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THE RELATION BETWEEN MAGNETIC PROPERTIES,
DENSITY, OPAQUE MINERALOGY AND CHEMISTRY
IN DRILL CORE FROM THE LAC DU BONNET
BATHOLITH, MANITOBA

by

BEVERLEY ANNE CHOMYN

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

Department of Geology

Carleton University

Ottawa, Ontario

January 1987

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THE RELATION BETWEEN MAGNETIC PROPERTIES,
DENSITY, OPAQUE MINERALOGY AND CHEMISTRY
IN DRILL CORE FROM THE LAC DU BONNET
BATHOLITH, MANITOBA

submitted by Beverley Anne Chomyn, B.Sc.

In partial fulfilment of the requirements for

the degree of Master of Science

Thesis Supervisor

Chairman, Department of Geology

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ABSTRACT

Measurements of magnetic susceptibility (MS), isothermal remanent magnetization (IRM), remanence, and density were used to assess the degree of fracturing and alteration in core samples of the granitoid Lac du Bonnet batholith in southeastern Manitoba.

Variation in susceptibility is largely controlled by the grain size and the relative abundance of iron oxide minerals. The magnetic minerals occur as monomineralic grains of magnetite, hematite and as aggregates of magnetite plus ilmenite, and hematite plus ilmenite. Within fracture zones hematite commonly replaces magnetite. Susceptibility minima reflect fractured and altered rock, as well as those cores depleted in the iron oxides. Susceptibility minima associated with major fractures are large-scale features in contrast to the small-scale features associated with iron oxide-depleted core. Uniform, background levels correspond to unaltered, non-fractured homogeneous rock, while susceptibility maxima reflect xenoliths and core containing coarse-grained magnetic minerals. The IRM measurements provide a quantitative assessment of alteration. Samples with the highest acquisition coercive force (H_{cr}') correspond to altered core, while lower H_{cr}' values reflect the presence of non-altered iron oxides as well as altered iron oxides in which magnetite replacement by hematite is incomplete. A combination of remanence and susceptibility gives some indication of alteration and fracturing in the core. The density determinations are not as sensitive as susceptibility to changes in magnetic oxide content. However, low densities together with very low susceptibilities are indicative of alteration. Silica, Al_2O_3 , CaO , Na_2O and K_2O contents of the core show no systematic variation between altered and non-altered core.

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CHAPTER I: Introduction

1.1 Introduction

The Canadian Nuclear Fuel Waste Management Program (CNFWMP) was formally initiated in June of 1978 as a joint responsibility of the Federal Government and the Government of Ontario (Boulton, 1978). Since its inception, the program has the prime objective of the safe and permanent disposal of nuclear waste to ensure that there will be no significant adverse effect on man or the environment. In furtherance of this objective the Canadian Government in April 1981, approved a ten-year generic research and development (R & D) program on nuclear waste management. The objective of the R & D program is to assess the basic safety and environmental aspects of isolating immobilized fuel waste by deep underground disposal in plutonic rock masses of the Canadian Shield (Dixon and Rosinger, 1983; Boulton, 1978; Boulton and Gibson, 1979). The R & D program has three major components (Rumery and Rosinger, 1983): (1) research on immobilization of fuel wastes, (2) geoscientific research entailing the development of methods for evaluating large plutonic masses in the Canadian Shield as potential hosts for immobilized nuclear fuel wastes, and (3) environmental and safety assessment of the effects of storage, transportation, immobilization and disposal of nuclear fuel waste on man and the environment.

The evaluation of large plutonic rock masses in the Canadian Shield as possible hosts for immobilized nuclear fuel waste involves a quantification of in situ mechanical, physical and chemical

properties of the rock, groundwater, groundwater-rock-radionuclide interactions, and an evaluation of the methods used in the characterization of the various rock bodies (Dormouth et al., 1984). Field work already has been carried out in five research areas, namely, Chalk River, East Bull Lake, Atikokan, Overflow Bay, and Whiteshell. All are located in Ontario with the exception of Whiteshell (Lac du Bonnet site) which is located in southeastern Manitoba.

In the event of a potential breach in waste containment, groundwater will most likely be the medium by which radionuclides are leached from the buried waste and transported to the biosphere. The fractures and fracture networks within these rocks are important because they can potentially serve as pathways along which contaminants can be transported to the surface. Because of the importance of fracturing and radionuclide movement, research within the geoscience program has concentrated on the detection of fracturing by downhole and in situ geophysical methods. Some of the standard borehole measurement techniques include electrical (resistivity, self-potential (SP) and induced polarization (IP)), radar, nuclear (gamma-gamma, neutron probe), thermal, sonic, and magnetic susceptibility logging. Surface measurement techniques include seismic refraction and reflection surveys, gravity, electrical (magnetotelluric, very low frequency electromagnetics, resistivity/IP), radar, and ground magnetic surveys (Soonawala et al., 1982). The measurement of the magnetic properties of core samples is just one aspect of a series of comprehensive geological and geophysical investigations that are being carried out as part of geoscientific research within the CNFWMP. Measurements include

in situ bulk magnetic susceptibility, as well as anisotropy of magnetic susceptibility, remanent magnetization, and magnetite/hematite ratios.

The objective in the present study is to evaluate the relationship among magnetic properties, mineralogy, density and bulk rock chemistry of a series of cores from the Lac du Bonnet batholith. The magnetic properties investigated include magnetic susceptibility (MS), remanence, and isothermal remanent magnetization (IRM).

1.2 Geology of the Lac du Bonnet Batholith

The Lac du Bonnet batholith is located in southeastern Manitoba within the English River Subprovince of the Canadian Shield (Figure 1) (Wilson, 1971; Tammemagi et al., 1980). Described as a pink, coarse-grained quartz monzonite (McKitchie, 1971), this flat, sheetlike, northwesterly-dipping body attains a maximum width of about 25 km and an areal extent of greater than 1000 km².

The post-tectonic Lac du Bonnet batholith, 2495 ± 130 Ma old (Penner and Clark, 1971), is one of the youngest intrusions in the region. Its southern border forms a gradational contact with gneissic rocks of the Winnipeg River Batholith Belt, and to the north it cuts mafic metavolcanics of the Bird River Greenstone Belt (see Figure 1).

The lithologic units of the batholith are described in detail by McKitchie (1971). The pluton is characterized by a well-jointed, homogeneous, equigranular, pink, quartz monzonite (McKitchie, 1971). The outer zone is made up of a pink porphyritic biotite with partly assimilated country rocks. Xenoliths of black, amphibolitized

Figure 1: Location and general geology of the Lac du Bonnet batholith and URL site.

paragneisses and schists are believed to be re-crystallized Bird River metasediments and metavolcanics. Aplites and pegmatites are common throughout the batholith.

At the URL site, five granitic phases have been identified (Brown and Soonawala, 1982). Unit one is a pink, porphyritic, biotite granite, unit two is a foliated, pink, biotite hornblende granite, unit three is a grey, quartz monzonite phase and unit four is a xenolith-rich tonalite, granodiorite and quartz monzodiorite. The fifth unit is described as a pink granite which locally contains fine-grained and coarse-grained porphyritic phases.

Units one and three are believed to be the principal phases of the Lac du Bonnet batholith. Unit one, the marginal phase, locally contains abundant, partially assimilated, country rocks. The core zone is made up of quartz monzonite (unit 3). A gradational contact exists between the outer and inner zones. The outer zone, however, is reddened by deuteric or meteoric solutions, and at the URL site is very fractured. The fine-grained granite of unit five is believed to be an early chill-zone and probably corresponds closely in composition to the original magma.

1.3 Sample Selection

Samples were selected from three boreholes, URL-1, URL-2 and URL-5 (the URL series). These were selected at a time when only six deep cores were drilled in the Lac du Bonnet batholith at the URL site. Presently there are 13 deep drilled cores (person. comm. G. Reeves, 1986) and some 107 shallow cores (<155 m) which form part of

the groundwater-monitoring network (Daymond and Reeves, 1985). Cores URL-1, URL-2 and URL-5 reach a maximum depth of 678.82 m, 1099.80 m and 500.47 m respectively. On the surface the boreholes are within several metres of each other.

Specimens were selected on the basis of magnetic susceptibility and petrographic features. Previous work (Coles and Morris, 1980; Morris, 1980; 1982; Lapointe et. al., 1982; Chomyn and Lapointe, 1984) revealed that varying levels of susceptibility can be correlated with lithologic features in the URL core. As a result of this work it was shown that magnetic susceptibility minima reflect altered and fractured rock. Background, uniform susceptibilities are associated with non-fractured core, while susceptibility maxima correspond to xenoliths containing magnetic minerals.

The samples examined in the present study include altered and fractured rock, unaltered core, and xenoliths containing magnetic minerals.

