CHAPTER 4: ALTERATION

4.1 Introduction
Visually and mineralogically three styles of alteration have been recognized in the stratigraphy of the Fenton Creek zone including: (1) possible hanging wall Fe-Mg alteration (2) fault-related quartz-sericite alteration (3) probable hydrothermal sericite-chlorite footwall alteration. The aim of this chapter is to describe and characterise the alteration styles present in the Fenton Creek stratigraphy with focus given to the probable footwall alteration and relate these styles of alteration to those that have been described regionally and in the Snow Lake Assemblage.

4.2 Methods and Data Set
Interpretation of the alteration is based on a total of 107 samples collected by the author from section 400N through the centre of the Fenton Creek Zone (Fig. 3.4) and diamond drill hole logs completed by staff of Hudson Bay Exploration and Development Company Limited. Sample preparation involved cutting samples on a diamond saw, photographing and staining for K-feldspar using sodium cobaltinitrite. From the 107 specimens, 45 representative samples were made into polished thin sections for detailed examination. The results of the examinations of hand samples and thin sections were then used in conjunction with geologic logs to characterise the alteration of the Fenton Creek zone. Diamond drillhole Har043 has been used to illustrate the various types of alteration since it cross-cuts all of the major lithologies from the hanging wall into the footwall and has been adequately sampled.

4.3 Previous Investigations
The metamorphic grade in the Fenton Creek region ranges from upper amphibolite, which complicates the recognition and discrimination hydrothermal alteration from regional metamorphism. Original diamond drillhole logging and geochemistry indicates possible alteration in the footwall and a larger zone of alteration occurring well into the hanging wall (Gilmore et al., 1999). The minerals comprising this alteration include K-feldspar, epidote, sillimanite, garnet, cordierite and muscovite (Gilmore et
al., 1999). Though many of the metamorphic minerals may indicate previously hydrothermally-altered volcanic/volcanioclastsic rocks, they are not exclusive to metamorphosed hydrothermal alteration and may simply reflect the metamorphosed primary composition of the precursor lithology.

Previous work on samples from the immediate footwall of drillhole Har023 (345.7m) by Harris (1998) and Wells (2000) indicate that the rocks contain quartz, cordierite, K-feldspar, muscovite, fuchsite and trace base metal sulphides. This association of minerals is interpreted to be a good indicator for massive sulphide mineralisation (Wells, 2000).

4.4 Regional Alteration

Regionally three styles of hydrothermal alteration related to volcanism and synvolcanic tonalite intrusions have been recognized in the Snow Lake Assemblage: (1.) Discordant (pipe-like) (2.) Semi-conformable (3.) Intrusive related alteration. (Galley et al., 1991; Galley and Franklin, 1991; Galley, 1993; Kraus and Williams, 1999). The mineralogy of the discordant pipe-like alteration is characterised by sericitized peripheries and chloritized cores, but also includes Fe-Mg metasomatism, silicification/albitization, and minor epidotization and pyritization (Galley et al., 1991). The mineralogy of the semi-conformable alteration is characterised by two main groups: (1.) zones of pervasive replacement by quartz and epidote and (2.) zones of chlorite and amphibole replacement (Galley and Bailes, 1993). A third poorly understood type of local semi-conformable amphibole +/- sulphide alteration has been observed within immediate hanging wall to some of the VHMS deposits (Bailes and Galley, 1991). Alteration in the subvolcanic intrusions consists of zones of disseminated chalcopyrite-pyrrhotite; fracture controlled epidote-quartz-hematite, chlorite-biotite-magnetite and chlorite-aluminosilicate alteration. This style of alteration has been noted by Walford and Franklin (1982) and Bailes and Galley (1991) within the Sneath Lake Pluton as close as 200 m from the Anderson, Stall and Rod deposits. Unlike the alteration styles in the Snow Lake assemblage no pipe-like alteration has been recognized in the Fenton Creek stratigraphy (Gilmore et al., 1999). However, three styles of alteration have been recognized in the Fenton Creek stratigraphy consisting of: (1) possible hangingwall calc-silicate alteration (2) alteration associated with hydrothermal fluids along faults and fractures (3) stratiform footwall alteration related to hydrothermal fluids generated during the formation of volcanic hosted massive sulphide deposits (Fig. 4.1).
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Interpreted Geology:
- Muskeg
- Dolomite
- Sandstone/regolith
- Granitic pegmatite
- Granitic intrusion
- Garnet-sillimanite schist
- Clinopyroxene-scapolite carbonate schist
- Quartz-biotite-sillimanite schist
- Garnet-graphite metasediment
- Biotite-amphibole-plagioclase schist
- Amphibole-clinoxyroxene-plagioclase schist
- Ore lense
- Quartz-muscovite-sillimanite schist

Figure 4.1 - Distribution of alteration
Section 400N showing the general locations of the 1. Fault-related alteration 2. Hangingwall alteration and 3. Footwall alteration observed in the Fenton Creek stratigraphy.
4.5 Hanging wall alteration

Original diamond drillhole logging indicates numerous patchy zones of calc-silicate, cordierite, sillimanite and garnet alteration that occur well into the hanging wall stratigraphy (Gilmore et al., 1999). These zones occur 40-60m into the hanging wall and range from 1 to >50m in apparent thickness and do not appear to correlate across or between sections with consistency.

In hand specimen the logged alteration varies dependent on the host rock. In the basic volcanic rocks the alteration occurs as green to light green, mottled bands of plagioclase, clinopyroxene +/- sphene (Figs. 4.2A and 4.2C). In the acid volcanic rocks of the hanging wall the logged alteration consists of bands of quartz, cordierite, biotite +/- garnet which occur in varying thicknesses from 0.25 to 1cm (Figs. 4.2E and Fig.4.2F).

In thin section the alteration in the basic volcanic rocks is an equigranular mosaic of 30-45% clinopyroxene, 40-50% plagioclase, 3-5% quartz, 3-5% biotite. Accessory minerals include 3-5% sphene occurring as sub-rounded to subangular blebs and 1-5% pyrrhotite and trace chalcopyrite (Figs. 4.2B and Fig.4.2D).

Determination as to the origin of this logged alteration whether, it is a result of metamorphism, metasomatism or hydrothermal processes is difficult to assess due to the high metamorphic grade. Visually the hanging wall rocks due appear to be altered, however, there is no geochemical support to indicate that this alteration has involved significant mass changes (Chapter 5). The observed alteration may be a result of metamorphism of a rock having a variable precursor composition or might reflect rocks which were H₂O rich versus H₂O poor during metamorphism. In any case this style of alteration does not appear to be related to the hydrothermal footwall alteration as evident by Figure 4.4A and 4.4B, which shows the inferred hydrothermal alteration does not extend into the hanging wall rocks. Further study is required to more confidently interpret the hanging wall alteration.

4.6 Fault-related alteration

The fault-related alteration occurs within and in close proximity to faults both in the upper hanging wall near the garnet-graphite metasediment and in the footwall to the ore position (Fig. 4.1). The zones vary in size from less than 1 meter to greater than 3 meters.
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Figure 4.2 - Hanging wall alteration

A) Clinopyroxene(Cpx)-plagioclase(Plag) schist originally logged as epidote altered metagreywacke. Sample 75503H drillhole Har010 (89.60m).

B) Previous plate showing coarse grained mosaic of plagioclase(Plag) and clinopyroxene(Cpx) (1.25x magnification, crossed nichols).

C) Biotite(Biot)-clinopyroxene(Cpx)-plagioclase(Plag) schist originally logged as calc-silicate altered greywacke. Sample H25862 drillhole Har043 (319.7m).

D) Previous plate showing coarse grained mosaic of plagioclase(Plag), clinopyroxene(Cpx) and sphene (1.25x magnification, crossed nichols).

E) Quartz(Qtz)-biotite(Biot)-sillimanite(Sill) schist (identified geochemically) originally logged as cordierite, biotite, sillimanite +/ - garnet alteration. Sample F70403 drillhole Har021 (174.7m).

F) Quartz(Qtz)-biotite(Biot)-cordierite(Cord) schist (identified geochemically) originally logged as metagreywacke reminiscent of cordierite, biotite, sillimanite +/- garnet alteration. Sample F70406 drillhole Har021 (250.8m).
In drill core the faults are often characterised by a bleached and Fe-oxide stained appearance and are sometimes marked by clay gouge. (Figs. 4.3A and 4.3B) In hand specimen fault alteration in the acid volcanic rocks is characterised by k-feldspar-sillimanite, which is highlighted when the sample is stained (Fig. 4.3C). This alteration is also seen in small veins and fractures where staining shows K-feldspar concentrated along the vein and as diffuse halos penetrating the host rocks (Fig. 4.3F).

In thin section the altered samples contain subhedral grains of K-feldspar, sillimanite knots, phlogopitic biotite +/- pyrrhotite occurring as fracture fill which may have been deposited during a later reactivation event (Figs. 4.3D, 4.3E and 4.3G).

It is interpreted that the fault alteration may have been quartz-sericite +/- pyrite that has been metamorphosed to K-feldspar and sillimanite by the following reaction:

\[
\text{muscovite + quartz} \rightarrow \text{K-feldspar + sillimanite + melt}
\]

### 4.7 Ore zone and footwall alteration

Diamond drillhole logging indicates numerous zones of K-feldspar, sillimanite, muscovite +/- garnet, cordierite and anthophyllite in the ore zone and footwall of the Fenton Creek deposit. These zones of alteration occur as patchy stratiform bodies ranging in apparent thickness from 2 to +40m thick (including the ore position) and are interpreted to have resulted from hydrothermal alteration associated with the formation of the massive sulphide lenses.

