**VOLCANOLOGY AND GEOCHEMISTRY OF ARCHEAN RHYOLITES AND
RELATED VOLCANICLASTIC ROCKS ASSOCIATED WITH THE KIDD CREEK
VOLCANOGENIC MASSIVE SULFIDE DEPOSIT, ABITIBI GREENSTONE BELT,
SUPERIOR PROVINCE, CANADA**

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Thesis submitted to the Faculty of Graduate Studies and Research in partial
fulfillment of the requirements for the degree of Doctor of Philosophy

Department of Earth Sciences
Carleton University
Ottawa, Ontario, Canada
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ABSTRACT

The Archean volcanogenic massive sulfide (VMS) ores of the Kidd Creek Mine occur within the Kidd Creek formation, a succession characterized by a predominance of rhyolitic volcanic and volcanoclastic rocks which represent a local felsic volcanic centre. The Kidd Creek formation is divisible into Lower, Middle, and Upper members with the known strata-bound massive sulfide lenses confined to the Middle member. The Lower member is dominated by coherent and autoclastic footwall (FW) rhyolite, the Middle member contains an abundance of bedded, polymict volcanoclastic rocks with subordinate argillite and massive sulfide, and the Upper member comprises coherent and autoclastic facies of quartz porphyritic (QP) rhyolite.

The QP rhyolite represents the last significant phase of felsic volcanism in the Kidd Creek Mine area. Facies analysis and morphological reconstruction using isopach maps indicate that the QP rhyolite erupted from two parallel fissures. Primarily passive fissure eruptions and endogenous dome growth resulted in the construction of two ridges that extend for at least 1.9 km. Continued hydrothermal activity in the Kidd Creek area after deposition of the known massive sulfide orebodies is recorded by hanging wall alteration, primarily sericitization, silicification, and feldspar destruction, within QP rhyolite. A spatial correlation between the south orebody of the Kidd Creek Mine and the north QP rhyolite ridge suggests that ore-forming hydrothermal discharge and

the subsequent eruption and alteration of the QP rhyolite may have been controlled by a common long-lived syn-volcanic structure.

The Kidd Creek rhyolites have relatively enriched, FIIIb incompatible element profiles; such rhyolites are favourable VMS exploration targets within the Superior Province (rare earth elements and high field strength elements remained relatively immobile in rhyolites outside the footwall stringer zone). Geochemical data demonstrate a close similarity between least-altered rhyolites of the Kidd Creek formation and the felsic igneous rocks of anomalous mid-ocean ridge spreading centres such as the rhyolites erupted from the central volcanoes Askja and Krafla in Iceland's eastern axial rift zone. A model is suggested in which the Kidd Creek rhyolites were derived by subsidence-induced partial melting of hydrated tholeiitic basalt within juvenile oceanic crust having a steep geothermal gradient (possibly related to an upwelling mantle plume).

Eleven rhyolite samples from the Kidd Creek Mine area yield a Sm-Nd isotopic regression age of 2733 ± 260 Ma, within error of previously determined U-Pb ages of zircons in Kidd Creek rhyolites which range from 2717 ± 2 to 2710.5 ± 1.1 Ma. With the exception of two intensely chloritized and sericitized footwall samples, $\epsilon_{\text{Nd}}(2712 \text{ Ma})$ values range from +1.1 to +4.2 and show no systematic variation with height through the stratigraphic succession. These values bracket the depleted mantle curve and do not suggest contamination by older crust. The ϵ_{Nd} values are consistent with the eruption of

the Kidd Creek rhyolites, and formation of the Kidd Creek orebodies, in an oceanic environment dominated by rocks of recent mantle derivation.

ACKNOWLEDGMENTS

This study was supported by an NSERC-Falconbridge Limited-Laurentian University collaborative Research and Development Grant, the Geological Survey of Canada, and the Minerals Program of the joint federal-provincial Northern Ontario Development Agreement (NODA). The geological base for the Kidd Creek mine area on which this study rests is the culmination of high quality work by many company geologists in both the mine and exploration groups. Assistance at the mine site by the staff of the geology department including, but not limited to, Ron Cook, Phil Olson, Dave Lockett, Ron Lemery, Dave Richardson, Peter Jurenovskis, Peter Manojlovic, Dean Crick, Dean MacEachern, Paul Simunovic, Paul Roos, Mike Welch, and Marilyn Schonfeld is gratefully acknowledged. Bob Stewart supervised the collection of many of the samples used to form the Falconbridge analytical database. Capable field assistance was provided by Dave Richardson (1993) and John Everest (1994).

I wish to express sincere thanks to my thesis supervisors, David Watkinson (Carleton University) and Harold Gibson (Laurentian University). Brian Cousens (Carleton) performed the Sm-Nd isotopic analyses, and both Brian Cousens and Tucker Barrie (G.S.C.) contributed to my understanding of the Sm-Nd isotopic system. Mark Hannington (G.S.C.) coordinated research efforts at Kidd Creek, and Wouter Bleeker (formerly Falconbridge Limited, now G.S.C.) advanced the understanding of structural relationships in the mine area. SEM instruction was provided by Peter Jones (Carleton). I am grateful to Dr. Richard Moore of Falconbridge Limited for serving as the external examiner, and to David Prior for providing technical support. Robert Whitehead of Laurentian University reviewed an early version of Chapter 3. Lastly, I wish to acknowledge financial support in the form of an NSERC scholarship.

ORIGINAL CONTRIBUTION

This thesis is based on approximately 12 months of detailed underground mapping at the Kidd Creek Mine completed by the author during 1993, 1994, and 1995. Where data from geological level plans and drill hole logs prepared by the Kidd Creek Mine Geology Department, Falconbridge Limited, have been incorporated into this study an appropriate reference is given. Whole rock analyses for samples collected on this project were performed by X-Ray Assay Laboratories, Toronto, Ontario. Sm-Nd isotopic analyses were performed by Dr. Brian Cousens at Carleton University. The volcanological portion of the QP rhyolite study, which forms part of Chapter 2, represents a collaborative effort with Dr. Harold Gibson of Laurentian University. Chapters 1, 3, 4, 5, the appendices, and the lithogeochemical part of Chapter 2 are essentially the sole work of the author (with the exception of cited material and analytical geochemistry) although input by several colleagues is acknowledged (see Acknowledgments).

Chapters 2, 3, and 4 were written in a manner which will facilitate the publication of the research contained in each of these chapters as scientific articles. Much of the material presented in Chapter 2 has been accepted, with revisions, for publication by Economic Geology in the paper "Anatomy, lithogeochemistry and emplacement mechanisms for the QP rhyolite, Kidd Creek Mine, Timmins, Ontario", authored by Prior, G.J., Gibson, H.L., Watkinson, D.H., and Cook, R.E.

DEDICATION

*With love to Sandra and Sarah,
My family that first day,
And to Allie, Kate, and Jackie,
Who joined us along the way.*

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Chapter 1

INTRODUCTION TO THESIS

The Kidd Creek deposit is a world-class volcanogenic massive sulfide (VMS) deposit located in northeastern Kidd Township 27 km north of Timmins, Ontario, Canada. The Cu-Zn-Pb-Ag ores of the Kidd Creek Mine formed during the Archean and are located in the western part of the southern Abitibi greenstone belt (Abitibi Subprovince) in the Superior Structural Province of the Canadian Shield (Figure 1.1 and 1.2). Orebodies are hosted primarily within a felsic volcanoclastic sequence, underlain and overlain by rhyolites, within a bimodal volcanic succession (Figure 1.3).

The bulk of this thesis is devoted to studies of three major aspects of the geology and lithogeochemistry of the Kidd Creek deposit. These studies are herein presented in Chapters 2, 3 and 4.

Chapter 2 addresses the geological setting of the Kidd Creek deposit in general and the physical volcanology and geochemistry of the QP rhyolite, the last significant product of felsic volcanism at Kidd Creek, in more detail (Figure 1.3). It is proposed in Chapter 2 that the predominantly felsic volcanic and volcanoclastic succession which contains the Kidd Creek orebodies be

informally named the Kidd Creek formation and that this formation may be subdivided into the Lower, Middle and Upper members. Applying this nomenclature the strata-bound massive sulfide orebodies of the Kidd Creek Mine lie within the Middle member of the Kidd Creek formation.

Quartz porphyritic QP rhyolite, which forms the Upper member of the Kidd Creek formation, was chosen in preference to FW (footwall) rhyolite of the Lower member for a detailed volcanological study because there are far more underground exposures and complete drill hole intersections through the QP rhyolite than the FW rhyolite. This reflects the fact that strata in the Kidd Creek Mine area, which dip steeply to the east, are overturned so the shafts and most diamond drill stations are located in the stratigraphic hanging wall (structural footwall). No underground workings and relatively few diamond drill holes penetrate to the stratigraphic base of the FW rhyolite. By studying rhyolite morphology and depositional processes a better understanding of the geological environment in which the Kidd Creek orebodies formed can be obtained. In addition to volcanological aspects, the QP rhyolite is interesting as it provides an example of extensive hydrothermal alteration within the stratigraphic hanging wall of a world-class VMS deposit. Hydrothermal alteration processes related to VMS formation are commonly recognized in the Superior Province within footwall rocks but alteration effects in hanging wall rocks are not as well documented.

In Chapter 3 a comparative lithogeochemical technique is developed to identify the tectonic environment in which the Kidd Creek rhyolites were erupted and the Kidd Creek VMS ores formed. The method relies on the identification of distinctive geochemical characteristics of post-Triassic felsic igneous rocks from different tectonic settings and the comparison of these features to the Kidd Creek rhyolites. Hydrothermal metasomatic effects on the original igneous geochemical (juvenile) compositions of the Kidd Creek rhyolites are minimized by selecting least-altered Kidd Creek rhyolites for comparative purposes and by basing the comparisons on the relatively immobile rare earth elements (REE) and high field strength elements (HFSE). The underlying premise of this research is that variability among rhyolite compositions is primarily a function of factors controlled by tectonic setting (i.e., available parental material and thermal regime) rather than factors related to individual magma chambers (i.e., differentiation processes). The study has exploration implications as the Kidd Creek rhyolites are geochemically similar to other “favourable” rhyolites in the Superior Province associated with VMS deposits (Leshner et al., 1986; Barrie et al., 1993).

Chapter 4 examines the Sm-Nd isotopic characteristics of the Kidd Creek rhyolites in order to address the following questions:

- (i) What is the source of the Kidd Creek rhyolites?
- (ii) Does the Nd isotopic composition of felsic magmas in the Kidd Creek area vary with stratigraphic position?
- (iii) Does strong hydrothermal alteration accompanied by LREE depletion, indicative of high water/rock ratios, affect Nd isotopic ratios?

Figure 1.1. Geology of the Abitibi Greenstone Belt, Superior Province, showing the location of the Kidd Creek Mine (after Jackson and Fyon, 1991).

Figure 1.2. Regional geology (modified after Bleeker, 1995a, and Huston et al., 1995).

Figure 1.3. Geology of the Kidd Creek Mine area at the 2800 Level (850 m below surface). Strata are overturned and dip steeply to the east. A = north orebody, B = south orebody, C = southwest orebody, mNg = mine grid north (azimuth 020°). Modified after Falconbridge Limited 2800 Level geology plans.

Chapter 2

VOLCANOLOGY AND GEOCHEMISTRY OF THE QP RHYOLITE

Introduction To Chapter 2

The quartz- and quartz-feldspar-porphyritic rhyolite that directly overlies the succession of bedded volcanoclastic deposits and massive sulfide lenses at the Kidd Creek Mine (Figure 1.3) is referred to, in mine terminology, as QP rhyolite. The QP rhyolite represents the last significant phase of rhyolitic volcanism at Kidd Creek and it has been interpreted as either a rhyolitic flow or pyroclastic deposit (Bleeker, 1994) (Figure 2.1). Field and petrographic evidence presented herein are consistent with its emplacement as a rhyolitic dome complex, the product of largely passive fissure eruptions. The objectives of this chapter are to describe the QP rhyolite, reconstruct its morphology and mechanisms of emplacement, document primary and alteration lithogeochemical characteristics, and illustrate its significance with respect to ore-forming processes at the Kidd Creek Mine. In addition, an informal stratigraphic nomenclature for the predominantly felsic volcanic and volcanoclastic succession which hosts the Kidd Creek deposit is proposed.

Geology of the Kidd Creek Mine Area

The Kidd Creek Mine extracts Cu-Zn-Pb-Ag ore from a volcanogenic massive sulfide (VMS) deposit of Archean age located in the Kidd-Munro assemblage within the western part of the southern Abitibi Greenstone Belt (Abitibi Subprovince) in the Superior Province of the Canadian Shield (Figures 1.1 and 1.2). The Kidd Munro assemblage is an east-west striking, steeply dipping succession of intercalated Archean ultramafic, mafic and felsic volcanic rocks and intrusions which range in age from about 2720 to 2710 Ma (Jackson and Fyon, 1992; Bleeker, 1995b, and references therein). Volcanic rocks in the Kidd Creek Mine area have been assigned to the Kidd Volcanic Complex (KVC) by Bleeker (1995b). Cumulative production and reserve figures for the Kidd Creek Mine total approximately 130 million metric tonnes at 2.4% Cu, 6.5% Zn, 0.2% Pb and 89 g/tonne Ag (Olson et al., 1994), approximately 30% of total VMS production and reserves within the Abitibi Greenstone Belt (Barrie et al., 1993). The mine exploits massive sulfide ores rich in sphalerite +/- galena, massive sulfide ores rich in chalcopyrite +/- bornite, sphalerite-rich sulfide breccia ores, and chalcopyrite-rich stringer sulfide ores. Host rocks to the orebodies are primarily rhyolitic to polymict volcanoclastic rocks of the Kidd Creek formation, a locally thickened felsic volcanic center in a geochemically bimodal (ultramafic-mafic and felsic) succession.

The Kidd Volcanic Complex (KVC) is a poorly exposed suite composed primarily of greenschist facies, subaqueous, strongly bimodal volcanic rocks. Volume contributions to the KVC are approximately 60% basaltic to andesitic

(icelandic) volcanic rocks (lavas, breccias, volcanoclastic sediments, and sills), 20% felsic volcanic rocks (rhyolite flows and felsic volcanoclastic rocks), 10% ultramafic rocks (komatiite and basaltic komatiite successions possibly containing subvolcanic sills and dikes), and less than 5% each of intermediate volcanic rocks, sedimentary rocks, granitoids, and late dikes (including lamprophyre dikes and dikes of the Matachewan swarm) (Bleeker, 1995b). The KVC extends for a minimum distance of 10 km to the east, north, and west of the Kidd Creek Mine. Immediately south of the mine rocks of the KVC are in thrust fault and/or unconformable contact with significantly younger (less than approximately 2699 Ma) greywacke turbidites of the Porcupine Group (Bleeker and Parish, 1995; Bleeker and Parrish, 1996). These greywackes are interpreted by Bleeker (1995b) to represent a post-volcanic flysch sequence deposited in response to crustal thickening and emergence.

The Kidd Volcanic Complex, as defined by Bleeker (1995b), includes all of the rocks which predate the Porcupine Group within a radius of at least 10 km from the Kidd Creek Mine. It is herein proposed, after consultation with the mine staff, that the 350 to 450 m thick, dominantly felsic volcanic and volcanoclastic succession which hosts the Kidd Creek deposit be informally named the Kidd Creek formation and that this formation be subdivided into the Lower, Middle and Upper members (Figure 2.1). The Kidd Creek formation rests on a thick sequence of ultramafic rocks which are composed in part of komatiitic flows with locally preserved spinifex texture and contain intercalations of rhyolite (Walker et al., 1975; Brisbin et al., 1990). The Lower member, located in the footwall to the massive sulfide orebodies, is dominated

by massive, flow-banded and autobrecciated rhyolite domes and cryptodomes (FW rhyolite) and contains chalcopyrite stringer mineralization. The Lower member is conformably overlain by the Middle member which contains the massive sulfide orebodies and is characterized by bedded volcanoclastic rocks. Rock types within the Middle member include polymict boulder and pebble conglomerates, commonly containing sulfide clasts, volcanoclastic sandstones and mudstones, graphitic argillites, rhyolite, autoclastic rhyolite breccia, rhyolite hyaloclastite, and massive sulfides. The volcanoclastic rocks are commonly, though not always, dominated by variably altered rhyolitic clasts. Other common clast types include altered mafic volcanic clasts, argillite clasts, sulfide clasts and quartz crystal clasts. The Upper member consists of quartz porphyritic, coherent and autoclastic QP rhyolite, locally up to 130m thick, which represents the last significant period of felsic volcanism at Kidd Creek (Figures 1.3 and 2.1). A thick (>1500 m) succession of pillowed basalt flows, pillow breccias, heterolithologic breccias, and interflow graphitic, cherty sediments conformably overlies the QP rhyolite (Bleeker, 1995b). The volcanic succession is intruded by fine-grained gabbro including two thick sills which separate the QP rhyolite from underlying volcanoclastic rocks of the Middle member and from the overlying basaltic succession. Major folds have ENE-trending axes and strata in the mine area become younger to the west (Bleeker and Parrish, 1996).

Rhyolites and felsic volcanoclastic rocks in both the footwall and hanging wall to the orebodies have undergone extensive silicification and sericitization, whereas zones of intense chloritization occur exclusively in the footwall.

Ultramafic rocks in the mine area commonly contain assemblages of serpentine, talc, magnesite and chlorite (J. Everest, written communication, 1995). The basaltic sequence overlying the felsic rocks and the fine-grained gabbro generally display little or no evidence of exposure to the Kidd Creek ore-forming event (Koopman et al., 1996; Huston and Taylor, 1996). All rocks in the Kidd Creek Mine area have undergone regional metamorphism at greenschist-facies conditions and most display penetrative deformation.

Bleeker and Parrish (1995) reported U-Pb zircon ages of 2714 ± 1.5 Ma for FW rhyolite of the Lower member and 2710.5 ± 1.1 Ma for QP rhyolite of the Upper member indicating that the entire 300 to 500 m thick Kidd Creek formation spans a 1.4 to 6.1 m.y. time interval. Previous U-Pb data on zircons from the footwall felsic sequence at Kidd Creek returned ages of 2717 ± 4 Ma and 2717 ± 2 Ma (Nunes and Pyke, 1982; Barrie and Davis, 1990). Sm-Nd isotopic data indicate derivation of the Kidd Creek rhyolites from a mantle or mantle-derived source consistent with results for igneous rocks of similar age throughout the southern Superior Province (Maas et al., 1986; Chapter 4).

The structural setting of the Kidd Creek Mine area is strongly controlled by two major F_1 folds, the axes of which are located north and south of the minesite (the southern F_1 fold axis is shown in Figure 1.3). The more northerly of these folds plunges 70° toward 020° (Bleeker, 1995b). Regionally, supracrustal rocks of the Kidd Volcanic Complex (KVC) have east-west trends but within the panel of strata between the two major F_1 fold hinges, a strike length of about 600 m, rocks have a northerly strike and dip steeply (70° to 80°)

to the east (Figure 2). Second order F_1 folds are the dominant structures throughout the mine and are best developed within volcanoclastic rocks and massive sulfide (Bleeker, 1994). However, second order F_1 folds are either not as well developed in, or they are not as apparent in the more coherent units such as the QP rhyolite and the thick mafic sills that dilate volcanic strata. Heterogeneous development of the dominant S_1 cleavage (axial planar to F_1 folds) and strong stretching lineation which plunges parallel to the F_1 folds , has resulted in variable modification of the shape of primary textures and structures (Bleeker, 1994). Primary textures and structures are, however, well preserved when viewed perpendicular to the pronounced stretching lineation, even in highly sheared exposures. Consequently the best exposures for mapping were the backs of underground workings rather than the walls and samples selected for thin section or polished slab examination were routinely cut to provide surfaces that are perpendicular to the stretching lineation.

The QP Rhyolite

QP rhyolite, the Upper member of the Kidd Creek formation, is subdivided into coherent and breccia facies. These facies have a distinct, predictable organization that defines the anatomy of the QP rhyolite.

Coherent Facies

The coherent facies is characterized by massive and flow-banded,

aphanitic, quartz and quartz-feldspar porphyritic rhyolite. Subhedral to anhedral, locally glomeroporphyritic and embayed, quartz phenocrysts typically comprise 8-12% of the rock (Figure A7.15). The quartz phenocrysts (<4 mm in diameter) occur within a recrystallized groundmass of quartz, sericite, and minor chlorite and carbonate. The groundmass contains as much as 35%, round, <2mm, composite quartz grains with sector extinction typical of recrystallized spherulites (Figures A7.16 and A7.17). Subhedral to euhedral albite phenocrysts, typically <5mm in size and locally glomeroporphyritic, are commonly partly to totally altered to sericite and carbonate assemblages (Figure A7.15). Albite phenocrysts, which locally form up to 5% of the QP rhyolite, are more readily recognizable in parts of the QP rhyolite on the south limb of the large, F_1 syncline (Figure 1.3). In the author's opinion this reflects better preservation (i.e., less alteration) of albite in parts of the south limb of the QP rhyolite, south of the F_1 fold axial plane, than in the north limb. There are no variations in major or trace element compositions or in quartz phenocryst abundances between the north and south limbs of the QP rhyolite which would support their being the products of separate magmas.

Broken phenocrysts were not observed and glomeroporphyritic textures occur locally. These features, as well as recrystallized quartz spherulites within the groundmass and lack of bedding, are compatible, along with the morphological features to be described, for the interpretation that the coherent rhyolite is a flow and not a pyroclastic deposit.

Coherent rhyolite exposed along the 2100 Access Drive occurs, in part,

as large lobes that range from several metres to >10 m across and are characterized by faintly flow-banded margins that locally contain 2-5% elongate quartz amygdules (<5mm in length; Figure 2.2). Toward the bottom, and less commonly toward the top, massive rhyolite lobes are surrounded by flow-banded, quartz (feldspar) porphyritic rhyolite. Flow banding typically parallels lobe margins and is locally flow folded. Flow-banded rhyolite at the base of the QP rhyolite contains dispersed, angular blocks of massive, white, quartz porphyritic rhyolite and lies in sharp contact with underlying rhyolite breccia; flow banding there is not contorted but parallels the contact with underlying breccia (Map 4).

Exposures of QP rhyolite dominated by massive and flow-banded rock are interpreted to represent a cross section through a subaqueous rhyolite flow or dome. The small volume of breccia with respect to massive and flow-banded rhyolite, and the occurrence of breccia primarily at the base of the flow, are interpreted to represent a vent-proximal flow facies (Figure 2.2).

Breccia Facies

Assuming that massive and flow-banded coherent rhyolite represents rhyolitic lava either as a dome or flow, then the breccia facies, as exposed along the 2101 and 1600 South Drives and the 2100, 1800 and 1700 Access Drives, may be divided on the basis of their distribution, into flank breccia and basal, flow foot breccia. Flank breccia consists of white to grey, pebble- to block-sized fragments of coherent quartz (feldspar) porphyritic rhyolite in a

quartz crystal-bearing hyaloclastite matrix (Figures 2.3, A7.18, A7.19).

White, quartz porphyritic massive rhyolite blocks, up to 30 cm in size, define crude, unsorted, non-graded, framework to matrix supported beds within the breccia. The breccias are locally sericitized. On the 2100 South Drive, flank breccia is conformably underlain by a 1.5 m thick unit of finely laminated to plane-bedded, siliceous and sphalerite-impregnated, volcanoclastic sandstone.

Flow foot breccia consists of 50 cm to 2 m thick beds of breccia and hyaloclastite containing angular to subangular, white silicified blocks of massive QP rhyolite (1cm to 40 cm in size), flow-banded QP rhyolite blocks, rare fragments of sericitized QP rhyolite, and tan, mafic, pebble-sized fragments (Figure A7.1 and Map 4). The breccias are matrix to framework supported and occasionally display normal grading. On the 1700, 1800 and 2100 levels, beds in the flow foot breccia are discordant with the flow-banded base of the QP flow which truncates the breccia units (Figure A7.1). The breccias are interpreted to be imbricated and their angular discordance with the flow base suggests an "upward" (towards the present day surface) and "north to south" flow direction. The matrices to flank and flow foot breccias consist primarily of QP rhyolite hyaloclastite and pebble-size aphyric to porphyritic rhyolite fragments. In addition, QP rhyolite flank and flow bottom breccias often contain up to 1% altered mafic fragments similar to the chilled mafic rocks of sill margins, apophyses and dikes.

Two large mafic sills dilate strata and separate the QP rhyolite from the

underlying volcanoclastic rocks of the Middle member and overlying basaltic flows (Figures 1.3 and 2.1). Where the sills intruded QP rhyolite breccia, the contact is not sharp and regular but is characterized by aphanitic, finger-like dikes and apophyses of mafic sills that intruded and autobrecciated into flow bottom and flank breccia as illustrated in Figures 2.3, A7.1 and A7.18. Breccia within decimeters of the dikes is a mixture of QP rhyolite and chilled, aphanitic mafic ("andesitic" in mine terminology) fragments. These "mixed breccias", containing both QP rhyolite and aphanitic mafic fragments, are interpreted as peperite breccia, the product of passive fragmentation of the sill margins during their emplacement into unconsolidated, wet, QP rhyolite breccia.

Exposures of QP rhyolite dominated by breccia and hyaloclastite are interpreted to represent a cross section through the flank (distal or marginal facies) of a subaqueous rhyolite flow or dome. (Figure 2.3). As illustrated in Map 4, flow foot breccia also occurs in proximal, near-vent facies but the proportion of breccia is volumetrically insignificant with respect to massive and flow-banded rhyolite.

Both the proximal and distal facies of the flow are commonly sericitized and silicified, and locally contain pyrite and sphalerite (1700 level and 2101 Drive South) indicating that hydrothermal activity continued after emplacement of the QP rhyolite flow. Gabbro sills and overlying basalt flows show limited evidence of hydrothermal alteration which is consistent with their emplacement during waning hydrothermal activity (Huston et al., 1995).

Geochemistry

All whole-rock chemical analyses were performed by X-Ray Assay Laboratories, Toronto, Ontario; a summary of their analytical techniques is presented in Appendix 3.

Protolith Composition

Because of extensive alteration it is unlikely that a true protolith composition for the QP rhyolite remains; however an estimation of the protolith composition may be obtained using the analytical values of least-altered samples. Six QP rhyolite samples which satisfy the geochemical criteria listed in Table 2.1 have been selected as representative of least-altered compositions (Table 2.2). The average of these six analyses provides a reasonable estimation of the protolith composition. Samples of the fragmental facies of the QP rhyolite were excluded because of possible contamination from other rock types.

Element Mobility

The content of any given element "X" within a rock sample may vary from that of the protolith due to (i) gains or losses of element X from the rock or (ii) gains or losses of one or more elements other than X from the rock due to the constant sum (closure) effect. The effect of constant sums (100 wt.%) on

chemical analyses is illustrated in Table 2.3 using an example of silicification in which 30 g of SiO_2 is added to the estimated QP rhyolite protolith composition. The results demonstrate that after recalculation to 100 g (100 wt.%): (i) all oxides other than SiO_2 have undergone apparent depletion (dilution) as a result of the mass gain accompanying silicification; (ii) the apparent addition of SiO_2 obtained by subtracting its value in the final analyses from the protolith content ($83.03 \text{ g} - 77.93 \text{ g} = 5.1 \text{ g}$) is much less than the actual SiO_2 addition (30 g); (iii) inter-element ratios for elements not added or subtracted remain constant between the analyses of protolith and altered rock (e.g., $\text{Al}_2\text{O}_3/\text{Zr}$ protolith = $\text{Al}_2\text{O}_3/\text{Zr}$ altered = 487).

A number of graphical representations have been developed for identifying elements which have remained relatively immobile within suites of altered rocks sharing common protoliths (e.g. Gresens, 1967, Grant, 1986, Babcock, 1973, MacLean, 1990; Huston, 1993). Figure 2.4 presents a spider diagram for 36 coherent facies QP rhyolite samples normalized to the estimated protolith composition of the QP rhyolite (eP_{QP}). The “spider” lines for which this type of diagram is named (lines connecting data points for individual samples) have been removed for clarity. For any sample which has not undergone significant mass change, elements which have remained immobile will have a value near 1.0 (i.e., immobile element abundances unchanged from the protolith composition). Provided element variations due to metasomatic gains and losses outweigh the effects of mass change, those elements whose values tend to cluster near 1.0 are those which have been the least mobile during metasomatism. In order to minimize the effects of mass change

a second spider diagram of the same samples is presented in Figure 2.5 which has been doubly normalized to the Zr value of the average least-altered QP rhyolite. Based upon this representation it can be determined that Al, Y, Zr, Nb and Ce were the least mobile elements; Si, Ti, Hf, Ta and Th have been moderately mobile, and the remaining elements shown in Figure 2.5 have been considerably mobile. This discussion of mobility is based on relative rather than absolute additions and depletions - a distinction most notable for SiO_2 which dominates most silicate rocks. For example, a 30% change in SiO_2 from the estimated QP rhyolite protolith composition results in a gain or loss of 23.4 g/100 g of rock (77.9 wt.% (protolith) $\times$ 0.50) whereas a 30% change in MgO produces a gain or loss of only 0.20 g/100 g of rock (0.65 wt.%(protolith) $\times$ 0.30).

Classification

In order to minimize the effects of alteration, classification schemes which use the less mobile elements have been employed. On the Nb/Y versus Zr/ TiO_2 classification diagram of Winchester and Floyd (1977) all QP rhyolite samples fall in the subalkaline part of the diagram, and nearly all are classified as rhyolite (Figure 2.6). All least-altered QP rhyolite samples have in excess of 74% SiO_2 indicating that the protolith may have been a high-Si rhyolite consistent with the abundance of quartz phenocrysts (caution is warranted as the QP rhyolite has undergone extensive silicification). Barrie et al., (1993) suggested 73% SiO_2 as the lower limit for high-Si rhyolite. Classification of the QP rhyolite as either calc-alkaline or tholeiitic is somewhat problematic. The commonly

used ternary plots of Irvine and Baragar (1971; AFM plot) and Jensen (1976, Jensen cation plot) have limited discrimination ability for rhyolitic compositions especially when Na, K, Fe and Mg metasomatism has occurred, as is the case for the QP rhyolite. For altered felsic volcanic rocks of the Abitibi Greenstone Belt in the Noranda area, Quebec, Ujike and Goodwin (1987) and Barrett et al. (1993) proposed the use of the chondrite-normalized La/Yb ratio as a means of discrimination, whereas MacLean and Barrett (1993) used a Zr versus Y diagram for the same purpose. Using La_N/Yb_N the least-altered QP rhyolite is classified as calc-alkaline whereas Zr/Y ratios place it in the tholeiitic field (Figure 2.7). Associated mafic volcanic and intrusive rocks in the Kidd Creek mine area have tholeiitic characteristics and QP rhyolite is geochemically very similar to rhyolite erupted in the tholeiitic terranes of Iceland (Chapter 3). Therefore, the QP rhyolite is best characterized as having a tholeiitic association. QP rhyolite samples have REE patterns which are intermediate between end member FIIIb and FIIIa felsic volcanic rocks (Leshner et al., 1986) but their pronounced negative Eu anomalies and elevated Th and U contents favour their inclusion in the FIIIb group. The REE characteristics of the Kidd Creek rhyolites are discussed in detail in Chapter 3.

Rhyolite Discrimination in the Kidd Creek Mine Area

The north and south orebodies at the Kidd Creek Mine are contained within felsic volcanoclastic rocks of the Middle member which appear to be derived predominantly from FW rhyolite of the Lower member. The QP and FW rhyolites are geochemically very similar (Chapter 3) but discrimination is

possible using selected elements which have remained relatively immobile. In Figure 2.8, a TiO_2 versus Nb diagram is presented for samples of QP rhyolite (coherent and breccia facies) and FW rhyolite (coherent and monomict breccia facies). The QP rhyolite may be distinguished from the FW rhyolite by its generally higher TiO_2 and lower Nb contents; a line drawn at a Nb/ TiO_2 ratio of 0.0175 serves to separate the two rock types. Both the QP and FW rhyolite data tend to occur in elongate fields with long axes trending toward the origin. This pattern is typical for immobile-element binary diagrams constructed for a suite of rock samples having a common protolith in which significant mass changes have occurred (MacLean, 1990). Three QP breccia samples fall in the FW rhyolite field which may reflect the incorporation of FW rhyolitic and/or mafic clasts. In Figure 2.9, an $\text{Al}_2\text{O}_3/\text{TiO}_2$ versus Nb/Zr discrimination diagram is presented. Good separation is attained using a Nb/Zr ratio of 0.085 with the QP rhyolites having the lower values. The $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio is a less precise discriminator; all Lower member rhyolite samples have ratios of greater than 85 and most QP rhyolite samples have ratios of less than 85. However, four of 48 QP rhyolite samples have ratios between 85 and 110.

Application of Geochemical Discrimination to the Distribution of Rhyolite in the Kidd Creek Mine Area

A large geochemical database (>1000 chemical analyses) exists for samples of exploration drill core from the Kidd Creek Mine area (Falconbridge Limited data). Locations of samples within a volume of rock between 400 and 1050 m below surface (between the 1300 and 3400 foot mine levels) are

shown in Figure 2.10. The $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios of 217 felsic volcanic and volcanoclastic rocks containing >65 wt.% SiO_2 have been contoured. As shown in Figure 2.9, $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios of <80 correspond to QP rhyolite whereas ratios of >90 indicate Lower member rhyolite affinities. Comparison of Figure 2.10, with the geological plan for 2800 Level (Figure 1.3) demonstrates the accuracy of the $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio as a tool for discriminating stratigraphy in the immediate vicinity of the mine (the small area with $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios of >90 south of the No.1 shaft represents a thin felsic tuffaceous unit overlying the QP rhyolite).

Host Rocks of the Southwest Orebody

The southwest orebody (345, 961 metric tonnes of ore with an average grade of 9.45% Zn, 0.84% Pb, 0.03% Cu and 340 g/t Ag; R. Cook, personal communication, 1995) is a small massive sulfide lens located in a structurally complicated area just north of the major fault which separates the Kidd Creek Mine package from a package of younger greywackes to the south (Bleeker, et al. 1996). The deposit is hosted by felsic volcanic rocks which appear to lie along strike from QP rhyolite and stratigraphically above the volcanoclastic sequence of the Middle member which hosts the north and south orebodies (Figure 1.3). If the southwest orebody is indeed hosted by QP rhyolite then it would demonstrate that ore formation continued after the eruption of the QP rhyolite which would greatly enhance the attractiveness of the QP rhyolite as an exploration target. Eight analyses of samples from the felsic volcanic rocks hosting the southwest orebody are shown on an $\text{Al}_2\text{O}_3/\text{TiO}_2$ versus Nb/Zr discrimination diagram in Figure 2.11. Seven of the eight values fall clearly

within the Lower member rhyolite field indicating that the southwest orebody lies within the same stratigraphic sequence as the north and south orebodies and not within the QP rhyolite. This is consistent with the generally quartz-phenocryst poor nature of the southwest orebody felsic volcanic rocks.

Alteration

The spider diagrams presented in Figures 2.4 and 2.5 demonstrate that although considerable element mobility and mass change have occurred within the QP rhyolite, several elements including Al have remained relatively immobile. A diagram of SiO_2 versus Al_2O_3 demonstrates that mass change effects, which control the apparent additions and depletions of Al, are largely controlled by gains and losses of Si with the data lying along a trend passing through the point 100 wt.% SiO_2 and 0 wt.% Al_2O_3 which represents infinite Si addition (Figure 2.12). The two samples which lie off the trend have undergone strong alteration (these samples contain up to 30.50 wt.% CaO and 24.00 wt.% CO_2). Al_2O_3 varies from 5.45 - 15.70 wt.% due almost entirely to mass change. This range of values may be expressed as a range factor (RF) defined simply as the maximum analytical value divided by the minimum analytical value for any given element in a suite of rocks having a common protolith:

$$\text{RF}(\text{Al}_2\text{O}_3) = \text{Al}_2\text{O}_3(\text{max}) / \text{Al}_2\text{O}_3(\text{min}) = 15.70 \text{ wt.\%} / 5.45 \text{ wt.\%} = 2.9$$

Range factor values for several elements of interest are listed in Table 2.4 for samples of coherent QP rhyolite. The relatively immobile elements Al,

Zr, Nb, Hf, Ta, Th and the REE have range factor values of generally less than 4 which primarily reflect dilution (mass gain) and concentration (mass loss) rather than mobility of Al, high field strength elements (HFSE) and REE. In contrast, several elements which are commonly mobilized during VMS hydrothermal alteration including Fe, Mn, Mg, Ca, Na₂, K₂, H₂O⁺, S, Cu, Zn, Rb, Sr and Ba have range factors that vary from 8.3 to 1146. Note the small range factor value for SiO₂ (2.4) despite the large range of SiO₂ values (49.1 wt.%). High range factor values of CaO (191) and CO₂ (2400) reflect, in part, the post-ore development of calcite along late fractures. These results indicate that within the QP rhyolite mass-change effects are relatively insignificant compared to metasomatic additions and depletions and need not be considered in a general study of alteration.

Alteration within the QP rhyolite is investigated using binary diagrams presented in Figures 2.13 to 2.16 for 48 samples from both the coherent and breccia facies of the QP rhyolite. The Fe₂O₃ versus H₂O⁺ and MgO versus H₂O⁺ plots show that 21 of the 48 samples are enriched in Fe, 18 of the 48 samples are enriched in Mg and that 17 of the 48 samples are enriched in H₂O⁺ relative to the fields containing the least altered QP rhyolite analyses. Strong correlations between Fe₂O₃, MgO and H₂O⁺, a lack of Fe₂O₃ - S correlation and generally low S values (only four samples contain greater than 0.25 wt.% S) indicate that the added Fe and Mg is being accommodated in chlorite (Table 2.5). The four QP rhyolite samples enriched in S (0.77 - 2.04 wt.% S) are all from the breccia facies suggesting that sulfide deposition was greatest within the relatively permeable fragmental zones. Three of the S enriched QP breccia

samples fall off the correlation trend between Fe_2O_3 and H_2O^+ in Figure 2.13 consistent with the presence of Fe sulfide. Twenty-two of the 48 QP rhyolite samples contain <1.0 wt.% Na_2O and 31 of the samples contain <2.0 wt.% Na_2O . The negative correlation between Na_2O and H_2O^+ reflects the development of a hydrous phyllosilicate alteration assemblage (sericite and chlorite) at the expense of plagioclase. The SiO_2 versus Al_2O_3 plot presented in Figure 2.12 reveals both silicification and silica depletion relative to the estimated protolith composition. Silica depletion commonly accompanies the development of phyllosilicate alteration assemblages (MacLean and Barrett, 1993). On a Cu versus Zn plot, 16 of the 48 samples (33%) display anomalous Cu (>40 ppm) and/or Zn (>150 ppm Zn) concentrations with values up to 541 ppm Cu and 1940 ppm Zn. Seven of the eight samples containing the highest Zn values are from the breccia facies suggesting that Zn deposition was greatest within the permeable breccia zones. The occurrence of extensive hydrothermal alteration within the QP rhyolite, documented above, indicates that the Kidd Creek hydrothermal system was still operating subsequent to eruption of QP rhyolite.

QP Rhyolite Morphology

The morphology of the QP Rhyolite is illustrated by the isopach and relief maps shown in Figures 2.17 and 2.18. Isopachs are based on continuous sections through the QP rhyolite, excluding mafic sills, in underground workings and drill core between the 800 to 4700 foot levels of the Kidd Creek

Mine. The QP rhyolite is viewed from the WNW, parallel to the F_1 fold axial plane and, as illustrated in these figures, has been unfolded about this plane. Isopachs south of the axial plane represent minimum thicknesses as the base of the QP rhyolite is in fault contact with a regionally extensive greywacke package to the south. The relief map in Figure 2.18 is constructed from the isopach map assuming a horizontal base for the QP flow. A horizontal base for the flow is a reasonable assumption considering that the footwall mixed fragmental unit, a succession of debris and mass flow deposits, would have been localized within and filled topographic irregularities. As further support, bedding within underlying, plane-bedded volcanoclastic sandstone parallels the flow base.

The isopach and relief maps clearly illustrate that the QP rhyolite consists of two separate ridges, a north ridge exposed in mine workings east of the mine shafts and a south ridge located south of the mine shafts. These two ridges are separated by the F_1 fold axis which occupies the intervening "valley". Paleotopographic domes situated along the ridges attain heights (thicknesses) of up to 130m. Within the area encompassed by Figures 2.17 and 2.18, the north and south ridges of the QP rhyolite flow have a combined volume of approximately 0.1 km^3 . The ridges show a pronounced elongation that is subparallel to the F_1 fold axis. This "vertical" elongation is interpreted to represent a primary trend that reflects the orientation of an underlying synvolcanic fissure. The location of the F_1 fold axis in the area between the two ridges, where the flow is thin, may reflect a primary zone of weakness that was exploited during folding. Thus, the plunge of the ridge axes and not the F_1 fold

axis may represent the trend of primary synvolcanic faults. A north-south profile across the north and south ridges, through the two highest QP rhyolite domes (Figure 2.19) depicts a paleotopography consistent with steep-sided domes with aspect ratios of 3 to 5 flanked by breccias (aspect ratio=horizontal extent/dome height: Walker, 1973). Aspect ratios of less than 10 clearly distinguish the QP rhyolite from pyroclastic flow or fall deposits.

The QP breccia isopach in Figure 2.20, constructed using data available from the mine workings only, illustrates that the breccia is thickest on the flanks of the “domes” and thins immediately below the domes. This distribution of breccia clearly supports an origin through shedding from the top and sides of the rhyolitic ridge during emplacement and growth of the dome. Shown on Figure 2.20 are two flow direction vectors based on the angular discordance between beds within the basal flow foot breccia, which dip away from the domes, and overlying flow-banded rhyolite. Note that the flow vectors are consistent with the isopach map as they indicate a flow direction that extends away from the dome.

Post-volcanic deformation may have elongated the QP rhyolite by up to 100% in the down-plunge dimension and shortened it by as much as 50% perpendicular to plunge (Bleeker, et al., 1996). Structural elongation and shortening has not, however, significantly modified the ridge and dome morphology of the QP rhyolite flow depicted in Figures 2.17 to 2.19. The north and south QP rhyolite ridges are remarkably similar, in mineralogy, textures, structures, morphology and scale to the undeformed Upper and Lower QP

flows of the Millenbach Rhyolite, host to the Millenbach massive sulfide deposits, at Noranda, Quebec (Gibson, 1990; Gibson and Watkinson, 1990).

Volcanic Reconstruction

The QP rhyolite erupted from two, parallel fissures, 800m apart, constructing two, elongate ridges where domes mark vent sites that had high lava extrusion rates and /or sustained eruptions. At the time of their eruption the ridges would have directly overlain their feeding fissures. The fissure below the south ridge is concealed (or removed) by the younger, fault-bounded greywacke. The feeding fissure beneath the north ridge should occur within the area of the mine workings, but QP rhyolite dikes have not been identified. This may reflect drainage and/or collapse of the fissure during waning QP rhyolite volcanism.

