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**Magnetite Zones at the Ansil Copper-Zinc Deposit,
Rouyn-Noranda, Quebec**

by

Raymond William Westendorp

**A thesis submitted to the Faculty of
Graduate Studies and Research in partial
fulfilment of the requirements for the degree of
Master of Science**

Department of Earth Sciences

**Carleton University
Ottawa, Ontario
August, 1992**

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Rouyn-Noranda, Quebec
submitted by Raymond William Westendorp, B.Sc. (Hons), B.Ed.
in partial fulfilment of the requirements
for the degree of Master of Science

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Abstract

The Ansil deposit, approximately 14 km northwest of Rouyn-Noranda, Quebec is unique in the Noranda mining camp because of the significant accumulation that constitutes nearly one fifth of the deposit volume, of magnetite.

Magnetite at the Ansil deposit occurs in four distinct locations: in the footwall zone; in the hanging wall zone; in a magnetite-quartz zone stratigraphically above the down-dip extension of the deposit; and in a stockwork zone stratigraphically below the footwall magnetite.

Evidence for partial replacement of sulfides by magnetite are: footwall and hanging wall magnetite form re-entrant cusps into massive sulfides; discontinuous pyrrhotite and chalcopyrite bands are subparallel to the magnetite-sulfide contact and where they are oblique to each other, magnetite terminates the sulfide bands; a pyrrhotite/chalcopyrite band as thick as 1 cm commonly occurs at the magnetite-sulfide contact; there is an enriched copper halo stratigraphically above the footwall magnetite zones; relict texture of "pyritic framboids" in magnetite; the footwall magnetite zone can be traced stratigraphically downward where it appears to be fed by a magnetite stockwork system; and, disseminated sulfide blebs commonly occur in massive and semi-massive magnetite and in the cores of zoned magnetite crystals.

Zoned magnetite crystals occur as two types: type 1 (stockwork zone) in which the cores contain varying amounts of calcite and as much as 1.393 silicon ions (3.4 wt. %, based on 32 oxygen atoms); and, type 2 (footwall, hanging wall and magnetite-quartz zone) in which the cores contain no calcite but up to 3.043 silicon ions (10.8 wt. %, based on 32 oxygen atoms). The magnetite grains are commonly rhombic in outline and may indicate magnetite replacement of carbonate.

Magnetite appears to have precipitated during the late-stages of volcanogenic massive sulfide formation, perhaps as the ratio of sea water to rock interaction increased possibly providing the amount of oxygen necessary to produce magnetite instead of sulfide minerals.

The Ansil deposit is also characterized by a skarn-type mineral assemblage in the hanging wall magnetite zone. The mineral assemblage contains andradite, ferroactinolite, zoned magnetite, chlorite and ilvaite.

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1 INTRODUCTION

The Ansil deposit is located approximately 14 km north west of Rouyn-Noranda, Quebec, within the Blake River Group. The deposit is a typical Noranda-type volcanogenic massive sulfide (VMS) deposit. It is a stratabound accumulation of massive sulfides, underlain by a sulfide stockwork zone within rhyolite and overlain by submarine mafic volcanic rocks.

The Ansil property was acquired in 1974 and the mine was discovered in 1981 by Falconbridge Copper Mines Ltd., now Minnova Inc. Production started in 1989 with pre-production ore reserves estimated at 1.58 million tonnes grading 7.2 % Cu, 0.9 % Zn, 26 g/t Ag and 1.6 g/t Au (Riverin et al., 1990). The deposit is currently in production and is 100 % owned by Minnova Inc.

Unlike other Noranda VMS deposits, the Ansil deposit is characterised by a significant amount, nearly one-fifth of the deposit volume, of magnetite. Magnetite occurs in four distinct settings (magnetite-rich units): in the footwall rocks directly below the Cu-rich part of the ore body; a stockwork zone stratigraphically below the footwall magnetite; in the hanging wall rocks directly above the Cu-rich part of the ore body; and, in a banded magnetite-quartz zone stratigraphically above the down-dip extension of the deposit.

1.1 Purpose

The purpose of this study was to combine detailed mapping of the magnetite occurrences where they were revealed in the development of the Cu-rich ore with a petrographic study with the following objectives:

- 1) to establish the reasons for the distribution of the magnetite associated with the Cu-rich ore deposit;
- 2) to characterize the macroscopic and microscopic features of magnetite and the relation to sulfides and silicates within the magnetite-rich units;
- 3) to establish the timing of the magnetite precipitating event(s); and,
- 4) to infer the possible origin(s) of the magnetite.

2 GEOLOGICAL SETTING OF THE ANSIL DEPOSIT

2.1 REGIONAL GEOLOGY OF THE NORANDA AREA

The Ansil deposit occurs within the Noranda cauldron and shield volcano (Gibson and Watkinson, 1990) in the Blake River Group of the Abitibi Greenstone Belt, southeastern part of the Superior Structural Province of the Canadian Shield (Figure 1).

The Blake River Group of the Noranda area is composed of four volcanic complexes, interpreted as large shield volcanoes, that are characterised by a concentration of felsic volcanic rocks, rapid facies changes and a marked variation in the thicknesses of individual units (de Rosen Spence, 1976; Goodwin, 1978; Gibson and Watkinson, 1990; Riverin et al., 1990).

Volcanic rocks of the Noranda area form the youngest Central Volcanic Complex (Gibson and Watkinson, 1990). The Noranda Volcanic Complex is approximately 2.7 Ga (Mortensen, 1987), 35 km in diameter and represents 7.5 to 9 km of volcanic strata consisting of rhyolitic, andesitic and basaltic flows and minor pyroclastic rocks. These have been metamorphosed to the greenschist facies, although some areas have higher or lower grade rocks. Spence and de Rosen Spence (1975) have divided the Noranda Volcanic Complex into 5 rhyolitic zones termed Rhyolite Zones 1-5. Gibson (1989)

Figure 1. Regional geology of the Noranda area, Quebec. (after Thurston *et al.*, 1984)

refers to Rhyolite Zones 1-5 as Cycles 1-5, where each cycle consists of an andesitic to basaltic basal unit (inter zone andesite) and mixed rhyolite and andesite upper unit. Cycle 3 or the "Mine Sequence" is host to most of the volcanogenic massive sulfide deposits in the Noranda camp (Figure 2) and consists of a bimodal succession of tholeiitic, basalt to rhyolite rocks interpreted to have been erupted during periods of cauldron subsidence within the upper, central part of the Noranda Shield Volcano (Gibson and Watkinson, 1990; Gibson, 1989). The Ansil deposit is stratigraphically the second lowest deposit discovered to date in the Mine Sequence (Figure 2).

2.2 LOCAL GEOLOGY

The Ansil deposit and host rocks have been described by Riverin et al., (1990); much of the local and mine geology description is taken from this paper. The deposit occurs at the contact between rhyolite of the Northwest formation and overlying andesite of the Rusty Ridge formation and is centred at a depth of 1.3 km from surface (Figure 3). Rhyolite of the Northwest formation consists of massive to flow-banded flows and flow breccias (Galley et al., 1990). The rhyolite is locally overlain by the Lewis tuff, a finely laminated, discontinuous, tuff unit. The Lewis tuff is the stratigraphic equivalent of the Ansil deposit.

Figure 2, Stratigraphic location of the Ansil copper deposit in the Rouyn-Noranda mining camp. The Corbet deposit is the only deposit discovered to date that is stratigraphically lower than the Ansil deposit. FA; Flavrian Andesite, AR; Ansil Rhyolite (QFP), NWR; Northwest Rhyolite, RRA; Rusty Ridge Andesite, LAR; Lower Amulet Rhyolite, UAR; Upper Amulet Rhyolite, MA; Millenbach Andesite, WA; Waite Andesite, MR; Millenbach Rhyolite, WR, Waite Rhyolite, AA; Amulet Andesite, ENR; East Norbec Rhyolite (QFP), NR; Newbec Rhyolite and FG; Flavrian Granite (after Gibson, 1989)

Figure 3. East-west geological section of the Ansil deposit
(after Riverin *et al.*, 1990)

The Cranston quartz-feldspar porphyry (QFP) dome, erupted north of the Ansil deposit, is represented by a discontinuous crystal tuff and forms part of the Lewis tuff in the mine area. This crystal tuff locally interfingers with the Ansil sulfides in the down-dip extremity of the deposit.

Andesite of the Rusty Ridge formation forms the hangingwall to the Ansil deposit (Figure 3) and is locally observed in contact with any one of massive sulfides, magnetite, rhyolite of the Northwest formation, the Cranston QFP. The Rusty Ridge formation consists of andesitic to basaltic, vesicular, pillowed and massive flows. One basaltic flow underlies the south east corner of the Ansil deposit, which indicates that the eruption of the Rusty Ridge was contemporaneous with the formation of the Ansil deposit.

2.3 MINE GEOLOGY

2.3.1 Massive Sulfides

The Ansil deposit strikes north-south and dips on average approximately 50°E; due to the irregular "staircase" topography of the footwall rhyolite, the deposit may dip from 0 to 90 degrees (Figure 3). The deposit has a strike length of 120 m and a dip length of 350 m. The western or upper part of the deposit consists of two Cu-rich massive sulfide lenses as thick as 40 m connected by a thinner (< 15 m) Cu-rich zone

(Figure 3). The mineralogy in this part of the deposit is dominated by chalcopyrite and pyrrhotite with minor sphalerite (< 1%). In its down-dip extremity, the eastern or lower part of the deposit is thinner and the mineralogy is dominated by banded sphalerite and chalcopyrite with minor pyrite.

2.3.2 Stockwork Sulfides

Stockwork or "stringer" sulfides occur in three distinct settings: a discordant pipe underneath the massive sulfides, a concordant zone directly below massive sulfides, and a diffuse discordant zone in the hanging wall to the massive sulfides. Each copper-rich sulfide lens is underlain by a distinct stockwork or stringer sulfide zone; however, the stockwork zones merge at depth forming one stockwork zone below the lower lens (Figure 3).

2.3.3 Magnetite-rich Units

Magnetite occurs in four distinct settings: in the footwall rocks directly below the Cu-rich part of the ore body, in the hanging wall directly above the Cu-rich part of the ore body, in a distinct stockwork zone below the deposit and in a banded magnetite-quartz unit stratigraphically above the down-dip extension of the deposit (Figure 4).

Figure 4, Schematic diagram of the magnetite-rich zones at the Ansil deposit. Magnetite occurs in the footwall to the massive sulfide deposit and can be traced downward into two distinct magnetite stockwork zones which appear to form one stockwork below the eastern footwall magnetite zone. The stockwork zone is disconformable within the rhyolite of the Northwest formation and the upper part of the Flavrian andesite. However, exploration diamond drilling has been used to trace the magnetite stockwork within the Flavrian andesite, where it is subparallel to the Flavrian andesite and overlying rhyolite contact until it is terminated at the Flavrian pluton contact.

3 MAGNETITE-RICH UNITS AT THE ANSIL MINE

3.1 Introduction

Magnetite has been mapped throughout the western or upper part of the deposit on levels 7B, 9, 9B, 9C and 10 (Figure 5). Forty eight underground samples were collected (Figure 5) and 145 thin and polished sections were made from underground samples and drill core. Based on observations from underground development and drill core, the magnetite-rich units occupy nearly one-fifth of the deposit volume. The lower Cu-rich massive sulfide lens is underlain by the thickest accumulation of massive to disseminated magnetite (10-15 m) (Figure 4). Magnetite also occurs below the upper lens (5 m thick) and, on top of and adjacent to the massive sulfide lenses where it attains a maximum thickness of 1 m and underlies basalt/andesite of the Rusty Ridge formation. Where magnetite is not massive it is disseminated in silicate minerals, predominantly chlorite, ferroactinolite, sericite, stilpnomelane, greenalite and quartz throughout the deposit. In the hanging wall, disseminated magnetite occurs with these silicate minerals plus andradite and ilvaite. Variably abundant metallic minerals are chalcopyrite, pyrrhotite, ilmenite, galena, sphalerite, mackinawite, argentian gold and native gold.