Microfractures or small-scale fractures (≤ 3 cm) as well as major fracture zones commonly occur throughout the core. The fractured samples were selected from the major fracture zones. These zones occur between 80 m to 160 m and 320 m to 340 m in core URL-1, from 40 m to 180 m in URL-2, and from 60 m to 120 m, 200 m to 240 m, and 250 m to 260 m in URL-5. The fracture frequencies range from 10 to 90 fractures/metre. Many of the fracture zones, particularly near the surface (< 200 m), are open (Dugal and Kamineni, 1981). Examination of the core in hand specimen has revealed that fracturing is associated with alteration. Feldspars have been altered to clay, and

common fracture fillings are hematite, goethite and calcite. The degree or intensity of alteration varies among fracture zones. In contrast, the unaltered core is made up of medium-grained, grey, homogeneous, non-fractured granite. Some intervals of core are rich in potassium feldspar while other sections contain mafic-rich inclusions.

A total of 87 specimens, 10 cm long and 4.5 cm wide, were examined. The sample numbers are given in Appendix A. Two 1 cm specimens were drilled from each of the 10 cm samples. Magnetic measurements, density determinations and polished thin sections were made from one of these specimens, and chemical analyses made on the other.

CHAPTER II: Opaque Mineralogy

2.1 The Iron Oxides: Magnetite, Hematite and Ilmenite

The magnetic component of rocks depends on the presence of certain minerals which control the intensity of remanent and induced magnetization. The most important of the common rock-forming magnetic minerals are the iron oxides. Their chemical compositions can be represented by the ternary system $\text{FeO-TiO}_2\text{-Fe}_2\text{O}_3$. Three main solid-solution series are represented by magnetite-ulvöspinel, ilmenite-hematite, and pseudobrookite-ferropseudobrookite. Magnetite is strongly magnetic, while hematite and ilmenite are weakly magnetic. In order of decreasing susceptibility the minerals are as follows (Telford et. al., 1978): magnetite > hematite > ilmenite.

2.2 Classification of Grain Types

The iron oxides in the samples studied are divided into two types. Type I are discrete, monomineralic magnetite, hematite or ilmenite grains. Type II are aggregates of magnetite, hematite and ilmenite grains. Both Types I and II, show different degrees of alteration within fractured and altered core.

Type I grains are the most common. In unaltered core, magnetite is the most abundant iron oxide and occurs as discrete, subhedral- to euhedral-shaped grains (Plate 1), that range from 100 μm to 800 μm in size. The larger grain sizes ($\geq 400 \mu\text{m}$) are abundant at deeper levels

within the core. In unaltered core these large magnetite grains commonly exhibit ilmenite exsolution lamellae (Plate 2). Both large and small grains are generally equant-shaped. The dominant length/width ratio of the grain is either 1:1 or 5:1 (Tables IV, V and VI, Appendix B).

In fractured and altered core, Type I magnetite has a substantially reduced grain size (commonly less than 100 μm) and abundance because of alteration to hematite. Hematite is, in nearly all cases, the dominant opaque. The abundance of magnetite to hematite ranges from 1:20 to 1:4. In samples from URL-2, where alteration is much less than that observed in the URL-1 and URL-5 samples, the magnetite grains range from 100 μm to 400 μm in size.

Ilmenite occurs in both altered and unaltered core and reaches up to 800 μm . The average grain size is <200 μm . Type I ilmenite grains are irregularly-shaped, elongate grains with a length/width ratio of 2:1. Small needle-like crystals $\leq 100 \mu\text{m}$ also occur in close association with biotite and hornblende. The larger grains of ilmenite are associated with unaltered core, and are generally found in non-fractured core. Type I ilmenite (>200 μm) in URL-1 samples, for example, occurs in non-fractured core at depths between 160 m and 200 m and at depths greater than 200 m (Table IV). Similarly, in URL-2 the first 180 m of core (fracture zone) is devoid of large-sized ilmenite. However, at greater depths (>400 m) several ilmenite grains occur.

Plate 1: Large (1.3 mm) grain of magnetite from unaltered core in URL-1 at 156 m.

Plate 2: Large (1.3 mm) grain of magnetite from URL-1 at 592 m showing exsolution lamellae of ilmenite.

Type I hematite occurs in two forms. The first occurs as tabular to fibrous inclusions in biotite, hornblende and feldspars. These hematite grains, normally $<100\text{ }\mu\text{m}$ in size with a length to width ratio of about 3:1, coincide with local alteration such as the presence of microfractures ($\leq 3\text{ cm}$ long), and with minor alteration along the margins of major fracture zones. The second form of Type I hematite consists of large subhedral to anhedral grains ($>200\text{ }\mu\text{m}$), and occurs within extensively fractured rock, e.g. in URL-1 at 100 m (Table IV), in URL-2 at 100 m (Table V) and URL-5 at 220 m (Table VI). Commonly within these fracture zones, hematite replaces magnetite.

In addition to the iron and iron-titanium oxides, discrete grains of pyrite and chalcopyrite ($<100\text{ }\mu\text{m}$ in size) are disseminated throughout the core. Most grains are unaltered and show only minor replacement by magnetite along their grain boundaries.

Type II are composite grains, i.e. they contain more than one mineral. In fresh samples the most common composite grains consist of magnetite and ilmenite and in altered core aggregates of hematite-ilmenite (Plate 3) predominate. These grain-aggregates reach up to $2000\text{ }\mu\text{m}$ in size and are commonly equidimensional. Type II are less common than Type I.

2.3 Alteration of the Iron Oxides

Circulating groundwaters can alter titanium-bearing magnetite to hematite or titanomaghemite and hematite-rutile phases (Buddington and Lindsay, 1964). The commonest form of alteration in the URL specimens is alteration of magnetite to hematite. The extent of replacement by

hematite is variable. Types I and II show various degrees of alteration. In some samples the extent of alteration is minor: hematite occurs mostly along magnetite grain boundaries (Plate 4). Replacement is more pronounced in the more intensely altered core from the fracture zones (Plates 5, 6 and 7). Complete replacement is shown in Plate 8. In addition, in extensively fractured and altered cores rutile occurs as needle-like intergrowths in hematite and as a replacement after ilmenite.

Plate 3: Large (1.5 mm) grain-aggregate of ilmenite (upper left) and hematite (centre) with relict cores of magnetite (grey blebs) contained in hematite. This grain-aggregate is from fractured rock at 92 m in URL-2.

Plate 4: Type 1 magnetite (0.5 mm) from fracture zone in URL-5 at 112.40 m, showing minor replacement by hematite (white) along its grain boundaries.

Plate 5: Hematite (0.7 mm) hosting relicts of magnetite (grey) within more altered core at 99 m in URL-5.

Plate 6: More extensive replacement of magnetite (grey blebs) by hematite (0.5 mm) from the fracture zone (103 m) in URL-5.

Plate 7: Near complete replacement of magnetite (grey blebs) by hematite (0.65 mm) from same fracture zone in URL-5 (103 m).

Plate 8: Complete replacement of magnetite by hematite in URL-1 at 110 m. (Field of view 1.75 mm).

CHAPTER III: MAGNETIC PROPERTIES AND DENSITY

3.1 Magnetic Susceptibility

Magnetic susceptibility is the measure of the ability of a sample to become temporarily magnetized in a magnetic field. The observed variation in bulk susceptibility is controlled largely by the presence of iron-titanium oxide minerals, their grain size and their relative abundance. Magnetite is the most important of the iron-titanium oxides based on its abundance and high values of magnetic susceptibility. Variations in susceptibility may arise from lithologic changes, alteration of primary iron oxide and possibly iron sulphide species, or by the introduction of secondary iron oxide and/or iron sulphide species via fluid migration along fractures. Consequently, the recognition of particular susceptibility signatures associated with alteration near fractures may provide a direct qualitative estimate of the significance of individual fracture sets for fluid movement (Coles, 1981; Lapointe et. al., 1982).

3.1.1 Methodology

Three sets of measurements were made. The first was made on the core at intervals of about 2 m with three measurements taken 0.1 m apart. The high number of measurements over 2.8 km of core thus provides a nearly continuous record of susceptibility variation. The data are shown in Tables IV, V and VI (Appendix B). The second measurement was made every 0.1 m within fracture zones and regions of marked lithological variation. Thirdly, measurements were made on the

individual 10 cm and 1 cm specimens and are listed in Tables VII, VIII and IX (Appendix C).

3.1.2 Magnetic Susceptibility Variation in

Cores URL-1, URL-2 and URL-5

Results of previous work (Lapointe et. al., 1982; Chomyn and Lapointe, 1984) showed that there are four levels of bulk susceptibility measured in the Lac du Bonnet core. These are: (i) susceptibility minima (0 to 5×10^{-3} SI units); (ii) susceptibility maxima (20 to 100×10^{-3} SI units); (iii) intermediate susceptibilities (10 to 20×10^{-3} SI units); and (v) background susceptibilities (7 to 10×10^{-3} SI units), i.e. an approximation of the observed background of the URL cores. Comparisons among the lithology, fracture and bulk magnetic susceptibility logs also showed a relation between the magnetic susceptibility and lithological variation in the core.