The QP rhyolite ridges are interpreted to have formed largely by endogenous growth, where each internal lobe represents a new pulse of magma that was emplaced into the flow. Endogenous growth of the flow/dome occurred along the ridge but was concentrated at two vent areas on the north ridge and one vent area on the south ridge within the area shown in Figure 2.17. Both flank- and flow foot breccias are interpreted to have been derived through slumping, mass wasting, of the rhyolite flow during endogenous dome growth. Flow foot breccia is essentially a flank breccia that has been over-ridden by coherent rhyolite during dome growth. Fragments of sericitized and

silicified rhyolite in flank and flow foot breccias are interpreted to have been derived from altered rhyolite that surrounded paleo-hotsprings on the dome surface. In this scenario the QP rhyolite is interpreted to have been emplaced during hydrothermal activity; an example of coincident and contemporaneous volcanism and alteration. The absence of basalt in the footwall rhyolite succession suggests that occasional, rounded to subangular, basaltic fragments (pebble-size to block-size) found within the breccias may have been derived from contemporaneous mafic volcanism or possibly through explosive eruptions during the initiation of QP rhyolitic eruptions; however, they may also be derived from an external source.

The feeding fissure for the north ridge marks a primary structure, possibly a synvolcanic fault that parallels the known ore bodies. Prior to the eruption of the QP rhyolite this fissure may have been the principal conduit that focused hydrothermal discharge responsible for the formation of the south and southwest orebodies. An ancillary, parallel structure may have been the principal conduit for ascending hydrothermal fluids which formed the north orebody. It is probable that the synvolcanic structure which controlled the eruption of the south QP rhyolite ridge may have also provided a conduit for ascending hydrothermal fluid. This suggests that there is a possibility for additional sulfide lenses to occur, at depth, below the younger greywacke where underlying volcanic strata may be preserved (Figure 2.21).

Mafic sills and overlying basalt flows show limited evidence of hydrothermal alteration (Huston, et al., 1995) which indicates that they were

emplaced during waning hydrothermal activity. Perhaps the emplacement of this thick, basaltic succession and co-magmatic sills may, in part, have been responsible for “shutting-down” the Kidd Creek hydrothermal system.

Figure 2.1. Stratigraphic column of the Kidd Creek formation, Kidd Creek Mine area (ages from Bleeker and Parrish, 1995).

COHERENT FACIES

33

BRECCIA FACIES

5 m
0

Figure 2.2. Idealized stratigraphic sections through coherent facies (vent-proximal) and breccia (distal) facies of the QP rhyolite. Drawing by H. Gibson.

NORTH

SOUTH

WEST WALL, 2101 DRIVE SOUTH

Gabbro Sill

QP Rhyolite Breccia Facies

Figure 2.3. Geological map of west wall of 2101 Drive South. The contact between the upper, chilled margin of the "wedge" gabbro sill and the breccia facies of the QP rhyolite is marked by peperitic breccias where fine-grained apophyses from the sill intruded, autobrecciated, and mixed with QP rhyolite fragmental material. Mapped by H. Gibson.

Figure 2.4. Spider diagram for coherent QP rhyolite showing analyses normalized to the estimated QP rhyolite protolith composition (eQP). 36 samples represented for Y (35), Ce and Th (30), Hf (20) and Ta (19).

Figure 2.5. Spider diagram for coherent QP rhyolite showing analyses normalized to (i) a constant Zr value, and (ii) the estimated QP rhyolite protolith composition (eP_{QP}). Normalization Factor for Zr (NF_{Zr}) = estimated protolith Zr / sample Zr. 48 samples represented for each element except for Y (35), Ce and Th (30), Hf (20) and Ta (19).

Figure 2.6. Nb/Y versus Zr/TiO₂ diagram showing coherent facies QP rhyolite samples (after Floyd and Winchester, 1977). Subalkaline fields: 1 = rhyolite, 2 = rhyodacite/dacite, 3 = andesite, 4 = andesite/basalt and 5 = basalt.

Figure 2.7. Zr/Y versus La_N/Yb_N diagram showing least-altered QP rhyolite samples. Zr/Y dividing lines from MacLean and Barrett (1993); La_N/Yb_N dividing line number 1 from Barrett et al. (1993); La_N/Yb_N dividing line number 2 from Ujike and Goodwin, 1987. Chondrite normalization values are those of Evensen et al. (1978) divided by 1.267 as recommended by Boynton (1984).

Figure 2.8. TiO₂ versus Nb discrimination diagram for the Kidd Creek rhyolites. Filled circles = coherent facies QP rhyolite samples; filled triangles = breccia facies QP rhyolite samples; open circles = coherent and autoclastic breccia samples of FW rhyolite.

Figure 2.9. $\text{Al}_2\text{O}_3/\text{TiO}_2$ versus Nb/Zr discrimination diagram for the Kidd Creek rhyolites. Filled circles = coherent facies QP rhyolite samples; filled triangles = breccia facies QP rhyolite samples; open circles = coherent and autoclastic breccia samples of FW rhyolite; stippled area = field of mafic igneous rocks.

Figure 2.10. $\text{Al}_2\text{O}_3/\text{TiO}_2$ contours for felsic ($>65\%$ SiO_2) volcanic and volcanoclastic rocks in the Kidd Creek Mine area between 410 and 1020 metres below surface (1300 to 3400 foot levels). Data is projected vertically onto the 2800 level. Dark grey = $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios of <80 (QP rhyolite), white = ratios of 80 to 90, light grey = ratios of >90 , black = north and south orebodies, heavy dashed lines = F_1 fold axes, arrows indicate top directions, MNG = mine grid north (azimuth 020°), and dots = felsic volcanic rock sample locations (approximately 50% of the 217 sample locations have been omitted for clarity). Areas with no felsic volcanic samples were assigned a background $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratio of 85. Geochemical and geological data from Falconbridge Limited.

Figure 2.11. $\text{Al}_2\text{O}_3/\text{TiO}_2$ versus Nb/Zr discrimination diagram for the Kidd Creek rhyolites showing samples of the rhyolitic rocks hosting the southwest orebody.

Figure 2.12. SiO_2 versus Al_2O_3 diagram. Filled circles = coherent facies QP rhyolite samples; filled triangles = breccia facies QP rhyolite samples; cross = estimated protolith composition; open box = field of least-altered QP rhyolite samples. Symbols enclosed by diamonds are from samples with strong calcite alteration (up to 31 wt.% CaO and 24 wt.% CO_2).

Figure 2.13. $\text{Fe}_2\text{O}_3(\text{t})$ versus H_2O^+ diagram (data in wt.%). $\text{Fe}_2\text{O}_3(\text{t})$ = total Fe; filled circles = coherent facies QP rhyolite samples; filled triangles = breccia facies QP rhyolite samples; cross = estimated protolith composition; open box = field of least-altered QP rhyolite samples. Symbols enclosed by circles are from samples enriched in S (0.77 - 2.04 wt.% S; remaining samples contain <0.25 wt.% S).

Figure 2.14. MgO versus H_2O^+ diagram (data in wt.%). Filled circles = coherent facies QP rhyolite samples; filled triangles = breccia facies QP rhyolite samples; cross = estimated protolith composition; open box = field of least-altered QP rhyolite samples.

Figure 2.15. Na_2O versus H_2O^+ diagram (data in wt.%). Filled circles = coherent facies QP rhyolite samples; filled triangles = breccia facies QP rhyolite samples; cross = estimated protolith composition; open box = field of least-altered QP rhyolite samples.

Figure 2.16. Cu versus Zn diagram (data in ppm). Filled circles = coherent facies QP rhyolite samples; filled triangles = breccia facies QP rhyolite samples; cross = estimated protolith composition; open box = field of least-altered QP rhyolite samples. Symbols enclosed by circles are from samples enriched in S (0.77 - 2.04 wt.% S; remaining samples contain <0.25 wt.% S).

Figure 2.17. Isopach of the QP rhyolite (coherent and breccia facies) between the 800 and 4700 foot levels (240 to 1430 metres below surface). Contour interval = 20 m, unlabelled contour intervals range from 60 m (light grey) to 120 m (dark grey). The view is toward the east-southeast along the F_1 fold axis. The QP rhyolite has been restored to its pre- F_1 configuration by unfolding about the F_1 hinge such that the base of the QP rhyolite is perpendicular to the F_1 axis and parallel to the F_1 hinge. The isopach is based on 99 continuous intersections, shown as dots, through the QP rhyolite in both diamond drill holes and in underground workings (data from Falconbridge Limited level plans and drill hole logs).

Figure 2.18. Paleotopographic reconstruction of the QP rhyolite (coherent and breccia facies) between the 800 and 4700 Levels. The reconstruction is based on the isopach map. Contour interval = 5 m with contours ranging from 0 to 130 m. The view is upward and toward the east-southeast along the F_1 fold axis. Vertical exaggeration is 4x.

Figure 2.19. North-south section across the north and south QP rhyolite ridges through the two highest domes (no vertical exaggeration).

Figure 2.20. Isopach of QP rhyolite breccia between the 700 (8-1) and 3400 Levels (210 to 1040 m below surface). Light grey = 0-4 m thickness, medium grey = 4-8 m thickness, dark grey = >8 m thickness, triangles = areas of maximum thickness (domes) in the QP rhyolite isopach, dots = data points (underground workings). Arrows indicate inferred flow direction in coherent rhyolite above basal breccia. Thickness data from Falconbridge Limited geological plans.

Figure 2.21. Reconstructed view of the Kidd Creek deposit area subsequent to QP rhyolite volcanism and the onset of mafic volcanism but before intrusion of "wedge" gabbro sill between Middle and Upper members.

Criteria	Least-Altered QP Rhyolite Samples
Na ₂ O	>0.95 wt.%
Loss on Ignition (L.O.I.)	<2.6 wt.%
CO ₂	<1.3 wt.%
H ₂ O	<1.8 wt.%
Cu	<20 ppm
Zn	<70 ppm
Alumina Saturation Index	<1.7
Ishikawa Index	<0.6
Goodfellow Index	<0.35

Table 2.1. Criteria used to select least-altered QP rhyolite samples.

Alumina Index: $Al/(2Ca+Na+K)$, elements expressed as molecular proportions (Shand, 1951).

Ishikawa Index: $(K_2O+MgO)/(K_2O+Na_2O+CaO+MgO)$, oxides expressed as wt.% (Ishikawa et al., 1976).

Goodfellow Index: $(MgO+FeO)/(MgO+FeO+CaO+Na_2O+K_2O)$, oxides expressed as wt.%, FeO = total Fe as FeO (Goodfellow, 1975; Riverin and Hodgson, 1980).

	1073- 667F	1073- 757F	1073- 823F	1073- 877F	14262	14266	eP _{QP}
DDH	1073	1073	1073	1073	2589	1073	
Footage	667	757	823	877	539	949	
SiO ₂ wt. %	75.7	81.3	80.1	74.3	79.7	76.5	77.9
TiO ₂ wt. %	0.150	0.135	0.139	0.178	0.120	0.147	0.145
Al ₂ O ₃ wt. %	12.00	10.40	10.90	13.30	11.30	11.10	11.50
Fe ₂ O ₃ wt. %	0.70	0.39	0.35	1.19	0.46	1.06	0.69
FeO wt. %	1.60	0.40	0.30	1.60	1.10	1.50	1.08
MnO wt. %	0.03	0.04	0.02	0.03	<0.01	0.11	0.04
MgO wt. %	1.51	0.14	0.17	1.18	0.41	0.49	0.65
CaO wt. %	1.85	1.03	1.14	2.38	0.48	3.44	1.72
Na ₂ O wt. %	1.27	3.29	3.91	0.97	4.39	1.52	2.56
K ₂ O wt. %	2.39	1.99	1.47	3.02	1.12	1.89	1.98
P ₂ O ₅ wt. %	0.02	0.02	0.02	0.02	<0.01	0.02	0.02
LOI wt. %	2.55	1.20	1.05	1.70	0.55	2.05	1.52
Sum wt. %	99.90	100.40	99.60	100.00	99.80	100.00	99.95
CO ₂ wt. %	0.72	0.26	0.74	0.14	0.01	1.23	0.52
H ₂ O ⁺ wt. %	1.7	0.4	0.5	1.5	0.6	1.1	1.0
C wt. %	0.39	0.21	0.31	0.06	0.01	0.45	0.24
S wt. %	<0.01	<0.01	<0.01	<0.01	0.08	<0.01	<0.01
Li ppm	13	3	4	13	6	9	8
Be ppm	2	2	1	2	2	2	2
F ppm	358.0	<20	123.0	505.0	<20	481.0	240.5
Sc ppm	3.0	2.2	2.5	3.4	2.4	3.3	2.8
Cr ppm	14.0	13.0	4.0	4.0	14.0	19.0	11.3
Ni ppm	8.0	3.0	2.0	2.0	<1	2.0	2.0
Cu ppm	8.9	4.5	2.5	10.4	19.7	9.8	9.3
Zn ppm	66.4	22.9	29.0	67.8	23.7	62.1	45.3
Ga ppm	28	27	29	32	28	27	29
Br ppm	n.a.	n.a.	n.a.	n.a.	1.5	1.2	0.5
Rb ppm	115	55	45	139	47	118	87
Sr ppm	69.4	49.0	50.2	97.0	62.4	190.0	86.3
Y ppm	81	75	58	93	82	91	80
Zr ppm	246	222	216	277	222	233	236
Nb ppm	16	14	19	18	19	16	17
Mo ppm	<1	<1	<1	<1	<1	<1	<1
Ag ppm	0.4	<0.1	0.2	0.3	<0.1	0.3	0.3
Sn ppm	11	<5	<5	12	11	5	8.0
Cs ppm	n.a.	n.a.	n.a.	n.a.	1.5	2.1	0.6
Ba ppm	257	522	338	401	360	381	377

Table 2.2. See following page for caption.

		1073- 667F	1073- 757F	1073- 823F	1073- 877F	14262	14266	eP _{QP}
La	ppm	41.0	35.3	34.9	46.5	41.9	39.0	39.8
Ce	ppm	92.4	79.3	79.2	107.0	94.0	87.3	89.9
Pr	ppm	9.8	8.4	8.5	11.5	10.1	9.2	9.6
Nd	ppm	41.6	36.3	35.7	50.1	44.1	39.9	41.3
Sm	ppm	9.60	8.70	8.30	12.20	10.40	9.60	9.8
Eu	ppm	1.50	1.26	1.27	1.64	1.50	1.47	1.4
Gd	ppm	10.4	9.4	9.0	12.8	10.9	10.5	10.5
Tb	ppm	2.1	1.9	1.7	2.5	2.1	2.0	2.1
Dy	ppm	11.0	10.6	8.6	13.0	11.1	10.8	10.9
Ho	ppm	2.96	2.94	2.18	3.52	2.91	3.04	2.9
Er	ppm	7.0	7.0	4.9	8.3	6.7	7.2	6.9
Tm	ppm	1.4	1.5	1.0	1.6	1.3	1.5	1.4
Yb	ppm	8.1	8.7	5.8	9.8	7.9	8.9	8.2
Lu	ppm	1.4	1.5	1.0	1.7	1.3	1.5	1.4
Hf	ppm	8.5	7.5	7.9	9.7	8.4	8.3	8.4
Ta	ppm	1.4	0.6	1.0	1.3	1.4	1.1	1.1
Au	ppb	n.a.	n.a.	n.a.	n.a.	<2	<2	<2
Pb	ppm	<2	<2	<2	<2	<2	<2	<2
Th	ppm	8.5	6.3	6.7	9.2	6.7	7.3	7.5
U	ppm	2.2	1.5	1.6	2.1	1.6	1.7	1.8
Goodfellow Index		0.40	0.12	0.11	0.38	0.24	0.30	0.26
Ishikawa Index		0.56	0.33	0.25	0.56	0.24	0.32	0.38
Alumina Index		1.66	1.30	1.28	1.59	1.48	1.11	1.40
La _N /Yb _N		3.41	2.74	4.06	3.20	3.58	2.95	3.32
Eu/Eu*		0.46	0.42	0.45	0.40	0.43	0.45	0.43

Table 2.2. Analyses of six least-altered QP rhyolite samples. Estimated protolith composition for the QP rhyolite (eP_{QP}) represents the average of the least-altered samples except for cases having some values below analytical detection for which median values are shown. Alteration indexes defined in Table 2.1; DDH = diamond drill hole; n.a. = not analyzed; N = chondrite normalized; Eu/Eu* = Eu_N/(0.5(Sm_N) + 0.5(Gd_N)). Chondrite normalization values are those of Evensen et al. (1978) divided by 1.267 as recommended by Boynton (1984).

	eP _{QP}	Add	AC ₁₃₀	AC ₁₀₀
SiO ₂	77.93 g	30.00 g	107.93 g	83.03 g
TiO ₂	0.145 g		0.145 g	0.111 g
Al ₂ O ₃	11.50 g		11.50 g	8.85 g
Fe ₂ O _{3(t)}	1.89 g		1.89 g	1.46 g
MnO	0.05 g		0.05 g	0.04 g
MgO	0.65 g		0.65 g	0.50 g
CaO	1.72 g		1.72 g	1.32 g
Na ₂ O	2.56 g		2.56 g	1.97 g
K ₂ O	1.98 g		1.98 g	1.52 g
P ₂ O ₅	0.02 g		0.02 g	0.02 g
LOI	1.52 g		1.52 g	1.17 g
Zr	0.0236 g		0.0236 g	0.0182 g
Nb	0.0017 g		0.0017 g	0.0013 g
Sum	100 g		130 g	100 g
Al ₂ O ₃ /Zr	487		487	487
Al ₂ O ₃ /Nb	6765		6765	6765

Table 2.3. Example of constant sum effect on analytical values starting with 100 g of protolith. Fe₂O_{3(t)} = total Fe; eP_{QP} = estimated protolith composition of the QP rhyolite; AC₁₃₀ = altered composition (130 g); AC₁₀₀ = altered composition recalculated to 100 g (100 wt.%).

		Number	Minimum	Maximum	Range	RF
SiO ₂	wt. %	36	35.0	84.1	49.1	2.4
TiO ₂	wt. %	36	0.070	0.270	0.200	3.9
Al ₂ O ₃	wt. %	36	5.45	15.70	10.25	2.9
Fe ₂ O _{3(t)}	wt. %	36	0.42	7.92	7.50	18.9
MnO	wt. %	35	0.01	0.51	0.50	51.0
MgO	wt. %	36	0.14	2.34	2.20	16.7
CaO	wt. %	36	0.16	30.50	30.34	190.6
Na ₂ O	wt. %	36	0.01	5.73	5.73	1146.0
K ₂ O	wt. %	36	0.25	4.36	4.11	17.4
CO ₂	wt. %	36	0.01	24.00	23.99	2400.0
H ₂ O ⁺	wt. %	36	0.4	3.3	2.9	8.3
C	wt. %	26	0.01	6.62	6.61	662.0
S	wt. %	26	0.009	0.222	0.213	24.7
Cr	ppm	27	2	180	178	90.0
Cu	ppm	36	2	268	266	148.9
Zn	ppm	36	11	355	344	31.1
Ga	ppm	32	9	32	23	3.6
Rb	ppm	36	11	163	152	14.8
Sr	ppm	36	5	190	185	38.0
Y	ppm	35	37	106	69	2.9
Zr	ppm	36	108	334	226	3.1
Nb	ppm	36	9	21	12	2.3
Ba	ppm	32	58	1830	1772	31.6
Ce	ppm	30	47.3	130.0	82.7	2.7
Yb	ppm	30	3.0	10.7	7.7	3.6
Hf	ppm	20	3.2	8.9	5.7	2.8
Ta	ppm	19	0.5	2.0	1.5	4.0
Th	ppm	30	1.5	9.2	7.7	6.1
U	ppm	30	0.4	2.6	2.2	6.5

Table 2.4. Range factor (RF) values for the coherent facies of the QP rhyolite.

Elements	Correlation	N
Fe ₂ O _{3(t)} - H ₂ O	0.80	46
MgO - H ₂ O	0.88	46
Na ₂ O - H ₂ O	-0.70	45
K ₂ O - H ₂ O	0.35	46
Fe ₂ O _{3(t)} - S	0.38	36
CaO - CO ₂	0.84	44

Table 2.5. Pearson correlation coefficients for QP rhyolite analyses (massive and breccia facies). CO₂-rich samples (>7 wt.%) omitted. N = number of samples. All data normalized to Zr to eliminate apparent correlations due to mass change (constant sum) effects: $N_A = S_A \times eP_{Zr} / S_{Zr}$ where N_A = normalized value for element 'A', S_A = sample value of element 'A'; eP_{Zr} = estimated protolith Zr content and S_{Zr} = sample Zr content.

Chapter 3

RARE EARTH AND HIGH FIELD STRENGTH ELEMENT GEOCHEMISTRY OF THE KIDD CREEK RHYOLITES: EVIDENCE FOR ARCHEAN FELSIC VOLCANISM AND VMS ORE FORMATION IN AN ICELAND-STYLE RIFT ENVIRONMENT

Introduction to Chapter 3

The Archean volcanogenic massive sulfide (Cu-Zn-Pb-Ag) ores of the Kidd Creek Mine are located in the western part of the southern Abitibi greenstone belt, Superior Structural Province, Canada (Figures 1.1 and 1.2). The deposits are hosted primarily within a felsic volcanoclastic sequence, underlain and overlain by rhyolites, within a bimodal volcanic succession (Figures 1.3 and 2.21). The spatial and temporal coexistence of rhyolites, especially those occurring within bimodal mafic-felsic volcanic sequences, and volcanogenic massive sulfide (VMS) deposits is a common, although not universal, association within the Superior Province (e.g., Franklin and Thorpe, 1982; Hutchinson, 1982). Furthermore, VMS deposits within the Superior Province are most likely to occur in proximity to rhyolites with elevated, unfractionated REE profiles and negative Eu anomalies (FIII rhyolites) which may be used as an exploration tool (Thurston, 1981; Leshner et al., 1986; Barrie et al., 1993). This relationship has been ascribed to the presence of

subvolcanic intrusions which yield rhyolitic magma and drive the VMS-forming hydrothermal convection systems (Campbell et al., 1981; Campbell et al., 1982; Leshar et al., 1986), and to high heat-flow environments coupled with favorable volcanological/tectonic settings (Barrie et al., 1993; Barrie, 1995). Previous researchers have suggested extensional mid-ocean ridge environments, such as the axial rift zones of Iceland and the Galapagos spreading centre, and extensional back-arc basin settings as modern analogues for the tectonic environment in which FIII rhyolites are erupted (Hart, 1984; Barrie and Davis, 1990; Barrie et al., 1993; Jackson et al., 1994).

In this chapter I explore two related hypotheses: (i) the incompatible trace element composition of the Kidd Creek rhyolites reflects a particular tectonic environment, and (ii) processes operative in that tectonic setting are favorable for the formation and preservation of VMS ores including the giant Kidd Creek deposit. Differences in chemical composition of basalts and, to a lesser extent, that of granitic rocks as a function of tectonic setting are well documented for modern environments (Pearce and Cann, 1973; Floyd and Winchester, 1978; Wood, 1980; Pearce et al., 1984). Discrimination of the tectonic environment in which the Kidd Creek rhyolites erupted is based upon incompatible element comparisons with post-Triassic felsic volcanic rocks and plagiogranites from known tectonic environments. Non-igneous (metasomatic) chemical variability is minimized by (i) using Kidd Creek data for least-altered samples, and (ii) by basing comparisons on the rare earth elements (REE)

and high field strength elements (HFSE). These elements remained relatively immobile during the Kidd Creek hydrothermal event outside the footwall stringer zone.

A Framework for Geochemical Comparison

Precursor composition for Kidd Creek rhyolites

All rhyolites in the Kidd Creek mine area have undergone some degree of hydrothermal alteration. In order to compare magmatic (pre-alteration) compositions I selected data for least altered, coherent rhyolites and based comparisons on relatively immobile elements. Six FW rhyolite samples (Lower member) and 6 QP rhyolite samples (Upper member) were selected as being representative of relatively unaltered Kidd Creek formation rhyolites - selection criteria and analyses of selected FW rhyolites are shown in Tables 3.1 and 3.2. Selection criteria and analyses of the 6 least altered QP rhyolite samples are presented in Tables 2.1 and 2.2. Analytical techniques are described in Appendix 3.

Element mobility

Within igneous rocks sharing the same protolith (magmatic) composition, constant interelement ratios are maintained between immobile elements during metasomatism, irrespective of overall mass change, whereas interelement ratios do not remain consistent between element pairs in which one or both elements been mobilized. (Gresens, 1967; Grant, 1986; MacLean, 1990). A spider diagram (Figure 3.1) illustrates compositional data for the six least-altered FW rhyolites, normalized to the composition of least-altered FW rhyolite sample 14259. The elements shown, listed in increasing atomic number, are commonly used in petrogenetic studies except for Al and Ga (e.g., Wood, 1980; Sun, 1980; Thompson, 1982; Sun and McDonough, 1989). Constant interelement ratios, which have values near 1.0 for these samples indicating no significant mass changes, are evident for Al, Ti, Ga, Y, Zr, Nb, Hf, Ta, Th, U and the REE. In contrast K, Sc, Rb, Sr, and Ba data indicate their considerable mobility. Similar results are obtained using the least-altered QP rhyolite samples (Table 2.5).

In order to test for the immobility of Al, Ti, Ga, Y, Zr, Nb, Hf, Ta, Th, U and the REE during intense alteration, data from strongly altered samples of the footwall stringer zones beneath the north and central orebodies were plotted on a least-altered FW rhyolite normalized spider diagram (Figure 3.2). The

altered samples are two chloritites ($<26\%$ SiO_2 , $>21\%$ Al_2O_3 , $>9\%$ MgO and $>10\%$ H_2O), one sericitite (58.2% SiO_2 , 23.9% Al_2O_3 , 5.9% K_2O), and five silicified autoclastic rhyolite breccia ("cherty breccia") samples ($84\text{--}89\%$ SiO_2 , $0.04\text{--}0.37\%$ Na_2O). The patterns show considerable scatter that is in part due to the mass change (closure) effects caused by silicification and chloritization (MacLean and Barrett, 1993). In order to overcome the problem of mass change effects the data have been doubly normalized to Al; the results are shown in Figure 3.3 (all element concentrations have been multiplied by a mass change factor (M.C.F.) which yields a constant Al value in the reconstructed composition (MacLean, 1990); $\text{M.C.F.} = \text{Al}_{\text{LA}}/\text{Al}_{\text{S}}$ where S is any sample and LA is least-altered sample 14259). Relatively constant interelement ratios exist for all samples between Al, Ti, Zr, Nb, Th and U, and in 7 of the 10 samples between these elements and the heavy rare earth elements Dy and Yb (Hf and Ta were not analyzed). However, the patterns of La, Nd and Eu indicate considerable loss of the LREE in the strongly altered stringer zone samples consistent with the findings of Campbell et al. (1984).

Compilation of post-Triassic data

The certainty with which tectonic environments may be identified in the geologic record is, in general, inversely related to age. As a consequence most of the analyses in the comparative database are from Cenozoic rocks but

some Jurassic and Cretaceous examples have been included. VMS deposits form at or below the seafloor so, where possible, samples for the post-Triassic comparative database were selected which originated in or near marine environments. In modern oceanic environments, felsic volcanism occurs at intraplate islands, ensimatic arcs, ensialic arcs and rift zones including non-spreading rifts, immature spreading centres and mature spreading centres (as used in this Chapter spreading refers to areas in which new oceanic crust is being created). The post-Triassic database consists of 41 published analyses of rocks considered to be representative of felsic igneous products in oceanic tectonic settings including samples of rhyolite, high-Si dacite, rhyodacite, dacite, pantellerite, comendite, plagiogranite and quartz diorite (Table 3.3). Volcanic rocks (flows, domes, pyroclastic rocks and high-level dikes) were chosen preferentially over plutonic rocks, and analyses with rhyolitic rather than dacitic compositions were selected where available to match the high-Si values of the Kidd Creek rhyolites.

The most striking difference between rhyolites of the Kidd Creek formation and the post-Triassic data is the difference in ages (2710-2715 Ma versus <200 Ma). Over time, the formation of continental crust has depleted the upper mantle in incompatible elements relative to the estimated composition of the primitive mantle (Hofmann, 1988). The mantle has also been modified by recycling of material in subducting oceanic plates and in cold plumes

(Campbell and Griffiths, 1993). The degree of change in mantle composition from the late Archean to present day continues to be a matter of controversy but most evidence suggests that sweeping changes in mantle composition during the past 2.7 billion years are unlikely (Taylor and McLennan, 1985; McCulloch and Bennet, 1994; Drummond and Defant, 1990; Condie, 1989). This contribution follows the implicit assumption of Condie (1989) that whatever changes have occurred are probably small relative to the magnitude of chemical variation imposed on magmas by tectonic environment (Appendix 2).

Comparison of the Kidd Creek Rhyolites To Post-Triassic Felsic Rock Suites

REE-HFSE spider diagrams: the basis for comparison

In order to make reasonable comparisons of primary petrochemical features where altered rocks are involved the effects of metasomatism must be minimized. The high field strength elements Y, Zr, Hf, Nb, Ta, Th and U (HFSE; Rollinson, 1993) and the rare earth elements (REE) were relatively immobile in rhyolites which escaped intense hydrothermal alteration at Kidd Creek whereas several other elements commonly used in petrogenetic studies have experienced considerable mobility. Geochemical comparison of these elements is facilitated by using a chondrite-normalized REE-HFSE spider

diagram as shown in Figure 3.4 for the 12 least altered Kidd Creek rhyolite compositions (chondrite normalization values are listed in Appendix 5). The left part of the diagrams consists of the familiar REE spider diagram while the high field strength elements Y, Zr, Hf, Nb, Ta, Th and U are listed in the right side of the diagram in order of increasing concentration in continental crust relative to primitive mantle - a measure of element incompatibility (Hofmann, 1988). Thus the most incompatible elements, La, Ce, Th and U, are located at the ends of the diagram and the least incompatible elements, the HREE and Y, are located near the centre. For many felsic volcanic suites, including rhyolites of the Kidd Creek formation, this arrangement of elements results in broad, concave-upward patterns disrupted by negative Eu anomalies.

Kidd Creek

All least-altered rhyolite samples from the Kidd Creek formation have nearly identical REE-HFSE profiles and were considered as a single group of rocks for this study; geochemical discrimination between FW rhyolite (Lower member) and QP rhyolite (Upper member) is discussed in Chapter 2 (Figures 2.8 to 2.10). The REE part of the spider diagram is characterized by relatively shallow slopes ($La_N/Yb_N = 2.7-4.1$) and moderate, negative Eu anomalies ($Eu/Eu^* = 0.32-0.50$). The overall slope is due to a moderately steep LREE profile with the HREE pattern being essentially flat. On the extended part of the

diagram the Kidd Creek rhyolites display a gradual overall increase from Y to Ta, a steep slope between Ta and Th and a very slight decline from Th to U. Overall the traces for the REE and HFSE define a broad, concave upward pattern with a moderate trough at Eu and a Th-U plateau. The unusual sawtooth pattern for the HREE data between Dy and Tm is believed to be an analytical artifact (REE analyses by ICPMS).

Intraplate oceanic islands

Intraplate oceanic islands consist of seamounts that are commonly regarded as the surface manifestations of mantle plumes or hotspots (Wilson, 1973; Wilson, 1989; McBirney, 1993). Rhyolite (including peralkaline rhyolite, comendite and pantellerite) is recorded in only a few of these islands and comparisons with Kidd Creek rhyolite are made using representative analyses from Gran Canaria (peralkaline rhyolite), Ascension (comendite) and Pinzon (tholeiitic rhyolite; Table 3.3). Rhyolites from the intraplate islands are characterized by strong enrichment in Nb, Ta, Zr and Hf resulting in a noticeable hump between Y and Th in the REE-HFSE profiles (Figure 3.5). Their REE profiles are relatively steep with variable Eu anomalies.

Ensimatic arcs

Comparative data for ensimatic island arcs consist of analyses of dacite and rhyolite erupted in arc and fore arc environments from four areas: (i) Fiji and the Tonga fore arc, (ii) Izu-Bonin arc and fore arc, (iii) Adak Island in the central Aleutians, and (iv) the Virgin Islands (Table 3.3). Felsic volcanic rocks from ensimatic arcs such as those of the western Pacific are characterized by relatively flat REE patterns, general absence of Eu anomalies, subdued Th contents and strongly depleted Nb and Ta values resulting in a distinct Nb-Ta trough on the REE-HFSE diagram (Figure 3.6).

Ensialic arcs

Ensialic arcs are represented in the database by analyses from (i) volcanic islands in the Aegean (Milos, Santorini), (ii) the Taupo volcanic zone, New Zealand, (iii) the Padang area, Sumatra, and (iv) the Valley of Ten Thousand Smokes, Alaska. Felsic volcanic rocks from ensialic arcs are characterized by LREE enrichment, moderately steep LREE trends, moderate to strong negative Eu anomalies, relatively flat HREE patterns and strong Th enrichments producing a steep slope between Y and Th on the REE-HFSE diagram (Figure 3.7).

High-Al arc suites (adakites)

Adakites, which occur in both ensialic and ensimatic Cenozoic arcs, include andesite, dacite and sodic rhyolite, with dacite most common, and their intrusive equivalents tonalite and trondhjemite (Defant and Drummond, 1990). Adakites appear to be equivalent to the high-Al trondhjemite-tonalite-dacite (TTD) suite of rocks which occur in terranes from the Archean to the Phanerozoic (Defant and Drummond, 1990; Drummond and Defant, 1990; Kay et al., 1993). These rocks are believed to form by direct melting of young, hot subducted oceanic crust (eclogite with or without amphibolite) leaving garnet and amphibole in the residue, making them genetically distinct from rocks derived by melting in the mantle wedge above the slab (Drummond and Defant, 1990, 1993; Defant and Drummond, 1990). This distinctiveness is readily apparent on a REE-HFSE spider diagram, shown in Figure 3.8, showing representative data for felsic volcanic samples from adakite/high-Al TTD suites (Table 3.3). The patterns are characterized by extremely steep REE profiles and the absence of negative Eu anomalies which clearly distinguishes them from mantle derived felsic igneous rocks.

Rift zones

Rift zones, a consequence of crustal extension, may be subdivided on the basis of (i) location (continental, back-arc, mid-ocean) and (ii) maturity. Rifts are initiated as non-spreading extensional zones in both oceanic and continental settings in which crust is thinned by block faulting and attenuation as a result of extensional tectonism, commonly accompanied by high heat flow, but true spreading - the formation of new oceanic crust - has not yet occurred. If extension is relaxed the rift may fail to open and an aborted (failed) rift is preserved in the geologic record. With continued extension continental rifts, back-arc rifts (marginal basins) and immature mid-ocean rifts may develop into mature mid-ocean ridges.

Mature mid-ocean ridges

Most felsic volcanism and plutonism along mid-ocean ridges (mature spreading centres) seems to occur along anomalous ridge segments characterized by the eruption of enriched MORB (E-MORB) or transitional (T-MORB) basalt. Iceland is both the most prolific known source of felsic magmatism in a mid-ocean ridge environment and the best documented (Saemundsson, 1978; O'Nions and Gronvold, 1973; MacDonald et al., 1987; Sigurdsson, 1977; Walker, 1966; Wood, 1978). Icelandic data used include

analyses for two rhyolites from the neovolcanic central volcanoes of the eastern axial rift zone (Askja and Krafla) and two rhyolites from Tertiary felsic volcanic complexes near Iceland's east coast (Thingmuli and Reydarfjordur). Data are also used for rhyodacite dredged from the Galapagos spreading centre, a plagiogranite from the mid-Atlantic ridge at 45°N and a quartz monzonite from the Argo Fracture Zone in the Indian Ocean (Table 3.3). The latter sample is somewhat atypical in that it is associated with LREE depleted (N-MORB) tholeiites (Engel and Fisher, 1975; Hedge et al., 1979).

The four Icelandic rhyolites are moderately enriched in LREE and the more incompatible HFSE resulting in shallow concave upward REE-HFSE patterns (Figure 3.9). Rhyolites from the neovolcanic, axial rift zone volcanoes Kerlingarfjoll and Namafjall, not shown on Figure 3.10, have similar REE patterns (O'Nions and Gronvold., 1973). The REE-HFSE trace of the Askja rhyolite is an almost perfect match for Kidd Creek rhyolites. The rhyolite data from Krafla, Thingmuli and Reydarfjordur are also quite similar to those of the Kidd Creek rhyolites but are displaced to somewhat higher values. The Galapagos spreading centre, Mid-Atlantic ridge, and Argo Fracture Zone data, shown in Figure 3.10, are also quite similar to Kidd Creek data except for slightly flatter REE slopes and the very pronounced negative Eu anomaly of the quartz monzonite from the Argo Fracture Zone.

Immature mid-ocean rifts

Immature mid-ocean rifts with associated felsic volcanism include (i) the non-spreading lateral rift (flank) zones of Iceland (Saemundsson, 1978), and (ii) the Terceira Rift zone of the Azores Archipelago, a recently formed spreading axis at the western end of the African-Eurasia plate boundary which is undergoing slow oblique extension (Mungall and Martin, 1995; White et al., 1979). Comparative analyses are presented for a pre-postglacial (>10,000 year old) peralkaline rhyolite and a postglacial subalkaline rhyolite from the Torfajokull volcanic complex in Iceland's South Eastern Zone (MacDonald et al., 1990; McGarvie et al., 1990) and a comendite from the island of Terceira in the Azores (Table 3.3). These samples have high overall REE and HFSE contents with particularly strong enrichments of Zr, Hf, Nb, Ta, Th, U and the LREE. Data for the two peralkaline samples, Azores T-13 and Torfajokull ORU5, show a Nb-Ta hump similar to intraplate oceanic islands (Figure 3.11).

Back-arc marginal basins

Felsic volcanic rocks from ensimatic marginal basins are represented in the database by analyses for a representative rhyolite from the Sumisu Rift, a back-arc basin behind the Izu-Bonin arc in the western Pacific, and a fresh

dacite glass and an altered dacite from the PACMANUS hydrothermal VMS deposit site in the eastern Manus back-arc basin south of New Ireland (Gill et al., 1992; Binns and Scott, 1993; Table 3.3). The Sumisu Rift rhyolite displays the Nb-Ta trough, lack of Eu anomaly, low overall REE-HREE contents and subdued Th and U values characteristic of ensimatic island arcs (Figure 3.12). However, compared to Izu arc, the Sumisu Rift rhyolites have the higher overall contents of REE and HFSE and display LREE enrichment (elevated La_N/Yb_N ratios). Both PACMANUS dacite samples display fairly flat REE patterns, lack Eu anomalies, and have low Th-U contents typical of ensimatic island arc felsic volcanic rocks (Figure 3.12). In addition the fresh dacite has a pronounced Nb trough (Nb was not analyzed in the altered sample and Ta was below the detection limit of 1 ppm). The elevated Ta value in the fresh dacite probably reflects Ta contamination from grinding in a tungsten carbide mill (R. A. Binns, CSIRO, Australia, written communication, 1995). Note the similarity between the REE-HFSE patterns of the fresh and altered PACMANUS dacites indicating relative immobility of the REE and HFSE in the PACMANUS hydrothermal system.

Comparative data for felsic igneous rocks formed in ensialic marginal basins are from (i) a preore and postore dacite from the Miocene succession hosting the Kuroko VMS ores of the Hokuroku District, Japan (aborted ensialic arc rift), (ii) Quaternary rhyodacite from Deception Island, Bransfield Strait

(back-arc spreading centre), and (iii) Late Jurassic plagiogranite from the Rocas Verdes ophiolite complex of southern Chile (aborted back-arc spreading centre; Table 3.3). The REE and HFSE patterns of the Deception Island rhyodacite and the Rocas Verdes plagiogranite are similar to those of the Kidd Creek rhyolites except for their shallower LREE slopes and distinctive Zr peaks relative to Nb (Figure 3.13). The Hokuroku dacite is similar to Kidd Creek rhyolite except for higher U/Th and U/Y ratios and generally lower overall REE-HFSE contents.

Continental rifts

Data are available from five areas in which subalkaline rhyolites have been erupted in association with continental rifting; (i) the Afar area, Ethiopia, (ii) the Salton Trough, California, (iii) the Red Sea coast, Saudi Arabia, (iv) the central Queensland coast, Australia, and (v) the Lord Howe Rise, Tasman Sea (Table 3.3). The Afar area is near the non-spreading Ethiopian Rift, the Salton Trough is in the incipient stages of spreading and the Red Sea is young spreading centre (Walter et al., 1987; Herzig and Jacobs, 1994; Pallister, 1987). The rhyolites from the Queensland coast and the Lord Howe Rise are of Cretaceous age and are believed to have erupted in small continental rift basins which formed prior to the breakup of eastern Australia and the opening of the Tasman Sea (Bloomer et al., 1994; Ewart et al., 1992).

Composition profiles for the Afar, Salton Trough and Saudi Arabia rhyolites are very similar and may be distinguished from the Queensland and Lord Howe Rise rhyolites; the latter have relatively low HREE and Y contents (Figure 3.14). All of the continental rift rhyolites shown on Figure 3.14 have REE and HFSE contents comparable to Kidd Creek rhyolite with the exceptions of Th and U enrichments and lower HREE and Y values in the Queensland-Lord Howe Rise rhyolites. The strong Th-U enrichment of the continental crust may explain the distinctive enrichment of Th and U in the continental rift rhyolites reflecting assimilation or partial melting of continental crust.

Discussion

Comparative geochemistry

There is good correlation among data for rhyolites of the Kidd Creek formation and (i) subalkaline rhyolites from mid-ocean ridges exemplified by Iceland, and (ii) subalkaline rhyolites associated with zones of continental rifting (Afar area, Red Sea and Salton Sea). The closest match is with rhyolite pumice from the 1875 eruption of Askja in Iceland's eastern axial rift zone. Relative to the Icelandic examples Kidd Creek rhyolites are somewhat

depleted in Nb and Ta whereas the continental rift rocks tend to have Nb-Ta values similar to those of Kidd Creek but Th and U enrichments typical of continental crust (Taylor and McLennan, 1985). Several lines of evidence are not compatible with a continental component in Kidd Creek rhyolites including (i) lack of continental clastic sedimentary rocks in the Kidd Creek area, (ii) general lack of inherited zircons in preorogenic (>2700 Ma) volcanic rocks in the Abitibi Greenstone Belt (Corfu, 1993), (iii) lack of inherited zircons in Kidd Creek rhyolite (Bleeker and Parrish, 1996; Barrie and Davis, 1990), and (iv) Pb and Sm-Nd isotopic results for Kidd Creek igneous rocks consistent with a mantle or mantle-derived source (Barrie et al., 1996; Chapter 4). In addition, the Kidd Creek ores have low $Pb/(Cu+Zn+Pb)$, typical of mid-ocean ridge deposits, whereas VMS deposits associated with continental crust, such as the Kuroko deposits and the modern seafloor deposits of the Okinawa trough, have high $Pb/(Cu+Zn+Pb)$ (Fouquet et al., 1993). Thus the closest geochemical match for Kidd Creek rhyolite is subalkaline rhyolite erupted from central volcanoes within Iceland's axial rift zones. Similarity between Kidd Creek and the axial rift zones of Iceland's is not limited to rhyolite geochemistry.

