith and Lindsley (1971) and Yamakawa (1971). Alteration is the interpretation made here. Inspection of the table of analytical data (Appendix A) shows several values that are anomalous compared to other values in the same crystal; these are marked 'alt*' (for alteration). They do not calculate to a satisfactory pyroxene stoichiometry, and are thus interpreted as altered material. Most of these are anomalously high in Al and Fe and low in Ca, Mg and Si, and are thus altered towards an epidote composition. For example, analysis X-3 in sample 4518 (Appendix A, #18) is anomalous in having high Al and Fe and low Si, Ca and Mg. In the same crystal, analysis X-1 is low in Ca only, an incipient leaching. A similar example is analysis B-4 in sample 5088 (Appendix A, #13; the anomalous point B in Fig. 7): at Wo_{25}, it is outside the cluster with lower Wo but does not show much change in the Fe/Mg ratio because some of the iron is oxidized. A different type of alteration is shown in analyses AA-2 and AA-3 of sample 4033 (Appendix A, #4; Fig. 5): they have high Si contents and the analysis may be flawed by the beam exiting two or more minerals.

Augites from the western edge of the Hook Lake Block (Schist Lake sub-block) are plotted in Figures 6 and 7. They are similar in composition to the other Hook Lake samples (Fig. 5 and 6) in that they have primitive compositions and a limited trend of Fe enrichment.

The lower half of Figure 7 depicts the major-element variation of augites from five rocks from the Flin Flon Block (4157, 398, 4518, 5174, and 454). Two of these, 398 and 5174, contain primitive compositions (~Fs_7), similar to augites from the Hook Lake Block. Pyroxenes from the other samples (4157, 4518, 454) have more iron ($Fs_{10–20}$) and are similar to the differentiated compositions of 5057 in the upper portions of the Hook Lake Block stratigraphy.

The quad compositions of the augite phenocrysts are summarized in Figure 9. The primitive compositions (marked P) of most crystals are diopsidic, and plot at the start of the tholeiitic Skaergaard trend. Compositions that are enriched in iron are marked F in Figure 9. The area marked A shows the approximate effect of incipient alteration.

The trend of Fe-enrichment is an igneous tholeiitic trend, which may be caused by differentiation or contamination and is small in extent ($Fs_{4–20}$). It is only the primitive Mg-rich portion of trends of other igneous bodies, such as the Skaergaard layered intrusion or the North Shore Volcanic Group of the Lake Superior region, so the authors consider crustal magma chamber residence or crustal contamination to be very minor effects.

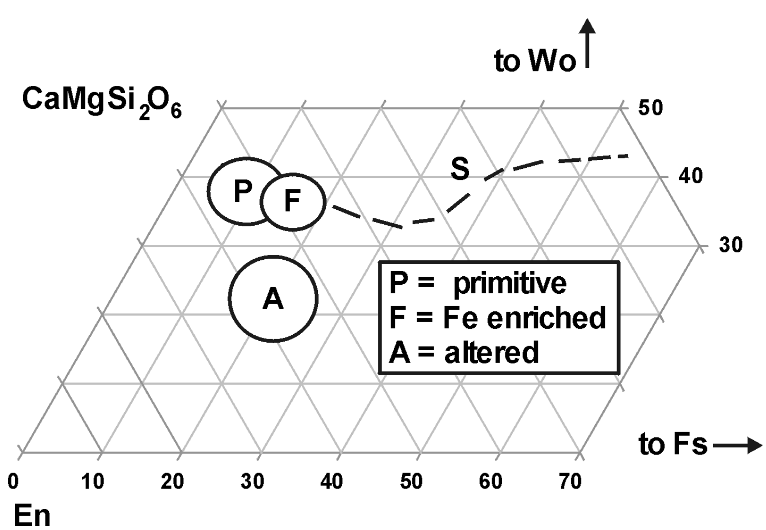

Figure 9: Summary of the pyroxene quad plots of augite compositions. Area P is the area of primitive augite compositions from this study, plus the compositions of augites from the Reed Lake pluton (Young 1992). Area F is the area of Fe-enriched Flin Flon augites. Area A is the area of altered compositions.

STRATIGRAPHIC VARIATION AND CORRELATION

The upper part of the Hook Lake Block stratigraphic section (units H to M, Fig. 3) does show a small amount of Fe enrichment at the top of the section. This can be seen by comparing values of Fs in Figure 5. The sample from the top of unit M (5057) is richest in Fe (clustered at Fs_{14}). The next two lower samples (5044 and 5046), from the lower portion of unit M, are mostly primitive (Fs_{5-10}) but with four point compositions in 5044 at Fs_{10-14}. Going down through the section, augites in sample 5011 from unit I, samples 5047, 4033 and 4073 from unit H (Fig. 5), and the three samples from the adjacent sub-block (279, 287, 313, correlated to unit H, Fig. 6), are all primitive, with Fs_{4-11}.

The sampled rocks from the Schist Lake sub-block (Fig. 6 and 7) also have augites of similar compositions and therefore support the interpretation (Bailes and Syme, 1989) that this sub-block contains a sequence of rocks stratigraphically equivalent to the main Hook Lake section.

Augite phenocrysts from the Flin Flon Block (Fig. 7) are also similar to those of the Hook Lake Block. They include both primitive and Fe-enriched compositions (areas P and F in Fig. 9). The rock units of the two blocks could not be correlated by mapping (Bailes and Syme, 1989), but they do have similar augites.

COMPARISON WITH OTHER SUITES

The Reed Lake pluton, a gabbroic and layered ultramafic pluton 80 km east of Flin Flon (Young, 1992), contains augites that have major- and minor-element compositions similar to those of the primitive Flin Flon augite phenocrysts (Fig. 9). By calculation of the Nimis geobarometer, the Reed Lake augites also crystallized at pressures less than 1 kbar, in accord with the interpretation of Young (1992) that the gabbro crystallized in a shallow subvolcanic chamber.

Middle Proterozoic diabase sills and dikes of the Lake Nipigon area (Ontario) contain pyroxenes similar to the augites in Hawaiian tholeiite (Sutcliffe, 1989). The Nipigon augites have compositions that differ from those of the Flin Flon volcanic rocks in having higher Fe, Ti and Cr, and lower Ca and Al. According to the system of Leterrier et al. (1982), they are subalkaline and 'nonorogenic'. They would plot in Figure 9 around the Fe-enriched 'F' area, but with more scatter. They lack Mg-rich primitive 'P' compositions, which are typical of the Flin Flon augites.