Measurements made in the present study show that magnetic susceptibility minima are common to all cores generally within the first 150 m, corresponding in most instances to zones of intense fracturing with fracture frequencies of 32 fractures/metre and greater. An example of this feature is the fracture zone in URL-1 between 80 m and 160 m. The recorded bulk susceptibility values are low (0 to 4×10^{-3} SI units) in comparison to the higher values measured in less-altered, non-fractured rock.

Occurrences of magnetic susceptibility lows not associated with major fracturing coincide with hematite-filled microfractures (≤ 3 cm long) and intervals of core that are depleted in iron oxides. These features produce poorly-defined lows and are not common.

Magnetic susceptibility maxima coincide with the presence of xenoliths and with intervals of core containing coarse-grained magnetic minerals. In samples from URL-1 maxima predominate in the intervals 400 m to 620 m. In URL-2, zones of susceptibility maxima are observed at depths between 350 m to 420 m and between 800 m to 1000 m. In URL-5, susceptibility maxima occur between 310 m to 450 m.

Intermediate levels (10 to 20×10^{-3} SI units) coincide with unaltered, coarse-grained, non-fractured core with abundant iron oxides. Average or background susceptibilities (7 to 10×10^{-3} SI units) correspond to homogeneous, non-fractured core.

Specimens listed in Tables I, II and III (Appendix A) were selected from each of the magnetic susceptibility zones. In cgs units (Tables VII, VIII and IX - Appendix C) susceptibility minima of the individual specimens lie between 0 and 0.20×10^{-3} cgs/cc. Average or background susceptibilities of unaltered, homogeneous granite range between 0.40 to 0.69×10^{-3} cgs/cc; intermediate levels range between 0.69 to 1.0×10^{-3} cgs/cc and maxima range from 0.75 to as high as 5.5×10^{-3} cgs/cc. To convert to SI units, the data must be multiplied by a factor of 4π . Once converted, the data are similar to the levels in bulk susceptibility measured by Chomyn and Lapointe (1984).

3.2 Density

Both rock density and susceptibility are related to mineral composition and content. Thus, any post-crystallization processes that affect iron oxides will affect both density and susceptibility. In granitoid rocks density variations are controlled by mafic minerals

(Henkel, 1970). Henkel (1976) used a combination of density and susceptibility to identify some of the secondary processes. For example, serpentinization of ultramafic rock could be identified on the basis of changes in density and susceptibility. However, secondary processes acting under isochemical conditions may not result in any change in susceptibility or density.

In the present study, an attempt was made to identify fracturing and alteration on the basis of density and susceptibility changes.

3.2.1 Methodology

The density of the sample was determined by first weighing the specimen in air (W_1) and then in water (W_2). The density of water (L) is close to 1 gm/cc. Density is then calculated using the following formula (Berry and Mason, 1959): $\text{density} = (W_1 / W_1 - W_2) \times L$.

3.3 Density and Magnetic Susceptibility

On a plot of density versus susceptibility, the data fall into two groups (Figure II a, b, and c). This subdivision is based mainly on differences in susceptibility. In all cores the bulk of the specimens plot in a region of susceptibilities that range from 0.10×10^{-3} cgs/cc to 5.50×10^{-3} cgs/cc and a density interval 2.64 to 2.68 gm/cc. Specimens within this first group are from both non-fractured and fractured core. However, more than 80% of the specimens that plot in this interval have opaque abundances $>0.25\%$. Magnetite is the dominant

opaque mineral with an average grain size of between 400 μm to 800 μm ; some grains are as large as 2020 μm (URL-1, no. 25 (592.00 m); URL-5, no. 21 (289.60 m). Magnetite occurs as subhedral to euhedral Type I grains and Type II grain-aggregates (Tables IV, V and VI - Appendix B). The large grains ($>500 \mu\text{m}$) commonly occur in non-fractured core, while grain sizes $\leq 200 \mu\text{m}$ are characteristic of specimens from fractured core where magnetite is replaced by hematite (URL-1, nos. 3 (80.00 m), 5 (100.00 m); URL-2, nos. 1 (50.77 m), 3 (115.35 m).

A second group of data plots in a region of low susceptibility ($.01$ to 0.13×10^{-3} cgs/cc) and density. Three-quarters of the data within this group are of extensively altered and fractured core. Samples URL-1 nos. 4 (85.46 m) and 6 (109.00 m) are from the upper fracture zone between 80 m to 160 m; URL-2 no. 2 (93.20 m) is from an intensively fractured zone between 40 m to 180 m, and samples URL-5, nos. 8 (99.44 m), 9 (103.00 m), 17 (190.40 m), 18 (216.90 m) and 20 (246.32 m) are from fractured core between 60 m to 260 m. Hematite, the dominant opaque within this second group is much larger in size (400 μm to 800 μm) than the magnetite within the first group. The remaining group two specimens are unaltered and generally have low iron oxide contents ($<0.25\%$) and contain pyrite and ilmenite as the dominant opaque, e.g. URL-1, no. 22 (397.20 m); URL-2, nos. 8 (200.40 m), 11 (355.60 m) and 14 (414.80 m); URL-5, nos. 22 (322.30 m), 23 (324.60 m), 28 (386.10 m). Despite the fact that altered and fractured samples, as well as iron oxide-depleted core show low susceptibilities and densities they can still be separated on the basis of density differences. The URL-1 and URL-5 specimens with densities <2.65 gm/cc are from the fracture zones and those with densities >2.65 gm/cc are from non-fractured iron oxide-depleted core.

Figure II a, b, c: (clockwise). Density-susceptibility plots of URL-1, URL-2, URL-5. Note two distinct groups based on high and low susceptibilities.

3.4 Natural Remanence and Magnetic Susceptibility

Using a combination of remanence and magnetic susceptibility it may be possible to identify fracturing and alteration within core. The ratio between remanent and induced magnetization, expressed as the so-called Q-value or Koenigsberger ratio, can be used to define grain size and oxide characteristics of rocks (Henkel, 1976). Henkel recognized distinct magnetic units within a granite body that seemed to relate to the type and degree of exsolution occurring in the magnetic minerals. Henkel's (1977) work on fracture zones several hundred metres wide and several tens of kilometres long, showed a decrease in susceptibility, in some cases by a factor of 40 and a decrease in remanence by a factor of 9. Thus the resultant Q-value of fractured rock can be quite large. Examination of a coarse-grained granite and a fine-grained volcanic, both containing magnetite showed different degrees of magnetization. The susceptibilities of the less altered specimens ranged from 10^{-3} to 10^{-2} cgs/cc with corresponding Q-value of approximately 0.1. By comparison, the susceptibilities of the altered specimens range between 10^{-5} and 10^{-4} cgs/cc with corresponding Q-value of 1 and slightly less than 1. Some similar trends are exhibited by the URL cores.

From plots of Koenigsberger ratio versus susceptibility (Figure III a, b, and c) two features are apparent. Firstly, in all cores the data can be subdivided into two susceptibility groups -- one group corresponds to low susceptibility (most are less than 0.10×10^{-3} cgs/cc), and the other has values greater than 0.10×10^{-3} cgs/cc. Secondly, specimens from the major fracture zones have

Q-values generally greater than 1. This is well-defined by the data from the URL-1 and URL-2 specimens.

The bulk of the URL specimens plot in the higher susceptibility interval. The data that plot within this interval are, for the most part, from non-fractured and unaltered samples. Samples with microfractures and also from the major fracture zones, account for less than one-quarter of the total specimens in this higher susceptibility region. The opaque abundances in the unaltered and non-fractured samples is generally equal to or greater than 0.50%. The dominant opaque is magnetite; ilmenite is second in abundance. Hematite, present only in fractured and altered samples, is second in abundance to magnetite.

In contrast, the bulk of the data in the lower susceptibility interval is from altered and fractured samples. Samples not from the fracture zones have either microfractures or have low iron oxide contents. The opaque abundance of this group is generally equal to or less than 0.25%. Specimens with low iron oxide contents have opaque abundances less than 0.25%. Hematite is the dominant opaque in fractured and altered core.

The second feature, although less well-defined, shows that the fractured and altered specimens in URL-1 and URL-2 plot in the region $Q \geq 1$. By comparison, the non-fractured and unaltered specimens plot in both regions, $Q \geq 1$ and $Q \leq 1$. However, the specimens from the major fracture zones are further distinguished from the unaltered specimens because they have lower susceptibilities than their unaltered equivalents.

Several specimens from both URL-1 and URL-2 plot in a region of both low susceptibility and $Q < 1$ (Figure III a nos. 13, 22, and 26; Figure III b nos. 11, 14, and 23). These specimens are depleted in iron oxides; all have opaque abundances of ≤ 0.25 . In addition, the URL-2 specimens have microfractures. In URL-5 it appears that the fractured and altered specimens are distinguished solely on the basis of susceptibility. That is, the fractured and altered specimens plot almost entirely within the lower susceptibility interval but within regions of both $Q \geq 1$ and $Q \leq 1$. Thus, there appears to be no relation between fractured and altered core, unaltered core and Q-values.