Within Iceland's neovolcanic zones subalkaline volcanism is concentrated along fissure swarms within extensional axial rift zones which represent extensions of the mid-Atlantic ridge (Saemundsson, 1978; Marsh et al., 1991; MacDonald et al., 1990). Central volcanoes formed within the axial rift

zones are compositionally bimodal being constructed primarily of basalt and rhyolite with a paucity of intermediate compositions (Carmicheal, 1964; McGarvie et al., 1990; Sigurdsson, 1977; MacDonald et al., 1987). A strong basalt-rhyolite bimodality also exists in the Kidd Creek area. A histogram (Figure 3.15) comparing the SiO_2 distribution of 542 volcanic rock analyses from Iceland (Sigurdsson, 1977) and 975 igneous rocks intersected in exploration drill holes in the Kidd Creek area (data from Falconbridge Ltd.) illustrates a pronounced gap in intermediate compositions. Note that ultramafic compositions are not shown and that the Kidd Creek data are biased by an overabundance of rhyolitic analyses as exploration drilling targeted felsic volcanic rocks. Icelandites, andesitic rocks with elevated Fe, Ti and P contents, occur in restricted amounts in both settings (Oskarsson et al., 1985; Wood, 1978; Barrie et al., 1996).

The subalkaline basalts of Iceland and the subvolcanic mafic sills at Kidd Creek both have E-MORB compositions as illustrated on the Th-Hf-Nb tectonomagmatic discrimination diagram in Figure 3.16. Mg-rich extrusive rocks, a product of high mantle temperatures (high degrees of partial melting), are a product of both the Kidd Creek and Iceland magmatic systems. Within Iceland, which is located above a mantle plume, picrites containing up to 20.6% MgO have been erupted in the eastern and western axial rift zones (Hemond et al., 1993). Within the ultramafic rocks beneath the Kidd Creek Mine

package, which include spinifex textured komatiite flows, less altered samples (<5% loss on ignition) contain up to 23.1% MgO (J. Everest, written communication, 1995).

Comparative volcanology

The Kidd Creek mine area represents a local centre of volcanism consisting mainly of rhyolitic lava and felsic volcanoclastic rocks, possibly within the upper part of a central volcanic complex, overlain by extensive basaltic flows, intruded by subvolcanic mafic sills, and underlain by ultramafic rocks. Reconstruction of rhyolite morphology at Kidd Creek indicates emplacement of the QP rhyolite along fissures spaced approximately 800 m apart (Figure 2.17 to 2.19). At the Torfajökull central volcano, Iceland, five postglacial silicic lava units have erupted from parallel volcanic fissures spaced approximately 1 to 3 km apart (MacDonald et al., 1990). There is a paucity of distally derived, non-volcanogenic sedimentary rocks at Kidd Creek, as well as in Iceland, which is consistent with (i) an environment located far from continental margins, and/or (ii) the construction of a large, volcanic edifice. The Kidd Creek VMS deposits have been interpreted to occur within a graben or half-graben (Bleeker and Parrish, 1996). The existence of coarse, polymict breccias, stratigraphic offsets, and the alignment of rhyolite ridges and elongate sulfide orebodies within the Kidd Creek succession are consistent with the development of

grabens or half-grabens during synvolcanic faulting along a rift zone, and with caldera development resulting from collapse within the upper part of a shield-like volcanic edifice. Over time Icelandic central volcanoes are displaced to the margins of the axial rift zone, become extinct and are eventually buried under younger flood basalts fed mainly by fissure eruptions (Walker, 1966; Saemundsson, 1978; Piper, 1971). These flood basalts may be similar to the thick succession of basaltic flows and breccias which overlie the QP rhyolite (Figures 1.3 and 2.21).

Fingers and lenses of rhyolite peperite, which indicate injection of a low-viscosity, high-temperature felsic magma, occur within footwall rocks of the Kidd Creek deposit (H. Gibson, personal communication, 1995). Barrie (1995) estimates temperatures of approximately 840°C to 920°C for rhyolites in the Kidd Creek area based on zircon geothermometry. Temperature estimates for rhyolite from the 1875 eruption of Askja in Iceland's eastern axial rift zone are in the range of 990°C to 1010°C suggestive of superheating by underlying basaltic magma (Sigurdsson and Sparks, 1981). High-temperature geothermal fields occur within the central volcanoes of Iceland; drilling beneath the Krafla caldera has revealed temperatures in excess of 340° at 2 km depth (Bjornsson et al., 1977; Saemundsson, 1978). Tertiary central volcanoes exposed in eastern Iceland reveal extensively propylitised cores representing

large hydrothermal reservoirs, each with a volume of the order of 100 km^3 , and there is a close coincidence between the distribution of felsic rocks and the areas of intense hydrothermal alteration (Walker, 1966).

Petrogenesis

Strong geochemical and volcanological similarities suggest that the petrogenetic history of the Kidd Creek rhyolites may be similar to that of rhyolites erupted from central volcanoes in the axial rift zones of Iceland. Several studies have concluded that Iceland rhyolites form by partial melting of juvenile crust with the rock type undergoing anatexis being either hydrated basalt, plagiogranite or felsic differentiates formed during the crystallization of mafic igneous bodies (O'Nions and Gronvold, 1973; Sigurdsson, 1977; Oskarsson et al., 1982; Marsh et al., 1991; Sigmarsson et al., 1991; Sigmarsson et al., 1992). Burial by subsequent eruptions and accompanying isostatic readjustments result in the rapid downward migration of crust with subsidence rates of up to several km/m.y. This subsidence coupled with high geothermal gradients (up to $160^\circ\text{C}/\text{km}$) in the axial rift zones provide favorable conditions for partial melting (Marsh et al., 1991; Meyer et al., 1985; and references therein). High magma production rates and Mg-rich picritic lavas are manifestations of an ascending plume (hotspot) beneath Iceland (Hemond

et al., 1993; Bjornsson, 1985). The komatiite-bearing ultramafic succession, which forms the footwall to the Kidd Creek Mine package, and high eruption temperatures for the rhyolites (Barrie, 1995) suggest that steep geothermal gradients, possibly related to a mantle plume, existed beneath Kidd Creek. Experimental study by Spulber and Rutherford (1983) has shown that 10% partial melting of an oceanic tholeiite from Kilauea, Hawaii, under relatively reducing conditions, can produce a rhyolitic melt (73.1% SiO₂, 4.32% Na₂O, 2.39% K₂O) similar to naturally occurring Icelandic rhyolites.

If the Iceland analogy is correct and the Kidd Creek rhyolites did indeed form by partial melting it may provide an explanation for the remarkable similarity between rhyolites at the base (FW rhyolites) and top (QP rhyolites) of the Kidd Creek formation which, according to U-Pb zircon dates, erupted at least 1.4 million years apart (Bleeker and Parrish, 1995). It is unlikely that a siliceous magma with nearly homogeneous composition was maintained for this time span or that fractional crystallization in two separate chambers produced such similar differentiates. However, if the rhyolites formed by near eutectic partial melting of a common parent under similar pressure-temperature conditions then compositionally similar rhyolitic products would be expected.

Information on the petrogenesis of the Kidd Creek rhyolites can also be obtained by evaluating their REE and HFSE contents which reflect source composition, source restite mineralogy, rhyolitic liquid composition, and magma temperature. Flat HREE profiles are incompatible with garnet or amphibole in the residue while negative Eu anomalies indicate retention of plagioclase (Hanson, 1978). The high overall REE and HFSE contents of the Kidd Creek rhyolites, compared to most subalkaline rhyolites, are compatible with (i) derivation from an incompatible element enriched source (e.g., E-MORB), and (ii) high magmatic temperatures (Montel, 1993; Watson and Harrison, 1983; Barrie, 1995). All of these characteristics are consistent with the formation of the Kidd Creek rhyolites by partial melting in an anomalous mid-ocean ridge environment with high heat flow. Magmatic temperatures of 840 to 920°C (Barrie, 1995) suggest that after they were formed the Kidd Creek rhyolite magmas continued to thermally interact with mafic-ultramafic magmas, possibly in a compositionally zoned magma chamber (Hildreth, 1979, 1981). High rhyolite magmatic temperatures are not consistent with a fractional crystallization model in which rhyolitic magma is only produced after much of the original basaltic magma has cooled and crystallized.

Comparison of the Kidd Creek Rhyolite With Other Superior Province Felsic Volcanic Rocks Associated With VMS Deposits

REE and HFSE abundances in post-Triassic felsic volcanic rocks and plagiogranites vary considerably between tectonic environments whereas within a tectonic environment most felsic igneous rocks display limited variability. Therefore, within post-Triassic felsic volcanic rocks geochemical variability of these elements is, to a large extent, controlled by tectonomagmatic processes. It is reasonable to hypothesize that much of the REE and HFSE variability observed in Archean successions may also be a product of tectonomagmatic processes.

Leshner et al. (1986), building on the work of Condie (1976; 1981) and Campbell et al. (1982), proposed the subdivision of Archean metavolcanic rocks into four groups based on trace element geochemistry (FI, FII, FIIIa and FIIIb). Average analyses for each of these groups, determined from data presented by Leshner et al. (1986), are shown in REE-HFSE diagrams in Figure 3.17. Comparison of the Archean group FI - FIIIb data to the REE-HFSE profiles of the post-Triassic data (Figures 3.5 to 3.14) indicate that group FI is similar to adakites, groups FII and FIIIa are similar to felsic volcanic rocks erupted in ensialic island arcs (e.g. Aegean island arc and New Zealand rhyolites) and ensialic back-arc basins (e.g. Hokuroku District high-Si dacites), and group

FIIIb is similar to the rhyolites and plagiogranites of mid-ocean ridges (e.g., rhyolites of Iceland's axial rift zones). Similar observations were made by Barrie et al. (1993). Thus the variability in REE and HFSE contents observed within felsic volcanic rocks of the Superior Province may be accounted for by differences in tectonic settings (tectonomagmatic variability). This does not necessarily imply that the tectonic processes operative during the late Archean were identical to those of the present day. One of the most striking features noted during the comparison of data from Superior Province felsic volcanic rocks to the post-Triassic data is the absence of a Superior Province geochemical analogue for ensimatic island arc felsic volcanic rocks (compare Figure 3.6 to Figure 3.17). This is particularly significant in light of many current models for the evolution of the Superior Province by accretion of oceanic terranes including island arcs (e.g. Jackson and Cruden, 1995; Jackson et al., 1994; Stern et al., 1994; Kimura et al., 1993; Hoffman, 1991).

Kidd Creek rhyolites have REE and HFSE abundances intermediate between FII, FIIIa and FIIIb felsic volcanic rocks but large negative Eu anomalies and small Zr_N/Y_N ratios, due to relative HREE and Y enrichment, favor their inclusion in the FIIIb group (Figure 3.17).

Formation and Preservation of the Kidd Creek VMS Deposit

Tectonomagmatic processes

Geochemical and volcanological similarities make it reasonable to speculate that many of the processes occurring in the central volcanoes of Iceland's axial rift zones also occurred at Kidd Creek. The most important of these, with respect to VMS formation, are high heat flow and subsidence. High heat flow drives the hydrothermal circulation system and may also result in production of rhyolitic magma by partial melting. Subsidence, either as a result of caldera collapse or graben development in an extensional environment, provides cross-strata permeability which focuses hydrothermal discharge. A second benefit of subsidence is that discharge is likely to occur within clastic/volcaniclastic debris covering the floor of the subsidence structure resulting in subseafloor sulfide mineralization by open space filling, hydraulic jacking or replacement, thereby improving the efficiency of sulfide deposition (i.e. less metal dispersed into seawater by "black smokers"). The TAG VMS deposit on the Mid-Atlantic Ridge, estimated to contain about 4 million tonnes of massive sulfides, is believed to be formed primarily by hydrothermal replacement within breccias (Humphris et al., 1995). A subseafloor replacement model has also been applied to the Horne deposit, the largest of the known VMS deposits in the Noranda camp (54.3 million tonnes of ore

extracted; Kerr and Gibson, 1993). Evidence of high heat flow during the formation of the Kidd Creek volcanic centre is recorded by komatiites, which have liquidus temperatures of about 1600°C (Campbell et al., 1989; Jochum et al., 1991), and zircon saturation temperatures of 840 to 920°C in Kidd Creek rhyolites (Barrie, 1995). The existence of a subsidence structure in the Kidd Creek mine area is suggested by a pronounced local thickening of felsic volcanoclastic rocks, and by the presence of heterolithic, poorly sorted, sulfide clast-bearing breccias.

Lifespan and volcanic accumulation rate

U-Pb dating of zircons by Bleeker and Parrish (1995) indicates that felsic volcanism at Kidd Creek occurred over a time interval of 1.4 Ma to 6.1 Ma which is somewhat anomalous for the emplacement of only 300 - 500 m of volcanic and volcanoclastic strata (average accumulation rate between 60 and 300 m per m.y.). Felsic volcanic complexes of Iceland have typical life spans of 0.5 - 1.0 million years and average accumulation rates of basaltic lava in Iceland have been estimated at 690 to 730 m per m.y. (Piper, 1971; McDougall et al., 1976, 1977). At Noranda, Quebec, the 7 to 9 km thick Noranda volcanic complex, interpreted to be a large shield volcano, may have been formed in as little as 3.5 m.y. for an average accumulation rate of between 2000 and 2600 m per m.y. (Mortensen, 1987; Gibson and Watkinson, 1990). Low accumulation

rates of lava and volcanoclastic material at Kidd Creek would have allowed hydrothermal convection to remain focused over long periods of time.

A model for the association of rhyolites and VMS deposits in ancient bimodal successions

A disproportionate number of ancient VMS deposits, including the Kidd Creek deposit, are underlain by rhyolitic volcanic rocks. More than 70% of VMS deposits on land are associated with felsic volcanic centres (Franklin et al., 1981) and 56% (284 of 508 deposits studied) are immediately underlain by rhyolitic rocks (Rona, 1988, and references therein). Only 86 of the 508 deposits studied (17%) are underlain by basalt ; the dominant volcanic product in most modern oceanic settings and in greenstone belts (Rona, 1988; Franklin and Thorpe, 1982; Goodwin, 1977). In contrast to ancient VMS deposits, modern seafloor sulfide deposits are commonly basalt or sediment hosted with no indication of contemporaneous rhyolites or dacites (Rona, 1988; Rona and Scott, 1993). This data suggests that felsic magmatic activity is favorable, but not essential, for the formation off VMS deposits.

One possible explanation for the rhyolite association lies in the physical differences between rhyolitic and mafic-ultramafic magmas; rhyolites being cooler, more viscous, and less dense. The model proposed below is based

loosely on (i) an Iceland axial rift central volcano with a summit caldera, and (ii) the geology of the Kidd Creek mine area. Rhyolite magma in contact with basaltic (-ultramafic) magma will ascend through the magmatic plumbing network because of its lower density; its viscosity lowered through superheating by the surrounding, hotter magma (the process by which the rhyolitic magma forms is immaterial to the model). Eventually the rhyolitic magma will collect in the upper part of the magma system, perhaps forming a compositionally zoned subvolcanic magma chamber (Hildreth, 1979, 1981), and felsic volcanism will commence. The low density cap of siliceous magma forms a physical barrier to the upward movement of more mafic magmas (Thurston et al., 1985) and subsequent eruptions of mafic (-ultramafic) magma will seek alternate routes to the surface. If the original conduit system fed the central part of a volcanic edifice, such as the caldera of a central volcano, pre-rhyolite basalt (-komatiites) would erupt near the summit whereas post-rhyolite magmas may work their way laterally along fissures and erupt on the flanks of the volcano or on the surrounding plain. Lateral magma flow along fissures away from central volcanoes has been documented in Iceland (Sigurdsson and Sparks, 1978; Sigurdsson and Sparks, 1981). This change in magma conduits, initiated by the introduction of rhyolitic magma, results in a period of relative volcanic quiescence in the summit area. However, hydrothermal convection, which is centred beneath the central volcano due to high magma productivity in this area, will continue to rise along subsidence faults and vent

in the caldera. Magma chamber recharge, accompanied by flank eruptions, provides sustained thermal energy to drive a long-lived hydrothermal convection system. The coupling of volcanic quiescence and long-lived hydrothermal venting in the summit caldera provide a fertile environment for the formation of VMS deposits. Eventually the summit of the central volcano is surmounted by basaltic lavas from distal fissure eruptions which seal off the hydrothermal system.

Tectonic preservation

From the perspective of land-based exploration the incorporation of seafloor VMS ores into a landmass is as important as their formation. Exploration of the present day seafloor leaves no doubt as to the capacity of basalt-dominated mid-ocean ridge systems to form VMS deposits in the absence of felsic volcanism (Rona, 1988; Rona and Scott, 1993) while deposits associated with rhyolites or dacites tend to occur in arc or back-arc settings (Binns and Scott, 1993; Fouquet et al., 1993; Halbach et al., 1993). Ancient VMS deposits preserved on land are generally associated with felsic volcanic rocks (Rona, 1988; Franklin and Thorpe, 1982; Hutchinson, 1982) suggesting that most normal mid-ocean ridge, basalt-hosted VMS deposits are consumed by subduction. Deposits formed in normal oceanic crust may be preserved by obduction but ophiolites are rare in the Archean (Helmstaedt et

al., 1986; Burke and Kidd, 1980), and several studies suggest that most ophiolites formed in supra-subduction zone environments and not at normal ridges (e.g., Alabaster et al., 1982; Coish and Rogers, 1987; Elthon, 1991; Taylor et al., 1992). One environment where the high VMS productivity of mid-ocean ridges is likely to be retained in ancient terrains is at anomalous ridge segments underlain by mantle plumes where high magma production rates form thick oceanic plateaux such as at Iceland. In contrast to normal oceanic crust these are buoyant bathymetric highs which are likely to be scraped off and accreted at destructive plate margins rather than subducted (Burke et al., 1976; Hoffman, 1991; Storey et al., 1991). An example of plateau accretion is provided by the komatiite-tholeiitic basalt sequence of Gorgona Island, Columbia, believed to have formed over the Galapagos hotspot in the Cretaceous and accreted to the Pacific continental margin of South America in the early Eocene (Storey et al., 1991).

Figure 3.1. Spider diagram of least-altered FW rhyolite samples normalized to FW rhyolite 14259. See text for details.

Figure 3.2. Spider diagram of strongly altered FW rhyolite samples from the stringer zone beneath the north orebody normalized to FW rhyolite sample 14259: circles = sericitite, squares = chloritite, triangles = cherty breccia. See text for details.

Figure 3.3. Spider diagram of strongly altered FW rhyolite samples from the stringer zone beneath the north orebody normalized to FW rhyolite sample 14259 and to a constant Al value: circles = chlorite, squares = sericitite, triangles = cherty breccia. See text for details.

Figure 3.4. Chondrite normalized REE-HFSE spider diagram of representative least-altered Kidd Creek rhyolites: circles = QP rhyolite, X = FW rhyolite. See Appendix 5 for normalization values.

Figure 3.5. Chondrite normalized REE-HFSE spider diagram of representative intraplate island samples: circle = Canary Islands peralkaline rhyolite (R1-623); square = Galapagos Islands rhyolite (DH-18C); diamond = Ascension Island comendite (A-35); stippled field = Kidd Creek rhyolites. See Table 3.3 for data sources and Appendix 5 for chondrite normalization values.

Figure 3.6. Chondrite normalized REE-HFSE spider diagram of representative ensimatic arc samples: circle = Fiji high-Si dacite (M96), square = Tonga Forearc rhyolite (841B-50R1-16-18); triangle = Izu-Bonin Arc rhyolite (788C-12H5-10-13); diamond = Izu-Bonin Forearc rhyolite (786B-21R2-28-32); cross = Adak Island rhyolite (75A-107); X = Virgin Islands keratophyre (18); stippled field = Kidd Creek rhyolites. See Table 3.3 for data sources and Appendix 5 for chondrite normalization values.

Figure 3.7. Chondrite normalized REE-HFSE diagram of representative ensialic arc samples: circle = Milos rhyolite, Aegean Sea, Greece (M-40); square = Santorini dacite, Aegean Sea, Greece (B8); triangle = Taupo Volcanic Zone rhyolite pumice, New Zealand (O/11); cross = Padang area rhyolite, West Sumatra (104-3); stippled field = 10,000 Smokes rhyolites, Katmai National Park, Alaska; See Table 3.3 for data sources and Appendix 5 for chondrite normalization values.

Figure 3.8. Chondrite normalized REE-HFSE diagram of representative adakite/high-Al TTD samples: circle = Cerro Pampa dacite, Argentina (RB7); square = Lautaro Volcanic Center dacite, Chile (L-1); triangle = Los Chocoyos rhyolite ash, Quezaltenango Valley, Guatemala (OL4); diamond = Mt. St. Helens dacite tephra, Washington state, U.S.A. (SH-17); cross = Mindanao Island adakite, Philippines (P-90-59A); stippled field = Kidd Creek rhyolites. See Table 3.3 for data sources and Appendix 5 for chondrite normalization values.

Figure 3.9. Chondrite normalized REE-HFSE diagram of representative Icelandic samples: circle = Askja rhyolite (102); square = Krafla rhyolite (ATHO); triangle = Thingmuli rhyolite (111), diamond = Reydarfjörður rhyolite (16); stippled field = Kidd Creek rhyolites. See Table 3.3 for data sources and Appendix 5 for chondrite normalization values.

Figure 3.10. Chondrite normalized REE-HFSE diagram of representative mid-ocean ridge samples: circle = Galapagos spreading center rhyodacite (997); square = Mid-Atlantic Ridge plagiogranite (AG-159-38); triangle = Argo Fracture Zone quartz monzonite (125-4(c)); stippled field = Kidd Creek rhyolites. See Table 3.3 for data sources and Appendix 5 for chondrite normalization values.

Figure 3.11. Chondrite normalized REE-HFSE diagram of representative immature mid-ocean rifts: circle = Azores comendite (T-13); square = Torfajokull peralkaline rhyolite (ORU5); triangle = Torfajokull subalkaline rhyolite (HRN40); stippled field = Kidd Creek rhyolites. See Table 3.3 for data sources and Appendix 5 for chondrite normalization values.

Figure 3.12. Chondrite normalized REE-HFSE diagram of ensimatic back-arc samples: circle = Sumisu Rift rhyolite (1895-4); square = PACMANUS fresh dacite; triangle = PACMANUS altered dacite; stippled field = Kidd Creek rhyolites. See Table 3.3 for data sources and Appendix 5 for chondrite normalization values.

Figure 3.13. Chondrite normalized REE-HFSE diagram of ensialic back-arc samples: circle = preore Hokuroku dacite (KK11); square = postore Hokuroku dacite (KK6); triangle = Deception Island rhyodacite (P.870.1); diamond = Rocas Verdes plagiogranite (average of PA28A and PA42B); stippled field = Kidd Creek rhyolites. See Table 3.3 for data sources and Appendix 5 for chondrite normalization values.

Figure 3.14. Chondrite normalized REE-HFSE diagram of representative continental rift samples: circle = Afar rhyolite, Ethiopia (76-41); square = Salton Buttes rhyolite, Salton Sea area, California, U.S.A. (170-21P); triangle = rhyolite from the Red Sea coastal plain, Saudi Arabia (Tv-165714); diamond = Whitsunday rhyolite, Queensland coast, Australia (Hs17); cross = Lord Howe Rise rhyolite, Tasman Sea (207A-40R1-98); X = average continental crust estimate of Taylor and McLennan (1985, p. 67); stippled field = Kidd Creek rhyolites. See Table 3.3 for data sources and Appendix 5 for chondrite normalization values.

Figure 3.15. Histogram of SiO_2 distribution in 542 volcanic rocks from Iceland and 975 igneous rocks from the Kidd Creek mine area. Iceland data from Sigurdsson (1977), Kidd Creek data from Falconbridge Ltd.

Figure 3.16. Th-Hf-Nb ternary diagram comparing mafic igneous rocks of the Kidd Creek mine area to subalkaline basalts from Iceland: circles = Kidd Creek basalts, squares = Kidd Creek subvolcanic mafic rocks; shaded area = field of 33 Icelandic basalts from MacDonald et al. (1987), O'Nions and Gronvold (1973), and Wood (1978). Diagram after Wood (1980): A = N-type MORB; B = E-type MORB; C = alkaline within plate basalts; D1 = calc-alkaline destructive plate margin basalts; D2 = primitive arc tholeiites.

Figure 3.17. Chondrite normalized REE-HFSE diagram of average FI (circle), FII (square), FIIIa (triangle), and FIIIb (diamond) felsic volcanic rocks of Leshner et al. (1986). Each average based on 6 to 10 samples. Shaded field = Kidd Creek rhyolites. See Appendix 5 for chondrite normalization values.

Criteria	Least-Altered FW Rhyolites
Na ₂ O	>2 wt. %
Loss on Ignition (L.O.I.)	<2.2 wt. %
CO ₂	<1.8 wt. %
H ₂ O	<1.1 wt. %
Cu	<11 ppm
Zn	<70 ppm
Alumina Saturation Index	<1.7
Ishikawa Index	<0.6
Goodfellow Index	<0.45

Table 3.1. Criteria used to select least-altered FW rhyolites.

Alumina Index: $Al/(2Ca+Na+K)$, elements expressed as molecular proportions (Shand, 1951).

Ishikawa Index: $(K_2O+MgO)/(K_2O+Na_2O+CaO+MgO)$, oxides expressed as wt.% (Ishikawa et al., 1976).

Goodfellow Index: $(MgO+FeO)/(MgO+FeO+CaO+Na_2O+K_2O)$, oxides expressed as wt.% (Goodfellow, 1975; Riverin and Hodgson, 1980).

		14255	14256	14259	14263	14264	14265
DDH		3229	2622	2796	10	628	1100
Footage		1453	433	704	1738	832	465
SiO ₂	wt. %	79.1	80.2	79.6	81.2	80.9	82.8
TiO ₂	wt. %	0.08	0.07	0.10	0.09	0.08	0.08
Al ₂ O ₃	wt. %	11.10	11.10	10.70	9.10	9.65	9.57
Fe ₂ O ₃	wt. %	0.99	0.09	0.83	0.34	0.52	0.04
FeO	wt. %	0.30	0.20	1.40	0.90	1.00	0.20
MnO	wt. %	<0.01	<0.01	0.02	0.07	0.08	<0.01
MgO	wt. %	0.92	0.32	0.36	0.05	0.10	<0.01
CaO	wt. %	0.77	0.58	0.96	1.32	1.24	0.23
Na ₂ O	wt. %	2.35	3.60	2.86	4.31	3.03	3.49
K ₂ O	wt. %	2.51	3.00	1.92	0.65	1.29	2.48
P ₂ O ₅	wt. %	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	wt. %	1.80	0.75	1.10	1.90	2.10	0.60
Sum	wt. %	100.0	99.9	100.0	100.0	100.1	99.5
CO ₂	wt. %	0.53	<0.01	0.38	1.57	1.70	0.16
H ₂ O ⁺	wt. %	1.0	0.6	0.9	0.5	0.6	0.2
C	wt. %	0.21	0.22	0.28	0.64	0.60	0.12
S	wt. %	<0.01	<0.01	0.03	0.04	0.05	0.02
Li	ppm	7	15	7	<1	<1	<1
Be	ppm	2	2	1	1	<0.5	2
F	ppm	<20	<20	<20	<20	<20	<20
Sc	ppm	1.6	1.1	1.8	0.8	1.0	1.6
Cr	ppm	4	14	15	23	16	15
Ni	ppm	8	1	3	2	2	<1
Cu	ppm	2.8	7.5	5.8	4.3	10.7	1.6
Zn	ppm	21.6	16.4	67.8	37.1	56.3	42.8
Ga	ppm	28	28	29	26	31	27
Br	ppm	2.5	1.7	1.7	2.7	1.4	2.1
Rb	ppm	43.0	46.0	63.0	20.0	36.0	53.0
Sr	ppm	9.9	56.4	40.5	41.4	34.6	18.6
Y	ppm	110.0	117.0	96.0	89.0	102.0	82.0
Zr	ppm	218.0	222.0	212.0	190.0	202.0	178.0
Nb	ppm	26.0	27.0	22.0	22.0	24.0	19.0
Mo	ppm	<1	<1	<1	<1	<1	2
Ag	ppm	0.4	0.4	<0.1	0.3	0.4	0.6
Sn	ppm	5	11	<5	<5	8	12

Table 3.2. See following page for caption.

		14255	14256	14259	14263	14264	14265
Cs	ppm	1.6	1.2	1.8	0.7	1.2	0.8
Ba	ppm	1150	640	425	218	383	502
La	ppm	46.7	53.0	51.0	42.9	47.0	42.9
Ce	ppm	103.0	115.0	113.0	95.9	106.0	97.6
Pr	ppm	11.0	12.5	12.3	10.4	11.7	11.0
Nd	ppm	49.4	56.1	56.1	46.8	52.3	50.0
Sm	ppm	12.60	13.80	13.40	11.30	13.50	12.20
Eu	ppm	1.41	1.52	1.58	1.69	2.32	1.69
Gd	ppm	14.0	15.4	14.0	12.3	14.9	12.6
Tb	ppm	2.8	2.9	2.6	2.3	2.9	2.3
Dy	ppm	14.7	14.6	13.0	11.1	14.9	11.3
Ho	ppm	4.00	3.91	3.39	2.92	3.90	2.88
Er	ppm	8.9	8.9	7.8	7.1	8.5	6.5
Tm	ppm	1.7	1.7	1.5	1.4	1.6	1.3
Yb	ppm	10.3	10.1	9.4	8.3	9.6	7.8
Lu	ppm	1.7	1.6	1.6	1.4	1.5	1.4
Hf	ppm	9.5	9.1	8.8	8.7	8.9	7.9
Ta	ppm	1.5	1.1	1.6	1.4	1.1	1.5
Au	ppb	<2	<2	<2	<2	<2	<2
Pb	ppm	<2	<2	<2	<2	<2	<2
Th	ppm	7.5	7.3	6.7	5.8	6.6	6.8
U	ppm	1.8	1.7	1.7	1.4	1.6	1.8
Goodfellow Index		0.27	0.08	0.30	0.17	0.22	0.04
Ishikawa Index		0.52	0.44	0.37	0.11	0.25	0.40
Alumina Index		1.63	1.30	1.47	1.05	1.30	1.32
La _N /Yb _N		3.06	3.54	3.66	3.48	3.30	3.71
Eu/Eu*		0.32	0.32	0.35	0.44	0.50	0.41

Table 3.2. Representative analyses of least-altered FW rhyolite samples from the Kidd Creek mine area. Alteration indexes defined in caption for Table 3.1; DDH = diamond drill hole; "N" denotes chondrite normalized value; $Eu/Eu^* = 2(Eu_N)/(Sm_N + Gd_N)$; see Appendix 5 for chondrite normalization values.

Location	Representative Sample	Age	Tectonic Setting At Time of Eruption/Intrusion	Petrochemistry	SiO ₂ (wt.%)	Rock Type	Reference
Intraplate Islands							
Gran Canaria, Canary Islands	R1-623	Miocene (14 Ma)	intraplate ocean island	peralkaline (alkaline-peralkaline suite)	77.4	high-silica crystal-poor peralkaline rhyolite	Freundt and Schmincke, 1995
Ascension Island, Atlantic Ocean	A35	Cenozoic	intraplate ocean island	peralkaline (alkaline-peralkaline suite)	74.05	comendite lava dome	Harris, 1983
Pinzon Island, Galapagos Archipelago	DH-18C	Pleistocene	intraplate ocean island (Galapagos hotspot)	tholeiitic	68.19	rhyolite lava dome, non-bimodal sequence	Bailis and Lindstrom, 1980
Ensimatic Arcs							
Vanua Levu Island, Fiji	M96	Miocene	ensimatic island arc	low-K, bimodal	79.4	high-Si dacite crystal tuff, Undo Group	Gill and Stork, 1979
Tonga Forearc	841B-50R1-16-18	Mid-Eocene	ensimatic island arc (presently trenchward of modern Tonga Platform)	low-K	78.63	rhyolite lava (flow or dome) from subaerial volcano	Bloomer et al., 1994
Izu-Bonin Arc	788C-12H5-10-13	Pliocene	ensimatic arc	low-K, bimodal	72.40	rhyolite pumice	Gill et al., 1992
Izu-Bonin Forearc	786B-21R2-28-32	Eocene (ca. 41 Ma)	outerarc high of forearc	boninite-andesite-dacite-rhyolite suite	71.12	hyalocalstite bearing rhyolite flow	Murton et al., 1992
Adak Island, Central Aleutians	75A-107	Holocene	ensimatic island arc	calc-alkaline	77.30	rhyolitic glass shards in tephra	Romick et al., 1992
Virgin Islands, Greater Antilles, Caribbean	18	Cretaceous	ensimatic island arc	primitive island arc	75.0	intrusive keratophyre	Donnelly et al., 1990
Ensialic Arcs							
Milos, Aegean Sea, Greece	M-40	Cenozoic	ensialic island arc	calc-alkaline	72.03	rhyolite lava flow	Fytikas et al., 1986
Santorini, Aegean Sea, Greece	B8	Quaternary	ensialic island arc	calc-alkaline	73.06	rhyolite	Huijsmans et al., 1988
Taupo volcanic zone, New Zealand	O/11	Pleistocene	ensialic island arc	medium-K to high-K	69.68	rhyolite pumice from Ongatiti and Ahuroa volcanoes (?)	Briggs et al., 1993
Padang, West Sumatra	104-3	Quaternary	ensialic island arc (formed on continental microplate)	calc-alkaline	70.38	pumiceous rhyolite tuff	Leo et al., 1980; Wilson, 1989
Valley of 10,000 Smokes, Katmai National Park, Alaska Peninsula	K-22	Holocene (1912 A.D.)	ensialic arc peninsula - eastern end of Aleutian arc	calc-alkaline	76.6	rhyolite dome microvesicular vitrophyre	Hildreth, 1983

Table 3.3 (caption on last page)

Adakites/High-Al Dacites						
Cerro Pampa, Argentina	RB7	Late Miocene (12.1 ± 0.7 Ma)	continental arc	medium-K, adakitic	67.88	dacite
Lautaro Volcanic Center, Chile	L-1	Pleistocene- Holocene	continental arc	medium-K, adakitic	66.78	dacite, Austral Volcanic Zone
Quezaltenango Valley, Guatemala	OL-4	Pleistocene	continental arc	medium to high-K, high-Al TTD suite	76.35	rhyolite ash (Los Chocoyos Ash)
Mt. St. Helens, Washington state, U.S.A.	SH-17	Pleistocene (3000-4000 years B.P.)	continental arc	calc-alkaline, adakitic	66.48	dacite tephra (Smith Creek eruption)
Zamboanga Peninsula, Mindanao Island, Philippines	P-90-59A	Middle Miocene (16.9 ± 0.4 Ma)	island arc	low-K, adakitic	67.80	adakite
						Sajona et al., 1993
Mature Mid-Ocean Ridges						
Askja, Iceland	102	Holocene (1875 A.D.)	Rift zone along mid-Atlantic ridge	subalkaline	72.63	rhyolite pumice, rhyolite obsidian
Krafla, Iceland	ATHO	Quaternary	Rift zone along mid-Atlantic ridge	subalkaline	74.48	rhyolite
Thingmuli, Iceland	I11	Tertiary	Rift zone along mid-Atlantic ridge	subalkaline	77.06	rhyolite
Reydarfjörður, Iceland	I6	Tertiary	Rift zone along mid-Atlantic ridge	subalkaline	71.60	rhyolite obsidian
Galapagos Spreading Center	997	Cenozoic	Galapagos Spreading Center	low-K - medium-K	70.71	rhyodacite
Mid-Atlantic Ridge, 45°N	AG-159-38	Miocene (≈9 Ma)	mid-Atlantic ridge	tholeiitic	na	plagiogranite
Argo Fracture Zone, Indian Ocean	125-4(c)	Cenozoic	Argo fracture zone, central Indian ridge	medium-K	75.07	quartz monzonite
						Aldiss, 1981; Aumento, 1969 Engel. and Fisher, 1975, Hedge et al., 1979

Table 3.3 (caption on last page)

Immature Mid-Ocean Rifts							
Azores Archipelago, Atlantic Ocean	T-13	Cenozoic	ocean islands on plate boundary undergoing slow, oblique extension	peralkaline (alkali basalt magma series)	67.03	comendite	White et al., 1979; Mungall and Martin, 1995
Torfajokull Volcano, Iceland (1)	ORU5	Cenozoic (pre-postglacial, >10,000 years B.P.)	lateral rift (flank) zone	peralkaline	74.25	rhyolite	McGarvie et al., 1990
Torfajokull Volcano, Iceland (2)	HRN40	Holocene (postglacial, 1085 years B.P.)	lateral rift (flank) zone	subalkaline	69.85	microporphyritic rhyolite	MacDonald et al., 1990
Ensimatic Backarc Rifts							
Sumisu Rift,Izu-Bonin Backarc	1895-4	Pleistocene	ensimatic backarc rift	low-K - medium-K, bimodal	73.81	rhyolite lava from ridge summit	Gill et al., 1992
PACMANUS Site, Eastern Manus Basin, SW Pacific (1)	fresh dacite	Cenozoic	back arc extensional basin with sea-floor spreading	medium-K	62.2	fresh and altered dacite associated with VMS deposit	Binns and Scott, 1993
PACMANUS Site, Eastern Manus Basin, SW Pacific (2)	altered dacite	Cenozoic	back arc extensional basin with sea-floor spreading	medium-K	51.1	fresh and altered dacite associated with VMS deposit	Binns and Scott, 1993
Ensialic Backarcs							
Hokuroku District, Japan (1)	KK11	Miocene (pre Kuroko VMS deposits)	failed rift within ensialic arc	calc-alkaline	76.37	silicic volcanic rocks (dacite/rhyolite)	Dudas et al., 1983; Cathles et al., 1983
Hokuroku District, Japan (2)	KK6	Miocene (post Kuroko VMS deposits)	failed rift within ensialic arc	calc-alkaline	75.28	silicic volcanic rocks (dacite/rhyolite)	Dudas et al., 1983; Cathles et al., 1983
Deception Island, Bransfield Strait	P.870.1	Quaternary	ensimatic marginal basin in initial stages of backarc spreading	low-K, calc-alkaline/tholeiitic, not bimodal	68.02	sodic rhyodacite from composite stratovolcano (post-caldera)	Weaver et al., 1979
Rocas-Verdes Ophiolite Complex, southern Chile	28A - 42B average	Late Jurassic	narrow marginal basin floored by oceanic crust produced by rifting and spreading behind a continental margin volcanic arc	tholeiitic, bimodal	74.59	plagiogranite	Saunders et al., 1979

Table 3.3 (caption on last page)

Continental Rifts							Walter et al., 1987
						na	
Afar Region, Ethiopia	76-41	Pliocene (3.9 Ma)	continental rift	tholeiitic		rhyolite (dome)	
Salton Buttes, Salton Sea Area, California	170-21P	post-Miocene (<4 Ma)	continental rift, probable spreading center	subalkaline		rhyolite	Herzig and Elders, 1988; Robinson and Elders, 1976
Red Sea Coastal Plain, Saudi Arabia	165714	Tertiary	continental rifting and spreading (opening of Red Sea)	subalkaline-alkaline, bimodal		perlite (rhyolite)	Pallister, 1987
Haslewood Island, Central Queensland Coast, Australia	Hs17	Lower Cretaceous	continental rift basins or troughs prior to actual rifting of E. Australia - possible failed rifts	calc-alkali - high-K		rhyolitic ignimbrite (Whitsunday volcanics)	Ewart et al., 1992
Lord Hose Rise, Tasman Sea	207A-40R1-98-101	Upper Cretaceous (93.7±1.2 Ma)	small continental rift basins pre- breakup of eastern Australia (opening of Tasman Sea)	high-K, not bimodal		rhyolite	Bloomer et al., 1994

Table 3.3. Summary of post-Triassic, felsic igneous rock comparison data.

Chapter 4

Sm-Nd ISOTOPIC STUDY OF RHYOLITES FROM THE LOWER AND UPPER MEMBERS OF THE KIDD CREEK FORMATION

Introduction To Chapter 4

Temporal and Tectonic Setting

Bleeker and Parrish (1995) reported U-Pb zircon ages of 2714.1 ± 1.5 Ma for rhyolite near the base of the Kidd Creek formation (FW rhyolite) and 2710.5 ± 1.1 Ma for rhyolite near the top of the Kidd Creek formation (QP rhyolite) for an average age of felsic volcanism at Kidd Creek of approximately 2712 Ma. Previous U-Pb data on zircons from the footwall felsic sequence at Kidd Creek returned ages of 2717 ± 4 Ma and 2717 ± 2 Ma (Nunes and Pyke, 1982; Barrie and Davis, 1990). Maas et al. (1986) determined a Sm-Nd isochron of 2674 ± 40 Ma based on samples of altered rhyolitic rocks from the Kidd Creek footwall succession. Other dating techniques have produced younger dates which are not within error of the U-Pb zircon ages; these may

reflect post-depositional metamorphic/metasomatic events (Barrie et al., 1996).

Many recent investigators of the evolution of the Superior Province favor models in which the southern Superior Province, including the Abitibi greenstone belt, is formed of oceanic terranes which were accreted along what is presently the southern edge of a continental mass, part of which is preserved in the northern Superior Province (Percival et al., 1994; Williams et al., 1992). Within the western part of the southern Abitibi Greenstone Belt, pre-orogenic magmatism spans the time interval from 2750 to 2700 Ma with most magmatic activity, including the Kidd Creek volcanism, occurring between 2720 and 2700 Ma (Corfu, 1993; Jackson and Fyon, 1991, Bleeker and Parrish, 1995). Most pre-tectonic rocks in the Abitibi Greenstone Belt have mantle-like Nd isotopic signatures and no evidence of zircon inheritance indicating little or no assimilation of older continental crust (Vervoort et al., 1994; Corfu, 1993).

Questions regarding the Sm-Nd isotope systematics of the Kidd Creek rhyolites

(i) *What is the source of the Kidd Creek rhyolites?* Rhyolites of the Kidd Creek formation (FW and QP rhyolites) may be related to mantle-derived mafic

magmas through fractional crystallization or partial melting, or they may have been formed by partial melting of older crustal material (e.g. felsic granulites or continentally-derived greywackes). In the first case they will have mantle-like Nd isotopic values whereas in the second case their Nd-isotopic ratios should reflect involvement of older crust.

(ii) Does the Nd isotopic composition of felsic magmas in the Kidd Creek area vary with stratigraphic position? Nd isotopic and geological stratigraphy for the Flin Flon and Snow Lake areas of Manitoba indicate that VMS deposits formed during or shortly after periods of isotopically primitive, mantle-derived felsic magmatism suggesting a relationship between VMS mineralization and the input of mantle-derived heat or fluids (Stern et al., 1992). Maas et al. (1986) presented Nd isotopic data for felsic volcanic rocks from the footwall of the Kidd Creek deposit but there are no previous Nd isotopic determinations on the hanging wall QP rhyolite.