Middle Proterozoic Keweenawan volcanic rocks of the North Shore Volcanic Group of the Lake Superior area (Konda and Green, 1974) are olivine tholeiite to rhyolite. The major-element compositional trend for these augites follows the Skaergaard tholeiitic trend across the major-element quad. They differ from the Flin Flon augites in that they lack primitive compositions and show a greater range of Fe enrichment. Also, they are enriched in Ti (0.93–1.16 wt.%) and therefore plot as 'calk-alkali' (vs. 'tholeiitic') on the Ti versus Al diagram and 'nonorogenic' (vs. 'orogenic') on the Ti+Cr versus Ca diagram of Leterrier et al. (1982).

Recent basaltic-andesitic volcanoes in the Hi-Al basalt zone of northeastern Japan are transitional alkaline to subalkaline, with calc-alkaline characteristics (Aoki and Fujimaki, 1982). The Itinome-gata volcanic augites are richer in Na, Al and Ti, similar in Ca, Fe and Mn, and lower in Cr, Mg and Si than the Flin Flon augites. They are weakly tholeiitic (vs. calc-alkaline), and transitional orogenic to nonorogenic in the diagrams of Leterrier et al. (1982). These differences may be explained by tectonic history. The Flin Flon basalt originated from depleted Proterozoic mantle, and was not contaminated as it erupted through a thin oceanic crust. In contrast, the Itinome-gata rocks are recent eruptions through a thicker crust at a continental margin.

INTERPRETATION OF ORIGIN

Pressure

Aoki and Kushiro (1968), Wass (1979) and Nimis (1995) have described the effect of pressure at the time of crystallization on the chemical composition of a clinopyroxene. Aoki and Kushiro (1968) have shown that the Al^{IV}/Al^{VI} ratio is an indicator of depth of crystallization, as it discriminates the compositions of eclogitic augites (high pressure), augites in 'basalt with granulite' (medium pressure) and augites in igneous rocks (low pressure). In the Flin Flon arc-assemblage augites, these ratios are high (3 to 20) and the augites plot in the igneous field, which denotes low pressure.

Nimis (1995) experimentally grew pyroxenes at pressures up to 42 kbar to calibrate pressure versus chemical composition of each site in the clinopyroxene structure. The results of calculation of pressure by his formula are given in the right-hand column of Appendix A. Most analyses of Flin Flon arc-assemblage augites calculate to a pressure of 0 kbar, which is consistent with crystallization during volcanic eruption.

In one rock (sample 5047 from unit 'H' of the Hook Lake section; Appendix A, #11), the values of Nimis pressure (Nimis P) are 1 to 3 kbar for nine analyses and 0 kbar for one. Crystallization of these augites at the depths corresponding to these pressures, 3 to 9 km, occurred during the pre-eruptive stage of volcanism. The augite crystals in 5047, four of which were analyzed, are equant euhedral crystals up to 1.5 by 2.2 mm in size and are larger and more abundant than in the other samples. These large crystals co-exist with small (0.2 x 0.7 mm) microphenocrysts of plagioclase (now altered) in a formerly glassy groundmass. These pyroxenes have the highest contents of Al found (*see* Appendix A): the average is 3.47 wt.% Al_2O_3 (compared to 2.63 and 2.37 wt.% for 4033 and 4073, the companion samples from unit 'H' of the Hook Lake section).

In sample 279 (Appendix A, #1) analysis A-5 provided a Nimis P of 2 kbar, whereas the other ten analyses gave Nimis P as zero. This analysis has the highest value of Al in the group, which raises the Nimis P. The point A-5 is within a large crystal, and zoning is not observed. It may be the point of nucleation at depth (2 kbar or ~6 km) in the pre-eruptive stage. This effect is also shown in crystal C of rock 4033 (Appendix A, #4), where the two analyses (C-4 and C-5) yielded the largest contents of Al and therefore a Nimis P of 1 kbar. Another example is provided by analyses CC-3 and CC-4 in rock 4160 (Appendix A, #7), where analyzed points in the core of a crystal had greater contents of Al and yielded Nimis P of 1 and 2 kbar.

High values of Al (which would produce Nimis P values of 1 to 9 kbar) are found in those pyroxenes that are identified as altered (indicated by 'alt*' in Appendix A). These analyses do not have good pyroxene stoichiometry, and calculation of a Nimis P is invalid.

IRON/MAGNESIUM PARTITIONING (AUGITE/LIQUID) AND TEMPERATURE

The compositions of augites in sample 5057 cluster about Ca/(Ca+Mg+Fe) = 0.395 and Fe/(Fe+Mg) = 0.262 (FeO/MgO = 0.35 mol ratio; FeO/MgO = 0.63 weight ratio). The bulk rock analysis (Bailes and Syme, 1989) can be used for a composition of liquid because the rock has only a small content (4%) of augite phenocrysts. Assuming that the iron was all ferrous at the time of eruption, then FeO_{total} = 8.26 wt.% and FeO/MgO = 1.939 (weight ratio). Thus, the distribution coefficient, $KD_{(FeO/MgO,\ augite/liquid)}$ = 0.33 (for both mol and weight ratios). This is comparable to $KD_{average}$ = 0.26 (weight ratios in the range 0.22–0.34) for MORB tholeiitic basalt, as reported by Bryan (1979). Also, le Roix et al. (1982) reported a $KD_{average}$ of 0.292 for MORB from Speiss Ridge; they made a correction for ferric iron content and noted that the value given by Bryan would also have been 0.29 if he had made a similar ferric iron allowance. For sample 5057, if the content of iron in the bulk rock analysis (FeO_{total}) was decreased by 15%, then $KD_{(augite/lquid)}$ is increased to 0.38.

A KD of 0.33 (for sample 5057) would compute to a temperature of 1217°C by the formula of Gamble and Taylor (1980). Their experiments were on lunar basalt compositions (richer in Ti and Fe, and poorer in Al and Na than 5057). This is an extrapolation to temperatures greater than their liquidus; nevertheless, this suggests that the basalt from the stratigraphic upper portions of the Hook Lake Block were extruded at relatively high temperatures compared to other basalt.

Tectonic setting

The contents of Ti, Na, Cr and Al have been found to vary in a systematic way among rocks of different known tectonic settings (e.g., LeBas, 1962; Aoki and Kushiro, 1968; Leterrier et al., 1982). In the Ti+Cr versus Ca diagram (Fig. 8a), the Flin Flon augites plot as '**orogenic basalt**' (as opposed to nonorogenic; Leterrier et al., 1982). The low values of Ti+Cr are characteristic.