In hand specimen it is often difficult to tell altered samples from unaltered samples without K-feldspar staining and/or detailed assessment of the mineralogy making note of the modal percentages of K-feldspar, sillimanite, muscovite, cordierite, garnet and anthophyllite. Though any one of the previously listed minerals taken by themselves do not indicate alteration, samples with high aluminous minerals and significant K-feldspar +/- disseminated base metals may indicate hydrothermal alteration (Wells, 2000). The observed mineralogy in conjunction with mass balance calculations and alteration indices (Chapter 5) suggests that the footwall and ore position has been subjected to weak sericite +/- chlorite hydrothermal alteration prior to high-grade metamorphism. The following reactions define the expected mineralogy following the high grade metamorphism of a chloritic and sericitic alteration zone.
Figure 4.3 - Fault and fracture related alteration

A) Fault zone from Har044-130m showing Fe-oxide staining and clay fault gouge.
B) Fault zone from Har044-133.5m showing Fe-oxide staining and sillimanite(Sill) knots.
C) Stained specimen from previous plate showing pervasive K-feldspar distribution Sample H25877 drillhole Har044 (134.5m).
D) Previous plate showing sillimanite(Sill) and phlogopitic biotite (Biot). Sample H25877 (2.5x magnification, crossed nicols).
E) Previous plate showing phlogopitic biotite(Biot)-sillimanite(Sill) and fracture filled pyrrhotite(Po). Sample H25877 (5x magnification, plane light).
F) Late stage quartz(Cqtz)-K-feldspar(Kfs) vein through mottled moderately foliated quartz-biotite-sillimanite schist. Sample G35271 drillhole Har018 (86.80m).
G) Previous plate showing K-feldspar(Kfs) alteration in quartz-biotite mosaic (5x magnification, crossed nicols)
Sericite alteration
muscovite + quartz -> K-feldspar + sillimanite + melt

Chlorite alteration
chlorite + muscovite -> cordierite + biotite + quartz + H₂O

Further metamorphic reactions

biotite + sillimanite + quartz -> K-feldspar + cordierite + melt
biotite + sillimanite + quartz -> K-feldspar + garnet + melt
anthophyllite -> cordierite + cummingtonite.

Figures 4.4 and 4.5 show a series of K-feldspar stained samples and photomicrographs from diamond drillhole Har043 from the hanging wall biotite-clinopyroxene-plagioclase/amphibole-plagioclase schist, through the ore position and into the footwall quartz-muscovite-sillimanite schist. The following observations/generalisations can be made based on the samples from drillhole Har043 and additional samples in Figure 4.6:

1. Alteration is confined to the footwall and does not extend into the hanging wall stratigraphy as evident by the lack K-feldspar and aluminous minerals in samples H25864 and 75530H (Figs. 4.4A and 4.4B).
2. Alteration appears to have a lower limit of approximately 25m into the footwall from the ore position as evident by sample H25869 that shows a lack of K-feldspar and preserved plagioclase.
3. K-feldspar, sillimanite +/- muscovite are the dominant alteration minerals proximal to the massive sulphide in the ore position (Figs. 4.4C-H and Figs. 4.5K-N).
4. Alteration minerals including K-feldspar, anthophyllite, cordierite, garnet and cummingtonite are more prevalent in the close to the massive sulphide (Figs. 4.5I-J and Figs. 4.6B-F).
5. Siliceous horizons within the ore zone stratigraphy may represent silicification associated with the alteration process. The horizons are fairly non-reactive to the alteration showing only minor K-feldspar-sillimanite alteration.

Based on these observations there appears to be good evidence to support weak sericite-chlorite hydrothermal alteration in the footwall to the massive sulphide lenses of the Fenton Creek zone. If there is alteration in the immediate hanging wall it is fairly subtle and may not be identifiable without the aid of more detailed geochemistry.
Figure 4.4 Footwall Alteration

A) Amphibole(Amph)-plagioclase(Plag) schist (H25884) stained for K-feldspar and (B) Biotite(Biot)-clinopyroxene(Cpx)-plagioclase(Plag) schist (75530H) stained for K-feldspar.

C) Stained specimen of quartz(Qtz)-K-feldspar(Kfs)-muscovite(Musc)-sillimanite(Sill) schist showing the distribution of K-feldspar. D) Previous plate showing fine grained muscovite(Musc), sillimanite(Sill) and K-feldspar(Kfs). Sample 75531 (1.25x magnification, crossed nicols).

E) Stained specimen of siliceous rock showing lack of K-feldspar. (F) Previous plate showing mosaic of quartz overprinted by clinopyroxene(Cpx). Sample H25865 (2.5x magnification, crossed nicols).

G) Stained specimen of K-feldspar(Kfs)-biotite(Biot)-sillimanite(Sill) schist showing the K-feldspar distribution. (H) Previous plate showing mosaic of K-feldspar(Kfs), sillimanite(Sill) and biotite(Biot). Sample H25866 (5x magnification, crossed nicols).
Figure 4.5 Footwall Alteration

I) Semi-massive pyrrhotite (Po)-sphalerite (Sph) rich ore with strong potassic alteration of the host rock. Previous plate showing granoblastic mosaic of K-feldspar (Kfs)-biotite (Biot)-anthophyllite (Anth)-cordierite (Cord). Sample 76532 (2.5x magnification, crossed nicols).

J) Stained sample from a siliceous band showing lack of K-feldspar. Previous plate showing highly strained quartz (Qtz) with muscovite (Musc) and sillimanite (Sill) along foliation. Sample 75533H (5x magnification, crossed nicols).

K) Quartz (Qtz)-biotite (Biot)-K-feldspar (Kfs)+/- pyrrhotite (Po) schist from the footwall stained for K-feldspar. Sample H25868.

L) Previous plate except not stained for K-feldspar.
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Figure 4.6 - Ore Zone Alteration

A) Quartz(Qtz)-muscovite(Musc)-sillimanite(Sill) schist showing sillimanite grains forming after muscovite. Sample 75521H drillhole Har018 (221.7m)(5x magnification, crossed nicols).

B) Recrystallized granoblastic mosaic of K-feldspar(Kfs) +/- pyrrhotite(Po) and biotite(Biot) within the ore of the Fenton Creek zone. Sample 75532H drillhole Har021 (401.25m)(2.5x magnification, crossed nicols).

C) Garnets(Gt) with retrograde chloritoid rims from massive pyrrhotite(Po). Sample 75513H drillhole Har010 (154.08m)(1.25x magnification, crossed nicols).

D) Mineralized graphitic metapelitic showing a large anthophyllite(Anth) porphyroblast in a mosaic of quartz(Qtz), K-feldspar(Kfs) and biotite(Biot) from sample 75507H Har010 (119.6m)(1.6x magnification, plane polarized light).

E) Cummingtonite(Cum) crystals with amphibole(Amp) cleavage intergrown with K-feldspar(Kfs) and sphalerite(Sph) Sample 75513H Har010 (154.08m)(5x magnification, plane polarized light).

F) Cordierite poikiloblasts intergrown with granoblastic mosaic of quartz(Qtz), K-feldspar(Kfs) and biotite(Biot). Sample 75507H drillhole Har010 (119.6m)(1.25x magnification, crossed nicols).
4.8 Summary

Three styles of alteration have been visually and minerallogically interpreted in the Fenton Creek stratigraphy including fault related quartz-sericite alteration that occurs in and around the fault zones, stratiform hydrothermal sericite +/- chlorite footwall alteration and possibly Fe-Mg hanging wall alteration, though more study is required. Most if not all of the primary alteration mineralogy has been metamorphosed into new metamorphic minerals and original textures have been destroyed and recrystallised into granoblastic mosaics. Unlike many of the known and well studied VHMS deposits in the Snow Lake Assemblage which have discordant pipe-like hydrothermal alteration with sericitized peripheries and chloritized cores, the hydrothermal alteration in the Fenton Creek zone appears to be weak, stratiform sericite +/- chlorite alteration and is confined to the footwall.
CHAPTER 5: LITHOGEOCHEMISTRY

5.1 Introduction
The sequence of metasedimentary and metavolcanic rock hosting the Fenton Creek zone have evolved through a complex history involving deposition, suspected hydrothermal alteration, multiple deformation-faulting-folding events and overprint by upper amphibolite metamorphism.

This chapter aims to describe the lithogeochemistry and alteration geochemistry of the Fenton Creek Zone, with the goal of providing geochemical signatures to discriminate the host lithologies, the alteration types and the elemental changes that occur within the host rocks. To aid in the identification and characterisation of the host lithologies and alteration a series of lithogeochemical plots developed by (Floyd and Winchester, 1975; Barrett et al., 1993; MacLean and Barrett, 1993) and others have been applied to the geochemical samples collected from the Fenton Creek property.

5.2 Sample Preparation, Analytical Techniques and Data processing
A total of 313 geochemical samples were collected and analysed from the Fenton Creek zone. All samples were collected by Hudson Bay Exploration And Development Company employees and consisted of approximately 15-20cm whole NQ sized diamond drill core taken every 30m and/or at a major change in lithology (Wells, 2000).