Figure III a, b and c: (clockwise). Koenigsberger ratio versus susceptibility plots for URL-1, URL-2 and URL-5. The bulk of the data from the fracture zones (square symbols) plot in a region of R/X 1 and low susceptibility. This feature is less well-defined in URL-5.

3.5 Isothermal Remanent Magnetization

One method used to determine alteration quantitatively is based on IRM measurements (Morris, 1983). IRM is defined as the moment remaining in a sample after application of a magnetic field. This is done at constant (usually room) temperature (Carmichael, 1981). The method is based on the different remanence coercivities which is the measure of a rock's ability to resist orientation of its magnetic direction due primarily to destructive geologic forces.

When a direct magnetic field is applied to randomly-oriented magnetic grains and subsequently removed there remains a remanent magnetization. Application of higher and higher fields increases the remanent magnetization until saturation magnetization is reached - at which point all atomic moments are aligned in their maximum ordered configuration. The curve which gives the relation between the acquired remanent magnetization and the applied direct field is the remanent acquisition curve. From this, the acquisition coercive force (H_{CR}') can be determined which is defined as the strength of the direct field to produce one half of the remanent saturation magnetization. Two parameters can be calculated from the IRM analysis, the acquisition coercive force and the ratio of maximum remanence saturation to bulk susceptibility (J_{sat}/X). Unlike susceptibility both these parameters are independent of oxide content.

3.5.1 Methodology

One-centimetre specimens were placed between the poles of an electromagnet. A direct magnetic field was applied parallel to the

cylinders of the electromagnet for 10 seconds. The specimen was removed and the remanent magnetization measured immediately with a spinner magnetometer in a zero magnetic field. The applied field was increased stepwise in increments of 200 Oe from 200 Oe to 10 kOe.

3.5.2 IRM, Grain Size Variation and Alteration

Dankers (1978) showed that different kinds of hematites (a kidney ore with a radial fibrous structure, a Kimberley hematite ore, and a poorly-crystallized, altered hematite), exhibited an increase in H_{Cr}' with decreases in grain size for all samples less than 30 μm . For grains coarser than 30 μm , the H_{Cr}' was practically independent of grain size in the fibrous and Kimberley hematite, and increased with increasing grain size in the altered, poorly crystallized ore. The difference in dependence of H_{Cr}' on grain size is thought to be due to the different domain configurations: the small grains would be single domains whereas the coarser grains would be multi-domains. In multi-domain grains the demagnetizing field of the grain as a whole would have the effect of reducing the H_{Cr}' value.

The H_{Cr}' values of unoxidized magnetites in Dankers' study were shown to be grain-size dependent. Generally the higher the H_{Cr}' , the smaller the grain size. The H_{Cr}' values were between 250 Oe and 630 Oe for grain sizes between 250 μm to 5 μm . The higher H_{Cr}' values (490 Oe to 675 Oe) corresponded to lamellar maghemite and was thought to be due to the very fine size of the lamellae. Similar

trends to those identified by Dankers are observed for hematite and magnetite in the URL samples.

The bulk of the URL-1 specimens plot in the H_{Cr}' interval 100 Oe to 250 Oe (Figure IV a). They are primarily from non-fractured core. The bulk of the URL-2 and URL-5 specimens plot in a higher interval, 100 Oe to 550 Oe (Figure IV b and c).

In all of the core specimens studied, the higher H_{Cr}' values are associated with fractured rock. In URL-2, for example, specimens within the first 400 m of core show higher H_{Cr}' values than at other depths. This region contains the only major fracture zone occurring between 40 to 180 m in the core. Similarly in URL-5, specimens with values in excess of 200 Oe are from fracture zones at 100 m, 220 m and, 250 m.

From these measurements it can be seen that the higher the H_{Cr}' the more altered and fractured the rock. For example, in URL-5 specimens 8 (99.44 m), 9 (103.00 m), 17 (190.40 m), 18 (216.90 m) and 20 (246.00 m) are fractured and altered. Their H_{Cr}' values are greater than 1400 Oe and as high as 6000 Oe. Specimen 2 (93.20 m) in URL-2 is from a zone of extensive fracturing between 95 to 110 m. The fracture frequency within this zone ranges from 30 to 80 fractures/metre. This specimen has the highest H_{Cr}' value (4000 Oe) of the URL-2 specimens. Specimen 3 (115.35 m) from a less-fractured interval (0 to 10 fractures/metre) by comparison has a corresponding lower H_{Cr}' value of 400 Oe.

In URL-1, the specimens from the upper fracture zone (between 80.00 m and 160.00 m) have high H_{Cr}' values, between 1000 Oe and 3000 Oe. There are no data for the second fracture zone at 330 m.

Figure IV a, b and c: (clockwise). IRM plots from URL-1, URL-2 and URL-5. The data from the fracture zones (square symbols) plot in a region of high $H_{CR'}$ (≥ 1000 Oe) and increasing $JSAT/X$. This trend is well-defined in URL-5 and less apparent in URL-2.

The advantage of IRM measurements over MS is that it quantitatively assesses alteration. Unlike magnetic susceptibility the values of H_{Cr}' reflect the types of minerals present and hence indicate whether or not the core is altered. For example, magnetite is the dominant opaque in specimens that have H_{Cr}' values equal to or less than 500 Oe. The bulk of these specimens are unaltered and non-fractured and have a corresponding average susceptibility of 0.60×10^{-3} cgs/cc. In URL-1, 16 of the 20 specimens (80%) that plot within the H_{Cr}' interval between 100 Oe to 250 Oe have Type I magnetite as the dominant opaque; three have ilmenite and one, pyrite. Type I magnetite occurs as large equant-sized grains and ranges in size from 400 μ m to 800 μ m. In xenolith zones, these grains are as large as 2000 μ m. Type II grain-aggregates are minor in occurrence. Similarly in URL-2, H_{Cr}' values between 100 Oe to 200 Oe correspond to samples with a high proportion of magnetite (70% to 95%). These specimens are mainly from depths below 400 m. The sizes of magnetite grains with low H_{Cr}' values (<200 Oe) are much larger (400 μ m to 800 μ m) than those with higher H_{Cr}' values (<400 μ m).

In URL-5 similar features are observed. Specimens with H_{Cr}' values <400 Oe contain magnetite as the dominant opaque and are coarse-grained (200 μ m to 800 μ m). Magnetite occurs as euhedral-shaped Type I grains. Ilmenite, second in abundance, occurs as elongated irregularly-shaped grains up to 400 μ m in size. In samples with H_{Cr}' values <200 Oe the proportion of magnetite to ilmenite is large (between 80 to 95% magnetite), whereas samples with H_{Cr}' values between 200 Oe to 400 Oe have nearly equal amounts of magnetite and ilmenite.

In contrast, in fractured core with corresponding high H_{cr}' (>500 Oe) and susceptibilities from 0 to 0.03×10^{-3} cgs/cc the dominant opaque is hematite. Specimens from the fracture zones in URL-5 (at 100 m, 220 m and 250 m), have high H_{cr}' values between 1400 Oe and 6000 Oe and contain mainly hematite with minor magnetite. The average ratio of hematite to magnetite is 80:20. Hematite occurs as large (400 μ m to 800 μ m) equant-shaped grains replacing magnetite. The average magnetite grain size within hematite is <100 μ m. Likewise in altered core from the fracture zone in URL-2 (40 m to 180 m) the major opaque hematite, ranges in size from 400 μ m to 800 μ m. Magnetite, occurs as small grains (<100 μ m), is the minor phase; its abundance is $<5\%$ of the opaque minerals. On the margin of this zone of intensive fracturing (~ 155 m), the mineralogy changes and magnetite is the dominant opaque from 200 μ m to 400 μ m in size and hematite the minor phase, occurs as small grains (100 μ m to 200 μ m). Similarly in URL-1, specimens from the upper fracture zone between 80 m to 110 m, exhibit high H_{cr}' values between 1000 Oe to 3000 Oe. These values correspond to hematite as the dominant opaque, occurring as large, (400 μ m to 800 μ m) equant-shaped grains. Its abundance relative to magnetite and ilmenite is 75% to 95%.

The bulk of the URL-2 and URL-5 specimens have J_{sat}/X values less than 100. Dankers' study showed that the saturation remanent magnetization became exponentially larger with decreasing grain size. In both URL-1 and URL-5 a trend is seen between J_{sat}/X values and fractured core. Small grain sizes of magnetite generally less than 100 μ m occur in the intensely fractured rock in URL-1 and URL-5. The J_{sat}/X values for these samples are equal to and greater than 500.