Flin Flon arc-assemblage rocks have the trace-element characteristics of magmas emplaced in arc settings (Syme, 1990; Stern et al., 1995a), displaying relative depletion in high field-strength elements (P, Hf, Zr, Ti, Y) and enrichment in large-ion lithophile elements (Rb, Ba, K, Th, Sr). The metavolcanic rocks in the Hook Lake and Flin Flon blocks, which are the focus of this study, further define tholeiitic whole-rock compositional trends (Stern et al., 1995a).

The data from augite chemistry and whole-rock geochemistry are thus wholly compatible, providing powerful independent evidence that these flows and redeposited pyroclastic rocks were emplaced in a tectonic setting characterized by oceanic subduction and juvenile-arc magmatism. The tholeiitic nature of the augites and their limited differentiation are indicators that the magma originated by melting of relatively homogeneous upper-mantle rocks, and that the magma was extruded quickly through the crust.

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APPENDIX A – CHEMICAL ANALYSES OF PYROXENES (IN WEIGHT PERCENT)

EMPA methods are described in Appendix B. FeO_{tot} = total iron as FeO

		SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO_{tot}	MnO	MgO	CaO	Na_2O	NiO	Total	P*
Averages													
Sample	Number												
1	279	52.53	0.08	2.57	0.55	4.49	0.29	17.01	22.79				
2	287	52.54		1.54	0.24	6.62	0.15	17.56	20.40				
3	313	52.83	0.04	2.42	0.41	5.12	0.24	18.18	21.46				
4	4033	52.30	0.12	2.63	0.25	5.67	0.14	16.57	22.10	0.09			
5	4073	52.75	0.17	2.37	0.41	4.97	0.14	16.80	22.42	0.10	0.03		
6	4158	51.82	0.16	2.75	0.19	6.32	0.17	16.09	21.75	0.10	0.03		
7	4160	51.73	0.17	2.81	0.56	7.14	0.20	16.27	20.50	0.11	0.02		
8	5011	52.26	0.23	2.85	0.43	6.98	0.30	15.83	22.64				
17	4157	51.92	0.17	2.45	0.14	9.11	0.26	16.16	19.95	0.12	0.00		
18	4518	52.61	0.07	1.81	0.13	8.21	0.24	16.99	19.69	0.11	0.03		
19	5174	51.89		2.17	0.36	5.86	0.14	17.01	20.90		0.03		
Crystal-spot													
1 Hook Lake Block #279	***(52-86-279-1)***												
A-1rim		53.12		2.15	0.40	4.91		17.75	21.97			100.30	0
A-2rim		52.88		2.60	0.43	4.99		17.48	22.16			100.54	0
A-3mid		52.30		2.87	0.85	4.70	0.31	16.85	22.92			100.80	0
A-4mid		52.31		2.69	0.37	5.75		16.53	22.18			99.82	0
A-5mid		52.24		3.63	0.18	5.32		16.75	22.17			100.29	2
A-6core		52.39		2.75	0.89	4.29		16.80	23.16			100.28	0
A-7core		52.81		2.26	0.68	5.24	0.27	17.13	22.69			101.08	0
A-8core		52.02		2.31	0.49	5.01		16.80	23.48			99.11	0
B-1		52.46	0.08	2.38	0.55	4.66		16.92	23.07			100.12	0
C-1rim		52.65		2.49	0.72	3.92		16.93	23.48			100.19	0
C-2core		52.61		2.10	0.52	3.91		17.13	23.41			99.68	0
AVG.		52.53		2.57	0.55	4.79		17.01	22.79				
2 Hook Lake Block #287	***(52-86-287-1)***												
A-1rim		52.35		1.98	0.15	6.17		17.20	20.51			98.36	0
A-2rim		51.71		1.83	0.28	6.11		17.06	21.04			98.03	0
A-3mid		52.49		1.37	0.30	6.21		17.53	20.76			98.66	0
A-4core		51.83		1.47	0.27	5.99		17.01	20.95			97.52	0
A-5rim		52.16		1.43	0.21	6.55		17.43	19.78			97.56	0
A-6rim		52.93		1.52	0.22	7.76		18.00	19.54			99.97	0
A-7rim		53.34		1.19		7.01		18.15	20.01			99.70	0
B-1		53.29		1.64		6.92		17.77	20.95			100.57	0
C-1		52.80		1.47		6.84	0.15	17.88	20.03			99.17	0

APPENDIX A – CHEMICAL ANALYSES OF PYROXENES (IN WEIGHT PERCENT) (continued)

Averages *Sample*	Number	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO_{tot}	MnO	MgO	CaO	Na_2O	NiO	Total	P*
3	***Hook Lake Block #313***	***(52-86-313-2)***											
	A-1rim	53.29		2.17	0.47	4.46		18.39	21.87			100.65	0
	A-2rim	53.70		1.96	0.43	4.45		18.57	22.13			101.25	0
	A-3core	52.35		2.72	0.00	5.04		17.72	21.83			99.66	0
	B-1rim	53.05		2.13	0.43	4.82		18.18	21.48			100.09	0
	B-2mid	53.19		2.17	0.31	4.61	0.24	18.44	21.79			100.74	0
	B-3core	53.50	0.04	1.61	0.98	3.71		19.33	21.67			100.83	0
	D-1alt*	53.29		1.83	0.28	7.33		18.54	19.19			100.46	0
	D-2alt	50.23		4.78	0.36	6.53		15.93	21.74			99.57	2
4	***Hook Lake Block #4033***	***(52-82-4033-1)***											
	A-1mid	52.84		1.46	0.61	3.85		16.87	23.88			99.51	0
	A-2mid	53.03		1.24	0.89	3.55		17.22	23.94			99.86	0
	AA-1alt*	51.68		2.63		7.17		16.04	21.62			99.15	0
	AA-2alt*	54.34		1.71		10.68		16.35	13.61			96.69	
	AA-3alt*	54.92		1.51		10.81		16.59	13.56			97.38	
	B-1rim	52.16		2.21	0.27	5.57		16.48	22.71			99.41	0
	B-2mid	52.03		2.12	0.26	6.67		16.95	21.38			99.14	0
	C-1rim	53.29	0.15	2.03	0.24	5.91	0.15	16.89	21.79	0.11		100.62	0
	C-2rim	52.79	0.17	2.25	0.32	5.85	0.14	16.79	21.79	0.08		100.21	0
	C-3rim	51.89	0.18	2.83	0.35	5.83	0.14	16.49	21.71	0.11		99.56	0
	C-4mid	51.99	0.08	3.28	0.36	4.39	0.09	16.49	23.11	0.09		99.89	1
	C-5mid	51.98	0.04	3.25	0.25	4.68	0.13	16.41	22.91	0.06		99.74	1
	C-6core	51.67	0.11	3.14	0.16	6.51	0.19	16.01	21.51	0.11		99.43	0
	C-7core	52.88	0.11	2.57	0.07	5.58	0.12	16.59	21.99	0.07		100.04	0
	AVG. B+C	52.30	0.12	2.63	0.25	5.67	0.14	16.57	22.10	0.09			
5	***Hook Lake Block #4073***	***(52-82-4073-1)***											
	A-1core	53.13		1.73	0.74	3.41		17.32	24.08			100.41	0
	A-2mid	52.81		1.67	0.72	3.98		17.08	23.44			99.71	0
	X-1rim	52.46		2.24	0.51	4.34		16.77	23.34			99.65	0
	X-2rim	52.65		2.23	0.62	3.85		17.05	23.38			99.76	0
	X-3core	52.85		1.77	0.71	3.85		17.26	23.29			99.92	0
	B-1rim	52.36		2.16	0.35	4.75		16.99	23.33			99.94	0
	B-2rim	52.95		1.54	0.57	3.71		17.36	23.12			99.25	0
	C-1rim	51.11	0.41	3.72	0.06	6.07		15.76	22.86			99.99	0
	C-2core	53.16		1.59	0.31	4.09		16.97	23.88			99.99	0
	C-3rim	52.03	0.27	2.96	0.26	6.63	0.20	16.48	20.33	0.11	0.02	99.27	1
	C-4mid	52.67	0.14	2.50	0.06	5.15	0.15	16.66	22.11	0.09	0.05	99.58	0
	C-5core	53.41	0.01	1.97	0.34	4.11	0.08	17.34	22.67	0.07	0.10	100.09	0
	C-6rim	53.15	0.18	2.14	0.24	6.11	0.21	16.87	21.17	0.09	0.00	100.16	0
	E-1core	52.33		2.32		4.65		16.79	23.35			99.89	0
	E-11core	52.66	0.20	2.47	0.44	4.77	0.10	16.62	22.23	0.08	0.04	99.60	0
	E-12core	53.24	0.17	2.45	0.43	4.66	0.15	16.90	22.35	0.11	0.01	100.5	0