The samples were sent to Act Labs in Toronto, where they were crushed with a steel jaw crusher, split and then pulverised using a chrome-steel disc mill. Analysis consisted of a combination XRF and ICP techniques for major and trace elements. Complete sample preparation and procedures are given in Appendix C.

Standards and duplicates were employed in all techniques to maintain quality control over the analyses. To check the precision of the analyses each element of interest for the duplicate samples were plotted on X-Y scatter diagram with a +/-10% error envelope. The results of this exercise indicate that most elements analysed by the ICP method fall within the +/- 10% error envelop with the exception of Ag and Co and to a lesser extent Mo and Ni that plot outside to the error margins by varying degrees. X-Y scatter diagrams for the elements analysed by XRF methods indicate that all elements with the exception
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of Nb and Y fall within a +/-10% error envelope. Complete results of the precision diagrams are given in Appendix D.

Examination of the HBED granitic geochemical standards indicate that the analyses obtained using the XRF techniques are both accurate and precise whereas, the results obtained using the ICP techniques are much more variable. This variability is likely due to incomplete/selective digestion and/or the degree of in homogeneity of the in house standard. Complete results of the standards are given in Appendix D.

As a final quality control test a scatter diagram of SiO₂ versus Cr and SiO₂ versus Cr₂O₃ were made to assess any possible contamination from the chromium-steel mill used in the sample process. The results of these plots show a general trend from high Cr in the mafic rocks (those with low SiO₂) to low Cr in the felsic rocks (those with low SiO₂), this positive correlation suggests that there was minimal contamination of the samples and therefore Cr can be used in discrimination diagrams. Geochemical scatter diagrams are given in Appendix E.

Following quality control procedures the geochemical data was inspected for analyses with values less than the detection limit and replaced with half of the detection limit. Employment of this procedure is common practice within the mineral exploration industry and has been applied to the geochemical analyses collected on the Fenton Creek property. Unprocessed geochemical analyses are given in Appendix F.

5.3 Geochemical characterisation of metavolcanics, metasediments and post kinematic intrusions.

The sequence of metavolcanic and metasedimentary rocks hosting the Fenton Creek zone have evolved through a complex history involving deposition, suspected hydrothermal alteration, multiple deformation-faulting-folding events and overprint by upper amphibolite metamorphism. This complex history has made identification of the rock units based solely on hand samples from diamond drill hole logging a difficult task. Recognition of rock units using a combined approach of lithogeochemistry and logged geology is an effective way to increase identification efficiencies.

Previous studies by Wells (2000) into the geochemical characteristic of the lithologies hosting the Fenton Creek zone utilized geochemical plots of Al₂O₃/TiO₂ (assumed relatively immobile) versus a variety of major and trace elements to divide and characterize a limited set of assumed metasedimentary samples into various groups (i.e. greywacke, siltstone,
argillite). Though this technique did have some success but it fails to address and quantify the potential original rock compositions, affinities and/or the presence/absence of hydrothermal alteration in a systematic way, information that would be very helpful in understanding and developing an exploration model for the deposit.

As early as the 1970's researchers including Cann (1970); Pearce (1973); Floyd (1975) recognized that Al, Nb, Ti, Y and Zr remain immobile during hydrothermal alteration and metamorphism up to greenschist facies.

In many VHMS districts including the Abatibi, Mount Read, and Flin Flon/Snow Lake belts, lithogeochemical studies of coherent volcanic rocks have confirmed that early observation that Al, Nb, Ti, Y and Zr remain essentially immobile during hydrothermal alteration and varying degrees of metamorphism up to middle amphibolite facies (Barrett et al., 1993; Maclean and Barrett, 1993; Barrett and Maclean, 1994; Leybourne et al., 1997) (Herrmann, 1998; Maxeiner et al., 1999).

Work by MacLean and Kranidiotis (1987) and MacLean and Barrett (1993) showed that if the suspected immobile elements are plotted against one another, samples demonstrating immobility will plot along a line which passes through the origin, with a high degree of correlation ($r^2$ = 0.90 to 0.99) for a single precursor system and can therefore, be considered related.

Application of the same techniques used for coherent volcanic rocks have proved equally effective helping to determine and characterise the providence, original composition/association and tectonic environment of volcaniclastic and/or volcanic sedimentary rocks (Lentz, 1996).

A series of immobile and immobile/mobile element plots including Zr versus TiO$_2$, Rb vs. Y/Nb, Y versus Zr/Y and LOG Ti/Zr versus LOG Cr/La have been used in conjunction with tectono-magmatic discrimination diagrams developed by Cann (1970); Pearce (1973); Floyd and Winchester (1975) to geochemically discriminate probable basic rocks, probable acid volcanic rocks, inferred metasedimentary rocks and intrusions of the Fenton Creek zone. These discrimination plots facilitate the comparison of the lithogeochemistry of the Fenton zone rocks with those from the Snow Lake Assemblage. The results of the discrimination process have been used in conjunction with geology to re-interpret the stratigraphy of the Fenton Creek zone and have been plotted along sections (Figs. 5.1, 5.2, 5.3).
Figure 5.1 Simplified diagram showing the distribution of lithogeochemical samples used with logged geology in the reconstruction of cross-section 300N (modified after data from HBED diamond drill logs Gilmore et al. 1999).
Figure 5.2 Simplified diagram showing the distribution of lithogeochemical samples used with logged geology in the reconstruction of cross-section 400N (modified after data from HBED diamond drill logs Gilmore et al. 1999).
Figure 5.3 Simplified diagram showing the distribution of lithogeochemical samples used with logged geology in the reconstruction of cross-section 500N (modified after data from HBED diamond drill logs Gilmore et al. 1999).
5.3.1 Testing for Immobile Elements

Prior to the application of discrimination diagrams based in part or wholly on immobile element it is good practice that one determines how immobile suspected immobile elements really are rather than simply assuming immobility. This is especially important if the rocks being studied have been subjected to high-grade metamorphism where elements, which are normally immobile, become mobile. To determine immobility all samples from each unit are plotted on X-Y scatter diagrams of suspected immobile elements. For coherent volcanic rocks element pairs are immobile if the samples plotted form along a linear trend with a high degree of correlation preferably through the origin (MacLean and Kranidiotis, 1987; MacLean and Barrett, 1993; Herrmann, 1998). This same technique can be applied to non-coherent rocks comprised of volcaniclastics and/or sediments provided one realises that there may be scatter of the data if the volcaniclastic/sediment has been sourced from different locations of different compositions and/or has been subjected to varying degrees of sedimentation.

Figure 5.4 shows the X-Y scatter plots for the selected geologic units within the Fenton Creek stratigraphy. The outcome of these plots indicate that little can be said about the immobility of elements within the metasediments, biotite-clinopyroxene-plagioclase and amphibole-plagioclase schists do to compositional variations. However, within the quartz-muscovite-sillimanite schist and quartz-biotite-sillimanite schist, Zr, TiO\textsubscript{2}, Al\textsubscript{2}O\textsubscript{3} + Nb appear to have remained relatively immobile as defined by the well-correlated linear trend of the samples through the origin. Nb and Y display characteristics of both immobility and mobility, however, these results are complicated by many samples plotting at/or near the analytical detection limits and/or the quality of the analytical analysis as referred to earlier in the quality control section (Appendix D).

As a result of the tests for immobility, discrimination diagrams that utilize Zr, TiO\textsubscript{2}, Al\textsubscript{2}O\textsubscript{3}, Nb and Y can be critically interpreted knowing which elements are immobile and which elements are not completely immobile. This knowledge of immobility is also required to determine which elements can be used as monitors in mass balance analysis.

5.3.2 Probable basic igneous rocks

The probable basic igneous rocks intersected in the Fenton Creek stratigraphy include the (1) clinopyroxene-scapolite-carbonate schist (2) amphibole-plagioclase schist (3) amphibolite (4) biotite-clinopyroxene-plagioclase schist. Geochemical discrimination of
Figure 5.4 X-Y Immobility scatterplots
X-Y scatter plots of possible immobile element pairs for all samples except for the granitic intrusives from the Fenton Creek stratigraphy. Note that samples from the quartz-muscovite-sillimanite schist and quartz-biotite-sillimanite schist plot along highly correlated linear trends which pass through the origin in Figures 5.10 A-C. These diagrams indicate that Zr, TiO2, Al2O3 and to a lesser extent Nb are relatively immobile in the qtz-musc-sill schist and quartz-biotite-sillimanite schist even at amphibolite/granulite grade metamorphism.
Figure 5.4 (cont) X-Y Immobility scatterplots
X-Y scatter plots of possible immobile element pairs for all samples except for the granitic intrusives from the Fenton Creek stratigraphy. Note fair amount of scatter in Y especially in the quartz-muscovite-sillimanite schist.
these probable basic units from the probable acid igneous rocks and metasediments using LOG Ti/Zr vs. LOG Cr/La and Zr versus TiO$_2$ diagrams show that rocks from these units plot in two Suites (Figs. 5.5A and 5.5B).