(iii) Does strong hydrothermal alteration effect Nd isotopic ratios? The LREE have been depleted within the footwall stringer zone beneath the north and central orebodies of the Kidd Creek mine indicating water/rock ratios of approximately 10^5 or greater (Campbell et al., 1984; Piepgras and Wasserburg, 1985; Michard and Albarede, 1986). At such high water/rock ratios the potential

exists for the Nd isotopic composition of wallrocks to be significantly influenced by the hydrothermal fluids, and Kidd Creek rhyolite data reported by Maas et al. (1986) show a decrease in average ϵ_{Nd} values with increasing LREE depletion (Figure 4.1).

Sample Distribution And Analytical Techniques

Sm-Nd isotopic analyses were determined in this study for 13 rhyolitic samples from the Kidd Creek Mine area (see Table 4.1 for sample descriptions, Table 4.2 for Sm-Nd isotopic analyses and Table 4.3 for major and trace element geochemistry).

Samples

Rhyolite samples from the Kidd Creek formation include 9 samples from the underground workings between the 1800 and 4700 levels (550 to 1430 m below surface) and 2 samples from the “east outcrop” located on the east rim of the open pit (Figure 4.2). These samples include coherent QP rhyolite from the Upper member, and samples of coherent rhyolite, rhyolite blocks (east outcrop samples), and autoclastic rhyolite breccia from the Lower

member (FW rhyolite). Most of the samples have been subjected to only weak to moderate silicification, sericitization and/or chloritization. However, four strongly altered samples from the stringer zone beneath the north and central orebodies were also analyzed - two strongly silicified, autoclastic rhyolite breccias ("cherty breccias"), one chloritite and one sericitite. The chloritite and sericitite occur in seams up to 1 m wide cutting the silicified rhyolitic host rocks. In addition to the Kidd Creek Mine samples, Sm-Nd isotopic analyses were determined for two weakly to moderately altered rhyolites collected near the Chance Cu-Zn deposit in north-central Kidd Township approximately 2 km northwest of the Kidd Creek Mine (AJ00691 and AJ09313; sample locations shown by Barrie et al. ,1996). Nd concentrations in the 11 rhyolitic samples range from 14.36 to 83.61 ppm with a median of 41.17 ppm and Sm contents vary from 4.36 to 21.43 ppm with a median of 9.83 ppm. The variations in Nd and Sm contents reflect (i) magmatic variability, (ii) LREE mobility, and/or (iii) apparent enrichment or depletion effects resulting from mass loss or mass gain, respectively. LREE-rich accessory minerals within the rhyolites, identified by S.E.M., include monazite, allanite, titanite, synchysite and bastnaesite.

Techniques

Samples were ground in an agate mill at XRAL Laboratories, Toronto, Canada, prior to Sm-Nd isotopic analyses performed by Dr. Brian Cousens at Carleton University, Ottawa, Canada. Analyses were obtained for both whole-rock samples and for residues remaining after acid leaching experiments. For whole-rock analyses approximately 100 milligrams of rock powder were spiked with a mixed ^{148}Nd - ^{149}Sm spike, dissolved in 50% HF-12N HNO_3 , then attacked with 8N HNO_3 and finally 6N HCl. The sample was then taken to dryness and the residue was taken up in 2.5N HCl and passed through a chromatographic column containing Dowex AG50-X8 cation resin to separate the rare earth elements from major elements and Sr. The rare earth element residues were dissolved in 0.26N HCl and loaded into a 10 ml glass chromatographic column containing a 2 cm high bed of Teflon powder coated with HDEHP [di (2-ethylhexyl) orthophosphoric acid (Richard et al., 1976)]. Nd was eluted using 0.26N HCl, followed by Sm in 0.5N HCl. Total procedural blanks for Nd were < 75 picograms. Concentrations are precise to $\pm 1\%$. A second split of rhyolite powder was subjected to a two-stage acid leaching process prior to dissolution. Powders were leached in 8N HNO_3 at room temperature for 3 hours, rinsed with H_2O , then leached for 3 hours in hot (120-150°C) 2N HCl,

and rinsed again with H₂O. The residues were spiked and processed in the same way as the unleached whole-rock powders.

Samples were loaded with 0.25N HCl on one side of a Re double filament and run at temperatures of 1780-1820° C on a Finnigan MAT 261 mass spectrometer operating in static mode. Isotope ratios were normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.72190$. $^{147}\text{Sm}/^{144}\text{Nd}$ ratios are reproducible to $\pm 1.0\%$ (2σ) and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios are reproducible to ± 0.000020 (2σ). These analytical errors correspond to approximately $\pm 0.5 \text{ } \epsilon_{\text{Nd}}$ units. Analyses of the USGS standard BCR-1 yield Nd = 29.02 ppm, Sm = 6.68 ppm and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512668 \pm 0.000020$ (n=4). The average of twenty-three determinations of the La Jolla standard (Sept. 1992 - Sept. 1994) is $^{143}\text{Nd}/^{144}\text{Nd} = 0.511874 \pm 0.000019$ (2σ). Analytical techniques for major and trace element whole-rocks analyses, performed by XRAL Laboratories, Toronto, Canada, are described in Appendix 3. LREE-rich minerals in the rhyolites were identified using a JEOL 6400 scanning electron microscope interfaced to a LINK Systems eXL LZ4 x-ray analyzer.

Sm-Nd Whole-Rock Isotope Systematics

Sm-Nd Regression Ages

Nd isotopic results for the 13 Kidd Creek whole-rock rhyolite samples are shown on a $^{147}\text{Sm}/^{144}\text{Nd}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ diagram in Figure 4.3. Two intensely chloritized and sericitized samples from the footwall of the central orebody, considered in detail in a subsequent section, plot well below the average trend and are not included in regression age calculations. A whole-rock regression age obtained using the 11 remaining rhyolite samples yields an age of 2733 ± 260 Ma (2 sigma errors), an initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.509221 and an M.S.W.D. value of 6.72 (regression lines and M.S.W.D. values calculated by the computer program Isoplot (version 2.82) using Yorkfit model 1 (Ludwig, 1995; York, 1969). The high M.S.W.D. value reflects the fact that three of the samples, 18-14046, 18-14051R and EO-92-9B, are not within error of the regression line. Recalculation without these three samples generates a whole-rock isochron of 2747 ± 95 Ma, an initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.509206 and an M.S.W.D. value of 1.57. The similarity in ages and the initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios indicates that the outlying samples do not significantly lever the regression line when included in the calculation. However, there is no *a priori* reason for omitting samples 18-14046, 18-14051R and EO-92-9B from the

calculations. The Sm-Nd isotopic age estimates obtained from the rhyolite samples are within error of the U-Pb zircon ages of 2714.1 ± 1.5 Ma for the footwall (FW) rhyolites and 2710.5 ± 1.1 Ma for the hanging wall (QP) rhyolites of Bleeker and Parrish (1995) and are similar to Sm-Nd age estimates for less altered basaltic, gabbroic and komatiitic samples reported by Barrie et al. (1996).

A previous Sm-Nd isotopic study of Kidd Creek rocks by Maas et al. (1986) reported analyses for 4 samples of weakly altered felsic volcanic rocks, 10 samples of strongly altered felsic volcanic rocks from the footwall stringer zone and 2 analyses of massive, stratiform Cu-rich ore. Using the altered felsic volcanic rock and massive sulfide data, Maas et al. (1986) determined a Sm-Nd isochron of 2674 ± 40 Ma. The weakly altered felsic volcanic rock data have a restricted range of intermediate $^{147}\text{Sm}/^{144}\text{Nd}$ ratios relative to the range of the isochron and do not significantly affect the age (Maas et al., 1986).

Initial ϵ_{Nd} Characteristics

Initial ϵ_{Nd} values, calculated for an age of 2712 Ma (the average rhyolite U-Pb zircon age of Bleeker and Parrish, 1995), are presented in Table 4.2. Excluding the footwall chloritite and sericitite samples ϵ_{Nd} values for the

rhyolite samples of this study range from +1.4 to +4.2. These values are similar to those obtained by Barrie et al. (1996) for less altered basalt and gabbro samples from the Kidd Creek hanging wall and for komatiite samples from the Kidd Creek footwall. The ϵ_{Nd} values for the rhyolitic footwall samples of Maas et al. (1986), recalculated for $T = 2712$ Ma and a present day chondritic $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.7219 for consistency with data presented in this study, range from +0.2 to +2.3.

Geochemistry of Phyllosilicate-Dominated Footwall Samples

Two samples of intensely altered rocks from the footwall of the central orebody on 4700 Level, a chloritite (sample 14267) and a sericitite (sample 14287), have anomalous $\epsilon_{\text{Nd}}(T)$ values of -3.6 and -5.1 respectively (Table 4.2). These samples are from irregular, discontinuous, Fe-chlorite-dominated lenses up to 1 meter wide associated with chalcopyrite stringers located stratigraphically below the economic chalcopyrite stringer zone. The chloritite and sericitite are identified as being the alteration products of rhyolitic protoliths as (i) they occur as alteration zones within rhyolitic assemblages, and (ii) they have ratios between relatively immobile incompatible (Zr) and compatible (Ti) elements nearly identical to those of less altered FW rhyolites despite

extensive metasomatism accompanied by mass loss (MacLean, 1990; Figure 4.4). In a $(\text{Na}_2\text{O}+\text{CaO}) - \text{K}_2\text{O} - (\text{FeO}+\text{MgO})$ diagram these samples plot along the $\text{K}_2\text{O} - (\text{FeO}+\text{MgO})$ join indicating total loss of (normative) plagioclase - the sericitite plots mid-way along the $\text{K}_2\text{O} - (\text{FeO}+\text{MgO})$ side whereas the chlorite plots at the $(\text{FeO}+\text{MgO})$ apex (Figure 4.5). The Fe/Mg cation ratio in the chloritite sample is 1.8. In a SiO_2 versus Al_2O_3 diagram the chloritite plots within a field defined by 29 analyses of chlorites from Abitibi VMS deposits which, combined with the data outlined above, indicates that the rock is composed almost entirely of Fe-chlorite (Figure 4.6). In the same diagram the sericitite plots near a field defined by 14 analyses of sericites from Abitibi VMS deposits along a tie-line between sericite compositions and least-altered FW rhyolites. Other geochemical features of note are high water contents (3.3 wt.% - sericitite, 10.6 wt.% - chloritite), high Cu (783 ppm - sericitite, 429 ppm - chloritite), elevated Zn in the chloritite (499 ppm), and anomalous F and Sn values in the sericitite (1430 ppm F, 71 ppm Sn). A chondrite-normalized REE plot demonstrates that the chloritite and sericitite samples have undergone extensive LREE depletion relative to less altered FW rhyolites (Figure 4.7). However, LREE depletion may also occur without anomalous Nd isotopic values as demonstrated by the samples of rhyolite breccia (14242 and 14281) which have also undergone strong LREE depletion but which maintain ϵ_{Nd} values similar to less altered rhyolites (ϵ_{Nd} of +3.2 and +2.6 respectively).

A relationship between increasing intensity of alteration, indicated by LREE depletion, and decreasing average ϵ_{Nd} values is suggested by the data of Maas et al. (1986) for rhyolitic samples from the Kidd Creek footwall (Figure 4.1). A highly altered rhyolite with an anomalously low ϵ_{Nd} value (-1.9 compared to average ϵ_{Nd} values of +3.2) and strong LREE depletion has also been reported from VMS footwall rocks in the Matagami district of Quebec (porphyritic metarhyolite of the Watson Lake Group; Vervoort et al., 1994).

Acid Leaching Results

Nine of the less altered rhyolite samples were subjected to an acid leach procedure to remove the more labile components (described in analytical techniques section) and the residues were analyzed for their Sm-Nd isotopic composition. In each case the residue had a lower Nd and Sm content than the whole-rock sample implying that a significant proportion of the LREE reside in labile components (Table 4.2). In 4 cases the residues have Sm-Nd isotopic values which plot well below the 2733 Ma regression line and have $^{147}\text{Sm}/^{144}\text{Nd}$ ratios which are significantly higher than the corresponding whole-rock samples indicating LREE depletion in the residues (Figure 4.8). Two point

regression ages calculated for these whole-rock - residue pairs returned values of 2182 ± 59 Ma, 1980 ± 89 Ma and 896 ± 110 Ma for samples KC-102A, AJ00691, 18-14046 and AJ09313 respectively whereas a zero age ($-41 \text{ Ma} \pm 280 \text{ Ma}$) was obtained using the whole-rock and residue analyses of sample AJ09313. These ages clearly do not correspond to late Archean magmatic or tectonic events and indicate that the Nd isotopic systems in these samples have not remained closed. It is interesting to note that (i) the residue data shown in Figure 4.8 are all displaced from the 2733 Ma regression line by approximately the same amount, and (ii) the sericitite and chloritite whole-rock analyses exhibit a similar displacement (Figure 4.3). Further work is required to determine the significance of these relationships.

Evolution of the Kidd Creek Formation in Light of Nd Isotopic Results

A plot of ϵ_{Nd} versus rock type, with data arranged in approximate stratigraphic sequence, is shown in Figure 4.9 for the Kidd Creek formation (data from this study and Maas et al., 1986). With the exception of the chloritite and sericitite samples, ϵ_{Nd} values range between 0.0 and +4.2 with most values between +1.0 and +3.0; there is no discernible relationship between ϵ_{Nd} values and stratigraphic position. These values are similar to data for

komatiites in the stratigraphic footwall to the Kidd Creek formation and less altered basalts and gabbros in the hanging wall to the Kidd Creek formation (Barrie et al., 1996) and indicate that the Nd isotopic composition of magmas in the Kidd Creek area did not change significantly over time. These results contrast with data for the Flin Flon and Snow Lake areas of Manitoba where considerable stratigraphic Nd isotopic variability exists and VMS deposits are associated with episodes of “mantle-derived felsic magmatism” (Stern et al., 1992, p. 82).

In the southern Superior Province at 2695 ± 10 Ma there was a shift in magma compositions from predominantly isotopically primitive, incompatible element depleted tholeiitic-komatiitic melts to predominantly incompatible element enriched alkalic melts (Barrie and Shirey, 1989). Figure 4.10 displays $\epsilon_{\text{Nd}}(\text{T})$ data for several pre-2695 Ma suites of southern Superior Province igneous rocks and mineral separates, described in the appendix 6, along with the Kidd Creek rhyolite data (this study), the depleted mantle trend of Stern et al. (1994) and a continental crustal trend based upon samples of Australian shale (Allegre and Rousseau, 1984). Note the similarity of the Kidd Creek rhyolite $\epsilon_{\text{Nd}}(\text{T})$ values (excluding the chloritite and sericitite samples) to other analyses from the southern Superior Province and that all data (excluding highly altered samples) are close to the depleted mantle curve. These results

are compatible with (i) the derivation of the Kidd Creek volcanic succession from the mantle or by melting of young (relative to the Kidd Creek rocks), mantle-derived crust with no input of continental material, and (ii) the suggestion that central volcanoes within the axial rift zones of Iceland provide an appropriate modern analogue for the Kidd Creek volcanic succession (Chapter 3 and references therein).

Nd Isotopic Shift in Altered Rhyolites

Three lines of evidence indicate that the Nd isotopic systems in some Kidd Creek rhyolite samples do not reflect magmatic values: (i) anomalously low $^{143}\text{Nd}/^{144}\text{Nd}$ ratios in chalcopyrite-stringer associated chloritite and sericitite samples from the footwall of the central orebody (ϵ_{Nd} (2712 Ma) = -3.6 and -5.1), (ii) anomalously low $^{143}\text{Nd}/^{144}\text{Nd}$ ratios in acid leach residues of samples KC-102A, 18-14046, AJ-00691 and AJ09313 (ϵ_{Nd} (2712 Ma) = -3.3 to -6.0), and (iii) the trend of decreasing ϵ_{Nd} (2712 Ma) values with increasing LREE depletion noted in the Maas et al. (1986) data. The data suggest that the negative $\epsilon_{\text{Nd}}(\text{T})$ signatures are related to hydrothermal alteration within the rhyolites and that the timing of the isotopic shifts is either syn-ore or post-ore.

Syn-ore model

Preferential leaching of ^{143}Nd relative to ^{144}Nd during hydrothermal alteration is not a viable hypothesis because their relative mass differences are too small to allow physical separation of the isotopes (Rollinson, 1993; Poitrasson et al., 1995). Therefore, if the isotopic shifts occurred during ore formation they must reflect high water/rock ratios and a negative $\epsilon_{\text{Nd}}(\text{T})$ signature in the hydrothermal fluids. This signature may have reflected the Nd isotopic composition of overlying seawater, or wallrocks within the flow path of the hydrothermal fluids.

Water Rock Ratios: The Nd content of hydrothermal fluids that formed the Kidd Creek deposit would have been derived from seawater modified by interaction with wallrocks. Measured Nd concentrations in modern seafloor hydrothermal vents range from 20×10^{-6} ppm to 2100×10^{-6} ppm compared to present day seawater values of approximately 2.5×10^{-6} and possible Archean seawater values of about 30×10^{-6} ppm (Piepgras and Wasserburg, 1980; Michard et al., 1983; Piepgras and Wasserburg, 1985; Michard and Albarede, 1986; Hinkley and Tatsumoto, 1987; Campbell et al., 1988; Jacobsen and Pimentel-Klose, 1988). Therefore, the observed isotopic shift in the chloritite and sericitite would have required minimum water/rock ratios of approximately

10^3 to 10^5 or greater (Faure, 1986; Valsami-Jones and Cann, 1994). LREE depletion within chloritite, sericitite and siliceous rhyolite breccia in the footwall of the north and central orebodies indicate water/rock ratios of approximately 10^5 or greater (Figure 4.7; Piepgras and Wasserburg, 1985; Michard and Albarede, 1986). Nd isotopic exchange during hydrothermal alteration in various geological settings has been documented by German et al. (1995), Schade et al. (1989), Tourpin et al. (1991), Valbracht (1992), Valsami-Jones and Cann (1994), Cliff and Rickard (1992), and Poitrasson et al. (1995).

Seawater Nd signature: In order for seawater to have been the source of the isotopic shifts noted in some samples, the $\epsilon_{Nd}(T)$ value of seawater above the Kidd Creek rhyolites would have had to have been -5 or less. The $\epsilon_{Nd}(T)$ values of Archean banded iron formations, which are probably representative of Nd isotopic compositions in Archean seawater, commonly vary from -1 to +4 but values of less than -5 have been reported (Jacobsen and Pimentel-Klose, 1988a; Jacobsen and Pimentel-Klose, 1988b; Shimizu et al., 1990; Miller and O'Nions, 1985). These values suggest that seawater with negative $\epsilon_{Nd}(T)$ values would have been restricted to environments near continental margins. However, such an environment is incompatible with the oceanic character of the pre-tectonic southern Superior Province making this model for the ϵ_{Nd} shifts unlikely.

Wallrock Nd signature: The Nd isotopic composition of seawater drawn downward into deep, high temperature convection systems is generally overwhelmed by Nd derived by leaching of LREE from the wallrocks (Piepgras and Wasserburg, 1985; Michard and Albarede, 1986; Hinkley and Tatsumoto, 1987; Valsami-Jones and Cann, 1994). Therefore, the presence of continentally derived material within the succession below Kidd Creek such as turbidite or pyroclastic air fall deposits could explain the ϵ_{Nd} shift in highly altered rocks but no such rock type is known to occur beneath the Kidd Creek deposit. For this model to apply the source of the negative ϵ_{Nd} signature is either buried well beneath the Kidd Creek formation or has been removed from the Kidd Creek area by tectonic means (e.g. accretion of volcanic edifice coupled with subduction of greywacke-bearing substrate - see arc-trench propagation model advocated by Hoffman (1991) for greenstone belt accretion).

Post-ore model

The model favored by the author is that the negative ϵ_{Nd} value reflect a disturbance in the isotopic system by metamorphic and/or metasomatic activity which post-dates deposition of the Kidd Creek ores. Resetting of the Sm-Nd

isotopic system followed by preferential leaching of Sm relative to Nd may account for the observed isotopic shifts in the chloritite and sericitite samples. That these shifts occur in intensely altered rocks could reflect preferential migration of late fluids through the permeable, phyllosilicate-rich zones and/or the relative stability with respect to post-ore events of REE-bearing hydrothermal alteration assemblages formed during the Kidd Creek mineralization event. Acid leaching experiments on less altered rhyolites indicate that a significant proportion of the LREE reside in labile minerals (Table 4.2). Post-ore mobility of LREE at Kidd Creek is demonstrated by the occurrence of hydrothermal monazite from the Kidd Creek mine with a U-Pb age of 2659 ± 3 Ma (Schandl and Gorton, 1991; Davis et al., 1994).

Figure 4.1. Nd/Sm versus $\epsilon_{\text{Nd}}(2712 \text{ Ma})$ diagram showing Kidd Creek data of Maas et al. (1986). Filled circles = weakly altered felsic volcanic rocks, open triangles = altered felsic volcanic rocks, CHUR = chondritic uniform reservoir.

Figure 4.2. Surface geology of the Kidd Creek Mine area (after Walker et al., 1975, and Olson et al., 1994). Sample sites: 1 = EO-92-9B, EO-92-10B; 2 = 2323-1, 2323-4; 3 = 23-14242, 47-14267, 47-14278, 47-14281; 4 = 18-14046, 18-14051R, KC-102A. All sample sites projected to surface except site 1 (east outcrop).

Figure 4.3. $^{147}\text{Sm}/^{144}\text{Nd}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ diagram showing Kidd Creek rhyolitic whole rock data (crosses): 1 = KC-102A, 2 = 18-14046, 3 = 18-14051R, 4 = 2323-4, 5 = EO-92-10B, 6 = EO-92-9B, 7 = AJ09313, 8 = 2323-1, 9 = 47-14281, 10 = 23-14242, 11 = AJ00691, C = 47-14267, S = 47-14278. Size of cross represents analytical error (2 s). Regression line calculated excluding chloritite (C) and sericitite (S) samples.

Figure 4.4. Zr versus TiO_2 diagram. Filled circles = FW rhyolite, triangles = rhyolite breccia, square = chloritite, diamond = sericitite, large ruled circle = field of 6 least-altered FW rhyolite samples (Chapter 3).

Figure 4.5. Ternary (Na_2O+CaO) - K_2O - ($FeO_{(t)}+MgO$) diagram for rhyolitic sample data from the Kidd Creek Mine area. Filled circles = FW rhyolite, open circles = QP rhyolite, triangles = rhyolite breccia, square = chloritite, diamond = sericite. Horizontal ruling = field of least-altered FW rhyolites (Chapter 3), vertical ruling = field of 13 out of 14 sericites from Abitibi VMS deposits. Twenty-nine chlorites from Abitibi VMS deposits plot within 1% of the $FeO_{(t)}+MgO$ apex. Chlorite and sericite data: Horne Mine - MacLean and Hoy (1991); Ansil Mine - Barrett et al. (1991); Delbridge Mine - Barrett et al. (1993); Kidd Creek Mine - Slack and Coad (1989).

Figure 4.7. Chondrite normalized REE spider diagram showing chloritite (square), sericitite (diamond), and silicified rhyolite breccia (triangle). Stippled field encloses the REE profiles of six least-altered FW rhyolites (Chapter 3).

Figure 4.8. $^{147}\text{Sm}/^{144}\text{Nd}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ diagram showing selected Kidd Creek whole rock samples (crosses: 1 = KC-102A, 3 = 18-14051R, 7 = AJ09313, 10 = 23-14242, and residues (boxes: 1R = KC-102A, 3R = 18-14051R, 7R = AJ09313, 10R = 23-14242). Size of symbol represents analytical error (2 s). Whole rock regression line from Figure 4.3.

Figure 4.9. $\epsilon_{Nd}(2712 \text{ Ma})$ values for the Kidd Creek formation arranged in approximate stratigraphic order. Filled circles = data from this study; open circles = data from Maas et al. (1986). The Maas et al. (1986) data, originally normalized to $^{146}\text{Nd}/^{142}\text{Nd} = 0.636151$, has been recalculated for a normalization value of $^{146}\text{Nd}/^{142}\text{Nd}$ of 0.7219 using the conversion factors of Shirey (1991). Error bars indicate estimated analytical uncertainty.

Figure 4.10. Age versus $\epsilon_{Nd}(T)$ values for Kidd Creek rhyolitic samples (this study) and pre-2695 Ma igneous rocks from the southern Superior Province. T = crystallization age, DM = depleted mantle trend (Stern et al., 1994). Continental crustal trend based on analyses of Australian shales (Allegre and Rousseau, 1984). KC_A = Kidd Creek rhyolites excluding chloritite and sericitite (n = 11); KC_B = Kidd Creek chloritite and sericitite (n = 2); 1 to 13 = southern Superior Province comparison data (see Appendix 6 for descriptions and sources). Analytical uncertainty in $\epsilon_{Nd}(T)$ values is approximately ± 0.5 epsilon units.

Sample	Sample Location	Rock Type
18-14046	1800 Level Access Drive (Upper member)	massive QP rhyolite, weak silica, sericite and carbonate alteration
18-14051R	1800 Level Access Drive (Upper member)	massive QP rhyolite, weak silica, sericite and carbonate alteration
KC-102A	2100 Level Access Drive (Upper Member)	massive to brecciated QP rhyolite, weak silica and carbonate alteration
2323-1	2323 Pillar Access Drive (Lower Member)	massive FW rhyolite, weakly to moderately silicified
2323-4	2300 NE Vent Raise Access (Lower Member)	massive FW rhyolite, weak silica and carbonate alteration
EO-92-9B	East Outcrop (Lower Member)	massive rhyolite block in rhyolite breccia, weak silica, carbonate and sericite alteration
EO-92-10B	East Outcrop (Lower Member)	massive rhyolite block in rhyolite breccia, weak silica and carbonate alteration
23-14242	2304 Fringe Drive (Lower Member)	rhyolite breccia near Cu-stringers, strongly silicified
47-14281	4700 Level Exploration Drive (Lower Member)	rhyolite breccia near Cu-stringers, strongly silicified
47-14267	4700 Level Exploration Drive (Lower Member)	chloritite, intensely altered zone within rhyolitic rocks
47-14278	4700 Level Exploration Drive (Lower Member)	sericitite, intensely altered zone within rhyolitic rocks
AJ00691	Chance Deposit Area, DDH K26-26, 191-194 m	massive rhyolite, weak sericite and carbonate alteration
AJ09313	Chance Deposit Area, DDH K64-28, 995-998 m	massive rhyolite, weak chlorite and moderate sericite alteration

Table 4.1. Sample locations and descriptions. The Chance deposit is located in north-central Kidd Township approximately 2 km northwest of the Kidd Creek Mine.

Sample	Nd (ppm)	Sm (ppm)	¹⁴⁷ Sm/ ¹⁴⁴ Nd(0)	¹⁴³ Nd/ ¹⁴⁴ Nd(0)	¹⁴³ Nd/ ¹⁴⁴ Nd(T)	ε _{Nd} (T)
Whole-Rock Analyses						
18-14046	52.65	11.90	0.137	0.511783 (±21)	0.509331	4.19
18-14051R	24.77	5.77	0.141	0.511711 (±23)	0.509188	1.37
KC-102A	38.01	8.45	0.134	0.511655 (±7)	0.509257	2.73
2323-1	42.10	11.12	0.160	0.512075 (±37)	0.509212	1.84
2323-4	36.79	8.74	0.144	0.511817 (±37)	0.509240	2.40
EO-92-9B	46.64	11.46	0.148	0.511845 (±24)	0.509197	1.54
EO-92-10B	41.17	9.83	0.144	0.511820 (±26)	0.509243	2.46
23-14242	16.86	5.17	0.185	0.512593 (±19)	0.509282	3.23
47-14281	14.36	4.36	0.183	0.512524 (±14)	0.509249	2.58
47-14267	52.19	13.78	0.160	0.511800 (±13)	0.508937	-3.56
47-14278	20.02	6.69	0.202	0.512471 (±13)	0.508856	-5.14
AJ00691	42.31	13.03	0.186	0.512569 (±18)	0.509241	2.41
AJ09313	83.61	21.43	0.155	0.511995 (±8)	0.509221	2.03
Residue Analyses						
18-14046	12.28	3.62	0.178	0.512024 (±34)	0.508839	-5.49
18-14051R	11.30	2.72	0.146	0.511866 (±116)	0.509253	2.66
KC-102A			0.260	0.513466 (±33)	0.508813	-5.98
2323-1	18.86	4.35	0.140	0.511732 (±15)	0.509227	2.14
2323-4	27.40	6.11	0.135	0.511667 (±12)	0.509251	2.62
EO-92-9B	25.84	6.67	0.156	0.512060 (±25)	0.509268	2.95
EO-92-10B	26.04	6.03	0.140	0.511724 (±51)	0.509219	1.98
AJ00691	11.53	5.16	0.271	0.513677 (±18)	0.508828	-5.71
AJ09313	21.80	6.13	0.170	0.511991 (±20)	0.508949	-3.32

Table 4.2. Sm-Nd isotopic results. T = 2712 Ma, 0 = present day. A present day ¹⁴³Nd/¹⁴⁴Nd reference value of 0.512638 for a chondritic reservoir (CHUR) has been used to calculate ε_{Nd}(T) (Faure, 1986). Values in parenthesis are within run 2 s errors for present day ¹⁴³Nd/¹⁴⁴Nd; estimated uncertainty in ε_{Nd}(T) is approximately ± 0.5 epsilon units.

Upper member			Lower member										Chance Deposit Area	
Sample	18-14046	18-14051	HG-2323-1	HG-2323-4	EO-92-9B	EO-92-10B	23-14242	47-14281	47-14267	47-14278	AJ-00691	AJ-09313		
Rock Type	QP rhyolite	QP rhyolite	FW rhyolite	FW rhyolite	block rhyolite	block rhyolite	breccia rhyolite	breccia rhyolite	chlorite	sericite	rhyolite	rhyolite		
SiO ₂	80.20	82.40	83.20	80.60	80.80	80.90	80.90	88.50	25.00	58.20	76.00	78.80		
TiO ₂	0.145	0.145	0.081	0.059	0.105	0.109	0.076	0.059	0.186	0.175	0.070	0.110		
Al ₂ O ₃	9.73	9.45	9.61	8.71	10.40	10.40	9.41	6.13	21.20	23.90	10.90	9.67		
Fe ₂ O ₃	2.39*	1.01*	0.17	0.40	0.21	0.18	0.75	0.34	4.68	1.91	1.41	1.87		
FeO	n.d.	n.d.	0.3	1.0	0.1	0.3	2.6	1.4	27.5	3.5	n.d.	n.d.		
MnO	0.08	0.05	0.04	0.12	0.03	0.02	<0.01	<0.01	0.09	0.02	0.07	0.05		
MgO	0.42	0.20	0.23	0.27	0.11	0.18	0.76	0.54	10.00	1.24	1.02	1.50		
CaO	1.03	0.82	0.46	1.80	0.16	0.09	0.23	0.02	0.04	0.11	0.81	1.92		
Na ₂ O	2.67	3.36	4.74	0.76	5.18	3.15	0.27	0.16	0.12	0.54	0.39	0.38		
K ₂ O	1.90	1.92	0.70	2.23	1.91	4.34	2.08	1.35	0.25	5.87	5.61	2.45		
P ₂ O ₅	0.04	0.03	0.03	0.20	0.02	0.03	<0.01	<0.01	<0.01	<0.01	0.02	0.04		
LOI	0.95	0.65	0.70	2.65	0.45	0.60	1.85	1.50	8.10	4.10	2.25	2.70		
Sum	99.60	100.00	100.40	98.80	99.60	100.50	99.20	100.10	100.20	99.90	98.70	99.60		
CO ₂	0.72	0.56	0.66	2.18	0.03	0.03	0.26	0.02	<0.01	0.01	n.d.	n.d.		
H ₂ O ⁺	0.8	0.5	0.4	0.8	0.3	0.3	1.5	1.2	10.6	3.3	n.d.	n.d.		
C	n.d.	n.d.	0.23	0.61	0.08	0.11	0.10	0.14	0.11	0.20	n.d.	n.d.		
S	0.03	0.04	0.01	0.02	0.01	0.01	0.29	0.04	0.06	0.38	n.d.	n.d.		
Li	n.d.	n.d.	2	3	<1	<1	20	6	154	21	n.d.	n.d.		
Be	n.d.	n.d.	2	3	2	2	1	<0.5	<0.5	1	n.d.	n.d.		
B	n.d.	n.d.	22	59	13	<10	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.		
F	n.d.	n.d.	79	185	36	67	935	351	486	1430	n.d.	n.d.		

Table 4.3. (page 1 of 3)

Sample	18- 14046	18- 14051	HG- 2323-1	HG- 2323-4	EO-92- 9B	EO-92- 10B	23- 14242	47- 14281	47- 14267	47- 14278	AJ 00691	AJ 09313
Sc	n.d.	n.d.	<1	1.00	0.79	1.07	1.20	0.70	1.70	2.30	n.d.	n.d.
V	n.d.	n.d.	5	4	<2	<2	<2	<2	14	<2	n.d.	n.d.
Cr	n.d.	n.d.	40	20	21	<2	13	4	14	7	n.d.	n.d.
Co	n.d.	n.d.	<1	<1	2	1	9	4	42	4	n.d.	n.d.
Ni	2	<1	<1	<1	1	2	<1	<1	14	<1	n.d.	n.d.
Cu	51	18	7	1	5	4	2430	285	429	783	n.d.	n.d.
Zn	73	38	23	35	28	24	400	28	499	97	n.d.	n.d.
Ga	n.d.	n.d.	18	15	21	18	31	25	75	45	n.d.	n.d.
As	n.d.	n.d.	5.8	0.6	0.5	<0.1	25.0	<3	<3	<3	n.d.	n.d.
Rb	48	36	20	49	34	68	53	36	11	135	123	89
Sr	23	33	41	37	39	38	21	7	5	22	17	29
Y	44	38	118	112	66	77	60	31	126	73	n.d.	n.d.
Zr	178	186	197	178	222	201	195	130	383	444	136	250
Nb	14	13	21	18	24	23	22	16	43	36	25	28
Mo	n.d.	n.d.	<1	<1	2	<1	<1	<1	<1	2	n.d.	n.d.
Ag	0.4	0.9	<0.1	<0.1	<0.1	0.5	4.2	0.5	1.5	1.0	n.d.	n.d.
Cd	n.d.	n.d.	<0.2	<0.2	<0.2	0.2	<1	<1	<1	<1	n.d.	n.d.
Sn	n.d.	n.d.	10	7	12	10	36	22	26	71	n.d.	n.d.
Sb	n.d.	n.d.	0.4	0.2	0.2	0.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cs	n.d.	n.d.	0.8	1.5	1.0	2.0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ba	n.d.	n.d.	541	587	534	904	153	156	87	392	n.d.	n.d.

Table 4.3. (page 2 of 3)

Sample	18- 14046	18- 14051	HG- 2323-1	HG- 2323-4	EO-92- 9B	EO-92- 10B	23- 14242	47- 14281	47- 14267	47- 14278	AJ 00691	AJ 09313
La	43	32	43	47	36	53	10	10	20	9	29	66
Ce	92	74	101	105	81	114	25	25	68	25	76	159
Pr	11.0	8.9	12.6	13.3	10.4	13.9	3.0	2.8	8.6	3.2	n.d.	n.d.
Nd	44.6	35.8	53.2	56.4	46.1	62.7	14.7	13.4	42.3	15.9	44.6	87.2
Sm	11.3	9.0	14.4	14.6	12.8	16.4	4.8	4.3	12.9	5.4	14.5	23.7
Eu	1.39	1.35	2.16	1.93	1.66	1.83	0.32	0.19	0.38	0.40	1.40	3.25
Gd	10.4	8.5	14.0	14.5	12.0	14.2	5.9	4.9	15.5	6.4	n.d.	n.d.
Tb	1.8	1.4	2.3	2.4	1.8	2.1	1.5	1.0	3.5	1.7	2.6	3.1
Dy	9.9	8.3	14.3	15.1	11.4	12.6	8.3	5.4	20.1	10.1	n.d.	n.d.
Ho	1.8	1.6	2.9	3.1	2.2	2.4	2.4	1.4	5.3	2.9	n.d.	n.d.
Er	5.1	4.8	8.5	9.2	6.4	7.4	6.2	3.4	12.9	7.1	n.d.	n.d.
Tm	0.7	0.7	1.3	1.4	0.9	1.1	1.3	0.7	2.6	1.4	n.d.	n.d.
Yb	4.2	4.9	8.5	9.0	6.2	8.8	8.0	4.3	16.5	8.2	9.9	6.6
Lu	0.60	0.73	1.23	1.31	0.90	1.34	1.38	0.71	2.72	1.21	1.37	0.93
Hf	n.d.	n.d.	8.3	8.3	7.5	9.5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ta	n.d.	n.d.	1.7	2.0	1.0	2.0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
W	n.d.	n.d.	2	3	1	2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Au	n.d.	n.d.	<2	<2	<2	<2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Tl	n.d.	n.d.	0.3	0.6	0.2	0.3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Pb	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	n.d.	n.d.
Bi	n.d.	n.d.	<0.5	<0.5	<1	<1	n.d.	<3	16	<3	n.d.	n.d.
Th	5.4	5.3	6.9	6.8	6.4	7.8	6.9	3.8	15.5	15.2	n.d.	n.d.
U	1.8	1.0	2.0	2.0	1.7	2.7	1.6	1.0	3.7	3.8	n.d.	n.d.

Table 4.3. Major and trace element compositions of representative samples. LOI = loss on ignition * = total Fe as Fe₂O₃, n.d. = not determined. Oxides, LOI, sum, C, and S reported in wt. %, all others in ppm except Au in ppb.

Chapter 5

SUMMARY AND CONCLUSIONS

It is proposed that the 350-450 m thick, predominantly felsic volcanic and volcanoclastic succession containing the Kidd Creek VMS deposit be informally named the Kidd Creek formation. The Kidd Creek formation is further subdivided on an informal basis into the Lower, Middle, and Upper members. The Lower member, in the stratigraphic footwall of the massive sulfide-bearing succession, is characterized by coherent rhyolite (FW rhyolite) and autoclastic rhyolite breccia. The Middle member, which hosts all of the known strata-bound orebodies, is composed primarily of a bedded sequence of volcanoclastic rocks (boulder conglomerate, pebble conglomerate, sandstone, mudstone) along with subordinate amounts of coherent and autoclastic rhyolite, argillite, and massive sulfide. The Upper member, located stratigraphically above the massive sulfide-bearing succession, consists of coherent and autoclastic facies of quartz-porphyrific rhyolite (QP rhyolite).

The QP rhyolite erupted from two, parallel fissures that are now subparallel to the F_1 fold axial plane. Two rhyolite domes were constructed above the north fissure to form the north ridge whereas one elongate dome was constructed above the south fissure to form the south ridge. These rhyolitic ridges extend for a least 1.9 km. The plunge of the ridge axes represents the intersection of primary synvolcanic faults with the paleoseafloor.

The synvolcanic fissure beneath the north ridge is interpreted to have acted as a conduit for ascending hydrothermal fluids before QP rhyolite volcanism and is interpreted to have exerted a strong influence on the location of hydrothermal discharge and the deposition of the south orebody. It is also probable that the synvolcanic fissure which controlled eruption of the south QP rhyolite ridge also acted as conduit for ascending hydrothermal fluids. This suggests exploration targets (i) at depth where the greywacke contact may have migrated southward thereby preserving strata beneath the south QP rhyolite ridge, and (ii) along the greywacke contact where fault slices of offset strata may be preserved (assuming that the greywacke contact does not represent an erosional unconformity).

Rhyolites of the Kidd Creek formation have tholeiitic affinities. REE patterns are intermediate between end member FIIIa and FIIIb felsic volcanic rocks but pronounced negative Eu anomalies and high Th and U contents favour their inclusion in the FIIIb group.

The QP rhyolite retains a record of hanging wall alteration, primarily in the form of sericitization, silicification and feldspar destruction, which may be detected visually and chemically. Therefore, the Kidd Creek hydrothermal system was operative before, during and after QP volcanism; however, no VMS ores are known to occur within or above the QP rhyolite.

The QP rhyolite represents the end of significant felsic volcanism in the Kidd Creek Mine area. Both the coherent and breccia facies of the QP rhyolite may be discriminated geochemically from felsic volcanic and volcanoclastic rocks in the Lower and Middle members of the Kidd Creek formation. This is particularly important as the QP rhyolite may mark the end of hydrothermal activity at the mine and exploration in and outside of the mine area should be focused on strata below the QP rhyolite or time-stratigraphic equivalent units.

The REE and the high field strength elements Y, Hf, Zr, Nb, Ta, Th and U were relatively immobile during hydrothermal alteration and subsequent metamorphism of coherent rhyolite within the Lower member (FW rhyolite) and Upper member (QP rhyolite) of the Kidd Creek formation. The preservation of constant interelement ratios, the test of element immobility in rocks sharing common protolith compositions, is readily apparent on spider diagrams normalized to appropriate least-altered analyses.

Least-altered rhyolites of the Kidd Creek formation were compared to post-Triassic oceanic rhyolites and plagiogranites of known tectonic environments on spider diagrams using incompatible elements that were relatively immobile during hydrothermal alteration (REE and HFSE). The Kidd Creek rhyolites are dissimilar to the post-Triassic felsic volcanic rocks and plagiogranites from intraplate islands, ensimatic island arcs, ensialic island arcs, ensimatic back-arc rifts, immature mid-ocean rifts and immature continental rifts. They are similar to rhyolites from mature continental rifts undergoing sea-floor spreading such as the Red Sea. However, the lack of thick terrigenous clastic

assemblages, and U-Pb and Sm-Nd isotopic data are not consistent with a continental rift environment for Kidd Creek area (Bleeker and Parrish, 1996; Barrie et al., 1996; Chapter 4). Kidd Creek rhyolites have strong REE and HFSE geochemical similarities to rhyolites and plagiogranites from anomalous mid-oceanic ridge spreading-Centre environments including the axial rift zones of Iceland, the Galapagos spreading Centre and the mid-Atlantic ridge at 45°N . The closest match is with rhyolites erupted from Askja and Krafla in Iceland's eastern axial rift zone. As at Kidd Creek, most post-Triassic spreading Centre environments that contain rhyolites and/or plagiogranites are compositionally bimodal and are characterized by incompatible element enriched basaltic rocks.

The similarity of Kidd Creek and Iceland's axial rift zones is not limited to rhyolite geochemistry. Kidd Creek basaltic rocks and the tholeiitic basalts of Iceland have similar incompatible element enriched geochemical signatures and both environments are also characterized by Mg-rich volcanic rocks indicative of high-temperature environments: spinifex-textured komatiite at Kidd Creek and picrite in Iceland. Within Iceland's axial rift zones the eruption of both rhyolites and basalts is strongly controlled by parallel fissure swarms with rhyolitic volcanism restricted to areas of high volcanic output which form central volcanoes. Kidd Creek represents a felsic volcanic Centre and the distribution of felsic volcanic ridges at Kidd Creek is consistent with eruption from parallel fissures.

