NOTE TO USERS

This reproduction is the best copy available.

UMI
A Petrological Investigation of the Copper Cliff Embayment Structure
Sudbury, Ontario

by

P. Clayton Capes

A thesis submitted in conformity with the requirements for the degree MSc.
Graduate Department of Geology
University of Toronto

Copyright by P. Clayton Capes 2001
The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author’s permission.

L’auteur a accordé une licence non-exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L’auteur conserve la propriété du droit d’auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-63057-9
The Copper Cliff embayment structure is located in the South Range of the Sudbury Igneous Complex (SIC). The embayment is composed predominantly of coarse-grained gabbronorite mesocumulates which grade outward into a fine-grained quartz monzogabbronorite orthocumulate characterized by large blue quartz crystals. The outermost region of the embayment is occupied by a thin discontinuous rind of diabasic textured quartz monzodiorite, which has traditionally been called quartz diorite.

The contact relationships within the embayment coupled with the geochemical data suggest that the quartz monzodiorite is a quenched liquid and the quartz monzogabbronorite and gabbronorite are cumulates derived from the residual. In addition, it appears that there are two distinct groups of rocks within the embayment; a high Al₂O₃ group and a low Al₂O₃ group, with the division occurring at approximately 15 wt%. The low Al values are found in rocks that tend to have higher than average inclusion numbers, and sulphide content.
Acknowledgements

I would like to thank Jim Mungall and Jacob Hanley at the University of Toronto for all their assistance with this project. I would also like to thank Gord Morrison and Chris Davies at INCO Exploration Sudbury for their advice and INCO Ltd. for both their financial and technical support. I would also like to acknowledge the work of Peter Lightfoot et al. 1997a, 199b, from which a large amount of data for various offsets and rocks from the SIC was obtained. Finally I would like to thank Sara Benjamin for her patience and attention during numerous discussions pertaining to the nature of the SIC.
# Table of Contents

List of Tables v
List of Plates vi
List of Figures vii
List of Appendices ix

1.1 Introduction 1
  1.2 Purpose 2

2 Previous Work 3

3 Regional Geology of Sudbury Area 4
  3.1 Main Mass 5
  3.2 Sublayer 7

4 Geology of Offset Dikes and Embayments 8
  4.1 Geology of the Offset Dikes 12
  4.2 Geology of the Copper Cliff Offset 14
  4.3 Geology of the Copper Cliff Embayment 16

5 Methods 22
  5.1 Sampling Program 24
  5.2 Sample Preparation 24
  5.3 Contamination 25
  5.4 Sample Analysis 25
  5.5 Data Validation 25

6 Microprobe Analysis 26
  6.1 Orthopyroxene 27
  6.2 Blue Quartz 27

7 Geochemistry 27
  7.1 Major Oxide Geochemistry of the Copper Cliff Embayment Rocks and SIC 28
  7.2 Trace Element Geochemistry for Copper Cliff Embayment Rocks 42
  7.3 REE Geochemistry for Copper Cliff Embayment Rocks 44
  7.4 Major Oxide Geochemistry for Sudbury Offset Environments 45

8 Discussion 47
  8.1 Relationship between QMD, QMGN, GN of Copper Cliff Embayment 47
  8.2 Relationship between Offset Dikes and Embayments 50
  8.3 Relationship between Copper Cliff and the Main Mass 51
  8.4 Copper Cliff Embayment and Dike Formation Model 53

9 Summary of Findings 58

10 Future Work 59

11 References 61

12 Table Captions 66
  Tables 67-73

13 Plate Captions 74
  Plates 76-85

14 Figure Captions 86
  Figures 89-141

15 Appendix Data Set 142
List of Tables

1. Reproducibility (error) on XRF on 10 consecutive samples
2. Error and precision of data analyzed on fused bead XRF at McGill University
3. INAA data precision check using UTB2 for samples run at University of Toronto
4. Standard values for QMD/QMGN/GN compared to international rock standards
5. Orthopyroxene data by Electron Microprobe at University of Toronto
6. Table of average rock values for Copper Cliff rocks and selected SIC rocks
List of Plates

1) Quartz Monzodiorite in Handsample
2) Quartz Monzodiorite in Thin Section
3) Contact of QMD with Country Rocks, Creighton Granite Pod in QMD Matrix
4) Quartz Monzogabbronorite in Hand Sample
5) QMGN in Thin Section
6) GN in Hand Sample
7) GN in Thin Section
8a) High relief inclusions with gossan
8b) High relief inclusions
9a) Low relief inclusions
9b) Low relief inclusions
10) Contact between inclusion rich and inclusion poor GN
11) Pod of Elsie Mtn. Fm in QMGN matrix -inclusions are sericitized staurolite
12a) Pod of coarse grained QMD in QMGN
12b) Pod of coarse grained QMD in QMGN
13) Band of pyroxenite pods in QMGN matrix
14a) Gossan/Inclusion rich outcrop
14b) Gossan/Inclusion rich outcrop
## List of Figures

1) Map showing the regional location of the SIC at the boundary between the Archean and Proterozoic provinces

2) Map showing SIC and the location of offsets and embayments

3) Map of Copper Cliff Dike, Project Study Area, rock standards collection sites

4) Stratigraphic Column of SIC

5) Diagram showing structure of an offset dike

6) Geology basemap of Copper Cliff embayment

7) Map showing inclusion population in Copper Cliff embayment

8) Air Photo of Copper Cliff Embayment showing Fault Structure

9) Map showing sulphide occurrence in the Copper Cliff embayment

10) Station Location Map for Copper Cliff embayment

11) Triple plot for OPX classification

12a) Al$_2$O$_3$ vs. MgO for surface and underground samples for the Copper Cliff Embayment

12b) Al$_2$O$_3$ variation with distance from East to West across the Copper Cliff Embayment

12c) False colour SURFER image showing Al$_2$O$_3$ variation for the entire Copper Cliff Embayment

15d) Al$_2$O$_3$ variation with distance for the Murray Mine Traverse

12e) Al$_2$O$_3$ vs. MgO for Copper Cliff, the Main Mass of the SIC, Inclusions and Country Rocks

13a) MgO variation with distance from East to West across the Copper Cliff Embayment

13b) False colour SURFER image showing MgO variation for the entire Copper Cliff Embayment

13c) MgO variation for the Murray Mine Traverse

14a) SiO$_2$ vs. MgO for surface and underground samples for the Copper Cliff Embayment

14b) SiO$_2$ vs. MgO for the Copper Cliff environment and major rock types of the SIC

15a) Fe$_2$O$_3$ vs. MgO for surface and drill core samples for the Copper Cliff Embayment

15b) Fe$_2$O$_3$ variation with distance from East to West across the Copper Cliff Embayment

15c) Fe$_2$O$_3$ variation for the Murray Mine Traverse

16) CaO vs. MgO for surface and drill core samples for the Copper Cliff Embayment

17a) Na$_2$O vs. MgO for surface and drill core samples for the Copper Cliff Embayment
17b) False colour image showing Na₂O variation for the entire Copper Cliff Embayment
18a) K₂O vs. MgO for surface and drill core samples for the Copper Cliff Embayment
18b) K₂O variation with distance from East to West across the Copper Cliff Embayment
18c) False colour image showing K₂O variation for the entire Copper Cliff Embayment
19a) TiO₂ vs. MgO for surface and drill core samples for the Copper Cliff Embayment
19b) TiO₂ variation with distance from East to West across the Copper Cliff Embayment
19c) False colour image showing TiO₂ variation for the entire Copper Cliff Embayment
19d) TiO₂ variation for the Murray Mine Traverse
20a) P₂O₅ vs. MgO for surface and drill core samples for the Copper Cliff Embayment
20b) P₂O₅ variation with distance from East to West across the Copper Cliff Embayment
20c) False colour image showing P₂O₅ variation for the entire Copper Cliff Embayment
20d) P₂O₅ variation for the Murray Mine Traverse
21a) S vs. MgO for underground and surface samples from the Copper Cliff Embayment
21b) S variation with distance for the entire Copper Cliff Embayment shown by false colour image
21c) S variation with distance for the Murray Mine Traverse
22) Zr vs. MgO for surface and underground samples from the Copper Cliff Embayment
23a) Y vs. MgO for surface and underground samples from the Copper Cliff Embayment
23b) Y vs. Zr for surface and drill core samples for the Copper Cliff Embayment
23c) False colour image showing Y variation for the entire Copper Cliff Embayment
23d) Lu vs. Zr for surface samples for the Copper Cliff Embayment
24a) Lu variation with distance from East to West across the Copper Cliff Embayment
24b) Lu variation for the Murray Mine Traverse
25) CI Normalized REE Spider Plot of Copper Cliff Rocks
26) Al₂O₃ vs. MgO variation for the Offset Dikes and Embayments from the entire Sudbury region
27) SiO₂ vs. MgO variation for the Offset Dikes and Embayments from the entire Sudbury region
28ab) Diagrams after Morrison (1984) of slump terraces which may help explain the formation and genesis of the Copper Cliff Embayment.
29abc) Diagrams showing a possible scenario for the formation of the Copper Cliff Embayment and Dike.
List of Appendices

1) Appendix 1  
Table of entire data set. Included are major elements, trace elements, and REE.
Introduction

The 1.85 Ga year old Sudbury Igneous Complex (SIC) is located at the main contact between the Early Proterozoic supracrustal Huronian rocks of the Southern Province and the Archean age plutonic rocks of the Superior Province (Figure 1). It is now generally believed to be the folded remnant of a 200-km wide meteorite impact crater which outcrops today as 60-km long, 27-km wide elliptical ring with its long axis striking northeast. The SIC has been of major importance for almost 150 years, since the first copper discovery in the area in 1856 by a government surveyor named Salter. Ores of the Sudbury district are estimated to contain $1648 \times 10^6$ tonnes of Ni, and comparably large amounts of copper, cobalt, gold, silver and approximately $10^8$ grams of PGE (Giblin, 1984).

The mineralization in Sudbury occurs in three general forms: contact-type deposits, footwall-type deposits, and offset type deposits. Contact-type deposits tend to occur as disseminated or massive sulphide bodies at or very near the contact of the SIC with the basement (Archean or Proterozoic) rocks. The Footwall-type deposits occur as veins, vein-stockworks, or sheet-like bodies of massive sulphide within breccia zones up to two km from the contact of the SIC with the basement rocks. The final mineralization type known as offset-type, occurs as massive to disseminated sulphide bodies within offset dikes and embayments which extend either radially or concentrically out from the SIC as far as 65 kilometers into the basement rocks.

Radial offset dikes such as the Foy, Worthington, Whistle or Copper Cliff dikes extend outward at high angles to the contact of the Sudbury Igneous Complex with the basement rocks. They begin as large funnel shaped embayments and narrow quickly to thin, often discontinuous dikes. Concentric offset dikes such as the Manchester, Frood-Stobie, or Vermilion offset dike, tend to strike parallel to the lower contact of the SIC and may be either continuous or discontinuous and do not initiate as embayments (Figure 2).

The Copper Cliff offset dike located in the South Range of the SIC begins as a 1.6 km wide funnel-shaped embayment where the SIC meets the basement Proterozoic rocks. The embayment extends south approximately one km where it narrows to less than 100 m and forms the Copper Cliff dike (Figure 3). The dike extends for another 19 km to the south at widths varying from 25-75 m and finally comes to its terminus south of Kelly Lake. Mineralization at the Copper Cliff offset dike was first discovered in 1884, and the Copper Cliff Mine was brought into production two years later.
The Copper Cliff Mine was the first underground mine at Sudbury but was short lived as interest shifted to more easily attainable deposits elsewhere in the district.

Further exploration by INCO in the 1950’s brought the Clarabelle Open Pit into production by 1960 and the Copper Cliff North and South Mines into production by 1968 and 1969 respectively. The Clarabelle Open Pit ceased production in 1977 but the North and South mines remain two of INCO’s four backbone in Sudbury as it is estimated that the Copper Cliff dike contains 15% (by weight) of the Cu-Ni mineralization in the Sudbury District. Despite the almost 120 years of mining and exploration of the Copper Cliff dike, no study of the Copper Cliff embayment has never been undertaken beyond surface mapping and thin section petrography (Slaught, 1951).

1.2 Purpose of Study

The purpose of this project is fourfold; i) To study the relationship between the different rock types within the Copper Cliff embayment, ii) to study the relationships between the rocks of the Copper Cliff embayment and the Copper Cliff dike, iii) to compare the Copper Cliff embayment with the rest of the offset and embayment environments in Sudbury, and iv) to study the relationships between the rocks of the Copper Cliff embayment and the rest of the Sudbury Igneous Complex. The investigation of these four points should provide a better understanding of the structure and composition of the embayment structures as well as better understanding of the processes involved in the formation of both the offset dikes and the embayments. The ore deposits and sulphide occurrences of the Copper Cliff environment were not the prime focus of this investigation. A full account of the ore and ore-hosting environment of the offsets can be found in papers by Cochrane (1984) and by Grant and Bite (1984).

The objectives of this study have been achieved by collecting and analyzing a large number of samples from the Copper Cliff embayment since such a task had never been done before. The development of a large database of geochemical data, especially for such a historically significant area, can only serve to help complete the puzzle of the formation and genesis of the SIC.
2 Previous Work on the Copper Cliff Dike and Embayment

Coleman (1903, 1913) was the first to study the Copper Cliff dike extensively, and was the first person to use the term “offset” to describe the nature of the intrusion. Coleman was also the first to use the term “funnel” to describe the nature of the contact relationships of the dike with the Sudbury Igneous Complex. The term funnel has since become synonymous with the term embayment, and can be applied to all of the radial offset dikes in Sudbury.

Collins (1937) was the first to describe the rocks of the Copper Cliff offset as quartz diorite, as opposed to norite as Coleman had. Collins recognized the distinct difference between the main mass norite and the material within the dike and embayments. Further work on the dike was done by Yates (1938), Slaught (1951), Souch et al. (1969). Their work focused on the genetic links between the dike and the rest of the SIC, as well as the ore bodies of the Copper Cliff dike and their relationship to the Sublayer. Pattison (1979) suggested that the ore deposits of the offset dikes were a result of the injection of sulphide-rich liquid outward into the basement rocks as a result of a meteorite impact.

More recently, Cochrane (1984) studied the ore deposits of the dike, choosing not to focus on the spatial and geochemical relationships between the dike material and the rest of the Sudbury Igneous Complex. Cochrane identified two different ore deposit types within the dike; a disseminated zone near the core of the dike (120 orebody) and a disseminated zone with additional stringer type mineralization near the eastern contact of the dyke (810 orebody). Cochrane discussed formation models for both types of ore bodies represented in the dike.

Grant and Bite (1984) discussed not only the Copper Cliff offset but also the other significant offsets in the Sudbury region. Grant and Bite, as did Cochrane, gave little attention to the Copper Cliff embayment and instead focused on the offset. Grant and Bite did however suggest a genetic connection of the dike to the SIC, and believed that the quartz diorite is slightly younger than the basal norite of the main mass as evidenced by the presence of inclusions of quartz diorite in basal norite. They also indicated that there has been a significant contribution from the country rocks to the geochemistry of the quartz diorite, and that there are zones of severely contaminated quartz diorite.
The map of the Sudbury Basin compiled by Dressler (1984) indicates that the Copper Cliff embayment is composed entirely of sublayer material, and that there is no change in rock type moving from the dike into the embayment.

The most recent investigation of the Copper Cliff dike was by Lightfoot et al. (1997a,b), who discussed the geochemistry of the main mass, sublayer, inclusions and the offset dikes of the SIC. They investigated in great detail the relationships between all of the above. Some of the more significant observations that emerged from this study are that there are two distinct phases of quartz diorite in all of the offset dikes; the dikes of the North and South range can be distinguished from each other geochemically, and finally that the quartz diorite is very similar to the felsic norite of the main mass of the SIC, suggesting a common magma source for the two rock types.

Not a single one of the studies listed above addresses the Copper Cliff embayment in any great detail, the main focus being the Copper Cliff dike.

3 Regional Geology of the Sudbury Area

The Sudbury Structure is composed of three parts; the 1.85 Ga old ring-shaped Sudbury Igneous Complex (SIC), the Whitewater group which fills the basin formed by the SIC and the breccias in the Archean and Proterozoic footwall rocks of the SIC. The SIC is located at the main contact between Early Proterozoic supracrustal rocks of the Southern Province (Huronian Supergroup) and Archean plutonic and migmatitic rocks of the Superior Province. The SIC is composed chiefly of norite, quartz gabbro, granophyre and a complex unit called the sublayer which hosts a significant proportion of the Cu-Ni deposits in Sudbury. The Whitewater group is composed of breccia, mudstone, siltstone and wacke. The Whitewater group and the breccias of the footwall rocks will not be discussed any further here.

The Sudbury Igneous Complex is generally separated into the North, South, and East Ranges. The East and North Ranges are geochemically similar but are both different from the South Range (Lightfoot et al., 1997a). Because of their similarities, the North and East Ranges will simply be referred to as the North Range for purposes of this report. The most significant differences are between the North and South Range, at least in part because the South Range has a strong metamorphic overprint while the North Range is largely unaltered. The SIC, once separated into North Range and South Range can then be further be subdivided into the main
mass and the sublayer. The main mass is made up of the lower zone, middle zone and upper zone and makes up the largest volume of rocks in the SIC. The lower zone consists of the mafic and felsic norites of the North Range, and the south range norite and quartz-rich norite of the South Range (Figure 4). Golightly (1994) estimated that the norites of the main mass make up 27% by weight of the total Sudbury Igneous Complex. The middle zone and upper zone consist of quartz gabbro and granophyre respectively, both of which are found throughout the SIC. The Sublayer is the rock unit that hosts most of the ore in the Sudbury district and is generally found below the lower Zone of the main mass, at the contact between the SIC and the footwall or basement rocks. The following rock descriptions are primarily taken from Naldrett et al. (1970) and Lightfoot et al. (1997a, 1997b).

3.1 Main Mass

Lower Zone

Quartz Rich Norite (QRNR)

The QRNR is the stratigraphically lowest member of the SIC. Like the south range norite (below) it consists of cumulus plagioclase and hypersthene with intercumulus quartz, K-feldspar, augite, magnetite and ilmenite. It is generally relatively fine-grained and does not display any igneous fabric. The QRNR contains up to 20% quartz and 25% biotite, and commonly contains pockets of quartz-K-feldspar granophyre whose abundance increases towards the lower contact. The most striking characteristic of the QRNR is the presence of large blue quartz crystals, which do not occur in the south range norite. Mafic minerals in the QRNR are almost ubiquitously uralitized.

South Range Norite (SRNR)

Stratigraphically upward from the QRNR is the SRNR. It is a medium to coarse grained, black rock consisting of cumulus plagioclase and hypersthene with intercumulus quartz, augite, magnetite and ilmenite. The SRNR often displays hypidiomorphic granular texture and a planar lamination defined by parallelism of the plagioclase grains (Naldrett and Hewins, 1984). The SRNR is black in its unaltered state but more often appears dark green due to the abundance of hornblende, which replaces both hypersthene and augite. The blue quartz that is so prevalent in the QRNR is not present in the SRNR. Moving upwards there is a gradational
contact into the quartz gabbro of the middle zone, marked by a decrease in hypersthene content, and an increase in augite, quartz, magnetite, ilmenite, and apatite.

**Mafic Norite**

The poikilitic textured mafic norite occurs as the basal unit of the SIC in the North Range. It has 40-60 modal % cumulate orthopyroxene, with 20-40% intercumulus plagioclase, 20-25% intercumulus quartz and micrographic intergrowth and 4-6 modal % intercumulus augite (Naldrett et al., 1970, Hewins, 1971). The mafic norite is sometimes referred to as melanorite (see below).

**Melanorite**

This is another rock type described by Lightfoot et al in the OGS report 5959. The melanorite is the dominant inclusion type in the sulphide rich portions of the Parkin, Foy, and Ministic offsets and is very common in the Whistle embayment. The melanorite occurs most often as either fine-grained or as coarse-grained fresh pods or bodies. The fine-grained melanorite is characterized by intercumulus plagioclase, augite and biotite and a 2mm grain size. The coarse grained melanorite is characterized by intercumulus plagioclase, biotite and a 2 cm grain size. The melanorite will be used alongside the igneous-textured sublayer matrix (below) in comparison to the Copper Cliff embayment rocks.

**Felsic Norite**

The hypidiomorphic granular-textured felsic norite occurs mainly in the North Range but may be found as discontinuous pods elsewhere in the SIC (Naldrett et al., 1970). It is a medium to coarse-grained rock that contains 40-55% plagioclase and <15% uralitized pyroxene as the cumulus phases. Augite (5-20%) and quartz showing micrographic intergrowths with K-feldspar (20-30%) are the main intercumulus phases with minor amounts of biotite, pyrite, apatite and ilmenite as accessory phases. The cumulus plagioclase is often zoned. The felsic norite lies stratigraphically above the mafic norite.
Middle Zone
Quartz Gabbro

The quartz gabbro is generally found as a layer less than 100 m thick and tends to be fairly oxide rich. The cumulus minerals are plagioclase, augite, ulvospinel, and apatite with intercumulus micrographic quartz-K-feldspar intergrowth. Uralitized pyroxene makes up 25% of the rock. Textural evidence suggests that it was all cumulus augite before alteration. This unit shows a general increase upward in quartz, augite, magnetite, ilmenite and apatite. The granophyre content increases upwards as the gradational contact with the upper zone is approached. Plagioclase is zoned and often cloudy with sericitic alteration.

Upper Zone
Granophyre

The granophyre makes up the greatest percentage of rocks in the Sudbury district; Golightly (1994) estimated that it makes up 73% by weight of the SIC. This would account for 10 053 km$^3$ of the inferred total 13 900 km$^3$ preserved volume of the SIC. Naldrett and Hewins (1984) indicate that the granophyre is generally a medium to coarse grained rock with granodioritic to quartz monzonitic composition with well developed tabular plagioclase (23%) distributed in a matrix of micrographic intergrowth (65%). Biotite and combined mafic minerals make up the remaining 12% of the rock.

3.2 Sublayer

Pattison (1974) first used the term sublayer to describe the fine to medium-grained quartz dioritic to noritic unit that hosts most of the Cu-Ni ores in Sudbury. The sublayer has a gradational contact with the overlying norite of the main mass and a generally sharp contact with the underlying footwall rocks. The sublayer is generally recognized by low modal quartz content, abundant pyroxenes and an increase in the amount of inclusions. There is no rock type in the South Range that can be described as the equivalent to the sublayer from the North Range. There is not even a concise definition of what constitutes the sublayer in the South Range. The ore-hosting phase of the South Range is dominantly quartz diorite and accordingly Cu-Ni
deposits in the South Range hosted in quartz diorite are often described as being hosted by the sublayer. Following Lightfoot et al (1997a) I will consider the sublayer to include "igneous-textured inclusion-rich sulphide-bearing sub-poikilitic to non-poikilitic textured noritic-gabbroic and melanoritic-melagabbroic rocks at the base of the SIC" and will not include the quartz diorite of the offsets and embayments.

Igneous Textured Sublayer Matrix

Lightfoot et al (1997a) describe a rock group in the Whistle embayment called the igneous-textured sublayer matrix (ITSM) which includes norites, gabbronorites, and gabbros with porphyritic to non-poikilitic texture, which also occurs in most of the other embayment environments. The ITSM has an elevated sulphide content which occurs as disseminations, blebs and pods of massive sulphide. The inclusion content is variable, ranging from 1% to 90%. The ITSM rocks are used in a later section in comparison to the rocks of the Copper Cliff dike and embayment.

Quartz Diorite

According to Grant and Bite (1984) there are three main types of quartz diorite. The first is hypersthene quartz diorite, which is a medium to coarse-grained rock. It consists of acicular hypersthene, plagioclase laths with interstitial quartz, potassium feldspar and granophyre. Biotite, apatite, titanite, ilmenite and leucoxene are accessory phases. The second type is known as two-pyroxene quartz diorite. It is very similar to the hypersthene quartz diorite except that there is a significant proportion of clinopyroxene. It is also finer grained and has an overall higher mafic content than the hypersthene quartz diorite. The final and most abundant type of quartz diorite is known as amphibole-biotite quartz diorite. It is characterized by abundant amphibole as both primary minerals and as pseudomorphs after pyroxene. The amphibole-biotite quartz diorite is the most common ore-hosting phase of the radial offset dikes.

4 Geology of the Offset Dikes and Embayments

In general, all of the offset dikes and embayments have the same structure and composition. They are primarily composed of what has been traditionally called quartz diorite. As Grant and Bite (1984)
pointed out the quartz diorite of both the North and South Ranges have approximately 20-35% normative orthoclase making them, according to Streckeisen's (1976) system of classification, quartz monzodiorites.

The quartz diorite occurs in the dikes as two separate and distinct phases; an inner discontinuous core of inclusion-rich, sulphide-rich, coarser-grained material (IQD) and an outer rim of inclusion-poor, sulphide-poor, fine-grained to quench-textured material (QD) (Figure 5). The IQD has long been an exploration target because of its elevated sulphide content, and is generally the ore-hosting phase of the offset dikes and embayments. There is a gradational transition from one phase of QD to another, but the transition from QD to basement rocks is sharp and well defined. There are often clearly definable chill margins, spherulitic texture and knife sharp boundaries indicating that hot dike material was injected into the relatively cold basement rocks and rapidly cooled after injection.

The inclusions within the IQD tend to differ from dike to dike but they are always related to the basement rocks into which the dike material was injected. In general, the inclusions are of granite, amphibolite, melanorite, diabase, metasediment and metavolcanics, with occasional exotic clasts and sometimes fragments of what appears to be an older generation of QD and basal main mass norite.

Although the offset dikes appear similar there are significant geochemical differences between individual offsets, between the offset dike material and the embayment material, and between offsets on the South Range and North Range. This will be discussed in a later section. Figure 2 is a diagram showing the locations of all of the offsets and embayments that will be discussed in the following section.

4.1.0 Foy Offset

The Foy radial offset dike is located in the North Range of the SIC in Bowell Township. It begins as a 400-m wide embayment and extends north for 28km to Tyrone Township, which was until recently believed to be the terminus. The dike continues north from Tyrone Township for approximately 65 km and has a width of 15-30 m at its terminus. The Foy offset has two branches. The first (radial) strikes NNE into Tyrone Township and the second (concentric) strikes WSW through Leinster, Harty and Hess Townships. Pattison (1979) found that the QD is fine grained at the margins of the dike and gradually coarsens towards the core, which is discontinuously inclusion and sulphide rich. There is no quartz diorite within the Foy embayment, which is
composed chiefly of norites and quartz gabbros. The first occurrence of QD is located a significant distance from the embayment within the offset.

4.1.1 Manchester Offset

The 12–30 m wide Manchester offset dike is located 5 km south of the South Range main mass in Falconbridge Township (Thompson 1957). It strikes continuously for 5 km at 050-055 and dips at 60-65. It then continues for a further two km as discontinuous pods within Sudbury Breccia. The dike has distinctive spherulitic texture along margins with an increase in grain size towards the center, although in general the dike remains fine-grained overall (Bite, 1974 and Grant and Bite, 1984). The mineralized zones tend to have greater development of granophyre and as a whole, the dike is inclusion free, in distinct contrast to all of the other offsets in Sudbury.

4.1.2 Whistle Embayment/Parkin Offset

The Parkin offset is located north of the Whistle embayment and it is generally believed that the two were once connected. The embayment is 350 wide at the contact with the SIC and narrows over 1.5 km where it is offset 2 km to the NW. The dike extends for a further 3.5 km as smaller branches, which combine over 1000 m to form a single 15-m wide branch. The single branch narrows to 1 m in width over 200 m where the QD then pinches out. It reappears to the north and extends for an additional 10 km. The dike is composed of pyroxene-rich quartz diorite and in the most southern portions occurs in sheets of variable thickness. The Whistle embayment is composed of what Lightfoot et al. (1997a) call ITSM. The core of the Whistle embayment is predominantly mafic, opx rich, gabbronorites and gabbros while the edges of the embayment tend to be less mafic, opx poor gabbronorite cumulates. The inclusion content of the ITSM in the Whistle embayment is highly variable ranging from 1% to 90%. The dominant inclusion types are melanorite, diabase, anorthosite, troctolite, gabbro, and occasionally pyroxenite.
4.1.3 Frood-Stobie Offset

The Frood-Stobie concentric offset dike is located 2 km south of the main mass in the South Range of the SIC. It extends for approximately 3000 m as discontinuous elliptical pods of quartz diorite in Sudbury Breccia.