Suite 1 is comprised of samples from the logged biotite-clinopyroxene-plagioclase schist and amphibolite. The biotite-clinopyroxene-plagioclase schist is characterised by average SiO$_2$ = 51.70 wt%, TiO$_2$ = 1.75 wt%, MgO = 4.60, CaO = 7.86 wt%, Na$_2$O = 2.49 wt% and K$_2$O = 2.53 wt% as well as elevated values of Ni, Co, Cr, Sc and Cu relative to rocks from Suite 2. The amphibolite is characterised by average SiO$_2$ = 49.69 wt%, TiO$_2$ = 1.37 wt%, MgO = 8.24, CaO = 7.86 wt%, Na$_2$O = 3.13 wt% and K$_2$O = 1.08 wt% (Complete listing of averaged analytical results for samples from Suite 1 are in Table 5.1)

Suite 2 is comprised of samples from clinopyroxene-scapolite-carbonate schist and amphibole-plagioclase schist and characterised by average SiO$_2$ = 54.29 wt%, TiO$_2$ = 0.96 wt%, MgO = 4.92, CaO = 9.65 wt%, Na$_2$O = 2.08 wt% and K$_2$O = 1.54 wt%. (Complete listing of averaged analytical results for samples from Suite 2 are in Table 5.1)

On the LOG Ti/Zr vs. LOG Cr/La discrimination diagram Suite 1 and 2 occur in a large cluster characterised by LOG Cr/La values ranging from approximately 1.5 to 2.3 and LOG Ti/Zr values from 0.1 to 2.5. Internally within this cluster Suite 2 can be seen to have higher LOG Cr/La compared to those of suite 1 indicating a more mafic unit with elevated Cr relative to La that is confirmed by the averaged Cr values in Table 5.1. The observed scatter in the datasets is likely a result of primary compositional variation and/or mechanical fractionation during sedimentation processes (Fig 5.5A).

On the Zr versus TiO$_2$ discrimination diagram suite 1 and 2 form two distinct and separate clusters. Suite 1 has an average Ti/Zr ratio of 62 and plots almost entirely within the basaltic composition field, while suite 2 has a higher Ti/Zr ratio averaging 103 and plots both within and across the basaltic composition field into the high Ti-basalt field (Fig. 5.5B). These ratios indicate that suite 1 and 2 may be from separate sources. Suite 1 contains samples which are from a probable a basaltic source, whereas, suite 2 is likely from a higher Ti-basaltic source. As with the previous discrimination diagram the scatter of this data set likely reflects compositional variations related to sedimentation processes and/or mixing of multiple sourced detritus.

Plotting of the data on Nb/Y versus Zr/Ti tectono-magmatic discrimination diagram after Winchester and Floyd (1975) shows that suite 1 and 2 plot in the subduction related basaltic
Figure 5.5 Geochemical discrimination diagrams for all recognized units from the Fenton Creek Zone
(A) Discrimination diagram of LOG Ti/Zr versus LOG Cr/La for all geochemical samples collected from the Fenton Creek zone.
(B) Discrimination diagram of Zr versus TiO₂ (rock classification fields after data from Large et. al 1985).

Within both plots variations within the rock suites 1-3 may reflect a combination of primary compositional variations and/or mechanical fractionation through sedimentation and/or alteration processes, especially in the suite 3 samples. Variation in suites 4 & 5 are believed to be primarily a result of hydrothermal alteration.

Amph=Amphibole, Biot=Biotite, Cpx=Clinopyroxene, Musc=Muscovite, Plag=Plagioclase, Qtz=Quartz, Sill=Sillimanite
Table 5.1 - Averaged analytical results for selected rock types from the Fenton Zone.

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<th>Pegmatite</th>
<th>Metasedime</th>
<th>Amph-plag schist</th>
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composition field consistent with findings of the previous discrimination diagrams (Fig. 5.6A).

As previously discussed in the regional geology section, the Snow Lake Assemblage contains three temporally distinct basalt types including the primitive and mature arc basalts and oceanic rift basalts. These basalts can be discriminated using a Ti vs. Cr diagram developed after (Pearce, 1975). Figure 5.6B shows a Cr versus Ti discrimination diagram modified after Bailes and Galley (1999) with samples from the three basalt types recognized in the Snow Lake Assemblage and the samples of basaltic composition from the Fenton Creek zone. The Fenton Creek samples plot remarkably near to the arc rift basalts of the Snow Creek Formation. Assuming that the Ti and Cr have remained relatively immobile, the Snow Creek Formation appears to be a potential source for the basaltic sediments/volcaniclastics comprising the stratigraphy of the Fenton Creek zone.

5.3.3 Probable acid volcanic rocks

The quartz-biotite-sillimanite schist and the quartz-muscovite-sillimanite schist represent probable acid volcanic rocks. Discrimination of these probable acid volcanic units was accommodated using LOG Ti/Zr vs. LOG Cr/La and Zr versus TiO₂ diagrams which show that rocks from these units plot in two suites (Figs. 5.5A and 5.5B). Suite 4 is comprised of samples from the quartz-biotite-sillimanite schist and characterised by average SiO₂ = 73.55 wt%, TiO₂ = 0.20 wt%, MgO = 2.10, CaO = 3.10 wt%, Na₂O = 2.05 wt% and K₂O = 2.42 wt% as well as elevated values of Ba and Zr relative to rocks from suite 5. Suite 5 is comprised of samples from quartz-muscovite-sillimanite schist and characterised by average SiO₂ = 75.25 wt%, TiO₂ = 0.24 wt%, MgO = 2.11 wt%, CaO = 2.55 wt%, Na₂O = 1.89 wt% and K₂O = 1.87 wt%. The averaged analytical results for the major elements support a bulk chemistry similar to that found in rhyolitic rocks. Complete listing of averaged analytical results for samples from suite 4 and 5 are in Table 5.1

On the LOG Ti/Zr versus LOG Cr/La discrimination diagram, Suite 4 and 5 occur in two relatively tight clusters divided primarily on the Cr and La contents. Suite 4 characterised by LOG Cr/La values ranging from approximately 0.75 to 1, while suite 5 ranges from approximately 0.5 to 0.75. The LOG Ti/Zr values for both suites cover similar ranges from 0 to 1.25 (Fig. 5.5A). The observed scatter of the two suites relative to the Ti and Zr values is likely a result of alteration processes that are better recognized on a Zr versus TiO₂ discrimination plots.
Figure 5.6 Nb/Y versus Zr/Ti tectono-magmatic and Cr versus Ti discrimination diagrams for probable basic volcanic rocks.

A) Discrimination diagram of Nb/Y vs. Zr/Ti (after Winchester and Floyd, 1975) showing the samples from suite 1 and 2.

B) Discrimination diagram of Cr vs Ti (after Bailes et al, 1999) showing the comparison between three different coherent basalts from the Snow Lake Assemblage and rocks of basaltic composition from the Fenton Creek zone.

Amph=Amphibole, Biot=Biotite, Cpx=Clinopyroxene, Musc=Muscovite, Plag=Plagioclase, Qtz=Quartz, Stil=Sillimanite
On the Zr versus TiO$_2$ discrimination diagram, Suite 4 and 5 form along two distinct lines which pass through the origin. Sample from suite 4 are characterized by an average Ti/Zr ratio of 8.2, whereas suite 5 is characterized by Ti/Zr ratio averaging 5.2. These ratios indicate that suite 4 and 5 are of rhyolitic composition (Fig. 5.5B).

Plotting of the data on Nb/Y versus Zr/Ti tectono-magmatic discrimination diagram after Winchester and Floyd (1975) shows that suite 4 plots as a cluster within the subduction related rhyodacite field while samples from suite 5 plot in the subduction related rhyolite composition field, which is consistent with findings of the previous discrimination diagrams (Fig. 5.7A). The scatter in the data for both suites of rocks is likely caused by a combination of analytical error in the measurement of the Nb and Y as indicated in the quality controls of duplicate samples (see Appendix C) and/or variation in the immobility of Nb and Y.

The Snow Lake Assemblage contains two geochemically distinct rhyolite types that are known to be associated with the formation of the polymetallic Zn/Cu massive sulphide deposits. As reviewed in the regional geology chapter these rhyolites include those formed in primitive arc setting and rhyolites formed in the mature arc settings. Using a Y + Nb versus Rb tectonic discrimination diagram developed by Pearce et. al, (1984) for discrimination of granitic rocks; Bailes and Galley (1999) have discriminated the least altered rhyolites of the primitive arc from those found in the mature arc. For comparison suites 4 and 5 from the Fenton Creek zone have been plotted with the primitive and mature arc rhyolites of the Snow Lake Assemblage in Figures 5.7B and 5.8A respectively. The results of these plots indicate that the suites 4 and 5 do not appear to be related to rhyolites from either the mature arc or primitive arc settings. Many controlling factors including homogeneity of the sample, the analytical techniques, detection limits, degree of metamorphism effecting the immobility of Nb, Y, Ti, and Zr, may have contributed to results.

5.3.4 Inferred metasedimentary rocks

The inferred metasedimentary rocks intersected in the Fenton Creek stratigraphy include the garnet-sillimanite schist, graphite-garnet metapelitic and clinopyroxene-quartz-carbonate psammites. The metasediments form one large cluster that has been labelled suite 3 using LOG Ti/Zr vs. LOG Cr/La and Zr versus TiO$_2$ discrimination diagrams (Figs. 5.5A and 5.5B). The metasediments (Suite 3) occur in a range of compositions but have average SiO$_2$ = 62.01 wt%, TiO$_2$ = 0.57 wt%, MgO = 4.12 wt%, CaO = 5.57 wt%, Na$_2$O = 2.09 wt% and K$_2$O = 2.17 wt% as well as elevated values of Pb, Zn, Cu, Mo, and Ag likely the result of often
Figure 5.7 Nb/Y versus Zr/Ti tectono-magmatic and Rb versus Y/Na discrimination diagrams for probable acid volcanic rocks.