By analogy to the central volcanoes of Iceland's axial rift zones, the Kidd Creek rhyolites and felsic volcanoclastic rocks, which host the Kidd Creek VMS deposit, are interpreted to have formed in or on oceanic crust characterized by a steep geothermal gradient and rapid subsidence, possibly above a rising mantle plume. This interpretation is supported by the presence of a komatiite-bearing ultramafic succession below the Kidd Creek formation and high rhyolite eruption temperatures (Barrie, 1995). This high-temperature environment, coupled with high cross stratal permeability due to faulting inherent in rift and caldera environments, provided ideal conditions to generate, sustain and focus the high-temperature hydrothermal system required to form the giant Kidd Creek deposit. In this model the komatiites, the rhyolites and the Cu-Zn-Pb-Ag ores are all manifestations of thermal and structural regimes within the crust.

The temporal and spatial association of rhyolites and VMS ores at Kidd Creek and many other VMS deposits in bimodal successions suggests that the formation of these orebodies may be related to the introduction of silicic melt into a mafic-ultramafic magmatic system. One possible explanation is that low-density, high-viscosity siliceous magma "clogs" the upper magma conduits creating a transient period of volcanic quiescence favorable for long-lived hydrothermal discharge.

Sm-Nd isotopic data are presented for 13 rhyolite samples (coherent and breccia facies) from the Kidd Creek Mine area. Excluding samples containing intense phyllosilicate alteration (chloritite and sericitite) a whole-

rock regression age of 2733 ± 260 Ma has been obtained based on 11 samples. This age is within error of the U-Pb zircon ages of 2714.1 ± 1.5 Ma for FW (footwall) rhyolite and 2710.5 ± 1.1 Ma for QP (hanging wall) rhyolite obtained by Bleeker and Parrish (1995).

The ϵ_{Nd} values for the Kidd Creek rhyolites, excluding chloritite and sericitite samples, range from +1.4 to +4.2 with an average of +2.43 ($n = 11$) when evaluated at 2712 Ma (the average of rhyolite U-Pb zircon ages determined by Bleeker and Parrish, 1995). A plot of Nd isotopic data for the Kidd Creek Mine formation against relative stratigraphic position shows no systematic variation in ϵ_{Nd} with stratigraphic height. When ϵ_{Nd} is plotted against age the Kidd Creek data, excluding the chloritite and sericitite analyses, form a cluster which straddles the depleted mantle curve with no evidence of contamination by older crust. The Kidd Creek ϵ_{Nd} values are similar to those obtained for Archean igneous rocks and mineral separates collected elsewhere in the southern Superior Province and are consistent with the formation of the Kidd Creek VMS deposit in an ensimatic environment, possibly at a mid-ocean rift, well removed from continental margins.

Two intensely altered, LREE depleted samples with rhyolitic protoliths, an Fe-rich chloritite and a sericitite associated with chalcopyrite stringers beneath the central orebody, return anomalously low $\epsilon_{Nd}(2712 \text{ Ma})$ values (-3.6 and -5.1). These results may record syn-ore isotopic exchange between hydrothermal fluids and wallrocks at high water/rock ratios. However, it is more likely that the negative ϵ_{Nd} shifts reflect disturbance of the Sm-Nd isotopic

system during metamorphism and/or metasomatism postdating volcanism and the formation of the VMS ores. This interpretation is supported by the occurrence at Kidd Creek of hydrothermal monazite with a U-Pb age of 2659 ± 3 Ma (Schandl and Gorton, 1991), and by acid leaching experiments which indicate that a significant proportion of the LREE reside in labile minerals.

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Appendix 1

VOLCANOLOGY AND GEOCHEMISTRY OF THE LOWER AND MIDDLE MEMBERS OF THE KIDD CREEK FORMATION

Geological mapping at the Kidd Creek Mine, and discussion with mine geological staff, has led to the subdivision of the Kidd Creek formation into the Lower, Middle and Upper members (some of this mapping is presented in Chapter 2 and in Maps 2 to 7). The volcanology and geochemistry of the Upper member, the QP rhyolite, are discussed at length in Chapter 2.

Lower Member of the Kidd Creek Formation

The term “FW rhyolite” is used by the author to refer to rhyolite within the Lower and Middle members of the Kidd Creek formation which may be distinguished chemically and petrographically from Upper member rhyolite (QP rhyolite; Chapter 2; Figures 1.3 and 2.21). The Lower member of the Kidd Creek formation is composed almost entirely of vent-proximal facies of FW rhyolite. Vent-proximal facies include massive and flow-banded coherent rhyolite, *in situ* to locally transported autoclastic rhyolite breccia, and rhyolite hyaloclastite (see Appendix 8 for a description of volcanoclastic rock terminology used in this thesis, and Appendix 10 for rock type descriptions). *In situ* FW rhyolite breccia is approximately equivalent to the “crackle-breccia” of

Coad (1985). The breccia and hyaloclastite of the Lower member are monomict and geochemically identical to the coherent rhyolite facies except for variability introduced by hydrothermal metasomatism. Both the monomict nature the Lower member volcanoclastic rocks and the geochemical homogeneity of the fragmental rocks with coherent rhyolite are incompatible with the mixing of clast types likely to occur during significant transport. Additional evidence for an autoclastic origin for the breccia and hyaloclastite include: (i) *in situ* autoclastic breccia is devoid of matrix (the darker areas between fragments are the result of phyllosilicate crystallization during alteration), (ii) coherent rhyolite grades with increasing multidirectional fracturing into autoclastic breccia (2323 Pillar Access Drive and 4700 Drill Drive; Figure A7.3 to A7.6; Map 6), and (iii) jig-saw fit texture is common within the autoclastic breccia and hyaloclastite (Figures A7.4 and A7.9); jig-saw fit texture implies that if the interfragmental material was removed the fragments would fit back together leaving little or no space between fragments). The rounded appearance of some fragments within autoclastic breccia (breccia-conglomerate) is ascribed to (i) alteration processes with more intense sericitization and chloritization alteration occurring near fracture intersections, and (ii) local resedimentation of some breccia (Figure A7.9). Silicified areas of autoclastic breccia are generally mapped as “cherty breccia” or “curdy rhyolite” by mine staff. Much of the chalcopyrite-rich stringer zone beneath the north and central orebodies occurs within silicified, autoclastic, rhyolite breccia of the Lower member (Figure A7.5). Other minerals accompanying the chalcopyrite are pyrrhotite, chlorite, sericite, tourmaline, and albite. Autoclastic breccia marginal to chalcopyrite stringer zones commonly contains sphalerite as

fracture-controlled to pervasive “stain” (very fine-grained, disseminated sphalerite; Figure A7.3, A7.4, and A7.9; Map 6). Sphalerite mineralization terminates abruptly at the contact between autoclastic breccia and coherent rhyolite (sphalerite-free). This relationship is thought to reflect a primary permeability contrast between coherent rhyolite and *in situ* rhyolite breccia during the mineralization event.

Distribution of Coherent Rhyolite Within the Lower Member

FW rhyolite in the Lower member of the Kidd Creek formation was mapped in the footwall of the north and central orebodies on 1600, 2300, and 4700 levels of the Kidd Creek Mine (Maps 2 and 6). This work indicates that rocks mapped as rhyolite by mine geologists correspond to the massive and flow-banded coherent facies of the FW rhyolite and exclude the autoclastic facies, much of which is mapped as “cherty breccia”. Figure A1.1 shows the distribution of coherent rhyolite in the footwall of the north and central orebodies from the 800 foot level (3085 m elevation) to the 6000 foot level (1512 m elevation), a vertical distance of 1573 m. The data for this diagram were taken from company level plans. The view in Figure A1.1 is toward the east from 12° above a horizontal plane. Behind the view (to the east and stratigraphically lower) ultramafic rocks are dominant while in front of the view (to the west and stratigraphically higher) the main rock types are autoclastic rhyolite, polymict pebble and boulder conglomerates, argillite and massive sulfides of the north and central orebodies.

Also shown on Figure A1.1 is the distribution of structurally related “fingers” of ultramafic rock which jut toward the west into the felsic volcanic and volcanoclastic pile. Regarding these ultramafic fingers, Bleeker (1995, p. 116) stated “... the apparent apophyses coincide with tight to isoclinal F1 hinges and are thus structural rather than primary features”. In the upper levels of the mine the southern ultramafic finger lies along the east-west shear zone. The northern ultramafic finger is situated at or near an abrupt change in strike of volcanic strata related to either tight folding, faulting, or both. Volcanic strata are west-facing in the immediate mine area and north-facing to the north and east of the mine.

Figure A1.1 demonstrates that coherent FW rhyolite of the Lower member of the Kidd Creek formation forms two distinct, parallel “ridges” approximately 200 m apart which plunge steeply to the north. Only the southern ridge is exposed in underground workings. The attitude of these FW rhyolite ridges is parallel to that of the QP rhyolite ridges of the Upper member (Chapter 2). Figure A1.1 shows that the two FW rhyolite ridges are continuous between the 800 foot level and 6000 foot levels and maps of the open pit show that these two ridges extend to surface (Walker and Mannard, 1974; Walker et al., 1975) for a total known length of 1.8 km. The area between the coherent rhyolite ridges consists primarily of rhyolite autoclastic breccia (“cherty breccia”) which hosts chalcopyrite-rich stringer ore beneath the north and central orebodies. These ridges are interpreted to occur directly over fissures which fed the rhyolitic volcanism. Parallelism between the FW rhyolite ridges and the

ultramafic trend suggests that the structures which control the location of the ultramafic fingers, which lie marginal to the rhyolite ridges, are parallel to the FW rhyolite feeding fissures. Parallelism between the FW rhyolite ridges of the Lower member, the structures controlling the ultramafic fingers, and the QP rhyolite ridges of the Upper member indicates that these trends represent a series of parallel, long-lived synvolcanic structures.

The two ridges shown in Figure A1.1 are interpreted to represent two linear bodies of coalescing rhyolite cryptodomes formed above their feeding fissures and below a covering of *in situ* autoclastic breccia. This interpretation is consistent with their morphology, the lack of internal flow contacts and interflow units, and the occurrence of complete lateral gradations between (i) unfractured coherent rhyolite, (ii) coherent rhyolite with polygonal fractures, and (iii) *in-situ* autoclastic rhyolite breccia.

Middle Member of the Kidd Creek Formation

The Middle member of the Kidd Creek formation is characterized by a suite of transported volcanoclastic rocks composed largely of resedimented autoclastic rhyolite fragments. Resedimentation is interpreted to have been a response to gravitational instability and transport possibly down a fault scarp or volcanic edifice. Volcanoclastic rock types of the Middle member include polymict boulder conglomerate, polymict pebble conglomerate, monomict rhyolite pebble conglomerate, sandstone and mudstone. Non-volcanoclastic

lithologic units within the Middle member are graphitic argillite and massive sulfide consisting of one or more of pyrite, sphalerite, galena, chalcopyrite, and pyrrhotite. Textures indicate that a large proportion of the massive sulfide ores formed by subseafloor replacement of volcanoclastic rocks. Evidence of replacement includes (i) the screens of rhyolite pebbles within massive sulfide ore mapped in 2129 Crosscut (Map 5), and (ii) the sulfide replacement front mapped at the top of the north orebody in 2421K Pillar Slot (Map 7). The common occurrence of pyrite and sphalerite ($\pm$ galena) clasts in polymict conglomerate within the Middle member demonstrates that early massive sulfide lenses underwent destruction and transport (locally the proportion of sphalerite-rich clasts within volcanoclastic conglomerate is high enough to be of ore grade). The rare occurrence of chalcopyrite clasts within volcanoclastic conglomerate indicates that either (i) destructive processes (e.g., erosion) rarely penetrated deeply enough to uncover stringer zone mineralization, or (ii) the stringer zone during the initial stages of deposit formation was pyrite- and sphalerite-rich rather than chalcopyrite-rich. The second interpretation is consistent with the replacement of massive pyrite-sphalerite by chalcopyrite (e.g. 2129 Crosscut), pyrite-sphalerite mineralization marginal to chalcopyrite stringers in the Lower member (Figures A7.2 to A7.4 and A7.9), and the occurrence of sphalerite-stained, pyrite-veined rhyolitic clasts within the volcanoclastic, polymict conglomerates (Figure A7.13). Hydrothermally altered, tan mafic clasts are also common in volcanoclastic breccias where they generally form less than 5% of the clast population but locally form up to 30% of the clasts. Argillite clasts are an important clast type stratigraphically above the graphitic argillite unit in the immediate hanging wall of the north orebody.

Locally, volcanoclastic rocks may have an argillaceous matrix.

The Middle member of the Kidd Creek formation also includes coherent rhyolite, autoclastic rhyolite breccia, and rhyolite hyaloclastite which are interlayered with volcanoclastic rocks (e.g. 1602 Drive South, 2129 Crosscut). Unlike the Lower member, where these rocks dominate, coherent and autoclastic rhyolites generally form less than 50% of stratigraphic successions within the Middle member. The recognition of coherent and autoclastic rhyolite within rocks of the Middle member is a new contribution to the geologic understanding of the Kidd Creek formation. Many of these rocks were formerly mapped as rhyolite tuffs (coherent rhyolite and rhyolite hyaloclastite) and “curdy rhyolite” (autoclastic rhyolite breccia-conglomerate).

Physical evidence of Middle member coherent and autoclastic rhyolite

(i) Coherent rhyolites, which are weakly quartz porphyritic, have randomly dispersed, generally intact quartz phenocrysts up to 2 mm across in an aphanitic groundmass (Figure A7.20). Less altered samples also contain a small percentage of intact, randomly distributed feldspars up to 2 mm across. Within these rocks there is no evidence of layering based on grain size, broken phenocrysts are not abundant, and no lithic clasts or bubble-wall shards were observed.

(ii) Coherent rhyolites are locally flow banded on a microscopic scale (Figure A7-24).

(iii) Some coherent rhyolite samples contain quartz spherulites up to 0.3 mm in diameter. Coherent rhyolites commonly contain spherical aggregates of quartz crystals (spherules) which are interpreted to be sector recrystallized spherulites (Figures A7.21 to A7.23).

(iii) Samples with definite spherulites contain a microscopic anastomosing fracture pattern caused by fractures wrapping around spherulites (i.e., fractures occupy the spaces between spherulites). A similar anastomosing fracture pattern is common in coherent rhyolites which contain spherules but lack clearly identifiable spherulites.

(iv) Autoclastic rhyolite breccia and rhyolite hyaloclastite are monomict (Figures A7.4, A7.9, and A7.25). For example, a polished slab of “curdy” rhyolite from 1602 Drive South is clearly a monomict rhyolite breccia-conglomerate (Figure A7.9).

(v) *In situ* rhyolite breccias display jig-saw fit texture (i.e. fragments may be visually put back together by removing matrix; Figure A7.4 and A7.9). Jig-saw fit texture is also locally present in rhyolite hyaloclastite.

(vi) All known rhyolites in the Kidd Creek Mine area are essentially non-vesicular. Therefore, local formation of tuff by magmatic eruption is unlikely; as noted above, bubble-wall glass shards are absent.

Geochemical evidence of Middle member coherent and autoclastic rhyolite

Figure A1.2 shows a plot of Zr versus TiO_2 for (i) ultramafic rock samples from stratigraphically below the Kidd Creek formation, (ii) Lower member rhyolites (RH_{LM} : coherent rhyolites and autoclastic breccias from underground and the east outcrop), (iii) argillites of the Middle member, (iv) mafic volcanic fragments within volcanoclastic conglomerate of the Middle member, (v) fine-grained gabbros and basalts of the wedge gabbro sill (between the Middle and Upper members), and (vi) mafic volcanic rocks, primarily basalts, from above the Kidd Creek formation. A similar diagram is presented in Figure A1.3 for rhyolites (coherent and autoclastic) and resedimented volcanoclastic rocks of the Middle member. Basaltic rocks in the Kidd Creek Mine area are divided into two groups, Al-rich and P-rich, as identified on the Al_2O_3 versus P_2O_5 diagram in Figure A1.4. The P-rich basaltic rocks, which also tend to be enriched in Ti, Fe, Zr, Nb, and LREE, grade into “icelandic” andesites with increasing silica content. Note in Figure A1.3 that the resedimented volcanoclastic rock samples tend to plot above the RH_{LM} field consistent with the introduction of mafic volcanic clasts $\pm$ argillite clasts ($\pm$ argillite matrix) during the resedimentation process. However, rocks from the Middle member identified as coherent or autoclastic rhyolite plot within the RH_{LM} field. The lack of a geochemical mixing component is inconsistent with an interpretation of these rocks as fine-grained,

distal, resedimented volcanoclastic material. Similar conclusions may be drawn from the Zr versus P_2O_5 plots presented in Figures A1.5 and A1.6. The strong linear trends of the rhyolite samples in Figures A1.2, A1.3, A1.5, and A1.6 reflects residual gains and losses of relatively immobile Zr, TiO_2 and P_2O_5 due to mass changes (the average least-altered, coherent, footwall rhyolite contains 204 ppm Zr). At infinite mass gain (infinite depletion of Zr, TiO_2 and P_2O_5) the mass change trends would intersect the origins of the diagrams).

Evidence From Polymict Volcanoclastic Conglomerates On The Timing of Basin Subsidence

The accumulation of a thick volcanoclastic succession and the pronounced elongation of the orebodies has led researchers to suggest that the Kidd Creek deposit formed in a basin, possibly a rift-related graben, created by subsidence along one or more synvolcanic structures (e.g., Gibson and Kerr, 1993; Bleeker, 1995). The presence of parallel, strongly elongate rhyolite ridges in both the Lower and Upper Kidd Creek formations is compatible with a rift model as is the chemistry of the rhyolites (Chapters 2, 3, and 4). The Kidd Creek formation was deposited on an ultramafic footwall - an extrusive origin for at least part of the ultramafic succession is demonstrated by the presence of spinifex-textured komatiite flows (J. Everest, written communication, 1995). If subsidence occurred prior to the onset of Kidd Creek formation felsic volcanism or if the subsidence exceeded the accumulation rate

of the Kidd Creek formation then ultramafic rocks would have been exposed on the basin walls (fault scarps). Therefore, early or rapid basin subsidence should be reflected by an ultramafic component within the polymict conglomerates.

No ultramafic clasts were identified by the author during underground mapping and subsequent sample examination. Similarly a study of polished slabs of volcanoclastic conglomerates from the Middle member, which included geochemical analysis of individual clasts, did not reveal ultramafic clasts (S. Petersen, written communication, 1993). However, this evidence does not exclude the possibility that ultramafic clasts were present in the original volcanoclastic conglomerates but have subsequently been rendered unrecognizable due to hydrothermal alteration and mechanical deformation.

In Figures A1.3 and A1.6 the Middle member volcanoclastic rocks appear to be displaced from the RH_{LU} field toward the MV_P and/or MV_{Al} fields rather than toward the UM field but the data are not conclusive. However, a Zr versus Ni diagram (Figure A1.7) demonstrates that the very low Ni values in the Middle member volcanoclastic rocks are clearly inconsistent with input of ultramafic or MV_{Al} clasts but are consistent with input of Ni-poor MV_P clasts. This is compatible with the fact that chemically analyzed mafic clasts from Middle member volcanoclastic conglomerates fall within the MV_P fields on Figures A1.2, A1.4, and A1.7. The lack of an ultramafic component within the polymict conglomerates suggests (i) it is unlikely that significant subsidence occurred before a substantial veneer of rhyolitic and P-rich basaltic (MV_P) rocks had been

extruded above the ultramafic succession, and/or (ii) the rate of subsidence did not exceed the input of Kidd Creek formation volcanic material into the basin. This raises the interesting possibility that subsidence was linked to the onset of rhyolitic and basaltic volcanism such as might occur from the development of a collapse caldera.

Figure A1.1. North-south section through the north and south ridges of coherent FW rhyolite viewed from the west at an angle of 12° above a horizontal plane. Areas of rhyolite shown with solid fill have reasonably well defined footwall contacts based on diamond drill hole data. Areas of rhyolite shown as lines lack sufficient diamond drill hole information to define footwall contacts.

Figure A1.2 (Part A). Zr versus TiO₂ diagram for Lower member rhyolites (FW rhyolites) and other rocks of the Kidd Creek Mine area.

-
- AI-RICH BASALT - ANDESITE
 - P-RICH BASALT - ICELANDIC ANDESITE
 - ◇ WEDGE GABBRO SILL
-

KIDD CREEK FORMATION

MIDDLE MEMBER

- ✧ MAFIC CLAST IN VOLCANICLASTIC CONGLOMERATE
- ✦ GRAPHITIC ARGILLITE
- Y VOLCANICLASTIC MUDSTONE
- ⊕ VOLCANICLASTIC SANDSTONE
- ✕ VOLCANICLASTIC PEBBLE CONGLOMERATE
- ▲ MIDDLE MEMBER AUTOCLASTIC RHYOLITE
- MIDDLE MEMBER COHERENT RHYOLITE

LOWER MEMBER

- ⊕ EAST OUTCROP AUTOCLASTIC RHYOLITE*
 - △ UNDERGROUND AUTOCLASTIC RHYOLITE
 - UNDERGROUND COHERENT RHYOLITE
-

◆ **ULTRAMAFIC ROCK**

- MV_{AI} AI-RICH MAFIC VOLCANIC ROCKS
- MV_P P-RICH MAFIC VOLCANIC AND INTRUSIVE ROCKS
- ARG GRAPHITIC ARGILLITE
- RH_{LA} LEAST-ALTERED LOWER MEMBER (FW) COHERENT RHYOLITE
- RH_{LU} LOWER MEMBER COHERENT AND AUTOCLASTIC RHYOLITE
- UM ULTRAMAFIC ROCK

* INCLUDES SAMPLES OF AUTOCLASTIC BRECCIA AND INDIVIDUAL RHYOLITE BLOCKS
SAMPLES CONTAINING > 5% CO₂ OR >4% S OMITTED
ARGILLITE ANALYSES FROM FALCONBRIDGE DATA (COLLECTED BY W. BLEEKER)

Figure A1.2 (Part B - Legend)

Figure A1.3. Zr versus TiO_2 diagram for Middle member rhyolites (FW rhyolites) and Middle member polymict volcaniclastic rocks (see Figure A1.2, part B, for legend). Fields from Figure A1.2.

Figure A1.4. Al_2O_3 versus P_2O_5 diagram for mafic and ultramafic rocks of the Kidd Creek Mine area (see Figure A1.2, part B, for legend).

Figure A1.5. Zr versus P_2O_5 diagram for Lower member rhyolites (FW rhyolites) and other rocks of the Kidd Creek Mine area (see Figure A1.2, part B, for legend).

Figure A1.6. Zr versus P₂O₅ diagram for Middle member rhyolites (FW rhyolites) and Middle member polymict volcaniclastic rocks (see Figure A1.2, part B, for legend). Fields from Figure A1.5.

Figure A1.7. Zr versus Ni diagram for Middle member polymict volcaniclastic rocks, mafic rocks, and ultramafic rocks of the Kidd Creek Mine area (see Figure A1.2, part B, for legend). Samples of rhyolite, argillite, P-rich mafic volcanic rocks, and the wedge gabbro sill are not plotted for clarity (these rocks are represented by fields).

Appendix 2

CHEMICAL EVOLUTION OF THE MANTLE SINCE THE LATE ARCHEAN

The formation of continental crust has enriched the crust and depleted the upper mantle in incompatible elements relative to the estimated composition of the primitive mantle (Hofmann, 1988). The mantle has also been modified by recycling of material in subducting oceanic plates and in cold plumes (Campbell and Griffiths, 1993). In this thesis comparisons are made between the composition of Kidd Creek rhyolite (ca. 2712 Ma) and post-Triassic (< about 200 Ma) felsic igneous rocks; this requires discussion as to the extent of chemical evolution within the upper and lower mantle since the late Archean.

1. The existence of a significant volume of emergent continental crust near the end of the Archean is established by significant increases in LREE, Th, and U contents and the La/Yb ratios of Proterozoic and Phanerozoic fine-grained clastic sedimentary rocks relative to their Archean equivalents (Taylor and McLennan, 1985). Two intermediate estimates for the percentage of the present mass of the continental crust formed by the end of the Archean are 50-60% (McCulloch and Bennet, 1994) and 70-90% (Taylor and McLennan, 1985). Large estimates suggest small changes in upper mantle composition during the Proterozoic and Phanerozoic related to crustal extraction. In the model of McCulloch and Bennet (1994), an increase in the proportion of mantle involved

in the extraction process (upper or depleted mantle) relative to primitive (undepleted) mantle buffers the trace element composition of the upper mantle such that by approximately 2700 Ma its trace-element composition was the same as at present except for an increase in the U and Th contents.

2. Comparisons of Archean and post-Archean tonalite reveal very similar trace element compositions except for strikingly lower contents of Ti, Y and HREE in the Archean samples (Condie, 1989b). The depletion of Y and the high La/YbN ratios of Archean relative to post-Archean trondhjemite, tonalite and granodiorite (TTG) are attributed to differences in magma generation processes at Archean and post-Archean destructive plate boundaries and not from a change in mantle composition (Martin 1986, 1993). In the Archean subducted oceanic crust was generally young and warm and the subducting slab reached melting conditions before dehydration occurred leaving a garnet- and hornblende-bearing residue which retained Y and the HREE. In contrast, subducting plates in post-Archean time tend to be old and cool so dehydration occurs before melting conditions are encountered. This fluid migrates into the overlying mantle wedge where it induces partial melting leaving a residue in which olivine and pyroxene are the dominant residual phases thereby avoiding strong source retention of HREE and Y (Martin, 1986, 1993). Drummond and Defant (1990) have demonstrated that in modern arc terranes where young (<20-30 Ma), hot oceanic plates are subducted high-Al trondhjemite-tonalite-dacite (TTD) suites with REE patterns almost identical to those of the Archean are still produced.

3. Sun and Nesbitt (1977) showed that Ti, Zr, Yb and Y each have the same degree of enrichment relative to primitive mantle (enrichment factor of 8.0) indicating no fractionation of these elements over time. They also concluded, based on a comparison of incompatible element ratios between Archean basalt and modern MORB that the mantle source of “normal” MORB is, relative to the source of 2.7 Ga basalt, “... severely depleted in highly incompatible elements such as Cs, Ba, Rb, U, Th, K, La and Nb, but has comparable abundances of less incompatible elements such as Ti, Zr, Y, Yb” (Sun and Nesbitt, 1977 p.429). However, Sun and Nesbitt (1977) made no allowance for the possibility that Archean basalt may not have formed at normal mid-ocean ridge spreading centres and do not consider that tectonic setting may strongly influence the trace element characteristics of basaltic rocks (Pearce and Cann, 1973; Floyd and Winchester, 1975; Pearce and Norry, 1979; Wood et al., 1979; Wood, 1980). Condie (1989a), based on a trace-element classification scheme, found that one of the most striking of features of Archean and Proterozoic greenstone belts is the rarity of basalt with N-MORB geochemical characteristics. Average incompatible element contents in greenstone-belt basalt tend to increase with time, except for Nb and Ta, and La/Sm ratios also increase from the Archean to post-Archean basalt (Condie, 1989a), opposite to the temporal trend advocated by Sun and Nesbitt (1977). The observed variations in average basalt compositions probably represent changes in the proportions of basalt from different tectonic environments (Condie, 1989a).

4. Evidence for temporal change in lower mantle composition since the late Archean is even more elusive than for the upper mantle. In a study of 207 basalt samples from several Archean greenstone belts Condie (1989a) found no samples with the chemical characteristics of within-plate basalt which could represent plume-derived magma from the lower mantle. Komatiite is another rock type that may form from plumes emanating from the lower mantle (Campbell et al., 1989; Campbell and Griffiths, 1993). Based on relative enrichments of highly incompatible elements in komatiite and picrite with decreasing age from the late Archean to the Phanerozoic, Campbell and Griffiths (1993) suggested that the composition of plume sources changed from MORB-type to OIB- (ocean island basalt) type at the Archean-Proterozoic boundary and that OIB-type plumes were absent during the Archean (cf. Condie, 1989a). They credit this change to the onset, somewhat earlier, of subduction as the principal mechanism of downward mass transfer. However, the Cretaceous komatiite of Gorgona Island, Columbia, is more strongly depleted in highly incompatible elements than many typical examples of late Archean komatiite (Campbell and Griffiths, 1993; Jochum, et al., 1991).

The evidence presented above suggests that sweeping changes in mantle composition during the past 2.7 billion years are unlikely. This thesis adheres to the implicit assumption of Condie (1989a) that whatever changes have occurred are probably small relative to the magnitude of chemical variation imposed on magmas by petrogenetic processes in different tectonic environments.

Appendix 3

ANALYTICAL TECHNIQUES

(analytical details presented below provided by XRAL Laboratories)

All analyses were performed by XRAL Laboratories, Toronto, Ontario. Samples were crushed in a steel jaw crusher followed by vibratory milling in agate using a pot ring and puck method. Silica cleaner was milled in pot between samples to eliminate the possibility of cross contamination.

The major elements (reported as oxides) were determined by X-ray fluorescence spectrometry (XRF). A 2 grams sample was roasted at 950°C for 1 hour, then fused with 7.7 grams of lithium tetraborate, and the melt was cast into a 40 mm button. The button was analyzed on a Philips PW1600 simultaneous X-ray fluorescence spectrometer calibrated using more than 40 reference materials. Loss on ignition (L.O.I.) was determined by the difference in sample weights before and after the roasting procedure. Samples with sums of less than 98 wt.% or greater than 101 wt.% were automatically repeated. Instrument precision on most elements is better than 0.5 wt.%. Detection limits for all of the major oxides and for L.O.I. were 0.01 wt.%.

Ferrous iron analyses were performed on a 0.5 gram sample digested with sulfuric, hydrochloric, and hydrofluoric acids using an oxidation technique

based on the quantitative oxidation of ferrous salts in acid solution to the ferric oxidation state by titration with a standardized potassium dichromate solution. A slight excess of potassium dichromate caused the redox indicator sodium diphenylamino-sulfonate to change to a violet colour.

Carbon dioxide content was measured by titration. 2N HClO_4 was added to the sample to release CO_2 which was then measured by titration using a coulometer. Total C and S were determined by combustion using a Leco procedure and F was analyzed by specific ion electrode using automated Lachat instrumentation.

H_2O^+ is the weight of crystallized or combined water in the sample. Moisture was removed from a 1.0 gram sample by drying at 110°C for 3 hours. The sample was then mixed with PbO and heated in a pyrex test tube in such a manner that any water vapour was condensed on a piece of preweighed paper in the upper, cooled part of test tube (cooled by ice in a polyethylene jacket). The weight gained by the paper was the amount of H_2O^+ in the sample.

Rb, Y, Zr, Nb, Ba, Sn, Ga and Ni values were determined by X-ray fluorescence spectrometry (XRF) using 40 mm diameter pressed pellets prepared from at least 5 grams of milled rock powder. Elements are analyzed in an inert nitrogen atmosphere employing a rhodium tube in a Phillips PW1400 wavelength dispersive X-ray spectrometer. The presence of percentage levels of any elements except the usual major rock forming constituents (e.g. sulfides) would have had an adverse effect on calibration.

Li, Be, Sc, V, Cr, Co, Ni, Cu, Zn, As, Sr, Mo, Ag, Cd, W, Pb and Bi analyses were obtained for 0.5 gram samples by ICP spectroscopy following a multi-acid (HF-HClO₄) digestion on a hot plate (some refractory minerals may remain incompletely attacked). In house standards and previously analyzed standards were run to monitor proper digestion procedures while synthetic standards were used to calibrate the instrument.

For REE, Th and U concentrations 0.1 g of sample was mixed with 0.5 g of Na₂O₂ and fused at 700° C, the fusion melt dissolved in 7% HNO₃ and analyses performed on a VG Plasma Quad inductively coupled plasma mass spectrometer. Au, Se, Br, Sb, Cs, Hf and Ta were determined by neutron activation (NA) analyses on irradiated 0.5 g samples after approximately 7 days of decay.

In addition to the analyses described above, comparative chemical determination for Y, Th, U, and the rare earth elements (REE) were obtained for 12 samples using different methods - REE, Th and U by neutron activation and Y by ICPMS (Table 3.1). Differences between analyses by two techniques for a given sample are generally less than 10% except for U in which the average difference is 16%. A binary plot showing the differences in values obtained by ICPMS and NA for La (average difference = 7.7%, maximum difference = 19%) is shown in Figure 3.1. In Figure 3.2 a REE spider diagram is shown for two Kidd Creek rhyolite samples with data by both ICPMS and NA analyses. Note the close agreement between values obtained by the two techniques (neither

technique returns Pm values and Gd, Dy, Ho, Er and Tm are not reported by NA). The unusual sawtooth pattern for the ICPMS data between Dy and Tm is believed to be an analytical artifact.

Tables A3.2 to A3.4 show major oxide and trace element values determined by XRAL Laboratories during 1995 and 1996 for geological reference standards (geostandards) SY-2 and SO-1. SY-2 is a syenite from the Bancroft area of eastern Ontario, and SO-1 is a clay soil collected near Hull, Quebec (Govindaraju, 1994). The results are summarized in Table 3.5 and Figures A3.3 and A3.4. The two major oxide determinations of SY-2 by XRF analyses of glass beads all fall within 7% of the recommended values and all but TiO_2 and P_2O_5 fall within about 1% of the recommended values (Table A3.2; difference = $\text{XRAL value} / \text{recommended value}$). For the two analyses of Rb, Sr, Y, Zr, Nb, and Ba (XRF on pressed pellets) the poorest results were a 19% difference between the recommended value and one determination of Ba, and a 17% difference between the recommended Nb value and one determination of Nb (Table A3.3). All of the remaining determinations were within 10% of the recommended values for SY-2. Six ICPMS analyses of geostandard SO-1 were performed for the rare earth elements (REE), U, and Th (Table A3.4). Differences between the working values and the XRAL results for Sm, Gd, Dy, Ho, Er, and Tm (middle to heavy REE) are commonly between 15% and 35%. It is in the middle to heavy part of Kidd Creek rhyolite REE spider diagrams that a pronounced sawtooth pattern occurs when XRAL ICPMS data is plotted (Figure A3.2). Determinations by

XRAL for the remaining REE, along with Th and U, were generally within 10% of the working values for SO-1.

A negative correlation exists for the XRF data between the accuracy of the XRAL results for the geostandards (relative to the recommended values) and the amount by which each element exceeds the detection limit of the analytical method (Table 3.5; Figure 3.3). XRAL defines detection limit "... as the level at which the chemist can expect +/-100% variation in the data" (L. Bloom, written communication, 1996). A negative correlation also occurs for the XRF data between the element concentrations in the geostandards (working values) and the reproducibility of the recommended geostandard values (Figure A3.4).

For each batch of samples a number of duplicate analyses were performed during the same analytical session using the same techniques. Comparisons between the original and duplicate analytical values, which provide a measure of precision (repeatability), are presented in Table A3.6. Repeatability is strongly influenced by the amount by which the content of an element in a sample exceeds the detection limit of the analytical method (Figure A3.5).

Element	Average ICPMS Value (ppm)	Second Method	Average Difference*	Maximum Difference**
Y	82	XRF	10%	17%
La	44.0	NA	7.7%	19%
Ce	98.7	NA	0.6%	13%
Nd	47.6	NA	6.4%	16%
Sm	11.7	NA	-2.7%	-8.9%
Eu	1.62	NA	-9.0%	-28.6%
Tb	2.38	NA	-10.0%	-23.1%
Yb	8.63	NA	0.2%	7.4%
Lu	1.42	NA	-7.4%	-10.8%
Th	6.7	NA	0.4%	6.9%
U	1.6	NA	16.2%	47%

Table A3.1. Comparison of analytical values for 12 samples obtained by ICPMS and a second technique (XRF or NA).

* relative to ICPMS data, e.g. average $[(Ce_{NA} - Ce_{ICPMS}) / Ce_{ICPMS}]$

** relative to ICPMS data, e.g. maximum $[(Ce_{NA} - Ce_{ICPMS}) / Ce_{ICPMS}]$

	SY-2 Working Values	SY-2			SY-2		
		XRF Analyses 1 (10-Feb-1996)			XRF Analyses 2 (10-Feb-1996)		
		Measured	Difference	% Difference	Measured	Difference	% Difference
SiO ₂	wt. %	59.68	-0.43	-1	59.79	-0.32	-1
TiO ₂	wt. %	0.14	-0.01	-7	0.14	-0.01	-7
Al ₂ O ₃	wt. %	11.91	-0.13	-1	11.86	-0.18	-1
Fe ₂ O ₃ (H)	wt. %	6.35	0.04	1	6.37	0.06	1
MnO	wt. %	0.32	0.00	0	0.32	0.00	0
MgO	wt. %	2.07	-0.01	0	2.67	-0.02	-1
CaO	wt. %	7.98	0.02	0	7.99	0.03	0
Na ₂ O	wt. %	4.31	0.03	1	4.34	0.03	1
K ₂ O	wt. %	4.47	0.02	0	4.49	0.04	1
P ₂ O ₅	wt. %	0.45	0.02	5	0.45	0.02	5
LOI	wt. %	1.2	0.12	11	1.2	0.12	11

Table A3 2. Comparison of two XRAL major-oxide determinations of SY-2 (glass bead XRF analyses) with recommended SY-2 working values (Govindaraju, 1994).

	SY-2 Working Values	SY-2			SY-2		
		XRF Analyses 3 (19-MAR-1996)			XRF Analyses 4 (26-MAR-96)		
		Measured	Difference	% Difference	Measured	Difference	% Difference
Rb	ppm	217	228	11	220	3	1
Sr	ppm	271	279	8	271	0	0
Y	ppm	128	137	9	133	5	4
Zr	ppm	280	280	0	268	-12	-4
Nb	ppm	29	27	-2	24	-5	-17
Ba	ppm	460	549	89	418	-42	-9

Table A3 3. Comparison of two XRAL Rb, Sr, Y, Zr, Nb, and Ba determinations of SY-2 (pressed pellet XRF analyses) with recommended SY-2 working values (Govindaraju, 1994).

SO-1		SO-1			SO-1		
	Working Values	ICPMS Analyses 1 (27-JUL-95)			ICPMS Analyses 2 (27-JUL-95)		
		Measured	Difference	% Difference	Measured	Difference	% Difference
La	54 ppm	57.2	3	6	52.2	-2	-4
Ce	102 ppm	118	16	16	105	3	3
Pr	11.8 ppm	13.4	1.6	14	12.3	0.5	4
Nd	44 ppm	49.4	5	11	46.8	3	7
Sm	7.9 ppm	10.5	2.6	33	9.5	1.6	20
Eu	1.57 ppm	1.49	-0.08	-5	1.52	-0.05	-3
Gd	6.1 ppm	8.1	2.0	33	7.6	1.5	25
Tb	0.88 ppm	0.8	-0.1	-11	0.92	0.04	5
Dy	4.5 ppm	5.2	0.7	16	5.1	0.6	13
Ho	1.1 ppm	0.76	-0.3	-27	0.90	-0.2	-18
Er	2 ppm	2.5	0.5	25	2.6	0.6	30
Tm	0.42 ppm	0.2	-0.2	-48	0.4	0	0
Yb	2.24 ppm	2.2	0	0	2.3	0.1	4
Lu	0.31 ppm	0.2	-0.1	-32	0.30	-0.01	-3
Th	12.4 ppm	12.1	-0.3	-2	11.7	-0.7	-6
U	1.71 ppm	1.53	-0.18	-11	1.53	-0.18	-11

Table A3.4. Part A.

SO-1		SO-1			SO-1		
	Working Values	ICPMS Analyses 3 (27-JUL-95)			ICPMS Analyses 4 (27-JUL-95)		
		Measured	Difference	% Difference	Measured	Difference	% Difference
La	54 ppm	55.9	2	4	59.7	6	11
Ce	102 ppm	114	12	12	116	14	14
Pr	11.8 ppm	13.3	1.5	13	13.8	2.0	17
Nd	44 ppm	49.8	6	14	50.9	7	16
Sm	7.9 ppm	10.5	2.6	33	10.8	2.9	37
Eu	1.57 ppm	1.64	0.07	4	1.68	0.11	7
Gd	6.1 ppm	7.5	1.4	23	8.2	2.1	34
Tb	0.88 ppm	1.0	0.12	14	1.1	0.2	23
Dy	4.5 ppm	5.4	0.9	20	5.6	1.1	24
Ho	1.1 ppm	0.87	-0.2	-18	1.05	0	0
Er	2 ppm	2.7	0.7	35	2.8	1	50
Tm	0.42 ppm	0.4	0.0	0	0.4	0	0
Yb	2.24 ppm	2.4	0.2	9	2.4	0.2	9
Lu	0.31 ppm	0.34	0.03	10	0.34	0.03	10
Th	12.4 ppm	12.0	-0.4	-3	12.9	0.5	4
U	1.71 ppm	1.63	-0.08	-5	1.8	0.1	6

Table A3.4. Part B.

	SO-1 Working Values	SO-1			SO-1			SO-1		
		ICPMS Analyses 5 (27-JUL-95)			ICPMS Analyses 6 (27-JUL-95)			ICPMS Analyses 6 (27-JUL-95)		
		Measured	Difference	% Difference	Measured	Difference	% Difference	Measured	Difference	% Difference
La	54 ppm	54.9	0.9	2	55.6	1.1	2	55.6	1.1	2
Ce	<u>102</u> ppm	107	5	5	113	11	11	113	11	11
Pr	<u>11.8</u> ppm	12.6	0.8	7	12.9	1.1	9	12.9	1.1	9
Nd	<u>44</u> ppm	47	3	7	47.4	3	7	47.4	3	7
Sm	<u>7.9</u> ppm	10.0	2.1	27	10.2	2.3	29	10.2	2.3	29
Eu	<u>1.57</u> ppm	1.85	0.28	18	1.75	0.18	11	1.75	0.18	11
Gd	<u>6.1</u> ppm	7.3	1.2	20	7.8	1.7	28	7.8	1.7	28
Tb	<u>0.88</u> ppm	1.0	0.1	11	0.8	-0.1	-11	0.8	-0.1	-11
Dy	<u>4.5</u> ppm	5.2	0.7	16	5	0.5	11	5	0.5	11
Ho	<u>1.1</u> ppm	0.89	-0.2	-18	0.72	-0.4	-36	0.72	-0.4	-36
Er	2 ppm	2.7	0.7	35	2.5	0.5	25	2.5	0.5	25
Tm	0.42 ppm	0.4	0	0	0.2	-0.2	-48	0.2	-0.2	-48
Yb	<u>2.24</u> ppm	2.2	0	0	2.2	0	0	2.2	0	0
Lu	<u>0.31</u> ppm	0.37	0.06	19	0.20	-0.11	-35	0.20	-0.11	-35
Th	<u>12.4</u> ppm	11.9	-0.5	-4	11.2	-1.2	-10	11.2	-1.2	-10
U	<u>1.71</u> ppm	1.66	-0.05	-3	1.4	-0.3	-18	1.4	-0.3	-18

Table A3.4. Part C.

Table A3.4 (Parts A to C). Comparison of six XRAL REE, Th and U determinations of SO-1 (ICPMS analyses) with SO-1 working values (Govindaraju, 1994). Underlined data are recommended values; others are proposed.