Averages *Sample*	Number	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO_{tot}	MnO	MgO	CaO	Na_2O	NiO	Total	P*
5	***Hook Lake Block #4073 (52-82-4073-1) (continued)***												
	E-13 mid	53.63	0.11	2.48	0.45	4.72	0.13	16.85	22.28	0.08	0.08	100.8	0
	E-14 mid	53.22	0.20	2.49	0.45	4.77	0.14	16.83	22.13	0.11	0.00	100.34	0
	E-17mid	53.19	0.12	2.44	0.43	4.68	0.09	16.80	22.64	0.08	0.00	100.47	0
	E-18mid	52.81	0.00	2.57	0.46	4.86	0.11	16.93	22.29	0.09	0.02	100.15	0
	E-19rim	52.83	0.19	2.62	0.55	4.78	0.11	16.82	22.25	0.08	0.02	100.25	0
	E-20rim	53.04	0.08	2.48	0.52	4.54	0.08	16.95	22.34	0.11	0.01	100.016	0
	E-15rim	52.95	0.23	2.55	0.34	5.88	0.16	16.39	21.98	0.11	0.03	100.62	0
	E-16rim	52.84	0.18	2.34	0.24	6.62	0.18	16.65	20.90	0.11	0.00	100.06	0
	O-1rim	52.13	0.19	3.04	0.28	6.98	0.18	15.97	21.08	0.14	0.05	100.03	0
	O-2rim	51.86	0.21	2.63	0.31	6.01	0.21	16.30	21.90	0.12	0.07	99.64	0
	O-3mid	52.86	0.13	2.79	0.53	4.63	0.08	16.95	22.26	0.09	0.02	100.34	0
	O-4rim	52.68	0.32	2.55	0.27	6.44	0.18	16.83	20.89	0.09	0.00	100.25	0
	AVG.	52.75	0.17	2.37	0.41	4.97	0.14	16.80	22.42	0.10	0.03		
6	***Hook Lake Block #4158 (52-82-4158-1)***												
	A-1rim	49.79	0.57	4.10	0.09	9.64	0.29	14.31	20.40	0.18	0.00	99.38	0
	A-2rim	50.26	0.31	3.74	0.07	9.47	0.20	14.35	20.29	0.13	0.00	98.82	0
	A-3mid	52.05	0.14	2.33	0.09	6.83	0.21	16.01	21.50	0.11	0.00	99.26	0
	A-4core	51.57	0.12	2.33	0.11	6.96	0.23	16.01	21.48	0.12	0.02	98.95	0
	A-5core	52.13	0.13	2.65	0.22	5.73	0.13	16.13	22.26	0.11	0.09	99.58	0
	A-6core	51.55	0.25	2.00	0.13	7.51	0.23	16.21	20.95	0.11	0.03	98.96	0
	A3-1rim	52.91	0.26	1.91	0.12	7.51	0.24	16.30	21.06	0.08	0.00	100.39	0
	A3-2rim	52.83	0.07	2.13	0.25	6.48	0.17	16.58	21.66	0.11	0.00	100.26	0
	A3-3core	52.01	0.03	3.07	0.27	5.17	0.16	16.31	22.43	0.09	0.05	99.59	0
	A3-4core	52.75	0.05	2.28	0.19	5.15	0.12	16.97	21.90	0.07	0.00	99.49	0
	A3-5core	51.75	0.16	3.04	0.23	6.44	0.16	16.01	22.08	0.16	0.01	100.01	0
	A3-6rim	52.19	0.25	3.16	0.31	4.93	0.13	16.49	22.77	0.08	0.11	100.43	0
	A3-7rim	51.85	0.04	3.09	0.26	5.04	0.17	16.36	22.41	0.09	0.00	99.32	0
	A3-8rim	51.82	0.17	2.72	0.31	6.13	0.14	15.86	21.86	0.11	0.03	99.15	0
	B-1rim	50.63	0.32	3.67	0.24	6.83	0.14	15.39	21.22	0.10	0.04	98.56	1
	B-2rim	52.31	0.15	2.15	0.11	6.33	0.16	16.25	21.67	0.11	0.04	99.29	0
	B-3rim	51.63	0.24	2.69	0.26	6.03	0.17	16.11	22.13	0.11	0.04	99.41	0
	B-4core	51.73	0.07	2.93	0.22	5.13	0.12	16.35	22.31	0.09	0.10	99.04	0
	B-5core	51.53	0.12	2.97	0.30	5.23	0.11	16.57	22.04	0.08	0.00	98.94	0
	B-6core	52.54	0.04	2.81	0.38	4.86	0.13	16.77	22.06	0.11	0.05	99.75	0
	B-7core	52.09	0.05	2.99	0.11	4.44	0.14	16.62	22.80	0.02	0.06	99.32	0
	B-8core	52.72	0.00	2.80	0.20	4.47	0.13	16.80	22.64	0.02	0.07	99.87	0
	B-9core	52.14	0.02	2.89	0.19	4.36	0.12	16.94	22.68	0.07	0.01	99.41	0
	B-10rim	51.52	0.11	2.93	0.20	5.38	0.11	16.52	22.38	0.07	0.06	99.14	0
	B-11rim	51.57	0.18	2.62	0.22	5.98	0.15	15.93	22.11	0.10	0.05	98.95	0
	B-12rim	51.96	0.15	2.63	0.23	6.09	0.17	15.83	22.33	0.11	0.10	99.58	0
	BB-1rim	52.43	0.16	2.02	0.12	6.60	0.13	16.62	21.31	0.11	0.09	99.58	0