A) Discrimination diagram of Nb/Y vs. Zr/Ti (after Winchester and Floyd, 1975) showing the samples from suite 4 and 5 that plot primarily within the rhyolite and ryhodacite fields. Variation in the immobile element ratios may reflect the high metamorphic grade especially in Nb and Y which appear to be slightly mobile.

B) Discrimination diagram of Y/Nb versus Rb (after Bailes et al, 1999) showing the comparison between the primitive rhyolite of the Snow Lake Assemblage plotted with the rhyolitic schists from the Fenton Creek zone. Caution must be used when interpreting the results of this diagram due to the questionable degree of mobility in Nb and Y from the Fenton Creek samples.

Amph=Amphibole, Biot=Biotite, Cpx=Clinopyroxene, Musc=Muscovite, Plag=Plagioclase, Qtz=Quartz, Sill=Sillimanite
being in close proximity to the ore horizon. Complete listing of averaged analytical results for samples from Suite 3 are in Table 5.1.

On the LOG Ti/Zr vs. LOG Cr/La discrimination diagram the metasediments (Suite 3) occur in a large cluster spanning a range LOG Cr/La ratios ranging from 0.1 to 1.5; however, the bulk of the samples plot with LOG Cr/La values of approximately 1.1 nearer to the rocks of Suite 4 and 5 rather than the probable basic rocks of Suite 1 and 2 (Fig 5.5A). The range in compositions may indicate that the sediments are from more than one source rock and/or have been sorted at some stage in the sedimentation process. During the maturation of sediment, resistant minerals like zircon and quartz may be concentrated while softer minerals like Fe-Ti-oxides, sphene, and chromite may be depleted which may explain some of the scatter in the plotted data.

On the Zr versus TiO$_2$ discrimination diagram the metasediments occur in a field between Suites 1 and 2 and Suites 4 and 5. The Ti/Zr ratios averages 23, and range in composition between dacite and andesite (Fig. 5.5B).

Excluding some of the extreme outliers the samples appear to form a trend of decreasing TiO$_2$ while increasing Zr. This might indicate magmatic fractionation of the source volcanic and/or mechanical fraction consistent with variably mineralogically mature sediment. Harker variation diagrams of SiO$_2$ versus Al$_2$O$_3$ and to a lesser extent SiO$_2$ versus Zr originally designed to show the maturity of a sandstone suggest that the sediments comprising Suite 3 may have been subjected to mechanical fractionation, although the systematics in discrimination sediments is fairly complex, even more so if the sediments have been subjected to high-grade metamorphism which can make oxides like SiO$_2$ fairly mobile (Figs. 5.8B and 5.9A).

Plotting of the data on Nb/Y versus Zr/Ti tectono-magmatic discrimination diagram indicate that Suite 3 plots in a loose cluster covering dacitic, andesitic and basaltic compositions in the subduction related portions of the plot (Fig. 5.9B). However, as with previous interpretations made from this diagram primary compositional variation and the assumption of immobility of the plotted elements must take into account.

5.3.5 Post kinematic granitic intrusions

Three types of granitic intrusion have been identified in the Fenton Creek stratigraphy including aplite, pegmatite and granite. Unlike the identification of the metasediments and metavolcanics, the granitic intrusions are easily identified by the fresh undeformed/
Chapter 5 - Lithogeochemistry

Figure 5.8 Rb versus Y/Nb discrimination diagram for probable acid volcanic rocks and SiO₂ versus Al₂O₃ Harker variation diagram from metasediments from the Fenton Creek zone.

A) Discrimination diagram of Y/Nb versus Rb developed by Pearce et al., 1984 and modified after Bailes et al., 1999 showing the comparison between the mature rhyolites of the Snow Lake Assemblage plotted with the rhyolitic schists from the Fenton Creek zone. As with the previous diagram caution must be exercised when interpreting the results of this diagram due to the mobility in Nb and Y from the Fenton Creek samples.

B) Harker variation diagram of SiO₂ versus Al₂O₃ used to determine the mineral maturity of sediment. As the sediment matures quartz (SiO₂) increases due to its resist properties while softer less stable minerals like feldspar (Al₂O₃) breakdown causing a decrease in Al₂O₃. Interpretation dependant on SiO₂ remaining immobile.

Amph=Amphibole, Biot=Biotite, Cpx=Clinopyroxene, Musc=Muscovite, Plag=Plagioclase, Qtz=Quartz, Sill=Sillimanite
Figure 5.9 Harker variation diagram of SiO$_2$ versus Zr and Nb/Y versus Zr/Ti tectono-magmatic discrimination diagrams for metasediments from the Fenton Creek zone.

A) Harker variation diagram of SiO$_2$ versus Zr used to determine the mineral maturity of sediment. Plotting of the metasediments from the Fenton Creek zone indicate complicated systematics of potentially more than one source rock. Interpretation based of SiO$_2$ remaining immobile.

B) Discrimination diagram of Nb/Y vs. Zr/Ti (after Winchester and Floyd, 1975) showing samples from metasediments that plot in a loose cluster in dacite/andesite/basalt subduction related fields. Variation in the immobile element ratios may be a result of sedimentation and/or reflect the high metamorphic grade especially in Nb and Y which appear to be slightly mobile.

Amph=Amphibole, Biot=Biotite, Cpx=Clinopyroxene, Musc=Muscovite, Plag=Plagioclase, Qtz=Quartz, Sill=Sillimanite.
metamorphosed textures. The granite range in composition but have average SiO₂ = 71.27 wt%, TiO₂ = 0.16 wt%, MgO = 1.22 wt%, CaO = 2.47 wt%, Na₂O = 3.20 wt% and K₂O = 4.64 wt% and no elevated base or precious metal values. The aplite and pegmatite have similar compositions that are slightly different from the granite. The aplite has averaged SiO₂ = 73.33 wt%, TiO₂ = 0.15 wt%, MgO = 0.82 wt%, CaO = 1.02 wt%, Na₂O = 2.69 wt% and K₂O = 4.74 wt% while the pegmatites have average SiO₂ = 73.23 wt%, TiO₂ = 0.15 wt%, MgO = 0.73 wt%, CaO = 1.77 wt%, Na₂O = 3.03 wt% and K₂O = 4.31 wt%. Complete listing of averaged analytical results for samples from granite, aplite and pegmatite are in Table 5.1.

Two main synvolcanic intrusive complexes have identified in the Snow Lake Assemblage including the Sneath Lake tonalite in the Primitive Arc sequence and the Richard Lake tonalite in the Mature Arc sequence. Work by Bailes and Galley (1999) has discriminated these intrusions using Y + Nb versus Rb tectonic discrimination diagram developed by Pearce (1984). Plotting the Fenton Creek intrusive rocks on the Y + Nb versus Rb tectonic discrimination diagram with the primitive arc intrusions (Sneath Lake) (Fig. 5.1 OA) and the mature arc intrusions (Richard Lake) (Fig 5.1 OB) shows that all of the Fenton Creek intrusions plot in volcanic arc granites field. The majority of the samples plot in a fairly tight field that appears unrelated to the primitive and mature arc synvolcanic intrusions. A few samples of granite and pegmatite do plot outside the main cluster in fields defined by the primitive and mature intrusions. These samples may represent intrusions related to those in the Snow Lake Assemblage or may simply be samples that have been mis-logged and require further investigation.

5.4 Mass balance analysis

Lithogeochemistry and more particularly immobile elements have proved very useful for the discrimination and classification of rocks within the Fenton Creek stratigraphy that have become visibly unrecognisable due to metamorphism and/or alteration. Immobile elements can also be used to estimate the elemental mass changes in the rocks that have been subjected to hydrothermal alteration. Numerous methods and techniques including Gresens Analysis (Gresens, 1967), Pearce Element Ratios (Pearce, 1976), Huston's Isocon method (modified Gresens Analysis)(Huston et al., 1992) and Maclean and Kranidiotis single precursor method (MacLean and Kranidiotis, 1987) have been developed utilizing immobile
Figure 5.10 Rb versus Y/Nb discrimination diagrams for primitive and mature arc granitic intrusions of the Snow Lake Assemblage plotted with Fenton Creek granitic intrusive rocks.

A) Discrimination diagram of Y/Nb versus Rb developed by Pearce et al., 1984 and modified after Bailes et al., 1999 showing the comparison between the primitive arc intrusions (Sneath Lake) of the Snow Lake Assemblage plotted with the granitic rocks from the Fenton Creek zone.

B) Discrimination diagram of Y/Nb versus Rb developed by Pearce et al., 1984 and modified after Bailes et al., 1999 showing the comparison between the mature arc intrusions (Richard Lake) of the Snow Lake Assemblage plotted with the granitic rocks from the Fenton Creek zone.