3.2 FOOTWALL MAGNETITE

Footwall magnetite is massive to disseminated, fine-grained, and extremely tough. The massive variety ranges from < 1 cm to 15 m thick, is rarely greater than 90 % magnetite and is generally associated with chlorite, ferroactinolite and sericite. Quartz and ankerite veins have also been observed within the magnetite or together. Locally, as much as 10 % blebs of chalcopyrite and pyrrhotite are observed in the magnetite (Figure 6). Some sulfide veins in the magnetite contain an anomalously high content of gold and argentian gold (Figure 7). The cores of argentian gold grains consist of approximately 50 % Au and 50 % Ag, but the rims are approximately 30 % Au and 70 % Ag. Sulfides adjacent to magnetite include an array of stilpnomelane crystals up to 25 μ m in length (Figure 7).

Magnetite generally exhibits re-entrant cusps into the massive sulfides (Figure 8) and appears to be replacing the sulfide minerals (Riverin et al., 1990). Locally, magnetite and massive sulfides are separated by a thin (< 2 mm) band of chlorite, calcite, ferroactinolite or pyrrhotite (Figure 6). Figure 9 from level 10 illustrates a typical magnetite-massive sulfide contact. Magnetite forms broad re-entrant cusps, as wide as 10 cm, into the massive sulfides and appears to have advanced into or replaced the massive sulfides. In general, a thin band of pyrrhotite up to 10 cm

Figure 6, Sample 9C-2. Magnetite from the footwall, Ansil mine, 9C level, typically exhibits re-entrant cusps into the massive sulfides. Magnetite is separated from the sulfide minerals by a thin (1-3 mm) band of chlorite. Sulfides are pyrrhotite-rich and contain chalcopyrite patches at the magnetite/sulfide contact. Chalcopyrite is disseminated throughout the massive pyrrhotite. Footwall magnetite contains disseminated pyrrhotite elongated perpendicular to the sulfide/magnetite contact, and minor chlorite. Ccp; chalcopyrite Po; pyrrhotite Mag; magnetite Cht; chlorite

Figure 7, A) footwall magnetite-massive sulfide contact showing a chalcopyrite veinlet extending downward into the magnetite. B) Detailed view of footwall magnetite-sulfide contact. C) Detailed view of veinlet in A. D) Chalcopyrite and pyrrhotite intergrown with stilpnomelane. Note that the stilpnomelane crystals are terminated by magnetite. Ccp; chalcopyrite Po; pyrrhotite Mag; magnetite Stp; stilpnomelane.

Figure 8, Photographs of the footwall magnetite-sulfide contact. A) Footwall magnetite-sulfide contact from level 9C. B) Detailed view of A showing variably thick chalcopyrite layer at magnetite contact. Note the chlorite clots near the magnetite-sulfide contact. C) Footwall magnetite-sulfide contact on level 9. D) Level 10 footwall magnetite-sulfide contact. Note quartz/carbonate vein with flecks of gold as large as 1.5 mm in diameter. Ccp; chalcopyrite Po; pyrrhotite Mag; magnetite VMS; volcanogenic massive sulfides Cht; chlorite Au; gold.

Figure 9, Footwall magnetite-massive sulfide contact on the 10th level at the Ansil mine. Massive to disseminated magnetite is overlain by massive chalcopyrite and pyrrhotite and generally forms reentrant cusps into the sulfide minerals. Pyrrhotite commonly separates footwall magnetite from chalcopyrite. Discontinuous pyrrhotite bands as wide as 30 mm are generally subparallel to the magnetite-sulfide contact and occur within 1 or 2 m of the contact. Ccp; chalcopyrite Po; pyrrhotite Mag; magnetite.

in thickness occurs at the magnetite-sulfide contact; however, chalcopyrite has also been mapped in several locations separating magnetite and massive pyrrhotite (Figure 8). Discontinuous pyrrhotite and chalcopyrite bands also occur within 2 m of the contact (Figure 9). Pyrrhotite bands ranging from 4 to 10 cm in thickness are predominant; however, chalcopyrite bands ranging from 1 mm to 5 cm in thickness have been mapped elsewhere in the deposit. The bands are generally subparallel to the magnetite-sulfide contact but may be oblique (Figure 9) and are probably a result of deformation rather than primary depositional features.

3.3 HANGING WALL MAGNETITE

Hanging wall magnetite units range from < 1 cm to 1 m in thickness and are similar in morphology to the footwall magnetite units directly below the massive sulfides. Hanging wall magnetite is generally intergrown with chlorite and ferroactinolite similar to footwall magnetite. Figure 10 illustrates an example of a typical hanging wall magnetite-massive sulfide contact; however, ilvaite and andradite are unique to the hanging wall magnetite on level 10 (Figure 11)

Andradite is massive to disseminated, pale red-brown and crystals that range from 2 mm to 6 cm in diameter in the hanging wall rocks. Where andradite is not massive, crystals are euhedral to subhedral in habit and contain a 1 to 3 mm

Figure 10, Hangingwall magnetite-massive sulfide contact on the 10th level at the Ansil mine. Magnetite is generally disseminated and mixed with silicate minerals in the hangingwall to the massive sulfides. Silicate minerals include ferroactinolite, chlorite, garnet, ilvaite and stilpnomelane. Magnetite forms reentrant cusps downward into the massive sulfides. Discontinuous pyrrhotite bands and blebs are subparallel to the hangingwall magnetite-sulfide contact; however, pyrrhotite was rarely mapped at the contact. Ccp; chalcocopyrite Po; pyrrhotite Mag; magnetite Silicates; andradite, ilvaite, ferroactinolite, chlorite.

Figure 11, Sample 10-8. Magnetite from the hangingwall, Ansil mine, 10th level at the magnetite/sulfide contact. The sulfide patch is completely enveloped by magnetite and the magnetite exhibits re-entrant cusps into the sulfide minerals; although the sulfide patch is chalcopyrite it is separated from the magnetite by a thin (1-2 mm) band of pyrrhotite. With increasing distance from the sulfides, the proportion of magnetite decreases while that of silicate minerals increases. Magnetite contains euhedral to anhedral ferroactinolite crystals 1-5 mm in length. The upper part of the sample consists of euhedral to subhedral andradite crystals 5-40 mm in diameter which contain irregular magnetite patches. Minor chalcopyrite and pyrrhotite are disseminated throughout the magnetite, ferroactinolite and andradite. Ccp; chalcopyrite Po; pyrrhotite Mag; magnetite Gnt; garnet Amp; amphibole.

replacement rim of chalcopyrite. Chalcopyrite veinlets are also visible within the andradite. Magnetite also replaces andradite along its grain boundaries but may replace most of a crystal. Ilvaite composing 1 to 2 % of the mineral assemblage is brittle and black in hand sample. Ilvaite is opaque in transmitted light, and in reflected light it is strongly bireflectant from steel-blue to pinkish-blue and is generally surrounded by magnetite.

Spheroidal magnetite and fragments of massive magnetite have also been mapped in the hangingwall magnetite (Figure 12). Spheroids range from 3 to 8 mm in diameter and generally contain chlorite and/or quartz cores (Figure 13). Chalcopyrite and pyrrhotite are disseminated throughout the silicate-rich parts but not in the magnetite-rich part of the spheroids. Magnetite-rich fragments range from < 1 cm to 15 cm in length and are irregular in shape and size. Locally, magnetite clots or crystals up to 2 mm in diameter occur in the spheroidal and fragmental rock.

Locally, the magnetite contains up to 3 % chalcopyrite and pyrrhotite as disseminated blebs and/or fracture fillings (Figure 13). Native gold grains as large as 1 mm in diameter are commonly associated with mackinawite at the sulfide-magnetite contact. Minor quartz and ankerite veins have also been observed, similar to those in the footwall magnetite.

Magnetite generally exhibits re-entrant cusps stratigraphically downward into the massive sulfides. The

Figure 12, Sample 9B. Magnetite from the hangingwall, Ansil mine, 9B level. Magnetite and chalcopyrite are separated by a thin (<2 mm) band of pyrrhotite. Magnetite spheroids typically contain a chlorite and/or quartz core and disseminated chalcopyrite. The spheroids range from 2-8 mm in length and 2-5 mm in width. Magnetite has banded, disseminated and fragmental textures. The magnetite is overlain by andesite of the Rusty Ridge formation. The contact is sharp and is obliquely crosscut by subparallel quartz veins perpendicular to the magnetite/sulfide contact. Chalcopyrite contains thin trails (bands) of <1 mm chlorite crystals. Chalcopyrite veins perpendicular to the sulfide/magnetite contact extend from the massive sulfides into the magnetite. Silicate minerals in this sample are quartz and chlorite. Ccp; chalcopyrite Po; pyrrhotite Mag; magnetite Cal; calcite Cht; chlorite.

Figure 13, Sample 9 level. Magnetite from the hangingwall, Ansil mine, 9th level. Magnetite exhibits banded, massive, spheroidal, disseminated and rim textures. The magnetite bands, consisting of <1 mm magnetite crystals are <1-8 mm thick and terminate at the sulfide contact. The bands are subparallel to each other and are separated by 1-4 mm thick quartz/chlorite-rich bands. In this sample the magnetite is in direct contact with chalcopyrite, and pyrrhotite is in contact with chlorite. Massive patches of magnetite consist of clusters of 1-2 mm individual euhedral to subhedral crystals. The magnetite spheroids are 1-7 mm in diameter, and generally have chlorite and/or quartz cores. Magnetite is overlain by andesite of the Rusty Ridge formation. The magnetite/andesite contact is sharp. Within the massive sulfides pyrrhotite and chalcopyrite form alternating bands 1-10 mm thick subparallel to the magnetite/sulfide contact. Chalcopyrite-bearing quartz veins crosscut the magnetite bands and generally terminate at the magnetite/andesite contact. Ccp; chalcopyrite Po; pyrrhotite Mag; magnetite Qtz; quartz Cht; chlorite.

magnetite-andesite contact is either gradational or extremely sharp, the latter a result of faulting (Figure 12, 13). Magnetite also occurs in contact with 3 cm of overlying tuff on the 9B level.

3.4 BANDED MAGNETITE

Banded magnetite-quartz was intersected in a drill hole (A-660) stratigraphically above the eastern or lower part of the ore body. The banded magnetite zone is 15 cm thick, has an unknown strike length and consists of continuous and discontinuous magnetite bands 1 to 10 mm thick intercalated with sericite-bearing and chlorite-bearing siliceous bands 1 mm to 2 cm thick. Magnetite bands display local buckling and back-veins into underlying siliceous bands. The magnetite bands are locally cross-cut by chalcopyrite-pyrrhotite-chlorite veins. Thin section study revealed round magnetite grains similar in texture to the hangingwall magnetite spheroids. The round grains range from 20 to 100 μ m in diameter and occur within the siliceous bands.

3.5 MAGNETITE STOCKWORK

A magnetite stockwork or "stringer zone" is similar in texture to typical sulfide stockwork. Disseminated blebs and veins range from < 1 mm to 1 cm in thickness, are commonly associated with chlorite and make up less than 1 % to nearly 100 % of the rock. The magnetite stockwork was traced downward using drill core, into the Flavrian formation where the stringer zone is apparently terminated by the Flavrian pluton. Within the Flavrian formation the stringer zone is

concordant to the contact between the andesite and the overlying rhyolite of the Northwest formation. The stringer zone is clearly discordant within the rhyolite and extends upward, grading into massive magnetite underlying the massive sulfides (Figure 4). No apparent physical connection between the stockwork and hangingwall magnetite has been located.