By comparison, the non-fractured core is coarse-grained and has grain sizes between 400 μm to 800 μm with corresponding J_{sat}/X values <100 . In URL-2 the J_{sat}/X values are <100 . Both fractured and altered samples and non-fractured and unaltered samples show similar J_{sat}/X values. There appears to be no relation between grain size and altered and fractured core.

CHAPTER IV: Chemistry

The major oxides and trace element abundance data are given in Appendix D. All were made by X-ray fluorescence analysis except for FeO, H₂O, CO₂, C, and S. All analyses were made at the Geological Survey of Canada. The uncertainty of the major elements is $\pm 2\%$ of the quoted value at the 2 σ level; trace elements have uncertainties of $\pm 10\%$.

Ferrous iron was determined by the Wilson titration method (Wilson, 1955). Total carbon, total water and sulphur were determined by volatilization and infrared absorptiometry (Bouvier and Abbey, 1980). Carbonate carbon was determined by traditional acid evolution (Johnson and Maxwell, 1981) followed by infrared detection. Non-carbonate carbon was determined by measuring the difference between total carbon and carbonate carbon.

The samples are classified using Streckeisen's normative classification (1976). Harker and AFM diagrams and various oxide/oxide plots were used to identify any major trends shown by the chemical compositions of the cores.

4.1 Streckeisen's Classification

Streckeisen (1976) classified igneous rocks on the basis of normative Or-Ab-An contents. Igneous rocks can be subdivided into the following three major groups based on their normative quartz content: (i) quartz-feldspar rocks with normative quartz greater than 17; (ii) feldspar rocks with normative quartz less than 17 and normative nepheline less than 7 and (iii) feldspar-foid rocks with

normative nepheline more than 7. All samples in this study fall within Group 1. Streckeisen further subdivided igneous rocks on the basis of their normative An/Or ratio (Table 1, Streckeisen, 1976). The bulk of the data plot in the alkali-feldspar granite fields (Figure V a, b and c).

4.2 Chemical Variation

In order to compare chemical differences from one hole to another, ternary plots were made of total Fe versus alkalis versus MgO. In URL-1 and URL-2 (Figure VI a and b) the bulk of the specimens plot in the $\text{Na}_2\text{O} + \text{K}_2\text{O}$ corner showing only slight Fe enrichment. Specimens 5 (100.00 m), 16 (221.80 m), 17 (230.10 m), 21 (356.80 m), 22 (397.20 m) and 25 (592.00 m) in URL-1 and 12 (397.50 m) and 17 (625.00 m) in URL-2 show some Fe enrichment relative to the other samples.

In general, the higher the iron content of a specimen the higher the susceptibility. In URL-1 with the exception of sample 22, the susceptibilities range from 0.64 to 2.10×10^{-3} cgs/cc and in URL-2 from 1.82 to 5.5×10^{-3} cgs/cc.

The URL-5 specimens are more iron enriched than the URL-1 and URL-2 specimens (Figure VI c). All URL-5 samples from depths greater than 300 m show an increase in iron-bearing minerals relative to samples from 300 m. This feature is reflected in the high measured susceptibilities of the specimens (Table IX) and the overall higher bulk susceptibilities of the URL-5 core (Table VII).

Figure V a, b and c: (clockwise). Normative Or-Ab-An plots of URL-1, URL-2 and URL-5 data. Note that the bulk of the data plot in the alkali-feldspar granite fields.

Figure VI a, b and c: (clockwise). AFM plots. In URL-1 and URL-2 most of the data plot in the $\text{Na}_2 + \text{K}_2\text{O}$ corner. The URL-5 samples show more iron enrichment.

In some cases, high Fe content corresponds to low susceptibility, e.g. URL-1 no. 22 (397.20 m), URL-5 no. 28 (386.10 m). The dominant opaque in such cases is not magnetite but minerals with low susceptibility such as pyrite and ilmenite.

A series of Harker diagrams are shown in Figures VII, VIII and XI. In URL-1 (Figure VII) and URL-2 (Figure VIII) slight increases in Al_2O_3 content, and depletion in K_2O , characterize specimens from the fracture zones. The URL-5 specimens show little variation in Al_2O_3 and K_2O contents between fractured and altered and non-fractured and unaltered core (Figure IX).

The CO_2 and H_2O contents of all cores show little variation. The bulk of the specimens plot between 0.2 and 0.4 weight % H_2O and 0.1 to 0.2 weight % CO_2 (Figure X a, b and c). Approximately 70% of the fractured specimens however, have H_2O values in excess of 0.4%.

Titanium (Figure XI a, b and c) is depleted in the fractured and altered specimens relative to unaltered core. This feature, to a certain extent, also apparent in the URL-5 specimens. Specimens from non-fractured core generally have values in excess of 1000 ppm Ti. In the case of K_2O fractured and altered specimens in URL-2 and URL-5 have higher potassium contents relative to non-altered core.

To summarize, samples from unaltered core, at depths >400 m exhibit higher Fe_2O_3 , K_2O , Ti, Rb contents, higher susceptibilities and lower Al_2O_3 , H_2O and Na_2O values, than altered core.

Figure VII. Silica variation diagrams of data from URL-1 specimens. Specimens from the fracture zone are nos. 3, 4, 6, 7 and 11.

Figure VIII: Silica variation diagrams of data from URL-2.
Specimens from the fracture zones are nos. 1, 2, 3, 4, 5 and 6.

Figure IX: Silica variation diagrams of data from URL-5.
Specimens from the fracture zones are nos. 3, 4, 5, 6, 7, 8, 9, 12, 17, 18, 19 and 20.

Figure X a, b and c: (clockwise). CO₂ versus H₂O plots. In all cores, the fractured and altered specimens generally have values greater than 0.4 wt. % H₂O. The altered and fractured specimens, in URL-1 are nos. 3, 4, 6, 7 and 11. In URL-2 they are nos. 1, 2, 3, 4, 5 and 6 and in URL-5 they are nos. 3, 4, 5, 6, 7, 8, 9, 12, 17, 18, 19 and 20.

Figure XI a, b and c: (clockwise). Plots of Ti versus SiO₂ for URL-1, URL-2 and URL-5.

Fracture specimens in URL-1 are nos. 3, 4, 6, 7 and 11. In URL-2 they are nos. 1, 2, 3, 4, 5 and 6 and in URL-5 they are nos. 3, 4, 5, 6, 7, 8, 9, 12, 17, 18, 19 and 20.

CHAPTER V: Discussion

A number of measurements and analyses have been carried out on core samples in an attempt to distinguish fractured and altered core from non-fractured and unaltered core. It has been discovered that some of the methods are better suited for this purpose than others.

The studies of the opaque minerals provide almost complete information on the alteration state of the core. However, the major drawback of this approach concerns the large number of samples required as well as the time and cost involved. Examination of the specimens in reflected light revealed that the dominant iron oxides are magnetite, hematite and ilmenite. These grains differ in abundance, size and shape throughout the core. In unaltered core the bulk of the specimens have opaque abundances that range from 0.50 to 0.75%, whereas in altered and fractured rock and intervals of low oxide content the average content is $\leq 0.25\%$. The Type I magnetite grains are the most common in non-fractured rock; ilmenite is second in abundance. Magnetite commonly occurs as large (400 μm to 800 μm) subhedral-euhedral shaped grains, while hematite is restricted to the fracture zones where it also occurs as large (400 μm to 800 μm) equant-shaped grains replacing magnetite. Small grain sizes ($< 100 \mu\text{m}$) of hematite are confined to the less altered intervals within these zones. The more altered the specimen, the most complete the replacement of magnetite by hematite. Where alteration is extensive, the alteration products themselves are broken down so that only relicts of hematite remain enveloped by rutile.

Susceptibility minima reflect fractured and altered core in contrast to the high levels that are associated with unaltered core and xenoliths. The use of susceptibility measurements, however, has its shortcomings. Difficulties arise in distinguishing altered and fractured core from unaltered and non-fractured core in two cases, namely where the replacement of magnetite by hematite is incomplete and secondly, where sections of the core are poor in iron oxides. If the replacement of magnetite by hematite is incomplete, the susceptibility values will be greater than zero. In such cases, the proportion of magnetite to hematite is nearly always 30% or greater. On the basis of MS values alone it is difficult to determine whether the levels of susceptibility are indicative of fractured core with some alteration or simply iron oxide-depleted core. For example, in URL-1, specimens 18 (240.10 m) and 26 (599.10 m) from unaltered core have low opaque mineral abundances (<0.25%). Their susceptibilities are low (0.07×10^{-3} cgs/cc and 0.04×10^{-3} cgs/cc, respectively). By comparison, sample no. 6 (109.00 m) within the fracture zone, has a similarly low susceptibility of 0.04×10^{-3} cgs/cc, but has an opaque abundance of 0.75% and the proportion of magnetite to hematite is 60/30. In this particular case, the low susceptibility is thought to be due to the alteration, though incomplete, of magnetite to hematite.