Reference Standard	Working Values	XRAL Method	XRAL Detection Limit	Number Of XRAL Analyses	Average XRAL Value	Average Difference	Average % Difference	Average XRAL Value/ Detection Limit
SiO ₂	wt.%	SY-2	0.01	2	59.74	-0.38	-0.6	5974
TiO ₂	wt.%	SY-2	0.01	2	0.14	-0.01	-6.7	14
Al ₂ O ₃	wt.%	SY-2	0.01	2	11.89	-0.15	-1.3	1189
Fe ₂ O _{3(l)}	wt.%	SY-2	0.01	2	6.36	0.05	0.8	636
MnO	wt.%	SY-2	0.01	2	0.32	0.00	0.0	32
MgO	wt.%	SY-2	0.01	2	2.68	-0.02	-0.6	268
CaO	wt.%	SY-2	0.01	2	7.99	0.03	0.3	799
Na ₂ O	wt.%	SY-2	0.01	2	4.34	0.03	0.7	434
K ₂ O	wt.%	SY-2	0.01	2	4.48	0.03	0.7	448
P ₂ O ₅	wt.%	SY-2	0.01	2	0.45	0.02	4.7	45
LOI	wt.%	SY-2	0.01	2	1.20	0.12	11.1	120
Rb	ppm	SY-2	10	2	224	7.00	3.2	22
Sr	ppm	SY-2	10	2	275	4.00	1.5	28
Y	ppm	SY-2	10	2	135	7.00	5.5	14
Zr	ppm	SY-2	10	2	274	-6.00	-2.1	27
Nb	ppm	SY-2	10	2	26	-3.50	-12.1	3
Ba	ppm	SY-2	10	2	484	23.50	5.1	48
La	ppm	SO-1	0.1	6	55.9	1.92	3.5	559
Ce	ppm	SO-1	0.1	6	112	10.17	10.0	1122
Pr	ppm	SO-1	0.2	6	13.1	1.25	10.6	65
Nd	ppm	SO-1	0.1	6	48.6	4.55	10.3	486
Sm	ppm	SO-1	0.1	6	10.3	2.35	29.7	103
Eu	ppm	SO-1	0.05	6	1.66	0.09	5.4	33
Gd	ppm	SO-1	0.1	6	7.8	1.65	27.0	78
Tb	ppm	SO-1	0.1	6	0.9	0.06	6.4	9
Dy	ppm	SO-1	0.1	6	5.3	0.75	16.7	53
Ho	ppm	SO-1	0.05	6	0.87	-0.24	-21.4	17
Er	ppm	SO-1	0.1	6	2.6	0.63	31.7	26
Tm	ppm	SO-1	0.1	6	0.3	-0.09	-20.6	3
Yb	ppm	SO-1	0.1	6	2.3	0.04	1.9	23
Lu	ppm	SO-1	0.05	6	0.29	-0.02	-5.9	6
Th	ppm	SO-1	0.1	6	12.0	-0.43	-3.5	120
U	ppm	SO-1	0.1	6	1.59	-0.12	-6.9	16

Table A3.5. Summary of determinations by XRAL on geostandards SY-1 and SO-1. Underlined working values are recommended; others are proposed (Govindaraju, 1994).

	No. of Duplicate Pairs (i)	Detection Limit (ii)	Minimum Duplicate Value (iii)	Maximum Duplicate Value	Median Duplicate Value (iii)	Max. Percentage Difference Between Duplicate Pairs (iv)	Avg. Percentage Difference Between Duplicate Pairs (v)	Median Duplicate Value/Detection Limit (vi)
SiO ₂	17	0.01	31.80	87.70	73.30	1.5	0.4	7330
TiO ₂	17	0.01	0.02	0.57	0.12	34.6	8.6	12
Al ₂ O ₃	16	0.01	1.80	14.60	11.20	0.8	0.4	1120
Fe ₂ O ₃	17	0.01	0.86	43.40	4.88	6.7	0.9	488
MnO	15	0.01	0.01	0.70	0.05	33.3	3.0	5
MgO	17	0.01	0.26	32.70	1.68	6.9	1.4	168
CaO	16	0.01	0.01	7.84	0.65	50.0	5.3	65
Na ₂ O	16	0.01	0.03	2.78	0.25	25.0	7.7	25
K ₂ O	14	0.01	0.08	4.63	2.55	20.0	2.9	255
P ₂ O ₅	13	0.01	0.02	0.07	0.03	0.0	0.0	3
Cr ₂ O ₃	3	0.01	0.01	0.26	0.19	5.6	3.2	19
LOI	17	0.01	1.75	24.90	2.70	8.3	2.3	270
Sum	17		98.70	100.30	99.90	1.2	0.4	
H ₂ O ⁺	31	0.1	0.8	10.7	1.7	14.3	3.6	17
CO ₂	29	0.01	0.04	28.60	0.72	33.3	4.6	72
FeO	22	0.10	0.40	27.50	3.05	33.3	3.9	31
C	19	0.01	0.02	7.94	0.23	25.0	2.8	23
S	29	0.01	0.01	12.00	0.22	50.0	5.2	43
Li	23	1	1	147	13	33.3	6.2	13
Be	19	0.5	1.1	5.0	3.0	50.0	18.9	6
B	16	10	11	83	37	28.6	11.7	4
F	17	10	61	1030	382	24.5	4.6	38
Cl	10	20	20	60	20	75.0	49.4	1
Sc	24	0.05	1.10	44.50	1.93	25.8	7.7	39
V	24	2	2	336	14	33.3	10.1	7
Cr	15	1	3	1200	160	25.0	8.5	160
Co	20	1	1	79	26	100.0	13.9	26

Table A3.6. (page 1 of 3)

	No. of Duplicate Pairs (i)	Detection Limit (ii)	Minimum		Maximum		Median Duplicate Value (iii)		Max. Percentage Difference Between Duplicate Pairs (iv)		Avg. Percentage Difference Between Duplicate Pairs (v)		Median Duplicate Value/Detection Limit (vi)	
			Duplicate Value (iii)	Duplicate Value (iii)	Duplicate Value	Duplicate Value	Duplicate Value (iii)	Duplicate Value (iii)	Duplicate Pairs (iv)	Duplicate Pairs (iv)	Duplicate Pairs (v)	Duplicate Pairs (v)	Value/Detection Limit (vi)	Value/Detection Limit (vi)
Ni ppm	27	1	1	1	2100	15	15	100.0	18.0	15	18.0	15	15	15
Cu ppm	30	0.5	3.5	3.5	38900.0	28.1	28.1	25.4	7.0	56	7.0	56	56	56
Zn ppm	30	0.5	21.2	21.2	94500.0	127.5	127.5	438.3	17.9	255	17.9	255	255	255
Ga ppm	24	1	10	10	33	21	21	23.8	4.0	21	4.0	21	21	21
Ge ppm	4	10	10	10	18	15	15	50.0	25.0	1	25.0	1	1	1
As ppm	7	0.1	0.3	0.3	26.0	0.7	0.7	250.0	42.8	7	42.8	7	7	7
Se ppm	0	1												
Br ppm	8	1	1	1	3	2	2	200.0	68.8	2	68.8	2	2	2
Rb ppm	27	2	2	2	153	42	42	33.3	5.3	21	5.3	21	21	21
Sr ppm	28	0.5	4.1	4.1	267.0	25.0	25.0	64.1	8.9	50	8.9	50	50	50
Y ppm	24	2	3	3	282	67	67	30.0	5.6	33	5.6	33	33	33
Zr ppm	27	1	20	20	281	173	173	16.5	2.3	173	2.3	173	173	173
Nb ppm	27	2	3	3	30	19	19	20.0	4.9	10	4.9	10	10	10
Mo ppm	11	1	1	1	3	2	2	100.0	47.2	2	47.2	2	2	2
Ag ppm	21	0.1	0.1	0.1	74.5	0.4	0.4	250.0	40.5	4	40.5	4	4	4
Cd ppm	7	0.2	0.2	0.2	16.1	0.2	0.2	21.4	3.2	1	3.2	1	1	1
In ppm	0	0.5												
Sn ppm	21	2	6	6	79	13	13	25.0	8.3	7	8.3	7	7	7
Sb ppm	6	0.1	0.1	0.1	0.4	0.1	0.1	100.0	45.6	1	45.6	1	1	1
Cs ppm	9	0.5	0.5	0.5	5.4	1.0	1.0	50.0	17.7	2	17.7	2	2	2
Ba ppm	22	10	29	29	1420	318	318	29.0	3.6	32	3.6	32	32	32
La ppm	22	0.1	0.5	0.5	80.8	32.5	32.5	31.2	4.9	325	4.9	325	325	325
Ce ppm	22	0.1	1.2	1.2	182.0	75.3	75.3	27.3	5.0	753	5.0	753	753	753
Pr ppm	22	0.1	0.1	0.1	22.9	9.3	9.3	30.1	6.1	93	6.1	93	93	93
Nd ppm	22	0.1	0.6	0.6	96.9	39.4	39.4	33.1	5.6	394	5.6	394	394	394
Sm ppm	22	0.1	0.3	0.3	24.9	10.6	10.6	50.0	7.9	106	7.9	106	106	106
Eu ppm	22	0.05	0.14	0.14	3.00	1.45	1.45	26.3	5.7	29	5.7	29	29	29
Gd ppm	22	0.1	0.3	0.3	28.2	12.3	12.3	19.0	4.8	123	4.8	123	123	123

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	No. of Duplicate Pairs (i)	Detection Limit (ii)	Minimum Duplicate Value (iii)		Maximum Duplicate Value	Median Duplicate Value (iii)	Max. Percentage Difference Between Duplicate Pairs (iv)		Avg. Percentage Difference Between Duplicate Pairs (v)		Median Duplicate Value/Detection Limit (vi)	
			Duplicate Value (iii)	Duplicate Value (iii)			Duplicate Pairs (iv)	Duplicate Pairs (iv)	Duplicate Pairs (v)	Duplicate Pairs (v)	Value (vi)	Limit (vi)
Tb ppm	21	0.1	0.3	6.0	1.9	24.0	4.2	19				
Dy ppm	22	0.1	0.3	32.7	12.4	28.6	5.7	124				
Ho ppm	22	0.05	0.09	8.97	2.52	22.3	4.7	50				
Er ppm	22	0.1	0.2	21.1	7.7	23.1	6.7	77				
Tm ppm	20	0.1	0.2	4.1	1.1	22.2	6.3	11				
Yb ppm	22	0.1	0.2	23.5	7.6	33.3	6.9	76				
Lu ppm	21	0.05	0.19	3.68	1.18	27.0	5.9	24				
Hf ppm	9	0.2	0.9	9.8	6.7	72.5	19.5	34				
Ta ppm	6	0.5	1.0	2.0	1.2	100.0	32.8	2				
W ppm	8	1	1	5	3	100.0	39.1	3				
Au ppm	0	2										
Hg ppm	12	5	5	165	10	40.0	19.3	2				
Tl ppm	13	0.01	0.10	1.40	0.30	66.7	16.2	30				
Pb ppm	9	2	3	4800	62	25.0	7.7	31				
Bi ppm	5	1	2	25	5	100.0	29.0	5				
Th ppm	16	0.1	0.1	13.2	4.4	100.0	16.7	44				
U ppm	14	0.1	0.1	3.0	1.3	35.7	10.7	13				

- (i) Number of duplicate pairs for which both analyses are above the detection limit.
Original and duplicate analyses were performed by XRAL Laboratories during the same analytical session.
Analyses performed between 02/93 and 03/95 (XRAL Reports 22671, 23490, 25836, 31620, and Work Order 32566)
- (ii) If detection limits vary between analytical batches the minimum detection limit is shown.
- (iii) Includes only those duplicate pairs for which both analyses are above detection limit.
- (iv) Maximum value of 100 x absolute value of (duplicate analyses - original analyses) / (original analyses)
- (v) Average value of 100 x absolute value of (duplicate analyses - original analyses) / (original analyses)
- (vi) A measure of the degree by which typical rock abundances exceed the detection limit.

Table A3.6. Repeatability statistics for duplicate pairs of analyses.

Figure A3.1. Comparison of La analyses obtained by ICPMS and neutron activation (NA).

Figure A3.2. Chondrite normalized REE patterns for two Kidd Creek rhyolites (QP rhyolite sample 14261 and FW rhyolite sample 14256) comparing results of REE analyses by ICPMS and neutron activation (NA): filled circles = 14261 by ICPMS; open circle = 14261 by NA; filled square = 14256 by ICPMS; open square = 14256 by NA).

Figure A3.3. Diagram showing average XRAL value / detection limit versus average difference between XRAL determinations and working values for reference samples SY-2 (XRF data) and SO-1 (ICPMS data).

Figure A3.4. Diagram showing element abundances in geostandards (working values) versus average differences between XRAL determinations and working values for reference samples SY-2 (XRF data) and SO-1 (ICPMS data).

Figure A3.5. Relationship between the median duplicate value to analytical detection limit ratio and repeatability.

Appendix 4

GEOCHEMICAL ANALYSES OF SAMPLES FROM THE 1600, 1800, 2100, 2300, AND 2400 LEVELS OF THE KIDD CREEK MINE

(see Maps 2 to 7 for sample locations and Appendix 9 for sample descriptions)

Rock Type Codes:

ARG	Argillite
FV	Felsic Volcanic Rock
ME	Mafic Extrusive Rock
MI	Mafic Subvolcanic Intrusive Rock
QPco	Coherent QP Rhyolite
QPbx	Autoclastic QP Rhyolite Breccia
QPcrbx	Coarse Autoclastic QP Rhyolite Breccia
RHco	Coherent FW Rhyolite
RHbx	Autoclastic FW Rhyolite Breccia
RHhy	FW Rhyolite Hyaloclastite
UM	Ultramafic Rock
VCbdcg	Volcaniclastic Boulder Conglomerate
VCpbcg	Polymict Volcaniclastic Pebble Conglomerate
VCsa	Volcaniclastic Sandstone
VCsamu	Volcaniclastic Sandy Mudstone
VCmusa	Volcaniclastic Muddy Sandstone

Sample		16-14061	16-14062	16-14063	16-14064	16-14066	16-14069	16-14074	16-14079	16-14080	16-14081
Rock Type		RHco	UM	UM	VCpbcg	VCsamu	VCsamu	RHbx-RHhy	VCsa	RHbx	VCbdcg
Member		Middle	Middle	Middle	Middle	Middle	Middle	Middle	Middle	Middle	Middle
SiO ₂	wt.%	77.0	30.8	31.6	40.6	85.2	73.6	73.8	66.6	71.8	45.0
TiO ₂	wt.%	0.12	0.09	0.09	0.18	0.25	0.29	0.07	0.09	0.11	0.19
Al ₂ O ₃	wt.%	12.10	1.96	1.79	5.44	8.75	11.10	10.90	9.73	11.70	8.62
Fe ₂ O _{3t}	wt.%	2.45	6.20	7.52	14.50	0.86	4.38	1.80	7.22	3.83	15.00
MnO	wt.%	0.03	0.12	0.15	0.12	0.02	0.03	0.06	0.07	0.06	0.04
MgO	wt.%	2.24	29.50	32.80	4.58	0.25	3.22	1.08	8.88	3.89	4.18
CaO	wt.%	0.23	1.45	0.84	3.03	<0.01	0.25	4.10	0.72	1.11	0.12
Na ₂ O	wt.%	0.20	0.09	0.07	1.34	0.27	0.28	0.18	0.08	0.21	1.14
K ₂ O	wt.%	3.35	<0.01	<0.01	0.31	2.49	2.15	3.17	0.27	2.44	1.00
P ₂ O ₅	wt.%	0.03	<0.01	<0.01	0.03	0.03	0.05	0.02	0.03	0.02	0.04
Cr ₂ O ₃	wt.%	<0.01	0.32	0.18	0.09	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	wt.%	2.20	29.90	24.80	9.05	1.75	3.15	3.25	5.00	3.55	9.45
Sum	wt.%	99.9	100.4	99.8	79.3	99.9	98.5	98.4	98.7	98.7	84.8
H ₂ O ⁺	wt.%	2.0	1.5	2.4	2.4	1.0	2.5	1.3	4.4	2.5	3.1
CO ₂	wt.%	0.29	28.40	22.00	4.79	0.05	0.37	3.38	1.12	1.73	0.16
FeO	wt.%	1.6	1.8	1.5	nd	nd	nd	nd	nd	2.4	nd
C	ppm	nd	7.95	6.02	nd	nd	nd	nd	nd	nd	nd
S	ppm	0.05	0.02	<0.01	12.10	0.62	1.00	0.67	0.47	0.38	11.40
Li	ppm	nd	6	7	nd	nd	nd	nd	nd	nd	nd
Be	ppm	nd	<0.5	<0.5	nd	nd	nd	nd	nd	nd	nd
B	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
F	ppm	nd	<20	131	nd	nd	nd	nd	nd	nd	nd
Cl	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sc	ppm	nd	6.8	6.7	nd	nd	nd	nd	nd	nd	nd
V	ppm	nd	22	23	nd	nd	nd	nd	nd	nd	nd
Cr	ppm	nd	711	484	nd	nd	nd	nd	nd	nd	nd
Co	ppm	nd	79	74	nd	nd	nd	nd	nd	nd	nd
Ni	ppm	<1	1650	2100	11	10	16	<1	5	<1	13
Cu	ppm	20	13	7	1650	981	1080	25	143	32	3370
Zn	ppm	165	105	53	93600	1600	2030	190	630	153	73600
Ga	ppm	nd	16	16	nd	nd	nd	nd	nd	nd	nd
As	ppm	nd	<3	<3	nd	nd	nd	nd	nd	nd	nd
Rb	ppm	113	7	3	11	64	68	96	10	77	33
Sr	ppm	12	20	8	18	15	22	33	6	19	13
Y	ppm	200	<2	4	121	84	91	111	66	117	94
Zr	ppm	240	19	19	104	138	176	220	200	228	175
Nb	ppm	30	6	5	19	17	19	26	23	25	17
Mo	ppm	nd	<1	<1	nd	nd	nd	nd	nd	nd	nd
Ag	ppm	0.5	0.4	0.3	75.2	2.5	12.4	0.9	6.1	1.5	102.0
Cd	ppm	nd	<1	<1	nd	nd	nd	nd	nd	nd	nd
Sn	ppm	nd	<5	8	nd	nd	nd	nd	nd	nd	nd
Sb	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cs	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ba	ppm	nd	93	64	nd	nd	nd	nd	nd	nd	nd
La	ppm	56.4	0.5	0.8	nd	nd	nd	nd	nd	56.3	nd
Ce	ppm	120	1.3	1.8	nd	nd	nd	nd	nd	121	nd
Pr	ppm	14.6	0.1	0.2	nd	nd	nd	nd	nd	15	nd
Nd	ppm	63.6	0.7	1.1	nd	nd	nd	nd	nd	61.4	nd
Sm	ppm	17.2	0.2	0.4	nd	nd	nd	nd	nd	14.8	nd
Eu	ppm	1.89	0.16	0.09	nd	nd	nd	nd	nd	1.46	nd
Gd	ppm	15.3	0.3	0.4	nd	nd	nd	nd	nd	12.1	nd
Tb	ppm	3.7	<0.1	<0.1	nd	nd	nd	nd	nd	2.5	nd
Dy	ppm	28.8	0.4	0.5	nd	nd	nd	nd	nd	17.5	nd
Ho	ppm	8.1	0.1	0.14	nd	nd	nd	nd	nd	4.74	nd
Er	ppm	18.3	0.2	0.3	nd	nd	nd	nd	nd	10.3	nd
Tm	ppm	4	<0.1	<0.1	nd	nd	nd	nd	nd	2.2	nd
Yb	ppm	22.2	0.3	0.4	nd	nd	nd	nd	nd	12.4	nd
Lu	ppm	3.05	<0.05	<0.05	nd	nd	nd	nd	nd	1.66	nd
Hf	ppm	10.0	nd	nd	nd	nd	nd	nd	nd	11.0	nd
Ta	ppm	2.1	nd	nd	nd	nd	nd	nd	nd	2.0	nd
W	ppm	nd	<10	<10	nd	nd	nd	nd	nd	nd	nd
Au	ppb	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Pb	ppm	<2	3	4	4810	32	110	2	215	63	2480
Th	ppm	8.3	<0.1	0.1	3.1	4.5	5.7	7.7	7.0	8.1	5.5
U	ppm	2.0	<0.1	<0.1	0.3	0.9	1.8	1.9	1.6	1.9	1.2

Sample		16-14082	16-14083	16-14084	16-14085	16-14086	16-14087	16-14088	16-14089	16-14090	16-14091
Rock Type		RHhy	MI	VCpbcg	HRhy	VCbdcg	VCsamu	VCsa	RHhy	VCsamu	VCpbcg-ARG
Member		Middle	Middle	Middle	Middle	Middle	Middle	Middle	Middle	Middle	Middle
SiO ₂	wt.%	75.4	40.7	59.3	75.3	48.1	69.5	56.2	69.6	59.8	65.5
TiO ₂	wt.%	0.10	0.84	0.22	0.08	0.19	0.28	0.31	0.12	0.35	0.53
Al ₂ O ₃	wt.%	11.60	12.50	9.24	8.45	7.69	9.33	8.91	12.40	13.40	11.50
Fe ₂ O ₃	wt.%	4.02	14.90	16.30	8.10	16.40	11.70	15.60	8.84	11.90	9.79
MnO	wt.%	0.04	0.34	0.09	0.05	0.08	0.08	0.24	0.07	0.09	0.07
MgO	wt.%	3.06	6.94	4.70	3.59	3.08	3.55	5.30	3.02	5.82	6.72
CaO	wt.%	0.24	7.81	0.15	0.01	0.16	0.11	0.07	0.10	0.54	<0.01
Na ₂ O	wt.%	0.24	0.21	0.45	0.08	1.08	0.17	0.45	0.23	0.24	0.13
K ₂ O	wt.%	2.44	1.72	0.10	0.80	0.34	0.61	0.04	2.08	1.53	0.99
P ₂ O ₅	wt.%	0.03	0.17	0.04	0.03	0.04	0.05	0.06	0.03	0.07	0.05
Cr ₂ O ₃	wt.%	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	wt.%	2.60	11.80	5.35	2.75	7.20	3.15	5.40	2.95	4.45	4.30
Sum	wt.%	99.8	97.9	95.9	99.2	84.4	98.5	92.6	99.4	98.2	99.6
H ₂ O ⁺	wt.%	2.4	3.9	4.6	3.1	3.8	3.8	4.7	3.5	4.6	4.5
CO ₂	wt.%	0.41	11.30	0.17	<0.01	0.13	0.09	0.02	0.03	0.67	0.03
FeO	wt.%	nd	nd	nd	nd	nd	nd	nd	7.1	nd	nd
C	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
S	ppm	0.06	0.15	3.35	0.18	8.58	0.45	3.48	0.04	0.26	0.03
Li	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Be	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
B	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
F	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cl	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sc	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
V	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cr	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Co	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ni	ppm	1	92	6	1	12	17	13	<1	28	27
Cu	ppm	41	79	451	632	1100	1240	10600	33	563	34
Zn	ppm	472	345	22900	415	75900	3250	25300	428	3580	224
Ga	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
As	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Rb	ppm	70	47	9	26	18	21	4	59	44	25
Sr	ppm	15	43	2	5	3	5	2	15	14	3
Y	ppm	56	20	102	61	90	81	76	54	77	130
Zr	ppm	221	101	165	171	148	152	151	237	193	154
Nb	ppm	27	9	23	19	18	17	17	25	22	23
Mo	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ag	ppm	1.5	1.0	40.2	35.1	51.9	71.3	30.1	1.1	8.3	0.5
Cd	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sn	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sb	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cs	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ba	ppm	nd	nd	nd	nd	nd	nd	nd	21.7	nd	nd
La	ppm	nd	nd	nd	nd	nd	nd	nd	51.2	nd	nd
Ce	ppm	nd	nd	nd	nd	nd	nd	nd	6.6	nd	nd
Pr	ppm	nd	nd	nd	nd	nd	nd	nd	27.8	nd	nd
Nd	ppm	nd	nd	nd	nd	nd	nd	nd	7.7	nd	nd
Sm	ppm	nd	nd	nd	nd	nd	nd	nd	0.7	nd	nd
Eu	ppm	nd	nd	nd	nd	nd	nd	nd	6.6	nd	nd
Gd	ppm	nd	nd	nd	nd	nd	nd	nd	1.6	nd	nd
Tb	ppm	nd	nd	nd	nd	nd	nd	nd	11.7	nd	nd
Dy	ppm	nd	nd	nd	nd	nd	nd	nd	3.25	nd	nd
Ho	ppm	nd	nd	nd	nd	nd	nd	nd	7.5	nd	nd
Er	ppm	nd	nd	nd	nd	nd	nd	nd	1.8	nd	nd
Tm	ppm	nd	nd	nd	nd	nd	nd	nd	10.4	nd	nd
Yb	ppm	nd	nd	nd	nd	nd	nd	nd	1.47	nd	nd
Lu	ppm	nd	nd	nd	nd	nd	nd	nd	11.0	nd	nd
Hf	ppm	nd	nd	nd	nd	nd	nd	nd	2.0	nd	nd
Ta	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
W	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Au	ppb	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Pb	ppm	41	21	1590	390	4770	1120	13	37	75	7
Th	ppm	6.9	0.6	5.3	6.0	4.8	4.6	5.1	8.9	6.4	4.4
U	ppm	1.5	<0.1	0.8	1.4	1.0	1.1	0.8	1.8	1.0	1.0

Sample		16-14092	16-14094	16-14099	16-14107	16-14131	16-14132	16-14133	16-14138	18-14046	18-14048
Rock Type		VCpbcg-ARG	VCsa	RHhy	ME-in-VCbdcg	RHco	RHco	RHco	VCmusa	QPco	QPco
Member		Middle	Middle	Middle	Middle	Middle	Middle	Middle	Middle	Upper	Upper
SiO ₂	wt.%	75.0	76.8	77.6	54.3	84.4	80.6	81.3	58.4	80.2	68.8
TiO ₂	wt.%	0.12	0.22	0.09	2.40	0.08	0.10	0.07	0.53	0.15	0.10
Al ₂ O ₃	wt.%	11.00	10.80	11.90	20.00	9.24	9.90	9.45	13.60	9.73	9.09
Fe ₂ O ₃	wt.%	4.17	2.25	2.49	6.86	0.44	2.74	1.52	17.30	2.39	1.81
MnO	wt.%	0.07	0.06	0.03	0.04	0.02	0.03	0.06	0.07	0.08	0.20
MgO	wt.%	3.49	2.16	2.20	6.07	0.28	0.18	0.26	1.16	0.42	1.33
CaO	wt.%	<0.01	1.38	0.21	0.39	0.33	0.33	2.15	<0.01	1.03	8.58
Na ₂ O	wt.%	0.16	0.44	0.17	0.33	0.25	1.58	1.27	0.40	2.67	0.20
K ₂ O	wt.%	2.37	2.75	3.25	4.00	2.56	2.16	2.12	2.49	1.90	2.26
P ₂ O ₅	wt.%	0.03	0.05	0.02	0.30	0.02	0.03	0.02	0.05	0.04	0.03
Cr ₂ O ₃	wt.%	<0.01	<0.01	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	wt.%	2.60	2.45	2.30	4.50	1.55	2.30	2.30	5.25	0.95	7.35
Sum	wt.%	99.0	99.4	100.3	99.2	99.2	99.9	100.5	99.3	99.6	99.7
H ₂ O ⁺	wt.%	2.6	1.7	2.1	4.6	1.0	0.9	0.9	<0.01	0.8	1.2
CO ₂	wt.%	0.04	1.68	0.18	0.03	0.50	0.41	1.83	<0.01	0.72	7.31
FeO	wt.%	nd	nd	nd	5.3	nd	nd	nd	nd	nd	nd
C	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
S	ppm	0.02	0.20	0.04	0.09	0.05	1.81	0.51	nd	0.03	0.01
Li	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Be	ppm	nd	nd	nd	nd	nd	nd	nd	1	nd	nd
B	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
F	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cl	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sc	ppm	nd	nd	nd	nd	nd	nd	nd	8.4	nd	nd
V	ppm	nd	nd	nd	nd	nd	nd	nd	71	nd	nd
Cr	ppm	nd	nd	nd	nd	nd	nd	nd	53	nd	nd
Co	ppm	nd	nd	nd	nd	nd	nd	nd	18	nd	nd
Ni	ppm	10	10	<1	58	1	<1	1	40	2	1
Cu	ppm	22	170	19	68	12	19	15	1010	51	15
Zn	ppm	96	358	141	745	49	95	61	3810	73	68
Ga	ppm	nd	nd	nd	nd	nd	nd	nd	23	nd	nd
As	ppm	nd	nd	nd	nd	nd	nd	nd	7.0	nd	nd
Rb	ppm	70	97	110	129	51	39	38	50	48	76
Sr	ppm	6	25	11	26	13	16	22	28	23	30
Y	ppm	74	186	83	20	73	94	80	197	44	62
Zr	ppm	210	185	233	144	174	201	188	193	178	178
Nb	ppm	23	21	28	21	21	24	21	28	14	14
Mo	ppm	nd	nd	nd	nd	nd	nd	nd	2	nd	nd
Ag	ppm	0.6	2.1	0.4	5.1	<0.1	0.7	0.2	13.6	0.4	0.4
Cd	ppm	nd	nd	nd	nd	nd	nd	nd	13.0	nd	nd
Sn	ppm	nd	nd	nd	nd	nd	nd	nd	875	nd	nd
Sb	ppm	nd	nd	nd	nd	nd	nd	nd	8.0	nd	nd
Cs	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ba	ppm	nd	nd	nd	nd	nd	nd	nd	213	nd	nd
La	ppm	nd	nd	nd	4.2	41.9	52.2	44.8	nd	43.2	31.6
Ce	ppm	nd	nd	nd	9	96.7	119	98.2	nd	92.1	70.7
Pr	ppm	nd	nd	nd	1.1	12.3	14.9	12.4	nd	11	8.6
Nd	ppm	nd	nd	nd	5.3	52.2	62.3	52.5	nd	44.6	34.9
Sm	ppm	nd	nd	nd	1.8	13.7	17.1	14.8	nd	11.3	9.1
Eu	ppm	nd	nd	nd	0.31	2.37	4.79	6.31	nd	1.39	1.09
Gd	ppm	nd	nd	nd	1.8	13.2	17	14.9	nd	10.4	9
Tb	ppm	nd	nd	nd	0.5	2.2	3	2.5	nd	1.8	1.6
Dy	ppm	nd	nd	nd	3.4	13.5	18.6	14.9	nd	9.9	10.3
Ho	ppm	nd	nd	nd	0.93	2.73	3.86	2.96	nd	1.84	2.26
Er	ppm	nd	nd	nd	2.1	8.1	11.5	8.9	nd	5.1	6.8
Tm	ppm	nd	nd	nd	0.5	1.2	1.7	1.3	nd	0.7	1
Yb	ppm	nd	nd	nd	3	7.8	10.9	8.7	nd	4.2	6.8
Lu	ppm	nd	nd	nd	0.43	1.14	1.63	1.33	nd	0.6	1.02
Hf	ppm	nd	nd	nd	4.3	nd	nd	nd	nd	nd	nd
Ta	ppm	nd	nd	nd	<0.5	nd	nd	nd	nd	nd	nd
W	ppm	nd	nd	nd	nd	nd	nd	nd	<10	nd	nd
Au	ppb	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Pb	ppm	<2	41	<2	425	<2	<2	<2	399	<2	<2
Th	ppm	6.6	5.7	7.8	0.6	6.3	6.8	6.0	nd	5.6	5.1
U	ppm	1.6	1.5	1.3	0.2	1.6	1.9	1.5	nd	1.7	1.5

Sample		18-14051	18-14054	18-14055	18-14058	21-14141	21-14142	21-14143	21-14144	21-14146	21-14148
Rock Type		QPco	QPbx	QPcrbx	QPco	RHco	RHco	FV-block	FV	FV	RHco
Member		Upper	Upper	Upper	Upper	Middle	Middle	Middle	Middle	Middle	Middle
SiO ₂	wt. %	82.4	67.3	69.5	67.0	77.9	79.8	46.9	68.1	55.9	79.3
TiO ₂	wt. %	0.15	0.56	0.16	0.18	0.14	0.08	0.03	0.08	0.05	0.05
Al ₂ O ₃	wt. %	9.45	12.30	14.60	15.20	9.34	9.97	4.46	11.90	10.90	6.31
Fe ₂ O _{3t}	wt. %	1.01	6.22	5.57	6.74	3.18	1.89	4.02	4.98	15.30	5.08
MnO	wt. %	0.05	0.12	0.09	0.17	0.03	0.03	0.31	0.06	0.10	0.08
MgO	wt. %	0.20	2.45	2.66	1.03	2.52	1.32	4.10	2.90	7.38	4.50
CaO	wt. %	0.82	2.23	0.48	2.65	0.89	1.46	19.00	2.56	0.17	0.31
Na ₂ O	wt. %	3.36	0.31	0.44	0.33	0.28	0.25	0.15	4.41	0.61	1.06
K ₂ O	wt. %	1.92	2.79	3.35	3.39	1.94	2.68	1.09	0.40	<0.01	0.04
P ₂ O ₅	wt. %	0.03	0.11	0.03	0.03	0.03	0.03	0.04	0.04	0.02	0.02
Cr ₂ O ₃	wt. %	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	wt. %	0.65	2.90	2.70	3.30	2.40	2.60	19.80	3.45	5.50	2.50
Sum	wt. %	100.0	97.3	99.6	100.0	98.6	100.1	99.9	98.9	95.9	99.3
H ₂ O ⁺	wt. %	0.5	2.6	2.9	2.5	1.9	1.4	0.7	1.7	5.4	2.3
CO ₂	wt. %	0.56	1.70	0.42	2.15	0.78	1.22	19.80	2.83	0.14	0.45
FeO	wt. %	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
C	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
S	ppm	0.04	1.26	0.03	0.03	0.06	0.02	0.02	0.05	1.79	0.07
Li	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Be	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
B	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
F	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cl	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sc	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
V	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cr	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Co	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ni	ppm	<1	22	<1	4	4	<1	1	1	<1	<1
Cu	ppm	18	277	18	90	238	20	23	268	528	268
Zn	ppm	38	441	248	85	281	46	95	833	30500	788
Ga	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
As	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Rb	ppm	36	83	99	93	59	79	32	17	4	5
Sr	ppm	33	21	16	19	8	11	63	33	3	6
Y	ppm	38	146	91	92	80	45	216	126	38	39
Zr	ppm	186	185	261	281	175	192	95	231	198	157
Nb	ppm	13	17	20	20	19	21	10	32	33	20
Mo	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ag	ppm	0.9	2.1	0.7	0.9	1.9	<0.1	0.4	2.0	1.7	0.5
Cd	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sn	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sb	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cs	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ba	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
La	ppm	32.2	37.8	47.7	35.5	nd	nd	nd	nd	nd	nd
Ce	ppm	74.1	81.8	108	79.3	nd	nd	nd	nd	nd	nd
Pr	ppm	8.9	9.9	13.2	9.6	nd	nd	nd	nd	nd	nd
Nd	ppm	35.8	41.1	54.9	39.4	nd	nd	nd	nd	nd	nd
Sm	ppm	9	11.9	14.1	10.5	nd	nd	nd	nd	nd	nd
Eu	ppm	1.35	2.23	1.95	1.49	nd	nd	nd	nd	nd	nd
Gd	ppm	8.5	13.9	14.1	11.5	nd	nd	nd	nd	nd	nd
Tb	ppm	1.4	2.9	2.5	2.3	nd	nd	nd	nd	nd	nd
Dy	ppm	8.3	20.8	16.3	15.5	nd	nd	nd	nd	nd	nd
Ho	ppm	1.58	4.68	3.45	3.43	nd	nd	nd	nd	nd	nd
Er	ppm	4.8	14.7	10.8	10.6	nd	nd	nd	nd	nd	nd
Tm	ppm	0.7	2.3	1.6	1.6	nd	nd	nd	nd	nd	nd
Yb	ppm	4.9	13.9	10.9	10.7	nd	nd	nd	nd	nd	nd
Lu	ppm	0.73	2.08	1.69	1.58	nd	nd	nd	nd	nd	nd
Hf	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ta	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
W	ppm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Au	ppb	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Pb	ppm	<2	43	2	<2	5	<2	<2	206	13	<2
Th	ppm	5.5	4.1	8.5	8.8	5.7	6.1	2.0	8.7	9.8	5.4
U	ppm	1.3	1.2	2.0	2.1	1.1	1.4	0.4	2.2	2.2	1.4

Sample		21-14149SR	21-14150	21-14151	21-14153	21-14155	21-14235	21-14236	23-14237	23-14238	23-14239
Rock Type		RHco	VCpbcg	VCpbcg	RHco	RHbx	RHco	RHco	RHbx	VCpbcg	VCpbcg
Member		Middle	Middle	Middle	Middle	Middle	Middle	Middle	Lower	Lower	Lower
SiO ₂	wt. %	73.7	72.0	76.5	78.9	81.0	72.6	70.3	74.7	71.3	56.0
TiO ₂	wt. %	0.07	0.30	0.16	0.09	0.06	0.10	0.11	0.05	0.20	0.24
Al ₂ O ₃	wt. %	8.58	8.94	7.58	8.64	5.94	12.90	14.20	6.57	11.60	19.30
Fe ₂ O ₃	wt. %	4.12	6.16	4.43	2.90	3.81	2.22	2.06	4.75	5.15	11.30
MnO	wt. %	0.01	0.04	0.04	0.03	0.04	0.05	0.05	<0.01	0.04	0.02
MgO	wt. %	8.69	7.86	6.47	4.46	4.87	1.54	1.17	0.41	2.41	2.47
CaO	wt. %	<0.01	0.07	0.43	0.36	0.43	2.63	2.40	0.07	0.37	0.14
Na ₂ O	wt. %	0.14	0.16	0.16	0.26	0.13	0.30	0.40	1.99	0.82	0.82
K ₂ O	wt. %	0.38	0.23	0.37	1.25	0.30	3.45	4.02	1.24	2.15	3.95
P ₂ O ₅	wt. %	<0.01	0.05	0.04	0.03	0.03	0.03	0.03	<0.01	0.02	0.03
Cr ₂ O ₃	wt. %	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	wt. %	4.10	3.90	3.60	2.85	2.80	3.85	3.65	3.70	3.25	5.75
Sum	wt. %	99.8	99.7	99.8	99.8	99.4	99.7	98.4	93.5	97.3	100.0
H ₂ O ⁺	wt. %	<0.01	3.8	3.0	2.2	2.3	1.7	1.6	1.4	2.5	3.2
CO ₂	wt. %	<0.01	0.05	0.62	0.52	0.61	2.40	2.47	0.10	0.45	0.02
FeO	wt. %	2.9	nd	3.3	nd	nd	1.4	0.9	nd	nd	nd
C	ppm	nd	nd	nd	nd	nd	0.68	0.71	nd	nd	nd
S	ppm	nd	0.09	0.01	0.02	0.02	0.12	0.49	4.28	1.15	4.05
Li	ppm	nd	nd	nd	nd	nd	14	9	10	39	45
Be	ppm	1	nd	nd	nd	nd	2	3	<0.5	2	1
B	ppm	nd	nd	nd	nd	nd	39	44	nd	nd	nd
F	ppm	nd	nd	nd	nd	nd	1800	1920	nd	nd	nd
Cl	ppm	nd	nd	nd	nd	nd	55	31	nd	nd	nd
Sc	ppm	11.0	nd	nd	nd	nd	2.0	2.0	<0.5	3.5	2.9
V	ppm	15	nd	nd	nd	nd	4	4	<2	19	17
Cr	ppm	<1	nd	nd	nd	nd	<2	<2	14	18	12
Co	ppm	4	nd	nd	nd	nd	<1	2	17	6	13
Ni	ppm	18	15	17	7	20	<1	1	1	12	14
Cu	ppm	67	207	11	7	16	18	29	477	483	794
Zn	ppm	1630	470	90	66	53	47	135	66100	15800	10500
Ga	ppm	47	nd	nd	nd	nd	25	26	<3	27	42
As	ppm	<3	nd	nd	nd	nd	1.8	15.0	3.0	<3	21.0
Rb	ppm	14	10	13	30	13	101	121	37	58	108
Sr	ppm	4	3	5	10	5	19	13	10	21	24
Y	ppm	81	92	78	82	64	103	87	<2	92	43
Zr	ppm	216	160	153	196	136	245	266	148	211	340
Nb	ppm	20	24	24	28	15	26	26	17	24	38
Mo	ppm	<1	nd	nd	nd	nd	<1	<1	<1	2	3
Ag	ppm	0.5	0.9	0.6	0.6	0.3	0.1	0.4	7.2	17.4	8.0
Cd	ppm	6.0	nd	nd	nd	nd	<0.2	0.8	237.0	64.0	43.0
Sn	ppm	5	nd	nd	nd	nd	14	13	182	348	205
Sb	ppm	<5	nd	nd	nd	nd	0.3	0.3	nd	nd	nd
Cs	ppm	nd	nd	nd	nd	nd	1.5	2.1	nd	nd	nd
Ba	ppm	95	nd	nd	nd	nd	400	397	139	234	361
La	ppm	2.5	nd	40.3	nd	nd	58.5	46.6	nd	nd	nd
Ce	ppm	6	nd	106	nd	nd	133	112	nd	nd	nd
Pr	ppm	0.9	nd	15.1	nd	nd	nd	nd	nd	nd	nd
Nd	ppm	5.1	nd	68.8	nd	nd	nd	nd	nd	nd	nd
Sm	ppm	3.6	nd	19.7	nd	nd	nd	nd	nd	nd	nd
Eu	ppm	0.6	nd	0.89	nd	nd	nd	nd	nd	nd	nd
Gd	ppm	4.7	nd	13.9	nd	nd	nd	nd	nd	nd	nd
Tb	ppm	1.5	nd	2.6	nd	nd	nd	nd	nd	nd	nd
Dy	ppm	12.1	nd	15.4	nd	nd	nd	nd	nd	nd	nd
Ho	ppm	3.38	nd	3.81	nd	nd	nd	nd	nd	nd	nd
Er	ppm	7.6	nd	7.7	nd	nd	nd	nd	nd	nd	nd
Tm	ppm	1.7	nd	1.7	nd	nd	nd	nd	nd	nd	nd
Yb	ppm	9.6	nd	9	nd	nd	nd	nd	nd	nd	nd
Lu	ppm	1.38	nd	1.21	nd	nd	nd	nd	nd	nd	nd
Hf	ppm	9.7	nd	6.5	nd	nd	11.0	14.0	nd	nd	nd
Ta	ppm	2.3	nd	1.3	nd	nd	3.0	3.1	nd	nd	nd
W	ppm	<10	nd	nd	nd	nd	5	4	<10	<10	<10
Au	ppb	nd	nd	nd	nd	nd	4	4	nd	nd	nd
Pb	ppm	6	<2	<2	<2	<2	<2	<2	5360	962	1220
Th	ppm	6.8	4.8	4.9	7.0	4.4	9.8	12.0	nd	nd	nd
U	ppm	2.0	1.2	1.0	1.8	0.9	2.7	2.6	nd	nd	nd