It is possible, but not obvious, that the magnetite stockwork resulted from replacement of sulfide stockwork; it is more likely that the fluids that precipitated magnetite migrated up a pathway distinct from the fluids that precipitated the sulfide stockwork zone. Evidence for this is an envelope of chlorite alteration adjacent to individual magnetite stringers.

4 ZONED MAGNETITE CRYSTALS

4.1 Location of Zoned Crystals

Zoned magnetite crystals (Westendorp et al., 1991) occur in all four magnetite-rich units throughout the vertical extent and strike length of the Ansil deposit. Zoned crystals are most easily recognized in polished sections from areas where the magnetite is not massive, such as in the magnetite stockwork and the banded magnetite-quartz units. There, euhedral magnetite crystals have grown within chlorite and ferroactinolite or epidote patches. The zoned magnetite crystals chemically analysed are from the footwall (level 9C, 6A), hangingwall (levels 6A and 10), stockwork zone (drill holes AN-460, 440, and level 8) and banded magnetite-chert zone (drill hole AN-660).

4.2 Morphology and Zonation

There are two distinct types of zoned magnetite crystals: zoned crystals from the stockwork zone (type 1); and, zoned crystals from the footwall, hangingwall and banded magnetite-quartz zone (type 2). Zoned magnetite from the stockwork (sample 8-1) consists of irregular to subhedral crystals, 10-50 μm in maximum dimension. Zonation in the type 1 magnetite crystals appear similar to type 2 magnetite; however,

stockwork magnetite contains calcite, chlorite, greenalite and stilpnomelane inclusions.

Zoned magnetite crystals of the second type range from 40 to 300 μm in maximum dimension and were first identified by examination of polished thin section using the reflected light microscope. Zonation is visible in reflected light as various shades of grey in euhedral, subhedral and anhedral magnetite crystals (Figure 14).

Scanning electron microscopy reveals compositional variation across the zoned magnetite crystals. For the grains shown in figure 14, the lightest grey zone represents extremely pure magnetite. In general, pure magnetite is restricted to the core and the rim of each zoned crystal. The core of the magnetite grain is always irregular in outline and may contain inclusions of chalcopyrite and/or pyrrhotite. The darkest grey zone which envelopes the core and generally mimics the crystal habit, is a silica-rich and iron-poor zone in each crystal. Increasingly lighter grey zones that occur outward from this high-silica zone have decreasing silica and increasing iron contents. A zone or band of ferroactinolite, chlorite and quartz inclusions generally occurs near the grain boundary and also mimics the crystal outline (Figure 14). Scanning electron microscopy using energy dispersive spectrometry was used to establish the chemical nature of the zoning. Only iron and silicon peaks were detected. This was followed by quantitative electron microprobe analyses using

Figure 14, Zoned magnetite from the Ansil mine. A) Zoned grain from the magnetite stockwork zone. Note the euhedral, rhombic outline. B) Magnetite from the footwall zone. C) Magnetite from the hanging wall zone, level 10. D) Magnetite grains from the hanging wall magnetite-quartz zone stratigraphically above the down-dip extension of the deposit.

wavelength dispersive spectrometry on a CAMEBAX instrument of BRGM-CNRS, Orleans, France. In addition to the measured elements, Co, Ni, Cr, and Ti were sought but not detected. Location points and complete chemical analyses of analysed areas in the magnetite grains are presented in Appendices 2 and 3.

4.3 Silicon Substitution in Magnetite

There is an inverse relationship between iron and silicon contents of the Ansil magnetite. This relationship is shown in Figure 15 as a linear regression and 95 % confidence-level lines ($r=.995$). Since silicon values are moderately variable from crystal to crystal, the silicon-rich analyses diverge slightly from the best-fit line; however, silicon analyses within a single crystal provide excellent correlation. All of the magnetite crystals identified as being zoned under the reflected light microscope exhibit the inverse iron and silicon relationship.

Magnetite is an inverse spinel; therefore, based on 32 oxygen atoms in the unit cell, it has 8 Fe^{+3} ions in 4-fold coordination, 8 Fe^{+3} ions in 6-fold coordination and 8 Fe^{+2} ions in 6-fold coordination (Deer et al., 1966). If Ca^{+2} , Mg^{+2} , Mn^{+2} and Si^{+4} are assumed to substitute for octahedral Fe^{+2} (Figure 15) calculated data reveal that the octahedral site would have 1 cation in excess. Therefore, Ca^{+2} , Mg^{+2} and Mn^{+2} must

Figure 15. A. Linear regression showing the inverse relationship between iron and silicon ions of zoned magnetite grains analyzed. Confidence levels are 95 percent. B. Linear regression showing the inverse relationship for one magnetite grain (sample ,AN-9C-1 appendix 1). Note that all 10 analyses are within the 95 percent confidence level lines. C. Linear regression showing the relationship between Si^{+4} ions plotted against Si^{+4} , Fe^{+3} and Al^{+3} ions. D. Linear regression showing the relationship between Si^{+4} ions plotted against Si^{+4} , Ca^{+2} , Mg^{+2} and Mn^{+2} ions.

substitute for Fe^{+2} and Si^{+4} for Fe^{+3} . A decrease of approximately 0.1 ions is observed when Al^{+3} and Si^{+4} are assumed to substitute for Fe^{+3} (Figure 15).

Silicon substitution is as abundant as 3.043 ions (per 32 oxygen atoms: i.e., 10.8 wt. %) in the type 2 zoned magnetite crystals and 1.393 ions (i.e. 3.4 wt %) in the type 1 (stockwork) magnetite. Vincent and Phillips (1954) suggested that up to 0.5 wt. % silicon can exist in the magnetite structure and probably replaces octahedral Fe^{+3} , as does Ti^{+4} in ulvospinel. However, due to its significantly smaller ionic radius than Ti^{+4} and its preference for 4-fold coordination, Si^{+4} should substitute for tetrahedral rather than octahedral Fe^{+3} .

During the substitution of Si^{+4} for tetrahedral Fe^{+3} , additional Fe^{+3} must be reduced to Fe^{+2} , or Fe^{+3} must be replaced by previously mentioned divalent cations, or vacancies must be created in the lattice structure, or any combination of these three cases must occur in order to maintain charge balance. Possible vacancies in the magnetite lattice are consistent with cation totals significantly less than 24 (Appendix 3).

5 DISCUSSION

5.1 Magnetite

One of the many enigmas at the Ansil mine is the occurrence of a very significant amount of magnetite, approximately 20 % of the deposit volume, compared to the general absence of magnetite in the Noranda-area deposits. The only other deposits in the Noranda area with significant recorded magnetite are the Horne and Corbet mines. The latter contained a small volume (less than 5 %) of magnetite in the massive sulfide ore (Knuckey and Watkins, 1982).

The magnetite-forming event is late relative to the formation of the Ansil massive sulfide deposit, as evidenced by:

- 1) Footwall and hangingwall magnetite forms re-entrant cusps into the massive chalcopyrite and pyrrhotite;
- 2) Discontinuous chalcopyrite and pyrrhotite bands are subparallel to the magnetite-sulfide contact within 1 or 2 m of the contact;
- 3) Disseminated pyrrhotite and chalcopyrite blebs commonly occur in magnetite;
- 4) Zoned magnetite grains in the footwall magnetite unit commonly contain grains of pyrrhotite and/or chalcopyrite in their cores;
- 5) A pyrrhotite band as thick as 1 cm commonly occurs at the footwall magnetite-sulfide contact;
- 6) There is an enriched copper and gold halo in the ore

up to several metres thick stratigraphically above the footwall magnetite suggesting zone refining and replacement;

7) The volume and location of the footwall magnetite is compatible with its own stockwork feeder system, replacing overlying sulfides; and,

8) Relict texture of "pyritic framboids" in hanging wall magnetite.

Magnetite generally forms re-entrant cusps as wide as 15 cm into the massive sulfides (Figure 9). This textural relationship is compatible with massive sulfide formation and later magnetite invasion or replacement of the chalcopyrite and pyrrhotite (Riverin et al., 1990).

Discontinuous pyrrhotite and chalcopyrite bands occur within 1 or 2 metres of the magnetite-sulfide contact (Figure 9). These bands, as wide as 10 cm, are parallel to the magnetite-sulfide contact; however, they appear to be a product of remobilization and not from primary deposition. When oblique to the magnetite-sulfide contact the sulfide bands are terminated at the magnetite contact. There are two possible methods of producing the irregular, discontinuous bands: metamorphic banding during tectonic deformation or, metamorphic banding during magnetite replacement of massive sulfides. Textural relationships are compatible with band formation during early magnetite precipitation, later cross-cut by an advancing front of magnetite precipitation (Figure 9).

Massive and semi-massive magnetite contain up to 10 % disseminated chalcopyrite and pyrrhotite blebs and grains (Figure 6). Rarely does magnetite occur within sulfides. This relationship may be explained by remnant sulfides from an incomplete replacement process.

Zoned magnetite grains particularly in the footwall and stockwork units contain chalcopyrite and pyrrhotite inclusions that may be the result of partial replacement by magnetite. Some zoned magnetite grains that have abundant, partly included calcite are rhombic in outline, (Figure 14), and may have replaced calcite or other ferruginous carbonate crystals. Early replacement of these crystals was by pure magnetite at the core and rim followed by siliceous magnetite replacement in the intermediate zones.

Copper grades as high as 20 % occur within 1-3 metres of the footwall magnetite-sulfide contact. It is possible that copper was remobilized as well as sulfur during the replacement of massive sulfides by magnetite. During the magnetite event, as copper and sulfur moved stratigraphically up the massive sulfide pile, only iron was left to combine with oxygen from seawater to form magnetite. Some of the copper and sulfur reacted with pyrrhotite in the massive sulfide pile, directly above the magnetite, to form chalcopyrite forming an enriched copper halo above the footwall magnetite-sulfide contact. The remainder of the copper and sulfur reacted with iron in the andesite of the

Rusty Ridge formation to form chalcopyrite in the hanging wall rocks. Locally, where all of the sulfur was not driven off by the magnetite iron and sulfur reacted to form a thin band (as wide as 1 cm) of residual pyrrhotite at the footwall magnetite-sulfide contact (Figure 10).

Based on the central location and significant volume of magnetite it is probable that the magnetite originated from hydrothermal fluids which arrived in their own stockwork feeder system. This system is interpreted to have formed after the sulfide stockwork. It is possible that immediately after the main sulfide-precipitating event that the sulfide stockwork sealed itself forcing magnetite-precipitating fluids to produce their own stockwork system. Magnetite with gangue also forms distinct stockwork zones in the footwall and locally cuts zones of sulfide stockwork. Locally sulfide stockwork also cross cuts magnetite zones eventually merging with overlying massive sulfides (Barrett et al., 1991), however, the contact is most often ambiguous. Magnetite stockwork leads upward to the disseminated and massive footwall magnetite. The peripheral location of the magnetite along the fringes of the copper-rich ore is compatible with a post-sulfide stockwork feeder system replacing sulfides along the perimeter of the chalcopyrite-pyrrhotite ore. Figure 16 shows the possible evolution of the magnetite zones.