4.1.4 Worthington Offset

The Worthington radial offset dike extends SW from the SW edge of the SIC in Denison Township to Lorne Township. The dike splits into an eastern and a western limb. The eastern limb tapers for 1500 m then broadens with depth. The western limb extends southwest for 15 km with a uniform thickness of 70 m. The contacts of the dike are knife-sharp and the QD gets finer grained towards them.

Like most of the offsets, the Worthington has both an inclusion-rich and an inclusion-poor zone. Pekeski et al (1994, 1995) noted that the inclusion-rich phase of QD within the core of the dike contains inclusions of inclusion free QD which resembles the marginal QD. They also noted inclusions, which appeared to be the basal quartz rich norite of the main mass. The core of the dike tends to be medium grained amphibole-biotite quartz diorite, whereas the margins tend to be pyroxene-amphibole quartz diorite.

4.1.5 Vermillion Offset

The Vermillion offset is located in Denison Township and is detached from the main mass of the SIC by a 2 km gap. It is a 200-m long NW trending dike of discontinuous ellipsoidal pods of amphibole-biotite quartz diorite. The QD pods are medium grained in their core and progressively finer grained towards the edges where there is often spherulitic texture. According to Grant and Bide (1984) there are occurrences of a medium-grained amphibole-biotite QD as inclusions within the finer grained amphibole biotite QD which is the common phase at the Vermillion offset.

4.1.6 Ministic Offset

The Ministic offset which is located in Cascaden Township west of the SIC has not been studied in very much detail. Farrell et al (1995) found that the dike has fine to medium grained amphibole-biotite QD in
the mineralized zones and a hypersthene-rich QD in the unmineralized zones. They also found what may have been a small embayment structure which is devoid of QD.

4.1.7 Kirkwood and McConnell Offset

The McConnell offset is approximately 1200 m long and lies SE of the Kirkwood offset, which is 1500 m in length and strikes East-West. The two offsets lie 600 m south of the main mass of the SIC in the South Range. They are both approximately 60 m wide and occur as discontinuous elliptical pods of amphibole-biotite quartz diorite in Sudbury Breccia. The pods have a medium grained core and a fine-grained edge. Grant and Biter (1984) indicate that based on field relations within the dike that the dike was emplaced as a liquid after the brecciation event.

4.1.8 Creighton Embayment

The Creighton embayment extends approximately 3km into the footwall rocks of the South Range (Pattison, 1979). He describes it as being filled with sulphide and inclusion rich quartz Irruptive norite (QRNR, basal norite). Sublayer (quartz monzodiorite) occupies the margins between the quartz rich norite and the footwall rocks. The relationship between the quartz diorite and the quartz rich norite is ambiguous but it appeared to Patterson that the quartz diorite was emplaced before the bulk of the embayment crystallized.

4.1.9 Trill Embayment

Little has been written on the Trill embayment. It occurs as a 45 plunging trough just south of the Ministic offset on the North Range of the SIC (Naldrett et al., 1999). The Trill embayment, much like many of the other embayments has sublayer norite at the base which grades upwards into mafic norite and felsic norite. Sulphide occurs primarily in the sublayer norite.

4.2 Copper Cliff Offset Dike

The Copper Cliff offset dike shown in Figure 3, begins as a 1.6-km wide funnel-shaped embayment where the Sudbury Igneous Complex contacts the Proterozoic-aged footwall rocks. The embayment extends south for approximately 1.5 km where it narrows to 100 m in width and becomes the dike
proper. The dike then continues south for an additional 17.5 km at an average width of 40 m. The Copper Cliff dike is offset several times over its 19 km length by east-west trending faults. The first break occurs at the Creighton Fault just south of the original Copper Cliff Mine, where the dike is displaced 20 m laterally. A second offset occurs south of Kelly Lake at the Murray Fault system. The dike extends for a further 10 km south at an average width of less than 10 m. The portion of the dike south of Kelly Lake is known as the distal portion of the Copper Cliff offset. The distal portion is geochemically, mineralogically and texturally much different from the proximal and embayment portions of the Copper Cliff dike. The distal quartz diorite has significant amounts of lathy blue-green amphibole pseudomorphs after pyroxene, altered smoky coloured plagioclase and abundant (~10%) granophyric intergrowth. Chlorite, epidote and carbonate are minor secondary minerals while biotite is not present (Grant and Bite, 1984).

The proximal portion of the Copper Cliff dike is structurally the same as the rest of the offset dikes in the Sudbury district. It has an outer rind of inclusion-free, sulphide-poor, fine-grained quartz diorite and an inner core of discontinuous coarse-grained, inclusion-rich, sulphide-rich quartz diorite. The proximal quartz diorite tends to be the amphibole-biotite variety, containing 35-45% plagioclase, 25-30% amphibole, 10-15% quartz, and 10-20% biotite with minor amounts of granophyre, apatite and sphene (Cochrane, 1984).

The discontinuous inclusion-rich core of the Copper Cliff dike contains two groups of inclusions. Most of the small inclusions (< two cm in size) are amphibolites, metasedimentary rocks, anorthosites and quartzites. The larger inclusions (> two cm in size) are generally gabbros, metapyroxenites, norites, quartz diorites and exotic material. The smaller inclusions are associated with zones with minor sulphides whereas the larger inclusions are associated with zones with significantly more sulphides.

The Copper Cliff dike intrudes into the Creighton and Murray Plutons as well as the Elsie Mtn Fm marginal to the SIC, and the sedimentary rocks of the Huronian Supergroup further to the south. The Creighton Pluton which lies to the west of the Copper Cliff offset is a mass of granitic rock six km wide, 21 km long and 2200 Ma year old (Dutch, 1977). The Murray Pluton is believed once to have been connected to the Creighton Pluton, but at the present erosional level of the Sudbury district there is no direct connection. The Elsie Mtn Fm which lies directly east of the Copper Cliff embayment is composed chiefly of metavolcanics and metasediments. In the area of the Copper Cliff dike, it is composed of mostly massive to pillowed metabasalt and to a lesser extent metagreywacke. The portions of the Copper Cliff dike south of the embayment go
through several different formations. In order from north to south, the dike passes through the Stobie Fm (massive to pillowed metabasalt, mafic pyroclastic rocks), the Copper Cliff Fm (rhyolite, dacite), the McKim Fm. (wacke, silty mudstone), Nipissing Intrusives (gabbro) and south of Kelly Lake the dike continues through the Ramsey Lake Fm. (conglomerate) and finally the Pecors Fm (wacke).

The contacts of the Copper Cliff offset are well defined and the host rocks are often brecciated, although the amount of breccia decreases toward the south. The highest concentration of breccia occurs where the dike is offset, and adjacent to ore bodies. The distal portions of the dike are in direct contact with the unbrecciated country rocks and display prominent chilled margins and spherulitic texture indicative of rapid cooling.

4.3 Geology of the Copper Cliff Embayment

There is a long history of mining and geology in Sudbury and because of that and the sheer number of people who have worked in the region, there is a large and confusing system of naming for the all of the rocks related to the SIC. There is commonly more than one name for a single rock type, and some names have entered common usage despite their failure to adhere to accepted nomenclature. For this reason, I have decided to forego any use of the traditional rock names for the Copper Cliff embayment rocks and instead use Streckeisen's (1976) system of classification for plutonic rocks. The three major name changes I introduce in this report are to change quartz diorite (QD) to quartz monzodiorite (QMD), quartz rich norite (basal norite or QRNR) to quartz monzogabbronorite (QMGN), and finally South Range norite (SRNR) to gabbbronorite (GN). These changes are discussed fully in a later section. The area of study for this report was restricted to the Copper Cliff embayment. The study area (Figure 3) extended south from the southern shore of Pump Lake to where the Copper Cliff embayment narrows and becomes the offset proper. The eastern and western boundaries of the study area were the east and west contacts of the Copper Cliff embayment with the footwall rocks. Since there was not a detailed geological base map of the Copper Cliff embayment, this was a priority of this study. The map produced over two field seasons is reproduced as Figure 6.
**Quartz Monzodiorite (QMD)**

The QMD, shown in purple in Figure 6, is highly variable in grain size but tends to be fine grained overall and commonly displays diabasic texture. It consists of 45 modal % plagioclase, 25% amphibole after pyroxene, 15% quartz and granophyric intergrowth, 5% K-feldspar (usually microcline or orthoclase) 15% biotite and variable amounts of titanite, chlorite and epidote depending on how altered the sample is (Plates 1, 2). The quartz is a dark smoky colour in hand sample and is often found as quartz/K-feldspar granophyric intergrowths. The amount of granophyric intergrowth is highly variable from sample to sample. It always occurs as small grains between larger quartz grains. Amphibole is generally deep green coloured hornblende or actinolite and can occur both as primary crystals and as secondary pseudomorphs after pyroxene. Unaltered pyroxene is uncommon and the few intact grains are clinoenstatite showing little compositional zonation from core to rim (See microprobe analyses, section 6.1). Biotite occurs as fine disseminations throughout the matrix commonly associated with minor sulphides. Plagioclase shows oscillatory zoning and is generally sericitized and altered with microinclusions of epidote. The QMD is dominantly inclusion free amphibole-biotite quartz monzodiorite, much like the proximal portions of the Copper Cliff dike.

The published compilation map of the Sudbury area shows the QMD as a thick (>100m) unit along the contacts of the Copper Cliff embayment, which projects 250 m up into the embayment from a point in the NW contact. My work shows (Figure 6) that not only is the spike mapped over an area in which there is no outcrop, but the QMD in general is a thin (<50m) discontinuous unit that often pinches out, and then reappears as isolated pods or outcrops. The most eastern and northern extent of the QMD occurs just east and south of the intersection between the road and railroad tracks in the northeastern corner of the map area. Here the QMD is a small isolated pod in direct contact with metabasalt of the Elsie Mtn Formation. There is well-developed thermal breccia with pods of basalt in a fine grained quartz diorite matrix. The western part of this outcrop was removed by construction so it is unknown whether there was a connection to the embayment or whether this is an isolated pod.

In the northwestern portion of the map area, the outcrop is poor and determining continuity between outcrops is difficult. In this area there are several isolated occurrences of QMD with the final series of outcrops paralleling the contact between the SIC and the basement rocks west of the western shore of Pump Lake. In this
area the QMD grades into QMGN and then GN over 10 m with no visible contacts between the QMD, QMGN and GN despite relatively fresh outcrop.

The contacts of the quartz monzodiorite with the country rocks (Creighton Granite and Elsie Mtn Fm) are generally well defined and commonly are igneous breccias. The breccia is composed of large clasts of granitic (on the western side of the embayment) or metasedimentary/metavolcanic material in a matrix of fine grained quartz monzodiorite (Plate 3). As well as being brecciated, the country rocks show extensive thermal alteration near their contacts with the QMD. Chilled margins are not visible, nor is the spherulitic texture described by Cochrane (1984) in the more distal portions of the Copper Cliff dike. The contact between the quartz monzodiorite and the quartz monzogabbbronorite is gradational over several meters.

There are several instances of QMD interfingering with the QMGN. As well, there is one fresh outcrop where there is a large (two meters in diameter) pod of coarse-grained QMD in a QMGN matrix. The edges of the pod are ragged and partially resorbed. The relationship between the QMD and the QMGN is often confusing. The quartz monzodiorite grades upsection to a mesocumulate-textured quartz monzogabbbronorite (QMGN) but tracing the contacts by simply looking at the weathered surface was found to be impossible. The thick (often 5-10 cm) weathering rind on the surface of nearly all outcrops made mapping extremely difficult. The determination of where the contacts between the embayment rocks lay required extensive sampling. It was often impossible to collect fresh samples and as such the contact of the QMD with the QMGN is not exact. Bearing this in mind, the instances of QMD interfingering with the QMGN occur in at least three separate areas of the embayment apart from the single outcrop, which completely encloses the QMD pod. It is possible that the apparent interfingering of the QMD with the QMGN is in fact a product of the poor exposure and that there are large rafts or pods of QMD completely enclosed within the QMGN. The interfingering or rafting of the QMD with the QMGN seems to imply a complicated crystallization history, which will be addressed fully in a later section.

**Quartz Monzogabbbronorite**

The QMGN shown in green in Figure 6, tends to be coarser grained than the QMD, displays obvious cumulate texture, and contains on average less quartz and granophyre than the QMD though in some cases these may reach up to 20%. The QMGN consists of about 40-55% cumulate plagioclase, 25-35% amphibole
(including amphibole after cumulate pyroxene) 5-20% intercumulus quartz, 10% biotite, 5% granophyric intergrowth, and variable but minor K-feldspar. Depending on the degree of alteration there may be varying amounts of chlorite, and epidote (Plates 4, 5).

The quartz in the QMGN tends to be either a dark smoky grey colour or a distinctive blue colour. The plagioclase is also very dark in appearance with numerous microinclusions. The rock is lent an overall dark green to black colour due to the presence of amphibole. The amphibole is either a dark green hornblende or actinolite. In most cases biotite makes up about 10% of the rock, but it is highly variable with some samples having as much as 25%. It occurs as large clots rather than the fine disseminations found in the QMD and is probably mostly secondary biotite developed from the alteration of amphibole. The pyroxene is always altered and for the most part has been replaced by amphibole (uralization). Microprobe analysis of the most unaltered pyroxenes indicates that they are clinoenstatites, much like those found in the QMD. There are many occurrences of pseudomorphic amphibole after augite. The amount of alteration in the samples makes it difficult to determine the proportion of CPX to OPX, hence the use of the name quartz monzogabbro-norite (and gabbro-norite in the following section). The most distinctive feature of this unit is the presence of blue quartz ranging from zero to 8% of the total quartz content. The blue quartz is occasionally found in very minor amounts (<1%) in the transition zone between the QMGN and the GN as well as the transition zone between the QMGN and the QMD. The blue quartz is completely absent within meters of the contact in these other units.

As was mentioned above the contact between the QMD and the QMGN is gradational over several meters, as is the contact between the QMGN and the overlying GN. As was found with the QMD, the QMGN is interfingered with the GN. There are marked increases in grain size from the QMD to the QMGN and again into the GN, which seems to indicate a large-scale temperature gradient from the cool country rocks to the relatively hot core of the embayment. The QMGN is petrologically very similar to the QRNR or basal norite of the SIC. They have the same mineral proportions, texture and the same characteristic blue quartz. Essentially the two appear to be the same rock unit, however because I have decided to forgo any use of the traditional terms for the SIC in the Copper Cliff embayment it would not be appropriate to refer to the QMGN as the QRNR.
Gabbronorite (GN)

The central mass of the embayment is composed of coarse-grained mesocumulate-textured gabbronorite, which has traditionally been referred to as the South Range norite and is shown in blue in Figure 6. It consists of 55% cumulus plagioclase, 25% amphibole after pyroxene, 15% biotite and generally much less than 5% quartz (Plates 6, 7). The differences between the QMGN and the GN are that the GN does not contain blue quartz, has much less quartz overall, does not contain granophyre, and is slightly more coarse grained. The GN is a very dark looking rock with a significantly higher proportion of mafic minerals than the quartz monzodiorite. Amphibole occurs as either dark green hornblende or actinolite and occurs as both primary intercumulus grains and as pseudomorphs after pyroxene. Plagioclase is commonly sericitized, zoned and contains numerous inclusions. Fresh plagioclase is most often a dark smoky colour in hand sample. The GN tends to be highly altered with chlorite and epidote often making up to 20% of the rock. Biotite occurs most often as fine disseminations throughout the rock and there is a strong affiliation of the biotite with sulphide. Sulphide always occurs with biotite, which commonly completely encloses the sulphide grains. Quartz is most often a dark smoky colour and near the contacts with QMGN, there is some blue quartz (less than 1%), which is absent further towards the center of the embayment structure.

The GN is the most inclusion rich unit of the embayment as will be discussed below. There are numerous outcrops that are both inclusion rich and contain a higher proportion of sulphides. These outcrops can easily be distinguished from the surrounding sulphide poor rocks by the rusty gossan appearance in the highest sulphide areas or by the crumblily iron rich nature of those outcrops somewhat poorer in sulphide. These samples were difficult to identify as GN or QMGN based on field observations. The Fe staining was pervasive and only thin section and geochemistry clearly indicated the rock type. Like the QMGN, this unit is the direct equivalent of the SRNR but that traditional name reveals little about the true nature of the rock without further reading of Sudbury literature.

Inclusions

The greatest number of inclusions occurs along a northeast/southwest trending belt, which spans the entire breadth of the embayment, and in smaller zones in the southeast and northwestern corners of the embayment. Figure 7 shows the distribution of inclusions for the Copper Cliff embayment. The inclusions take
two forms, either high weathering relief (Plates 8a, 8b) or low weathering relief (Plates 9a, 9b). The low relief inclusions tend to be almost exclusively amphibolite or pyroxenite, whereas the high weathering relief inclusions are generally more heterogeneous being metasediments, metavolcanics, anorthosites, granites and unidentified lithologies. The inclusions range in size from < 1 cm in diameter to rafts that are nearly 20 m long and tend to occur as either subrounded or as lath shapes. There are many inclusions with a gossanous weathered surface, which appear to be fine-grained mafic/ultramafics. The low relief amphibolites and most of the laminated metasedimentary inclusions are completely sulphide free. The thick weathering rind and advanced state of decomposition of all the inclusions, especially the ones with abundant sulphide grains made identification extremely difficult.

The inclusions occur in zones and a high inclusion population zone (>30% of the rock) can be in direct contact with a zone with no inclusions (Plate 10). There is no apparent difference either geochemically or mineralogically between the two zones other than the presence of inclusions. This zone is located at the western end of the NW-SE trending ridge that runs across the embayment.

Within the major northeast-southwest trending belt of inclusion rich rock, there is a large raft of metasediment possibly from the Elsie Mtn Fm. The margins of this raft are strongly sheared and it is adjacent to a fault that spans the entire width of the embayment and offsets the igneous units in the northeastern corner. The raft is exposed in three outcrops the largest being 20 m long and the smallest less than two m long (Figure 6). Another large pod of what may be McKim Fm metasediment was found in the throat of the embayment (Plate 11). The pod, which has sharp contacts with the GN matrix, is several meters in length and is characterized by sericitized staurolite much like what was observed by Dressler (1984).

The inclusion rich zone which occurs in the NW corner of the study area consists almost exclusively of bright green amphibolite pods ranging in size from 5 cm to greater than 5 meters in length hosted in a coarse-grained QMGN matrix. The pods occur in thick band, which runs from the contact of the embayment with the Creighton Pluton to the shoreline of Pump Lake where it disappears. The band ranges from 10 meters across to less than 1 meter and is variable in width along its entire 100-meter length (Plate 13). The band may continue north of Pump Lake but it is interrupted by an east-west trending late stage diabase dike on the shoreline and there is virtually no outcrop north of the lake. These pods are found in several other locations in the embayment, but they are always isolated pods or clusters of pods.
There are also several examples of coarse grained amphibole-biotite quartz monzodiorite pods completely enclosed in quartz monzogabbonorite (Plates 12a, 12b). The quartz monzodiorite pods have ragged contacts with the quartz monzogabbonorite matrix.

Discordant Structures

The fault mentioned in the previous section runs from the northeast corner of the Copper Cliff embayment through the core and ends at the western contact of the embayment rocks with the Creighton Pluton. The structure can be seen on air photos of the embayment as a large trough with a ridge running parallel to it on the north side (Figure 8). The fault may also continue further to the south-west into the Creighton Pluton. This structure was mapped as a fault on the original geology map of the Copper Cliff embayment (Author unknown, date unknown, scale 1:26 000) which was used as a base map for this project. There is no indication of this structure at depth from drill core data or from modeling of the embayment. I believe that the erroneous large spike of QMD shown on the published map (Dressler, 1984) follows this structure. The structure is best observed in the northeast corner of the embayment at the contact of the embayment with the country rocks where the structure offsets the contact by approximately 20 meters. There is no foliation or lineation of the adjacent rocks, but the offset is accompanied by a higher than average number of quartz veins and inclusions. The offset affects not only the embayment rocks but also the granite of the Creighton Pluton (a small mass occurs on the east side of the embayment). Further SW along the structure are the three large outcrops of metasediment. There is a strong foliation in the GN outcrop, which is north (CC5-1) of the rafted metasediment. (See Figure 10 for station locations). The strike and dip of the foliation in the GN is 268°/Steep to the SE. This foliation could be a drag effect of the raft being transported, but that is pure speculation at this point. There has been some significant amount of folding of the largest rafted pod (CC7-1) as evidenced by several folded quartz veins with the shortening direction perpendicular to the trend of the structure. There is no more evidence of the rafted metasediments as fragments, foliation, or otherwise either north or south of the structure beyond the SW tip of station CC7-1. To the southwest of CC7-1 a large ridge occurs on the north side of the structure. This ridge carries the most significant number of inclusions for the entire Copper Cliff embayment. Most of these inclusions are laminated metasediments, anorthosites, mafic/ultramafic fragments, and metavolcanics. The structure appears as a large trough south of the large ridge, and there are very few outcrops within the trough.
The southern side of the structure has much less relief than the northern side. The outcrops are generally flat, but still contain a high percentage of inclusions, especially gossanous inclusions and low weathering relief inclusions. The mostly unidentified, low weathering relief, inclusions do not contain sulphides. The inclusion rich zone ends abruptly at station CC150-1 and starts again at station CC150-2. The contact between the inclusion poor part (SW) of the outcrop and the inclusion rich part (NE) of the outcrop is knife sharp and trends perpendicular (126°/Steep to the SW) to the large fault structure (Plate 10). The zone of inclusion rich material is only 2.5 meters wide and has a second area of inclusion free material on the extreme NE edge of the outcrop. There is no evidence either to the north or to the south of CC150 of the contact. Further to the SW the ridge ends and the trough widens. There is no outcrop in the trough from the end of the ridge to the edge of the Copper Cliff embayment. The inclusion population drops off dramatically from the end of the ridge as well. Surprisingly, there is no offset apparent on the western side of the embayment and there is no evidence of QMD along the contacts. However, there is a prominent lineament in the Creighton Granite along strike. The QMD appears to pinch out just south of the fault structure and reappears again just to the north of the structure. If the structure were a simple sinistral strike slip fault as it appears to be on the east side of the funnel then there should be a similar offset pattern on the west side of the embayment. There is no QMD and an average thickness of QMGN to the north of the structure and a thinner than normal QMGN to the south of the structure. The QMD south of the structure forks into two thin branches, one of which narrows towards the contact and the Creighton Pluton. The second trends almost exactly north and pinches out 20 meters before the edge of the trough. The second branch ends at station CC83-1, which is fine-grained QMGN. There is no discernible contact or change in the host rocks, but the QMD simply thinned out over two meters: (Figure 6).

**Sulphide Occurrences**

Sulphide is present to some degree in all of the rock types within the embayment as either blebs or fine disseminations throughout the matrix. The amount and mode of sulphide occurrence is vastly different both from rock type to rock type and often from sample to sample of the same rock type. Figure 9 is a map of the sulphide distribution as either gossanous (sulphide rich outcrops) and/or inclusions with gossan. In all cases, there is a strong association of sulphide with biotite. Most often dark brown biotite surrounds sulphide grains. In the quartz monzodiorite, biotite occurs as large clusters with large chalcopyrite grains, whereas in the quartz
monzogabbro-norite and gabbronorite biotite is more often found as fine disseminations with the sulphide throughout the rock. The highest occurrence of sulphide is found in association with a relatively high density of inclusions. In several locations, there is a thick gossan and greater than 30% inclusions (Plates 14a, 14b). In several other locations the inclusions themselves are sulphide rich and display a gossan where they are exposed at the outcrop surface. The greatest occurrence of both sulphide and inclusions occurs to the south and east of the large fault through the embayment, while the north and west side of the fault (excepting directly adjacent to the fault) is relatively free of both.

Opaque Mineralogy

According to Cochrane (1984), the sulphide mineralogy of the Copper Cliff dike ore zones is dominantly pyrrhotite, pentlandite and chalcopyrite with the chalcopyrite being slightly more abundant than pyrrhotite. The Copper Cliff embayment sulphide mineralogy is slightly different with chalcopyrite and pyrite being the two dominant mineral species. Sulphide content of the embayment rocks rarely reaches 3% and in most cases is less than 1%. Magnetite and ilmenite are the most common accessory opaque phases. A more complete and thorough description of the sulphide mineralogy can be found in Cochrane (1984).

5 Methods

5.1 Sampling Program

Samples were collected from surface at the Copper Cliff embayment as shown in Figure 10. Surface samples were selected to be as unweathered and unaltered as possible. Great care was also taken to ensure that each sample was representative by taking multiple samples from each location. A total of 345 samples were collected from the surface at the Copper Cliff embayment. Of those samples, 308 were samples of the three major rock types and 37 were samples of inclusions. Of the surface samples taken from the Copper Cliff embayment there are 28 samples from two traverses, which ran from the contact of the Creighton Granite with the western side of the embayment. Both traverses represent the transition from the granite footwall rocks, through the quartz monzodiorite at the contact and into quartz monzogabbro-norite, towards the core of the embayment. Traverse #1 was a 30 m traverse with samples taken every meter and Traverse #2 (Figure 10, detail) was a 75 meter traverse with samples taken every 5 meters.
Additional samples of quartz diorite, quartz rich norite and south range norite were collected from the Sudbury Igneous Complex as shown in Figure 3 to be used as rock standards in the petrological and geochemical classification of the Copper Cliff embayment rocks. The quartz diorite standards were collected from the Copper Cliff dike north of the Creighton Fault, and north of Hwy 17, but south of the termination of the Copper Cliff embayment. Several other samples were taken from just south of the terminus of the embayment for comparison to the quartz diorite standards taken further south. The quartz rich norite and South Range norite standards were taken from beside the CNR tracks beside the Murray Mine Historical Site (Figure 3). A 483 meter traverse was done at this location and samples were collected every 25 m. A sample was collected at 8 meters from the first sample because it marked the transition from QMD to QRNR (QMGN). A sample was not collected at 333 meters due to a lack of outcrop; the next sample was taken at 358 meters. This traverse represents the complete transition from footwall rocks to the basal norite and through to the south range norite.

Samples of Creighton Granite, as well as samples from the Elsie Mtn Fm (metavolcanics and metasediments) were collected both proximal to the contact of the Copper Cliff embayment as well as distally as shown in Figure 3.

A total of six drill holes were sampled. Three were from a fan of exploration drill holes (holes 102-622, 102-623, 102-624) radiating out underground from the 2000 foot level, 191 footwall drift into the 191 orebody from the Copper Cliff North Mine shaft under the embayment at depth. These three holes represent the transition from the eastern limb of the Creighton Pluton at depth into QMD and into the granite of the western limb of the Creighton pluton. The depth from which these three holes were drilled from is at the point where the Copper Cliff embayment narrows and becomes the Copper Cliff dike. The drill holes pass from relatively unmineralized inclusion -free amphibole-biotite QMD to inclusion -rich, sulphide rich QMD. There are 0.3 meter long sections throughout the holes that are massive sulphide in a fine grained inclusion rich QMD matrix.

The remaining three holes (holes 97171, 97172, and 97173) were collared at surface on the shore of Pump Lake and passed through the embayment to the footwall contact. Holes 97171, and 97172 were collared on the north shore of Pump Lake, while hole 97173 was collared on the south shore. These three holes represent the transition from metasediment of the footwall rocks to a thin rind of quartz monzodiorite and quartz
monzogabbro to gabbro. Large sections starting at approximately 1400 feet from surface of all three holes were removed by INCO for analysis. The missing sections span from 1400 feet deep to approximately 3200 feet deep and are rich in sulphide and inclusions. The sulphides from these sections are hosted in primarily gabbro. The bottom of the holes end in Creighton Granite.

Samples were collected every 10 meters and additional samples were taken at contacts and any other important transitions in the holes.

5.2 Sample Preparation

A total of 271 samples, ranging from 0.5 – 2 kg, were analyzed by X-Ray Fluorescence (XRF) on fused bead and pressed powder, and by Instrumental Neutron Activation Analysis (INAA). The samples were initially cut to eliminate any remaining weathering rind and to separate inclusions from the matrix in those samples containing inclusions greater than one cm in diameter. The samples were then cut into cubes approximately two cm x two cm x four cm and crushed in a flat soft steel jaw mill. The crushed samples were then powdered in a 99.85% pure alumina puck mill for three-five minutes to less than 200 mesh in size.