Sample		23-14240	23-14241	23-14242	23-14243	23-14244	23-14245	23-14246	HG-2323-1	HG-2323-2	HG-2323-3
Rock Type		RHbx	RHco	RHco	RHco	RHco	RHbx	RHbx	RHco	RHco	RHco
Member		Lower	Lower	Lower	Lower	Lower	Lower	Lower	Lower	Lower	Lower
SiO ₂	wt. %	82.9	81.8	80.9	84.6	83.5	79.5	86.0	83.2	83.9	82.4
TiO ₂	wt. %	0.07	0.07	0.08	0.06	0.07	0.08	0.08	0.08	0.07	0.11
Al ₂ O ₃	wt. %	8.78	10.20	9.41	9.24	9.07	8.69	8.09	9.61	9.20	9.42
Fe ₂ O _{3t}	wt. %	0.79	0.81	3.64	0.45	0.83	6.50	1.32	0.50	0.44	0.60
MnO	wt. %	<0.01	0.02	<0.01	0.02	0.04	0.04	<0.01	0.04	0.04	0.06
MgO	wt. %	0.08	0.33	0.76	0.17	0.13	0.98	0.17	0.23	0.22	0.26
CaO	wt. %	0.08	0.85	0.23	0.51	1.32	0.14	0.14	0.46	0.41	0.62
Na ₂ O	wt. %	1.99	2.95	0.27	3.04	1.98	0.47	0.37	4.74	4.69	5.12
K ₂ O	wt. %	1.67	1.56	2.08	1.30	1.69	1.43	2.07	0.70	0.62	0.60
P ₂ O ₅	wt. %	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.03	0.03	0.03
Cr ₂ O ₃	wt. %	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	wt. %	2.15	1.20	1.85	0.80	1.75	2.30	1.85	0.70	0.60	0.70
Sum	wt. %	98.5	99.8	99.2	100.2	100.4	100.1	100.1	100.4	100.3	100.0
H ₂ O ⁺	wt. %	1.0	0.6	1.5	0.4	0.5	1.8	0.8	0.4	0.3	0.2
CO ₂	wt. %	0.02	1.08	0.26	0.71	1.31	0.21	0.16	0.66	0.58	0.86
FeO	wt. %	0.7	nd	2.6	nd	nd	nd	0.2	0.3	0.2	0.3
C	ppm	0.04	nd	0.10	nd	nd	nd	0.13	0.23	0.20	0.26
S	ppm	1.82	0.29	0.29	0.02	<0.01	0.71	0.63	0.01	0.01	0.01
Li	ppm	3	<1	20	<1	<1	24	7	2	2	2
Be	ppm	<0.5	2	1	1	2	<0.5	<0.5	2	2	2
B	ppm	nd	nd	nd	nd	nd	nd	nd	22	21	18
F	ppm	876	nd	935	nd	nd	nd	825	79	77	69
Cl	ppm	nd	nd	nd	nd	nd	nd	nd	39	30	42
Sc	ppm	<0.5	0.7	1.2	0.7	1.0	0.5	1.5	<1	<1	<1
V	ppm	<2	<2	<2	<2	<2	2	<2	5	<2	3
Cr	ppm	8	2	13	14	4	16	15	40	32	48
Co	ppm	22	<1	9	<1	<1	6	14	<1	<1	<1
Ni	ppm	2	<1	<1	<1	<1	<1	3	<1	<1	<1
Cu	ppm	191	38	2430	3	5	167	170	7	10	6
Zn	ppm	27100	156	400	52	41	169	47	23	25	25
Ga	ppm	18	28	31	29	28	32	34	18	16	18
As	ppm	340.0	<3	25.0	<3	<3	<3	<3	5.8	7.9	19.0
Rb	ppm	42	33	53	36	47	34	53	20	16	22
Sr	ppm	23	25	21	24	38	18	21	41	36	38
Y	ppm	17	71	60	107	125	39	100	118	95	101
Zr	ppm	176	213	195	191	189	182	168	197	186	202
Nb	ppm	21	24	22	20	21	21	20	21	21	24
Mo	ppm	<1	<1	<1	<1	<1	<1	36	<1	<1	<1
Ag	ppm	9.3	0.6	4.2	0.2	0.3	0.3	0.6	<0.1	<0.1	<0.1
Cd	ppm	165.0	<1	<1	<1	<1	<1	<1	<0.2	<0.2	<0.2
Sn	ppm	124	12	36		10	49	23	10	8	14
Sb	ppm	nd	nd	nd	nd	nd	nd	nd	0.4	0.4	0.3
Cs	ppm	nd	nd	nd	nd	nd	nd	nd	0.8	0.7	0.5
Ba	ppm	129	421	153	436	435	125	155	541	500	378
La	ppm	6.1	nd	9.6	nd	nd	nd	19	43.2	41.1	50.8
Ce	ppm	16.9	nd	25	nd	nd	nd	52.6	101	95	114
Pr	ppm	1.8	nd	3	nd	nd	nd	6.2	nd	nd	nd
Nd	ppm	7.7	nd	14.7	nd	nd	nd	27.8	nd	nd	nd
Sm	ppm	1.4	nd	4.8	nd	nd	nd	6.4	nd	nd	nd
Eu	ppm	0.14	nd	0.32	nd	nd	nd	0.36	nd	nd	nd
Gd	ppm	1.3	nd	5.9	nd	nd	nd	7.3	nd	nd	nd
Tb	ppm	0.3	nd	1.5	nd	nd	nd	1.6	nd	nd	nd
Dy	ppm	2.6	nd	8.3	nd	nd	nd	9.9	nd	nd	nd
Ho	ppm	0.95	nd	2.42	nd	nd	nd	3.1	nd	nd	nd
Er	ppm	2.9	nd	6.2	nd	nd	nd	7.6	nd	nd	nd
Tm	ppm	0.7	nd	1.3	nd	nd	nd	1.5	nd	nd	nd
Yb	ppm	4.8	nd	8	nd	nd	nd	8.4	nd	nd	nd
Lu	ppm	0.87	nd	1.38	nd	nd	nd	1.39	nd	nd	nd
Hf	ppm	nd	nd	nd	nd	nd	nd	nd	8.3	7.0	7.6
Ta	ppm	nd	nd	nd	nd	nd	nd	nd	1.7	0.5	0.9
W	ppm	<10	<10	<10	<10	<10	<10	<10	2	1	2
Au	ppb	nd	nd	nd	nd	nd	nd	nd	<2	<2	<2
Pb	ppm	18	<2	<2	<2	<2	3	5	<2	<2	<2
Th	ppm	6.7	nd	6.9	nd	nd	nd	6.2	6.9	6.3	6.9
U	ppm	1.7	nd	1.6	nd	nd	nd	1.6	2.0	2.2	2.2

Sample		HG-2323-3	HG-2323-4	24-14228	24-14230	RC-2420-4
Rock Type		RHco	RHco	VCsa-ARG	RHhy-VCpbcg	ARG
Member		Lower	Lower	Middle	Middle	Middle
SiO ₂	wt.%	82.4	80.6	60.0	80.2	64.3
TiO ₂	wt.%	0.11	0.06	0.32	0.08	0.22
Al ₂ O ₃	wt.%	9.42	8.71	15.60	11.50	8.34
Fe ₂ O ₃	wt.%	0.60	1.51	6.79	1.84	7.77
MnO	wt.%	0.06	0.12	0.02	<0.01	<0.01
MgO	wt.%	0.26	0.27	2.25	1.24	0.60
CaO	wt.%	0.62	1.80	0.24	0.21	0.23
Na ₂ O	wt.%	5.12	0.76	1.85	0.73	1.13
K ₂ O	wt.%	0.60	2.23	2.65	2.11	1.76
P ₂ O ₅	wt.%	0.03	0.02	0.04	<0.01	0.04
Cr ₂ O ₃	wt.%	<0.01	<0.01	<0.01	<0.01	0.04
LOI	wt.%	0.70	2.65	4.65	2.15	15.10
Sum	wt.%	100.0	98.8	94.4	100.1	99.5
H ₂ O ⁺	wt.%	0.2	0.8	nd	nd	<0.01
CO ₂	wt.%	0.86	2.18	nd	nd	<0.01
FeO	wt.%	0.3	1.0	4.0	1.2	0.3
C	ppm	0.26	0.61	0.14	0.07	9.82
S	ppm	0.01	0.02	3.32	0.24	6.20
Li	ppm	2	3	nd	nd	nd
Be	ppm	2	3	2	1	1
B	ppm	18	59	nd	nd	nd
F	ppm	69	185	nd	nd	nd
Cl	ppm	42	56	nd	nd	nd
Sc	ppm	<1	1.0	6.9	2.0	5.8
V	ppm	3	4	36	<2	40
Cr	ppm	48	20	32	5	163
Co	ppm	<1	<1	33	<1	47
Ni	ppm	<1	<1	48	1	179
Cu	ppm	6	1	600	47	145
Zn	ppm	25	35	>10000	390	>10000
Ga	ppm	18	15	<3	20	19
As	ppm	19.0	0.6	47.0	5.0	64.0
Rb	ppm	22	49	69	67	50
Sr	ppm	38	37	51	49	26
Y	ppm	101	112	157	73	28
Zr	ppm	202	178	266	227	126
Nb	ppm	24	18	26	24	16
Mo	ppm	<1	<1	14	2	10
Ag	ppm	<0.1	<0.1	35.2	1.0	>1000
Cd	ppm	<0.2	<0.2	301.0	2.0	122.0
Sn	ppm	14	7	539	36	142
Sb	ppm	0.3	0.2	25.0	<5	36.0
Cs	ppm	0.5	1.5	nd	nd	nd
Ba	ppm	378	587	222	160	144
La	ppm	50.8	46.6	nd	nd	29.6
Ce	ppm	114	105	nd	nd	58.9
Pr	ppm	nd	nd	nd	nd	7.3
Nd	ppm	nd	nd	nd	nd	30.3
Sm	ppm	nd	nd	nd	nd	7.4
Eu	ppm	nd	nd	nd	nd	1.53
Gd	ppm	nd	nd	nd	nd	6.4
Tb	ppm	nd	nd	nd	nd	1.3
Dy	ppm	nd	nd	nd	nd	9.1
Ho	ppm	nd	nd	nd	nd	2.44
Er	ppm	nd	nd	nd	nd	5.2
Tm	ppm	nd	nd	nd	nd	1.1
Yb	ppm	nd	nd	nd	nd	6.3
Lu	ppm	nd	nd	nd	nd	0.89
Hf	ppm	7.6	8.3	9.7	nd	4.4
Ta	ppm	0.9	2.0	2.1	nd	0.9
W	ppm	2	3	<10	<10	<10
Au	ppb	<2	<2	nd	nd	nd
Pb	ppm	<2	<2	1050	34	3660
Th	ppm	6.9	6.8	9.6	nd	3.6
U	ppm	2.2	2.0	2.7	nd	1.0

Appendix 5

CHONDRITE NORMALIZATION VALUES

Rare earth element (REE) values are normalized to average CI (CI1) chondrite values of Evensen et al. (1978) multiplied by 1.267 as recommended by Boynton (1984), while the HFSE are normalized to the average CI chondrite values of Anders and Grevesse (1989) also multiplied by a factor of 1.267. All values in ppm.

La	0.310	Tb	0.0474	Y	1.98
Ce	0.808	Dy	0.322	Zr	4.99
Pr	0.122	Ho	0.0718	Hf	0.132
Nd	0.600	Er	0.210	Nb	0.312
Sm	0.195	Tm	0.0324	Ta	0.0180
Eu	0.0735	Yb	0.209	Th	0.0372
Gd	0.259	Lu	0.0322	U	0.010

Appendix 6

DESCRIPTION OF SAMPLE SUITES WITH Nd ISOTOPIC DATA SHOWN IN FIGURE 4.10

The comparison sample suites with Nd isotopic data shown in Figure 4.10, listed in order of increasing age, are: 1. komatiitic and tholeiitic lavas, Newton Township, Swayze Belt, Ontario (Cattell et al., 1984), 2. Noranda district volcanic and intrusive rocks, Quebec (Vervoort et al., 1994), 3. clinopyroxene separates from igneous rocks of the Abitibi greenstone belt (Machado et al., 1986), 4. intrusive/volcanic rocks and mineral separates from the Kamiskotia area, Ontario (Barrie and Shirey, 1991), 5. tonalite-granodiorite gneiss, Wawa gneiss terrane, Ontario (Shaw et al., 1994), 6. komatiite flows of the Alexo area, Ontario (Dupre et al., 1984), 7. komatiites from Pyke Hill, Munro Township, Ontario (Walker et al., 1988), 8. gabbros and pyroxenites from the Munro-Warden Sill and gabbro-textured and spinifex-textured lavas from Fred's Flow, Munro Township, Ontario (Zindler, 1982; age from Walker et al., 1988), 9. lower mafic volcanic rocks of the Kamiskotia area, Ontario (Barrie and Shirey, 1991), 10_A. VMS footwall rhyolites and Bell River granophyres, Quebec (Vervoort et al., 1994), 10_B. highly altered Matagami district VMS footwall rhyolite, 11. gabbros (whole-rock and mineral separates) and basalts, Mulcahy Lake area, Wabigoon Subprovince (Morrison et al., 1985), 12. anorthosite, gabbro and metabasalt from the Bad Vermilion Lake anorthosite complex, Rainy Lake area, Ontario (Ashwal et al., 1985) and 13. tholeiitic basalts, Keewatin Group,

Rainy Lake area, Ontario (Shirey and Hanson, 1986). All ϵ_{Nd} values presented are calculated relative to a present day chondritic $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.7219.

Appendix 7

PHOTOGRAPHS AND MICROPHOTOGRAPHS

Figure A7.1 (following page)

A. Photograph by H. Gibson of back of 2100 Access Drive, rock bolt plate is 13 cm across. Bedded QP rhyolite breccia near stratigraphic base of QP rhyolite succession (flow foot breccia), Upper member, Kidd Creek formation. Depositional units within the breccia are characterized by differences in fragment size and density. Most of the blocks are white (silicified), greenish colouration in some blocks is due to sericitization.

B. Photograph by H. Gibson, 2101 Drive South. Irregular dikes, apophyses and fragments of altered basalt or andesite (tan) within flank breccia facies of QP rhyolite (Upper member, Kidd Creek formation).

A

B

Figure A7.2 (following page)

A. Photograph of back of 23 NE Vent Raise Access (2323 Pillar Access area), 12 m south of survey point 7913. Flow banded coherent rhyolite.

B. Photograph of back of 2323 Pillar Access Drive, 8 m southwest of survey point 7907. Pyrite stringers along polygonal fractures in coherent rhyolite.

A

B

Figure A7.3 (following page)

A. Photograph of back of 2323 Pillar Access Drive, directly southeast of survey point 7907, field of view is approximately 1 m. Strong polygonal fracturing in coherent rhyolite.

B. Photograph of southeast wall of 2323 Pillar Access Drive, 27 m southwest of survey point 7907. Autoclastic rhyolite breccia impregnated by sphalerite along fractures. Note elongation and steep plunge of fragments.

A

B

Figure A7.4 (following page)

A. Photograph of back of 60735 Crosscut, 1 m southwest of survey point 8131, metal screen has a 10 cm mesh. Silicified, in situ rhyolite breccia (Lower member of Kidd Creek formation). Note reddish brown sphalerite stain in lower part of photograph.

B. Photograph of back of 60735 Crosscut, 1 m southwest of survey point 8131, metal screen has a 10 cm mesh. Silicified, in situ rhyolite breccia (Lower member of Kidd Creek formation). Note reddish brown sphalerite stain throughout photograph.

A

B

Figure A7.5 (following page)

A. Photograph of back of 2304 Fringe Drive, 30 m north of survey point 7913, rock bolt plate is 13 cm across. Silicified, in situ rhyolite breccia cut by chalcopyrite stringers (Lower member of Kidd Creek formation). Dark areas within rhyolite breccia are zones of chlorite $\pm$ sericite alteration.

B. Photograph of back of 2304 Fringe Drive, 24 m north of survey point 7913, rock bolt plate is 13 cm across. Silicified, in situ rhyolite breccia cut by chalcopyrite stringers and partly replaced by chalcopyrite (Lower member of Kidd Creek formation). Chloritization, sericitization, and chalcopyrite mineralization are concentrated along fractures in breccia.

A

B

Figure A7.6 (following page)

A. Photograph of back of 60735 Crosscut, 23 m northeast of survey point 8089. Polymict volcaniclastic pebble conglomerate dominated by rhyolite clasts (Middle member of Kidd Creek formation). Elongate, tan, mafic volcanic clasts up to 2 cm long are also visible (e.g. clast near centre of photograph). On a metre scale this unit is bedded and weakly graded. Note dark gray-black mudstone layer near right edge of photograph.

B. Photograph of back of 6001 Drive South, 0.5 m west of survey point 8094, metal screen has a 10 cm mesh. Contact between in situ autoclastic rhyolite breccia displaying jig-saw fit texture (left side of photograph) and polymict, volcaniclastic pebble conglomerate (left side of photograph). Broken piece of screen is very near contact.

A

B

Figure A7.7 (following page)

A. Photograph of southwest wall of 6001 Drive South, 2.5 m southeast of survey point 8094, metal screen has a 10 cm mesh, rock bolt plate is 13 cm across. Pyrite and sphalerite-pyrite boulders within volcanoclastic boulder conglomerate.

B. Photograph near top of wall immediately west of survey point 7986 in 2421-K-Pillar Slot, pen is 11 cm long. Polymict volcanoclastic conglomerate. Note fracturing in sphalerite stained rhyolite boulder bear centre of photograph. An altered mafic clast (tan, approximately 3 cm long, irregular outline) is located between the sphalerite-rich clast in the lower left of photograph and the large pyrite clast below pen.

A

B

Figure A7.8 (following page)

A. Photograph of back of 2129 Crosscut, approximately 17 m east of survey point 7448. Strongly sericitized rhyolite in hanging wall of north orebody.

B. Photograph of southeast wall of 4700 Hanging Wall Drill Drive (structural HW, stratigraphic FW), 31 m northeast of survey point 7316, pen is 11 cm long. Chalcopyrite stringer (30 cm wide) and black chlorite stringers (e.g. behind pen) within silicified autoclastic rhyolite breccia.

A

B

Figure A7.9 (following page)

A. Photograph of polished rock slab 16-14080. Transported, monomict, autoclastic rhyolite breccia-conglomerate (mapped as curdy rhyolite by mine staff). Note flow banded rhyolite fragment near centre of photograph. Fragments are variably silicified, matrix alteration is primarily sericitization with only weak chloritization despite dark colour. Mineralization consists of 1% to 3% disseminated and blebby pyrite. Sample collected from back of 1628-R-Slot-Access 6 m west of survey point 7935 (Middle member of Kidd Creek formation).

B. Photograph of polished rock slab 16-14128. Silicified, monomict, in situ rhyolite breccia. Orange-brown colouration is due to very fine grained (0.01-0.05 mm) disseminated sphalerite (sphalerite stain). The rock also contains trace - 2% disseminated pyrite. Dark alteration along fractures is intense sericitization. Sample collected from east wall of 1602 Drive North, 8.5 m south of survey point 2413 (Lower member of Kidd Creek formation).

C. Photograph of polished rock slab 16-14134. Silicified, monomict, in situ rhyolite breccia with pronounced orange-brown sphalerite stain (5-15% very fine grained, disseminated sphalerite) and minor pyrite. Fractures are sericitized. Sample collected from east wall of 1602 Drive North, 2 m north of survey point 2423 (Lower member of Kidd Creek formation).

Figure A7.10 (following page)

A. Photograph of polished rock slab 21-14150A. Volcaniclastic, unsorted, polymict pebble conglomerate containing light grey, silicified rhyolite clasts (dominant) and tan mafic clasts. Matrix is chloritic. Mineralization consists of trace-2% disseminated and blebby pyrite. Sample collected from back of 2129 Crosscut, 1 m west of survey point 7585, in footwall of south orebody (Middle member of Kidd Creek formation).

B. Photograph of polished rock slab RC-2420-3. Volcaniclastic, unsorted, polymict pebble conglomerate containing rhyolite, mafic, argillite, sphalerite, and pyrite clasts in an argillaceous matrix. Sample collected by Ron Cook in northwest wall of 2420 Crosscut, immediately northwest west of survey point 7980, in hanging wall of north orebody (Middle member of Kidd Creek formation).

Figure A7.11 (following page)

- A. Photograph of polished rock slab 21-14158. Volcaniclastic polymict pebble conglomerate dominated by rhyolite clasts partly replaced by chalcopryrite (10-20% blebby, disseminated, and veinlet-controlled chalcopryrite). Sample collected from south wall of 2129 Crosscut, 7 m east of survey point 7453, in zone of semi-massive to heavily disseminated chalcopryrite within south orebody (Middle member of Kidd Creek formation).
- B. Photograph of polished rock slab 21-14145. Volcaniclastic polymict pebble conglomerate containing light grey rhyolite clasts (dominant) and tan mafic clasts containing 15-25% stockwork and replacement chalcopryrite. Sample collected from north wall of 2129 Crosscut, 3 m west of survey point 7453, in zone of semi-massive to heavily disseminated chalcopryrite within south orebody (Middle member of Kidd Creek formation).
- C. Photograph of polished rock slab RC-2420-2. Volcaniclastic polymict pebble conglomerate with argillaceous matrix. Mineralization includes 20-30% reddish brown, replacement sphalerite, 5-10% blebby and disseminated pyrrhotite, and 3-5% blebby and veinlet-controlled pyrite. Sample collected by Ron Cook in northwest wall of 2420 Crosscut, 6 m west of survey point 7980, in the hanging wall of the north orebody (Middle member of Kidd Creek formation).

A **B** **C**

Figure A7.12 (following page)

A. Photograph of polished rock slab 16-14081. Volcaniclastic polymict boulder conglomerate containing rhyolite (including sphalerite-stained rhyolite), mafic, polymict pebble conglomerate, argillite, quartz crystal, sphalerite, and pyrite clasts. Matrix contains pervasive sericite-chlorite alteration. Sample collected from back of 1628-R-Slot Access (1602 Drive South area), 14 m west of survey point 7935 (Middle member of Kidd Creek formation).

B. Photograph of polished rock slab 16-14086. Volcaniclastic polymict boulder conglomerate similar to 16-14081. Photograph shows strong elongation of sulfide fragments parallel to steep F1 plunge direction (compare to sample 16-14081 which was cut perpendicular to plunge). Sample collected from east wall of 1602 Drive South, 3.6 m south of survey point 2052 (Middle member of Kidd Creek formation).

Figure A7.13 (following page)

A. Photograph of polished rock slab 16-14103. Part of clast within volcanoclastic boulder conglomerate of light reddish-brown, sphalerite-rich massive sulfide cut by multidirectional veinlets of pyrite and galena. Sample collected from back of 1628-R-Slot Access (1602 Drive South area) near north wall, 10.7 m west of survey point 7935 (Middle member of Kidd Creek formation).

B. Photograph of polished rock slab 16-14104. Part of clast within volcanoclastic boulder conglomerate of dark grey, rhyolitic host rock cut by pyrite-sphalerite stockwork. Sphalerite appears to predate pyrite. Sample collected from back of 1628-R-Slot Access (1602 Drive South area), 12 m west of survey point 7935 (Middle member of Kidd Creek formation).

A

B

Figure A7.14 (following page)

A. Photograph of polished rock slab 16-14138. Volcaniclastic muddy sandstone dominated by rhyolite and quartz crystal grains bedded on a mm scale due to grain size variation (many laminae grade from sandstone to mudstone). The rock is sericitized and chloritized, and contains 5-15% blebby and disseminated pyrite which occurs preferentially along sandy parts of laminae. Sample collected from east wall of 1602 Drive North, 4.6 m north of survey point 2423 (3 m wide zone of transported volcaniclastic rocks within autoclastic rhyolite breccia, Middle member of Kidd Creek formation).

B. Photograph of polished rock slab 48-14207. Irregular intrusion of altered, tan, subvolcanic mafic rock into felsic volcaniclastic rock (dark grey) at stratigraphic base of wedge gabbro sill. Peperite of mafic volcanic fragments developed locally (e.g. centre of photograph). Peperite development indicates intrusion of mafic rock into unconsolidated felsic volcaniclastic material. Sample collected from back of 48780 Crosscut, near south wall, 0.5 m east of survey point 8096 (Middle member of Kidd Creek formation).

A **B**

Figure A7.15 (following page)

A. Photomicrograph of thin section 18-14046, crossed nicols, field of view is 10.8 mm x 7.4 mm. Coherent QP rhyolite (Upper member, Kidd Creek formation), phenocryst population dominated by quartz but two small feldspar phenocrysts occur near top of photograph. Sample is from 1829 Crosscut.

B. Photomicrograph of thin section 18-14046, crossed nicols, field of view is 5.2 mm x 3.6 mm. Glomeroporphyritic aggregate of feldspar in coherent QP rhyolite (Upper member, Kidd Creek formation). Feldspars are weakly to moderately altered to carbonate, groundmass is moderately sericitized and weakly chloritized. Sample is from 1829 Crosscut.

A

B

Figure A7.16 (following page)

A. Microphotograph of thin section 18-14050, crossed nicols, field of view is 1.3 mm x 0.9 mm. Quartz phenocryst (0.40 mm long) rimmed by spherulitic crystals in coherent QP rhyolite. Veinlet in lower right corner of microphotograph is composed of carbonate and quartz. Sample is from 1829 Crosscut (Upper member, Kidd Creek formation).

B. Microphotograph of thin section 18-14050, crossed nicols, field of view is 0.65 mm x 0.45 mm. Quartz phenocryst (0.21 mm across) and spherulite (0.20 mm across) in coherent QP rhyolite. Note spherulitic rim on phenocryst. Sample is from 1829 Crosscut (Upper member, Kidd Creek formation).

A

B

Figure A7.17 (following page)

A. Microphotograph of thin section 18-14050, crossed nicols, field of view is 0.65 mm x 0.45 mm. Spherulitic coherent QP rhyolite. Large spherulite near centre of microphotograph is 0.24 mm across. Sample is from 1829 Crosscut (Upper member, Kidd Creek formation).

B. Microphotograph of thin section 18-14050, plane light, field of view is 2.6 mm x 1.8 mm. Spherulitic, coherent QP rhyolite. Small, dark minerals are stilpnomelane. Sample is from 1829 Crosscut (Upper member, Kidd Creek formation).

A

B

Figure A7.18 (following page)

A. Photomicrograph of thin section HG-2101-22A, plane light, field of view is 5.2 mm x 3.6 mm. Rhyolite-clast and quartz crystal-rich, bedded, volcanoclastic sandstone (probably resedimented QP rhyolite hyaloclastite), Upper member, Kidd Creek formation. Note quartz phenocrysts in some of the rhyolite clasts. Sample is from 2101 Drive South.

B. Photomicrograph of thin section HG-2101-11, plane light, field of view is 10.8 mm x 7.4 mm. Small apophysis of basalt or andesite (dark) intruding QP rhyolite hyaloclastite (Upper member, Kidd Creek formation). Opaque mineral is pyrite. Sample is from 2101 Drive South.

A

B

Figure A7.19 (following page)

A. Microphotograph of thin section 2578-1017, plane light, field of view is 10.8 mm x 7.4 mm. QP rhyolite hyaloclastite (Upper member of Kidd Creek formation) locally displaying jigsaw-fit texture. Note flow banding in fragments near centre of microphotograph. Sample collected at 1017 ft (310 m) from the collar in diamond drill hole 2578, a relatively flat hole collared on 1600 Level.

A. Microphotograph of thin section 16-14138, plane light, field of view is 10.8 mm x 7.4 mm. Volcaniclastic sandstone with graded bedding, opaque mineral is pyrite. Sample is from 1602 Drive North (small area of transported volcaniclastic rocks within Lower member of Kidd Creek formation).

A

B

Figure A7.20 (following page)

A. Microphotograph of thin section 21-14236B-E, plane light, field of view is 5.2 mm x 3.6 mm. One large quartz phenocryst (1.1 mm across) and two small quartz phenocrysts in strongly sericitized coherent rhyolite. Dark gray-brown spots are carbonate alteration. Sample is from the immediate hanging wall of the south orebody in 2129 Crosscut (Middle member, Kidd Creek formation).

B. Microphotograph of thin section EO-92-1, plane light, field of view is 5.2 mm x 3.6 mm. Perlitic fractures in coherent rhyolite block from East Outcrop rhyolite breccia (Lower member, Kidd Creek formation).

A

B

Figure A7.21 (following page)

A. Photomicrograph of thin section 21-14149-2, crossed nicols, field of view is 1.3 mm x 0.9 mm. Spherulitic coherent rhyolite, large spherulite near centre of view is 0.55 mm across. Material surrounding spherulite is mainly chlorite with some sericite. Sample is from the immediate footwall of the south orebody in 2129 Crosscut (Middle member, Kidd Creek formation).

B. Photomicrograph of thin section 21-14149-2, crossed nicols, field of view is 1.3 mm x 0.9 mm. Spherulitic coherent rhyolite, large spherulite near centre of view is 0.5 mm across. Material surrounding spherulites is mainly chlorite with some sericite. Sample is from the immediate footwall of the south orebody in 2129 Crosscut (Middle member, Kidd Creek formation).

A

B

Figure A7.22 (following page)

A. Photomicrograph of thin section 21-14149-2, plane light, field of view is 5.2 mm x 3.6 mm. Zone of spherulites in coherent rhyolite. Note development of anastomosing fractures in areas where spherulites coalesce. Material between spherulites consists chlorite and minor sericite. Sample is from the immediate footwall of the south orebody in 2129 Crosscut (Middle member, Kidd Creek formation).

B. Same as A with crossed nicols.

A

B

Figure A7.23 (following page)

A. Microphotograph of thin section 16-14061, plane light, field of view is 2.6 mm x 1.8 mm. Small spherules (recrystallized spherulites) in coherent rhyolite. Feldspar phenocryst pseudomorph (sericitized) is 0.7 mm across. Material between spherules is predominantly sericite. Sample is from 1602 Drive South (Lower member, Kidd Creek formation).

B. Microphotograph of thin section 21-14149-2, plane light, field of view is 10.8 mm x 7.4 mm. Spherulitic coherent rhyolite. Material between spherules is predominantly chlorite with minor sericite. Sample is from 2129 Crosscut in the immediate footwall of the south orebody (Middle member, Kidd Creek formation).

A

B

Figure A7.24 (following page)

A. Microphotograph of thin section 16-14061, plane light, field of view is 10.8 mm x 7.4 mm. Contorted flow banding in coherent rhyolite resulting from variable density of spherules (recrystallized spherulites). Spherules are densely packed and coalesced within white bands. Sample is from 1602 Drive South (Middle member, Kidd Creek formation).

B. Microphotograph of thin section 16-14061, plane light, field of view is 10.8 mm x 7.4 mm. Contorted flow banding as in A.

A

B

Figure A7.25 (following page)

A. Microphotograph of thin section 21-14150, plane light, field of view is 10.8 mm x 7.4 mm. Polymict volcanoclastic pebble conglomerate composed of rhyolite clasts, quartz crystal clasts (white, unaltered material), and mafic clasts (part of a large mafic clast is visible in the upper right part of microphotograph). Note angularity of some fragments. Sample is from 2129 Crosscut in the footwall of the south orebody (Middle member, Kidd Creek formation).

B. Microphotograph of thin section 16-14106, plane light, field of view is 10.8 mm x 7.4 mm. Contact between in situ rhyolite hyaloclastite (on left) and polymict volcanoclastic pebble conglomerate (on right). Note jigsaw-fit texture in hyaloclastite. Sample is from 2129 Crosscut in the footwall of the south orebody (Middle member, Kidd Creek formation).

A

B

Appendix 8

VOLCANICLASTIC ROCK TERMINOLOGY USED IN THESIS

“There is, at present, no adequate terminology for autoclastic deposits, nor for resedimented syn-eruptive pyroclastic and autoclastic deposits” (McPhie et al., 1993, p. 8). The rock classification scheme used by company geologists at the Kidd Creek Mine includes several pyroclastic terms, including “tuff”, “lapillistone”, and “agglomerate”, which are used in a non-genetic sense to indicate fragment size in volcanoclastic rocks (Walker and Mannard, 1974). However, when applied rigorously the use of pyroclastic terminology implies formation by pyroclastic processes. This thesis demonstrates that little, if any, of the volume of volcanoclastic rock present in the Kidd Creek formation was formed by pyroclastic processes in the classic sense:

“Pyroclastic - primary volcanoclastic deposits made of particles (pyroclasts) generated by explosive eruptions and deposited by primary volcanic processes (fallout, flow, surge)” (McPhie et al., 1993, p. 94). “Note, in particular that “tuff” is reserved for primary pyroclastic deposits” (McPhie et al., 1993, p. 8).

“pyroclastic (py-ro-clas'-tic) Pertaining to clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent” (Bates and Jackson, 1987, p. 540).

“Pyroclastic deposits are those formed by the fragmentation of magma and rock by explosive volcanic activity” (Wright et al., 1980, p. 315).

Schmid (1981), in recommendations of the IUGS Subcommittee on the systematics of igneous rocks, suggested broadening the definition of pyroclastic deposit to include all rocks composed of fragments generated by volcanic action:

“Pyroclastic deposits (=“pyroclastics”) include both consolidated and unconsolidated assemblages of pyroclasts. They must contain more than 75% pyroclasts by volume.... Pyroclasts are the individual crystals, crystal fragments, glass fragments, and rock fragments generated by disruption as a direct result of volcanic action” (Schmid, 1981, p. 42).

Using the definitions of Schmid (1981) volcanogenic autoclastic deposits are considered to be pyroclastic and, therefore, pyroclastic terminology can be applied (for example, an autoclastic breccia might be mapped as a rhyolite lapillistone). However, even using Schmid's definition, pyroclastic nomenclature should not be applied to resedimented volcanoclastic rocks.

In this thesis rocks formed by autoclastic processes are not considered to be pyroclastic rocks, consistent with McPhie et al. (1993), Bates and Jackson (1987), and Wright et al. (1980). The classification scheme I have adopted for the volcanoclastic rocks of the Kidd Creek formation is presented in Table A8.1.

Fragment Size	Volcaniclastic Rocks	
	Autoclastic Deposits (in-situ to locally transported) - generally monomict -	Epiclastic Deposits - generally polymict -
<1/16 mm (<0.0625 mm)	hyaloclastite	volcaniclastic mudstone
1/16-2 mm	hyaloclastite	volcaniclastic sandstone
2-64 mm	autoclastic breccia*	volcaniclastic pebble conglomerate
>64 mm	coarse autoclastic breccia*	volcaniclastic boulder conglomerate

* breccia-conglomerate if fragments have been rounded by abrasion or alteration

Table A8.1. Classification of volcaniclastic rocks formed by autoclastic or epiclastic processes (modified after McPhie et al., 1993).

Appendix 9

DESCRIPTIONS OF ROCK SAMPLE FROM THE 1600, 1800, 2100, 2300, AND 2400 LEVELS OF THE KIDD CREEK MINE

- Notes:
- i. sample number prefix denotes mine level
 - ii. see Maps 2 to 7 for sample locations
 - iii. “x” beneath sample number denotes geochemical analyses

Abbreviations Used In Rock Descriptions

General Abbreviations

carb	carbonate
chl	chlorite
cp	chalcopyrite
cr	coarse
diss	disseminated
fc	Fe-carbonate
fd	feldspar
fn	fine
FOL	foliation
gal	galena
gr	grained
HS	hand sample
md	medium
pheno	phenocryst
plag	plagioclase
py	pyrite
qz	quartz
ser	sericite
sph	sphalerite
sx	sulfide
tour	tourmaline
tr	trace
TS	thin section
v	very
xtal	crystal

Alteration Intensities

n	nil (0%)
vw	very weak (<2%)
w	weak (2-10%)
m	moderate (10-30%)
s	strong (30-50%)
i	intense (>50%)

Alteration Styles

B	blebby
D	disseminated
F	foliation controlled
H	hairline veinlet (<1 mm) controlled
L	veinlet (1-10 mm) controlled
P	pervasive
R	fracture controlled
S	spotty
V	vein (>10 mm) controlled
X	crystal replacement

- 16-14060**
1602 DR S
coherent rhyolite, flow banded (sub-mm scale), pronounced microscopic anastomosing fracture pattern, weak foliation, 1-2% qz phenos (random, up to 1.2 mm across, intact to broken, commonly rimmed by 2° qz), possibly 1-2% fd pheno pseudomorphs (carb-ser) up to 2 mm long, m-sPser, wScarb (qz-ser rock), no sulfides
- 16-14061**
1602 DR S
x
flow banded coherent rhyolite, strong anastomosing fracture pattern, well developed flow banding (mm to sub-mm scale), wFOL (locally crenulated), tr-1% qz phenos (subhedral-euhedral, up to 1 mm across), tr-1% fd pheno pseudomorphs (ser-qz±chl) up to 2 mm long, sPser (qz-ser rock), no sulfides
- 16-14062**
1602 DR S
x
ultramafic rock, sLScarb (some pink carbonate)
- 16-14063**
1602 DR S
x
ultramafic rock, sVPcarb, vwSfuchsite, no sulfides
- 16-14064**
1602 DR S
x
volcaniclastic pebble conglomerate, polymict, contains sx clast, matrix alteration: w-mPser-chl, locally wLcarb, wDtour, 30-40% py-sph, clasts + diss
- 16-14065**
1602 DR S
volcaniclastic pebble conglomerate, polymict, contains sx clasts, flow banded rhyolite clast in TS, minor proportion of sph-chl±albite clasts, wPHser, vwDtour, vwHqz, vwScarb, 20-30%py, 5-10%sph, 1-2%gal - clasts + 2° BD
- 16-14066**
1602 DR S
x
volcaniclastic sandy mudstone composed predominantly of rhyolite and qz xtall clasts, largest clast is 0.6 mm across, 1-2% sand sized (>0.06 mm) clasts, sPser (qz-ser rock), 1-2%Dpy
- 16-14067**
1602 DR S
autoclastic rhyolite breccia, local in situ breccia texture (microscopic)
- 16-14068**
1602 DR S
volcaniclastic mudstone in sharp contact with graded volcaniclastic sandstone, sandstone is light grey, lower 2 cm of sandstone is very cr gr with clasts up to 5 mm of rhy and black argillite, sandstone matrix alteration: sPser-chl; mudstone: sPser, argillite clasts: iPchl, tr-2%Dpy, mainly in sandstone
- 16-14069**
1602 DR S
x
volcaniclastic sandy mudstone, composed predominantly of rhyolite clasts and qz xtalls, lt grey, grainy in TS, largest clast is 0.26 mm across (qz xtall), sPser, wScarb, 1-3%Dpy
- 16-14070**
1602 DR S
contact between coherent rhyolite and in-situ rhyolite hyaloclastite, wFOL, grey alteration zone and increased sericitization along contact, rhyolite: tr-1% qz phenos, hyaloclastite: jig-saw fit common, fragments up to 1.5 mm across (TS), a few show flow banding(?), 1-2% qz xtalls up to 1.5 mm across, m-sPchl-(ser), w-mFser, vwSchl, no sulfides

- 16-14071**
1602 DR S
volcaniclastic boulder conglomerate, polymict, m-sPchl, 10-20% py-sph clasts + diss
- 16-14072**
1602 DR S
rhyolite hyaloclastite, local jig saw fit texture, anastomosing fracture pattern well developed in 60-80% of TS, wFOL, sPFser, wSchl, vwScarb, 1-3%Dsph (commonly rimmed by chl), 1-2%Dpy, trDgal
- 16-14073**
1602 DR S
volcaniclastic boulder conglomerate, polymict, contains sulfide clasts, TS contains 35x15 mm light grey, aphanitic, strongly altered (qz-ser) rhy clast with incipient fracturing at 1 end
- 16-14074**
1602 DR S
x
rhyolite autoclastic breccia - rhyolite hyaloclastite, breccia is strongly silicified and sericitized, white to light green (ser), monomict, largest fragment is 1.5x1 cm, breccia contains a 3 cm wide zone of dark gray hyaloclastite, 1-2% qz eyes to 2 mm, breccia: sPqz, sPser, w-mLSfc, 1-3%Dpy located preferentially in hyaloclastite
- 16-14075**
1602 DR S
ultramafic rock, mVcarb, wVfuchsite (halo on carbonate vein), no sulfides
- 16-14076**
1602 DR S
felsic volcaniclastic rock, collected near ultramafic rocks and E-W shear, s-iPchl, w-mSfc (1-2 mm fc spots); qz-chl-(fc) rock, no sulfides
- 16-14077**
1602 DR S
large clast in volcaniclastic boulder conglomerate, 45x15 cm, felsic volcaniclastic sandstone, 1-2% qz crystals (some broken)
- 16-14078**
1602 DR S
cp clast in volcaniclastic boulder conglomerate
- 16-14079**
1602 DR S
x
volcaniclastic sandstone (distal hyaloclastite?), polymict, matrix supported, not foliated, clasts: broken qz xtals>rhy clasts>chloritized mafic clasts, grain size = 0.02 - 2 mm, most clasts subround-subangular, granular hand sample, apx. 1% tan mafic clasts up to 3x3 mm, sPchl, wHchl, wScarb, 1-3%DBpy, trDgal
- 16-14080**
1602 DR S
x
autoclastic rhyolite breccia-conglomerate, transported, monomict, lt gray clasts in dark gray matrix, 1 clast flow banded, clasts subround unsorted and variably silicified, largest clast 7.5 x 4 cm, clasts: iP(H)si, matrix: sPser, vw-wPchl, wLcarb-(albite); qz-ser rock, 1-3%DBpy
- 16-14081**
1602 DR S
x
volcaniclastic boulder conglomerate, 40-60% subrnd-subang unsorted clasts up to 6x4 cm (py-sph clasts, rhy clasts, volcaniclastic sandstone clasts, altered (tan) mafic clasts, qz xtall clasts), matrix alteration: mPser-chl, 15-35% py-sph, clasts+diss, trLcp