During the early stages of sulfide (pyrrhotite and chalcopyrite) precipitation hydrothermal fluids contained

Figure 16, Schematic diagram of the Ansil deposit showing the evolution of the magnetite-rich zones. The top diagram shows an early stage of magnetite-rich zone development. The bottom diagram shows a very late magnetite-rich zone development where a large part of the massive sulfide deposit has been replaced by massive to disseminated magnetite. The upper and lower footwall magnetite-rich zones are underlain by disconformable magnetite stockwork zones. Magnetite has also accumulated in the hangingwall to the deposit in contact with and stratigraphically above the Ansil massive sulfides. Hangingwall magnetite and massive sulfides are overlain by andesite of the Rusty Ridge formation. Conformable breccia shown in the massive sulfide pile is discussed by Galley *et al.*, 1991. Mag; magnetite vms; volcanogenic massive sulfides.

significant copper and iron and probably contained sulfur in concentrations of at least 10^{-2} M. However, as the system evolved and most of the sulfur was used to precipitate chalcopyrite and pyrrhotite, the concentration of sulfur could have been reduced to $10^{-3.5}$ M, increasing the fO_2 within the hydrothermal fluids. Oxygen fugacity could have also been increased significantly during sustained mixing of hydrothermal fluids with ambient seawater (Hannington and Scott, 1989). Large (1977) shows that it is possible to precipitate chalcopyrite and pyrrhotite during the early and middle stages of hydrothermal activity and magnetite during the waning stages of the hydrothermal event under the general conditions of $\log fO_2$ near -35, temperature at 250°C , pH near neutral and fS_2 changing from 10^{-2} to $10^{-3.5}$ M. Evidence that magnetite occurs in recent massive sulfide deposits was noted by Oudin (1981), where Cu-rich chimneys from the East Pacific Rise contained zoned magnetite with as much as 1.70 wt. % silicon

Zoned magnetite is very pure (core area) but may contain zones as rich as 3.4 wt. % SiO_2 in stockwork magnetite and 10.5 wt. % SiO_2 in footwall magnetite (Appendix 3). The very high silica content in type 2 magnetite was not found in the stockwork magnetite because the intermediate zones in some grains are calcite-rich with lesser amounts of other silicates. Based on the central and peripheral distribution of magnetite, (Figure 4), the rhomboid outline of some

magnetite grains, (Figure 14) with calcite inclusions, magnetite and perhaps some silicates, may have partly replaced calcite in the stockwork and footwall magnetite units. If siliceous magnetite is a result of replacement of calcite crystals, then further, late-stage replacement of calcite in the intermediate zones of magnetite might have produced very siliceous magnetite similar in composition to the magnetite in the footwall, hangingwall and banded magnetite-quartz zones elsewhere in the deposit. It is also possible that original carbonates were zoned with iron-rich cores and rims but more calcic intermediate zones.

5.2 Skarn-type Mineral Assemblage

There is also an unusual occurrence of andradite garnet in the hangingwall to the massive sulfide deposit. Garnet occurs in a skarn-like mineral assemblage including ferroactinolite, zoned magnetite, ilvaite, greenalite, stilpnomelane and Fe-rich chlorite (Figure 11). The Tengumori deposit in Japan, described by Shiga (1989), is a skarn deposit dominated by copper sulfide ore with diopside-hedenbergite, grandite (andradite-bearing garnet), actinolite and zoned silician magnetite with as much as 5.5 wt. % silicon. The proposed partial replacement of calcite in the stockwork and resulting expulsion of Ca and CO₂ may explain the skarn-like mineral assemblage at the hangingwall contact

between the massive sulfides, hangingwall magnetite and andesite of the Rusty Ridge formation. During replacement of calcite, fluid containing Ca and CO₂ among other species may have been flushed up the stockwork system, reacted with the hangingwall rocks and precipitated magnetite, andradite, ferroactinolite, chlorite and ilvaite. The precipitation could have been triggered by changes in pH, Eh and temperature when rising hydrothermal fluids mixed with connate sea water in the altered rocks at the top of the massive sulfide deposit.

Gamble (1982) demonstrates that it is possible to produce a mineral assemblage of pyrrhotite, magnetite, andradite and quartz at a temperature of 300°C, log f_{O_2} near -34 and pressure at 2 kb. Eniaudi et al (1981) predict a similar assemblage where andradite is created at the expense of magnetite, quartz and calcite at 500 bars, log f_{O_2} at -30 to -35, temperature at 300°C and XCO₂ less than 0.1. Einaudi and Burt (1982) suggest that amphibole, chlorite and ilvaite could be formed as "late" minerals in an Fe-rich, S-poor skarn. Greenalite and stilpnomelane also occur in the skarn-type mineral assemblage and can form at temperatures ranging from 150 to 350°C in which greenalite is probably replaced by stilpnomelane (Klein, 1974).

Skarn mineral formation may also have been facilitated by the insulating effect of hot andesite from the Rusty Ridge formation capping the massive sulfide deposit. Continued

hydrothermal action may have resulted in increasing temperatures and skarn mineral formation. The significant occurrence of skarn-type minerals in the hangingwall to the deposit could account for some of the calcium released during possible replacement of calcite by magnetite but not necessarily all of the calcium released from the stockwork zone.

The abundance of amphibole, however, might account for this. Amphibole occurs throughout the Ansil deposit in the footwall and hangingwall zones; the amphibole at the Ansil deposit is ferroactinolite (Figure 17; Leake, 1978, Richard and Clarke, 1990).

5.3 Gold distribution at Ansil

Gold at the Ansil deposit occurs in 5 different settings: in late-stage quartz-carbonate veins; in chalcopyrite and pyrrhotite veins; in the sulfide stockwork zone; associated with massive chalcopyrite and pyrrhotite; and, associated with banded sphalerite in the down-dip extension of the deposit.

Gold flecks as large as 2 mm in diameter occur in quartz-carbonate veins (Figure 8D). Evidence for "late-stage" formation is the fact that these veins cross-cut rhyolite of the Northwest formation and footwall magnetite zones. These veins contain variable amounts of chalcopyrite and/or pyrrhotite (as much as 10 %), quartz, calcite, iron carbonate

Figure 17, Computer-generated plot for amphiboles (Richard and Clarke, 1990) based on the classification of amphiboles by Leake (1978). Five amphiboles were analysed; however, 2 samples have silicon values greater than 8 and were not plotted on the diagram. The three samples shown were classified as ferroactinolite.

and gold.

Chalcopyrite/pyrrhotite veins extend downward into the footwall magnetite. These veins appear to have filled fractures in the footwall magnetite. During deformation the magnetite probably fractured and the fractures could have been filled with remobilized chalcopyrite and pyrrhotite. Gold is zoned in the sulfide veins. The cores of the gold grains contain approximately 50 % gold and 50 % silver; however, the rims contain approximately 30 % gold and 70 % silver. It is interesting to note that these gold grains are often located in close proximity to sphalerite grains.

Gold also occurs within the upper, copper-rich massive sulfide mound. Gold concentrations are as abundant as 20 ppm and is closely associated with areas of copper enrichment (Barrett et al., 1991).

Gold has also been mapped in the sulfide stockwork zone. The stockwork feeders are characterized by a copper-rich core and a zinc-rich perimeter. The gold is associated with the copper-rich part of the feeder pipe.

Gold is associated with zinc-rich sulfides in the down-dip extension of the deposit. There gold is concentrated as much as 3 ppm in the banded spalerite, quartz +/- pyrite +/- chalcopyrite rock (Barrett et al., 1991).

Gold could have originated with any one of the zinc, copper or iron (magnetite) precipitating events or perhaps during an earlier carbonate precipitating event. Barrett et

al (1991) suggested that the restriction of the highest gold values to the massive pyrrhotite-chalcopyrite ores indicates that the gold was syngenetically introduced with the base metals. Gold can be mobilized in Ca, Si, Fe, CO₂-bearing solutions near neutral pH, perhaps as Au(HS)⁻ complexes (Seward, 1984). Therefore, hydrothermal fluids may become enriched in gold by dissolving it from preexisting sulfides in their path (Hannington and Scott, 1989). However, as the conditions become more oxidizing, facilitating magnetite precipitation, gold solubility decreases and gold will precipitate. Therefore, gold may be flushed up into the massive sulfide pile concentrating it in the pyrrhotite-chalcopyrite ore or it may be locally precipitated in fractures in magnetite with mobilized sulfides. Evidence for this is shown in figures 7 and 8. This is consistent with a zone-refining model, whereby gold deposited in the early stages of mineralization at the bottom of the deposit is remobilized and reconcentrated elsewhere in the deposit (Hannington and Scott, 1989), in this case near the magnetite-sulfide contact.

The formation of magnetite could be a product of temperature increase. Assuming constant fS_2 , fO_2 , and pH a rise in temperature could stabilize the hydrothermal fluid in the magnetite field instead of the pyrrhotite field (Large, 1977).

The formation of magnetite could also be the product of hydrothermal source different from the massive sulfides. The

new source could involve a mix of convecting seawater and magmatic fluid or magmatic fluid only causing a decrease in the concentration of sulfur, copper and zinc. Gibson and Watkinson (1990) suggest that it is possible to produce some massive sulfide deposits from magmatic fluids.

Magnetite might not have been the final mineral-forming event at the Ansil Cu-Zn deposit. It is possible that the latest mineral forming event was a result of Au-rich, CO₂-bearing fluid which could have produced the Au-bearing carbonate veins that cross cut the magnetite.

6 Conclusions

Magnetite at the Ansil deposit appears to have been precipitated during the late-stages of volcanogenic massive sulfide formation. Evidence to support this conclusion includes: footwall and hanging wall magnetite generally forms re-entrant cusps into massive sulfides; discontinuous chalcopyrite and pyrrhotite bands are subparallel to the magnetite-sulfide contact and where they are oblique to this contact, they are terminated by magnetite; disseminated chalcopyrite and pyrrhotite blebs commonly occur in magnetite; zoned magnetite grains from the footwall zone contain flecks of pyrrhotite and/or chalcopyrite in their cores; a pyrrhotite or chalcopyrite band commonly occurs at the magnetite-sulfide contact; there is an enriched copper halo stratigraphically

above the footwall magnetite-sulfide contact; and, footwall magnetite has been traced vertically downward where it merges with a magnetite stockwork zone independent of the sulfide stockwork.

The magnetite precipitating event appears to have occurred near the end of the massive sulfide event as the metal-bearing fluids became more oxidizing, perhaps due to an increase in the ratio of sea water to hydrothermal fluids. An increase in the activity of sea water could account for an increase in the amount of oxygen available to produce magnetite and a decrease in the amount of sulfur available to precipitate chalcopyrite and/or pyrrhotite.

During the formation of the magnetite zones, copper as chalcopyrite and gold were remobilized within the volcanogenic massive sulfide deposit. Copper was concentrated in a higher-grade chalcopyrite zone directly above the footwall magnetite and was remobilized into the hanging wall andesite of the Rusty Ridge formation. Gold was locally remobilized into quartz-carbonate veins and sulfide-filled fractures in magnetite.