The samples were then made into pressed powder pellets for XRF using approximately four grams of material, INAA pellets using 0.2 grams of material, and fused beads using four grams of material. The remaining material was then stored or used to make duplicates to ensure accurate results. Of the 271 samples analyzed 122 were from the surface of the Copper Cliff embayment (QMD, QMGN, GN samples), 106 were from drill core through the Copper Cliff embayment, 19 were QRNR and SRNR from the Murray Mine Historical Site, 6 were from the Creighton Pluton, 5 were from the Elsie Mtn. Fm, 5 were from the Copper Cliff offset, and 8 were inclusions from the Copper Cliff embayment.

5.3 Contamination

Samples were thoroughly cleaned with water after cutting and dried with compressed air both after cleaning and before they were crushed. Contamination after crushing was tracked by running 99.85% pure silica sand through the jaw crusher and alumina mill after every sixth sample.
5.4 Sample Analysis

All major oxides as well as Ni, Co, and Cu were analyzed at McGill University by XRF on fused bead. Samples were also analyzed on a Phillips PW2404 X-ray Fluorescence Spectrometer with a Rhodium X-ray tube and a PW2510 Automated Sampler at the University of Toronto for the elements Ba, Ni, Co, Cu, Zn, F, Cl, Br, S, Nb, Zr, V, Sr, Rb, Cr and Y. Samples were run for 18 minutes for everything except the halogens, which were run for 4 minutes.

Samples were also analyzed for Cr, La, Ce, Nd, Sm, Eu, Tb, Yb, Lu, Th, U, Cs, Hf, Ta, Sb, Mo, Sc, W, Au, and As by INAA at the University of Toronto. The samples were sent to the SLOWPOKE II reactor at the Royal Military College in Kingston, Ontario to be irradiated and were then analyzed using an Aptec Coaxial Germanium Crystal Detector at U of T for a minimum of 10 000 seconds at times 7 and 40 days after irradiation.

Microprobe analysis of orthopyroxene was performed on three samples using a Cameca SX-50 Electron Microprobe with TAP, LIF, and PET wavelength dispersive spectrometers, at the University of Toronto.

5.5 Data Validation

Several samples selected at random were made into 10 pellets each and analyzed on the XRF at the University of Toronto and the values agree very well from one sample to the next. The results for one of these tests are shown in Table 1. The largest discrepancy in reproducibility for this test was for Ba, Zr, and Cr with 19.45 ppm and 9.06 ppm and 6.40 ppm at two standard deviations. The machine error therefore is very good for the trace elements on the XRF at the University of Toronto.

Included in each batch sent to McGill University were duplicates of samples within a single batch, as well as a duplicate from a previous batch to ensure that data within the set and between two different sets were comparable. Also included were examples of in-house standards UTB2, UTG1, and UTA1. The data reproducibility is excellent for the more reliable UTB2 and UTA1 but less satisfactory for UTG1, which is known to suffer from inhomogeneities (M. Gorton, 2000 personal communication). The results are shown in
Table 2. The composition of UTG1 is not known with as much precision as UTB2 and UTA1 and consequently the data show much greater error. There is 62% error in the results for MgO, 13.33% for MnO and 17.78% for P2O5 for UTG1. The highest errors for UTA1 are for MnO with 15.71% and MgO with 9.57%. However, the UTB2 values for MgO have less than 4% error which equates to 0.2% at 2 standard deviations. The error for MnO is less than 5% error and less than 7% error for Na2O. The rest of the elements show excellent reproducibility and accuracy, except for Ni, Co, and Cu which are poor and as such these values will not be used for this study. The error for these trace elements is most likely due to the small amount of material used to form the beads and from the process of making the fused beads which requires that the sample be diluted several times.

Samples of UTB2 were included in each run for INAA and indicate very little deviation between sample sets (Table 3). The highest error is for Hf with 17% and a corresponding two standard deviations of 6.98 ppm. The only other elements with any significant error from accepted values would be Nd, which has less than 10% error (16.75 ppm at two standard deviations) and W has 22.85 ppm at two standard deviations.

6 Microprobe Analysis

6.1 Orthopyroxenes

Intact and unaltered pyroxenes are uncommon in the rocks from the Copper Cliff embayment. In most cases the pyroxenes are uralitized or now exist as amphibole pseudomorphs after pyroxene. Because of this pervasive alteration of the pyroxenes it is extremely difficult to determine their original composition. Three samples out of the 106 that had been made into thin sections contained fresh pyroxene and were selected for analysis on the electron microprobe at the University of Toronto. Five pyroxene grains per sample were analyzed at three points representing a path from the core to the rim. There was little variation between the points in the core and the points at the rims of the grains. There was also little variation between samples, including samples taken from exploration drill core and surface samples. Table 5 shows the results of the microprobe analysis. In all cases, the pyroxene was a clinoenstatite, a low Fe, high Mg type of pyroxene, (Figure 11) with an average Mg# (atomic Mg/(Mg +Fe)) of 0.5473.
6.2 Blue Quartz

Microprobe analysis was also used to try to determine the source of the distinct blue colour that is so prevalent in the quartz of the QMGN or basal norite of the main mass of the SIC. Silva (1996) investigated blue quartz from the Antequera-Olivera Ophite in Spain and determined the source of the colour to be microinclusions of aerinite (a zeolite-facies hydrothermal silicate-carbonate). The blue quartz from Silva’s study appears blue in both reflected and transmitted light, which is not the case with the blue quartz from Sudbury. The blue quartz from Sudbury only appears blue in reflected light, in transmitted light the quartz appears colourless and indistinguishable from colourless or smokey quartz. Another study by Zolensky et al. (1988) on blue quartz in Llano rhyolite from Texas found that the blue colour originated from microinclusions of ilmenite. Their work found these microinclusions produced the blue colour by Rayleigh scattering and that the blue quartz had elevated Fe and Ti contents compared to colourless quartz. The microprobe analysis of the blue quartz from Copper Cliff did not indicate an elevated Fe or Ti level, nor were any microinclusions identified that were without question ilmenite. A third possibility is that the quartz may have been deformed and due to the skewing of the crystal lattice, the quartz appears blue (G. Henderson, 2000, personal communication). Thin section analysis did not reveal any major deformation in the quartz so the probability that the blue colour was deformation induced is low. A fourth possibility is that the blue colour is because of sub-microscopic inclusions of rutile (Fronde, 1962). The blue colour (often referred to as the “Tyndall effect”) is only visible in reflected light and in transmitted light, the quartz appears slightly pinkish. Since there was no evidence indicating an elevated Ti content in the quartz and there was no evidence of a pinkish hue to the quartz in transmitted light, the colour at Copper Cliff is not likely to be a result of rutile. Microprobe analysis of the blue quartz was not conclusive in terms of composition, but the analysis did show a high level of microinclusions in all of the quartz. There are also elevated levels of TiO₂ in the QMGN compared to the GN and so the most likely case is that there are microinclusions of either ilmenite or rutile within the quartz, but at such a scale as to make microprobe analysis inconclusive.

7 Geochemistry

The purpose of the sampling program was to determine what relationships, if any, exist between the rock types within the embayment, but also to determine the relationships between the Copper Cliff embayment
and the other offset environments as well as the rest of the SIC. Because the rocks of the Copper Cliff embayment may also have been contaminated by a number of sources including the country rocks surrounding the embayment, and by the large inclusion population found throughout the embayment, a number of samples were taken from both of these groups. The country rocks are predominantly granites of the Creighton Granite to the west of the embayment and the metasediments and the basalts of the Elsie Mtn. Fm to the east of the embayment. The inclusions are a mix of fragments from the country rocks, amphibolites, pods of QMD, and a large set of unidentifiable mafic inclusions. The data used for the following analyses comes from surface samples, drill core samples and from several traverses.

Synthetic Traverses #1 and #2 were constructed using data from outcrops from the Copper Cliff embayment. These two traverses span a west to east transect across the embayment from QMD through QMGN and GN and back to QMGN and GMD again. The outcrops are as evenly spaced and in a straight line as surface exposure would allow. The QD, QRNR, and SRNR collected in the Murray Mine Traverse are the equivalent to the QMD, QMGN and GN of the Copper Cliff embayment. Traverses were used to determine if there was a definable transition from one rock type to another within the embayment, and if that transition was present for the equivalent rocks at the Murray Mine site.

7.1 Major Oxide Geochemistry of the Copper Cliff Embayment and the SIC

The following section deals with major element variations for the Copper Cliff embayment rocks, the country rocks surrounding the embayment and the inclusion population from embayment rocks. The Copper Cliff rocks have also been plotted in comparison to the rest of the major rock types in the SIC as well as in comparison to the rest of the offset dikes and embayments in the Sudbury area. The data have been plotted as major oxides vs. MgO, as major oxide variation for two synthetic traverses from east to west across the embayment, and as false colour element variation images for the entire embayment.

The major oxide data were plotted against MgO instead of SiO₂ because Mg is compatible in OPX and consequently is a good indicator of crystal fractionation. The SiO₂ content of the major rock types in this study is too similar to be of much value in distinguishing between them.

As a comparison, the data from the Murray Mine traverse have been included to represent the compositional transition that occurs in the lower zone of the SIC. The data have been plotted as major oxide
variation with distance from the footwall rocks. A meter scale traverse from the western side of the embayment has also been used to determine whether any large-scale trends could also be found on a small scale. The small scale traverse (Traverse #2, See Figure 10) will not be graphically reproduced here since there is very little correlation between the large scale trends discussed below and the small scale trends observed for Traverse #2.

$\text{Al}_2\text{O}_3$

The relationship of $\text{Al}_2\text{O}_3$ to MgO is shown in Figure 12a. The QMD from the Copper Cliff embayment is plotted as diamonds. The data for all the igneous rocks belonging to the SIC in my dataset show a clear separation into two distinct populations on this diagram. One group is characterized by relatively high MgO and $\text{Al}_2\text{O}_3 < 15\%$, whereas the other has generally lower MgO and $\text{Al}_2\text{O}_3 > 15\%$. On the basis of this division, I have coded the symbols such that in this and all subsequent variation diagrams, the high MgO population is represented by open symbols and the low MgO population is represented by filled symbols. Because all significant concentrations of sulphide in the embayment and offset are hosted by rocks in the low $\text{Al}_2\text{O}_3$ group, all members of this group will be referred to as the "low Al" group or simply low Al samples in the following discussion. This group includes many samples that do not have any significant amount of sulphide visible. The other group are the "high Al" samples which are samples associated with outcrops with very few inclusions and less than the average amount of sulphide. Diamonds represent samples of QMD, squares represent QMGN and triangles represent GN. There is a tight cluster for the high Al samples of QMD centered on 4.5 wt% MgO and 16 wt% $\text{Al}_2\text{O}_3$. The low Al QMD samples are centered around 5 wt% MgO and 14 wt% $\text{Al}_2\text{O}_3$ and tend to be more widely scattered. There is a significant amount of overlap between the QMGN samples and the QMD samples. The high Al QMGN is tightly centered on 5 wt% MgO and 16 wt% $\text{Al}_2\text{O}_3$ whereas the low Al QMGN has much more scatter and centers on 7 wt% MgO and 14 wt% $\text{Al}_2\text{O}_3$. The high Al GN samples cluster tightly on 6.5wt% MgO and have an average $\text{Al}_2\text{O}_3$ value of 17.5wt%, which is higher than either the QMD or the QMGN. The low Al samples of GN have a large scatter with respect to both MgO and $\text{Al}_2\text{O}_3$. The MgO values on average range from 9 to 11 wt% and the $\text{Al}_2\text{O}_3$ values range from 10 to 15.5 wt%. Also plotted on this graph are samples of inclusions from within the Copper Cliff embayment (shown as open circles), samples of Creighton Granite (shown as small x's), samples of metasediment and basalt from the Elsie Mtn Fm (shown as stars), the composition of OPX, plagioclase and K-feldspar (shown as
solid circles), and a crystallization model generated by MELTS (Ghiorso and Sack 1995) (shown as large X's). These symbols will be used in all subsequent graphs. MELTS is software that allows models of different crystallization histories to be created which are dependent on different initial conditions such as temperature, pressure, \( fO_2 \) and magma compositions. The trendline produced by MELTS takes the initial composition (in this case least altered Onaping glass) and models the resulting composition with respect to equilibrium fractionation and crystal accumulation as temperature decreases.

A tie line between the composition of plagioclase and the composition of OPX represents an idealized crystal accumulation trend. Both MELTS and petrographic observation show that the principal cumulus phases from the Sudbury magmas were OPX and plagioclase, so that any pure adcumulate assemblage must plot somewhere along this line. Both the low Al group data and the high Al data trend in the direction of this tie line. The QMD tends to have much less OPX than the GN and this is most likely what produces the trend from low MgO in the QMD to high MgO in the GN. The low Al samples tend to have even greater amounts of OPX, especially the low Al GN. If the QMD represents an initial liquid composition as the petrology seems to support then the QMGN and GN (meso-adcumulates) could have formed by a combination of fractional crystallization and crystal accumulation from the residual liquid left after the crystallization of QMD.

The MELTS trendline was created using data from the least altered glass from the Onaping Fm (Ames, 1999) as the initial composition. The model simulated equilibrium fractionation at an oxygen fugacity buffered to the assemblage Fayalite-Magnetite-Quartz. The trend shows crystallization of only OPX until approximately 85% liquid remains, at which point the trend line curves with the onset of plagioclase crystallization. There is a second bend in the trendline where K-feldspar begins to crystallize, but this bend is not discernible in many of the major oxide plots. The MELTS model is not well constrained at such low temperatures and felsic magma compositions, and the final bend is not reliable. The initial composition of the liquid from the Onaping glass is close to that of the QMD. There is however a distinct compositional difference between the low Al and high Al QMD. This seems to indicate that there are two distinct starting compositions for the QMD.

The spatial variation in \( Al_2O_3 \) for the Copper Cliff embayment is shown in Figure 12b. There are two different synthetic traverses plotted, which span the embayment from east to west. Synthetic Traverse #1 is represented by a dashed line and diamond shaped points and Synthetic Traverse #2 is represented by a solid line
and square points. The east side of the each traverse starts in QMD for the first two locations. The next two outcrops are QMGN, which are then followed by six GN outcrops in the core of the embayment. The western side of the traverse ends in QMGN (two locations) and QMD (final location). There is no clear trend in either traverse, although it does appear that there are slightly elevated Al2O3 values in the GN (core) compared to the QMD (margins). This is most likely because the QMD and QMGN for both traverses is the high Al type whereas the GN is for the most part in the low Al group. The GN samples, whether low Al or not, tend to have higher Al2O3 than either the QMGN or QMD. If the synthetic traverses were through all high Al samples or all low Al samples there might be a more noticeable trend across the Copper Cliff embayment. The overall spatial variation of Al2O3 for the Copper Cliff embayment is shown in Figure 12c, which is a SURFER false colour image of the embayment. The image was produced from 105 sample sites from the embayment and by using kriging to interpolate between the points. The lower Al2O3 values are shown in blue while the higher values are shown in purple and red. The division between rock types is again not distinct, but the difference between the low Al and high Al samples is. There is a large area in the core of the embayment, which has depleted Al2O3 values. There are also several smaller areas with low Al2O3. The edges of the embayment show elevated Al2O3. The lowest Al2O3 value sites correspond with the locations with the highest inclusion populations and higher levels of sulphide. This same relationship is observable in the data collected from the Murray Mine Traverse, which is shown in Figure 12d. This graph shows the variation in Al2O3 over the 483 m traverse distance, which spans the transition from QD (QMD) to QRNR (QMGN) to SRNR (GN). The QD samples are generally inclusion free and sulphide poor and have a high Al2O3 content ranging from 16 to 16.5 wt%. The QRNR, which is often heavily mineralized, has low Al2O3 values, ranging from 12.8 wt% to 14 wt%. The SRNR, which occurs at the end of the traverse, tends to have high Al2O3 values, which reflect the lack of inclusions and sulphide poor nature of the rock. The data from the Murray Mine Traverse corresponds well with the observation of two distinct rock groups one related to mineralization and one related to high Al rocks.

The dependence of Al2O3 on MgO for most of the major rock types of the SIC as well as the Copper Cliff rocks is shown in Figure 12e. In addition to the rock types listed for Figure 12a, there are several other significant rock types, which are included in this plot. The data for these rock types has been taken from the OGS Open File Report 5959 (Lightfoot et al, 1997a). The volumetrically dominant granophyre samples are shown by light coloured solid squares with dark borders and are centered on 3 wt% MgO and 13 wt% Al2O3.
The granophyre field occupies the same region as the end of the MELTS trend where both plagioclase and K-feldspar are crystallizing with OPX and CPX. There is a compositional gap between the granophyre and the QMD from the Copper Cliff embayment and dike. The gap ranges from three to five wt% MgO, and ends at the QMD, or at the initial composition of the MELTS model (Onaping glass). Overlapping the high Al samples from the Copper Cliff embayment are samples of felsic norite shown as black x’s on a light coloured square. The felsic norite generally has higher than 15wt% Al₂O₃ and between 5 and 8 wt% MgO. There are two groups of igneous textured sublayer matrix (ITSM) which are shown by light coloured solid circles with a dark border. The first overlaps with the high Al samples from the Copper Cliff embayment. The second group overlaps the composition of the low Al GN. There is a large amount of scatter within the ITSM and there is no clear distinction between the two groups as there is for the Copper Cliff rocks. The sublayer norite shown by open circles occur near the end of the overall crystallization trend. The sublayer norite has low Al₂O₃ and high MgO averaging 7wt% and 14wt% respectively. The mafic norite shown by short lines occupies the gap in between the GN of Copper Cliff and the sublayer norite. Finally, the melanorite shown by small stars spans a wide range of compositions. It overlaps from the low Al QMGN to beyond the sublayer norite at the end of the trend. The melanorite samples are from several different locations around the SIC which may account in part for the large range in compositions.

The overall trend of the SIC rocks parallels the ideal crystal accumulation trendline from QMD toward the tieline connecting OPX to plagioclase. The SIC rocks plot along a tie line from the composition of the unaltered Onaping glasses to the composition of OPX. The exception to this is the high Al samples from Copper Cliff, which plot slightly higher than the MELTS projected crystallization trend. The high Al samples also trend at an angle to the rest of the SIC rocks. The data for the inclusion population of the Copper Cliff embayment plots high on the ideal trendline from plagioclase to orthopyroxene and could be a major factor in the composition of the Copper Cliff rocks. The rocks belonging to the high Al group may have been formed by a combination of contamination and crystal accumulation of both OPX and plagioclase whereas the low Al samples may have had less contamination and were formed as a result of crystal accumulation of primarily OPX.
MgO

MgO is an excellent indicator in these rocks on the amount of fractionation and crystal sorting that has occurred since it partitions primarily into OPX. The quenched QMD of the Copper Cliff embayment tends to have little OPX while the meso-adcumulate QMGN and GN tend to have a significant proportion. The spatial distribution of MgO in the Copper Cliff rocks is indicated by the synthetic traverses across the embayment shown in Figure 13a. The QMD at the margins on both the east and west sides of the embayment have low MgO consistent with their low OPX content, whereas the core of GN and QMGN have elevated MgO values. Both the low Al and the high Al QMD samples have low MgO values whereas the QMGN and GN have high MgO values. The low Al QMD has 4-6.5% MgO, the QMGN has 6-8% MgO and the GN has between 8.5 and 13% MgO (Figure 12a). The high Al samples have a much narrower range of values with the QMD ranging from 4-6%, the QMGN from 4.5-6% and the GN from 5.5-7% MgO.

The overall MgO variation is shown by the false colour image of the Copper Cliff embayment in Figure 13b. There is a distinct increase in MgO in the core of the embayment and in the north west corner of the study area towards the lower units on the Main Mass of the SIC. The lowest MgO values occupy a thin rind along the edges of the embayment, corresponding to the occurrence of diabasic-textured QMD, which contains no textural evidence of OPX accumulation.

The data from the Murray Mine Traverse shown in Figure 13c indicates a trend that is the opposite of the Copper Cliff embayment trend. The SRNR has lower MgO values than the QRNR or the QD. The QRNR has the highest MgO values. This may be related indirectly to the amount of sulphide in the QRNR compared to the QD and SRNR in this traverse. The low Al samples tend to have higher MgO values than the high Al and so the opposing trend for MgO observed at the Murray Mine may be a product of this association. The QD and SRNR are both high Al and as expected have comparatively low MgO values. The QD has the lowest MgO values for this traverse averaging less than 5wt%, whereas the SRNR samples average 6wt%. If the QRNR from this location had been high Al then there may have been a more recognizable trend from low MgO in the QD through the QRNR to high values in the SRNR.
The relationship between SiO$_2$ and MgO for the Copper Cliff embayment rocks is shown in Figure 14a. As is the case with all of the Sudbury rocks the Copper Cliff embayment rocks all display elevated levels of SiO$_2$ compared to similar mafic rock types from other locations. Norite and a quartz diorite worldwide in terms of silica content are normally quite distinct, with norite having approximately 52% (NIM-N) whereas quartz diorites (SKD-1) have 60% (Govindaraja, 1994). In the SIC there is generally less than a one to five percent difference, which makes SiO$_2$ content difficult to use in distinguishing between rock types.

There are however, several trends shown in Figure 14a, which need to be addressed. The first is the relationship between the QMD, QMGN and the GN of the Copper Cliff embayment. In general, there is less silica in the GN than in the QMGN and QMD. The distinction between the rock types is minor in terms of silica but there is a difference. The mesocumulate to adcumulate textured GN which contain both the lowest SiO$_2$ and highest MgO may be explained in terms of the crystal accumulation trend shown by the tie-line between plagioclase and OPX. The GN has significantly more accumulated OPX and much less quartz than the other rock types. The fractional crystallization and accumulation of OPX allowed little interstitial space for the formation of quartz from trapped melt. The QMGN in contrast has much less OPX and significantly more interstitial quartz, while still being a cumulate. The QMD however is not a cumulate rock but still plots very close to the composition of both the QMGN and GN in terms of SiO$_2$ and MgO content. This is consistent with derivation of the GN and QMGN from an initial liquid composition very similar to the QMD.

A second trend that is important is the major distinction between the low Al and the high Al rocks. The low Al and high Al samples are represented by open and solid symbols respectively as was described above. The low Al samples generally contain <55% SiO$_2$ whereas the high Al samples contain >55% although there is not as clear a distinction with SiO$_2$ as there was with Al$_2$O$_3$. There is a significant amount of overlap between the samples especially the low Al samples, which show a large amount of scatter.

The third trend which may help explain the scatter in the low Al samples and the tight clustering of the high Al samples is the trend of the low Al samples towards the composition of the inclusion population and country rocks surrounding the embayment. In most cases, the inclusions (except granites) shown by solid circles have significantly less SiO$_2$ than the embayment rocks. The samples of Elsie Mtn Fm metasediment and basalt shown by stars also have very low SiO$_2$ values compared to the embayment rocks. The low Al samples
tend to also be the samples with the highest number of inclusions and so a possible cause of the large scatter in the low Al samples may be that they are severely contaminated. The trend towards the inclusion population seems to support this hypothesis since the scatter can not easily be explained in terms of simple crystal accumulation or fractionation involving plagioclase and OPX in a liquid similar to the Onaping glasses. The samples of Creighton Granite from the west side of the embayment plot much higher than any of the Copper Cliff rocks and may have had much less impact on the SIC magma composition than the Elsie Mtn Fm rocks or the inclusions. This will be discussed more fully in a later section.

The relationship between SiO$_2$ and MgO for the major rock types of the SIC is shown in Figure 14b. The data show a curved trend extending from the granophyre (high SiO$_2$/low MgO) to the sublayer and melanorite (low SiO$_2$/high MgO). The major trend line moves from the granophyre to the QMD of the Copper Cliff embayment and dike. There is however a major compositional gap between the granophyre and the QMD from approximately 63wt% SiO$_2$ to 60wt% SiO$_2$ and between 4 wt% MgO and 2 wt% MgO. The MELTS model trendline initiates at the 63wt% SiO$_2$ and 4.5 wt% MgO at least partially spanning the compositional gap. When this is coupled with the contamination trend is considered the gap is narrowed. The amount of contamination that has occurred in the QMD from Copper Cliff may account for the silica depletion and elevation in MgO. The overall Mg-enrichment trend of the mafic members of the SIC continues through the QMGN and GN of the Copper Cliff embayment and into the ITSM, low Al GN rocks from Copper Cliff, and the mafic norite of the north range. The trend passes through the sublayer norite and ends at the more mafic samples of melanorite. There tends to be a significant amount of overlap between the ITSM and the low Al GN and QMGN rocks from Copper Cliff.

Fe$_2$O$_3$

The dependence of Fe$_2$O$_3$ on MgO for the Copper Cliff embayment rocks is shown in Figure 15a. There is little correlation between the crystal accumulation trend between OPX and plagioclase and the overall trend from QMD to GN. There are two different trends for the Copper Cliff rocks, both of which are at an angle to the accumulation trend. The high Al samples tend to have decreasing Fe$_2$O$_3$ values with increasing MgO, whereas the low Al samples have increasing Fe$_2$O$_3$ values with increasing MgO. These observations are consistent with the presence of abundant Fe-rich OPX in the cumulates of the low Al trend, and the relative
importance of iron-free plagioclase in the high Al cumulates. Addition of Fe from sulphide is unlikely to affect visibly the total amount of Fe$_2$O$_3$ present in the analyses because few of the rocks analyzed contain more than a fraction of a percent of sulphide. In general, the QMD has higher values than both the QMGN and the GN whether in low Al group or not. The low Al QMD averages 10-14% Fe$_2$O$_3$, whereas both the QMGN and GN average 8-10% Fe$_2$O$_3$. The high Al QMD averages 8-10% Fe$_2$O$_3$ as does the QMGN, whereas the GN has between 7 and 8% Fe. The Fe$_2$O$_3$ data has more scatter for the low Al rocks than the high Al.

Unlike Al$_2$O$_3$ and SiO$_2$ the Fe$_2$O$_3$ data for the high Al rocks cluster tightly around the unaltered Onaping glass composition at 5wt% MgO and 9wt% Fe$_2$O$_3$. The low Al QMD samples scatter to higher Fe$_2$O$_3$ compositions in the direction of a large number of inclusions from the Copper Cliff emplacement and the samples of Elsie Mtn Fm metasediment and basalt. The low Al QMGN and GN follow a tie line linking the initial composition of the MELTS trend and the composition of OPX. This suggests that the initial liquid from which the low Al samples are derived was crystallizing almost exclusively OPX, since plagioclase accumulation would deflect the trend toward the origin. The high Al QMD samples which plot at the same composition as the Onaping glass trend at angle from the low Al group towards lower Fe$_2$O$_3$ values. The angle and direction of the high Al sample trend may indicate that the initial liquid composition was crystallizing both OPX and plagioclase. There are also several iron poor inclusions, as well as the Creighton Granite samples that plot well below the Copper Cliff rocks from one to six wt% Fe$_2$O$_3$. The high Al samples could have formed from a process of crystal accumulation of plagioclase and OPX, possibly with a significant contaminant contribution from the iron poor inclusions and country rocks. The low Al samples may have formed from a similar process of crystal accumulation of primarily OPX, and a significant contaminant contribution from the iron rich inclusions and Elsie Mtn Fm rocks. This could account in part for the differing trendlines for the low Al and high Al samples.

The spatial distribution of Fe$_2$O$_3$ in the Copper Cliff emplacement is shown by Figure 15b, showing the two E-W traverses. There is marked decrease in Fe$_2$O$_3$ from the east to the west perhaps because the western side of the embayment is in contact with iron poor Creighton Granite while the east side is in contact with the relatively iron rich Elsie Mtn Fm metasediments and metavolcanics. The spatial relationship of Fe$_2$O$_3$ with distance at the Murray Mine traverse is shown in Figure 15c. The Fe$_2$O$_3$ in the QD is low, the QRNR is high and the SRNR is lower than either of the other two rock types. The elevated levels of Fe$_2$O$_3$ in the low Al
QRNR are consistent with the trend observed at Copper Cliff where all of the low Al samples had elevated Fe compared to the high Al. Again, this seems to imply the existence of two separate magma batches with differing initial liquid compositions.

CaO

The dependence of CaO on MgO for the Copper Cliff embayment rocks is shown in Figure 16. There is a large amount of scatter for all of the Copper Cliff data, although the low Al samples tend to have a greater range than the high Al. The CaO content increases from the high Al QMD through QMGN and GN ranging from 6 to 8wt%. The low Al rocks have the opposite trend and Ca content decreases from the QMD through the GN. The low Al QMD ranges from 5-8wt% CaO whereas the QMGN ranges from 6-7wt% and the GN from 4-6wt%. The low Al samples follow the crystal accumulation trendline toward OPX but the high Al trend is at an angle to it. All of the Copper Cliff QMD samples have a 3 wt% higher CaO content compared to the Onaping glass used as the initial composition for the MELTS model. The inclusion population and Elsie Mtn Fm rocks all have CaO contents of between 8 and 12 wt%. Contamination of the Copper Cliff rocks by these high Ca inclusions could elevate the entire data set from the 3wt% CaO level of the Onaping glass to the observed concentrations around 6 wt%.