Amph=Amphibole, Biot=Biotite, Cpx=Clinopyroxene, Musc=Muscovite, Plag=Plagioclase, Qtz=Quartz, Sill=Stillimanite
elements as monitors of mass transfer in volcanic rocks which have been subjected to hydrothermal alteration. This study has chosen to use the single precursor method developed by Maclean and Kranidiotis (1987) to quantify the mass changes in the quartz-muscovite-sillimanite schist (footwall) and quartz-biotite-sillimanite schist (hangingwall), which are thought to have been subjected to variable amounts of hydrothermal alteration.

5.4.1 Methodology and treatment of data

The single precursor method developed Maclean and Kranidiotis (1987) consists of 6 steps which involve (1) Determine the immobile elements (2) Verify that the volcanic units are from a single precursor and not from a multiple precursor system (3) Inspecting data for outliers (4) Determine a least altered composition (5) Calculate the absolute mass change (6) Plot bar graphs for visual comparison of mass changes.

Immobile Elements

As determined previously in section 5.3.1 Zr, Ti, Al + Nb have been shown to be suitable immobile monitors for use in mass balance calculations. From the plots in Figure 5.4 the Zr versus TiO$_2$ and Zr versus Al$_2$O$_3$ displayed the best immobility with $r^2 = 0.939$ and 0.974 within the quartz-muscovite-sillimanite schist and $r^2 = 0.977$ and 0.983 in the quartz-biotite-sillimanite schist respectively, therefore, Zr has been chosen as the immobile element monitor.

Volcanic Units and Inspection

The inferred volcanic units within the Fenton Creek stratigraphy include the quartz-muscovite-sillimanite schist, quartz-biotite-sillimanite schist, biotite-clinopyroxene-plagioclase schist and the amphibole-plagioclase schist. Of these units only the quartz-muscovite-sillimanite schist and quartz-biotite-sillimanite schist demonstrate that they had a similar precursor composition as indicated by their well correlated linear trends through the origin (Fig. 5.4A-D) Both the biotite-clinopyroxene-plagioclase schist and the amphibole-plagioclase schist plot as clusters in Figures 5.4A-D suggesting that their primary compositions were not the same. This variation in the primary compositions makes samples from these suites unsuitable for mass balance calculations. For simplicity the rocks of these system will be treated as being from a single precursor system.

Inspection of the data from quartz-muscovite-sillimanite schist and quartz-biotite-sillimanite schist indicated that there were no outlier samples that could justifiably be removed.
Determination of least altered samples

In coherent unmetamorphosed volcanic rocks least altered samples are chosen based on the following criteria after Paradis et. al. (in publication): (1) samples are chosen from the same volcanic complex or flow (2) samples should contain preserved primary volcanic textures and show little to no evidence of alteration both in hand specimen and at the microscopic level (3) least altered sample should not be deformed to avoid structurally induced volume changes.

Due to the high-grade upper amphibolite metamorphism, uncertain protolith, and limited hand specimens of the quartz-muscovite-sillimanite schist and quartz-biotite-sillimanite schist, many of the traditional criteria used to determine a least altered sample cannot be applied. Failing the use of these criteria the following modified criteria were used to pick least altered samples from the Fenton Creek quartz-muscovite-sillimanite schist and quartz-biotite-sillimanite schist:

1. Least altered samples chosen from hand specimens collected along section 400N.
2. Samples chosen as far away from the ore position as possible.
3. Samples chosen away from known faults.
4. Samples chosen with the least amount of visual alteration including sillimanite, garnet and K-feldspar.
5. Ishikawa Alteration Index between 20-60, which represents least altered rocks (Large et al., 2001).

Based on the modified criteria the composition of sample G35276 was chosen as a least altered sample for the quartz-muscovite-sillimanite schist and the averaged composition of samples H25853 and H25883 were used as a least altered sample for the quartz-biotite-sillimanite schist.

5.4.2 Results of mass balance calculations

The results of the mass balance calculations indicate that there have been minor mass gains and losses of various elements in the quartz-muscovite-sillimanite schist (footwall) and quartz-biotite-sillimanite schist (hanging wall). Bar graphs of the mass balance calculation have been generated to visibly illustrate mass gains and losses. Figure 5.11 shows the mass changes for an averaged composition of samples from section 400N while Figure 5.12 shows the mass changes for an averaged composition including all samples from the deposit.
Chapter 5 - Lithogeochemistry

Figure 5.11 Relative and absolute mass gains and losses of major and trace elements, as calculated by the Maclean and Kranidiotis (1987) method for the qtz-biot-sill schist and qtz-musc-sill schist of the Fenton Creek stratigraphy.

A) Relative and absolute mass gains and losses of major and trace elements for averaged composition of quartz-biotite-sillimanite schist samples collected from selected drillholes along section 400N from the Fenton Creek stratigraphy.

B) Relative and absolute mass gains and losses of major and trace elements for averaged composition of quartz-muscovite-sillimanite schist samples collected from selected drillholes along section 400N from the Fenton Creek stratigraphy.
Figure 5.12 Relative and absolute mass gains and losses of major and trace elements, as calculated by the Maclean and Kranidiotis (1987) method for the Qtz-Bt-Sil schist and Qtz-Musc-Sil schist of the Fenton Creek stratigraphy.

A) Relative and absolute mass gains and losses of major and trace elements for averaged composition of all quartz-biotite-sillimanite schist samples from the Fenton Creek Stratigraphy.

B) Relative and absolute mass gains and losses of major and trace elements for averaged composition of all quartz-muscovite-sillimanite schist samples from the Fenton Creek Stratigraphy.
In general the absolute mass changes observed in all the volcanic rocks of the Fenton Creek zone are relatively small and very subtle. Mass balance calculations using an average composition from samples along section 400N show an absolute mass depletion of Si (-5g/100g), Al (-1.25g/100g) and Na (-1.25g/100g) in the hanging wall quartz-biotite-sillimanite schist with no significant mass gains. The relative mass changes show an increase in Cu, Pb, Zn and a depletion of Na, Sb and Mo; however, these changes are very small and probably do not represent any significant changes to the mass of the system (Fig. 5.11A). Similar results are seen using the entire data set of quartz-biotite-sillimanite schist samples from all sections with Si (-6.7g/100g), Al (-1.5 g/100g) and Na (1.1 g/100g) and relative mass changes showing an increase in Cu, and Pb +/- Zn and a depletion of Na, Sb and Mo (Fig. 5.12A).

In the footwall mass balance calculations using an average composition from samples along section 400N show an absolute mass depletion of Si (-7.8g/100g), Al (-0.5g/100g) and Na (-0.8g/100g) and an enrichment of Ca (+1.8g/100g) and Mg (0.5g/100g). The relative mass changes show an increase in Mn, Mg, Ca, Cu, Ag, W, Co and Sc and a depletion of Na, P, Y Cr Ni, and Mo. As with the mass changes seen in the hanging wall, these changes with the exception of silica and possibly calcium are very small (Fig. 5.11B). Mass balance results using the entire data set of quartz-muscovite-sillimanite schist samples from all sections with Si (-8.3g/100g), Al (-1 g/100g) and Na (0.8 g/100g) and relative mass changes showing an increase in Mn, Mg, Ca, K, Cu, Co and Sc and a depletion of Na, P, Y and Cr (Fig. 5.12B).

5.5 Down hole plots

Down hole geochemical plots combined with geological logs can be an effective tool to visually correlate geology, alteration and lithogeochemical pathfinder elements relative to the ore position. Successful application of this technique requires consistent regular sampling of all units in the stratigraphy both above and below the ore position. To illustrate the use of this technique diamond drill hole Har043 was chosen since it intersects most of the stratigraphy previously reviewed in the local geology and has been sampled on a fairly regular interval (Figs 5.13 to 5.15).

5.5.1 Footwall

In diamond drill hole Har043 the footwall is characterised by three geochemical samples which have SiO₂ = 60-73 wt%, TiO₂ = 0.2-0.5 wt%, K₂O = 0.6-3.8 wt%, Na₂O = 1.2-3.9 wt%,
CaO = 2-10 wt% and MgO 1.7-2.9 wt% and are consistent with the logged quartz-muscovite-sillimanite and quartz-biotite-sillimanite schist. Alteration in the footwall is represented by the gradual increase in K₂O and the decrease in the Na₂O towards the ore position (Fig. 5.13A). Metal values in the footwall consist of Fe₂O₃ = 1.3-6 wt%, Cu = 11-73 ppm, Zn = 34-47 ppm, Pb = 1-39 ppm, Co = 3-14 ppm and Ni = 4-33 ppm. Most of the metal values indicate a variable increase towards the ore position, however Cu shows the most uniform trend (Fig. 5.13B). Various alteration indices were plotted including:

Ishikawa Alteration index (Ishikawa et al., 1976)
\[ AI = 100(MgO + K₂O)/(MgO + K₂O + Na₂O + CaO) \]

Chlorite-carbonate-pyrite index (Large et al., 2001)
\[ CCPI = 100(FeO + MgO)/(FeO + MgO + K₂O + Na₂O) \]

Spitz Index (Spitz and Darling, 1975)
\[ SPITZ = Al₂O₃/Na₂O \]

Goodfellow's alteration index (Goodfellow, 1975)
\[ GOODFELLOW = (MgO + FeO)/(MgO + FeO + CaO + Na₂O) \]

Ishikawa and Goodfellow's alteration indexes show a reasonable increase in intensity towards the ore position, while the Spitz ratio and CCPI indices show no appreciable trend towards the ore position (5.13C).