In the case of cores depleted in iron oxides, the corresponding susceptibilities may be similar to the low levels of susceptibility that characterize the fracture zones. Here again difficulties may arise in distinguishing the two different types. However, this problem may be resolved depending on the size of the sample. For example, examination of the bulk susceptibility logs of the cores (Appendix B),

shows that the major fracture zones are large-scale features that extend for metres. The fracture frequencies range from 10 to 90 fractures/metre. The resultant susceptibility pattern about this zone of fracturing resembles a well-defined 'trough'. By comparison, the susceptibility patterns of the iron oxide-depleted cores are much smaller-scale features and the corresponding low susceptibilities are sporadic and poorly defined. On the hand-specimen scale it may be difficult to resolve differences between low susceptibilities arising from fracturing and alteration and lows attributed to mafic-poor core. In both cases the levels of susceptibility may be similar.

It has also been shown that IRM measurements of the core is a more effective method for distinguishing altered from unaltered specimens. The data indicate that the highest H_{cr}' values correspond to the most altered specimens within the fracture zones. Values from 1000 Oe to 6000 Oe correspond to the presence of hematite within these zones. However, commonly where the replacement of magnetite by hematite is incomplete, relict grains of magnetite are contained within hematite. Since the H_{cr}' values depend on the proportion of magnetite to hematite in the samples, the greater the proportion of magnetite (>30%) the lower the H_{cr}' value. In those cases where the magnetite grains within hematite are large enough (100 μ m to 200 μ m) to act as single grains, the H_{cr}' values can be as low as 400 Oe.

Unaltered specimens contain magnetite as the dominant opaque ($\geq 75\%$), and the corresponding H_{cr}' values are between 100 Oe and 250 Oe. Combinations of ilmenite and magnetite, however, give

H_{Cr}' values in the range of 300 Oe to 700 Oe. Thus, H_{Cr}' values between 400 Oe and 700 Oe do not necessarily correspond to altered core. The extent of alteration can only be determined conclusively by examination of samples in reflected light. However, high values in H_{Cr}' (>1000 Oe) with corresponding low susceptibilities are positive indications of alteration.

The J_{sat}/X values are good indicators of grain size reduction during alteration if used in combination with high H_{Cr}' values (>1000 Oe). That is, high H_{Cr}' values are diagnostic of hematite and hence of alteration. Any corresponding decrease in grain size is attributed to reduction processes during alteration. If used alone, increases in J_{sat}/X could be attributed to processes unrelated to alteration, e.g. small magnetite grain sizes and low iron oxide content.

The density-magnetic susceptibility plots provide another approach in distinguishing altered from non-altered core. However, it has clearly been shown that density is not as sensitive an indicator to such changes in the core as the IRM and susceptibility measurements. In all cores the distinction between altered and unaltered core is mainly based on differences in susceptibility. Only slight decreases in density (values <2.65 gm/cc) are associated with fractured and altered core.

The measurement of density and magnetic susceptibility is however, effective for identifying specimens with coarse-grained oxides with opaque abundances in excess of 1%. Specimens with high opaque abundances are restricted mainly to the xenolith zones, and their densities, the highest of the URL specimens, are between 2.67 gm/cc and 2.70 gm/cc. By comparison the average density of

unaltered, homogeneous core is 2.65 gm/cc. The altered specimens, with corresponding H_{cr} values >1000 Oe have susceptibilities one to two orders of magnitude less than their unaltered equivalents and densities between 2.61 gm/cc to 2.64 gm/cc. An important feature of the density measurements is that it may be possible to distinguish between altered specimens and specimens with low iron oxide content. Altered specimens from the fracture zones have densities ≤ 2.64 gm/cc and low susceptibilities. The unaltered specimens with low iron oxide contents ($<0.25\%$) likewise have low susceptibilities but their densities are slightly greater (≥ 2.65 gm/cc) than the altered and fractured specimens.

Henkel's studies (1977) of fracture zones showed that remanence and susceptibility plots could be used to distinguish between fractured and non-fractured rock. However, before such an approach can be used, there must be carriers of the stable components of remanent magnetization, notably small grains (Larsen, 1969). The technique does not work well in the present study because of the large-grained, multi-domain magnetites which are likely to carry an unstable remanence. Magnetite and hematite grains are commonly 400 μ m to 800 μ m in size. Once again the major trends are identified by magnetic susceptibility, the bulk of the unaltered specimens plot in the interval 0.32 to 9.2×10^{-3} cgs/cc, the altered specimens within the interval 0.01 to 0.14×10^{-3} cgs/cc.

There appears to be no well-defined trends in Q-value and alteration of the cores. In URL-1 and URL-2 the fracture specimens have Q-values greater than 1, but this is not true for the URL-5 samples. The latter are coarse-grained and have corresponding

higher bulk susceptibilities than cores URL-1 and URL-2. It is suggested that the larger grains of magnetite are unsuitable as stable carriers of remanence and thus there is no meaningful relation between Q-value and susceptibility.

A major assumption in remanence measurements is that each grain has acquired remanence by similar acquisition processes. That is, all grains were magnetized to the same degree under constant cooling. This may not be true for all grains. Hematite, for example, may have acquired its remanence chemically. In addition, the magnetic minerals in the xenoliths more than likely acquired their remanences under thermo-chemical conditions quite different from those that existed within the main body of the pluton. The presence of xenoliths in URL-5 may, in part, account for the absence of meaningful trends in remanence.

Few of the major oxides such as Al_2O_3 , SiO_2 , CaO , MgO and MnO , reflect changes in the rock that can be used to distinguish altered and unaltered core. Of these, the H_2O determinations, particularly specimens with $H_2O \geq 0.4$ weight %, are good indications of altered specimens. The increased H_2O contents may in part be attributed to hydration and hydrolysis reactions during weathering. Iron enrichment is observed in the URL-5 specimens, to a lesser extent in the URL-1 specimens and no trend is observed for the URL-2 core data. The URL-5 core has higher bulk susceptibilities (Table VI), and higher iron oxide content than URL-1 and URL-2. Thus, increased iron contents in this case is not necessarily indicative of alteration. Decreases in Ti content are characteristic of specimens

from the fracture zones in URL-1 and URL-5 and to a less extent in URL-2. This observation may, in part, be attributed to the alteration and breakdown of titanium-bearing magnetite and ilmenite. Ilmenite and magnetite, notably absent from the fracture zones, commonly occur as large, grains in unaltered core.

CHAPTER VI: Conclusions

A number of measurements have been made on cores from the Lac du Bonnet batholith, Manitoba, in order to assess the degree of alteration of the batholith. Measurements include magnetic susceptibility, density, isothermal remanent magnetization and remanence. In addition, reflected light microscopy studies and chemical analyses were performed on the samples. The main conclusions of this study are:

1. The Lac du Bonnet batholith is lithologically heterogeneous. Lithological variations occur on the scale of centimetres.
2. The dominant iron oxides are magnetite, hematite and ilmenite. These minerals occur as two types. Type I are discrete monomineralic grains of which magnetite is the most abundant. Type II are grain-aggregates of two or more minerals, notably magnetite-ilmenite. Type I are common throughout the core. Type II generally occur at greater depths in the core.
3. In unaltered core, magnetite occurs as large (400 μm to 800 μm) equant grains, whereas magnetite occurs as much smaller grains (<100 μm) in altered core. Hematite, restricted to fracture zones and associated alteration, commonly occurs as large (400 μm to 800 μm) equant-shaped grains replacing magnetite, and also as small tabular to fibrous crystals along grain boundaries of magnetite, biotite and the feldspars. Ilmenite occurs as small (generally

<100 μm) and large grains (>800 μm) in unaltered core. The large grains occur at depths >400 m.

4. The iron oxide abundances range from $\leq 0.25\%$ to 3.50% of the total mineral content of the sample studied. Unaltered core averages between 0.50% and 0.75% iron oxides. Zones rich in xenoliths and coarse-grained, magnetite-bearing samples have values 0.75% .

5. Magnetic susceptibility measurements of the core is an effective method to identify variations in the iron-titanium mineralogy of the core. The levels of susceptibility are related to the type of magnetic minerals present, their composition, abundance, and grain size.

6. The magnetic zones based on susceptibility measurements and petrographic examination of the core are: (i) susceptibility minima that correspond to fractured and altered core, and iron-oxide depleted core; (ii) susceptibility maxima that are associated with xenoliths containing magnetic minerals; (iii) uniform, 'average' levels of susceptibility within unaltered homogeneous core; and (iv) intermediate levels of susceptibility that correspond to core intervals containing coarse-grained, magnetic minerals.

7. None of the magnetic methods and methods using a combination of magnetic and rock properties, completely distinguishes between altered specimens and iron-oxide depleted core. The density versus susceptibility measurements are the most definitive. Specimens with low susceptibilities and densities < 2.64 gm/cc characterize altered fracture zones. In contrast, specimens with low iron oxide contents have similar low susceptibilities but their densities are greater (≥ 2.65 gm/cc). Unfortunately the density changes are slight and do not reflect compositional changes associated with the alteration of the iron oxides.