The QD from the Murray Mine Traverse has low Ca, but the QRNR has low to medium CaO levels. The SRNR is relatively quite rich in Ca, which is consistent with being in the high Al group of rocks.

Na$_2$O

The relationship between Na$_2$O and MgO is shown in Figure 17a. In general, the QMD has elevated Na$_2$O in comparison to the QMGN and GN of the Copper Cliff embayment. The QMD tends to have values greater than 3 wt % while the QMGN and GN range from the 2 to 3 wt%. There is also a significant division between the low Al samples and the high Al samples. The low Al outcrops tend to have depleted Na$_2$O and more scatter in the data set than the high Al samples which have elevated Na$_2$O and cluster more tightly. Within the two groups of rocks, QMD always occupies the field of highest Na$_2$O values whereas the GN occupies the lowest values. The QMD of the low Al group has 3% Na, the QMGN 2.5% and the GN 2%. The high Al QMD has 3.25% Na, the QMGN 3%, and the GN 2.75%. This is consistent with what is observed for
the Murray Mine traverse where the high Al QD and SRNR are high and the low Al QRNR is low. All of the Copper Cliff rocks follow a trend parallel to the tie-line from OPX to plagioclase. The samples are however much poorer in Na2O than the either the tie-line or the MELTS model. The samples fall off the line in the direction of some of the inclusions and the Elsie Mtn Fm rocks. The Creighton granite inclusions also have low Na2O and may have contributed to the deviation from the ideal crystallization trend. Some of the observed Na2O depletion might also be related to the greenschist facies metamorphic overprint imposed during the Penokean Orogeny.

Shown in Figure 17b is the spatial variation of Na2O for the entire Copper Cliff embayment. This false colour image shows the GN core of the embayment and several other small areas as being low in Na2O whereas the margins are consistently one to two wt% higher. The lowest Na2O regions also correspond with the highest incidences of inclusions and sulphide.

Overall Na2O content decreases with increasing MgO content for most of the rocks from the SIC apparently reflecting dilution by cumulus OPX. This trend is followed by both the low Al and high Al rocks from Copper Cliff. The low Al GN samples from Copper Cliff plot in the same MgO and Na2O range as ITSM samples from the McCreedy West and Frasier Mines.

K2O

The dependence of K2O on MgO is shown in Figure 18a. The K2O values are consistently higher in the QMD averaging 1.5-2 wt% whereas the QMGN and GN samples average 0.5 to 1% K2O. There is little difference in K2O content between the low Al and high Al samples although the high Al samples have K2O contents that decrease more steeply with increasing MgO content trend than do those in the low Al samples. Both the low Al and high Al QMD samples center around 5 wt% MgO and 1.8 wt% K2O. There is no clear separation as there was in elements such as Al2O3. Since both low Al and high Al QMD samples have similar K2O contents, it appears that the two initial liquid compositions also had similar K2O levels. The steeper trendline of the high Al samples is skewed in the direction of the low K2O (0.25 to 1.5 wt%) inclusion population. The skewed trendline can be explained by crystal accumulation of plagioclase and OPX into the high Al suite, and dominantly OPX into the low Al suite.
In the E-W trending traverses across the embayment shown in Figure 18b, the samples from the western side of the embayment are enriched in K₂O compared to the eastern side. The western side is in contact with rocks of the Creighton Pluton. Local contamination of these rocks by K-rich granite would produce this spatial distribution west to east. The effect does not penetrate very far into the embayment.

The spatial variation of K₂O for the entire Copper Cliff embayment is shown in Figure 18c, which is a false colour image, produced using SURFER. The GN core has consistently lower K₂O values than the QMD margins. There is a distinct transition generally within 100 m of the embayment contact from QMD to GN or low K₂O material. This is consistent with what was found at the Murray Mine Traverse where the QMD was high with >2% K₂O, the QMGN had a strong decreasing trend from 2.3% down to 1.1%. The SRNR averages about 1.3% K₂O.

TiO₂

The relationship between TiO₂ and MgO for the Copper Cliff embayment rocks is shown in Figure 19a. In general, the QMD have TiO₂ values in the range 0.75-1 wt%. The QMGN samples fall between 0.5-0.75% and the GN around 0.5%. Unlike the data for Al₂O₃, the trend lines of the low Al and high Al QMD, QMGN and GN for TiO₂ extend in the same direction. The high Al sample set however has a much steeper trend line than the low Al sample set. The low Al data set follows an OPX accumulation trend whereas the high Al follows a more plagioclase-rich assemblage and is skewed in the direction of a set of TiO₂ poor inclusions. The obvious scatter in the low Al QMD samples may be caused by the assimilation of materials represented by the suite of TiO₂ rich inclusions and rocks from the Elsie Mtn Fm. As with the data for Al₂O₃ the data for TiO₂ does not deviate too much from the model trendline produced by MELTS. The data set is higher overall than the Onaping glass composition and, as mentioned above, is skewed off the ideal trendline in the direction of the inclusion and country rock data from the Copper Cliff embayment.

Shown in Figure 19b are the synthetic traverses, which reflect the spatial relationship of TiO₂ in the Copper Cliff embayment. Both traverses indicate that there are elevated TiO₂ levels in the QMD and relatively depleted levels in the QMGN and GN. The margins of the embayment range from 0.8 to 1 wt% TiO₂ in the east and 0.76 to 0.9 wt% on the west side. The disparity between the two contacts may be due to the contamination of the east side by high TiO₂ rocks from the Elsie Mtn Fm. and dilution on the west side by low TiO₂ Creighton...
Granite. The core of the embayment composed chiefly of GN averages 0.5 wt% which grades upsection to the QMGN at a TiO₂ level of 0.5 to 0.8 wt%. The false colour image of the TiO₂ variation for the Copper Cliff embayment is shown in Figure 19c. Again, TiO₂ is low in the core of the embayment and increases toward the QMD along the margins. In this case, the rind of QMD appears to be less than 100 m thick in most locations and in several locations is discontinuous along the contact.

The TiO₂ variation with distance for the Murray Mine Traverse shown in Figure 19d shows the same general trend as the Copper Cliff rocks with high Ti values in the QD and low in the SRNR. The low Al QNR has elevated TiO₂ levels compared to the high Al QD and SRNR which is consistent with what was found at the Copper Cliff embayment.

P₂O₅

The dependence of P₂O₅ on MgO for the Copper Cliff embayment rocks is shown by Figure 20a. The QMD has elevated levels of P₂O₅ averaging 0.20-0.25%, compared to the QMGN and GN which have relatively low values, varying between 0.15-0.20% and 0.10-0.15% respectively. Much like K₂O and TiO₂ the high Al samples have a much steeper trendline from QMD to GN than the low Al samples. There is a lot of overlap and scatter for all the samples but more so for the low Al samples. All of the QMD samples have elevated P₂O₅ compared to the initial composition of the Onaping glass from the MELTS trend.

The Elsie Mtn Fm rocks generally have higher P₂O₅ than the Copper Cliff rocks, whereas almost all of the inclusions have depleted P₂O₅ with values ranging from 0.04 to 0.1 wt%. The scatter of the data may be a result of contamination of the initial melt composition by these inclusions. The observed trend of decreasing P₂O₅ content with increasing MgO is consistent with accumulation of OPX. The relationship between P₂O₅ and distance for the Copper Cliff embayment is shown in Figure 20b. Both of the synthetic traverses show the same trend. The QMD at the contacts of the embayment have high P₂O₅ ranging from 0.2 to 0.3 wt%. The GN at the core of embayment has low P averaging 0.14 wt% which increases towards the contacts to approximately 0.17 wt% in the QMGN. A similar relationship for the entire embayment is shown by the false colour variation diagram in Figure 20c. The QMD at the margins forms a thin, discontinuous rind of high P while the QMGN and GN form a core of low P₂O₅.
In comparison the variation of P₂O₅ for the Murray Mine Traverse is shown in Figure 20d. There is an overall trend from high P₂O₅ in the QD to low P₂O₅ in the SRNR. The low Al QRNR is elevated in P₂O₅ due to the shallower trend towards low P₂O₅ with increasing MgO values.

**Sulphur**

Shown in Figure 21a is the relationship between S and MgO for the Copper Cliff rocks. There is a tremendous amount of scatter and overlap for all of the samples. The QMD is plotted as diamonds, filled diamonds indicate high Al samples while open diamonds indicate low Al samples. The high Al samples of QMGN are shown by solid squares and the high Al samples of GN are shown by solid triangles. Similarly, the low Al QMGN and GN are shown by open squares and open triangles respectively. The low Al samples tend to have much higher S than the high Al samples although there are numerous samples that plot as a low Al sample in terms of Al₂O₃ but do not have high S contents. The average low Al QMD contains 11 911 ppm S, while the high Al QMD contains only 1144 ppm. There is little difference between the high Al and low Al QMGN samples, which average 1966 and 2182 ppm S respectively. The low Al GN samples have an average of 4024 ppm S while the high Al contain only 877 ppm. There is no other relationship discernible for S in the Copper Cliff rocks other than the difference between the low Al and high Al groups. The spatial variation of S for the entire Copper Cliff embayment is shown in Figure 21b. There are several locations with high sulphur content which correspond with the locations with the highest inclusion populations as well as the greatest amount of gossan. The highest reading, at station 70 (Figure 11) also happens to be the thickest gossan (Plates 14a, 14b) found in the embayment as well as a location with greater than 10% inclusions (Figures 8, 10). The same can be said about stations 72-1, 72-2, 149, 200, 201, and 222. These stations all have high S, some degree of gossan and higher than average inclusion populations. At many of the low Al outcrops, there was little visible difference between them and the supposedly high Al outcrops. Not all “low Al” locations had visible inclusions or a gossan. The greatest number of these locations occurred in the core of the embayment to the south-east of the large fault. In addition the samples taken from drill core proximal to ore zones also plot in the “low Al” category and have some of the highest S contents, while not appearing to have greater than average sulphide contents when examined in hand specimen.
The S variation with distance for the Murray Mine Traverse is shown in Figure 2.1c. The QD in this case has low S, while the low Al QRNR has a very high S content which drops gradually with the corresponding decrease in sulphide away from the footwall contact. The SRNR averages less than 1000 ppm S, much like the high Al GN from the Copper Cliff embayment. It should be noted that S was analyzed as a trace element by pressed powder pellet at the University of Toronto and the high levels (94 000 ppm) may have affected the quality of the data.

7.2 Trace Element Geochemistry of the Copper Cliff Embayment in Relation to the Footwall Rocks Surrounding the Embayment and the Inclusion Population of the Embayment

All of the trace elements analyzed for were plotted using several different methods. All elements were plotted versus distance for the Copper Cliff embayment as well as for the samples taken near the Murray Mine Historical Site. The elements were also plotted versus Zr to determine if there were any major trends relative to the other rocks within the embayment as well as to other rocks from around the SIC. Finally, each element was plotted using SURFER, which produces a false colour map of the study area showing the concentration distribution of each element. There was no trend found for As, Ba, Cs, Cu, Mo, Ni, Sb, Sc, Sr, U, V, W, and Zn. The rest of the trace elements divided into those that were high in the QMD and low in the QMGN and GN and those that were low in the QMD high in the QMGN and GN. The elements that are high in the QMD are F, Hf, Nb, Rb, Ta, Th, Y, and Zr. The elements that are low in the QMD compared to the QMGN and GN are Cl, Co, and Cr. The Cl, Co, Cr, and Hf trends are weak and will not be discussed here. The trend in the data that occurs for such elements as F, Cl may or may not be related to the overall crystallization history of the Copper Cliff embayment. These elements are extremely mobile during greenschist facies metamorphism and as such the trends produced from these elements are suspect. In the same respect, the lack of a trend for elements such as Ba may also be the result of hydrothermal alteration and not a reflection of the original crystallization history of these rocks.

In almost every graph of trace element versus Zr there is a generally linear trend moving from the inclusions near the origin through the GN, QMGN, QMD and towards the Creighton Granite samples. There is generally large scatter within the rock types for Zr and in most cases large overlap. There was no trace element
data available to produce a MELTS model, nor was there trace element data for the Onaping glass to compare initial compositions.

Zr

The relationship of Zr with MgO is shown in Figure 22. There is tremendous scatter and overlap for both groups but in general, the high Al QMD averages 100 ppm Zr while the low Al samples average 150 ppm. The high Al GN samples average 75 ppm Zr while the low Al samples average 100 ppm. The two groups have parallel trends towards high MgO and low Zr. The decreasing Zr trend from QMD to GN is consistent with crystal accumulation and fractionation. The inclusion population shown by solid circles tends to have variable Zr, but both the Elsie Mtn Fm rocks and the Creighton Granite samples have elevated Zr and could be the cause of the large scatter in the data if they contaminated the Copper Cliff rocks.

Y

Shown in Figure 23a is the dependence of Y on MgO. Y in the Copper Cliff rocks shows one of the strongest trends moving from the high levels in the QMD to moderate and low levels in the QMGN and GN of the core of the embayment. The QMD generally ranges from 20-35 ppm and may reach as high as 65 ppm Y. The QMGN and GN tend to have lower values, around 15-25 ppm and 10-18 ppm respectively. Unlike the trend for Zr, the low Al and high Al rocks have trendlines for Y at an angle to each other. The high Al samples have a steeper trend towards low Y and high MgO, whereas the trendline for the low Al rocks is flatter but still trends towards low Y and high MgO. These trends again reflect accumulation of a more magnesian assemblage in the low Al group.

The relationship between Y and Zr is shown in Figure 23b. Symbols follow from the previous graph, but in addition to these are trendlines showing the composition of both the inclusion population and basalt from the Elsie Mtn Fm. These trendlines bracket the Copper Cliff data set. Contamination of the Copper Cliff rocks by these inclusions and country rocks could produce the scatter in the data. The high Al samples have a trendline that is much steeper than the low Al which may reflect the difference in the contaminants. The inclusion population was for the most part collected from low Al outcrops and as such, it would be consistent to have the low Al samples parallel the inclusion population trendline.
The false colour image of the embayment shown in Figure 23c produced by using SURFER illustrates the high Y rind along the margins of the embayment and the Y poor core. The rind of high Y values is thin, generally less than 100 m. There is an abrupt transition to low Y, which corresponds to the mapped transition to cumulate QMGN. There are several locations with much higher Y values than the surrounding rocks. These samples were visibly contaminated with granite and metasediment.

Nb, Rb, Ta and Th all show very similar behaviour to Y. The inclusion population and the Elsie Mtn Fm rocks bracket the Copper Cliff samples. The high Al samples have a steep trend possibly pulled by the composition of the Elsie Mtn Fm rocks while the low Al samples have a flatter trend that is more like the inclusion population trendline.

7.3 REE

Of the REE only Ce, Eu, La, Lu, Sm, Tb, and Yb were analyzed due to instrument limitations. These elements were plotted in the same manner as the trace elements (See above). Of the REE, only Ce did not have any discernible trend. The other six elements were all high in the QMD compared to the levels in the QMGN and GN. Again data for REE was not available for a MELTS model or for Onaping glass.

Lu

The relationship between Lu and Zr is shown in Figure 24a. This figure will be used to describe the behaviour of all of the REE since they are all extremely similar. There is a significant amount of both scatter and overlap of the data but in general, there are elevated levels of Lu in the QMD compared to the QMGN and GN in the core of the embayment. The QMD ranges from 0.3 to 0.6 ppm Lu, while the QMGN ranges from 0.3 to 0.4 ppm. The GN, with the least amount of overlap with the other samples ranges from 0.2 to 0.3 ppm Lu. The inclusion population has low Lu and the Elsie Mtn Fm and Creighton Pluton rocks have high Lu; again contamination by these rocks is a possible explanation for the scatter of the data.

Shown in Figure 24b is the Lu variation with distance across the Copper Cliff embayment. Synthetic Traverse #1 and #2 have Lu levels for the QMD of 0.4 ppm and 0.4-1 ppm respectively. The QMGN and GN for these two traverses range from 0.2 ppm to 0.6 ppm. The QMD sample at the western end of Synthetic
Traverse #2 (give station location) is greatly elevated compared to the other samples and is most likely highly contaminated by the relatively Lu rich Creighton Granite.

A similar overall trend is shown in Figure 24c of the Murray Mine Traverse. The QD at the start of the traverse has approximately 0.37 ppm Lu. There is a gradual drop in Lu levels through the low Al QRNR. There is no apparent difference in terms of REE between low Al and high Al samples. The SRNR has the lowest average Lu levels.

**REE and Trace Element Spider Plot**

When the REE and trace element data for the Copper Cliff embayment are normalized to CI Chondrite (Sun and McDunough 1989) we find that all three rock types within the embayment are relatively enriched in the LFSE and depleted in the HFSE (Figure 25). The average QMD, QMGN and GN all have parallel REE patterns although the QMD data are offset to slightly higher averages than either the QMGN or GN, which most likely reflects the accumulation of mafic minerals in the latter two.

There is a slightly steeper slope to the graph for the LREE, which becomes shallower and almost level for the HREE. This trend has been noted by numerous other authors. There are also depleted levels of Rb, Nb, and Ta for all the plotted rock types except for the average upper crust. The depletion in Nb and Ta are most likely the result of the contamination of the SIC by calc-alkaline rocks from the surrounding footwall rocks. The Sr depletion in the granophyre relative to the Copper Cliff rocks most likely represents the fractionation of plagioclase. The relative abundance of the rest of the REE in the granophyre is likely the product of it being formed from the residual liquid after the formation of the mafic cumulates. There is no Eu anomaly for all the rocks except the granophyre, which has a slight negative anomaly and the GN, which has a slight positive anomaly.

The QMD from the Copper Cliff embayment and the data from the Copper Cliff offset are identical through the LFSE but tend to have minor variations in the HFSE, perhaps reflecting the greater ease of homogenization of the relatively mobile LFSE. The Copper Cliff offset rocks tend to match the QMGN from the embayment through the HFSE, although the variation from the QMD to the QMGN is minor.

### 7.4 Major Oxide Variations for Sudbury Offset Dikes and Embayments
The major oxide data for the entire set of offset dikes and embayments in the Sudbury area has a significant amount of overlap and scatter. Only Al₂O₃ vs. MgO and SiO₂ vs. MgO will be discussed in detail. The remaining graphs are very similar to these two elements and can be summarized in relation to them. In general, the offset environments split into two overlapping but distinguishable groups. The first group includes the South Range offset environments: the Worthington offset, Creighton embayment, Vermillion offset, and the Copper Cliff offset and embayment. The second group consists of offset environments from the North Range: the Parkin offset, Ministic offset, the Foy offset and the Manchester offset, which is the exception to the rule as it is a South Range offset. The two groups are indistinguishable for Al₂O₃ but separate into a high silica group (North Range) and a low silica group (South Range).

In addition to low silica, the South Range group is depleted in K₂O. The South Range group also has elevated Fe₂O₃, CaO, TiO₂ and P₂O₅ compared to the North range group. The plots for Na₂O and MnO were much like that for Al₂O₃ in that there was no discernible relationship between the various offset environments.

The dependence of Al₂O₃ on MgO for all of the dikes and embayments from the Sudbury area is shown in Figure 26. There is little distinction between most of the offset dikes with respect to Al₂O₃. However the Copper Cliff data, both embayment and dike, have higher Al₂O₃ contents than all the other offsets. The high Al Copper Cliff rocks generally have greater than 15 wt. % Al₂O₃ while the other offsets all have between 12.5 to 15 wt. %. The one striking observation is that the Copper Cliff dike material plots in the same region as the high Al QMD from the Copper Cliff embayment. The samples collected from the Copper Cliff dike were taken from locations with little sulphide and few inclusions.

The dependence of silica on MgO for data representing the entire group of offset dikes and embayments in the SIC is shown in Figure 27. The offset dikes tend to split into two groups with respect to SiO₂. The high silica group are predominantly from the North Range and consists of the QD from the Parkin, Manchester, Ministic and Foy offsets which all have greater than 58 wt. % SiO₂. The second group, all from the South Range, consists of the Worthington, Creighton, Vermillion and the Copper Cliff offset dikes and the Copper Cliff embayment which all have less than 58 wt. % SiO₂. The data from the Copper Cliff dike and the rocks from the embayment not related to inclusion and gossan rich outcrops all cluster between 55 and 58 % SiO₂. The data from drill core and from gossan/inclusion rich outcrops at the surface show large scatter and tends to be silica depleted, even in comparison to the other QMD rocks from the Copper Cliff embayment.
8 Discussion

The major points to consider up to this point are that the QMD appears to be a quenched liquid both from its diabasic texture and from its geochemical composition. The QMD is very similar to the liquid composition determined by Ames (2000) for the least altered Onaping glass. The QMGN and GN appear to be cumulates derived from the residual melt from the crystallization of the QMD. This is based on their mesocumulate to adcumulate texture and their geochemical relationship to the QMD. The QMGN and GN have strong trendlines towards the more mafic cumulates rocks of the SIC. This trend may be explained by equilibrium fractionation and crystal accumulation of orthopyroxene and plagioclase from the initial composition of QMD.

There is considerable scatter in the compositions of the QMD, which is consistent with extensive local contamination. The major trendlines mentioned above do not correspond exactly with a simple crystal accumulation trend and the deviation from it cannot be easily explained except in terms on contamination. The trendlines are skewed in the direction on both the inclusion populations of the Copper Cliff embayment and the country rocks that surround the embayment.

Possible the most interesting finding is that there appear to be two separate magmatic lineages derived from two completely distinct starting liquids. The first lineage referred to as the "low Al" group shows simple opx accumulation, whereas the second lineage referred to as the "high Al" group shows opx-plag accumulation. These major findings, their relevance and importance will be discussed further in the following sections.

8.1 Relationship between QMD, QMGN, and GN within the Copper Cliff Embayment

The diabasic texture of the quartz monzodiorite of the Copper Cliff embayment indicates that it is a quenched liquid. Its extreme geochemical heterogeneity suggests that it has assimilated a considerable amount of country rock. Alternatively, it may be considered to be an incompletely homogenized impact melt. This is best illustrated by the geochemical heterogeneity between samples within meters of each other within the same outcrop. There is as much variability in the data for major oxides, trace elements or REE from the 75 m Traverse #2 on the west side of the embayment as there is in the synthetic traverse across the entire embayment. This, the abundance of inclusions, and the complexly interfingered contact of the QMD with the brecciated
country rock indicate that local contamination played a significant role in the composition of the embayment rocks. The small-scale heterogeneity moving away from the contact and the general lack of inclusions other than the brecciated zones at the margins seems to also point to local contamination. Inclusions of country rock may have been small enough and the heat in the system high enough to have completely digested the small inclusions in the QMGN and GN.

The major geochemical heterogeneity for all elements that was found for Traverse #2 is not evident in hand specimen or at the outcrop scale between samples less than 1 meter apart. There may have been large inclusions suspended in the matrix that the thick weathering rind on all the outcrop surfaces may have hidden. The likelihood that any such large inclusions went undiscovered is low considering the number of fresh pieces investigated. It is more likely that there were many smaller inclusions that were completed assimilated by the crystallizing QMGN and GN but that the magma was not thoroughly mixed after this occurred.

The QMGN and GN appear to be cumulate rocks derived from the residual liquid left after the rapid crystallization of the QMD along the margins of the embayment. The very similar incompatible element trends displayed by the QMD, QMGN and GN despite the effects of local contamination indicate that all three came from the same magma source. Additional evidence to support that the QMD, QMGN and GN are genetically related is their similarity petrologically. Their pyroxene composition, which varies less than a few wt% for all rock types, and the presence of blue quartz in the transitional rocks between the QMD and the QMGN and between the QMGN and GN are both prime examples. The gradational changes in grain size, quartz content, and mafic minerals from the edge of the embayment to the core without any abrupt interruptions or discontinuities also seems to support the genetic link between the three rock types and argues against their origin as separate batches of magmas.

The highly variable thickness and often discontinuous nature of the QMD may simply be the effects of local variations in temperature. The zones where there is little QMD probably retained more heat and were never truly quenched, allowing the development of cumulate-textured QMGN along the contacts rather than QMD. The areas with a relatively thicker mass of QMD were most likely the regions which cooled relatively rapidly. This may be an effect of heterogeneous temperature distribution in the country rocks after the Sudbury Impact, or simply a function of the embayment contact geometry, where the projecting nature of the contact allowed the more rapid cooling of magma confined in the embayment. There are several instances of extremely
irregular gradational contacts within the Embayment (Figure 6). There are large fingers of QMD in QMGN and vice versa, as well as fingers of QMGN into GN. These fingers are most likely attributable to the heterogeneous heat distribution within the residual melt during crystallization. It may also possibly be the result of more than one pulse of magma into the system or of erosion of early-formed cumulates by magma convection. This will be considered further in the section concerning the formation and genesis of the Copper Cliff dike and embayment. Considering the large variety in grain size and the geochemical signature within the QMD (as well as the QMGN and GN) it is most likely that a combination of contact geometry and pods of country rocks entrained in the melt contributed to the present form of the QMD. Zones containing greater amounts of country rock inclusions should tend to show the greatest heterogeneity as well as the thickest mass of QMD because larger numbers of cold inclusions would promote faster cooling.

Texturally the QMGN is a mesocumulate with plagioclase and opx forming the cumulus grains and quartz plus accessory minerals forming the intercumulus material, whereas the GN is an orthocumulate with a higher percentage of mafic minerals and much less quartz. These rocks represent an increasing temperature gradient from the margins of the embayment to its core, which continues towards the core of the SIC.

Although genetically linked, the QMD is significantly different from the other rocks of the Copper Cliff embayment. Since the QMD is a quenched rock and the QMGN and GN are the result of crystal accumulation processes, there should be very noticeable distinction between them. The QMD tends to show elevated SiO₂, Na₂O, P₂O₅, K₂O, all of the REE analyzed for, and the trace elements F, Hf, Nb, Rb, Ta, Th, Y, and Zr. The QMD tends to be depleted of the rest of the major oxides, and Cl, Co and Cr. The elevated silica and sodium are most likely the result of the silica and plagioclase content of the QMD compared to the QMGN and GN which have significantly higher amounts of mafic minerals. The increase in MgO and Fe₂O₃ from the QMD to the GN in the core most likely represents the same trend, i.e. the decrease in plagioclase and quartz and the increase in mafic minerals. The REE and trace elements, which are elevated in the QMD, tend to be incompatible elements rejected by crystallizing opx and plag and are most likely depleted in the QMGN and GN relative to the QMD due to dilution by cumulus phases.
8.2 Relationship between the Copper Cliff Embayment and the Offset Dikes of the SIC

There are clear similarities between the offset dikes of the South Range of the SIC and those of the North Range of the SIC. The South Range offsets which are geochemically similar include the Worthington, Vermillion, Creighton embayment, and both the Copper Cliff dike and embayment. The Foy, Whistle/Parkin, and Ministic offsets, which all occur in the North Range resemble the Manchester offset, which occurs in the South Range. The South Range group, apart from Manchester, have low SiO₂ and K₂O and high Fe₂O₃, MnO, TiO₂, CaO, and MgO. The similarities in composition between the offsets in the South Range and their difference in comparison to those of the North Range and the Manchester offset may be the result of the nature of the country rocks into which they have intruded (c.f., Grant and Bite, 1984). With the exception of the Manchester offset, all of the South Range offsets intrude into the same country rocks: mainly mafic metavolcanic and metasediments of the Elliot Lake Group. The Manchester offset occurs in sediments of the Quirke Lake Group. The North range offsets intrude predominantly migmatites and felsic plutonic rocks except for the Parkin offset which intrudes mafic metavolcanics, Nipissing intrusives and the same sediments of the Quirke Lake group that the Manchester offset occurs in.

The initial compositional difference that the country rocks may have imparted between the North and South range offsets may have been further exaggerated by the metamorphic alteration of the entire South Range. Assimilation of more mafic country rocks would be more difficult than assimilation of granitic country rocks (Grant and Bite 1984) and consequently the amount of contamination may be a function of the type of country rock the offset intrudes into. The reason that the Manchester offset is so different from the other offsets may be that it is the only offset to have no inclusion-bearing QD. This may have something to do with its distinction from the South Range offsets in general and all of the offsets in terms of Na₂O.