APPENDIX A – CHEMICAL ANALYSES OF PYROXENES (IN WEIGHT PERCENT) (continued)

Averages *Sample*	Number	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO_{tot}	MnO	MgO	CaO	Na_2O	NiO	Total	P*
6	***Hook Lake Block #4158 (52-82-4158-1) (continued)***												
	BB-2rim	51.43	0.26	2.46	0.02	8.20	0.15	15.47	20.93	0.14	0.00	99.07	0
	BB-3core	52.19	0.01	2.35	0.12	7.19	0.20	15.87	21.40	0.10	0.04	99.47	0
	BB-4core	51.92	0.18	2.56	0.20	6.38	0.18	16.08	21.96	0.08	0.08	99.61	0
	BB-5core	51.80	0.15	2.23	0.04	7.85	0.20	15.93	20.80	0.15	0.00	99.15	0
	BB-6rim	51.22	0.15	2.82	0.33	6.38	0.20	16.18	21.32	0.09	0.06	98.76	0
	BB-7rim	51.29	0.27	2.64	0.18	6.48	0.17	16.26	21.28	0.06	0.03	98.66	0
	C-1rim	51.45	0.18	2.28	0.04	7.55	0.22	15.53	21.33	0.11	0.00	98.68	0
	C-2rim	51.51	0.21	2.24	0.07	9.15	0.27	15.51	20.41	0.12	0.05	99.54	0
	C-3rim	52.21	0.11	2.24	0.11	7.99	0.24	15.76	20.73	0.13	0.01	99.53	0
	C-4core	52.07	0.17	2.86	0.31	5.02	0.20	16.43	22.37	0.09	0.00	99.53	1
	C-5core	52.11	0.11	2.96	0.30	4.99	0.18	16.24	22.39	0.09	0.05	99.42	0
	C-6core	51.82	0.17	3.23	0.32	5.18	0.17	16.26	22.23	0.08	0.01	99.47	1
	C-7core	51.54	0.21	3.32	0.31	5.31	0.15	16.18	22.26	0.12	0.07	99.46	0
	C-8core	52.24	0.09	3.04	0.27	5.11	0.17	16.23	22.75	0.10	0.00	100.02	0
	C-9core	51.47	0.17	3.59	0.22	5.25	0.15	16.05	22.49	0.11	0.02	99.53	1
	C-10core	51.47	0.15	3.54	0.24	5.26	0.07	16.22	22.44	0.11	0.03	99.48	1
	C-11rim	52.19	0.23	2.41	0.10	7.57	0.20	15.72	20.94	0.13	0.05	99.53	0
	C-12rim	51.69	0.30	2.47	0.07	7.45	0.25	15.72	20.89	0.10	0.02	99.26	0
	C-13rim	51.77	0.21	2.46	0.14	7.83	0.16	15.75	21.03	0.12	0.01	99.48	0
	AVG.	51.82	0.16	2.75	0.19	6.32	0.17	16.09	21.75	0.10	0.03		
7	***Hook Lake Block #4160 (52-82-4160-1)***												
	A-1rim	51.55	0.25	2.81	0.66	7.81	0.17	16.86	19.14	0.11	0.03	99.38	1
	A-2rim	51.63	0.15	2.79	0.65	8.18	0.33	16.46	19.29	0.15	0.04	99.67	1
	A-3mid	52.14	0.15	2.57	0.53	5.35	0.14	16.80	21.61	0.07	0.03	99.38	0
	A-4core	52.90	0.05	2.43	0.56	5.61	0.18	17.05	21.48	0.09	0.06	100.4	0
	A-5core	51.42	0.11	3.78	0.84	5.81	0.12	15.85	21.43	0.10	0.00	99.45	1
	B-1rim	52.66	0.19	2.06	0.60	7.01	0.22	16.87	20.42	0.11	0.08	100.04	0
	B-2rim	52.49	0.08	2.00	0.48	7.15	0.22	16.82	20.43	0.14	0.01	99.82	0
	B-3core	53.02	0.11	1.69	0.46	7.52	0.16	17.43	19.36	0.07	0.07	99.88	0
	B-4core	53.14	0.06	1.54	0.35	8.03	0.24	17.51	19.24	0.07	0.00	100.19	0
	C-1rim	52.67	0.19	1.44	0.09	8.59	0.23	17.07	18.67	0.13	0.00	99.09	0
	C-2rim	52.73	0.18	1.87	0.57	6.50	0.20	16.81	20.26	0.12	0.01	99.25	0
	C-3core	50.63	0.23	3.75	0.85	6.52	0.22	15.80	21.19	0.14	0.00	99.32	0
	C-4core	50.48	0.16	4.01	0.89	5.90	0.11	15.84	21.41	0.11	0.05	98.96	0
	C-5rim	52.66	0.08	1.72	0.36	7.23	0.18	16.93	20.17	0.08	0.00	99.4	0
	CC-1rim	52.00	0.28	2.42	0.26	8.50	0.17	15.96	19.73	0.11	0.00	99.45	0
	CC-2rim	52.11	0.22	2.38	0.25	8.28	0.24	15.90	19.89	0.12	0.01	99.41	0
	CC-3	51.39	0.16	3.63	0.72	6.43	0.14	15.69	20.93	0.14	0.02	99.25	1
	CC-4core	50.10	0.35	5.00	0.63	6.71	0.14	15.16	20.99	0.12	0.07	99.28	2
	CC-5	52.61	0.11	2.93	0.62	6.36	0.16	15.68	21.66	0.12	0.00	100.26	0
	CC-6rim	52.21	0.19	1.69	0.02	11.67	0.35	15.78	17.38	0.13	0.00	99.44	0