8. The use of magnetic susceptibility measurements in identifying altered and fractured rock is difficult because low susceptibilities are also caused by changes in mineralogy unrelated to fracturing and alteration. It is possible for samples with low iron oxide contents to give low susceptibility readings of the same order of magnitude as altered core. In large-scale features such as the major fracture zones, the susceptibility pattern is generally distinct and easily distinguished from iron oxide-depleted core. However, on the hand-specimen scale the use of magnetic susceptibility alone will not distinguish between alteration and low iron oxide content.

9. IRM measurement is, in some ways, a more effective technique than MS for identifying altered core. With IRM it is possible to indirectly measure changes in grain size and magnetic mineral content. For example, coarse-grained magnetite within unaltered and non-fractured core will have an H_{Cr} of < 400 Oe. Medium- to fine-

grained hematite in altered and fractured core will have H_{cr} values >1000 Oe, and a mixture of magnetite and hematite will have intermediate H_{cr} levels of between 400 Oe to 600 Oe. Thus, in distinguishing between altered and unaltered samples, the controlling factor is the ratio of magnetite to hematite.

The major disadvantage of measuring IRM is that it is both costly and time-consuming. In addition, the effectiveness of the technique depends on the number of samples measured. MS on the other hand, is a fast, inexpensive method that provides a nearly continuous log of susceptibility variation.

10. Remanence-susceptibility measurements can be used to subdivide the specimens into altered and unaltered core, largely on the basis of high and low susceptibilities. The coarse-grained nature of the core is not suitable as a carrier of stable remanence. This is particularly evident in the coarse-grained magnetic oxides found in the URL-5 specimens. In low susceptibility intervals altered specimens have Q value ≥ 1 . This feature is best defined in the URL-1 specimens, less evident in URL-2 and absent in the URL-5 samples.

11. The best method to identify depleted iron oxides and altered core is the measurement of magnetic susceptibility. Petrographic studies help to quantitatively assess the extent of alteration within the samples. IRM measurements and microscopy should be used together to quantitatively assess the extent of alteration of the core.

APPENDIX A:Table I: List of URL-1 Specimens

Sample No.:	Sample Depth (metres)
1	41.00
2	68.00
3	80.00
4	85.46
5	100.00
6	109.00
7	110.28
8	110.80
9	129.00
10	130.00
11	130.90
12	156.30
13	176.40
14	200.70
15	221.10
16	221.80
17	230.10
18	240.10
19	253.00
20	302.00
21	356.80
22	397.20
23	436.30
24	442.00
25	592.00
26	599.10
27	601.90
28	615.50
29	648.10
30	662.00

Table II: List of URL-2 Specimens

Sample No.:	Sample Depth (metres)
1	50.77
2	93.20
3	115.35
4	155.60
5	179.10
6	179.20
7	187.20
8	200.40
9	256.10
10	355.40
11	355.60
12	397.50
13	399.20
14	414.80
15	447.00
16	585.50
17	625.00
18	705.60
19	736.43
20	851.10
21	871.60
22	903.71
23	904.60
24	1001.10
25	1094.00

Table III: List of URL-5 Specimens

Sample No.:	Sample Depth (metres)
1	16.00
2	21.10
3	28.90
4	76.00
5	81.80
6	90.50
7	92.00
8	99.44
9	103.00
10	103.49
11	105.50
12	112.40
13	113.00
14	120.70
15	126.70
16	157.00
17	190.40
18	216.90
19	218.37
20	246.32
21	289.60
22	322.30
23	324.60
24	324.70
25	324.80
26	369.00
27	385.80
28	386.10
29	413.50
30	449.20
31	451.00
32	496.00

APPENDIX B:Mineralogic Tables and Bulk Susceptibility Logs*

Table IV. Mineralogic Tables and Bulk Susceptibility Logs of URL-1

Table V. Mineralogic Tables and Bulk Susceptibility Logs of URL-2

Table VI. Mineralogic Tables and Bulk Susceptibility Logs of URL-5

* Note, the smoothed susceptibility curve is obtained by averaging three measurements, 0.1 m apart, per susceptibility sampling interval and smoothed by a seven point running mean. The horizontal lines in the raw data join maximum and minimum susceptibility measurements within the 2 m interval. Total fractures were determined visually.

MINERALOGY

MAGNETIC SUSCEPTIBILITY - URL - 1

GRAIN CLASSIFICATION				OPAQUE MINERALOGY			
TYPE 1	TYPE 2	ALTERATION OF OPAQUES	ORDER OF OCCURRENCE	MAGNETITE	HEMATITE	ILMENITE	SULPHIDES
50.77		mag → hem	hem > mag, hem lam in mag	—	—	—	50.77
83.20		mag → hem	hem > mag > il	—	—	—	83.20
115.38		mag → hem	hem > mag > py	—	—	—	115.38
158.80		mag → hem	mag > hem > py	—	—	—	158.80
178.10		mag → hem	mag > hem > il	—	—	—	178.10
178.20		mag → hem	mag > hem > il	—	—	—	178.20
187.20			mag > il, il lam in mag	—	—	—	187.20
200.40			mag > py	—	—	—	200.40
288.10			mag > il > py	—	—	—	288.10
358.40			mag > il, il lam in mag	—	—	—	358.40
358.80			mag > il	—	—	—	358.80
387.80		mag → hem	mag > hem > il	—	—	—	387.80
388.20			il > py	—	—	—	388.20
414.80			mag > py	—	—	—	414.80
447.00			mag > il	—	—	—	447.00
588.50			mag > il, il lam in mag	—	—	—	588.50
625.00			mag > il > py	—	—	—	625.00
703.00			mag > il	—	—	—	703.00
738.43			mag > il	—	—	—	738.43
881.10			mag > il	—	—	—	881.10
871.80			mag > il	—	—	—	871.80
903.71			mag > il, il lam in mag	—	—	—	903.71
904.80			mag > py	—	—	—	904.80
1001.10			mag > il	—	—	—	1001.10
1084.00		mag → hem	mag > il > hem	—	—	—	1084.00

cp - chalcopyrite
 hem - hematite
 il - ilmenite
 mag - magnetite
 py - pyrite
 rl - rutile

GRAIN LENGTH IN MICRONS

<100 —
 100 - 200 —
 200 - 400 —
 400 - 800 —
 >800 —

LENGTH/WIDTH RATIO

1:1 — 1-1.5:1
 1.5-2:1 — 2-2.5:1
 2.5-3:1 — 3-3.5:1
 >3.5:1 —

MAGNETIC SUSCEPTIBILITY URL - 2

RAW SUSCEPTIBILITY
 (N x 10⁻⁷)

50

100

DEPTH
 IN
 METRES

20
 100
 200
 300
 400
 500
 600
 700
 800
 900
 1000
 1100

MINERALOGY

ILMENITE

SULPHIDES

LENGTH/WIDTH RATIO

1.1 — 1-1.5
1.5-2.1 — 2-2.5
2.5-3.1 — 3-3.5
>3.5

MAGNETIC SUSCEPTIBILITY URL - 2

RAW SUSCEPTIBILITY
(10^{-6})

SUSCEPTIBILITY
(10^{-6})

50 100

DEPTH
IN
METRES

400

500

600

700

800

900

1000

1100

TOTAL
MAGNETIC SUSCEPTIBILITY

GRAIN CLASSIFICATION

OPAQUE MINERALOGY

MAGNETIC SUSCEPTIBILITY URL - 5

RAW SUSCEPTIBILITY
(150-1000 G)

SMOOTHED SUSCEPTIBILITY
(150-1000 G)

GRAIN CLASSIFICATION	ALTERATION OF OPAQUES	ORDER OF OCCURRENCE	MAGNETITE	HEMATITE	ILMENITE	SULPHIDES
10 00						
21 10						
28 00						
28 00						
81 00						
90 50						
92 00						
98 40						
102 00						
102 40						
108 50						
112 40						
113 00						
120 70						
128 70						
167 00						
190 40						
218 00						
218 37						
248 32						
288 40						
322 30						
324 40						
324 70						
324 80						
388 00						
388 80						
388 10						
413 50						
448 20						
451 00						
488 00						

CP - chalcopyrite

hem - hematite

il - ilmenite

mag - magnetite

py - pyrite

rt - rutile

lam - lamellae

GRAIN LENGTH IN MICRONS

<100

100 - 200

200 - 400

400 - 800

>800

LENGTH/WIDTH RATIO

1:1 - 1:1.5

1.5:1 - 2:2.5

2.5:1 - 3:3.5

>3.5:1

DEPTH
IN
METERS

MINERALOGY.