The low Al QMD rocks of the Copper Cliff embayment are unlike most of the other QD rocks from the other offsets. They tend to have lower SiO₂, lower Al₂O₃, and higher MgO and Fe₂O₃ than all of the other offsets except for some of the Worthington offset rocks. This could be a product of contamination, since most of the low Al QMD samples occur closest to mafic metavolcanics which if they could be assimilated would increase the MgO and Fe₂O₃ concentrations and reduce the abundances of SiO₂ and Na₂O. None of the other offset dike rocks in the Sudbury area are compositionally like the distal portions of the Copper Cliff dike. There are some similarities between the low Al QMD of the embayment and the distal part
of the offset but the similarites are not very strong. They both have depleted SiO₂ and elevated MgO, CaO, and Fe₂O₃ (Table #7). The abundances are much different, suggesting a link between the two or any other rock in the Copper Cliff embayment would be pure speculation.

Although there are no two offsets that have exactly the same composition, petrological, structural, and geochemical similarities between offsets suggest a common magma source for all of the dikes and embayments. The similarities in structure in that all (except the Manchester) have an inclusion rich core and a fine grained inclusion poor margin, indicate that all of the dikes were probably emplaced in a very similar manner. The geochemical similarities between all of the offsets despite the difference in the host rocks that they intrude into also suggest a common magma origin. The minor differences between the offsets may be explained by local contamination differences. The differences between the North Range and the South Range offsets can be explained by the level of alteration in the South Range compared to the North Range and again the differences in the type of rocks that the offsets intrude into.

8.3 Relationship between the Copper Cliff Embayment rocks and the Main Mass

The relationship between the rocks of the Copper Cliff embayment with the rest of the SIC is a contentious one. Pattison (1979) believed that the sublayer (offset filling material) was emplaced before the crystallization of the SIC, whereas Souch et al (1969) contended that the offset material and the norites of the SIC formed simultaneously. The picture is complicated further by the possibility is that there is more than phase of QMD (QD) within the offsets. The first may represent the earliest crystallizing phase of the SIC and the second would presumably represent the magma of the SIC at some later time in its crystallization history. The SIC rocks would then represent the rocks produced by crystal accumulation and crystal fractionation from the residual liquid after the initial crystallization of the QMD. The evidence is strongly in favor of the latter scenario. This will be addressed further in the final discussion section, which deals with possible models for the formation of the Copper Cliff offset and embayment.

The QMD from the Copper Cliff embayment when plotted with the other major rocks types of the SIC always plots at or near the beginning of the crystal accumulation trend from plagioclase rich rocks (granophyre) to the more mafic opx rich rocks (mafic norite, melanorite). The QMD fits the trend very well although there is probably a large contaminant influence on not only the composition of the QMD but all of the rocks of the SIC.
The QMGN and GN of the Copper Cliff embayment are most closely related to the QRNR and SRNR of the Main Mass. The major differences between the Copper Cliff QMGN and GN to the QRNR and SRNR are in the trends for Na$_2$O, Fe$_2$O$_3$, CaO and MgO. The Copper Cliff rocks show a definite trend for Na$_2$O, Fe$_2$O$_3$ and CaO where the QMD has high values and the QMGN and GN have lower values. The Murray Mine Traverse has high Na in the QD and the SRNR but low Na in the QRNR. The Fe values are low in the QD and SRNR but high in the QRNR. The Ca values are low in the QD and high for both the QRNR and SRNR. The QMD from the Copper Cliff embayment has low MgO values while the QMGN and GN have higher values. The data from the Murray Mine Traverse indicates that the QRNR has the highest MgO values while the QD has medium levels and the SRNR has the lowest MgO values. The explanation for the differences for these trends is most likely due to the QRNR from the Murray Mine Traverse being low Al while both the QD and SRNR are not. When the Murray Mine Traverse trends are compared to the Copper Cliff rocks in light of this characteristic the trends make sense since the low Al samples tend to have higher MgO, Fe$_2$O$_3$, CaO and lower Na$_2$O.

In all other trends, the Murray Mine rocks match the Copper Cliff rocks, and in most cases have the same abundances. An average of the Major Oxide abundances for the Copper Cliff rocks and the QRNR and SRNR are shown in Table 6. There is little, if any difference between the rock types in hand samples except that the grain size for both the QMGN and GN is slightly finer than for the corresponding main mass rocks. The differences in the geochemical trends is most likely not a matter of contamination differences since both the Copper Cliff embayment and the main mass rocks from the Murray Mine Historical Site occur near similar rocks of the Elsie Mtn Fm.

The low Al GN from the Copper Cliff embayment is geochemically very similar to the ITSM from the Whistle, McCreedy West and Frasier Mines and to the less MgO-rich melanorites and mafic norites from the North Range. The high Al QMGN and GN are very similar to the ITSM from the Creighton, Crean Hill and Little Stobie Mines. However based on the parallel REE patterns of the SIC rocks and the Copper Cliff rocks (Figure 25), the excellent geochemical correlation between the less mafic norites of the main mass and the Copper Cliff norites (Figure 14b), and the petrological similarities between the QMGN and GN to the QRNR and the SRNR, it is clear that there is a strong relationship between them. The Copper Cliff QMGN and GN most likely formed by crystal accumulation into strongly contaminated QMD magma after the rapid crystallization of the QMD at the margins of the embayment. This is seen most strongly by the trends for Al$_2$O$_3$.
vs. MgO, SiO₂ vs. MgO and Fe₂O₃ vs. MgO shown in Figures 12a, 14a and 15a respectively. The difference then between the Copper Cliff norites and the norites of the lower Main Mass in the South Range is probably the degree of contamination undergone by the initial liquid and the amount of time available for crystallization and crystal sorting processes. The Copper Cliff rocks were most likely more strongly influenced by contaminants since they formed in a more confined environment. The Copper Cliff rocks also probably cooled much faster than their main mass counterparts, again most likely due to the confined crystallization environment. The similarity of the low Al rocks from the Copper Cliff embayment to the ITSM associated with other sublayer deposits suggests that all were formed as a result of the operation of similar processes.

The low Al and high Al samples from Copper Cliff appear to have been formed by two distinct magma sources. This is evident in most of the major oxide plots, but most clearly in the plot of Al₂O₃ vs. MgO (Figure 12a). There is a clear gap between the low Al and high Al samples at approximately 15 wt% Al₂O₃. Neither the low Al QMD nor the high Al QMD have compositions which match exactly that of the initial liquid composition of the Onaping glass (Ames, 2000). The evidence for two separate initial magma compositions is also apparent in plots of MgO, and Na₂O variation with distance for the Murray Mine Traverse.

The position of low Al samples directly adjacent to high Al samples with little visible petrological difference is puzzling. There may have been more than one pulse of magma into the embayment, which could account for the geochemical differences but not the petrological similarities. A second possible cause is the hydrothermal alteration of the already crystallized rocks. For example the highly mobile alkalis, could have been remobilized and concentrated during the greenschist metamorphism of the area. This would be consistent with the lack of difference between the low Al and high Al rocks in terms of the REE, and other immobile elements. However, the relative immobility of Al₂O₃ during metamorphism suggests that the differences are largely primary in origin. The remobilization of elements during metamorphism would not likely affect the crystal accumulation trends that are evident in the major oxide plots.

8.4 Copper Cliff Embayment and Dike Formation Model

The crystallization history and genesis of the offset dikes and embayments is a subject that has received considerable attention (Pattison, 1979, Grant and Bite, 1984, Dressler, 1984, Morris and Pay, 1981, Naldrett et al, 1984, Lightfoot et al 1997a,b). The timing of their formation with respect to the rest of the SIC is
both complex and confusing. There is evidence to support both an early and a late timing for the formation of the offset environments (Pattison, 1979; Grant and Bite, 1984). The data regarding the relationship between the Copper Cliff embayment, dike and the main mass of the SIC in this report may help clarify the sequence of events that formed the Sudbury structure.

There are only three possible scenarios for the formation of the Copper Cliff embayment. The first is that the embayment and the dike formed simultaneously as a single cooling unit. The second is that the dike was formed after the embayment magma was largely solidified, and the third is that the dike formed before the embayment. It seems unlikely that the embayment was formed after the dike given the stratigraphic relationship between the QMD, QMGN and GN observed in the embayment. The strongest evidence for this is occurrence of QMGN pods in both the embayment and the dike. There is no other instance of QMGN in offset dikes. If the dike had formed first then there would have to be another source for the QMGN pods. There does not appear to be any other source for these pods other for them to have come from the early crystallizing embayment. The structure of the SIC would also make it difficult for the early formation and crystallization of the dike before the formation of the embayment, unless the two were unrelated, which is clear that they are not. We are then left with two possible scenarios. In the first scenario, it is possible to consider the formation of both the embayment and the dike as either a single pulse of magma, or as more than one pulse. In the second scenario it is only possible to consider the formation of the embayment and the dike as more than one pulse, since it would be very difficult to have more than one generation of QMD contained within the dike and the embayment from a single pulse of magma.

If the dike and embayment were formed simultaneously and filled by a single pulse of magma, then there would be several characteristics that would be evident despite the metamorphism that has occurred in the South Range. The QMD within the dike and the embayment should be geochemically identical except for the local variations caused by the assimilation and contamination of country rocks, which differ in type along the length of the dike. Grant and Bite (1984) found that there were significant differences between the proximal parts of the Copper Cliff Dike and the distal parts south of Kelly Lake that could not be attributed to contamination differences. They concluded that this implies that the more mafic distal part was formed first and that a second pulse of magma formed the proximal part afterwards.
In addition to this, the single pulse of magma would then have needed to carry the inclusions of QMD and QMGN from a different location. There is no evidence for a second source of QMD and QMGN fragments other than the Copper Cliff embayment itself. Furthermore, in the case of a single pulse of liquid, there should also be no evidence of any succession of pulses, or contacts between different phases of QMD either from paleomagnetic data, field evidence, or from geochemical data. The presence of two geochemically distinct magma trends for the low Al and high Al rocks of the Copper Cliff embayment could represent two pulses of magma. The initial pulse of magma could be the high Al phase while the second one could be the low Al one, which brought with it the majority of sulphide and inclusions. In light of this it seems more likely that the Copper Cliff dike was formed by successive pulse of magma rather than just a single intrusive event. The question remains whether the dike and embayment formed simultaneously or whether they were formed as separate events.

In the case where the dike and the embayment formed simultaneously but from successive pulses of magma we would expect to see a slightly different scenario than what has been described above for the simultaneous formation from a single pulse. The initial pulse of magma would fill the embayment and dike and be quenched by the cold country rocks. This would produce the spherulitic-textured, fine-grained marginal QMD in the dike and the fine-grained QMD along the margin of the embayment. The increase in heat moving away from the contacts and towards the core of the embayment would allow the slower crystallization and accumulation of the QMGN and GN cumulates. This first pulse may be the initial more mafic pulse envisioned by Grant and Bite, which would fill the entire length of the Copper Cliff dike. The lower MgO content of the high Al group of rocks from the Copper Cliff embayment does not seem to fit with the more OPX rich QMD noted by Grant and Bite in the distal portions of the Copper Cliff dike. It is possible that there has been more than two pulses, one of which could have been this more mafic phase observed south of Kelly Lake.

The amount of time available for crystallization would be dependent on how much time elapsed between the first pulse and the second. The time available before the second pulse of magma would determine the thickness of the QMD and QMGN in the embayment. The second pulse would have to carry with it the inclusions and fragments to form the discontinuous core of inclusion rich material within the dike. In order for both QMD and QMGN to be available to be sampled by the second pulse of magma and form inclusions within the dike, there would have to be a significant amount of crystallization within the embayment and consequently
a notable amount of time between the first and second pulses of magma. The entry of the second pulse of magma along the trend of the dike without sharp crosscutting relations requires that the dike remained incompletely crystallized along its length. If there were successive pulses after the second one they too would follow the path of the first and second pulses. The low Al group of rocks from the Copper Cliff embayment could represent this second pulse of magma since they are associated with both high numbers of inclusions and a higher than average sulphide (sulphur) content.

In the second scenario where the dike and the embayment are formed at different times from several pulses of magma, the embayment would be the first feature to begin crystallization. The embayment would begin to crystallize before other areas along the contact of the SIC simply because of the distance it has intruded into the country rocks. This relief, although in many cases relatively small, would be enough to form fine-grained, inclusion-free QMD along the margin of the contact. This situation, where the embayment and dike begins as a shallow protrusion into the footwall rocks is best described by Morrison (1984) as a slump terraces along the impact crater wall. Essentially a large depression could form along the unstable crater walls by collapse of the underlying brecciated footwall rocks from the pressure of the overlying magma pool. As Millereit et al (1994) most recently pointed out, seismic data from the south range shows the contact of the SIC crater wall with the footwall rocks to be steeply dipping (45° or greater). The paleomagnetic work of Morris (1979) indicates that this present steep dip was not the condition during the formation and genesis of the SIC. Instead, the walls of the crater were dipping at somewhere from 5 to 20 degrees. Figure 28a and 28b show a modified version of Morrison's slump terraces both before and after the rotation of the South Range contact with the footwall rocks. Once the slump terraces of Morrison are rotated to the original 5-20 degrees the down and outward injection of the liquid, the crystal accumulation by gravity settling to form the norites of the main mass, and the inclusion of large rafts of country rock in both the embayment and the dike make more sense spatially. After the walls of the crater assumed their present dip, and the present erosion level is reached the surface expression of, the Copper Cliff dike and embayment also make more sense spatially.

The zones along the originally gently sloping contact with the footwall rocks would cool rapidly forming the QMD, while the core of the embayment would crystallize and accumulate the QMGN and eventually GN cumulates. After the initial crystallization within the embayment the dike would then be formed. This could be achieved by a breach in the embayment walls caused by an influx of magma, which would force
its way into the country rocks by fracturing them and thus forming the dike. Grant and Bite (1984) describe a situation where the slump terrace or embayment wall could be breached to allow the formation of the dike. They postulate that such an injection of magma could be triggered by an increase in the confining pressure within the embayment resulting from “post-cratering tectonic readjustment”. In essence, the walls of the crater would slump or cave causing an increase in the pressure within the confined space of the embayment. In this scenario, the initial influx of magma into the embayment could inject the distal mafic portion of the Copper Cliff dike and the high Al₂O₃ group of rocks. A second pulse, possibly represented by the low Al₂O₃ group of rocks, carrying partially crystalline QMD and QMGN could then be injected into the existing fracture formed by the first pulse widening it. The highest velocity zone within the core of the injecting liquid would carry and deposit the inclusions in the core of the dike forming the IQD.

Whether the Copper Cliff dike and embayment formed simultaneously or whether the embayment formed first and then the dike is difficult to establish. A possible model for formation of the Copper Cliff embayment is presented in Figures 29a, 29b, 29c. In the first step, the Sudbury crater is formed by a large meteorite impact, which also brecciates the country rock. Dilatant fracturing under a slump terrace (Morrison 1984) lying on the crater wall at an angle between 5 and 20 degrees allowed melt to intrude into the country rocks. Some crystallization of QMD and QMGN occurs along the margins of the slump contact with the relatively cool country rocks. Large blocks of material, both fragments of brecciated country rock and partially-crystalline QMD and QMGN, fall from the upper portions of the slump feature. The magma injected into the country rocks cools rapidly at its margins and forms the inclusion-free, quench textured QMD and the furthest reaching magma forms the distal, geochemically different, QMD south of Kelly Lake.

In the second step (Figure 29b) the slump feature is reactivated to permit further injection of liquid out into the country rocks. The liquid takes with it the large blocks of country rock and fragments of the previously crystallized QMD and QMGN in the core of the flow where the velocity is the highest. The liquid reuses the incompletely solidified core of the initial pulse of liquid and widens it. In the third step shown in Figure 29c (assuming only two pulses of magma) the inner core of inclusion-rich material crystallizes as a coarser grained QMD. The slump or embayment continues to crystallize as the SIC cools and forms more QMGN and GN by crystal accumulation.
The evidence from the Copper Cliff environment to support this hypothesis is firstly the presence of inclusions of an older generation of QMD and QMGN within the inclusion-rich zones of the dike and in portions of the embayment. Secondly the differing composition of the distal portions of the Copper Cliff dike cannot be accounted for by differing contaminants (Grant and Bite, 1984). Thirdly, the geochemical and petrological similarities between the proximal QD of the Copper Cliff dike and the QMD from the Copper Cliff embayment suggest that they crystallized from the same magma body. More work still needs to be done in order to determine with more confidence the sequence of events that formed the Copper Cliff dike and embayment.

9 Summary of Findings

This investigation although primarily involved with the Copper Cliff embayment has had to address the relationships between the embayment rocks and the Copper Cliff offset, the rest of the offset dikes, and the main mass of the SIC. The major findings are as follows.

i) The Copper Cliff embayment is composed of three recognizable rock types, which show gradational contacts in the field; the quartz monzodiorite, quartz monzogabbro-norite and the gabbro-norite.

ii) The QMD forms a thin discontinuous rind along the margins of the Copper Cliff embayment, and is most likely the product of a quenched liquid.

iii) The QMGN and GN are cumulates derived from the QMD.

iv) The QMD tends to show elevated SiO₂, Na₂O, P₂O₅, K₂O, all of the REE analyzed for, and for the trace elements F, Hf, Nb, Rb, Ta, Th, Y, and Zr. The QMD tends to be depleted of the rest of the major oxides, and Cl, Co and Cr.

v) There is a clear distinction between the major oxide composition of rocks that are related to mineralization and those that barren. Rocks that are inclusion rich and sulphide rich or are from underground drill core proximal to ore have low Al₂O₃ values and higher MgO values than rocks from surface that are inclusion poor and sulphide poor.

vi) The low Al and high Al QMD from the Copper Cliff embayment appear to have completely distinct initial liquid compositions, an observation supported by a similar trend from the Murray Mine Traverse.
vii) The rocks associated with mineralization from the Copper Cliff embayment are similar to the ITSM from the Whistle embayment.
viii) A simple model to explain the genesis of the Copper Cliff environment was developed. It appears that the Copper Cliff embayment and the offset were formed simultaneously, but contain multiple pulses of magma.
ix) The low Al and high Al groups of rocks from the Copper Cliff Embayment could represent multiple pulses of magma.
x) Inclusions of QMD in QMGN within the embayment imply that there was a significant amount of crystallization within the embayment before the final formation and crystallization of the Copper Cliff offset dike.
xi) The Copper Cliff embayment resembles geochemically the other South Range offset dikes and is dissimilar geochemically to the North Range offsets.
xii) There appears to have been a massive amount of local contamination of the Copper Cliff embayment rocks, as evidenced by the small-scale geochemical heterogeneity of the rocks.
xiii) The Copper Cliff rocks fit an overall crystallization trend for the entire Sudbury Igneous Complex. They fit between the granophyre and the melanorite (mafic norite).
xiv) The Copper Cliff rocks have similar trace element abundances and REE patterns to those of the main mass rocks indicating that they probably came from the same magma source.

10 Future Work

Although this was a comprehensive study of the Copper Cliff embayment, there are still many issues that need to be addressed before a clear picture of the genesis of the offset environments is complete. The relationship between the distal portion of the Copper Cliff offset, the inclusion-free quartz monzodiorite and the inclusion-rich quartz monzodiorite of the proximal Copper Cliff offset and the Copper Cliff embayment should be further investigated in full. This would require a more complete analysis of both the distal and proximal portions of the dike, which could then be combined with the data from this report. Specifically the composition of the fragments of QMD and QMGN within the QMD of the offset and embayment should be analyzed to determine their origin.
More work should be done to determine if there is the same distinction between rocks with low Al$_2$O$_3$ large numbers of inclusions and higher than average sulphide content and rocks that have high Al$_2$O$_3$, and no association with inclusion or sulphide as has been found in the Copper Cliff embayment, in other offset environments. If this relationship should prove to be common to more than just the Copper Cliff embayment then an attempt should be made to refine this tool for possible use in exploration.

A closer look should be taken at the structural discontinuity that runs NE-SW through the Copper Cliff embayment and its possible expression at depth. The inclusion population from adjacent to this structure should also be looked at in more detail. If possible a larger sample set should be analyzed and their relationship to the SIC and the Copper Cliff embayment determined. There should also be an attempt to determine the amount of contamination that has occurred in the Copper Cliff embayment. Furthermore, it is vital to know if that contamination is primarily from the assimilation of country rocks or primarily from the inclusion population some of which are not locally derived rocks.
11 References


Coleman, A.P. The Nickel Industry with Special Reference to the Sudbury Region, Ontario: Ottawa Government Printing Bureau. 1913


Dressler, B.O., General Geology of the Sudbury Area. OGS Special Volume 1. 1984. Chapter 4. 1984


Lightfoot, P.C., Doherty, W., Farrell, K., Keays, RR., Moore, M., Pekeski, D. Geochemistry of the Main Mass, Sublayer, Offsets, and Inclusions from the Sudbury Igneous Complex, Ontario. OGS OFR 5959. 1997a


Streckeisen, A., To each plutonic rock its proper name. Earth-Science Reviews, 12, 1-33. 1976


Yates, A.B. The Sudbury Intrusive; Royal Society of Canada Transactions, 3rd Series, Section 4, 32, 1938. p. 151-172
1) Reproducibility for the XRF at the University of Toronto. Ten pressed powder pellets from the same sample were run and the results indicate a good precision.

2) Analysis of precision for data obtained by fused glass disc at the University of McGill. The data represents three groups of 100 samples each. The data within a group has good precision, as does the data between groups.

3) Measure of precision for INAA at the University of Toronto. A sample of the in-house standard UTB2 was sent with every 10 samples for irradiation.

4) Results from analysis of rock standards, and their comparison with international standards of the same rock type. The Sudbury samples all have elevated silica in comparison to international standards of the same rock type.

5) Geochemical analysis of orthopyroxene from the Copper Cliff embayment by electron microprobe analysis. There is no indication of zoning within the OPX grains, and all analyses indicate clinoenstatite as the OPX species. MINPET software was used to determine OPX species.

6) Table of average rock compositions from the Copper Cliff environment and from several rock types from the main mass of the SIC.
Table #1
Reproducibility of data on XRF at UoT. 10 runs of the same powder, represents 100% of sample, no sieving or mechanical sorting.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sum of conc. (%)</th>
<th>Na2O (%)</th>
<th>MgO (%)</th>
<th>Al2O3 (%)</th>
<th>SiO2 (%)</th>
<th>P2O5 (%)</th>
<th>K2O (%)</th>
<th>CaO (%)</th>
<th>TiO2 (%)</th>
<th>MnO (%)</th>
<th>Fe2O3 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>2.1</td>
<td>6.4</td>
<td>12.3</td>
<td>48.3</td>
<td>0.3</td>
<td>1.7</td>
<td>5.4</td>
<td>0.7</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>2.1</td>
<td>6.3</td>
<td>12.4</td>
<td>48.4</td>
<td>0.2</td>
<td>1.7</td>
<td>5.2</td>
<td>0.7</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>3</td>
<td>99.997</td>
<td>2.2</td>
<td>6.5</td>
<td>12.4</td>
<td>48.6</td>
<td>0.2</td>
<td>1.7</td>
<td>5.3</td>
<td>0.7</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>4</td>
<td>100.002</td>
<td>2.1</td>
<td>6.5</td>
<td>12.3</td>
<td>48.2</td>
<td>0.2</td>
<td>1.7</td>
<td>5.3</td>
<td>0.7</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>99.998</td>
<td>2.1</td>
<td>6.5</td>
<td>12.3</td>
<td>48.3</td>
<td>0.2</td>
<td>1.7</td>
<td>5.3</td>
<td>0.7</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>6</td>
<td>99.997</td>
<td>2.1</td>
<td>6.5</td>
<td>12.4</td>
<td>48.6</td>
<td>0.2</td>
<td>1.7</td>
<td>5.3</td>
<td>0.7</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>7</td>
<td>100.006</td>
<td>2.1</td>
<td>6.5</td>
<td>12.2</td>
<td>47.5</td>
<td>0.2</td>
<td>1.7</td>
<td>5.3</td>
<td>0.7</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>8</td>
<td>99.998</td>
<td>2.1</td>
<td>6.3</td>
<td>12.1</td>
<td>47.6</td>
<td>0.3</td>
<td>1.7</td>
<td>5.3</td>
<td>0.7</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>9</td>
<td>100</td>
<td>2.1</td>
<td>6.3</td>
<td>12.1</td>
<td>47.6</td>
<td>0.3</td>
<td>1.7</td>
<td>5.3</td>
<td>0.7</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>10</td>
<td>99.993</td>
<td>2.1</td>
<td>6.4</td>
<td>12.4</td>
<td>48.7</td>
<td>0.3</td>
<td>1.7</td>
<td>5.4</td>
<td>0.7</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Avg.</strong></td>
<td><strong>2.11</strong></td>
<td><strong>6.43</strong></td>
<td><strong>12.35</strong></td>
<td><strong>48.93</strong></td>
<td><strong>0.24</strong></td>
<td><strong>1.7</strong></td>
<td><strong>5.3</strong></td>
<td><strong>0.7</strong></td>
<td><strong>0.7</strong></td>
<td><strong>0.1</strong></td>
<td><strong>8.1</strong></td>
</tr>
</tbody>
</table>

| 1 Std. Dev. | 0.032 | 0.082 | 0.143 | 0.004 | 0.082 | 0.000 | 0.057 | 0.000 | 0.090 | 0.110 |
| 2 Std. Dev. | 0.08 | 0.18 | 0.28 | 0.12 | 0.21 | 0.10 | 0.00 | 0.11 | 0.00 | 0.23 |

Table #2
Reproducibility of data on XRF at UoT. 10 runs of the same powder, represents 100% of sample, no sieving or mechanical sorting.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>Y (ppm)</th>
<th>Zr (ppm)</th>
<th>Nb (ppm)</th>
<th>Th (ppm)</th>
<th>U (ppm)</th>
<th>V (ppm)</th>
<th>Cr (ppm)</th>
<th>Ni (ppm)</th>
<th>Ba (ppm)</th>
<th>H2O (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40.6</td>
<td>338.3</td>
<td>16.3</td>
<td>56.0</td>
<td>31.0</td>
<td>5.6</td>
<td>0.2</td>
<td>168.4</td>
<td>470.9</td>
<td>158.5</td>
<td>531.2</td>
<td>14.42</td>
</tr>
<tr>
<td>2</td>
<td>39.8</td>
<td>331.8</td>
<td>16.0</td>
<td>56.0</td>
<td>32.0</td>
<td>5.6</td>
<td>0.2</td>
<td>167.4</td>
<td>476.4</td>
<td>158.3</td>
<td>534.1</td>
<td>16.53</td>
</tr>
<tr>
<td>3</td>
<td>41.3</td>
<td>337.0</td>
<td>16.2</td>
<td>62.0</td>
<td>34.4</td>
<td>4.1</td>
<td>0.9</td>
<td>171.1</td>
<td>472.7</td>
<td>159.9</td>
<td>542.3</td>
<td>13.98</td>
</tr>
<tr>
<td>4</td>
<td>40.6</td>
<td>334.5</td>
<td>16.2</td>
<td>56.5</td>
<td>33.5</td>
<td>4.3</td>
<td>1.2</td>
<td>170.2</td>
<td>478.5</td>
<td>159.1</td>
<td>556.8</td>
<td>14.46</td>
</tr>
<tr>
<td>5</td>
<td>40.9</td>
<td>339.1</td>
<td>15.9</td>
<td>57.0</td>
<td>35.1</td>
<td>5.1</td>
<td>1.4</td>
<td>172.4</td>
<td>478.8</td>
<td>157.8</td>
<td>546.8</td>
<td>14.23</td>
</tr>
<tr>
<td>6</td>
<td>40.6</td>
<td>338.9</td>
<td>16.8</td>
<td>56.5</td>
<td>35.7</td>
<td>5.1</td>
<td>3</td>
<td>171.9</td>
<td>472.3</td>
<td>157.4</td>
<td>546.8</td>
<td>13.59</td>
</tr>
<tr>
<td>7</td>
<td>41.1</td>
<td>334.1</td>
<td>16.1</td>
<td>64.4</td>
<td>33.7</td>
<td>6.2</td>
<td>1.6</td>
<td>175.7</td>
<td>478.8</td>
<td>180.5</td>
<td>551.7</td>
<td>15.23</td>
</tr>
<tr>
<td>8</td>
<td>40.6</td>
<td>333.8</td>
<td>16.5</td>
<td>53.5</td>
<td>32.3</td>
<td>5.3</td>
<td>0.6</td>
<td>173.3</td>
<td>469.8</td>
<td>159.4</td>
<td>523.2</td>
<td>15.65</td>
</tr>
<tr>
<td>9</td>
<td>39.5</td>
<td>335.3</td>
<td>16.4</td>
<td>49.2</td>
<td>34.4</td>
<td>5.2</td>
<td>0.7</td>
<td>167.7</td>
<td>470.1</td>
<td>159.9</td>
<td>537.2</td>
<td>15.50</td>
</tr>
<tr>
<td>10</td>
<td>40.6</td>
<td>338.5</td>
<td>16.2</td>
<td>61.4</td>
<td>36.9</td>
<td>4.3</td>
<td>2.4</td>
<td>167.9</td>
<td>471.1</td>
<td>156.2</td>
<td>541.8</td>
<td>13.93</td>
</tr>
<tr>
<td><strong>Avg.</strong></td>
<td><strong>40.6</strong></td>
<td><strong>337.2</strong></td>
<td><strong>16.3</strong></td>
<td><strong>57.8</strong></td>
<td><strong>34.9</strong></td>
<td><strong>6.02</strong></td>
<td><strong>1.97</strong></td>
<td><strong>171.5</strong></td>
<td><strong>473.4</strong></td>
<td><strong>157.9</strong></td>
<td><strong>540.9</strong></td>
<td><strong>14.79</strong></td>
</tr>
</tbody>
</table>

| 1 Std. Dev. | 0.875 | 2.816 | 0.298 | 5.328 | 1.865 | 0.844 | 0.838 | 2.128 | 3.166 | 1.442 | 9.722 | 0.942 |
| 2 Std. Dev. | 1.15  | 5.42  | 0.83  | 9.08  | 3.13  | 1.28  | 1.87  | 4.34  | 6.40  | 2.88  | 19.45  | 1.88   |
Check for accuracy and precision of data from McGill University, samples analyzed on fused bead by XRF