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Appendix 1
Level plans of the Ansil Mine
(see back pocket)

Appendix 2**Location points for analyses of zoned magnetite**

Analyses	Sample	Zone
1-10	AN-9C-3	Footwall
11-19	AN-9C-1	Footwall
20-29	AN-9C-1	Footwall
30-39	AN-9C-3	Footwall
40-45	A-460-1	Stockwork
46-52	AN-6A-MT4	Footwall
53-58	A-660-1	Banded
59-62	A-440-2	Stockwork
63-67	AN-10-8	Hanging Wall
68-71	AN-10-8	Hanging Wall
72-75	No Picture	
76-80	A-660-1	Banded
81-87	No Picture	
88-107	AN-8-1	Stockwork

Appendix 3
Electron microprobe analyses for each zoned magnetite

	1		2		3	
Si	0.000	(0.0)	0.000	(0.0)	0.001	(0.0)
Fe ⁺²	7.996	(30.7)	7.974	(31.1)	7.940	(30.5)
Fe ⁺³	15.963	(68.1)	15.967	(69.1)	15.993	(68.3)
Al	0.030	(0.1)	0.028	(0.1)	0.000	(0.1)
Ca	0.014	(0.0)	0.009	(0.0)	0.010	(0.0)
Mg	0.000	(0.0)	0.024	(0.1)	0.057	(0.1)
Mn	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Tot.	24.003	(98.9)	24.001	(100.4)	24.001	(98.9)

	4		5		6	
Si	1.342	(4.5)	1.259	(4.3)	1.298	(4.3)
Fe ⁺²	6.976	(28.2)	6.973	(28.7)	7.048	(28.2)
Fe ⁺³	14.407	(64.8)	14.506	(66.3)	14.474	(64.4)
Al	0.141	(0.4)	0.134	(0.4)	0.129	(0.4)
Ca	0.219	(0.7)	0.201	(0.7)	0.196	(0.6)
Mg	0.297	(0.7)	0.327	(0.8)	0.253	(0.6)
Mn	0.000	(0.0)	0.020	(0.1)	0.000	(0.0)
Tot.	23.383	(99.3)	23.420	(101.3)	23.399	(98.7)

	7		8		9	
Si	0.022	(0.1)	0.017	(0.1)	0.000	(0.1)
Fe ⁺²	7.971	(30.5)	7.984	(30.7)	7.979	(30.9)
Fe ⁺³	15.951	(67.9)	15.957	(68.2)	15.938	(68.6)
Al	0.012	(0.0)	0.013	(0.0)	0.021	(0.1)
Ca	0.030	(0.1)	0.025	(0.1)	0.009	(0.0)
Mg	0.009	(0.0)	0.001	(0.0)	0.000	(0.0)
Mn	0.001	(0.0)	0.000	(0.0)	0.000	(0.0)
Tot.	23.996	(98.6)	23.997	(99.1)	23.983	(99.7)

	10		11		12	
Si	0.000	(0.2)	0.265	(0.9)	1.616	(5.6)
Fe ⁺²	7.952	(31.3)	7.771	(30.3)	7.119	(29.2)
Fe ⁺³	15.897	(69.5)	15.652	(67.8)	14.200	(64.8)
Al	0.033	(0.1)	0.081	(0.2)	0.150	(0.4)
Ca	0.025	(0.1)	0.001	(0.0)	0.066	(0.2)
Mg	0.000	(0.0)	0.071	(0.2)	0.050	(0.0)
Mn	0.013	(0.1)	0.025	(0.1)	0.005	(0.0)
Tot.	23.977	(101.3)	23.866	(99.5)	23.206	(100.2)

	13		14		15	
Si	0.243	(0.8)	1.256	(4.3)	1.267	(4.3)
Fe ⁺²	7.881	(29.8)	7.329	(29.7)	7.296	(29.4)
Fe ⁺³	15.727	(67.7)	14.559	(65.5)	14.596	(65.3)
Al	0.028	(0.1)	0.142	(0.4)	0.118	(0.3)
Ca	0.001	(0.0)	0.085	(0.3)	0.037	(0.1)
Mg	0.055	(0.1)	0.021	(0.1)	0.042	(0.1)
Mn	0.012	(0.0)	0.000	(0.0)	0.019	(0.1)
Tot.	23.947	(98.5)	23.392	(100.3)	23.374	(99.6)

	16		17		18	
Si	0.022	(0.1)	1.542	(5.3)	0.060	(0.2)
Fe ⁺²	7.987	(30.5)	7.135	(29.1)	7.970	(30.8)
Fe ⁺³	15.967	(67.9)	14.249	(64.5)	15.925	(68.1)
Al	0.006	(0.0)	0.172	(0.5)	0.015	(0.0)
Ca	0.005	(0.0)	0.074	(0.2)	0.000	(0.0)
Mg	0.000	(0.0)	0.043	(0.1)	0.000	(0.0)
Mn	0.000	(0.0)	0.033	(0.1)	0.000	(0.0)
Tot.	23.987	(98.5)	23.248	(99.8)	23.970	(99.4)

	19		20		21	
Si	0.203	(0.7)	0.592	(2.0)	0.146	(0.5)
Fe ⁺²	7.893	(30.5)	7.690	(30.3)	7.927	(30.6)
Fe ⁺³	15.786	(67.7)	15.219	(66.6)	15.804	(67.9)
Al	0.000	(0.0)	0.171	(0.5)	0.049	(0.1)
Ca	0.020	(0.1)	0.035	(0.1)	0.000	(0.0)
Mg	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Mn	0.000	(0.0)	0.005	(0.1)	0.000	(0.0)
Tot.	23.902	(99.0)	23.712	(99.6)	23.926	(99.1)

	22		23		24	
Si	0.069	(0.2)	0.000	(0.0)	0.035	(0.1)
Fe ⁺²	7.964	(30.8)	7.996	(31.4)	7.980	(30.7)
Fe ⁺³	15.909	(68.4)	15.989	(69.8)	15.955	(68.2)
Al	0.022	(0.1)	0.010	(0.0)	0.009	(0.0)
Ca	0.000	(0.0)	0.000	(0.0)	0.001	(0.0)
Mg	0.002	(0.0)	0.002	(0.0)	0.002	(0.0)
Mn	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Tot.	23.966	(99.5)	23.997	(101.2)	23.982	(99.0)

	25		26		27	
Si	0.000	(0.0)	1.430	(4.9)	1.363	(4.7)
Fe ⁺²	7.965	(30.8)	7.204	(29.5)	7.204	(29.8)
Fe ⁺³	15.994	(68.8)	14.387	(65.5)	14.505	(66.6)
Al	0.006	(0.0)	0.148	(0.4)	0.098	(0.3)
Ca	0.000	(0.0)	0.068	(0.2)	0.066	(0.2)
Mg	0.022	(0.1)	0.064	(0.2)	0.079	(0.2)
Mn	0.013	(0.1)	0.000	(0.0)	0.019	(0.1)
Tot.	24.000	(59.8)	23.301	(100.7)	23.334	(101.9)

	28		29		30	
Si	1.346	(4.6)	1.432	(4.8)	0.017	(0.1)
Fe ⁺²	7.152	(29.1)	7.173	(29.0)	7.963	(30.5)
Fe ⁺³	14.523	(65.7)	14.418	(64.8)	15.981	(68.1)
Al	0.094	(0.3)	0.117	(0.3)	0.001	(0.0)
Ca	0.074	(0.2)	0.067	(0.2)	0.000	(0.0)
Mg	0.139	(0.3)	0.086	(0.2)	0.029	(0.1)
Mn	0.017	(0.1)	0.008	(0.0)	0.000	(0.0)
Tot.	23.345	(100.3)	23.301	(99.3)	23.991	(98.8)

	31		32		33	
Si	0.000	(0.0)	0.000	(0.0)	1.336	(4.6)
Fe ⁺²	7.998	(30.8)	7.982	(30.7)	7.033	(28.8)
Fe ⁺³	15.993	(68.5)	15.997	(68.5)	14.450	(65.8)
Al	0.007	(0.0)	0.000	(0.0)	0.115	(0.3)
Ca	0.000	(0.0)	0.005	(0.0)	0.198	(0.6)
Mg	0.002	(0.0)	0.000	(0.0)	0.236	(0.5)
Mn	0.000	(0.0)	0.017	(0.1)	0.013	(0.1)
Tot.	24.000	(99.3)	24.001	(99.3)	23.381	(100.7)

	34		35		36	
Si	1.323	(4.5)	1.103	(3.7)	0.000	(0.0)
Fe ⁺²	7.088	(28.6)	7.242	(29.1)	7.941	(30.9)
Fe ⁺³	14.490	(64.9)	14.700	(65.6)	15.968	(67.0)
Al	0.098	(0.3)	0.109	(0.3)	0.008	(0.0)
Ca	0.178	(0.6)	0.174	(0.5)	0.048	(0.2)
Mg	0.206	(0.5)	0.152	(0.3)	0.043	(0.1)
Mn	0.000	(0.0)	0.010	(0.0)	0.003	(0.0)
Tot.	23.383	(99.4)	23.490	(99.5)	24.011	(98.2)

	37		38		39	
Si	0.491	(1.6)	0.050	(0.2)	0.002	(0.0)
Fe ⁺²	7.529	(29.5)	7.942	(30.8)	7.964	(31.1)
Fe ⁺³	15.479	(67.4)	15.911	(68.5)	15.990	(69.4)
Al	0.003	(0.0)	0.019	(0.1)	0.000	(0.0)
Ca	0.048	(0.2)	0.040	(0.1)	0.015	(0.1)
Mg	0.173	(0.4)	0.000	(0.0)	0.031	(0.1)
Mn	0.039	(0.2)	0.023	(0.1)	0.000	(0.0)
Tot.	23.762	(99.3)	23.985	(99.8)	24.002	(100.7)

	40		41		42	
Si	0.010	(0.0)	1.512	(5.2)	0.789	(2.7)
Fe ⁺²	7.980	(31.1)	6.873	(28.1)	7.569	(30.6)
Fe ⁺³	15.970	(69.1)	14.124	(64.2)	15.177	(68.2)
Al	0.003	(0.0)	0.208	(0.6)	0.025	(0.1)
Ca	0.013	(0.0)	0.196	(0.6)	0.015	(0.1)
Mg	0.000	(0.0)	0.311	(0.7)	0.024	(0.1)
Mn	0.007	(0.0)	0.000	(0.0)	0.008	(0.0)
Tot.	23.983	(100.2)	23.224	(99.4)	23.607	(101.8)

	43		44		45	
Si	0.057	(0.2)	1.554	(5.3)	1.848	(6.5)
Fe ⁺²	7.904	(31.1)	6.861	(28.0)	6.627	(27.8)
Fe ⁺³	15.887	(69.7)	14.046	(63.6)	13.804	(64.2)
Al	0.005	(0.0)	0.255	(0.7)	0.186	(0.6)
Ca	0.036	(0.1)	0.203	(0.7)	0.277	(0.9)
Mg	0.038	(0.1)	0.305	(0.7)	0.369	(0.9)
Mn	0.024	(0.1)	0.001	(0.0)	0.000	(0.0)
Tot.	23.951	(101.3)	22.925	(99.0)	23.111	(100.9)

	46		47		48	
Si	0.014	(0.1)	1.064	(3.6)	1.054	(3.6)
Fe ⁺²	7.990	(31.3)	7.338	(30.0)	7.455	(30.6)
Fe ⁺³	15.927	(68.5)	14.868	(66.6)	14.911	(66.1)
Al	0.043	(0.1)	0.044	(0.1)	0.010	(0.0)
Ca	0.000	(0.0)	0.046	(0.2)	0.048	(0.2)
Mg	0.000	(0.0)	0.118	(0.3)	0.006	(0.0)
Mn	0.017	(0.1)	0.000	(0.0)	0.000	(0.0)
Tot.	23.981	(100.1)	23.478	(100.8)	23.484	(100.5)

	49		50		51	
Si	0.693	(2.4)	0.039	(0.1)	0.803	(2.7)
Fe ⁺²	7.570	(30.9)	7.938	(31.3)	7.494	(30.4)
Fe ⁺³	15.266	(67.3)	15.914	(68.8)	15.102	(67.0)
Al	0.009	(0.0)	0.000	(0.0)	0.054	(0.2)
Ca	0.033	(0.1)	0.013	(0.0)	0.078	(0.3)
Mg	0.066	(0.2)	0.000	(0.0)	0.077	(0.2)
Mn	0.007	(0.0)	0.036	(0.1)	0.007	(0.0)
Tot.	23.644	(100.9)	23.940	(100.3)	23.615	(100.8)

	52		53		54	
Si	0.976	(3.3)	1.619	(5.7)	1.596	(5.6)
Fe ⁺²	7.497	(30.7)	7.095	(30.1)	7.156	(30.1)
Fe ⁺³	14.949	(66.0)	14.021	(63.0)	14.069	(63.8)
Al	0.007	(0.0)	0.257	(0.8)	0.249	(0.7)
Ca	0.012	(0.0)	0.112	(0.4)	0.081	(0.3)
Mg	0.017	(0.0)	0.064	(0.2)	0.020	(0.1)
Mn	0.000	(0.0)	0.023	(0.1)	0.016	(0.1)
Tot.	23.458	(100.0)	23.191	(100.3)	23.187	(100.7)