5.5.2 Ore Zone

In diamond drill hole Har043 the ore zone is characterised by three geochemical samples which have SiO₂ = 57-71 wt%, TiO₂ = 0.2-1.3 wt%, K₂O = 1.1-5.5 wt%, Na₂O = 0.5-3.0 wt%, CaO = 1.1-5.6 wt% and MgO 2-3.5 wt%. Based on the SiO₂, TiO₂, and to a lesser degree K₂O values samples H25865 and H25867 are likely quartz-muscovite-sillimanite schist and/or metasediment while sample H25866 is more likened to the biotite-amphibole schist and semi-massive mineralisation (Fig. 5.13A). A maximum level of K₂O nearly 5.5 wt% and a minimum in the amount of Na₂O 0.5 wt% in sample H25866 is interpreted to represent the strongest alteration in the ore zone. Both CaO and MgO show little change in their levels from the footwall through the ore position. Metal values in the ore consist of Fe₂O₃ = 3-8.5 wt%, Cu = 129-1240 ppm, Zn = 93-3300 ppm, Pb = 9-237 ppm, Co = 4-27 ppm and Ni = 7-17 ppm. Metal values in the lithogeochemical samples taken near the ore zone show elevated levels in all elements above, but copper shows the most significant increases followed by zinc and lead (Fig 5.13B). In the ore zone the Spitz ratio, Ishikawa, Goodfellow's
Figure 5.13A Downhole geochemical plot of selected oxides for Har 043
Down hole geochemical plot showing oxides of SiO$_2$, TiO$_2$, K$_2$O, Na$_2$O, CaO and MgO from diamond drill hole 043. Note that geochemical analyses for the post granitic intrusions have been removed from the plot for purposes of clarity.
Figure 5.13B Downhole geochemical plot of selected metals for Har 043

Downhole geochemical plot showing base metals analysed using ICP-MS from diamond drill hole 043. Note that geochemical analyses for the post granitic intrusions have been removed from the plot for purposes of clarity.
Figure 5.13C Downhole geochemical plots of selected alteration indices for ddh Har 043.
Downhole geochemical plots from diamond drill hole 043 showing various alteration indices used to characterise the alteration in the footwall of the Fenton Creek zone. Note that geochemical analyses for the post granitic intrusions have been removed from the plot for purposes of clarity.
alteration indexes all achieve maximum values. Of the alteration indices the Ishikawa and
Goodfellow's alteration indices show the greatest increase in intensity towards in the ore
zone. The CCPI index shows no appreciable increase in the ore position (Fig. 5.13C).

5.5.3 Hanging wall

In diamond drill hole Har043 the immediate hanging wall to the ore zone, is a unit of
amphibole-plagioclase schist and biotite-clinopyroxene schist that is overlayed by a thicker
unit of quartz-biotite-sillimanite schist including a minor amphibolite and garnet-graphite
metasedimentary unit. A total of twelve geochemical samples characterise the geochemistry
of these units. The amphibole-plagioclase schist and biotite-clinopyroxene schist is
characterised by $SiO_2 = 50-63$ wt%, $TiO_2 = 0.7-1.7$ wt%, $K_2O = 0.5-1.5$ wt%, $Na_2O = 1.4-2.8$
wt%, $CaO = 2-10$ wt% and $MgO = 2-7$ wt%. The overall geochemical trend in this unit in
samples H25864 to H25862 from high to low values of $SiO_2$ and low to high values of $TiO_2$,
$CaO$ and $MgO$ may indicate mixing of source rocks and/or magmatic fractionation of
numerous flows from an andesitic through to a basaltic composition, however, further detailed
sampling of this and other holes is required to make this determination.

The quartz-biotite-sillimanite schist is characterised by $SiO_2 = 72-78$ wt%, $TiO_2 = 0.1-0.25$
wt%, $K_2O = 0.4-4.1$ wt%, $Na_2O = 0.6-3.3$ wt%, $CaO = 1-7$ wt% and $MgO = 1.4-3$ wt%. No
observable geochemical trends exist in this quartz-biotite-sillimanite schist with the exception
variations within samples collected from the amphibolite and metasedimentary units. Sample
H25855 shows high $K_2O$ values coupled with lower $Na_2O$, however, this sample is near a
recognized fault and has a high frequency of small pegmatite intrusions that may have
influenced the $K_2O$ levels.

The main amphibolite unit in the stratigraphy occurs between 240-260m and has $SiO_2$,
$TiO_2$, $K_2O$, $Na_2O$, $CaO$ and $MgO$ values similar to those found in the amphibole-plagioclase
schist and biotite-clinopyroxene schist. A minor occurrence with similar compositions occurs
at 330m.

The garnet-graphite metasediments in the stratigraphy occur both in the ore position and
in the hanging wall between 100-130m. The metasediment in the hanging wall is
characterised by two samples (H25851 and H25852) which contain $SiO_2 = 62$ wt%, $TiO_2 =
0.5$ wt%, $K_2O = 1.8-2.1$ wt%, $Na_2O = 2.5-3.2$ wt%, $CaO = 4-7$ wt% and $MgO = 2.2-2.7$ wt%.
Metal values in hanging wall strongly reflect the different lithologies present in the stratigraphy.
Overall the trends are fairly flat except in the garnet-graphite metasediment where there is
a coincident increase Fe$_2$O$_3$, Zn, Pb, Co and Ni with a corresponding depletion in Cu. In general the alteration indices are also fairly flat with most peaks and troughs reflecting the lithologies. The only noticeable increase in alteration intensity is seen in the garnet-graphitic metasediment where the Goodfellow alteration index, and to a lesser extent the Ishikawa alteration index, show small increases above the background levels.

5.6 Alteration Box Plot

Another simple but effective way of measuring the degree and types of alteration in volcanic rocks is the alteration box plot developed by Large et al. (2001). The alteration box plot is a simple graphical representation on which lithogeochemical data for altered volcanic rocks is plotted to help determine (1) Is the alteration caused by a hydrothermal system? and if so (2). Where is the ore body in relationship to the defined altered rocks? (Large et al., 2001) The method plots Ishikawa Alteration Index (AI) along the x-axis versus Chlorite-carbonate-pyrite index (CCPI) along the y-axis. The Ishikawa AI was developed to provide a measure of the intensity of chlorite and sericite alteration often observed in the footwall of VHMS deposits by ratioing the elements gained (MgO + K$_2$O) over the elements lost and gained (MgO + K$_2$O + Na$_2$O + CaO) (Large et al., 2001).

The Chlorite-carbonate-pyrite index (CCPI) was developed to measure the increase in MgO and FeO associated with Mg-Fe chlorite development commonly seen replacing albite, K-feldspar and/or sericite in the inner alteration zones of many VHMS deposits (Large et al., 2001). The CCPI index is also strongly effected by Mg-Fe carbonate alteration as well as pyrite, magnetite and/or hematite enrichments all of which are typically found in the inner alteration zones of many VHMS deposits (Large et al., 2001). However, one limiting factor to the use of the CCPI index is that it is strongly effected by magmatic fractionation and primary composition of the volcanic rocks (Large et al., 2001). Therefore, interpretations when using the box plot should be limited to comparison of volcanic rocks which have the same affinities. For a more detailed description of the alteration box plot methods and limitations see Large et al. (2001).

5.6.1 Box plot results for hanging wall and footwall rocks of the Fenton Creek volcanics

Interpretation of the box plot is best made using both lithogeochemistry and mineralogies observed in the hand samples. As a comparison Figure 5.14 shows box plots with
generalized expected trends for hydrothermally altered volcanics and expected trends from diagenetic processes as determined by the numerous case studies (Rosebery, Thalanga, Hellyer and Western Tharsis) (Large et al., 2001). These general trends are used to assist in the interpretation of the Fenton Creek hanging and footwall lithologies.

Box plot for samples from the hanging wall rhyodacite of the Fenton Creek zone (Figure 5.15) suggest that the hanging wall does not appear to have been subjected to much

A. Hydrothermal trends

B. Diagenetic trends

Figure 5.14 Box plots of diagenetic trends and hydrothermal trends from Large et al. (2001)
A. Box plot showing various common hydrothermal alteration trends VHMS deposits.
B. Box plot showing various common diagenetic alteration trends observed in VHMS deposits.
hydrothermal alteration. Samples do appear to have shifted upward to the right and down and to the left of the least altered dacite box, however, without knowing precisely what the least altered sample is it is difficult to interpret anymore for the box plot. Based on hand sample investigations this shift is likely due to pyrrhotite (formerly pyrite) which is seen throughout the samples.

The box plot for the footwall rhyolite from the Fenton Creek zone (Figure 5.16) confirm previous observations that the footwall samples appear to have been subjected to weak sericite +/- chlorite hydrothermal alteration as defined by the linear trend from least altered box to right and upper right of the diagram. Based on hand sample investigations these trends are likely due to increased pyrrhotite, K-feldspar, sericite +/- anthophyllite-cordierite towards the ore position.

Figure 5.15 Alteration box plot modified after Large et al. (2001) showing rhyodacitic volcanioclastics from the hanging wall of the Fenton Creek deposit.