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Description</th>
<th>SiO₂ F.B. (%)</th>
<th>Al₂O₃ F.B. (%)</th>
<th>MnO F.B. (%)</th>
<th>MgO F.B. (%)</th>
<th>CaO F.B. (%)</th>
<th>Na₂O F.B. (%)</th>
<th>K₂O F.B. (%)</th>
<th>TiO₂ F.B. (%)</th>
<th>P₂O₅ F.B. (%)</th>
<th>Fe₂O₃ F.B. (%)</th>
<th>LOI F.B. (%)</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCA1-UTA1</td>
<td>UTA1</td>
<td>61.35</td>
<td>18.17</td>
<td>0.081</td>
<td>2.52</td>
<td>5.96</td>
<td>4.22</td>
<td>1.74</td>
<td>0.827</td>
<td>0.193</td>
<td>5.29</td>
<td>-0.06</td>
<td>100.291</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>-0.87</td>
<td>-2.66</td>
<td>-15.71</td>
<td>-8.77</td>
<td>2.30</td>
<td>0.24</td>
<td>2.79</td>
<td>-1.86</td>
<td>2.04</td>
<td>116.87</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>CC400-UTG1</td>
<td>UTG1</td>
<td>70.82</td>
<td>14.78</td>
<td>0.034</td>
<td>0.81</td>
<td>1.60</td>
<td>4.17</td>
<td>4.20</td>
<td>0.343</td>
<td>0.106</td>
<td>2.06</td>
<td>0.98</td>
<td>98.903</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>0.81</td>
<td>-3.00</td>
<td>-13.33</td>
<td>-22.90</td>
<td>-3.23</td>
<td>-2.46</td>
<td>3.67</td>
<td>-2.94</td>
<td>-17.78</td>
<td>-13.81</td>
<td>-22.80</td>
<td>-0.82</td>
</tr>
<tr>
<td>CC582-UTB2</td>
<td>UTB2</td>
<td>55.99</td>
<td>13.66</td>
<td>0.181</td>
<td>3.33</td>
<td>6.70</td>
<td>3.33</td>
<td>1.93</td>
<td>0.316</td>
<td>0.126</td>
<td>12.65</td>
<td>0.58</td>
<td>100.881</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>55.95</td>
<td>13.66</td>
<td>0.16</td>
<td>3.32</td>
<td>6.73</td>
<td>3.28</td>
<td>1.93</td>
<td>0.315</td>
<td>0.122</td>
<td>12.84</td>
<td>0.55</td>
<td>100.43</td>
</tr>
<tr>
<td></td>
<td>1 Std. Dev</td>
<td>0.06</td>
<td>0.00</td>
<td>0.02</td>
<td>0.04</td>
<td>0.07</td>
<td>0.20</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 Std. Dev</td>
<td>0.13</td>
<td>0.00</td>
<td>0.001</td>
<td>0.04</td>
<td>0.07</td>
<td>0.20</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>UTB2 Standard</td>
<td>66.2</td>
<td>13.4</td>
<td>0.19</td>
<td>3.2</td>
<td>6.8</td>
<td>3.06</td>
<td>1.95</td>
<td>0.31</td>
<td>12.7</td>
<td>1.89</td>
<td></td>
<td>100.34</td>
</tr>
<tr>
<td></td>
<td>Error</td>
<td>-1.38</td>
<td>-1.94</td>
<td>4.47</td>
<td>-3.88</td>
<td>1.10</td>
<td>-6.84</td>
<td>1.03</td>
<td>1.67</td>
<td>-1.77</td>
<td>0.81</td>
<td>88.41</td>
<td></td>
</tr>
<tr>
<td>CC18-1</td>
<td>SRNR</td>
<td>57.35</td>
<td>17.24</td>
<td>0.109</td>
<td>5.61</td>
<td>6.79</td>
<td>2.98</td>
<td>1.37</td>
<td>0.488</td>
<td>0.182</td>
<td>7.30</td>
<td>1.04</td>
<td>100.44</td>
</tr>
<tr>
<td></td>
<td>Difference</td>
<td>0.22</td>
<td>0.17</td>
<td>0.00</td>
<td>0.01</td>
<td>0.04</td>
<td>0.01</td>
<td>0.04</td>
<td>0.01</td>
<td>0.01</td>
<td>0.06</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>CC214-1</td>
<td>Quartz Diorite</td>
<td>56.18</td>
<td>16.12</td>
<td>0.123</td>
<td>4.46</td>
<td>5.90</td>
<td>3.18</td>
<td>2.28</td>
<td>0.803</td>
<td>0.204</td>
<td>9.76</td>
<td>0.83</td>
<td>99.60</td>
</tr>
<tr>
<td></td>
<td>CheckFBXRF</td>
<td>56.67</td>
<td>16.00</td>
<td>0.123</td>
<td>4.55</td>
<td>5.87</td>
<td>3.35</td>
<td>2.25</td>
<td>0.768</td>
<td>0.126</td>
<td>9.69</td>
<td>0.65</td>
<td>99.28</td>
</tr>
<tr>
<td></td>
<td>Difference</td>
<td>0.41</td>
<td>0.12</td>
<td>0.00</td>
<td>0.10</td>
<td>0.03</td>
<td>0.17</td>
<td>0.01</td>
<td>0.02</td>
<td>0.00</td>
<td>0.07</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>CC432-CC97171-1000</td>
<td>56.30</td>
<td>11.58</td>
<td>0.174</td>
<td>11.35</td>
<td>4.56</td>
<td>2.15</td>
<td>1.41</td>
<td>0.449</td>
<td>0.115</td>
<td>9.71</td>
<td>2.22</td>
<td>100.018</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Difference</td>
<td>0.06</td>
<td>0.01</td>
<td>0.00</td>
<td>0.04</td>
<td>0.01</td>
<td>0.09</td>
<td>0.00</td>
<td>0.02</td>
<td>0.03</td>
<td>0.04</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>CC501-CC97171-1000</td>
<td>56.35</td>
<td>11.57</td>
<td>0.170</td>
<td>11.39</td>
<td>4.55</td>
<td>2.24</td>
<td>1.41</td>
<td>0.471</td>
<td>0.089</td>
<td>9.75</td>
<td>1.99</td>
<td>98.98</td>
<td></td>
</tr>
</tbody>
</table>
## Table 3

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Description</th>
<th>Cr (UAT)</th>
<th>Na (UAT)</th>
<th>K (UAT)</th>
<th>Al (UAT)</th>
<th>Fe (UAT)</th>
<th>Ni (UAT)</th>
<th>Cu (UAT)</th>
<th>Pb (UAT)</th>
<th>Zn (UAT)</th>
<th>Ag (UAT)</th>
<th>Au (UAT)</th>
<th>As (UAT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTB2 INAA Check</td>
<td>6.717</td>
<td>24.72</td>
<td>98.41</td>
<td>27.83</td>
<td>6.328</td>
<td>1.786</td>
<td>1.524</td>
<td>3.965</td>
<td>0.443</td>
<td>6.335</td>
<td>1.667</td>
<td>5.116</td>
<td>0.9462</td>
</tr>
<tr>
<td>UTB2 INAA Check</td>
<td>6.641</td>
<td>24.91</td>
<td>57.72</td>
<td>27.57</td>
<td>6.396</td>
<td>2.035</td>
<td>0.6233</td>
<td>3.271</td>
<td>0.4725</td>
<td>6.166</td>
<td>1.611</td>
<td>5.106</td>
<td>0.9326</td>
</tr>
<tr>
<td>UTB2 INAA Check</td>
<td>7.868</td>
<td>23.99</td>
<td>55.27</td>
<td>27.35</td>
<td>6.260</td>
<td>1.785</td>
<td>0.927</td>
<td>3.18</td>
<td>0.4685</td>
<td>6.344</td>
<td>1.423</td>
<td>4.508</td>
<td>0.8112</td>
</tr>
<tr>
<td>UTB2 INAA Check</td>
<td>8.928</td>
<td>24.97</td>
<td>55.30</td>
<td>3.182</td>
<td>6.310</td>
<td>1.905</td>
<td>1.119</td>
<td>3.112</td>
<td>0.4681</td>
<td>6.324</td>
<td>1.43</td>
<td>4.877</td>
<td>0.8339</td>
</tr>
<tr>
<td>UTB2 INAA Check</td>
<td>8.19</td>
<td>24.17</td>
<td>58.85</td>
<td>28.43</td>
<td>6.438</td>
<td>1.932</td>
<td>0.7454</td>
<td>3.196</td>
<td>0.4892</td>
<td>6.653</td>
<td>1.488</td>
<td>4.215</td>
<td>0.9172</td>
</tr>
<tr>
<td>UTB2 INAA Check</td>
<td>8.903</td>
<td>24.82</td>
<td>55.27</td>
<td>28.29</td>
<td>8.349</td>
<td>1.874</td>
<td>0.9648</td>
<td>3.315</td>
<td>0.5882</td>
<td>8.368</td>
<td>1.452</td>
<td>17.72</td>
<td>0.689</td>
</tr>
<tr>
<td>UTB2 INAA Check</td>
<td>9.533</td>
<td>25.53</td>
<td>57.5</td>
<td>28.23</td>
<td>6.035</td>
<td>1.875</td>
<td>1.047</td>
<td>3.53</td>
<td>0.4277</td>
<td>6.561</td>
<td>1.138</td>
<td>4.415</td>
<td>0.8488</td>
</tr>
<tr>
<td>UTB2 INAA Check</td>
<td>9.693</td>
<td>29.58</td>
<td>60.98</td>
<td>29.73</td>
<td>8.858</td>
<td>1.811</td>
<td>0.8845</td>
<td>3.428</td>
<td>0.5224</td>
<td>7.173</td>
<td>1.586</td>
<td>2.634</td>
<td>0.8764</td>
</tr>
<tr>
<td>UTB2 INAA Check</td>
<td>9.930</td>
<td>24.93</td>
<td>59.77</td>
<td>28.31</td>
<td>1.993</td>
<td>1.729</td>
<td>0.9403</td>
<td>3.254</td>
<td>0.5039</td>
<td>8.759</td>
<td>1.484</td>
<td>4.032</td>
<td>0.8477</td>
</tr>
</tbody>
</table>

**Average:**

- Cr UAT:
- Na UAT:
- K UAT:
- Al UAT:
- Fe UAT:
- Ni UAT:
- Cu UAT:
- Pb UAT:
- Zn UAT:
- Ag UAT:
- Au UAT:
- As UAT:

**1 Standard Deviation**:

- Cr UAT:
- Na UAT:
- K UAT:
- Al UAT:
- Fe UAT:
- Ni UAT:
- Cu UAT:
- Pb UAT:
- Zn UAT:
- Ag UAT:
- Au UAT:
- As UAT:

**2 Standard Deviation**:

- Cr UAT:
- Na UAT:
- K UAT:
- Al UAT:
- Fe UAT:
- Ni UAT:
- Cu UAT:
- Pb UAT:
- Zn UAT:
- Ag UAT:
- Au UAT:
- As UAT:

**Error (%)**:

- Cr UAT:
- Na UAT:
- K UAT:
- Al UAT:
- Fe UAT:
- Ni UAT:
- Cu UAT:
- Pb UAT:
- Zn UAT:
- Ag UAT:
- Au UAT:
- As UAT:
<table>
<thead>
<tr>
<th>Table 64</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| QCD | Quartile 1 (25%) | 0.018 | 0.033 | 0.038 | 0.050 | 0.060 | 0.063 | 0.064 | 0.064 | 0.066 |
| CDD | Quartile 1 (25%) | 0.011 | 0.022 | 0.030 | 0.038 | 0.046 | 0.050 | 0.053 | 0.056 | 0.060 |
| ... |

| Avg QMRR | 62.66 | 57.97 | 61.08 | 58.02 | 56.88 | 54.58 | 53.54 | 52.56 | 51.58 |
| 1 Std. Dev | 4.89 | 3.60 | 4.10 | 3.30 | 3.20 | 2.80 | 2.60 | 2.40 | 2.20 |
| 2 Std. Dev | 9.78 | 7.20 | 8.20 | 6.60 | 6.40 | 5.60 | 5.20 | 4.80 | 4.40 |

*No international standards for QMRR*
<table>
<thead>
<tr>
<th>Slice Numbers</th>
<th>OPX wt %</th>
<th>Mgo wt %</th>
<th>An2O3 wt %</th>
<th>V2O5 wt %</th>
<th>NiO wt %</th>
<th>FeO wt %</th>
<th>NiO wt %</th>
<th>Cr2O3 wt %</th>
<th>Total wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>466</td>
<td>0.002364</td>
<td>25.377936</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>468</td>
<td>0.0014182</td>
<td>25.088931</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>470</td>
<td>0.0016859</td>
<td>24.036151</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>472</td>
<td>0.00249714</td>
<td>25.317509</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>474</td>
<td>0.0052975</td>
<td>25.715924</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>476</td>
<td>0.0024017</td>
<td>25.331862</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>478</td>
<td>0.00507714</td>
<td>25.317509</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>480</td>
<td>0.0024017</td>
<td>25.331862</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>482</td>
<td>0.00507714</td>
<td>25.317509</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>484</td>
<td>0.0024017</td>
<td>25.331862</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>486</td>
<td>0.00507714</td>
<td>25.317509</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>488</td>
<td>0.0024017</td>
<td>25.331862</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>490</td>
<td>0.00507714</td>
<td>25.317509</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>492</td>
<td>0.0024017</td>
<td>25.331862</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>494</td>
<td>0.00507714</td>
<td>25.317509</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>496</td>
<td>0.0024017</td>
<td>25.331862</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>498</td>
<td>0.00507714</td>
<td>25.317509</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
<tr>
<td>500</td>
<td>0.0024017</td>
<td>25.331862</td>
<td>1.000000</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
<td>0.0018664</td>
<td>0.0034479</td>
</tr>
</tbody>
</table>

**Table 5**

OPX composition from analyses on electron microprobe at 1.e-5T.
Table #6 Average Major Oxide Compositions for Copper Cliff and selected SiC Rocks

<table>
<thead>
<tr>
<th></th>
<th>Copper Cliff Low Al Mass</th>
<th>Copper Cliff High Al Mass</th>
<th>Copper Cliff Low Al. QMGN</th>
<th>Copper Cliff High Al. QMGN</th>
<th>Main Mass QRNR</th>
<th>Copper Cliff Low Al. GN</th>
<th>Copper Cliff High Al. GN</th>
<th>Main Mass SRNR</th>
<th>Copper Cliff Dike QD</th>
<th>Copper Cliff Distal QD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>53.36</td>
<td>57.92</td>
<td>50.41</td>
<td>56.53</td>
<td>56.7</td>
<td>53.18</td>
<td>56.59</td>
<td>53.7</td>
<td>55.3</td>
<td>50.7</td>
</tr>
<tr>
<td>Al2O3</td>
<td>12.98</td>
<td>15.78</td>
<td>12.13</td>
<td>15.77</td>
<td>16.3</td>
<td>13.58</td>
<td>16.69</td>
<td>17.6</td>
<td>14.3</td>
<td>16.3</td>
</tr>
<tr>
<td>MnO</td>
<td>0.13</td>
<td>0.12</td>
<td>0.12</td>
<td>0.13</td>
<td>0.12</td>
<td>0.14</td>
<td>0.12</td>
<td>0.12</td>
<td>0.15</td>
<td>0.17</td>
</tr>
<tr>
<td>MgO</td>
<td>4.74</td>
<td>4.49</td>
<td>7.87</td>
<td>5.52</td>
<td>6.1</td>
<td>9.25</td>
<td>5.71</td>
<td>6.83</td>
<td>4.43</td>
<td>4.91</td>
</tr>
<tr>
<td>CaO</td>
<td>6.19</td>
<td>6.13</td>
<td>6.17</td>
<td>6.48</td>
<td>6.68</td>
<td>5.55</td>
<td>6.64</td>
<td>7.8</td>
<td>6.71</td>
<td>7.92</td>
</tr>
<tr>
<td>Na2O</td>
<td>2.72</td>
<td>3.19</td>
<td>2.23</td>
<td>2.95</td>
<td>2.35</td>
<td>3.17</td>
<td>2.61</td>
<td>2.76</td>
<td>1.7</td>
<td>1.66</td>
</tr>
<tr>
<td>K2O</td>
<td>1.9</td>
<td>1.97</td>
<td>1.64</td>
<td>1.65</td>
<td>1.4</td>
<td>1.37</td>
<td>1.35</td>
<td>0.96</td>
<td>1.7</td>
<td>1.66</td>
</tr>
<tr>
<td>TiO2</td>
<td>0.77</td>
<td>0.79</td>
<td>0.65</td>
<td>0.7</td>
<td>0.57</td>
<td>0.52</td>
<td>0.6</td>
<td>0.38</td>
<td>0.94</td>
<td>1.56</td>
</tr>
<tr>
<td>P2O5</td>
<td>0.2</td>
<td>0.22</td>
<td>0.21</td>
<td>0.18</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>11.23</td>
<td>8.46</td>
<td>9.77</td>
<td>9.02</td>
<td>8.27</td>
<td>10.02</td>
<td>7.87</td>
<td>7.76</td>
<td>12</td>
<td>12.7</td>
</tr>
</tbody>
</table>

QRNR, SRNR, Copper Cliff Dike, Copper Cliff Distal Values from Grant and Bite (1984)
13 Plate Captions

1) Handsample of Quartz Monzodiorite; Example of fine-grained diabasic-textured inclusion-free amphibole-biotite quartz monzodiorite from the margins of the Copper Cliff Embayment.

2) Thin Section of Quartz Monzodiorite showing fine grained diabasic texture. All pyroxene has been altered to green amphibole, primarily hornblende. Opaques are always surrounded by dark brown secondary biotite. Quartz and plagioclase make up the bulk of the slide.

3) Photo from western contact of the Copper Cliff Embayment with the Creighton Pluton. Depicted is a large pod of Creighton Granite in a fine grained quartz monzodiorite matrix. The edges of the pod are ragged and appear to have been partially assimilated by the QMD. Large plagioclase grains, coarser grain size overall and much higher proportions of quartz are common in proximity to such large pods and within several meters of the contact.

4) Quartz monzogabbronorite in handsample. This sample displays the characteristic blue quartz of the quartz rich norite or basal unit of the Main Mass of the SIC. Blue qtz grains range in size from <1 mm to 1 cm in diameter and makes up 65% of the total quartz in this sample.

5) Quartz monzogabbronorite in thin section. This sample is one of the few with intact cumulus orthopyroxene (clinoenstatite). Alteration of the rims of the opx to hornblende is common. Large zoned cumulus plagioclase grains make up 45% of the sample. Quartz, both blue and smoky grey, fill the intercumulus spaces. Biotite is mostly an alteration product and makes up less than 5% of this sample. Opaques include sulphide grains (cpy, po) magnetite and ilmenite. Chlorite and epidote are common alteration minerals.

6) Gabbronorite in handsample. This is a good example of relatively unaltered GN. It is a dark black rock containing mostly opx, amphibole, plagioclase and biotite. Quartz is smoky grey and makes up less than 5% of this sample. Most of the GN from the Copper Cliff Embayment appears much greener from the green hornblende (+ actinolite) content.

7) Gabbronorite in thin section. This is a mesocumulate textured GN with rare intact opx (thin section not the same sample as handsample described above). Cumulus plagioclase and amphibole after opx make up the bulk of this sample with minor amounts of qtz filling the intercumulus spaces. Biotite always accompanies sulphide grains, but may also occur as large grains and clots without sulphide. Amphibole is commonly hornblende and actinolite.

8a) Photo of high weathering relief inclusions from ridge of inclusion rich GN in Copper Cliff Embayment. Inclusions are mostly rounded to subrounded laminated metasediments and mafic metavolcanics. The large inclusion in the middle of the plate has a minor amount of iron oxide staining that is common to a large proportion of the inclusions. Samples tend to be very thin in the Z direction, occurring as flat discs.

8b) Photo of high weathering relief inclusions from ridge of inclusion rich GN in Copper Cliff Embayment. Included in inclusion set are laminated metasediments, mafic-ultramafic fragments, and anorthositic fragments.

9ab) Photo of low weathering relief pyroxenite and amphibolite pods from NW corner of the Copper Cliff Embayment. These inclusions occur in a wide band that extends for over 100 meters to the southern shore of Pump Lake. Inclusions range in size from 1 cm to greater than 5 meters in length. The matrix is a coarse grained QMGN.

10) Photo stations CC150-1 and CC150-2. The left-hand side of the photo shows the inclusion rich (>30%) GN while the middle depicts the abrupt transition to the inclusion free GN. To the extreme right in the photo the eastern contact of the 2.5 meter wide inclusion free zone ends as abruptly as it began. Again the rock has >30% inclusions. The contact between inclusion rich and...
inclusion poor trends perpendicular to the NE-SW trending fault structure that runs across the Copper Cliff Embayment.

11) Photo of large pod of what the Author believes to be metasediment with sericitized staurolite from the McKim Fm. This pod is located near the throat of the Copper Cliff Embayment at the southern end of station CC63. The edges of the pod were obscured by the thick weathering rind so the nature of the pods contacts with the GN are unknown.

12ab) Photos of large coarse-grained QMD pod in QMGN. These photos illustrate the partially resorbed nature of the pods contacts with the QMGN. The QMD is again amphibole-biotite and is inclusion free. A sample could not be collected. Station location is CC145

13) Photo of 10 m wide band of pyroxenite pods on the NW side of the Copper Cliff Embayment. The largest pod is 5 m in length and 1 m wide, but there are pods as small as several centimeters. The inclusions are hosted in a fine-grained QMGN and make up 80-90% of the outcrop. The inclusion-rich band is not traceable north of inlet of Pump Lake or south towards the contact of the Creighton Pluton.

14ab) Photos depicting inclusion and gossan rich outcrops proximal to the Clarabelle Open Pit. The rock is believed to be GN but the extreme oxidation of the sulphides in these samples has masked the other minerals.
Plate #6

Field of View = 1.5 cm

Plate #7

Field of View = 1.5 cm

Plag.

Qtz

Amph.

OPX

Sulphide surrounded by Biotite
Figure Captions

1) Map of the general location of the Sudbury Igneous Complex. The SIC is located at the contact between the early Proterozoic aged rocks of the Southern Province and the Archean aged rocks of the Superior Province. It occurs in mostly felsic plutons, metasediments and mafic metavolcanics.

2) Generalized diagram of the SIC showing the locations of the major offsets and embayment environments. The Copper Cliff dike and embayment occur in the South Range of the SIC.

3) Diagram depicting the Copper Cliff environment in its entirety. Shown are the major mines of the Copper Cliff offset and the relevant faults that offset the dike. Also shown is the study area for this report, and the location for the standards used for this report. Samples were collected to represent possible contaminants to the Copper Cliff embayment rocks. Samples of the Creighton Granite were collected both proximal to the embayment and distally. Samples from the Copper Cliff dike were taken north of Hwy. 17 at two different locations. Elsie Mtn. Fm. samples were collected on the basis of needing both metasediment and mafic metavolcanics. The final sample location was at the Murray Mine Historical Site for samples of QRNR and SRNR.

4) Stratigraphic sections of the North and South Ranges of the SIC modified after Lightfoot et al. (1997a)

5) Diagram of a typical offset dike. The inner core is a coarse-grained inclusion-rich, sulphide-rich, quartz diorite (quartz monzodiorite). The outer rind is an inclusion-free, sulphide-poor quartz diorite. There is a variable thickness transitional zone in between the two extremes of the core and the margins. The outer rind of inclusion free QD may represent an earlier pulse of injected magma while the core may be a later pulse.

6) Geology Base map of the Copper Cliff embayment produced by Clayton Capes and Jacob Hanley. Shown is the Creighton Pluton to the west (pink) and the Elsie Mtn Fm to the East (orange). The purple along the contacts of the embayment is the QMD, the green is the QMGN and the blue is the GN.

7) Diagram showing the inclusion population of the rocks of the Copper Cliff embayment. The inclusions are clustered on the east side of the embayment and along the fault structure running NE-SW.

8) Air photo (89-4618, 32-193) of the Copper Cliff embayment. Shown by white outline is NE-SW trending fault structure that has both high levels of inclusions and sulphide.

9) Diagram showing the occurrence of gossan in the Copper Cliff embayment. Two types occur, either a pervasive gossan or a gossan related to the inclusion population. Again, the gossan tends to cluster on the East side of the embayment.

10) Station location map for the Copper Cliff embayment. 100% of the embayment was sampled. Blown up is the 75-meter traverse completed at on the west side of the embayment. Samples were taken every 5 meters..