	55		56		57	
Si	1.626	(5.7)	0.061	(0.2)	0.646	(2.2)
Fe ⁺²	7.122	(29.9)	7.918	(31.4)	7.669	(31.0)
Fe ⁺³	14.089	(63.7)	15.899	(68.2)	15.273	(67.5)
Al	0.187	(0.6)	0.013	(0.0)	0.059	(0.2)
Ca	0.100	(0.3)	0.021	(0.1)	0.020	(0.1)
Mg	0.028	(0.1)	0.016	(0.0)	0.000	(0.0)
Mn	0.000	(0.0)	0.021	(0.1)	0.000	(0.0)
Tot.	23.152	(100.3)	23.949	(100.0)	23.667	(101.0)

	58		59		60	
Si	0.040	(0.1)	1.377	(4.7)	0.110	(0.4)
Fe ⁺²	7.970	(31.7)	7.292	(29.9)	7.934	(31.3)
Fe ⁺³	15.958	(68.4)	14.093	(64.1)	15.836	(69.5)
Al	0.000	(0.0)	0.391	(1.1)	0.029	(0.1)
Ca	0.000	(0.0)	0.111	(0.4)	0.000	(0.0)
Mg	0.010	(0.0)	0.000	(0.0)	0.000	(0.0)
Mn	0.000	(0.0)	0.000	(0.0)	0.015	(0.1)
Tot.	23.978	(100.2)	23.264	(99.2)	23.924	(101.4)

	61		62		63	
Si	0.000	(0.0)	1.361	(4.6)	1.343	(4.5)
Fe ⁺²	7.987	(31.1)	7.294	(29.6)	7.043	(28.0)
Fe ⁺³	15.980	(69.1)	14.146	(63.8)	14.247	(63.9)
Al	0.011	(0.0)	0.442	(1.3)	0.251	(0.7)
Ca	0.000	(0.0)	0.000	(0.0)	0.295	(0.9)
Mg	0.008	(0.0)	0.000	(0.0)	0.214	(0.5)
Mn	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Tot.	23.986	(100.2)	23.243	(99.3)	23.393	(98.5)

	64		65		66	
Si	1.345	(4.5)	0.149	(0.5)	1.954	(6.7)
Fe ⁺²	7.079	(28.1)	7.866	(30.1)	6.571	(27.0)
Fe ⁺³	14.222	(63.9)	15.809	(68.2)	13.737	(62.7)
Al	0.232	(0.7)	0.008	(0.0)	0.136	(0.4)
Ca	0.322	(1.0)	0.032	(0.1)	0.313	(1.0)
Mg	0.172	(0.4)	0.044	(0.1)	0.358	(0.8)
Mn	0.000	(0.0)	0.010	(0.0)	0.016	(0.1)
Tot.	23.372	(98.6)	23.918	(99.0)	23.085	(98.7)

	67		68		69	
Si	0.415	(1.4)	1.547	(5.2)	1.277	(4.2)
Fe ⁺²	7.723	(30.1)	6.940	(27.8)	7.179	(28.3)
Fe ⁺³	15.491	(67.1)	13.903	(63.0)	14.434	(64.3)
Al	0.046	(0.1)	0.254	(0.7)	0.149	(0.4)
Ca	0.047	(0.1)	0.366	(1.2)	0.241	(0.7)
Mg	0.050	(0.1)	0.197	(0.4)	0.111	(0.3)
Mn	0.000	(0.0)	0.000	(0.0)	0.002	(0.0)
Tot.	23.772	(98.9)	23.207	(98.3)	23.393	(98.2)

	70		71		72	
Si	0.449	(1.4)	0.395	(1.3)	1.392	(4.6)
Fe ⁺²	7.770	(29.8)	7.748	(30.5)	7.170	(28.5)
Fe ⁺³	15.538	(67.2)	15.548	(68.1)	14.379	(64.4)
Al	0.000	(0.0)	0.013	(0.0)	0.163	(0.5)
Ca	0.007	(0.0)	0.025	(0.1)	0.089	(0.3)
Mg	0.000	(0.0)	0.029	(0.1)	0.080	(0.2)
Mn	0.000	(0.0)	0.033	(0.1)	0.025	(0.1)
Tot.	23.764	(98.4)	23.791	(100.2)	23.298	(98.6)

	73		74		75	
Si	1.743	(5.9)	0.176	(0.6)	0.184	(0.6)
Fe ⁺²	7.045	(28.7)	7.907	(30.0)	7.839	(29.8)
Fe ⁺³	14.074	(63.6)	15.792	(68.7)	15.807	(68.7)
Al	0.135	(0.4)	0.011	(0.0)	0.000	(0.0)
Ca	0.058	(0.2)	0.021	(0.6)	0.016	(0.1)
Mg	0.041	(0.1)	0.000	(0.0)	0.035	(0.1)
Mn	0.018	(0.1)	0.000	(0.0)	0.030	(0.1)
Tot.	23.114	(99.0)	23.907	(99.9)	23.911	(99.4)

	76		77		78	
Si	0.511	(1.7)	3.043	(10.8)	0.921	(3.1)
Fe ⁺²	7.736	(29.9)	6.469	(27.4)	7.525	(29.8)
Fe ⁺³	15.445	(67.3)	12.907	(60.9)	14.955	(65.9)
Al	0.001	(0.0)	0.003	(0.0)	0.101	(0.3)
Ca	0.000	(0.0)	0.023	(0.1)	0.038	(0.1)
Mg	0.000	(0.0)	0.002	(0.0)	0.000	(0.0)
Mn	0.014	(0.1)	0.003	(0.0)	0.004	(0.0)
Tot.	23.707	(99.0)	22.450	(99.2)	23.544	(99.2)

	79		80		81	
Si	0.740	(2.4)	0.599	(1.9)	0.765	(2.6)
Fe ⁺²	7.595	(29.4)	7.662	(29.7)	7.259	(30.2)
Fe ⁺³	15.207	(67.4)	15.299	(67.8)	14.026	(65.2)
Al	0.021	(0.1)	0.039	(0.1)	0.192	(0.5)
Ca	0.001	(0.0)	0.034	(0.1)	0.072	(0.2)
Mg	0.000	(0.0)	0.021	(0.1)	0.000	(0.0)
Mn	0.030	(0.1)	0.000	(0.0)	0.000	(0.0)
Tot.	23.594	(99.4)	23.654	(99.7)	23.688	(100.0)

	82		83		84	
Si	1.364	(4.8)	0.088	(0.3)	1.859	(6.6)
Fe ⁺²	7.259	(30.4)	7.897	(31.1)	6.630	(28.0)
Fe ⁺³	14.026	(65.2)	15.870	(69.4)	13.736	(64.5)
Al	0.449	(1.3)	0.013	(0.0)	0.364	(1.1)
Ca	0.117	(0.4)	0.011	(0.0)	0.033	(0.1)
Mg	0.027	(0.0)	0.035	(0.1)	0.412	(1.0)
Mn	0.000	(0.0)	0.019	(0.1)	0.023	(0.1)
Tot.	23.481	(99.9)	23.986	(99.9)	23.102	(98.0)

	85		86		87	
Si	0.519	(1.7)	0.800	(2.7)	0.185	(0.6)
Fe ⁺²	7.714	(30.5)	7.654	(31.2)	7.895	(31.4)
Fe ⁺³	15.185	(66.7)	14.654	(66.3)	15.772	(69.7)
Al	0.147	(0.4)	0.275	(0.8)	0.019	(0.1)
Ca	0.042	(0.1)	0.020	(0.1)	0.001	(0.0)
Mg	0.000	(0.0)	0.040	(0.1)	0.014	(0.0)
Mn	0.009	(0.0)	0.000	(0.0)	0.000	(0.0)
Tot.	23.102	(100.0)	23.672	(99.8)	23.921	(99.9)

	98		89		90	
Si	0.246	(0.8)	0.000	(0.0)	0.791	(2.6)
Fe ⁺²	8.816	(31.4)	7.896	(30.3)	8.733	(34.1)
Fe ⁺³	15.507	(66.1)	16.000	(68.1)	14.420	(62.5)
Al	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Ca	0.060	(0.2)	0.104	(0.3)	0.056	(0.2)
Mg	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Mn	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Tot.	23.999	(98.5)	24.000	(98.7)	24.000	(99.4)

	91		92		93	
Si	0.238	(0.8)	0.263	(0.8)	0.899	(2.9)
Fe ⁺²	8.237	(31.5)	8.263	(31.6)	8.820	(33.8)
Fe ⁺³	15.524	(65.9)	15.474	(65.7)	14.201	(60.5)
Al	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Ca	0.000	(0.0)	0.000	(0.0)	0.080	(0.2)
Mg	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Mn	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Tot.	23.999	(98.1)	24.000	(98.1)	24.000	(97.4)

	94		95		96	
Si	0.815	(2.6)	0.905	(2.9)	0.298	(1.0)
Fe ⁺²	8.753	(33.6)	8.846	(33.6)	8.299	(31.6)
Fe ⁺³	14.368	(61.4)	14.191	(59.8)	15.403	(65.3)
Al	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Ca	0.063	(0.2)	0.057	(0.2)	0.000	(0.0)
Mg	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Mn	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Tot.	23.999	(97.8)	23.999	(96.4)	24.000	(97.9)

	97		98		99	
Si	0.217	(0.7)	0.193	(0.6)	0.687	(2.2)
Fe ⁺²	8.217	(31.2)	8.116	(30.7)	8.620	(32.8)
Fe ⁺³	15.566	(65.7)	15.516	(65.7)	14.625	(61.9)
Al	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Ca	0.000	(0.0)	0.074	(0.2)	0.067	(0.2)
Mg	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Mn	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Tot.	24.000	(97.6)	23.999	(97.2)	23.999	(97.1)

	100		101		102	
Si	0.947	(3.0)	0.641	(2.1)	1.016	(3.3)
Fe ⁺²	8.818	(33.9)	8.510	(32.6)	8.830	(33.8)
Fe ⁺³	14.107	(60.2)	14.719	(62.6)	13.969	(59.4)
Al	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Ca	0.127	(0.4)	0.131	(0.4)	0.184	(0.6)
Mg	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Mn	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Tot.	23.999	(97.4)	24.001	(97.6)	23.999	(96.9)

	103		104		105	
Si	1.092	(3.4)	0.793	(2.5)	0.231	(0.7)
Fe ⁺²	8.885	(33.1)	8.717	(33.4)	7.921	(30.4)
Fe ⁺³	13.817	(57.2)	14.413	(61.3)	15.538	(66.2)
Al	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Ca	0.206	(0.6)	0.077	(0.2)	0.050	(0.2)
Mg	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Mn	0.000	(0.0)	0.000	(0.0)	0.000	(0.0)
Tot.	24.000	(94.3)	24.000	(97.5)	24.000	(98.0)

	106		107	
Si	0.263	(0.9)	0.248	(0.8)
Fe ⁺²	8.262	(32.0)	8.248	(31.1)
Fe ⁺³	15.359	(66.0)	15.504	(64.9)
Al	0.117	(0.3)	0.000	(0.0)
Ca	0.000	(0.0)	0.000	(0.0)
Mg	0.000	(0.0)	0.000	(0.0)
Mn	0.000	(0.0)	0.000	(0.0)
Tot.	24.001	(99.2)	24.000	(96.8)