APPENDIX A – CHEMICAL ANALYSES OF PYROXENES (IN WEIGHT PERCENT) (continued)

Averages *Sample* Number	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO_{tot}	MnO	MgO	CaO	Na_2O	NiO	Total	P*
7 Hook Lake Block #4160 (52-82-4160-1) (Con't)												
CC-7rim	52.70	0.22	1.53	0.04	9.83	0.32	16.29	18.08	0.06	0.04	99.11	0
CC-8rim	51.47	0.22	2.72	0.73	6.87		16.14	21.24			99.37	0
D-1mid	51.10	0.27	3.16	0.83	6.75	0.13	15.86	21.58			99.68	0
D-2mid	51.90		2.80	0.57	6.99		16.45	20.96			99.67	0
E-1rim	51.99		2.53	0.46	6.53	0.27	16.51	21.27			99.56	0
E-2mid	51.70		2.43	0.62	5.36		16.83	22.25			99.19	0
F-1alt*	47.05		9.03	0.83	5.94	0.25	14.11	20.08			97.29	9
F-2mid	50.96		3.26	0.76	6.15		15.99	21.82			98.94	0
F-3rim	51.96		1.71	0.38	6.89		16.37	20.98			98.29	0
G-1mid	50.27	0.31	4.72	0.75	6.15		15.34	22.26			99.80	0
H-1alt*	52.11		0.90	0.71	9.06		16.45	19.69			98.21	0
H-2mid	51.46	0.22	2.72	0.73	6.87		16.14	21.24			99.38	0
AVG.	51.73	0.17	2.81	0.56	7.14	0.20	16.27	20.50	0.11	0.02		
8 Hook Lake Block #5011 (07-82-5011-1)												
A-1core	51.32		4.63	0.87	5.67		15.68	22.62			100.79	1
B-1rim	52.36	0.19	2.51		8.19		15.66	22.33			101.24	0
B-2core	51.91	0.24	2.33		8.90		15.39	22.10			100.87	0
B-3core	53.09		1.52		7.38		16.79	21.83			100.61	0
B-4rim	52.64	0.25	2.36		7.37		15.71	23.13			101.46	0
B-5mid	53.10		2.11		6.73	0.30	15.63	23.24			101.11	0
B-6mid	52.55		2.28		6.64		15.99	23.09			100.55	0
C-1mid	51.93		3.74	0.35	6.20		15.53	22.91			100.66	0
C-2core	51.46		4.16	0.50	5.71		16.08	22.55			100.46	1
AVG.	52.26	0.23	2.85	0.43	6.98		15.83	22.64				
9 Hook Lake Block #5044 (07-82-5044-2)												
A-1rim	51.70		1.77		7.68		16.08	21.30			98.54	0
A-2core	52.70		1.39	0.52	3.45		17.08	23.88			99.02	0
A-3rim	52.83		1.19	0.50	3.32		17.25	23.98			99.07	0
C-1rim	51.48		1.59		8.56		14.67	21.76			98.06	0
C-2core	51.72		1.75		8.08		16.24	20.68			98.47	0
C-3core	51.54		2.50		6.24		16.47	22.64			99.39	0
E-1rim	51.92		1.38		9.31	0.26	15.81	20.47			99.15	0
D-1rim	51.17		2.63	0.37	4.83		15.98	23.48			98.46	0
D-2mid	51.58		3.01		4.66		16.00	23.61			98.86	0
D-3core	51.55		2.22		5.80		16.16	23.02			98.75	0
AVG.	51.82		1.94		6.19		16.17	22.48				

APPENDIX A – CHEMICAL ANALYSES OF PYROXENES (IN WEIGHT PERCENT) (continued)

Averages *Sample*	Number	**SiO_2**	**TiO_2**	**Al_2O_3**	**Cr_2O_3**	**FeO_{tot}**	**MnO**	**MgO**	**CaO**	**Na_2O**	**NiO**	**Total**	**P***
10	***Hook Lake Block #5046 (07-82-5046-1)***												
	B-1rim	53.02		1.96		6.79		16.50	22.54			100.81	0
	B-2core	52.83		1.79	0.29	6.90		16.65	22.28			100.74	0
	B-3mid	52.56	0.25	2.51		7.31		16.25	21.88			100.76	0
	D-1mid	53.12		1.49		7.59		16.52	21.89			100.61	0
	C-1rim	51.73	0.30	3.49		8.98		15.53	21.45			101.4	0
	C-2mid	51.08	0.29	3.36		8.98		15.24	21.10			100.05	0
	C-3rim	50.93	0.33	3.57		9.07		15.44	21.00			100.35	0
	E-1rim	53.22		1.66	0.18	8.07		16.32	22.01			101.46	0
	E-2core	52.67		1.92	0.04	7.20		16.50	22.12			100.45	0
	E-3rim	51.88	0.15	2.86		9.99		16.33	19.42			100.63	0
	AVG.	52.30	0.26	2.46	0.17	8.09		16.13	21.57				
11	***Hook Lake Block #5047 (07-82-5047-1)***												
	A-1rim	53.00		2.92	0.30	4.75		17.74	21.91			100.62	0
	A-2mid	52.33		4.11		4.82		16.75	21.62			99.63	1
	A-3core	52.05		3.00	0.42	4.25		17.62	21.92			99.26	3
	B-1mid	51.69		3.81		5.46		16.98	21.73			99.67	1
	C-1rim	49.07		4.90	0.50	6.84	0.41	16.23	20.21			98.16	2
	C-2mid	51.49		3.33		5.01		15.97	22.12			97.92	2
	C-3core	52.10		3.87		4.53		17.27	22.29			100.06	2
	E-1rim	52.45		2.58	0.41	4.27		17.63	22.07			99.41	1
	E-2mid	52.00	0.03	3.03	0.46	4.28		17.75	21.63			99.18	1
	E-3core	52.38		3.10	0.41	3.85		17.64	21.67			99.05	2
	AVG.	51.86		3.47	0.42	4.81		17.16	21.72				
12	***Hook Lake Block #5057 (07-82-5057-10)***												
	A-1mid	52.14		1.99		9.78	0.36	15.26	20.24			99.77	0
	A-2mid	51.47	0.16	1.99		10.82	0.50	13.42	21.55			99.91	0
	H-1mid	52.53		1.22		10.19	0.16	16.13	19.96			100.19	0
	C-1rim	52.68	0.21	1.34		10.31	0.28	16.06	19.85			100.73	0
	C-2mid	51.98		1.42		9.62		16.09	19.62			98.73	0
	C-3core	52.45	0.10	1.38		9.60		16.32	19.72			99.57	0
	D-1mid	52.57		1.30		10.23	0.26	16.14	19.30			99.8	0
	E-1rim	52.43		1.33		10.43	0.25	15.24	20.18			99.86	0
	E-2rim	53.11		1.36		9.80		16.55	19.30			100.12	0
	E-3core	52.57		1.24		9.65		16.08	20.33			99.87	0
	AVG.	52.39		1.46		10.04		15.73	20.01				