11) Triple plot of Wo-Fs-En orthopyroxene. All of the OPX grains analyzed in this report plot in the Clinopyroxene region bordering on Pigeonite. Produced using MINPET

12a) $\text{Al}_2\text{O}_3$ vs. MgO for surface and underground samples for the Copper Cliff Embayment

12b) $\text{Al}_2\text{O}_3$ variation with distance from East to West across the Copper Cliff Embayment

12c) False colour SURFER image showing $\text{Al}_2\text{O}_3$ variation for the entire Copper Cliff Embayment
12d) $\text{Al}_2\text{O}_3$ variation with distance for the Murray Mine Traverse
12e) $\text{Al}_2\text{O}_3$ vs. $\text{MgO}$ for Copper Cliff, the Main Mass of the SIC, Inclusions and Country Rocks
13a) $\text{MgO}$ variation with distance from East to West across the Copper Cliff Embayment
13b) False colour SURFER image showing $\text{MgO}$ variation for the entire Copper Cliff Embayment
13c) $\text{MgO}$ variation for the Murray Mine Traverse
14a) $\text{SiO}_2$ vs. $\text{MgO}$ for surface and underground samples for the Copper Cliff Embayment
14b) $\text{SiO}_2$ vs. $\text{MgO}$ for the Copper Cliff environment and major rock types of the SIC
15a) $\text{Fe}_2\text{O}_3$ vs. $\text{MgO}$ for surface and drill core samples for the Copper Cliff Embayment
15b) $\text{Fe}_2\text{O}_3$ variation with distance from East to West across the Copper Cliff Embayment
15c) $\text{Fe}_2\text{O}_3$ variation for the Murray Mine Traverse
16) $\text{CaO}$ vs. $\text{MgO}$ for surface and drill core samples for the Copper Cliff Embayment
17a) $\text{Na}_2\text{O}$ vs. $\text{MgO}$ for surface and drill core samples for the Copper Cliff Embayment
17b) False colour image showing $\text{Na}_2\text{O}$ variation for the entire Copper Cliff Embayment
18a) $\text{K}_2\text{O}$ vs. $\text{MgO}$ for surface and drill core samples for the Copper Cliff Embayment
18b) $\text{K}_2\text{O}$ variation with distance from East to West across the Copper Cliff Embayment
18c) False colour image showing $\text{K}_2\text{O}$ variation for the entire Copper Cliff Embayment
19a) $\text{TiO}_2$ vs. $\text{MgO}$ for surface and drill core samples for the Copper Cliff Embayment
19b) $\text{TiO}_2$ variation with distance from East to West across the Copper Cliff Embayment
19c) False colour image showing $\text{TiO}_2$ variation for the entire Copper Cliff Embayment
19d) $\text{TiO}_2$ variation for the Murray Mine Traverse
20a) $\text{P}_2\text{O}_5$ vs. $\text{MgO}$ for surface and drill core samples for the Copper Cliff Embayment
20b) $\text{P}_2\text{O}_5$ variation with distance from East to West across the Copper Cliff Embayment
20c) False colour image showing $\text{P}_2\text{O}_5$ variation for the entire Copper Cliff Embayment
20d) $\text{P}_2\text{O}_5$ variation for the Murray Mine Traverse
21a) $\text{S}$ vs. $\text{MgO}$ for underground and surface samples from the Copper Cliff Embayment
21b) $\text{S}$ variation with distance for the entire Copper Cliff Embayment shown by false colour image
21c) $\text{S}$ variation with distance for the Murray Mine Traverse
22) $\text{Zr}$ vs. $\text{MgO}$ for surface and underground samples from the Copper Cliff Embayment
23a) Y vs. MgO for surface and underground samples from the Copper Cliff Embayment
23b) Y vs. Zr for surface and drill core samples for the Copper Cliff Embayment
23c) False colour image showing Y variation for the entire Copper Cliff Embayment
23d) Lu vs. Zr for surface samples for the Copper Cliff Embayment
24a) Lu variation with distance from East to West across the Copper Cliff Embayment
24b) Lu variation for the Murray Mine Traverse
25) CI Normalized REE Spider Plot of Copper Cliff Rocks
26) Al₂O₃ vs. MgO variation for the Offset Dikes and Embayments from the entire Sudbury region
27) SiO₂ vs. MgO variation for the Offset Dikes and Embayments from the entire Sudbury region
28ab) Diagram modified after Morrison (1984) of slump terraces which may help explain the formation and genesis of the Copper Cliff Embayment.
29abc) Diagrams showing a possible scenario for the formation of the Copper Cliff Embayment and Dike.
Middle Proterozoic Felsic plutons and complexes

Archean rocks
Felsic Plutons, Gneissic, migmatitic, metavolcanics and metasediments

Proterozoic and/or Archean Gneiss covered by Phanerozoic material

Grenville Province
Early and Middle Proterozoic Gneissic and Plutonic rocks

Early Proterozoic rocks
Huronian Supergroup
Figure #2

1     Foy Offset   6     Frood-Stobie Offset
1a    Tyrone Extension  7     Copper Cliff Offset
1b    Hess Extension   8     Creighton Offset
2     Parkin Offset   9     Vermillion Offset
2a    Whistle Embayment 10    Worthington Offset
3     MacLennan Offset 11    Trill Embayment
4     Manchester Offset 12    Ministic Offset
5     Kirkwood & McConnell
Figure #3

#1 Distal Creighton Granite Standards (unit a)
#2 Copper Cliff Dike Standards (unit b)
#3 Copper Cliff Dike Standards
#4 Elsie Mtn. Fm Standards (unit c)
#5 Elsie Mtn. Fm Standards
#6 Proximal Creighton Granite Standards
#7 QRNR & SRNR Standards, Murray Mine Traverse (unit d)

A Creighton Pluton
B Copper Cliff Dike and Embayment
C Elsie Mtn Fm
D Main Mass of SIC
E Stobie Fm
F Copper Cliff Fm
G McKim Fm
H Nipissing Intrusive rocks
I Mississagi Fm
J Ramsay Lake Fm
K Pecors Fm

Scale 1: 50 000 (After Dresler, 1984)
Modified after Lightfoot et al (1997)
Fine grained (often spherulitic)
inclusion poor, sulphide poor,
quartz monzodiorite (quartz diorite)

Transitional quartz monzodiorite,
occasional inclusions, minor sulphide,
coarser grained

Coarse grained inclusion rich, sulphide
rich quartz monzodiorite. Often discontinuous
along length of dike

Inclusions of primarily country
rocks (granites, metasediments,
metavolcanics) with occasional
examples of a different generation
of quartz monzodiorite and quartz
monzogabbro-norite (basal norite)
Inclusion Population of the Copper Cliff Embayment

Figure 7

0% Inclusions
1-5% Inclusions
5-10% Inclusions
>10% Inclusions

Fault
Railroad Tracks
Road

95
Figure #8

Air Photo 89-4618.32-193

NE-SW Trending Fault Structure
Figure 9

Gossan Occurrences of the Copper Cliff Embayment

Pervasive Gossan

Inclusions which show Gossan

Fault
Railroad Tracks
Road

100 m

Clayton Capes & Jacob Henley 2000
Figure #11

The diagram illustrates a staging of mineral compositions, indicated by:

- **Wo** (Woollastonite)
- **En** (Enstatite)
- **Fs** (Fayalite)

Intermediate phases include:

- **Diopside**
- **Hedenbergite**
- **Augite**
- **Pigeonite**

The diagram also notes a composition:

- **OPX Composition**
Figure 128

Al₂O₃ vs MgO for Underground and Surface samples for the Copper Hill Embayment
Figure 12b

Al₂O₃ Variation from East to West across the Copper Cliff Embayment

Location

East

West

QMD

QMGN

GN

QMGN

QMD

Location
Figure 12c

Al₂O₃ Variation for the Copper Cliff Embayment

+ Sample Location

18.0
17.5
17.0
16.5
16.0
15.5
15.0
14.5
14.0
13.5
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0

100 m
Figure 12e
Al₂O₃ vs. MgO for Copper Cliff Environment and selected rock types from the SIC
Figure #13b

MgO Variation for the Copper Cliff Embayment

+ Sample Location

MgO wt% 16.00 15.00 14.00 13.00 12.00 11.00 10.00 9.00 8.00 7.00 6.00 5.00 4.00 3.00 2.00

100 m
Figure 14b

SIO2 vs. MgO for Copper Cliff Environment and Selected Rock Types from the SIC
Figure 15a

Fe$_2$O$_3$ vs MgO for Underground and Surface samples for the Copper Cliff Embayment
Figure 15c
Fe₂O₃ variation with distance from the Murray Mine Historical Site
Figure 16
CaO vs MgO for Underground and Surface samples for the Copper Cliff Embayment.

- High Al-QMD
- High Al-QMGN
- High Al-GN
- Creighton granite
- Inclusions
- Low Al-QMD
- Low Al-QMGN
- Low Al-GN
- OPX, Plag, K-Spar
- MELTS

Contamination
High Al
Low Al
Crystal Accumulation
OPX
K-Spar
Plag
Figure #17b

Na₂O Variation for the Copper Cliff

Na₂O wt%
Figure 18a

K2O vs MgO for underground and surface samples for the Copper Cliff Embayment
Figure #18c

K₂O Variation
For the Copper Cliff Embayment
Figure 19a
TiO₂ vs MgO for Underground and Surface samples for the Copper Cliff Embayment

---

Contamination

Crystal Accumulation

Low Al

High Al

Plag

OPX, Plag, K-Spar

MELTS

High Al-QMD

High Al-QMGN

High Al-GN

Creighton granite

Metased/Bas

Inclusions

Low Al-QMD

Low Al-QMGN

Low Al-GN

OPX, Plag, K-Spar

MELTS
Figure 28:
P'O4 Variation from East to West Across the Copper Cliff Embayment
Figure #20c

P_2O_5 Variation for the Copper Cliff Embayment

+ Sample Location
Figure 21b

S variation for the Copper Cliff Embayment

S (ppm)

- Sample location

100 m
Figure 22

Zr vs. Mgo for underground and surface samples from the Copper Cliff Enrichment Floor.
Figure 23a
Y vs. MgO for underground and surface samples from the Copper Cliff Embayment
Figure 2.3b

Y vs. Zr for Underground and Surface Samples from the Copper Cliff Embayment
Figure #23c

Y Variation for the Copper Cliff Embayment
Figure 24b
Lu variation from East to West across the Copper Cliff Embayment

Location

QMD
QMGN
GN
QMD
QMGN

Lu (ppm)

East
West
Figure 24e
Lu Variation with distance from Murray Mine Historical Site
Figure 26

Al₂O₃ variation for Offset Dike Quartz Diorites

Copper Cliff High Al rocks
Minnial
Worthington
Foy
McConnell
Creighton
Manchester
Parkin

MgO (wt. %)

Al₂O₃ (wt. %)
Figure #31a

Embayment structure

After Morrison (1984)

SIC Liquid

Inclusion Free QMD

Figure #31b

QMGN

Brecciated Footwall rocks

Erosional Level?
| Surface Samples | BDO | ADO | BNO | ABO | CDA | ACO | BDC | ADC | RDO | TRO | PDO | FDO | LOI | Total |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|
| C029-1          | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | 100   |
| C029-2          | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | 100   |
| C029-3          | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | 100   |
| C029-4          | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | QBD | 100   |

---

**Note:** The table above contains data related to surface samples, but the specific values for each sample are not visible in the image provided.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Description</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>CaO</th>
<th>MgO</th>
<th>Na$_2$O</th>
<th>K$_2$O</th>
<th>TiO$_2$</th>
<th>P$_2$O$_5$</th>
<th>Fe$_2$O$_3$</th>
<th>LOI</th>
<th>F+Ori</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>C171-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C287-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C327-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C367-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C407-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C447-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C487-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C527-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C567-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C607-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C647-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C687-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C727-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C767-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C807-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C847-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C887-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
<tr>
<td>C928-1</td>
<td>G11</td>
<td>10.13</td>
<td>16.19</td>
<td>8.70</td>
<td>3.67</td>
<td>8.79</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td></td>
<td></td>
<td>32.26</td>
</tr>
</tbody>
</table>

---

**Note:** The values in the table represent percentages of the total composition of the samples. The columns indicate the percentage of each element in the composition. The last column 'Total' sums up all the elements to 100%.
| Sample | Description | B102 | A2023 | BrO | BrCl | ClO | CaO | Li | Ts | Fe | Mg | Mn | Na | P | Si | S | Total |
|--------|-------------|------|-------|-----|------|-----|-----|----|----|----|----|----|----|----|---|---|---|-------|
|       |             | F.E. | F.E. | F.E.| F.E.| F.E.| F.E.| F.E.| F.E.| F.E.| F.E.| F.E.| F.E.| F.E.| F.E.| F.E.| F.E.  |
| C2302  | QO          | 50.09| 13.02| 0.358| 24.13| 4.13| 6.00| 2.80| 1.17| 2.169| 0.380| 17.39| 0.27| 100.53|
|       | C2303       | 50.13| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2304       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2305       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2306       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2307       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2308       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2309       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2310       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2311       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2312       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2313       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2314       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2315       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2316       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2317       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2318       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|
|       | C2319       | 50.04| 13.02| 0.258| 22.02| 4.07| 6.53| 4.32| 0.90| 1.744| 0.052| 4.78 | 0.38| 100.29|

|                   |       |       |       |       |       |       |       |       |       |       |       |       |       |     |       |       |       |

Note: The table provides data on various chemical compositions in different samples.
<table>
<thead>
<tr>
<th>Sample</th>
<th>M</th>
<th>S</th>
<th>E</th>
<th>T</th>
<th>Y</th>
<th>L</th>
<th>P</th>
<th>N</th>
<th>H</th>
<th>F</th>
<th>T</th>
<th>B</th>
<th>M</th>
<th>Co</th>
<th>Co</th>
<th>Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>1002</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1005</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1006</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1008</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1009</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1011</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1013</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1014</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1015</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1018</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1019</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- Data from discovery
- C0001
- C0002
- C0003
- C0004
- C0005
- C0006
- C0007
- C0008
- C0009
- C0010
- C0011
- C0012
- C0013
- C0014
- C0015
- C0016
- C0017
- C0018
- C0019

**Additional notes:**
- Data analysis by
- Method:
- Data processing

**References:**
- [Reference 1](#)
- [Reference 2](#)
<table>
<thead>
<tr>
<th>Sample name</th>
<th>Description</th>
<th>Ca</th>
<th>Ca II</th>
<th>Ca III</th>
<th>Si</th>
<th>Si II</th>
<th>Si III</th>
<th>Zn</th>
<th>Zn II</th>
<th>Zn III</th>
<th>W</th>
<th>W II</th>
<th>Y</th>
<th>Y II</th>
<th>Cl</th>
<th>Br</th>
</tr>
</thead>
<tbody>
<tr>
<td>INCLUS91</td>
<td></td>
<td>427</td>
<td>0.028</td>
<td>290</td>
<td>6.027</td>
<td>0.023</td>
<td>30</td>
<td>7.78</td>
<td>1.889</td>
<td>81.9</td>
<td>88.6</td>
<td>34.3</td>
<td>5.01</td>
<td>2.5</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>INCLUS92</td>
<td></td>
<td>445</td>
<td>0.024</td>
<td>240</td>
<td>12.82</td>
<td>0.023</td>
<td>30</td>
<td>9.699</td>
<td>1.53</td>
<td>21.1</td>
<td>84.7</td>
<td>4.4</td>
<td>5.01</td>
<td>2.5</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>INCLUS93</td>
<td></td>
<td>518</td>
<td>0.028</td>
<td>290</td>
<td>14.78</td>
<td>0.029</td>
<td>60</td>
<td>8.628</td>
<td>11.24</td>
<td>3.232</td>
<td>143.3</td>
<td>338.3</td>
<td>23.9</td>
<td>5.01</td>
<td>2.5</td>
<td>2.1</td>
</tr>
<tr>
<td>INCLUS94</td>
<td></td>
<td>518</td>
<td>0.011</td>
<td>110</td>
<td>12.181</td>
<td>0.005</td>
<td>50</td>
<td>3.003</td>
<td>5.081</td>
<td>179.2</td>
<td>311.5</td>
<td>2.2</td>
<td>5.01</td>
<td>2.5</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>INCLUS95</td>
<td></td>
<td>357</td>
<td>0.008</td>
<td>80</td>
<td>5.479</td>
<td>0.003</td>
<td>30</td>
<td>2.057</td>
<td>2.356</td>
<td>4.086</td>
<td>133.3</td>
<td>214.2</td>
<td>1.4</td>
<td>5.01</td>
<td>2.5</td>
<td>2.1</td>
</tr>
<tr>
<td>INCLUS96</td>
<td></td>
<td>353</td>
<td>0.008</td>
<td>80</td>
<td>5.095</td>
<td>0.005</td>
<td>50</td>
<td>13.07</td>
<td>9.223</td>
<td>22.3</td>
<td>232.3</td>
<td>2.4</td>
<td>5.01</td>
<td>2.5</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>AMPH41</td>
<td>Amphibolite</td>
<td>102</td>
<td>0.003</td>
<td>60</td>
<td>45.211</td>
<td>0.025</td>
<td>250</td>
<td>9.042</td>
<td>0.0447</td>
<td>7.83</td>
<td>607.6</td>
<td>6.8</td>
<td>5.01</td>
<td>2.5</td>
<td>2.1</td>
<td></td>
</tr>
</tbody>
</table>

metals from discovery outcrop
| 0  | CC300  | GO | 678 | 0.013 | 150  | 18.43 | 0.013 | 150  | 2.824 | 381.9 | 380.4 | 29  |
| 8  | CC301  | GO | 1042 | 0.058 | 360  | 19.11 | 0.012 | 120  | 4.226 | 387.9 | 473.3 | 17  |
| 56 | CC302  | GRMR | 1210 | 0.048 | 480  | 24.38 | 0.015 | 130  | 6.398 | 5.07  | 586.2 | 1.5  |
| 83 | CC303  | GRMR | 1888 | 0.076 | 790  | 24.57 | 0.017 | 170  | 5.578 | 2.57  | 511.6 | 2.8  |
| 108 | CC304 | GRMR | 1112 | 0.050 | 500  | 21.57 | 0.012 | 120  | 3.184 | 387.6 | 19  | 5.01 | 2.5 | 2.1 |
| 133 | CC305 | GRMR | 946 | 0.037 | 375  | 23.95 | 0.011 | 110  | 1.811 | 1.678 | 308.5 | 13  |
| 158 | CC306 | GRMR | 396 | 0.050 | 95   | 17.71 | 0.021 | 100  | 0.798 | 0.954 | 386.5 | 165.3 | 26  |
| 163 | CC307 | GRMR | 396 | 0.050 | 95   | 17.71 | 0.021 | 100  | 0.798 | 0.954 | 386.5 | 165.3 | 26  |
| 209 | CC308 | GRMR | 288 | 0.007 | 70   | 26.90 | 0.009 | 60   | 1.071 | 2.091 | 5.773 | 370.4 | 12  |
| 239 | CC309 | GRMR | 263 | 0.007 | 70   | 26.90 | 0.009 | 60   | 1.071 | 2.091 | 5.773 | 370.4 | 12  |
| 254 | CC310 | GRMR | 501 | 0.008 | 60   | 19   | 0.008 | 60   | 1.036 | 1.965 | 402.7 | 163.3 | 4  |
| 325 | CC311 | GRMR | 148 | 0.003 | 30   | 15.31 | 0.006 | 60   | 13.91 | 1.738 | 230.8 | 250.5 | 67  |
| 309 | CC312 | GRMR | 218 | 0.004 | 40   | 16.36 | 0.008 | 80   | 16.6  | 6   | 323.9 | 756.4 | 1.7  |
| 359 | CC313 | GRMR | 112 | 0.004 | 40   | 17.92 | 0.008 | 80   | 18.98 | 7.911 | 307.3 | 1252.3 | 1.7  |
| 383 | CC314 | GRMR | 114 | 0.004 | 40   | 23.2 | 0.011 | 100  | 1.098 | 3.105 | 372.8 | 305.4 | 14  |
| 408 | CC315 | GRMR | 287 | 0.004 | 40   | 18.42 | 0.007 | 70   | 0.5647 | 0.9719 | 246.6 | 1716.7 | 16.6 |
| 433 | CC316 | GRMR | 108 | 0.003 | 30   | 17.14 | 0.006 | 60   | 1.098 | 2.892 | 585.8 | 1805.9 | 6.5  |
| 458 | CC317 | GRMR | 148 | 0.005 | 50   | 19.18 | 0.011 | 110  | 1.914 | 3.427 | 384.3 | 338.6 | 14.9 |
| 483 | CC318 | GRMR | 309 | 0.005 | 50   | 17.95 | 0.007 | 70   | 1.522 | 4.539 | 390.4 | 1365.3 | 32  |
### Table: Undergrad Samples

<table>
<thead>
<tr>
<th>Depth</th>
<th>Sample</th>
<th>Rock Type</th>
<th>BOC</th>
<th>ASDO</th>
<th>Rd</th>
<th>Rd</th>
<th>Cao</th>
<th>NBO</th>
<th>KVO</th>
<th>POCO</th>
<th>Fo100S</th>
<th>Co10</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fe3</td>
<td>Fe2</td>
<td>Fe1</td>
<td>Fe</td>
<td>Fe</td>
<td>Fe</td>
<td>Fe</td>
<td>Fe</td>
<td>Fe</td>
<td>Fe</td>
<td>Fe</td>
</tr>
<tr>
<td>2</td>
<td>#1</td>
<td>Granite</td>
<td>67.4</td>
<td>6.2</td>
<td>0.02</td>
<td>0.2</td>
<td>1</td>
<td>2.2</td>
<td>4.7</td>
<td>0.153</td>
<td>0.028</td>
<td>1.504</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>#2</td>
<td>Amphibole</td>
<td>48.2</td>
<td>12.4</td>
<td>0.26</td>
<td>0.6</td>
<td>11</td>
<td>2.5</td>
<td>1.6</td>
<td>0.118</td>
<td>0.010</td>
<td>1.471</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>#2</td>
<td>Granite</td>
<td>44.7</td>
<td>12.2</td>
<td>0.26</td>
<td>0.7</td>
<td>11</td>
<td>2.5</td>
<td>1.5</td>
<td>0.109</td>
<td>0.014</td>
<td>1.232</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>#2</td>
<td>Granite</td>
<td>52.8</td>
<td>12.0</td>
<td>0.23</td>
<td>0.6</td>
<td>12</td>
<td>2.5</td>
<td>1.8</td>
<td>0.169</td>
<td>0.024</td>
<td>1.802</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>#2</td>
<td>Granite</td>
<td>62.4</td>
<td>11.7</td>
<td>0.083</td>
<td>2.6</td>
<td>5</td>
<td>1.2</td>
<td>2.1</td>
<td>0.275</td>
<td>0.038</td>
<td>7.681</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>#2</td>
<td>Granite</td>
<td>54.3</td>
<td>13.8</td>
<td>0.143</td>
<td>4.5</td>
<td>5</td>
<td>3.3</td>
<td>1.6</td>
<td>0.084</td>
<td>0.027</td>
<td>13.966</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>#2</td>
<td>Granite</td>
<td>74</td>
<td>12.8</td>
<td>0.114</td>
<td>4.3</td>
<td>6</td>
<td>2.7</td>
<td>1.8</td>
<td>0.837</td>
<td>0.023</td>
<td>11.986</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>#2</td>
<td>Granite</td>
<td>52.9</td>
<td>13.7</td>
<td>0.22</td>
<td>5.6</td>
<td>6</td>
<td>2.9</td>
<td>1.7</td>
<td>0.354</td>
<td>0.012</td>
<td>7.471</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>#2</td>
<td>Granite</td>
<td>53.4</td>
<td>13.7</td>
<td>0.116</td>
<td>5.6</td>
<td>6</td>
<td>3.1</td>
<td>2.2</td>
<td>0.783</td>
<td>0.023</td>
<td>9.851</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>#2</td>
<td>Granite</td>
<td>60.1</td>
<td>12.7</td>
<td>0.21</td>
<td>5.6</td>
<td>6</td>
<td>2.8</td>
<td>1.9</td>
<td>0.622</td>
<td>0.017</td>
<td>7.781</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>#2</td>
<td>Granite</td>
<td>53.9</td>
<td>14.2</td>
<td>0.108</td>
<td>5.8</td>
<td>6</td>
<td>2.8</td>
<td>2.0</td>
<td>0.62</td>
<td>0.017</td>
<td>7.805</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>#2</td>
<td>Granite</td>
<td>68.3</td>
<td>14.6</td>
<td>0.25</td>
<td>6.5</td>
<td>6</td>
<td>3.7</td>
<td>2.5</td>
<td>0.891</td>
<td>0.029</td>
<td>24.531</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>#2</td>
<td>Granite</td>
<td>58.8</td>
<td>14.4</td>
<td>0.23</td>
<td>6.5</td>
<td>6</td>
<td>3.7</td>
<td>2.5</td>
<td>0.891</td>
<td>0.029</td>
<td>24.531</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>#2</td>
<td>Granite</td>
<td>58.3</td>
<td>14.4</td>
<td>0.23</td>
<td>6.5</td>
<td>6</td>
<td>3.7</td>
<td>2.5</td>
<td>0.891</td>
<td>0.029</td>
<td>24.531</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>#2</td>
<td>Granite</td>
<td>68.3</td>
<td>13.0</td>
<td>0.124</td>
<td>6.2</td>
<td>5.3</td>
<td>2.8</td>
<td>2.3</td>
<td>0.470</td>
<td>0.019</td>
<td>16.81</td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>#2</td>
<td>Granite</td>
<td>54.6</td>
<td>13.5</td>
<td>0.124</td>
<td>6.4</td>
<td>5.3</td>
<td>3.1</td>
<td>2.4</td>
<td>0.639</td>
<td>0.022</td>
<td>11.94</td>
<td></td>
</tr>
<tr>
<td>47</td>
<td>#2</td>
<td>Granite</td>
<td>51.9</td>
<td>16.5</td>
<td>0.151</td>
<td>6.3</td>
<td>5.7</td>
<td>3.2</td>
<td>2.3</td>
<td>0.571</td>
<td>0.029</td>
<td>11.10</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>#2</td>
<td>Granite</td>
<td>53.2</td>
<td>14.8</td>
<td>0.177</td>
<td>6.7</td>
<td>5.2</td>
<td>2.9</td>
<td>1.9</td>
<td>0.899</td>
<td>0.034</td>
<td>15.98</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>#2</td>
<td>Granite</td>
<td>47.2</td>
<td>15.1</td>
<td>0.145</td>
<td>6.1</td>
<td>5.6</td>
<td>2.8</td>
<td>1.9</td>
<td>0.987</td>
<td>0.042</td>
<td>16.42</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>#2</td>
<td>Granite</td>
<td>49.1</td>
<td>15.4</td>
<td>0.132</td>
<td>6.4</td>
<td>5.7</td>
<td>2.9</td>
<td>1.9</td>
<td>0.899</td>
<td>0.034</td>
<td>15.98</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>#2</td>
<td>Granite</td>
<td>52.8</td>
<td>14.9</td>
<td>0.145</td>
<td>6.4</td>
<td>5.7</td>
<td>2.8</td>
<td>1.9</td>
<td>0.884</td>
<td>0.034</td>
<td>15.98</td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>#2</td>
<td>Granite</td>
<td>48.9</td>
<td>13.8</td>
<td>0.198</td>
<td>5.8</td>
<td>5.1</td>
<td>3.1</td>
<td>2.5</td>
<td>1.064</td>
<td>0.040</td>
<td>16.29</td>
<td></td>
</tr>
<tr>
<td>92</td>
<td>#2</td>
<td>QDWeiss contact</td>
<td>57.8</td>
<td>15.7</td>
<td>0.150</td>
<td>6.1</td>
<td>5.7</td>
<td>3.2</td>
<td>2.0</td>
<td>0.912</td>
<td>0.042</td>
<td>18.87</td>
<td></td>
</tr>
<tr>
<td>103</td>
<td>#2</td>
<td>QDWeiss contact</td>
<td>57.0</td>
<td>14.8</td>
<td>0.160</td>
<td>6.4</td>
<td>5.6</td>
<td>3.2</td>
<td>2.3</td>
<td>0.828</td>
<td>0.040</td>
<td>15.15</td>
<td></td>
</tr>
<tr>
<td>176</td>
<td>3</td>
<td>Igneous</td>
<td>57.4</td>
<td>14.5</td>
<td>0.125</td>
<td>6.2</td>
<td>5.3</td>
<td>3.2</td>
<td>2.4</td>
<td>0.729</td>
<td>0.029</td>
<td>14.24</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>#2</td>
<td>Igneous</td>
<td>56.1</td>
<td>14.8</td>
<td>0.142</td>
<td>6.3</td>
<td>5.8</td>
<td>3.3</td>
<td>2.5</td>
<td>0.374</td>
<td>0.014</td>
<td>7.242</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>#2</td>
<td>Igneous</td>
<td>56.0</td>
<td>14.7</td>
<td>0.119</td>
<td>6.0</td>
<td>5.6</td>
<td>2.7</td>
<td>2.0</td>
<td>0.776</td>
<td>0.025</td>
<td>13.43</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>#2</td>
<td>Igneous</td>
<td>51.5</td>
<td>13.8</td>
<td>0.145</td>
<td>6.0</td>
<td>5.6</td>
<td>2.9</td>
<td>2.5</td>
<td>0.648</td>
<td>0.032</td>
<td>13.28</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>#2</td>
<td>Igneous</td>
<td>58.3</td>
<td>14.9</td>
<td>0.120</td>
<td>6.0</td>
<td>5.6</td>
<td>2.9</td>
<td>2.5</td>
<td>0.672</td>
<td>0.032</td>
<td>14.00</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>#2</td>
<td>Igneous</td>
<td>51.4</td>
<td>12.8</td>
<td>0.125</td>
<td>6.8</td>
<td>5.2</td>
<td>1.5</td>
<td>2.0</td>
<td>0.859</td>
<td>0.032</td>
<td>14.00</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>#2</td>
<td>Igneous</td>
<td>54.3</td>
<td>13.1</td>
<td>0.145</td>
<td>6.4</td>
<td>5.6</td>
<td>2.9</td>
<td>2.5</td>
<td>0.751</td>
<td>0.032</td>
<td>14.00</td>
<td></td>
</tr>
<tr>
<td>470</td>
<td>#2</td>
<td>Igneous</td>
<td>53.0</td>
<td>16.5</td>
<td>0.151</td>
<td>6.3</td>
<td>5.7</td>
<td>3.2</td>
<td>2.3</td>
<td>0.571</td>
<td>0.029</td>
<td>11.10</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>#2</td>
<td>Igneous</td>
<td>53.2</td>
<td>14.8</td>
<td>0.177</td>
<td>6.7</td>
<td>5.2</td>
<td>2.9</td>
<td>1.9</td>
<td>0.899</td>
<td>0.034</td>
<td>15.98</td>
<td></td>
</tr>
<tr>
<td>529</td>
<td>#2</td>
<td>Igneous</td>
<td>39.7</td>
<td>13.8</td>
<td>0.122</td>
<td>4.3</td>
<td>5.6</td>
<td>3.5</td>
<td>3.2</td>
<td>0.822</td>
<td>0.023</td>
<td>9.533</td>
<td></td>
</tr>
<tr>
<td>529</td>
<td>#2</td>
<td>Igneous</td>
<td>45.1</td>
<td>12.6</td>
<td>0.125</td>
<td>4.3</td>
<td>5.6</td>
<td>3.5</td>
<td>3.2</td>
<td>0.822</td>
<td>0.023</td>
<td>9.533</td>
<td></td>
</tr>
<tr>
<td>532</td>
<td>#2</td>
<td>Igneous</td>
<td>68.0</td>
<td>11.5</td>
<td>0.034</td>
<td>4.4</td>
<td>6</td>
<td>1.9</td>
<td>3</td>
<td>4</td>
<td>0.275</td>
<td>0.074</td>
<td>9.449</td>
</tr>
</tbody>
</table>