Appendix 4
Electron microprobe analyses of silicate minerals

Chlorite analyses

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	1		2		3	
Si	5.398	(23.6)	5.463	(24.1)	5.135	(22.4)
Fe	7.265	(37.9)	7.286	(38.5)	8.637	(45.1)
Al	5.332	(19.8)	5.110	(19.2)	5.572	(20.7)
Ca	0.003	(0.0)	0.005	(0.0)	0.000	(0.0)
Mg	1.820	(5.3)	1.735	(6.0)	0.675	(2.0)
Mn	0.103	(0.5)	0.078	(0.4)	0.050	(0.3)
Na	0.000	(0.0)	0.037	(0.1)	0.000	(0.0)
K	0.000	(0.0)	0.005	(0.0)	0.000	(0.0)
Cr	0.000	(0.0)	0.008	(0.0)	0.000	(0.0)
Ti	0.007	(0.0)	0.000	(0.0)	0.006	(0.0)
H ₂ O		(11.5)		(10.6)		(10.5)
Tot.	19.929	(98.6)	19.999	(98.9)	20.038	(101.0)
	4		5		6	
Si	5.157	(22.4)	5.256	(22.5)	5.442	(23.4)
Fe	8.450	(44.0)	7.971	(40.8)	7.934	(40.9)
Al	5.635	(20.8)	5.109	(18.6)	5.043	(18.4)
Ca	0.000	(0.0)	--	--	--	--
Mg	0.689	(2.0)	1.722	(5.0)	1.616	(4.7)
Mn	0.081	(0.4)	0.132	(0.7)	--	--
Na	0.008	(0.0)	--	--	--	--
K	0.001	(0.0)	--	--	--	--
Cr	0.002	(0.0)	--	--	--	--
Ti	0.003	(0.0)	--	--	--	--
H ₂ O		(10.4)				
Tot.	20.026	(100.1)	20.190	(87.6)	20.036	(87.4)
	7		8		9	
Si	5.339	(22.9)	5.690	(25.9)	5.798	(25.4)
Fe	7.948	(40.7)	7.507	(40.8)	7.783	(40.8)
Al	5.035	(18.3)	5.006	(19.3)	4.524	(16.8)
Ca	--	--	--	--	0.252	(1.0)
Mg	1.658	(4.8)	1.605	(4.9)	1.582	(4.7)
Mn	0.096	(0.5)	--	--	--	--
Na	--	--	--	--	--	--
K	--	--	--	--	--	--
Cr	--	--	--	--	--	--
Ti	0.034	(0.2)	--	--	--	--
H ₂ O						
Tot.	20.109	(87.3)	19.808	(91.0)	19.940	(88.7)

	10		11		12	
Si	5.214	(22.8)	5.175	(22.6)	5.188	(22.9)
Fe	8.054	(42.1)	8.154	(42.6)	7.937	(41.9)
Al	5.312	(19.7)	5.311	(19.7)	5.388	(20.2)
Ca	0.042	(0.2)	0.035	(0.1)	0.034	(0.1)
Mg	1.507	(4.4)	1.494	(4.4)	1.588	(4.7)
Mn	--	--	--	--	--	--
Na	--	--	--	--	--	--
K	--	--	--	--	--	--
Cr	--	--	--	--	--	--
Ti	--	--	--	--	--	--
H ₂ O	--	--	--	--	--	--
Tot.	20.130	(89.1)	20.169	(89.5)	20.135	(89.9)

	13		14	
Si	5.146	(22.4)	5.220	(23.1)
Fe	8.155	(42.5)	7.959	(42.0)
Al	5.425	(20.0)	5.417	(20.3)
Ca	--	--	0.035	(0.1)
Mg	1.415	(4.1)	1.440	(4.3)
Mn	--	--	--	--
Na	--	--	--	--
K	--	--	--	--
Cr	--	--	--	--
Ti	--	--	--	--
H ₂ O	--	--	--	--
Tot.	20.141	(89.0)	20.071	(89.8)

Epidote analyses

	1		2	
Si	6.091	(38.1)	6.023	(38.2)
Fe	1.857	(15.4)	1.683	(14.2)
Al	4.133	(21.9)	4.428	(23.8)
Ca	3.789	(22.1)	3.670	(21.7)
Mg	0.000	(0.0)	0.008	(0.0)
Mn	0.038	(0.3)	0.027	(0.2)
Na	0.012	(0.0)	0.014	(0.0)
K	0.000	(0.0)	0.003	(0.0)
Cr	0.001	(0.0)	0.006	(0.1)
Ti	0.000	(0.0)	0.033	(0.3)
H ₂ O		(1.9)		(1.9)
Tot.	15.920	(99.7)	15.892	(100.4)

Garnet analyses

	1		2	
Si	6.054	(36.1)	6.062	(35.8)
Fe ²⁺	0.034	(0.2)	0.007	(0.1)
Fe ³⁺	3.737	(29.6)	3.822	(30.0)
Al	0.212	(1.1)	0.116	(0.6)
Ca	5.841	(32.5)	5.917	(32.6)
Mg	0.032	(0.1)	0.004	(0.0)
Mn	0.036	(0.3)	0.021	(0.2)
Na	0.011	(0.0)	0.008	(0.0)
K	0.002	(0.0)	0.000	(0.0)
Cr	0.003	(0.0)	0.007	(0.1)
Ti	0.005	(0.0)	0.002	(0.0)
Tot.	15.969	(100.0)	15.966	(99.2)

Greenalite analyses

	1		2	
Si	2.120	(35.3)	2.133	(35.9)
Fe	2.575	(51.2)	2.577	(51.9)
Al	--	--	--	--
Ca	0.031	(0.5)	0.036	(0.6)
Mg	0.133	(1.5)	0.117	(1.3)
Mn	0.067	(1.3)	0.042	(0.8)
Na	--	--	--	--
K	--	--	--	--
Cr	--	--	--	--
Ti	--	--	--	--
Cl	0.090	(0.7)	0.072	(0.6)
Tot.	5.015	(90.4)	4.975	(91.0)

Stilpnomelane analyses

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	1		2		3	
Si	7.425	(45.4)	7.378	(45.5)	8.104	(45.8)
Fe	5.075	(37.1)	5.027	(37.1)	4.308	(29.1)
Al	0.858	(4.5)	0.891	(4.7)	1.044	(5.0)
Ca	0.044	(0.3)	0.025	(0.1)	0.019	(0.1)
Mg	0.492	(2.0)	0.580	(2.4)	1.485	(5.6)
Mn	--	--	--	--	0.066	(0.4)
Na	--	--	--	--	0.138	(0.4)
K	0.553	(2.7)	0.611	(3.0)	0.562	(2.5)
Cr	--	--	--	--	--	--
Ti	--	--	--	--	--	--
Cl	0.048	(0.1)	0.060	(0.2)	0.004	(0.0)
H ₂ O	--	--	--	--	--	(10.2)
Tot.	14.495	(92.1)	14.572	(92.9)	15.721	(99.1)

	4		5	
Si	8.161	(46.8)	8.100	(47.0)
Fe	4.270	(29.3)	4.389	(30.4)
Al	1.024	(5.0)	1.029	(5.1)
Ca	0.020	(0.1)	0.017	(0.1)
Mg	1.396	(5.4)	1.429	(5.6)
Mn	0.081	(0.6)	0.059	(0.4)
Na	0.197	(0.6)	0.176	(0.5)
K	0.553	(2.5)	0.549	(2.5)
Cr	--	--	--	--
Ti	--	--	--	--
Cl	0.015	(0.1)	0.023	(0.1)
H ₂ O	--	(10.2)	--	(10.3)
Tot.	15.702	(100.5)	15.748	(102.0)

Appendix 5
Analyses of ferroactinolite

Amphibole sample 1

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			Fe ⁺²	15-NK	15-K	13-CNK	AV(2+4)
SiO ₂	48.80	TSi	7.643	7.598	7.523	7.503	7.551
TiO ₂	0.00	TAl	0.357	0.386	0.382	0.381	0.383
Al ₂ O ₃	2.10	TFe ⁺³	0.000	0.016	0.095	0.116	0.066
Cr ₂ O ₃	0.00	TTi	0.000	0.000	0.000	0.000	0.000
FeO	29.50	SUM IN T	8.000	8.000	8.000	8.000	8.000
MnO	0.30	CAl	0.031	0.000	0.000	0.000	0.000
MgO	5.60	CCr	0.000	0.000	0.000	0.000	0.000
CaO	11.00	CFe ⁺³	0.000	0.251	0.627	0.723	0.487
Na ₂ O	0.50	CTi	0.000	0.000	0.000	0.000	0.000
K ₂ O	0.00	CMg	1.307	1.300	1.287	1.283	1.291
Cl	0.00	CFe ⁺²	3.662	3.450	3.081	2.955	3.202
F	0.00	CMn	0.000	0.000	0.006	0.039	0.020
Total	97.80	CCa	0.000	0.000	0.000	0.000	0.000
		SUM IN C	5.000	5.000	5.000	5.000	5.000
		BMg	0.000	0.000	0.000	0.000	0.000
		BFe ⁺²	0.202	0.125	0.000	0.000	0.063
		BMn	0.040	0.040	0.034	0.000	0.020
		BCa	1.758	1.835	1.187	1.812	1.824
		BNa	0.000	0.000	0.149	0.149	0.075
		SUM IN B	2.000	2.000	2.000	1.961	1.981
		ACa	0.088	0.000	0.000	0.000	0.000
		ANa	0.152	0.151	0.000	0.000	0.075
		AK	0.000	0.000	0.000	0.000	0.000
		SUM IN A	0.239	0.151	0.000	0.000	0.075
		CCl	0.000	0.000	0.000	0.000	0.000
		CF	0.000	0.000	0.000	0.000	0.000
		SUM CATS	15.239	15.151	15.000	14.961	15.056
		SUM OXY	23.000	23.000	23.000	23.000	23.000

METHOD	GROUP	NAME
Fe ⁺²	Calcic	Ferro-actinolite
15-NK	Calcic	Ferro-actinolite
15-K	Calcic	Ferro-actinolite
13-CNK	Calcic	Ferro-actinolite
AVG (2+4)	Calcic	Ferro-actinolite

Amphibole sample 2

			Fe ⁺²	15-NK	15-K	13-CNK	AV(2+4)
SiO ₂	52.80	TSi	8.106	8.197	8.180	8.132	8.164
TiO ₂	0.00	TAl	0.000	0.000	0.000	0.000	0.000
Al ₂ O ₃	0.50	TFe ⁺³	0.000	0.000	0.000	0.000	0.000
Cr ₂ O ₃	0.00	TTi	0.000	0.000	0.000	0.000	0.000
FeO	27.70	SUM IN T	8.106	8.197	8.180	8.132	8.164
MnO	0.30	CAl	0.091	0.092	0.091	0.091	0.091
MgO	5.10	CCr	0.000	0.000	0.000	0.000	0.000
CaO	11.40	CFe ⁺³	0.000	0.000	0.000	0.000	0.000
Na ₂ O	0.10	CTi	0.000	0.000	0.000	0.000	0.000
K ₂ O	0.00	CMg	1.167	1.180	1.178	1.171	1.175
Cl	0.00	CFe ⁺²	3.556	3.596	3.589	3.568	3.582
F	0.00	CMn	0.039	0.039	0.039	0.039	0.039
Total	97.90	CCa	0.147	0.093	0.103	0.132	0.112
		SUM IN C	5.000	5.000	5.000	5.000	5.000
		BMg	0.000	0.000	0.000	0.000	0.000
		BFe ⁺²	0.000	0.000	0.000	0.000	0.000
		BMn	0.000	0.000	0.000	0.000	0.000
		BCa	1.728	1.803	1.790	1.750	1.777
		BNa	0.030	0.030	0.030	0.030	0.030
		SUM IN B	1.758	1.834	1.820	1.779	1.806
		ACa	0.000	0.000	0.000	0.000	0.000
		ANa	0.000	0.000	0.000	0.000	0.000
		AK	0.000	0.000	0.000	0.000	0.000
		SUM IN A	0.000	0.000	0.000	0.000	0.000
		CCl	0.000	0.000	0.000	0.000	0.000
		CF	0.000	0.000	0.000	0.000	0.000
		SUM CATS	14.864	15.030	15.000	14.911	14.971
		SUM OXY	23.000	23.257	23.211	23.073	23.165