Alteration box plot showing the hanging wall quartz-biotite-sillimanite schists as compared to the least altered box proposed by Large et al. (2001). Note general shift of samples up and to the right caused by increases in pyrrhotite and few samples moving towards the sericite and chlorite positions.
5.7 Summary

Lithogeochemistry has proven to be a very effective tool for discriminating the geologic units of the Fenton Creek stratigraphy. The results of the geochemical discrimination suggest that the stratigraphy of the Fenton Creek property can be divided into the following units: (1) probable acid volcanic/volcaniclastic footwall and upper hanging wall of rhyolite and rhyodacite-dacite composition respectively, (2) ore zone of mixed metasediment and/or footwall and hanging wall rocks, (3) probable basic volcanic/volcaniclastic rocks and amphibolite of basaltic composition in the lower hanging wall and (4) post kinematic granitic intrusions. Application geochemical discrimination diagrams with data from the Snow Lake Assemblage, suggest that the probable acid volcanic rocks and the post kinematic intrusions of the Fenton Creek stratigraphy are not from the same source as the rhyolite and granitic intrusions in the Snow Lake Assemblage and therefore, may be from a different source. Discrimination plots of the probable basic volcanic/volcaniclastic rocks with data from the Snow Lake Assemblage show that probable basic volcanic/volcaniclastic rocks
from the Fenton Creek stratigraphy correlated with the arc-rift basalts of the Snow Creek Formation rather than the basalts from the primitive or mature arc settings.

Mass balance calculations performed on the probable volcanic/volcaniclastic rocks of the footwall indicate that there is evidence of a mass loss in Si and Na and a mass gain Ca and K in the footwall. This mass change is also observed in the hanging wall but at to a lesser degree. These results depend very highly on the selection of a least altered precursor rock, which in the case of the Fenton Creek stratigraphy was difficult to determine due to the metamorphic grade.

Further evidence of the mass changes in the footwall and hanging wall was effectively displayed visually using a downhole geochemical plot. There is an increase in potassium and base metals including copper from the footwall towards the ore zone where samples are depleted in sodium and possible calcium. These trends correlate well with the observed geology and are interpreted to be subtle sercice footwall alteration that is also identified by increases in the Ishikawa and Goodfellow alteration indexes. Based on lithogeochemical evidence there is little to no evidence of alteration within the hanging wall rocks. As mention in Chapter 4 the visual alteration may be a result of compositional variations or rocks with different H₂O contents that have been variably metamorphosed.

Application of the alteration box plot developed by Large et al. (2001) confirms previous findings that the footwall rhyolites appear to have been subjected to weak sercite +/- chlorite alteration. The box plot of the hanging wall rhyodacites shows that there is little evidence of hydrothermal alteration however, the trends are not as clear as seen in the footwall.
6.1 Introduction

The meta-pelitic rocks in the ore zones contain variable amounts of graphite ranging from trace to a few percent. The graphite appears laterally contiguous and can be traced from hole to hole along the study section 400N. Within the Fenton Creek ore zones carbon occurs in graphite and as carbonate cement. The source of carbon responsible for the graphite is unknown, however, various sources might include: (1) accumulation of organic material by biogenic activity at the site of sulphide deposition (2) accumulation of organic material at the site of sulphide deposition resulting from organic detritus settling out of the water column (3) precipitation of hydrothermal graphite during ore formation through fluid/rock interaction. The origin of the graphite may help determine the presence or absence of a seafloor position within the stratigraphy hosting the ore lenses of the Fenton Creek zones.

6.1.1 Methods

Determination of the source of carbon responsible for the formation of graphite is best made using $^{13}\text{C}/^{12}\text{C}$ ratio, which can be determined using conventional mass spectrometry methods. A total of 3 samples containing visible graphite were collected from diamond drill core and comprised 2 samples from Cu-Zn mineralised graphitic ore and 1 sample from non-mineralised graphitic meta-pelite in the hanging wall of the Fenton Creek zone. Sample locations and rock descriptions can be found in Appendix A. The graphite from these samples is typically concentrated along foliation bedding structures and is amenable to extraction with a pin and/or drill. Utilizing this method approximately 5mg of graphite per sample was extracted and placed into labelled plastic sample containers and sent to the Central Science Laboratory at the University of Tasmania for determination of the $^{13}\text{C}/^{12}\text{C}$ ratio. Complete sample preparation and procedures are given in Appendix E.

6.1.2 Results

The results of the carbon isotope analysis indicate that the $\delta^{13}\text{C}$ with respect to PDB falls within a narrow range between -16.93 to -16.44%, with an average of -16.64%, which is consistent with values seen in sedimentary organic carbon or biomass source that has been modified by high-grade metamorphism. Complete results are shown in Table 6.1.
6.1.3 Interpretations

In nature carbon occurs as \( \text{CO}_2 \), carbonates and bicarbonates (oxidized forms), as methane and organic carbon (reduced form) and as diamond and graphite (Rollinson, 1993). These various forms of carbon occur in four major \( \delta^{13} \text{C} \) reservoirs, each with different isotope compositions as summarized in Figure 6.1 after (Rollinson, 1993).

Table 6.1 Analytical results for determination of \( \delta^{13} \text{C} \) from graphite samples collected from the Fenton Creek zone

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Wt (mg)</th>
<th>Yield (mmHg)</th>
<th>( \delta^{13} \text{C} ) (wrt PDB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75507H</td>
<td>6</td>
<td>9.6</td>
<td>-16.44</td>
</tr>
<tr>
<td>75615H</td>
<td>6.1</td>
<td>12.4</td>
<td>-16.56</td>
</tr>
<tr>
<td>75520H</td>
<td>4.9</td>
<td>6.8</td>
<td>-16.93</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>-16.64</strong></td>
</tr>
<tr>
<td><strong>Minimum</strong></td>
<td></td>
<td></td>
<td><strong>-16.93</strong></td>
</tr>
<tr>
<td><strong>Maximum</strong></td>
<td></td>
<td></td>
<td><strong>-16.44</strong></td>
</tr>
<tr>
<td><strong>Standard deviation</strong></td>
<td></td>
<td></td>
<td><strong>0.25541</strong></td>
</tr>
</tbody>
</table>

Isotope compositions are highly variable due to kinetic and/or equilibrium fractionation processes. One of the most important fractionation processes is the conversion of inorganic carbon into organic carbon. During this process the isotopically light carbon \( ^{12} \text{C} \) is preferentially concentrated into organic carbon resulting in relatively light \( \delta^{13} \text{C} \) as seen in terrestrial biomass \(-26\% \pm 7\% \) (Schidlowski, 1987). Based on this evidence the graphite from the Fenton Creek zone with an average \( \delta^{13} \text{C} = -16.64\% \) is not likely to be of biogenic origin unless it has been modified by some other process.

The kinetic processes related to high-grade metamorphism are factors likely to have affected the isotopic composition of \( \delta^{13} \text{C} \) from the Fenton Creek zone that has been subjected to upper amphibolite to granulite facies metamorphism. Experimental research by has shown that in systems which have both organic carbon and carbonate the \( \Delta(\text{cc-gr}) \) decreases with increasing temperature as values tend to reach equilibrium (Bottinga, 1969; Valley and O, 1981; Kreulen and van, 1983; Wada and Suzuki, 1983; Arneth et al., 1985; Schidlowski, 1987) (Fig 6.2). Therefore, this process may have played a significant role shifting the isotopic signature of the carbon found in the graphite from a lighter to heavier value.

Another consideration to made when interpreting the isotope compositions are variations with time. Isotope compositions of organic carbon as well as the carbon found in carbonate
Figure 6.1 $\delta^{13}$C values for graphite samples from the Fenton Creek zone plotted on diagram showing ranges of $\delta^{13}$C values in natural carbon-bearing samples modified after (Rollinson, 1993)

Figure 5.2 Decrease of carbon isotope fractionations between sedimentary organic and carbonate carbon as a function of increasing metamorphic temperature (Schidlowski, 1987).
have remained relatively constant through time with minor oscillations caused by involvement of methane. Figure 6.3 after Schidlowski (1987) summarizes the $\delta^{13}C$ variations with time for carbon from carbonate and organic sources. Plotting of the Fenton Creek zone results on this diagram indicates that the carbon from graphite does have a biological signature. Also shown on this diagram is a dataset for the Isua metasedimentary suite which has been interpreted to have been subjected to secondary alteration as a result of high temperature $^{13}C/^{12}C$ exchange (Schidlowski, 1987).

In conclusion there is strong evidence to suggest that the source of the carbon forming the graphite is of biogenic origin and that the original isotopic signature has been shifted due to autotrophic organisms.

Figure 5.3 Range of $\delta^{13}C$ isotope compositions of organic carbon ($C_{org}$) and carbonate ($C_{carb}$) as a function of time as compared to modern day contributors to the biomass: (1) C3 plants, (2) C4 plants (3) CAM plants; (4) eukaryotic algae; (5a,b) natural and cultured cyanobacteria (6) groups of photosynthetic bacteria and other cyanobacteria; (7) methylogenetic bacteria; (8) methanotrophic bacteria. Also note data for Isua metasedimentary suite in which $\delta^{13}C$ isotope compositions for organic carbon ($C_{org}$) are interpreted to have been shifted to more positive values as a result of high temperature $^{13}C/^{12}C$ exchange during amphibolite metamorphism. Carbon from Fenton Creek graphite plots on the boundary at -16.44‰ (modified after Schidlowski, 1987).
to high grade amphibolite to granulite metamorphism. This finding lends support to a seafloor position at the site of sulphide mineralisation.