- 16-14082**
1602 DR S
x
rhyolite hyaloclastite - coherent rhyolite, moderate anastomosing fracture pattern (40-50% of TS), vwFOL, m-sPser (qz-ser rock), vw-wSchl (commonly rimming sph grains), 1-3%Dpy, tr-3%Dsph
- 16-14083**
1602 DR S
x
mafic intrusive rock, very fn gr, md gray, sLSfc-qz, mDleucoxene, trDpy
- 16-14084**
1602 DR S
x
volcaniclastic pebble conglomerate, polymict, sx-rich, dk gray gritty matrix, one siliceous clast contains tourmaline, matrix alteration: m-sPchl, 10-30% py- and sph-rich clasts
- 16-14085**
1602 DR S
x
rhyolite hyaloclastite, md gray, vf gr, 1-2% siliceous rhyolite clasts up to 6x4 mm, no sulfides
- 16-14086**
1602 DR S
x
volcaniclastic boulder conglomerate, polymict, 20-40% clasts - sx(sph-py), volcaniclastic sandstone, rhyolite, and altered (tan) mafic clasts, sph clasts are chl-rich, matrix is dark grey, very fn gr (gritty), matrix alteration: m-sPchl, 10-20% sph-py, mostly clasts, may also contain some 2° mineralization
- 16-14087**
1602 DR S
x
volcaniclastic sandy mudstone, siliceous, dk gray, gritty, mFOL, composed mainly of qz xtalls and rhyolite clasts, most clasts are between 0.02 and 0.2 mm across, folded py veinlet in TS, sPchl, wPser, nil-2%LDpy
- 16-14088**
1602 DR S
x
volcaniclastic sandstone, felsic, medium grey, matrix supported, weakly graded, polymict, major clasts types (>90%) are recrystallized rhyolite and qz xtalls (subrnd to subang), 30-50% relatively coarse grains (sand sized, mainly 0.03-1.4 mm) in a muddy matrix, sPchl, 3-5%BDsph, 1-3%Dpy (cubes to 7mm), tr-2%Bcp
- 16-14089**
1602 DR S
x
rhyolite hyaloclastite, fragment supported, unsorted, monomict TS: largest fragment is about 4 mm across, larger clasts show variable degrees of fragmentation, fragments subround to subangular, HS: medium-dark grey, indistinct clasts up to 1.5x1.0 cm, sPser-chl (qz-ser-chl rock); sPchl zones within large fragments (glass hydration?), no sulfides
- 16-14090**
1602 DR S
x
volcaniclastic sandy mudstone, felsic, (bedded), polymict, one sandstone laminae in TS (1.0 mm thick) average gr size <0.05 mm, qz xtall and rhyolite clasts dominant, largest clast (0.88 mm across) is composed of chl-sph, sPser-chl, wSfc, vwHqz, no sulfides
- 16-14091**
1602 DR S
x
volcaniclastic pebble conglomerate with argillaceous matrix, polymict, rhyolite fragments are up to 6x4 mm, 2-5% tan mafic clasts up to 10x4mm, some very irregular (delicate), 1-2% qz xtalls, m-sPLchl, w-mPser, nil-trDpy
- 16-14092**
1602 DR S
x
volcaniclastic pebble conglomerate - graphitic argillite contact, pebble conglomerate has strongly chloritized, argillaceous matrix, argillaceous matrix: s-iPLchl, vw-wPser, no sulfides

- 16-14093**
1602 DR S
autoclastic rhyolite breccia-hyaloclastite(?) broken qz phenos, mPchl, vw-wDtour, 2-3%Dpo, 1-2%Dpy (some cubes), trDcp
- 16-14094**
1602 DR S
x
volcaniclastic sandstone, light grey, felsic, poorly sorted, matrix supported, polymict (rhyolite clasts dominant), wFOL, apx 10% subround rhyolite clasts to 15x10mm (most <4 mm), 1-5% sericitic wispy clasts, (fiamme-like) up to 18x3mm(TS), one contains abundant spheriolites, another contains poss flattened vesicles (qz amygdules), wispy clast alteration: iPser; rhy clasts: iPqz, matrix: sPser, mSfc (some rhombs), trDpy
- 16-14095**
1602 DR S
coherent rhyolite, (similar to 14061), strong anastomosing fracture pattern, in contact with volcaniclastic unit containing 2.5 cm altered mafic clast, next largest is tan mafic clast of 8x4 mm, large clast has a felty texture of acicular plag pseudos (sericitic) in a chloritic groundmass, mPser (qz-ser rock), trDpy
- 16-14099**
1602 DR S
x
rhyolite hyaloclastite, medium-dark grey, very fn gr, weakly mottled appearance, 2-3% oval white blebs to 2 mm long, contains coherent rhyolite blocks up to 8x3 cm (very difficult to see in underground exposures), mPchl-ser, trDpy
- 16-14100**
1602 DR S
contact between rhyolite hyaloclastite and volcaniclastic mudstone, sPser, mScarb, n-wSchl, 15-20%LDpy in TS, nearly all in one 0.8 mm wide veinlet
- 16-14101**
1602 DR S
strongly mineralized (py-sph) rhyolitic clast in volcaniclastic boulder conglomerate, medium gray to reddish brown (sph stain)
- 16-14102**
1602 DR S
py-sph-(gal)-rich clast in volcaniclastic boulder conglomerate, strongly mineralized part of same clast as sample 14101
- 16-14103**
1602 DR S
massive sulfide clast in volcaniclastic boulder conglomerate, light reddish-brown, sph-rich, massive sph cut by multidirectional veinlets of pyrite and galena
- 16-14104**
1602 DR S
mineralized rhyolitic clast in volcaniclastic boulder conglomerate, dark gray rhyolitic host rock cut by multidirectional (stockwork) py-sph veinlets, 40-60%Lpy-sph
- 16-14105**
1602 DR S
pyritic zone within autoclastic rhyolite breccia
- 16-14106**
1602 DR S
volcaniclastic boulder conglomerate containing zone of in situ rhyolite hyaloclastite, most clasts in sample are pebble-size, local jig-saw fit in hyaloclastite (TS), hyaloclastite fracturing becomes more intense toward contact (TS), possible injection of rhyolite into volcaniclastic material, matrix: sPser; some clasts: sPchl, VCbdcg: 1-3%Dpy; RHhy: no sulfides

- 16-14107**
1602 DR S
x
large mafic clast from volcanoclastic polymict boulder conglomerate, HS: tan (light brown), appears to contain fine gr acicular xtalls TS: felty texture of very elongate fd pseudomorphs (strongly sericitized), 0.5-1.5 mm long, rare qz phenos, groundmass alteration: sPchl, no sulfides
- 16-14108**
1602 DR S
volcanoclastic sandy mudstone, lt grey, very fine gr, weakly bedded, one 1 cm thick bed is distinctly more sand-rich, 1-2% randomly distributed anhedral qz crystals up to 2 mm diameter, possible pyroclastic tuff, sPser, no sulfides
- 16-14128**
1602 DR N
autoclastic rhyolite breccia, sphalerite-stained, monomict, unsorted, light grey, siliceous rhyolite fragments up to 6x3 cm, commonly showing internal fracturing, 1-2% randomly distributed qz phenos (fractured, intact to weakly fragmented), rhy fragments are recrystallized qz-(ser) rock, interfragmental fractures are dark grey, alteration of rhyolite fragments: s-iPqz, wPser, matrix: iPser, 3-5%SDHsph (zones of disseminated 0.01-0.05 mm sph grains create "stain), tr-2%DLpy
- 16-14129**
1602 DR N
autoclastic rhyolite breccia, similar to 16-14128
- 16-14130**
1602 DR N
coherent rhyolite, md-dk grey
- 16-14131**
1602 DR N
x
coherent rhyolite, tr-1% anhedral-subhedral qz phenos up to 0.8 mm across, possible linear zones of recrystallized spherioides (flow banding?), mFHPser, sPqz (qz-ser rock), vwScarb, vwHqz, no sulfides
- 16-14132**
1602 DR N
x
coherent rhyolite, spherioiditic (recrystallized), weakly-moderately fractured on microscopic scale, weak foliation 1-2% anhedral to subhedral, strongly fractured qz phenos up to 1.2 mm across (some show resorption effects), tr-1% altered subhedral plag phenos up to 1.6 mm long (m-s alteration to carb + qz), sPqz, mPser, wScarb, wLqz-py-carb, 5-10%LDpy (veinlets include qz and carb)
- 16-14133**
1602 DR N
x
coherent rhyolite, weak anastomose fracture pattern (microscopic), tr-1% subhedral - anhedral qz phenos up to 0.8 mm across (not fractured), sPHqz, sPser, wSHcarb, 3-10%DBHpy - some diss py consists of microscopic (0.01-0.03 mm) grains
- 16-14134**
1602 DR N
autoclastic rhyolite breccia, siliceous, strong sphalerite stain, lt gray to orange-brown 1-2% subhedral-anhedral qz phenos up to 1.2 mm across, weak foliation, sPqz, m-sPFser, 5-15%HDsph, 2-5%Hpy (some sph accompanied by chl)
- 16-14135**
1602 DR N
volcanoclastic pebble conglomerate, lt grey, rhyolite clast dominated, apx 50% clasts (in part matrix supported) clasts are unsorted, subround-subangular, up to 3x2 cm, m-sPqz, mFPser, wScarb, wSchl (commonly rims py grains), 5-20%DBpy, some cubic forms (therefore not clasts)

- 16-14136**
1602 DR N
coherent rhyolite
- 16-14137**
1602 DR N
autoclastic rhyolite breccia
- 16-14138**
1602 DR N
x
volcaniclastic muddy sandstone, md grey, v fn gr (most grains between <0.01 and 0.50 mm across) delicately bedded on mm scale due to grain size variation (many laminae grade from sandstone to mudstone) most clasts are round-subround but a few are subangular, nearly all clasts are rhy or qz xtalls, sPser-chl, 5-15%BDpy, occurs preferentially along sandy parts of laminae
- 16-14139**
1602 DR N
autoclastic rhyolite breccia
- 18-14044**
1829 XC
coherent QP rhyolite, 10-15% anhedral to subhedral qz phenos up to 1.5 mm across, 1-3% sericite-altered, anhedral to subhedral twinned plag phenos up to 1 mm long, phenos are randomly distributed, irregular sericitized fractures locally create pseudofragmental texture, m-sPHqz, mRPser, w-iXser (relacing plag), wScarb, vwHqz-carb, vwSstlpnomelane, no sulfides
- 18-14045**
1829 XC
QP rhyolite, possible hyaloclastite
- 18-14046**
1829 XC
x
coherent QP rhyolite, 15-20% anhedral-subhedral qz phenos up to 2 mm across, 2-4% weakly sericitized plag phenos up to 2 mm long, phenos are randomly distributed, qz veinlet is cut by carbonate veinlet in TS, microscopic, anastomosing, sericitized fractures are common in TS, m-sPqz, mRPser, mSPchl, w-mXser (replacing plag), vwHqz, vwHScarb, no sulfides
- 18-14047**
1829 XC
coherent QP rhyolite, contains intensely sericitized fd pseudos and 1 possible granophyre grain, s-iPser, wSbio(?)
- 18-14048**
1829 XC
x
coherent QP rhyolite, underground exposure is flow banded, 10-15% anhedral-subhedral qz phenos up to 1 mm across, no recognizable fd phenos, zones of high density anastomosing fractures occur in TS, m-sPqz, m-sFRPser, w-mScarb, no sulfides
- 18-14049**
1829 XC
coherent rhyolite, spherulitic (recrystallized), sericitization between spherules imparts a pseudoclastic texture in TS (similar to sandy mudstone), plagioclase phenocrysts present, m-sPser, wSstlpnomelane, no sulfides

- 18-14050**
1829 XC
coherent QP rhyolite, varies from strongly spherulitic (pseudoclastic) to non-spherulitic, some spherules show good radial extinction, spherulites up to 0.3 mm across (most <0.2 mm across), most qz phenos are rimmed by spherulitic crystals (this feature not observed in QP rhyolite samples in which spherulites are absent), mPser, sStilpnomelane
- 18-14051**
1829 XC
x
coherent QP rhyolite, 10-15% anhedral-subhedral qz phenos up to 3 mm across, 3-5% anhedral-subhedral, sericitized plag phenos up to 1 mm long, some plagioclase occurs in glomerporphyritic aggregates, TS is weakly banded due to variations in intensity of microscopic sericitized, anastomosing fractures, m-sPqz, m-sFPser, m-iXser (replacing plag), vwSstilpnomelane, vwScarb, no sulfides
- 18-14052**
1829 XC
coherent QP rhyolite
- 18-14053**
1829 XC
coherent QP rhyolite, entire groundmass appears to be spherulitic (looks somewhat like very fn gr sand), no spherules with radial extinction noted
- 18-14054**
1829 XC
x
QP rhyolite breccia-conglomerate, clast supported, polymict, dominated by subround to round QP clasts, 1-3% altered, angular to subangular mafic clasts, some dominated by fd pseudomorphs (sericitized) displaying a felty (pilotaxitic) texture, mafic clasts may represent juvenile, injected magma (pepperite), some Sser probably represents fd pseudos, m-sPqz, m-sPSser, w-mScarb, 1-2%Dpy
- 18-14055**
1829 XC
x
coarse QP rhyolite breccia-conglomerate, unsorted, matrix supported, monomict, unit contains 5-15% rounded fragments from 5 mm to 40 cm long, most fragments (by volume) are > 5 cm long, nearly all clasts are "bleached" white to light grey (silicified), matrix is dark grey, matrix alteration: sPser, mPqz; QP rhyolite clast alteration: s-iPqz, wHqz, wPser, no sulfides
- 18-14056**
1829 XC
basalt/andesite from margin of subvolcanic wedge gabbro sill, strong carbonate and chlorite alteration
- 18-14057**
1829 XC
coherent QP rhyolite, pronounced foliation
- 18-14058**
1829 XC
x
coherent QP rhyolite, 10-15% anhedral-subhedral qz phenos up to 2 mm across, 1-3% possible anhedral to subhedral fd pheno pseudomorphs up to 2 mm long (large sericite spots), m-sPser, m-sPqz, vwHScarb, vwHqz, vwSchl-stilpnomelane-py, trace py associated with spotty chl-stilpnomelane
- 18-14059**
1829 XC
coherent QP rhyolite, 15-25% qz phenos

- 21-14140**
2129 XC
x
subvolcanic basalt/andesite from margin of wedge gabbro sill, very strongly altered, 10-20% Dleucoxene (very fn gr, white to light pink), trDpy
- 21-14141**
2129 XC
x
coherent rhyolite, light grey, strong anastomosing fracture pattern, 1-2% qz phenos, subhedral-anhedral, up to 1.5 mm across, 1-2% fd pheno pseudomorphs (carb-chl), phenos concentrated at one side of TS (flow layering?), s-iPser, sPqz, wHScarb (qz-ser rock), no sulfides
- 21-14142**
2129 XC
x
coherent rhyolite, light greenish-gray, non-foliated, tr-2% qz phenos, with intersecting rectilinear fractures filled with qz-carb veinlets (no anastomosing fractures), sPqz, sPser, wHSqz-carb (qz cores, carb margins, dark gray in HS), n-wSchl, no sulfides
- 21-14143**
2129 XC
x
clast or pseudoclast of strongly carbonate-altered felsic (qz-ser-carb) rock, boulder-size, sharp contacts, located in coherent rhyolite, sPqz, sPser, sSPcarb, no sulfides
- 21-14144**
2129 XC
x
felsic (qz-ser-chl) rock, aphanitic, sPqz, mPser, w-mPSchl
- 21-14145**
2129 XC
volcaniclastic pebble conglomerate, cp-rich, polymict, dominantly rhyolite clasts but includes 1-3% altered (tan) mafic clasts, one end of slab consists of coherent rhyolite (block?) with a minimum width of 8 cm, gangue associated with cp includes carb, qz, chl, tour, and albite, 15-25% LBcp, most occurs along multidirectional veinlets (stockwork), tr-2%Bpo
- 21-14146**
2129 XC
x
felsic, aphanitic rock, exhibits pseudofragmental texture (oval to irregular domains (up to 8x4 mm in TS) of light grey-white, aphanitic, recrystallized qz occur separated from one another by v irregular, dark greenish-gray chloritic fractures), apx. 5% hydrothermal, very irregular albite porphyroblasts containing qz and chl inclusions, sPqz, sRchl, vwScarb, tr-5%Dsph (very fn gr)
- 21-14147**
2129 XC
volcaniclastic pebble conglomerate, matrix supported, 5-10% pebbles in a dark grey matrix, clast population dominated by rhyolite with subordinate tan (altered) mafic clasts, chl-carb-albite-ser alteration, albite associated with cp, 4-6% DLcp, nil-2%Dsph
- 21-14148**
2129 XC
x
coherent rhyolite, light-medium grey, strongly spherulitic (recrystallized), no qz phenos in TS, spherule density varies across TS from tightly packed (coalesced) to zones where spherules are isolated from one another, sample is from unmineralized "island" in semi-masive to massive, cp-rich sulfides, sPVqz, w-mSchl, wLSfc, trDpy
- 21-14149**
2129 XC
x
coherent rhyolite, massive, dark grey, aphanitic, trace qz phenos, contains 5 cm wide zone of well developed spherulites up to 0.3 mm in diameter, strong anastomose fracture pattern, coarse spherulite (0.1-0.3 mm) zone has narrow gradational to sharp contact w zone of <0.1 mm qz grains which are probably small, recrystallized spherulites, s-iPqz (spherules), mPSchl, w-mLqz-tour-carb-cp-sph,

2-4%Lcp, 1-2%Lsph (in qz-tour-cp-sph veinlets)

21-14150

2129 XC

x

volcaniclastic pebble conglomerate, unsorted, 20-30% angular to round clasts in dark grey, aphanitic matrix, clasts are dominantly light grey to white rhyolite, some with qz phenos, with 1-3% altered (tan), mafic clasts (chl-ser-qz-opaque phase), largest clasts is 1.8x1.3 mm, slab B contains a 5 cm wide, siliceous, mottled white to lt brn clast or dike, rhy clasts: s-iPqz, n-wSchl, matrix: sPqz, mPchl, wHqz, tr-2%DBpy

21-14151

2129 XC

x

volcaniclastic pebble conglomerate, matrix supported, 20-40% round to angular clasts up to 4x2x1.5 cm in dark grey matrix, white to dark grey rhyolite clasts are dominant, 1-3% altered (tan) mafic clasts up to 7x5 mm, 1-3% small, black, soft, argillite clasts up to 6x3 mm, sPqz, mPchl-ser, no sulfides

21-14152

2129 XC

aphanitic felsic rock, massive, medium grey, cut by brown veins of qz-ser up to 2.5 cm wide with aphanitic qz margins up to 5 mm wide, locally these qz margins are continuous with qz-(tour?) veins up to 2 cm wide, mVser, w-mVLqz-tour-(native Ag?-cp), wScarb, tr-0.5%VLnative Ag and trVLcp in qz-(tour?) veins and veinlets

21-14153

2129 XC

x

coherent rhyolite, md grey, massive, spherulitic (recrystallized), random distribution of large spherules up to 0.5 mm in dia, sericitized and chloritized fractures pass between spherulites creating an anastomosing fracture pattern, fc spots are up to 5 mm across, spherical, no evidence of elongation (strain), sPHqz, sRPser-chl, wSfc, no sulfides

21-14154

2129 XC

volcaniclastic pebble conglomerate, unsorted, matrix supported, polymict: angular to round rhy clasts (dominant), 20% soft, black arg clasts (convoluted contact relationships), 1-5% altered (tan) mafic clasts (chl-qz-opaque phase), some wispy, up to 18x2 mm, some qz crystal clasts, and a few clasts which appear to be liberated spherulites, matrix: sPqz, sPchl, wSfc; rhy clasts: iPqz, wPchl, no sulfides

21-14155

2129 XC

x

rhyolite breccia-conglomerate, resedimented, essentially monomict (angular to round rhy clast dominate, some qz crystal clasts), unsorted, matrix supported, md-dark grey, most clasts are indistinct in HS, matrix: sPchl-(ser), w-mScarb; rhy clasts: s-iPqz, no sulfides

21-14156

2129 XC

strongly altered volcaniclastic pebble conglomerate (?), dark grey, 2-3% anhedral, subangular qz xtalls, some chl spots may represent argillite clasts, sPHqz, sPRSchl, no sulfides

21-14157

2129 XC

volcaniclastic pebble conglomerate, cp-rich, matrix supported to clast supported, unsorted, dominated by lt grey rhyolite clasts, in TS one large rhyolite clast (22x12 mm) contains recrystallized spherulites, gangue associated with cp includes chl and minor albite and carb (albite appears fresh), matrix: sPchl, 10-20%BLcp, locally semi-massive

- 21-14158**
2129 XC
volcaniclastic pebble conglomerate, cp-rich, clasts dominated by light grey rhyolite, sPSLchl, 10-20%BDLcp, trace sph associated with cp
- 21-14159**
2129 XC
volcaniclastic pebble conglomerate, 5-20% clasts, rhyolite clast dominated, largest clast is 4x1.5 cm, minor proportion of altered (tan) mafic clasts (chl-qz-ser-opaque phase), generally lt grey rock with abundant black chloritic spots up to 1 mm across, matrix: sPFser, m-sPqz, w-mSchl, vwScarb., 1-2%BDpo
- 21-14235**
2129 XC
x
coherent rhyolite, strongly sericitized, similar to 21-14236
- 21-14236**
2129 XC
x
coherent rhyolite containing 1-5% volcaniclastic pebble conglomerate lenses, lt green (sericitized), aphanitic rhyolite containing 5-25% randomly distributed, carb-rich dk grey alteration blebs up to 2x1 cm (pseudoclasts), 1-3% qz phenos up to 2 mm across, tr-1% white fd phenos to 1 mm long, conglomerate occurs in lenses up to 5 cm across and contains rhy and altered (tan) mafic clasts, s-iPser, mBcarb, w-mSHfc-qz (<1 to 1mm disseminated spots, some form coalesced "beads" along fractures), tr-2%Dpy
- 23-14237**
2323 PIL. ACC.
x
in situ rhyolite breccia, 1-2% qz phenos to 2 mm, contains separate sph-rich and py-rich veinlets, gangue in sph veinlets is qz, ser, and tourmaline, gangue in py veinlets is qz, ser, tourmaline, and chlorite, sPqz, m-sPser, wHqz, vwLtour (in sph and py veinlets), 3-7%LDsph, 2-5%LBDpy, sph and py tend to occur separately
- 23-14238**
2323 PIL. ACC.
x
volcaniclastic pebble conglomerate, polymict, unsorted, local microscopic kink banding (F2) of main foliation (F1), sPqz, sFPser, 1-5%BDpy, some blebs may represent clasts
- 23-14239**
2323 PIL. ACC.
x
volcaniclastic pebble conglomerate, polymict, unsorted, contains sx-rich clasts, s-iPser, m-sPqz, 3-7% clastic+diss py, trace clastic sph
- 23-14240**
2323 PIL. ACC.
x
in situ rhyolite breccia, tr-1% qz phenos to 2 mm across, extensive curvilinear (anastomosing) sericitic fractures on 1- 5 mm scale, contains 1-5% very irregular, unaltered plagioclase porphyroblasts, some occur in irregular plag-rich and sph-rich veinlets (TS-B), possible perlitic fractures in TS-B, fragment alteration: s-iPqz, mPHser; interfragmental alteration: s-iPser, mPqz: both: vw-wSalb, 3-7%LDsph, 2-5%LDpy, both sph and py-sph veinlets occur
- 23-14241**
2323 PIL. ACC.
x
coherent rhyolite, 1-2% anhedral qz phenos up to 1 mm across, recrystallized microscopic spherulitic texture accompanied by anastomosing microscopic fracture pattern, sPqz, m-sPser, mPcarb, no sulfides
- 23-14242**
2323 PIL. ACC.
x
coherent rhyolite, probably fragment within in situ rhyolite breccia, 1-2% anhedral qz phenos up to 2 mm across, microscopic recrystallized spherulitic texture and anastomosing fracture pattern, s-iPqz, m-sPFser, no sulfides

- 23-14243**
2323 PIL. ACC.
x
coherent rhyolite, tr-1% qz phenos up to 1 mm across, sphurilitic (recrystallized), spherule density varies sharply across TS, s-iPqz, m-sPser, wScarb, no sulfides
- 23-14244**
2323 PIL. ACC.
x
coherent rhyolite, 1-2% anhedral qz phenos up to 1 mm across, spherulitic (recrystallized), strong intersecting curvilinear (anastomosing) fracture pattern observed in TS, sPqz, sFPser, wScarb, no sulfides
- 23-14245**
2323 PIL. ACC.
x
in situ rhyolite breccia, 1-2% anhedral qz phenos up to 1 mm across, s-iPqz, sPFser, py blebs contain chloritic fractures, 1-5%Bpy
- 23-14246**
2323 PIL. ACC.
x
in situ rhyolite breccia, cp-rich, in situ bx texture in TS is best observed with hand lens, gangue associated with cp-po mineralization includes qz, plag and tour but not chl, wallrock adjacent to cp-po veinlets is sericitic, s-iPqz, sPser, 10-20%LBcp-po (cp is dominant)
- 23-14247**
2323 PIL. ACC.
x
in situ rhyolite breccia, cp-rich, gangue associated with cp mineralization includes plag, qz, carb, and minor tourmaline (very plag-rich), locally massive cp contains fd "microlites", s-iPqz, sPRser, vwHScarb, 40-60%LBcp, 3-5%Bpy, no po
- 23-HG-2323-1**
2323 PIL. ACC.
x
coherent rhyolite, dark grey-brown to black
- 23-HG-2323-2**
2323 PIL. ACC.
x
coherent rhyolite, dark grey-brown to black
- 23-HG-2323-3**
2323 PIL. ACC.
x
coherent rhyolite, light grey
- 23-HG-2323-4**
2323 PIL. ACC.
x
coherent rhyolite, from area of flow banding
- 24-14228**
2421 K
x
volcaniclastic sandy mudstone - volcaniclastic sandstone - argillite, black, non-graphitic, mm to cm scale bedding, sand-size clasts (up to 1 mm dia) are rhy fragments and qz xtalls, contains bedding parallel (primary?) py laminae and indistinct brownish laminae which probably contain diss sph, the unit contains many small scale folds (1-10 cm scale), wk-mod foliation, w-sPser, 3-7%py laminae up to 2 mm thick, possibly 2-5%Dsph contained in brownish laminae up to 5 mm across (separate from py)
- 24-14229**
2421 K
volcaniclastic pebble conglomerate, polymict (rhyolite and altered, tan basalt), rhy clasts up to 1.5 x 1.0 cm, black aphanitic matrix, m-sFPser, 3-7%DBpy

24-14230

2421 K

x

rhyolite hyaloclastite - volcanoclastic pebble conglomerate, monomict to very weakly polymict, rhyolite fragment dominated, probable transported rhyolite hyaloclastite (clasts have abundant, internal, irregular, multidirectional fractures), wk-mod foliation, sPser (primarily in matrix), trace-2%Dpy

24-14231

2421 K

volcanoclastic boulder conglomerate, polymict (py-sph, rhy, and altered tan mafic clasts), black aphanitic matrix with 1-2% qz eyes up to 2 mm across, some rhy clasts are strongly stained with sph, wk-mod foliation, sFPser, wBcarbonate (associated with sph clasts or 2nd sph), weak cr gr qz in py pressure shadows, 10-20%py (clasts+diss), 5-10%sph (primarily as clasts)

24-14232

2421 K

boulder conglomerate, polymict (rhyolite and altered tan mafic clasts), wk-mod foliation, sPFser, vwLcarb, 5-15%py and 3-7%sph: clasts, blebs and diss, trace-2%Bpo in mafic clasts

24-14233

2421 K

volcanoclastic boulder conglomerate, polymict (py, sph, rhy, arg, altered tan mafic clasts), black aphanitic matrix with 1-2% qz eyes up to 2 mm across, mFser, wScarb, 5-15%py, 3-7%sph: clasts, blebs and diss, trace blebby cp

24-14234

2421 K

massive sulfide, massive sph-py ore (not a clast) containing 10-20% qz-rich gangue, sph is medium reddish brown and banded, py is blebby, 30-50%sph, 30-50%py, trace galena

24-RC-2420-4

2421K

x

graphitic argillite, black, aphanitic, moderately foliated (sample collected by R. Cook at the intersection of 2420 XC and the NE wall of 2421"K" DD., w-mFgraphite, vw-wHqz-ser, poss vwDtourmaline, 5-15%LBpy, 1-5%sph associated with py veinlets

Appendix 10

DESCRIPTIONS OF FELSIC VOLCANIC AND VOLCANICLASTIC UNITS BETWEEN THE 1600 AND 2400 LEVELS OF THE KIDD CREEK MINE

Coherent FW Rhyolite (RHco): Light to dark grey to light green (sericitic), aphanitic rock containing 0.5 to 2% anhedral to subhedral quartz phenocrysts up to 2 - 3 mm in diameter (subhedral to euhedral, generally intact, some rimmed by secondary quartz, some embayed due to resorption), and nil to 2% carbonate-, sericite-, chlorite-, and quartz-altered subhedral plagioclase phenocrysts and pseudomorphs up to 2 mm long (Figure A7-20). Coherent rhyolite locally contains well developed, moderately to densely packed spherulites up to 0.3 mm in diameter (Figures A7.21 to A7.23). Some samples display a microscopic anastomosing pattern of curvilinear sericitic fractures which curve through the rock in such a manner as to avoid passing through the spherulites. Strongly recrystallized samples which display an anastomosing fracture pattern are interpreted to have been spherulitic. In addition to the anastomosing fracture pattern described above, microscopic perlitic fracturing was noted in a sample of a coherent rhyolite block within the east outcrop rhyolite breccia (Figure A7.20B). The unit locally displays well developed, mm-scale, planar to locally contorted flow-banding which is visible in underground exposures and in blocks in the east outcrop (Figure A7.2). At a microscopic scale some flow-banding appears to reflect linear zones of recrystallized spherulites (Figure A7.24). The best exposures of flow-banding occur in

coherent rhyolite of the Lower member. However, near the west end of 2129 Crosscut, in the hanging wall of the South orebody (Middle member), variable intensity of sericitization within rhyolite imparts a banded appearance on a 1 to 20 mm scale to the rock which may reflect original flow-banding (Figure A7.8A). Exposures of coherent FW rhyolite are non-foliated to weakly foliated (microscopic examination shows that the main foliation is locally crenulated).

Alteration includes pervasive and hairline veinlet-controlled silicification, pervasive, foliation-controlled and hairline veinlet-controlled sericitization, pervasive, spotty and fracture-controlled chloritization, and vein-controlled and spotty Fe-carbonate +/- quartz alteration (some exposures contain dark grey blebs of Fe-carbonate up 2 cm x 1 cm across). Near the west end of 2129 Crosscut subspherical, medium grey, carbonate-altered fragments or pseudofragments up to 30 cm across occur.

Rocks contains from nil to 10% pyrite which occurs primarily in multidirectional veinlets but some disseminated and blebby pyrite is also present (Figure A7.2). In the immediate footwall of the South orebody in 2129 Crosscut silicified, spherulitic rhyolite contains 10 to 30% chalcopyrite and honey-coloured sphalerite in a well developed stockwork.

Autoclastic Rhyolite Breccia (RHbx): This unit is monomict, unsorted, commonly sphalerite stained (2323 Crosscut and 1602 Drive North), and light to medium grey to orange-brown (sphalerite stained areas). The rock is composed primarily of light grey, siliceous, recrystallized rhyolite fragments,

generally from 1 to 10 cm across, which contain trace-2% randomly distributed, subhedral to anhedral quartz phenocrysts up to 2 mm across. Fragments commonly contain internal polygonal fracturing.

Exposures of *In situ* facies autoclastic breccia commonly display jigsaw-fit texture (Figures A7.9A) and grade, with decreasing fracture intensity, into polygonally fractured coherent rhyolite. Interfragmental fractures are dark grey due to phyllosilicate alteration (Figures A7.3 and A7.4). With increasing fracture-controlled sericitization and/or chloritization alteration selvages on fractures widen, jigsaw-fit texture is lost, and “domains” of siliceous rhyolite between fractures take on a rounded appearance (Figure A7.6B; some of these exposures have been mapped by company geologists as rhyolite lapilli tuff).

Transported autoclastic breccia is monomict, clast supported, and characterized by subangular to subround, light grey, siliceous fragments, a dark grey, sericitic-chloritic, hyaloclastite matrix, and a high fragment to matrix ratio. The name breccia-conglomerate is appropriate for many of these rocks to reflect fragment rounded nature of the fragments. Flow-banded rhyolite fragments occur in some exposures (Figure 7.9A).

Alteration includes (i) pervasive and hairline veinlet-controlled silicification of the rhyolite fragments, (ii) fracture-controlled, foliation-controlled, and pervasive (matrix) sericitization and chloritization, and (iii) very weak to moderate veinlet-controlled and spotty Fe-carbonate alteration. A general progression of mineralization in autoclastic rhyolite breccia outward from the

chalcopyrite stringer zone is (i) chalcopyrite-pyrrhotite stringers (Figures A7.5, A7.8), (ii) disseminated, spotty, and hairline veinlet-controlled sphalerite (sphalerite “stained” zones are created by disseminated 0.01-0.05 mm sphalerite grains), and (iii) disseminated, veinlet-controlled and blebby pyrite (Figure 7.9A).

Rhyolite Hyaloclastite (RHhy): Medium to dark grey, fragment-supported, unsorted, monomict to weakly polymict, mainly aphanitic rock dominated by subround-subangular, sub-mm to mm rhyolite fragments (Figure A7.25B). The rock locally contains up to 5% white to light grey to dark grey, round rhyolite fragments up to 1.5 cm across (dark rhyolitic clasts are difficult to distinguish in walls), and locally contains a minor proportion (up to 3%) of altered (tan) mafic clasts up to 15x5 cm. In hand sample the matrix appears granular on 0.1 to 1 mm scale, contains nil-2% quartz crystals, and displays nil - moderate foliation (foliation imparts a tuffaceous appearance). In thin section fragments locally display jigsaw-fit texture and some clasts display an anastomosing fracture pattern believed to reflect the presence of (recrystallized) spherulitic texture (see coherent FW rhyolite description).

Alteration styles include pervasive to foliation-controlled sericitization, pervasive to spotty and veinlet-controlled chloritization, and spotty and hairline veinlet Fe-carbonate alteration. Typical mineralization consists of nil-3% disseminated to blebby pyrite, nil-5% disseminated to blebby sphalerite (commonly mantled by chlorite), nil to 2% blebby chalcopyrite, and nil to trace disseminated galena.

Polymict Volcaniclastic Boulder Conglomerate (VCbdcg): Clast-supported to matrix-supported, polymict, fragmental rock containing up to 60% subround to subangular, unsorted clasts: light to dark grey rhyolite clasts, volcaniclastic sandstone-mudstone clasts, tan (altered) mafic clasts, pyrite, pyrite-sphalerite, sphalerite, sphalerite-galena (rare), galena (very rare), and chalcopyrite (very rare) clasts (Figures A7.7, A7.12, and A7.13). Silicate and sulfide clasts greater than 1 m long are not uncommon (the largest mapped clast is a 2.3 m long volcaniclastic sandy-mudstone clast in 1602 Drive South). Matrix is dark grey (chloritic), very fine-grained, gritty, and contains trace to 2% quartz eyes up to 3 mm across. The rock is non-foliated to weakly foliated. Alteration minerals includes pervasive (matrix) chlorite +/- sericite, and hairline veinlet and spotty Fe-carbonate. Mineralization consists of 10-35% pyrite and sphalerite both as clasts and as secondary mineralization (disseminated and in blebs and lenses), and nil to trace veinlet chalcopyrite. Sphalerite clasts are chlorite-rich.

Polymict Volcaniclastic Pebble Conglomerate (VCpbcg): This is a light to dark grey, unsorted to poorly sorted, matrix-supported to clast-supported, polymict, fragmental rock containing 10-60% round to angular clasts: rhyolite clasts, sulfide clasts, tan (carbonate-, sericite-, and chlorite-altered) mafic clasts, volcaniclastic rock clasts, argillite clasts and quartz crystal clasts (Figures A7.6, A7.10, and A7.25). The matrix is very fine-grained (gritty), and light to dark grey. This unit generally displays weak, steeply dipping foliation. Clasts are commonly 2 mm to 2 cm across and the largest clasts are <15 cm across. Graded bedding occurs locally. Some tan mafic clasts have wispy outlines and

may represent juvenile material (e.g. peperite; Figure A7.14). In both the pebble and boulder conglomerates rhyolite clasts (light to dark grey) tend to be well rounded and sub-spherical to weakly elongated whereas sulfide and argillite clasts tend to be strongly elongated parallel to foliation (up to 8:1). Foliation is steep so elongation is much more pronounced in the walls than in the backs of underground workings (Figure. A7.12). The unit varies from having an extensive mixture of clast types to being strongly dominated by rhyolitic clasts. Sample 14094 from 1602 Drive South contains wispy, strongly sericitized fragments, which locally contain spherulites, that may represent altered juvenile clasts.

Alteration includes foliation-controlled, pervasive(matrix), and spotty sericitization and chloritization, pervasive and hairline veinlet-controlled silicification, spotty and hairline fracture-controlled Fe-carbonate, and disseminated tourmaline (associated with sulfide mineralization). The chlorite/sericite ratio increases with proximity to sulfides

Mineralization away from the massive sulfide zone generally consists of nil to 5% pyrite, disseminated and in blebs up to 4 cm across. Near the massive sulfides the VCpbcg unit contains 5 to 40% replacement sulfide mineralization, including sphalerite, pyrite, galena, chalcopryite, and pyrrhotite (Figure A7.11). The sulfides occur primarily as matrix replacement but also occur as stringers and irregular blebs. This material grades into massive sulfide ore. Gangue associated with chalcopryite-rich zones includes carbonate, quartz, chlorite, tourmaline, and albite. Locally this unit contains up to 30% sulfide clasts (pyrite and sphalerite $\pm$ galena).

Volcaniclastic Sandstone (VCsa): Felsic, medium grey, polymict, matrix-supported, weakly graded rock. Major clast types (>90%) are subround to subangular recrystallized rhyolite and quartz crystals. Sample 14088 from the margin of the central orebody in 1602 Drive South has undergone strong pervasive chloritization and contains 3-5% blebby and disseminated sphalerite, 1-3% disseminated pyrite (some pyrite cubes up to 7 mm across) and trace-2% blebby chalcopyrite.

Volcaniclastic Sandy Mudstone (VCsamu): This unit is generally light to medium grey but grades to dark grey, has a homogeneous, slightly gritty, siliceous, aphanitic appearance in hand sample, is non-foliated to moderately foliated and is locally weakly bedded (Figure A7.14). Most of the material is commonly less than 1/16 mm across (mudstone) but some samples contain an appreciable quantify of very fine-grained sand. The sand size material consists primarily of rhyolite clasts (up to 0.6 mm across) and quartz crystals (up to 3 mm across, intact and broken). In addition, chloritized mafic clasts up to 1 mm across and chlorite-sphalerite clasts up to 0.9 mm across occur locally. The unit contains pervasive sericite and chlorite-sericite alteration, spotty Fe-carbonate alteration, and hairline veinlets of quartz. Mineralization consists of nil to 3% pyrite - disseminated, blebby, and veinlets.

Volcaniclastic Muddy Sandstone (VCmusa): Medium grey, very fine-grained rock (most grains between <0.01 and 0.5 mm across) delicately bedded at a mm scale due to grain size variation (Figure A7-19B; many laminae grade from sandstone to mudstone). Most clasts are round to subround but a few are subangular, and most sand-size material consists almost entirely of rhyolite clasts and quartz crystal clasts. The alteration assemblage is dominated by pervasive sericite-chlorite alteration. Mineralization consists of 5-15% blebby and disseminated pyrite which occurs preferentially within the sandy parts of laminae.

Coherent QP Rhyolite (QPco): Light-medium grey, to medium brown, to light green (sericitized) rock containing 10-20% anhedral to subhedral quartz phenocrysts up to 3 mm in diameter. In addition, up to 5% sericite-altered, anhedral to subhedral plagioclase phenocrysts up to 2 mm long occur in some rocks, in some instances in glomeroporphyritic aggregates (Figure A7.15). With increasing alteration a progression exists from (i) sericitized plagioclase phenocrysts, to (ii) sericite-rich feldspar pseudomorphs, to (iii) sericite-rich patches, to (iv) rocks in which there is no petrographic evidence of feldspar phenocrysts. Phenocrysts and phenocryst pseudomorphs are randomly distributed. Exposures are massive to locally flow-banded (near stratigraphic base of unit; Map 4), non-foliated to weakly foliated, and commonly weakly jointed. Fragments of QP rhyolite occur infrequently within the flow-banded zone. Coherent QP rhyolite is locally spherulitic with the density of recrystallized spherulites varying from low to high (Figures A7.16 and A7-17). Spherulites are up to 0.3 mm in diameter. Spherulitic samples exhibit a microscopic

anastomosing sericitic fracture pattern (fractures pass around spherulites) which imparts a pseudoclastic texture (reminiscent of very fine-grained sandstone). In some strongly recrystallized samples the presence of a similar anastomosing fracture pattern suggests that recrystallized quartz aggregates (spherules) in these rocks also represent recrystallized spherulites. Alteration includes pervasive and hairline veinlet-controlled silicification, pervasive, fracture-controlled and foliation-controlled sericitization, spotty and pervasive chloritization (significant chloritization occurs in a minority of samples), spotty and hairline veinlet-controlled Fe-carbonate alteration, spotty stilpnomelane alteration, and sericite - carbonate alteration of plagioclase phenocrysts. The unit generally contains from 0 to 2% disseminated pyrite.

QP Rhyolite Coarse Autoclastic Breccia (QPcrbx): This unit was mapped on 1829 Crosscut where it occurs beneath the QP rhyolite autoclastic breccia and flow-banded QP rhyolite at the stratigraphic base of the QP rhyolite stratigraphy (Map 4). The unit, shown in Figure A7-1, contains 5-15% angular to subround fragments from 0.5-40 cm across of which most fragments (by volume) are greater than 5 cm across (exposures with abundant subround fragments may be identified as coarse breccia-conglomerate). In the walls the fragments are commonly elongate 1:1 to 2:1 with the axes of elongation having steep easterly plunges subparallel to foliation. All of the fragments appear to be QP rhyolite (monomict) and the vast majority are white to light grey (silicified). The matrix is dark grey and non-foliated to weakly foliated. Matrix alteration includes strong pervasive and fracture-controlled sericitization and moderate pervasive silicification. The QP rhyolite clasts exhibit strong to intense pervasive

silicification, weak pervasive sericitization, and weak hairline veinlet-controlled quartz alteration. No sulfides were observed in the 1829 Crosscut exposure.

QP Rhyolite Autoclastic Breccia (QPbx): In 1829 Crosscut this unit, up to 2 m wide, is located stratigraphically above QP rhyolite autoclastic coarse breccia (QPcrbx; gradational contact) and below flow-banded QP rhyolite (QPco; sharp contact). The unit contains 30-60% fragments, is clast-supported to matrix-supported, and is weakly polymict. Fragment population is dominated by subround QP rhyolite fragments from 0.5-10 cm across with the majority being majority less than 4 cm across (these rocks may be referred to as breccia-conglomerates). Most QP rhyolite fragments are light greenish-grey (sericitized) while 5-10% of the fragments are medium grey QP rhyolite. In the walls the QP rhyolite fragments commonly exhibit down-plunge elongations of 2:1 to 3:1 with steep axes of elongation subparallel to foliation. Locally up to 3% of the fragments are angular to subangular, altered, tan mafic clasts, some of which are dominated by sericitic feldspar pseudomorphs displaying a felty (pilotaxitic) texture. The mafic clasts, which are much more angular than the rhyolite clasts, may represent juvenile, injected magma (peperite) or vent-proximal pyroclasts. The matrix is dark grey and non-foliated to weakly foliated. Alteration includes moderate-strong pervasive silicification, moderate-strong pervasive and spotty sericitization, and weak-moderate spotty carbonate alteration. The exposure in 1829 Crosscut contains 1-2% disseminated and blebby pyrite.

MAP 1. LOCATION OF MAPS 2 TO 7 PROJECTED ONTO THE 1600 LEVEL, KIDD CREEK MINE (AFTER FALCONBRIDGE LEVEL PLANS)

LEGEND FOR MAPS 1 TO 7

1972
520
1961
966
C.H.D.
P.H.S.

Map 2. GEOLOGY OF 1602 DRIVE NORTH, KIDD CREEK MINE