METHOD

GROUP

NAME

Fe ⁺²	Calcic
15-NK	Calcic
15-K	Calcic
13-CNK	Calcic
AVG (2+4)	Calcic

Amphibole sample 3

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			Fe ⁺²	15-NK	15-K	13-CNK	AV(2+4)
SiO ₂	50.00	TSi	7.814	7.763	7.748	7.741	7.752
TiO ₂	0.00	TAl	0.147	0.147	0.146	0.146	0.146
Al ₂ O ₃	0.80	TFe ⁺³	0.000	0.090	0.106	0.113	0.102
Cr ₂ O ₃	0.00	TTi	0.000	0.000	0.000	0.000	0.000
FeO	27.60	SUM IN T	7.961	8.000	8.000	8.000	8.000
MnO	0.30	CAI	0.000	0.000	0.000	0.000	0.000
MgO	6.50	CCr	0.000	0.000	0.000	0.000	0.000
CaO	11.80	CFe ⁺³	0.000	0.207	0.283	0.314	0.260
Na ₂ O	0.10	CTi	0.000	0.000	0.000	0.000	0.000
K ₂ O	0.00	CMg	1.514	1.504	1.501	1.500	1.502
Cl	0.00	CFe ⁺²	3.486	3.287	3.188	3.147	3.217
F	0.00	CMn	0.000	0.003	0.029	0.039	0.021
Total	97.10	CCa	0.000	0.000	0.000	0.000	0.000
		SUM IN C	5.000	5.000	5.000	5.000	5.000
		BMg	0.000	0.000	0.000	0.000	0.000
		BFe ⁺²	0.121	0.000	0.000	0.000	0.000
		BMn	0.040	0.037	0.011	0.000	0.018
		BCa	1.839	1.963	1.959	1.958	1.960
		BNa	0.000	0.000	0.030	0.030	0.015
		SUM IN B	2.000	2.000	2.000	1.988	1.994
		ACa	0.137	0.000	0.000	0.000	0.000
		ANa	0.030	0.030	0.000	0.000	0.015
		AK	0.000	0.000	0.000	0.000	0.000
		SUM IN A	0.167	0.030	0.000	0.000	0.015
		CCl	0.000	0.000	0.000	0.000	0.000
		CF	0.000	0.000	0.000	0.000	0.000
		SUM CATS	15.128	15.030	15.000	14.988	15.009
		SUM OXY	23.000	23.000	23.000	23.000	23.000

METHOD

GROUP

NAME

Fe ⁺²	Calcic	Ferroactinolite
15-NK	Calcic	Ferroactinolite
15-K	Calcic	Ferroactinolite
13-CNK	Calcic	Ferroactinolite
AVG(2+4)	Calcic	Ferroactinolite

Amphibole sample 4

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			Fe ⁺²	15-NK	15-K	13-CNK	AV(2+4)
SiO ₂	49.30	TSi	7.826	7.776	7.745	7.773	7.774
TiO ₂	0.00	TAl	0.094	0.093	0.093	0.093	0.093
Al ₂ O ₃	0.50	TFe ⁺³	0.000	0.131	0.163	0.134	0.133
Cr ₂ O ₃	0.00	TTi	0.000	0.000	0.000	0.000	0.000
FeO	29.70	SUM IN T	7.920	8.000	8.000	8.000	8.000
MnO	0.50	CAl	0.000	0.000	0.000	0.000	0.000
MgO	4.90	CCr	0.000	0.000	0.000	0.000	0.000
CaO	11.80	CFe ⁺³	0.000	0.163	0.316	0.179	0.171
Na ₂ O	0.20	CTi	0.000	0.000	0.000	0.000	0.000
K ₂ O	0.00	CMg	1.159	1.152	1.147	1.151	1.152
Cl	0.00	CFe ⁺²	3.841	3.624	3.423	3.603	3.613
F	0.00	CMn	0.000	0.061	0.067	0.067	0.064
Total	96.90	CCa	0.000	0.000	0.047	0.000	0.000
		SUM IN C	5.000	5.000	5.000	5.000	5.000
		BMg	0.000	0.000	0.000	0.000	0.000
		BFe ⁺²	0.102	0.000	0.000	0.000	0.000
		BMn	0.067	0.006	0.000	0.000	0.003
		BCa	1.830	1.994	1.939	1.993	1.994
		BNa	0.000	0.000	0.061	0.007	0.003
		SUM IN B	2.000	2.000	2.000	2.000	2.000
		ACa	0.177	0.000	0.000	0.000	0.000
		ANa	0.062	0.061	0.000	0.055	0.058
		AK	0.000	0.000	0.000	0.000	0.000
		SUM IN A	0.238	0.061	0.000	0.055	0.058
		CCl	0.000	0.000	0.000	0.000	0.000
		CF	0.000	0.000	0.000	0.000	0.000
		SUM CATS	15.158	15.061	15.000	15.055	15.058
		SUM OXY	23.000	23.000	23.000	23.000	23.000

METHOD	GROUP	NAME
Fe ⁺²	Calcic	Ferroactinolite
15-NK	Calcic	Ferroactinolite
15-K	Calcic	Ferroactinolite
13-CNK	Calcic	Ferroactinolite
AVG(2+4)	Calcic	Ferroactinolite

Amphibole sample 5

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			Fe ²⁺	15-NK	15-K	13-CNK	AV(2+4)
SiO ₂	52.90	TSi	7.991	8.036	8.004	7.977	8.006
TiO ₂	0.00	TAl	0.009	0.000	0.000	0.023	0.011
Al ₂ O ₃	0.70	TFe ³⁺	0.000	0.000	0.000	0.000	0.000
Cr ₂ O ₃	0.00	TTi	0.000	0.000	0.000	0.000	0.000
FeO	23.80	SUM IN T	8.000	8.036	8.004	8.000	8.018
MnO	0.60	CAl	0.116	0.125	0.125	0.102	0.113
MgO	8.10	CCr	0.000	0.000	0.000	0.000	0.000
CaO	11.70	CFe ³⁺	0.000	0.000	0.000	0.082	0.041
Na ₂ O	0.20	CTi	0.000	0.000	0.000	0.000	0.000
K ₂ O	0.00	CMg	1.824	1.834	1.827	1.820	1.827
Cl	0.00	CFe ²⁺	3.007	3.024	3.012	2.919	2.972
F	0.00	CMn	0.053	0.017	0.037	0.077	0.047
Total	98.00	CCa	0.000	0.000	0.000	0.000	0.000
		SUM IN C	5.000	5.000	5.000	5.000	5.000
		BMg	0.000	0.000	0.000	0.000	0.000
		BFe ²⁺	0.000	0.000	0.000	0.000	0.000
		BMn	0.023	0.060	0.040	0.000	0.030
		BCa	1.894	1.904	1.897	1.890	1.897
		BNa	0.059	0.036	0.059	0.058	0.047
		SUM IN B	1.976	2.000	1.996	1.949	1.974
		ACa	0.000	0.000	0.000	0.000	0.000
		ANa	0.000	0.023	0.000	0.000	0.012
		AK	0.000	0.000	0.000	0.000	0.000
		SUM IN A	0.000	0.023	0.000	0.000	0.012
		CCl	0.000	0.000	0.000	0.000	0.000
		CF	0.000	0.000	0.000	0.000	0.000
		SUM CATS	14.976	15.059	15.000	14.949	15.004
		SUM OXY	23.000	23.128	23.037	23.000	23.064

METHOD	GROUP	NAME
Fe ²⁺	Calcic	Ferroactinolite
15-NK	Calcic	
15-K	Calcic	
13-CNK	Calcic	Ferroactinolite
AV(2+4)	Calcic	

Appendix 6
Petrographic analyses of thin sections

Section	Ccp	Mag	Po	Cht	And	Au	Act	Stp	Ilv	Gre	Qtz	Cal	Other
A-660-1		x		x							x		
AN-10-8-1	x	x	x	x	x		x						
AN-9B-9		x	x	x			x						
AN-84-3		x		x							x	x	
AN-190-1		x		x				x					Ilm
AN-95		x	x	x				x					
AN-75		x		x							x		
AN-26R-1		x		x							x		
AN-7B-5	x	x	x	x									Mak
AN-6A-4	x	x	x	x							x	x	
6A-4140-1	x	x	x	x		x					x		Mak, Sph
AN 10-8-2	x	x	x	x	x		x	x	x		x		
AN-10-12-1	x	x	x	x	x		x		x		x	x	
AN-10-12-2	x	x	x	x	x		x						
7B-3-1	x	x	x	x		x	x						
7B-3-2	x	x	x	x				x				x	
A-460-1	x	x	x	x							x	x	Sph
A-9-MT-4	x	x	x	x							x		Ilm
A-9-MT-B	x	x	x	x		x					x		Sph
A-9C-1	x	x	x				x	x			x	x	
AN-9C-3	x	x	x	x			x				x	x	
AN-9C-5	x	x	x	x			x	x				x	
A-411-2	x	x		x				x			x		Ilm
A-411-1	x	x	x	x				x			x		Ilm
A-114		x		x							x	x	
A-9-MT-2	x	x	x	x			x	x					
A-446-2	x	x	x	x							x		Ilm
A-446-4	x	x		x							x		
A-9-MT-6	x	x	x	x			x				x		
A-9-MT-A	x	x	x	x				x			x		
A-9-MT-3	x	x	x	x				x			x		Fsp
A-194		x	x	x				x			x	x	
A-77	x	x	x	x				x			x		
AN-7B-2	x		x	x			x				x	x	Sph
A-467	x	x	x								x		Ser
A-460-2	x	x	x	x							x		Sph
A-446-1	x	x		x							x	x	Py
A-446-3		x		x							x	Py,	Ilm
AN-8-1	x	x		x						x	x	x	

39025E

39050E

39075E

39100E

46615N

46600N

46575N

46550N

SUB7BP.DWG
-ascale 500

FAIRCHILD
DIVISION I AC BUREAU
ANSEL
SUBS 7B 7B

Drawn By	Date	Rev
10/15/78	10/15/78	1

21 of/de 2

FM 1 3/4"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISIONSM RESOLUTION TARGETS

PIONEERS IN METHYLENE BLUE TESTING SINCE 1974

1800 COUNTY ROAD 6, BURNVILLE, NH 03033 USA
TEL: 603-485-7857 FAX: 603-485-7857 TLA: P0000000

46575N

46575

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MINNOVA Inc.

DIVISION LAC DUFALT

ANSIL

NIVEAU 9

DESSINE PAR	DATE 01/06/90	NO. DE DESSIN
APPROUVE PAR	ECHELLE 1 : 500	REV.

46450

46525N

46575N

46550N

46525N

46500N

46475N

MINNOVA Inc.

DIVISION LAC DUFALT

ANSIL

SOUS-NIVEAU 9B

SUB9BP.DWG
-scale 500

DESINE PAR	DATE	NO. DE DESSIN
	31/05/90	
APPROVE PAR	EDITION	REV.
	1 - 500

46575N

46550N

46525N

46500N

MINNOVA Inc.

DIVISION LAC DUFALT

ANSIL

SOUS-NIVEAU 9C

SUB9CP.DWG
-scale 500

DESSEINE PAR	DATE	N° DE DESSIN
APProuvé PAR	01/06/90	
	ECHELLE	REV.
	1 : 500

MINNOVA Inc.

DIVISION LAC DUFALT

ANSIL

NIVEAU 10

DESSINE PAR	DATE	NO. DE DESSIN
	01/06/90	
APPROUVE PAR	ECHELLE	REV.
	1 : 500	

END

25 | 05 | 93

FIN