APPENDIX A – CHEMICAL ANALYSES OF PYROXENES (IN WEIGHT PERCENT) (continued)

Averages *Sample*	Number	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO_{tot}	MnO	MgO	CaO	Na_2O	NiO	Total	P*
12	***Hook Lake Block #5057 (07-82-5057-10)***												
	A-1mid	52.14		1.99		9.78	0.36	15.26	20.24			99.77	0
	A-2mid	51.47	0.16	1.99		10.82	0.50	13.42	21.55			99.91	0
	H-1mid	52.53		1.22		10.19	0.16	16.13	19.96			100.19	0
	C-1rim	52.68	0.21	1.34		10.31	0.28	16.06	19.85			100.73	0
	C-2mid	51.98		1.42		9.62		16.09	19.62			98.73	0
	C-3core	52.45	0.10	1.38		9.60		16.32	19.72			99.57	0
	D-1mid	52.57		1.30		10.23	0.26	16.14	19.30			99.8	0
	E-1rim	52.43		1.33		10.43	0.25	15.24	20.18			99.86	0
	E-2rim	53.11		1.36		9.80		16.55	19.30			100.12	0
	E-3core	52.57		1.24		9.65		16.08	20.33			99.87	0
	AVG.	52.39		1.46		10.04		15.73	20.01				
13	***Hook Lake Block #5088 (07-82-5088-1)***												
	B-1core	52.24		1.92		8.88		16.35	19.55		0.01	98.95	0
	B-2mid	51.96		2.01		9.14		16.66	19.75		0.01	99.53	0
	B-3mid	52.50		2.04		8.76		16.37	19.95		0.01	99.63	0
	B-4alt*	48.34		4.56		11.32	0.25	16.48	16.05		0.04	97.04	3
	C-1core	51.49	0.13	2.91		5.01		15.93	23.37		0.04	98.88	0
	C-2core	51.39	0.06	3.20		5.49		15.52	23.45		0.04	99.15	0
	C-3mid	51.31		2.81		8.73		15.58	20.59		0.02	99.04	0
	C-4rim	51.69	0.13	2.47		8.45		16.08	20.63		0.05	99.50	0
	D-1core	51.35		2.36		6.31		16.02	22.09		0.03	98.16	0
	D-2mid	51.49		1.60		8.93		15.67	20.32		0.04	98.05	0
	D-3mid	52.13		1.73		8.63	0.29	16.26	19.71		0.04	98.79	0
	D-4rim	51.51		1.92	0.07	8.34	0.19	16.06	20.08		0.02	98.19	0
	AVG.	51.45		2.46		8.17		16.08	20.46		0.03		
14	***Hook Lake Block #5131 (07-82-5131)***												
	B-1	51.98		3.15		4.79		16.06	23.54			99.52	0
	B-2	52.00		3.02		3.98		16.44	23.88			99.32	0
	D-1mid	52.08		2.22		5.76		16.46	22.68			99.2	0
	D-2core	52.10		1.88		7.48		16.77	20.61			98.84	0
	D-3rim	51.92		2.10		5.66		16.44	22.16			98.28	0
	D-4core	51.95	0.14	1.59		7.90		17.12	20.47			99.17	0
	E-1core	51.88		3.10		4.20		16.23	23.73			99.14	0
	E-2rim	52.31		2.70	0.17	3.74		16.68	24.32			99.92	0
	F-1mid	51.98		1.62		7.27		16.83	21.03			98.73	0
	A-1rim	51.76		2.19		6.44		16.42	22.13			98.94	0
	AVG.	52.00		2.36		5.72		16.55	22.46				

APPENDIX A – CHEMICAL ANALYSES OF PYROXENES (IN WEIGHT PERCENT) (continued)

Averages *Sample*	Number	SiO_2	TiO_2	Al_2O	Cr_2O_3	FeO_{tot}	MnO	MgO	CaO	Na_2O	NiO	Total	P*
15	***Flin Flon Block #398***		***(52-86-398-1)***										
	A-1rim	52.36	0.24	2.19	0.36	5.77		17.10	22.62			100.64	0
	A-2mid	52.04		2.38	0.51	6.18		16.74	22.14			99.99	0
	A-3mid	52.15		1.29		8.70		16.77	19.39			98.30	0
	A-4mid	52.07		2.29		5.58		16.26	23.11			99.31	0
	C-1core	53.34	0.15	1.53		7.73		17.14	20.59			100.48	0
	C-2rim	52.19		2.94	0.68	5.26		16.12	23.19			100.38	0
	D-1rim	53.13		1.64	0.23	8.50		17.14	20.29			100.93	0
	D-2core	52.67	0.21	1.62	0.28	8.35		16.68	20.41			100.22	0
	F-1mid	51.9		2.63	0.37	5.16		16.55	23.29			99.90	0
	F-2rim	51.69		2.42	0.37	6.66	0.30	16.02	22.35			99.81	0
	AVG.	52.35	0.20	2.09	0.39	6.79		16.65	21.74				
16	***Flin Flon Block #454***		***(52-86-454-1)***										
	A-1rim	51.78		1.84		10.75		15.43	19.64			99.44	0
	A-2mid	51.78		1.58		11.34	0.36	14.83	19.26			99.15	0
	A-3core	51.71	0.22	1.53		10.98	0.34	14.83	19.98			99.59	0
	B-1rim	51.41		1.84		11.13		14.67	19.96			99.01	0
	B-2core	52.20		1.99		6.65		15.87	23.10			99.81	0
	X-1rim	50.56	0.24	1.73		12.98	0.40	15.18	17.31			98.40	0
	X-2core	50.22	0.28	2.42		13.35	0.35	14.04	18.61			99.27	0
	C-1rim	52.15		1.23		10.96		15.91	19.36			99.61	0
	C-2rim	51.21	0.24	1.63		10.57		14.86	20.30			98.81	0
	C-3core	51.37	0.24	1.43		10.49	0.35	13.97	20.89			98.74	0
	AVG.	51.44	0.24	1.72		10.92	0.36	14.96	19.84				
17	***Flin Flon Block #4157***		***(52-82-4157-1)***										
	A-1rim	51.48	0.17	2.65	0.23	8.39	0.18	16.55	19.40	0.10	0.00	99.16	0
	A-2rim	52.48	0.13	2.38	0.15	8.12	0.27	16.55	19.54	0.07	0.00	99.68	0
	A-3rim	51.90	0.12	2.73	0.18	8.77	0.24	16.61	19.01	0.09	0.00	99.66	0
	A-4rimalt*	52.21	0.00	2.40	0.00	19.19	0.28	10.55	12.40	0.17	0.00	97.19	
	A-5core	51.36	0.17	2.61	0.19	9.25	0.29	15.77	19.01	0.11	0.00	98.76	0
	A-6core	52.16	0.18	2.55	0.17	8.98	0.28	15.85	19.65	0.13	0.00	99.95	0
	A-7core	51.57	0.27	2.62	0.10	8.90	0.33	16.34	18.97	0.13	0.00	99.24	0
	A-8core	51.65	0.20	2.57	0.05	9.50	0.22	16.30	18.86	0.12	0.00	99.46	0
	A-9core	52.23	0.26	2.59	0.09	9.30	0.24	16.23	19.00	0.14	0.00	100.08	0
	A-10rim	52.28	0.24	2.32	0.13	9.91	0.31	16.10	18.73	0.09	0.00	100.12	0
	A-11core	51.58		2.23		8.58		16.14	20.39			99.02	0
	A-12rim	51.78		2.06	0.09	7.96		16.34	20.59			98.81	0
	A-13rim	52.29	0.21	2.09		9.58		16.41	19.59			100.16	0
	C-1alt*	38.95		26.39		8.19			24.70			98.47	0