**Note:** All values are in percentage (%). Fe refers to iron.
<table>
<thead>
<tr>
<th>Depth</th>
<th>Sample</th>
<th>Grain Type</th>
<th>Yb</th>
<th>U</th>
<th>Co</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>3k</td>
<td>1k</td>
<td>3k</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>Quartz+ rich Nodite</td>
<td>6.3</td>
<td>1.5</td>
<td>0.063</td>
</tr>
<tr>
<td>200</td>
<td>2</td>
<td>Quartz+ rich Nodite</td>
<td>5.1</td>
<td>3.1</td>
<td>0.063</td>
</tr>
<tr>
<td>300</td>
<td>3</td>
<td>Quartz+ rich Nodite</td>
<td>5.8</td>
<td>1.9</td>
<td>0.063</td>
</tr>
<tr>
<td>410</td>
<td>4</td>
<td>Quartz+ rich Nodite</td>
<td>5.2</td>
<td>0.6</td>
<td>0.063</td>
</tr>
<tr>
<td>500</td>
<td>5</td>
<td>Quartz+ rich Nodite</td>
<td>5.6</td>
<td>1.1</td>
<td>0.063</td>
</tr>
<tr>
<td>600</td>
<td>6</td>
<td>Quartz+ rich Nodite</td>
<td>6.6</td>
<td>2.9</td>
<td>0.063</td>
</tr>
<tr>
<td>700</td>
<td>7</td>
<td>Quartz+ rich Nodite</td>
<td>5.8</td>
<td>1.5</td>
<td>0.063</td>
</tr>
<tr>
<td>800</td>
<td>8</td>
<td>Quartz+ rich Nodite</td>
<td>5.1</td>
<td>2.1</td>
<td>0.063</td>
</tr>
<tr>
<td>900</td>
<td>9</td>
<td>Quartz+ rich Nodite</td>
<td>6.2</td>
<td>1.7</td>
<td>0.063</td>
</tr>
<tr>
<td>1000</td>
<td>10</td>
<td>Quartz+ rich Nodite</td>
<td>5.9</td>
<td>2.9</td>
<td>0.063</td>
</tr>
<tr>
<td>1100</td>
<td>11</td>
<td>Quartz+ rich Nodite</td>
<td>5.4</td>
<td>1.2</td>
<td>0.063</td>
</tr>
<tr>
<td>1200</td>
<td>12</td>
<td>Quartz+ rich Nodite</td>
<td>6.4</td>
<td>0.8</td>
<td>0.063</td>
</tr>
<tr>
<td>1300</td>
<td>13</td>
<td>Quartz+ rich Nodite</td>
<td>8.1</td>
<td>0.1</td>
<td>0.063</td>
</tr>
<tr>
<td>1400</td>
<td>14</td>
<td>Quartz+ rich Nodite</td>
<td>7.7</td>
<td>1.3</td>
<td>0.063</td>
</tr>
<tr>
<td>1500</td>
<td>15</td>
<td>Quartz+ rich Nodite</td>
<td>10.7</td>
<td>3.8</td>
<td>0.063</td>
</tr>
<tr>
<td>1600</td>
<td>16</td>
<td>Quartz+ rich Nodite</td>
<td>4.6</td>
<td>1.2</td>
<td>0.063</td>
</tr>
<tr>
<td>1700</td>
<td>17</td>
<td>Quartz+ rich Nodite</td>
<td>2.9</td>
<td>0.4</td>
<td>0.063</td>
</tr>
<tr>
<td>1800</td>
<td>18</td>
<td>Quartz+ rich Nodite</td>
<td>2.8</td>
<td>0.4</td>
<td>0.063</td>
</tr>
<tr>
<td>1900</td>
<td>19</td>
<td>Quartz+ rich Nodite</td>
<td>6.3</td>
<td>1.3</td>
<td>0.063</td>
</tr>
<tr>
<td>Column</td>
<td>Percentage</td>
<td>Percentage</td>
<td>Percentage</td>
<td>Percentage</td>
<td>Percentage</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
<td>------------</td>
<td>------------</td>
<td>------------</td>
<td>------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** The table contains numerical data and percentages, but the specific context or meaning of the table is not clear from the image alone.
<table>
<thead>
<tr>
<th></th>
<th>South Range North T-S</th>
<th>South Range North T-S</th>
<th>South Range North T-S</th>
<th>South Range North T-S</th>
<th>South Range North T-S</th>
<th>South Range North T-S</th>
<th>South Range North T-S</th>
<th>South Range North T-S</th>
<th>South Range North T-S</th>
<th>South Range North T-S</th>
<th>South Range North T-S</th>
<th>South Range North T-S</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>56.63</td>
<td>11.53</td>
<td>0.112</td>
<td>6.02</td>
<td>7.34</td>
<td>2.87</td>
<td>1.36</td>
<td>0.48</td>
<td>0.85</td>
<td>7.94</td>
<td>0.67</td>
<td>0.49</td>
</tr>
<tr>
<td>100</td>
<td>53.85</td>
<td>10.24</td>
<td>0.206</td>
<td>8.48</td>
<td>7.43</td>
<td>2.13</td>
<td>1.96</td>
<td>0.57</td>
<td>0.18</td>
<td>8.18</td>
<td>2.98</td>
<td>2.81</td>
</tr>
<tr>
<td>150</td>
<td>55.63</td>
<td>13.17</td>
<td>0.248</td>
<td>4.30</td>
<td>4.68</td>
<td>2.70</td>
<td>1.97</td>
<td>0.57</td>
<td>0.19</td>
<td>8.06</td>
<td>1.33</td>
<td>1.35</td>
</tr>
<tr>
<td>200</td>
<td>57.23</td>
<td>16.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>250</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>300</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>350</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>400</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>450</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>500</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>550</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>600</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>650</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>700</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>750</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>800</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>850</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>900</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>950</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
<tr>
<td>1000</td>
<td>59.62</td>
<td>19.15</td>
<td>0.133</td>
<td>1.96</td>
<td>2.68</td>
<td>2.36</td>
<td>1.58</td>
<td>0.61</td>
<td>0.79</td>
<td>9.75</td>
<td>2.51</td>
<td>2.58</td>
</tr>
</tbody>
</table>

*Note: The table represents data from South Range North T-S, with columns for various parameters such as FEOR, FEOS, FEOR, FEOS, etc.*

---

**Abbreviations:***

- FEOR: Form data
- FEOS: Open data
- FEOR: Recorded data
- FEOS: Observed data
<table>
<thead>
<tr>
<th>S</th>
<th>B</th>
<th>Hb</th>
<th>Zn</th>
<th>V</th>
<th>Mn</th>
<th>Cu</th>
<th>Cr</th>
<th>T</th>
<th>Fe</th>
<th>Mn</th>
<th>Cr</th>
<th>T</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1</td>
<td>South Range Norte-TS</td>
<td>0.155</td>
<td>1550</td>
<td>4.4</td>
<td>234</td>
<td>182</td>
<td>2</td>
<td>417</td>
<td>82</td>
<td>62.1</td>
<td>643.9</td>
<td>238</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>South Range Norte-TS</td>
<td>0.227</td>
<td>2270</td>
<td>7</td>
<td>67.3</td>
<td>138.3</td>
<td>322.2</td>
<td>48.9</td>
<td>473.9</td>
<td>804.6</td>
<td>17.2</td>
<td>303.9</td>
</tr>
<tr>
<td>150</td>
<td>3</td>
<td>Quarto Rich Norte</td>
<td>0.058</td>
<td>58</td>
<td>7.6</td>
<td>67.3</td>
<td>139.9</td>
<td>362.9</td>
<td>69.3</td>
<td>627</td>
<td>547.4</td>
<td>18</td>
<td>60.7</td>
</tr>
<tr>
<td>200</td>
<td>4</td>
<td>Quarto Rich Norte</td>
<td>0.148</td>
<td>1480</td>
<td>6.1</td>
<td>68.2</td>
<td>143.7</td>
<td>248.2</td>
<td>31.8</td>
<td>330.1</td>
<td>689.9</td>
<td>18.1</td>
<td>187.9</td>
</tr>
<tr>
<td>250</td>
<td>5</td>
<td>Quarto Rich Norte</td>
<td>0.183</td>
<td>1830</td>
<td>6</td>
<td>62.2</td>
<td>149.6</td>
<td>285.6</td>
<td>43.2</td>
<td>399.6</td>
<td>1087.3</td>
<td>14.8</td>
<td>481.5</td>
</tr>
<tr>
<td>300</td>
<td>6</td>
<td>Quarto Rich Norte</td>
<td>0.202</td>
<td>2020</td>
<td>5.8</td>
<td>62.2</td>
<td>152.7</td>
<td>285</td>
<td>50</td>
<td>429.8</td>
<td>786.3</td>
<td>17.1</td>
<td>135.3</td>
</tr>
<tr>
<td>345</td>
<td>7</td>
<td>Quarto Rich Norte</td>
<td>0.25</td>
<td>2500</td>
<td>5.4</td>
<td>64.1</td>
<td>166.8</td>
<td>400.2</td>
<td>50.6</td>
<td>530.4</td>
<td>352</td>
<td>19.9</td>
<td>108.7</td>
</tr>
<tr>
<td>400</td>
<td>8</td>
<td>Quarto Rich Norte</td>
<td>0.271</td>
<td>2710</td>
<td>5.8</td>
<td>62.1</td>
<td>173.3</td>
<td>423.5</td>
<td>44.7</td>
<td>474.2</td>
<td>764.3</td>
<td>19.7</td>
<td>720.9</td>
</tr>
<tr>
<td>450</td>
<td>9</td>
<td>Quarto Rich Norte</td>
<td>0.286</td>
<td>2860</td>
<td>6.5</td>
<td>64.1</td>
<td>187.1</td>
<td>452.4</td>
<td>50.5</td>
<td>551.1</td>
<td>350</td>
<td>23.5</td>
<td>166.7</td>
</tr>
<tr>
<td>500</td>
<td>10</td>
<td>Quarto Rich Norte</td>
<td>0.343</td>
<td>3430</td>
<td>6.8</td>
<td>60.1</td>
<td>182.3</td>
<td>399.8</td>
<td>57.7</td>
<td>470.9</td>
<td>243.9</td>
<td>19.8</td>
<td>182.2</td>
</tr>
<tr>
<td>550</td>
<td>11</td>
<td>Quarto Rich Norte</td>
<td>0.396</td>
<td>3960</td>
<td>7.2</td>
<td>122.6</td>
<td>128.7</td>
<td>370.9</td>
<td>42.2</td>
<td>388.2</td>
<td>646.9</td>
<td>15.3</td>
<td>173.4</td>
</tr>
<tr>
<td>600</td>
<td>12</td>
<td>Quarto Rich Norte</td>
<td>0.385</td>
<td>3850</td>
<td>6.7</td>
<td>61.1</td>
<td>163.5</td>
<td>342.9</td>
<td>78.5</td>
<td>589.4</td>
<td>274.5</td>
<td>22.3</td>
<td>503.8</td>
</tr>
<tr>
<td>650</td>
<td>13</td>
<td>Quarto Rich Norte</td>
<td>0.444</td>
<td>4440</td>
<td>6.4</td>
<td>234.3</td>
<td>180.9</td>
<td>418.1</td>
<td>62.8</td>
<td>998.3</td>
<td>237.6</td>
<td>22.9</td>
<td>221</td>
</tr>
<tr>
<td>700</td>
<td>14</td>
<td>Quarto Rich Norte</td>
<td>0.384</td>
<td>3840</td>
<td>6.2</td>
<td>100.2</td>
<td>182.4</td>
<td>378.9</td>
<td>52.5</td>
<td>511.8</td>
<td>228.1</td>
<td>25.8</td>
<td>1430.7</td>
</tr>
<tr>
<td>70</td>
<td>15</td>
<td>South Range Norte-TS</td>
<td>0.086</td>
<td>860</td>
<td>6</td>
<td>62.1</td>
<td>153.8</td>
<td>269.4</td>
<td>50.2</td>
<td>424.1</td>
<td>763.5</td>
<td>17.9</td>
<td>148.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>S</th>
<th>B</th>
<th>Hb</th>
<th>Zn</th>
<th>V</th>
<th>Mn</th>
<th>Cu</th>
<th>Cr</th>
<th>T</th>
<th>Fe</th>
<th>Mn</th>
<th>Cr</th>
<th>T</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>79</td>
<td>1</td>
<td>South Range Norte-TS</td>
<td>0.062</td>
<td>620</td>
<td>6.5</td>
<td>60.9</td>
<td>128.3</td>
<td>371.2</td>
<td>42.1</td>
<td>372.8</td>
<td>640.8</td>
<td>15.7</td>
<td>174</td>
</tr>
<tr>
<td>80</td>
<td>2</td>
<td>South Range Norte-TS</td>
<td>0.072</td>
<td>720</td>
<td>7.3</td>
<td>65.6</td>
<td>125.3</td>
<td>368.8</td>
<td>43.1</td>
<td>450.1</td>
<td>608.6</td>
<td>18.1</td>
<td>67.5</td>
</tr>
<tr>
<td>82</td>
<td>3</td>
<td>South Range Norte-TS</td>
<td>0.208</td>
<td>2080</td>
<td>7.6</td>
<td>101.7</td>
<td>135.9</td>
<td>409.6</td>
<td>57.4</td>
<td>426.4</td>
<td>714.8</td>
<td>15.8</td>
<td>148.2</td>
</tr>
<tr>
<td>210</td>
<td>4</td>
<td>Shear Zone-TS</td>
<td>0.016</td>
<td>160</td>
<td>6.3</td>
<td>100.9</td>
<td>163.4</td>
<td>283.4</td>
<td>33.5</td>
<td>286</td>
<td>908.6</td>
<td>18.1</td>
<td>128.3</td>
</tr>
<tr>
<td>300</td>
<td>5</td>
<td>South Range Norte</td>
<td>0.271</td>
<td>2710</td>
<td>5.8</td>
<td>116.7</td>
<td>137.6</td>
<td>245.7</td>
<td>38.2</td>
<td>413.8</td>
<td>1178.9</td>
<td>15.8</td>
<td>236</td>
</tr>
<tr>
<td>360</td>
<td>6</td>
<td>South Range Norte-TS</td>
<td>0.016</td>
<td>160</td>
<td>9.2</td>
<td>74.7</td>
<td>146</td>
<td>406.7</td>
<td>55.8</td>
<td>547.6</td>
<td>195.6</td>
<td>22</td>
<td>56.5</td>
</tr>
<tr>
<td>510</td>
<td>7</td>
<td>South Range Norte</td>
<td>0.19</td>
<td>1900</td>
<td>1.6</td>
<td>130.2</td>
<td>137.8</td>
<td>338.4</td>
<td>38.9</td>
<td>315.1</td>
<td>1105</td>
<td>15.3</td>
<td>162.9</td>
</tr>
<tr>
<td>605</td>
<td>8</td>
<td>South Range Norte-TS</td>
<td>0.233</td>
<td>2330</td>
<td>6.5</td>
<td>86.6</td>
<td>131</td>
<td>320.6</td>
<td>48.6</td>
<td>324.9</td>
<td>625.4</td>
<td>15.4</td>
<td>209</td>
</tr>
<tr>
<td>700</td>
<td>9</td>
<td>South Range Norte-TS</td>
<td>1.738</td>
<td>17380</td>
<td>6</td>
<td>50.1</td>
<td>18.8</td>
<td>304.9</td>
<td>46.1</td>
<td>404.8</td>
<td>806</td>
<td>16</td>
<td>1103.2</td>
</tr>
<tr>
<td>800</td>
<td>10</td>
<td>South Range Norte</td>
<td>2.381</td>
<td>23810</td>
<td>8.2</td>
<td>37.7</td>
<td>111.5</td>
<td>316.1</td>
<td>41.2</td>
<td>428.9</td>
<td>337.9</td>
<td>14.1</td>
<td>1578.5</td>
</tr>
<tr>
<td>900</td>
<td>11</td>
<td>South Range Norte</td>
<td>0.883</td>
<td>8830</td>
<td>8.7</td>
<td>103.9</td>
<td>185.3</td>
<td>377.4</td>
<td>52.8</td>
<td>501.4</td>
<td>1235.9</td>
<td>25.8</td>
<td>1437.9</td>
</tr>
<tr>
<td>980</td>
<td>12</td>
<td>South Range Norte</td>
<td>0.943</td>
<td>9430</td>
<td>8.7</td>
<td>101.4</td>
<td>277.8</td>
<td>109.4</td>
<td>44.2</td>
<td>553.9</td>
<td>363.5</td>
<td>23.3</td>
<td>419.3</td>
</tr>
<tr>
<td>990</td>
<td>13</td>
<td>Quarto Rich Norte-TS</td>
<td>0.205</td>
<td>2050</td>
<td>8.4</td>
<td>55.6</td>
<td>185.9</td>
<td>402.2</td>
<td>161</td>
<td>568.6</td>
<td>502.2</td>
<td>22.8</td>
<td>294.4</td>
</tr>
<tr>
<td>1000</td>
<td>14</td>
<td>Quarto Rich Norte-TS</td>
<td>0.25</td>
<td>2500</td>
<td>8.2</td>
<td>116.2</td>
<td>187.1</td>
<td>390.9</td>
<td>50.3</td>
<td>417.9</td>
<td>713.8</td>
<td>17.1</td>
<td>284.4</td>
</tr>
<tr>
<td>1100</td>
<td>15</td>
<td>Quarto Rich Norte</td>
<td>0.355</td>
<td>3550</td>
<td>8.7</td>
<td>77.9</td>
<td>132.8</td>
<td>260.3</td>
<td>43.2</td>
<td>407</td>
<td>1140.4</td>
<td>15.5</td>
<td>171.2</td>
</tr>
<tr>
<td>1200</td>
<td>16</td>
<td>Quarto Rich Norte</td>
<td>0.357</td>
<td>3570</td>
<td>9.8</td>
<td>67.9</td>
<td>133.2</td>
<td>260.5</td>
<td>53.4</td>
<td>507.5</td>
<td>447.4</td>
<td>14</td>
<td>62.8</td>
</tr>
<tr>
<td>1253</td>
<td>17</td>
<td>South Range Norte-TS</td>
<td>0.085</td>
<td>850</td>
<td>9.7</td>
<td>605.3</td>
<td>190.4</td>
<td>408.8</td>
<td>44.3</td>
<td>630.4</td>
<td>182.8</td>
<td>25.2</td>
<td>113.7</td>
</tr>
<tr>
<td>Well</td>
<td>Depth</td>
<td>South Range Nodto-TS</td>
<td>Th (ppm)</td>
<td>U (ppm)</td>
<td>Co (ppm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-------</td>
<td>----------------------</td>
<td>----------</td>
<td>---------</td>
<td>----------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>1</td>
<td>South Range Nodto-TS</td>
<td>57 25</td>
<td>61 98</td>
<td>0.003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>South Range Nodto-TS</td>
<td>64 16</td>
<td>52 07</td>
<td>0.004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>3</td>
<td>Quartz Rich Nodto</td>
<td>82 18</td>
<td>5 01</td>
<td>0.004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>4</td>
<td>Quartz Rich Nodto</td>
<td>7 03</td>
<td>62 03</td>
<td>0.003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>5</td>
<td>Quartz Rich Nodto</td>
<td>5 03</td>
<td>62 03</td>
<td>0.003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>348</td>
<td>6</td>
<td>Quartz Rich Nodto</td>
<td>11 18</td>
<td>59 01</td>
<td>0.007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>401</td>
<td>7</td>
<td>Quartz Rich Nodto</td>
<td>3 03</td>
<td>62 03</td>
<td>0.003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>402</td>
<td>8</td>
<td>Quartz Rich Nodto</td>
<td>11 18</td>
<td>59 01</td>
<td>0.007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>450</td>
<td>9</td>
<td>Quartz Rich Nodto</td>
<td>7 03</td>
<td>62 03</td>
<td>0.003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>10</td>
<td>Quartz Rich Nodto</td>
<td>11 18</td>
<td>59 01</td>
<td>0.007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>550</td>
<td>11</td>
<td>Quartz Rich Nodto</td>
<td>11 18</td>
<td>59 01</td>
<td>0.007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>550</td>
<td>12</td>
<td>Quartz Rich Nodto</td>
<td>11 18</td>
<td>59 01</td>
<td>0.007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>550</td>
<td>13</td>
<td>Quartz Rich Nodto</td>
<td>11 18</td>
<td>59 01</td>
<td>0.007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>550</td>
<td>14</td>
<td>Quartz Rich Nodto</td>
<td>11 18</td>
<td>59 01</td>
<td>0.007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>550</td>
<td>15</td>
<td>Quartz Rich Nodto</td>
<td>11 18</td>
<td>59 01</td>
<td>0.007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>550</td>
<td>16</td>
<td>Quartz Rich Nodto</td>
<td>11 18</td>
<td>59 01</td>
<td>0.007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>550</td>
<td>17</td>
<td>Quartz Rich Nodto</td>
<td>11 18</td>
<td>59 01</td>
<td>0.007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>550</td>
<td>18</td>
<td>Quartz Rich Nodto</td>
<td>11 18</td>
<td>59 01</td>
<td>0.007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>550</td>
<td>19</td>
<td>Quartz Rich Nodto</td>
<td>11 18</td>
<td>59 01</td>
<td>0.007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>550</td>
<td>20</td>
<td>Quartz Rich Nodto</td>
<td>11 18</td>
<td>59 01</td>
<td>0.007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The table lists the depth in feet (ft) and the concentrations of Th, U, and Co in parts per million (ppm) for different samples.
<table>
<thead>
<tr>
<th>No</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>6th</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1</td>
<td>South Range NW-15</td>
<td>0.011</td>
<td>0.009</td>
<td>357.1</td>
<td>438.3</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>South Range NW-15</td>
<td>0.02</td>
<td>0.011</td>
<td>425.7</td>
<td>471.8</td>
</tr>
<tr>
<td>150</td>
<td>3</td>
<td>Quartz Rich NW-15</td>
<td>0.004</td>
<td>0.009</td>
<td>415.6</td>
<td>427.5</td>
</tr>
<tr>
<td>200</td>
<td>4</td>
<td>Quartz Rich NW-15</td>
<td>0.017</td>
<td>0.028</td>
<td>267.3</td>
<td>323.9</td>
</tr>
<tr>
<td>250</td>
<td>5</td>
<td>Quartz Rich NW-15</td>
<td>0.051</td>
<td>0.099</td>
<td>262.9</td>
<td>413.3</td>
</tr>
<tr>
<td>300</td>
<td>6</td>
<td>Quartz Rich NW-15</td>
<td>0.028</td>
<td>0.029</td>
<td>391.4</td>
<td>740.1</td>
</tr>
<tr>
<td>350</td>
<td>7</td>
<td>Quartz Rich NW-15</td>
<td>0.007</td>
<td>0.027</td>
<td>348.1</td>
<td>670.9</td>
</tr>
<tr>
<td>400</td>
<td>8</td>
<td>Quartz Rich NW-15</td>
<td>0.005</td>
<td>0.059</td>
<td>30.3</td>
<td>715.9</td>
</tr>
<tr>
<td>450</td>
<td>9</td>
<td>Quartz Rich NW-15</td>
<td>0.015</td>
<td>0.01</td>
<td>301.8</td>
<td>444.3</td>
</tr>
<tr>
<td>500</td>
<td>10</td>
<td>Quartz Rich NW-15</td>
<td>0.013</td>
<td>0.01</td>
<td>409.6</td>
<td>415</td>
</tr>
<tr>
<td>550</td>
<td>11</td>
<td>Quartz Rich NW-15</td>
<td>0.007</td>
<td>0.008</td>
<td>379.8</td>
<td>850.1</td>
</tr>
<tr>
<td>600</td>
<td>12</td>
<td>Quartz Rich NW-15</td>
<td>0.057</td>
<td>0.008</td>
<td>388.2</td>
<td>888.9</td>
</tr>
<tr>
<td>650</td>
<td>13</td>
<td>Quartz Rich NW-15</td>
<td>0.658</td>
<td>0.61</td>
<td>305.3</td>
<td>886.1</td>
</tr>
<tr>
<td>700</td>
<td>14</td>
<td>Quartz Rich NW-15</td>
<td>0.171</td>
<td>0.01</td>
<td>438.5</td>
<td>458.4</td>
</tr>
<tr>
<td>750</td>
<td>15</td>
<td>South Range NW-15</td>
<td>0.014</td>
<td>0.008</td>
<td>340.1</td>
<td>1024.2</td>
</tr>
<tr>
<td>800</td>
<td>16</td>
<td>South Range NW-15</td>
<td>0.027</td>
<td>0.01</td>
<td>238.1</td>
<td>529.3</td>
</tr>
<tr>
<td>850</td>
<td>17</td>
<td>South Range NW-15</td>
<td>0.009</td>
<td>0.009</td>
<td>398.6</td>
<td>1262.3</td>
</tr>
<tr>
<td>900</td>
<td>18</td>
<td>South Range NW-15</td>
<td>0.007</td>
<td>0.009</td>
<td>384.4</td>
<td>1154.3</td>
</tr>
<tr>
<td>950</td>
<td>19</td>
<td>South Range NW-15</td>
<td>0.004</td>
<td>0.01</td>
<td>235.8</td>
<td>326.7</td>
</tr>
<tr>
<td>1000</td>
<td>20</td>
<td>South Range NW-15</td>
<td>0.015</td>
<td>0.009</td>
<td>266.2</td>
<td>341.1</td>
</tr>
<tr>
<td>1050</td>
<td>21</td>
<td>South Range NW-15</td>
<td>0.009</td>
<td>0.011</td>
<td>467.1</td>
<td>547</td>
</tr>
<tr>
<td>1100</td>
<td>22</td>
<td>South Range NW-15</td>
<td>0.001</td>
<td>0.01</td>
<td>467.1</td>
<td>656.5</td>
</tr>
<tr>
<td>1150</td>
<td>23</td>
<td>South Range NW-15</td>
<td>0.011</td>
<td>0.009</td>
<td>298.8</td>
<td>946.5</td>
</tr>
<tr>
<td>1200</td>
<td>24</td>
<td>South Range NW-15</td>
<td>0.019</td>
<td>0.011</td>
<td>168.4</td>
<td>607</td>
</tr>
<tr>
<td>1250</td>
<td>25</td>
<td>South Range NW-15</td>
<td>0.086</td>
<td>0.017</td>
<td>718.3</td>
<td>108</td>
</tr>
<tr>
<td>1300</td>
<td>26</td>
<td>Quartz Rich NW-15</td>
<td>0.023</td>
<td>0.01</td>
<td>473.1</td>
<td>1482.2</td>
</tr>
<tr>
<td>1350</td>
<td>27</td>
<td>Quartz Rich NW-15</td>
<td>0.037</td>
<td>0.008</td>
<td>379.3</td>
<td>886.1</td>
</tr>
<tr>
<td>1400</td>
<td>28</td>
<td>Quartz Rich NW-15</td>
<td>0.085</td>
<td>0.009</td>
<td>425.7</td>
<td>882.9</td>
</tr>
<tr>
<td>1450</td>
<td>29</td>
<td>Quartz Rich NW-15</td>
<td>0.082</td>
<td>0.009</td>
<td>376.8</td>
<td>841.4</td>
</tr>
<tr>
<td>1500</td>
<td>30</td>
<td>Quartz Rich NW-15</td>
<td>0.019</td>
<td>0.009</td>
<td>338.8</td>
<td>712.1</td>
</tr>
</tbody>
</table>