APPENDIX A – CHEMICAL ANALYSES OF PYROXENES (IN WEIGHT PERCENT) (continued)

Averages *Sample*	Number	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO_{tot}	MnO	MgO	CaO	Na_2O	NiO	Total	P*
18	***Flin Flon Block #4518***	***(52-82-4518-1)***											
	A-1rim	52.16	0.03	1.81	0.12	8.83	0.27	17.14	18.75	0.14	0.08	99.33	0
	A-2core	52.29	0.03	1.96	0.18	8.26	0.22	17.01	19.26	0.11	0.01	99.30	0
	A-3core	52.22	0.06	1.73	0.12	8.56	0.30	17.32	18.68	0.11	0.00	99.08	0
	A-4rim	52.00	0.01	2.14	0.13	8.44	0.14	17.51	18.41	0.10	0.04	98.90	1
	A-5core	52.84		1.53		8.22		17.45	19.86			99.90	0
	X-1rim	53.01		1.58		8.54		17.73	16.12			96.98	3
	X-2mid	52.56		1.86		7.53		16.89	20.38			99.22	0
	X-3alt*	44.33		7.44	0.19	13.44		15.69	13.59			94.68	6
	X-4core	52.85		1.48		7.99		17.17	20.20			99.69	0
	X-5core	52.76		1.51		7.87	0.23	17.01	20.75			100.13	0
	X-6rim	53.09		1.63		7.95		16.84	20.34			99.85	0
	D3-1core	52.49		1.81	0.14	7.88		16.78	20.41			99.51	0
	E1-1core	52.61		1.41		7.92		17.10	20.43			99.47	0
	B2-1rim	52.42	0.13	2.24	0.18	8.52	0.23	17.08	18.82	0.12	0.02	99.75	0
	B2-2core	52.55	0.11	2.13	0.10	8.99	0.29	16.89	18.16	0.11	0.00	99.34	0
	B2-3core	52.34	0.05	1.98	0.09	8.62	0.25	17.22	18.66	0.09	0.00	99.29	0
	B2-4rim	52.49	0.17	2.29	0.16	8.74	0.23	17.04	18.65	0.11	0.06	99.93	1
	C-1	52.53		1.59		7.59	0.27	16.72	20.50			99.21	
19	***Flin Flon Block #5174***	***(07-82-5174-1)***											
	A-1core	52.83		1.94	0.30	6.43	0.08	17.15	20.50		0.02	99.25	1
	A-2core	52.30		1.45	0.31	6.82		17.84	20.71		0.02	100.14	0
	A-3mid	53.17		1.70	0.25	6.61		17.48	20.22		0.06	99.49	0
	A-4rim	53.18		1.81	0.28	6.44		17.63	20.47		0.05	99.86	0
	B-1core	51.60		3.31	0.65	4.77		16.59	22.39		0.06	99.37	1
	B-2core	51.54		3.32	0.44	4.69		16.34	22.27		0.04	98.64	1
	B-3mid	52.32		2.03	0.26	6.45	0.19	17.05	20.76		0.06	99.12	0
	B-4rim	52.26		2.58	0.32	6.46		16.80	20.73		0.03	99.18	0
	C-1core	51.54		1.51	0.30	5.75		16.80	20.71		0.02	96.63	0
	C-2mid	50.96		2.60	0.31	5.39		17.17	19.95		0.02	96.40	1
	C-3rim	51.30		1.98	0.5	5.35		16.72	21.68		0.02	97.55	0
	D-1core	50.57		2.11	0.33	5.5		16.75	20.62		0.02	95.90	0
	D-2rim	51.00		1.91	0.41	5.51		16.84	20.65		0.03	96.35	0

*alt, anomalous composition

P*, pressure (kbar) at crystallization, by the method of Nimis (1995)

APPENDIX B – EMPA ANALYTICAL METHODS

Analyses that did not include Na_2O were done on the MAC-5 microprobe at the University of Manitoba (R. Chapman, operator) under the following conditions: filament voltage 15 kV, current 10 nA, spot size of about 4 x 4 µm on the surface of the sample and 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 were made using the MAGIC V program. Fayalite, jadeite, augite and other international standards were used.

Analyses that did include Na_2O were done on the Cameca® CAMEBAX SX50 microprobe at the University of Manitoba (R. Chapman, operator), under the following conditions: filament voltage 15 kV, current 10 nA, spot size about 1 x 2 µm and 20 s count time. Data reduction was carried out using the PAP program (Pouchou and Pichoir, 1985).

APPENDIX C: ASSIGNMENT OF CATIONS

The computer program of Cebria Gomez (1990) was used. The calculation produces ferric iron by charge balance, and a.f.u. (atoms per formula unit), on the basis of four cations and six anions (Hamm and Vieten, 1971; Papike et al. 1974). The major elements Ca-Mg-Fe were plotted as the components Wo-En-Fs in the pyroxene quad using the system of Lindsley and Andersen (1983).