ILMENITE

SULPHIDES

LENGTH/WIDTH RATIO

1 1 — 1 1 5 1 •
1 5 2 1 — 2 2 5 1 •
2 5 3 1 — 3 3 5 1 •
— 3 5 1 •

MAGNETIC SUSCEPTIBILITY URL - 5

RAW SUSCEPTIBILITY
(G/100 G)

SMOOTHED SUSCEPTIBILITY
(G/100 G)

50

100

150

200

250

DEPTH
IN
METRES

100

200

300

TOTAL FRACTURES

Table VII. Magnetic Properties, Relative Abundance of Magnetic Minerals and Density Measurements (U.S.)

Site no.	Sample depth (meters)	Rock type	Density g/cc	Susceptibility $\times 10^{-3}$ cgs/cc (Z)	Remanence $\times 10^{-3}$ cgs/cc (H)	Isotropy ratio (H/Z)	Saturation remanence $\times 10^{-3}$ cgs/cc (Jsat)	Jsat/g	Acquisition coercive force Oe. (H_{CB})	Grading Mineralogy	
										Abundance %	Order of occurrence
1	41.00	igneous - granite	2.64	0.42	0.32	0.76	28.40	62.42	420.70	0.75	mag > 11 > non
2	64.00	igneous - granite	2.68	0.72	0.73	0.32	42.47	99.26	120.25	0.75	mag > 11 > non
3	80.00	igneous - granite	2.64	0.62	0.50	0.94	23.00	53.23	1250	0.90	non > mag > 11
4	85.44	alkali - felsic									
		granite	2.61	0.07	0.14	2.00	33.90	49.01	2590	0.75	non > mag > 27
5	100.00	igneous - granite	2.68	0.94	0.79	0.31	133.00	162.77	133.00	0.75	mag > non > 11
6	109.00	igneous - granite	2.62	0.04	0.10	2.90	20.70	517.30	1750	0.75	non > mag > 11 > 15
7	110.78	metamorphic - granite	2.64	0.03	0.10	3.33	16.90	563.33	2050	1.0	non > mag > 15
8	110.00	metamorphic - granite	2.65	0.03	0.12	4.00	10.10	603.33	167.59	0.75	non > mag > 15
9	119.00	vein	2.66	0.61	3.57	5.05	159.00	260.66	120.00	0.75	non > mag
10	120.00	igneous - granite	2.65	0.29	0.30	1.31	1.90	69.32	155.32	0.90	mag > non > 11
11	120.00	igneous - granite	2.65	0.10	0.10	1.00	5.52	56.20	127.10	0.75	mag > 11
12	154.20	igneous - granite	2.65	0.49	0.54	1.10	36.90	75.31	135.00	0.90	mag > 11 > non
13	174.40	igneous - granite	2.65	0.62	0.27	0.44	30.00	61.29	120.20	0.75	11 > mag > 27
14	200.70	igneous - granite	2.64	0.74	3.40	4.66	67.20	92.19	100.00	0.75-1.0	mag > 11
15	221.10	metamorphic - granite	2.65	0.76	0.48	0.63	55.55	79.16	170.90	0.75	mag > 11
16	221.00	metamorphic - granite	2.65	1.20	4.00	3.69	105.50	127.31	420.00	0.75	11
17	230.10	metamorphic - granite	2.65	0.64	0.10	0.28	27.40	42.81	91.49	0.75	mag > 11
18	240.10	igneous - granite	2.61	0.07	0.04	0.97	3.97	64.17	244.00	0.75	mag > 11
19	253.00	metamorphic - granite	2.64	0.24	0.07	0.29	17.71	48.79	133.04	0.75	mag > 11
20	302.00	igneous - granite	2.65	0.75	0.20	0.35	30.00	40.13	124.94	0.75	mag > 11
21	316.00	igneous - granite	2.65	0.06	0.30	0.42	53.21	61.07	116.79	0.90	mag > 17
22	397.20	metamorphic - granite	2.67	0.07	0.04	0.57	5.09	84.14	124.34	0.75	27 > 11
23	436.20	igneous - granite	2.64	0.60	0.61	0.64	34.50	57.50	114.99	0.90	mag > 11
24	442.00	igneous - granite	2.63	0.64	0.82	1.29	41.10	64.20	113.78	0.90-0.75	mag > 11 > non
25	502.00	alkali - felsic	2.64	2.10	0.53	0.25	116.00	53.24	140.00	0.75-1.0	mag > 11
		granite									
26	599.10	alkali - felsic	2.65	0.04	0.02	0.90	3.94	79.20	336.13	0.75	mag > 11
27	601.90	alkali - felsic									
		granite	2.61	0.29	0.08	2.26	19.75	50.04	137.54	0.90	11 > non
28	615.50	metamorphic - granite	2.66	0.32	0.13	0.61	17.00	53.13	133.28	0.75	11 > mag > 27
29	646.10	igneous - granite	2.65	0.82	0.73	0.09	44.00	53.66	214.04	1.0	mag > 11
30	662.00	metamorphic - granite	2.66	0.87	0.37	0.43	45.00	53.79	161.04	0.70-0.75	mag > 11

Note: 10 cgs/cc to SI units, multiply susceptibility value by 10.
Data types are based on major ratios (Structure, 1967, Table 1).

Table VIII: Magnetic Properties, Relative Abundance of Magnetic Minerals and Density Measurements in UGL-2

Site No.	Sample depth (metres)	Rock type	Density g/cc	Susceptibility $\times 10^{-3}$ cgs/cc (x)	Remanence $\times 10^{-3}$ emu/cc (R)	Koenigsberger ratio (R/x)	Saturation		Acquisition coercive force Oe.	Abundance %	Optical Mineralogy	
							Remanence $\times 10^{-3}$ emu/cc (Jsat)	Heat $\times 10^{-3}$ (Jsat)			Order of occurrence	Relative proportions
UGL-2	1	50.77 alkali - feldspar granite	2.82	0.13	0.13	1.00	7.90	40.77	190.05	0.75	mag > mag	90:10
	2	93.20 syeno - granite	2.64	0.02	0.03	1.50	1.96	96.00	6000.00	0.75	mag > mag > il	95:3:2
	3	115.35 syeno - granite	2.62	0.10	0.14	1.40	6.64	66.40	390.00	0.75	mag > mag > py	50:45:5
	4	155.80 monzo - granite	2.65	0.76	1.26	1.66	61.50	80.92	508.00	0.50	mag > mag > py	60:35:40:3:5
	5	179.10 syeno - granite	2.64	0.44	0.40	0.91	30.30	68.86	423.84	0.50	mag > mag > il	70:25:30:3:5
	6	179.20 syeno - granite	2.64	0.45	0.80	1.76	29.35	65.22	483.72	0.50	mag > mag > il	70:25:30:2:5
	7	187.20 syeno - granite	2.64	0.59	0.40	0.68	29.15	49.41	460.00	0.25	mag > il	80:20
	8	200.40 monzo - granite	2.64	0.07	0.08	1.14	4.16	59.63	489.29	<0.25	mag > py	95:100:2:5
	9	254.10 monzo - granite	2.64	0.66	0.34	0.52	30.90	46.82	128.43	0.75	mag > il > py	80:15:20:1:5
	10	355.40 syeno - granite	2.65	1.83	2.54	1.39	100.55	54.95	550.57	0.75	mag > il	95:5
	11	355.60 alkali - feldspar granite	2.62	0.08	0.01	0.13	1.19	14.88	550.57	<0.25	mag > il	60:40
	12	397.50 syeno - granite	2.61	0.32	0.45	1.41	14.05	43.91	420.27	0.25	mag > mag > il	60:35:40:2:5
	13	399.20 monzo - granite	2.64	0.12	0.12	1.00	5.80	48.33	249.54	0.50	il > py	95:5
	14	414.80 monzo - granite	2.62	0.03	0.01	0.33	0.90	30.00	390.24	<0.25	mag > py	50:50
	15	447.90 monzo - granite	2.67	0.96	4.86	5.06	85.95	89.53	110.74	<0.25	mag > il	50:50
	16	505.50 syeno - granite	2.64	0.78	0.03	0.04	54.00	69.23	308.82	0.75	mag > il	98:2
	17	645.00 monzo - granite	2.69	3.00	0.75	0.25	289.50	96.50	165.31	0.75	mag > il > py	70:25:30:2:5
	18	705.50 syeno - granite	2.66	0.52	0.06	0.12	41.75	80.29	117.14	0.25	mag > il	55:45
	19	736.40 alkali - feldspar granite	2.66	3.90	9.21	2.36	184.00	47.18	174.68	3.50	mag > il	60:40
	20	851.10 monzo - granite	2.64	0.13	0.14	1.04	7.32	56.31	357.87	<0.25	mag > il	80:20
	21	871.60 syeno - granite	2.65	0.53	0.58	1.09	38.60	72.83	122.30	<0.25	mag > il	70:30
	22	903.71 monzo - granite	2.67	5.50	43.80	7.96	350.00	63.64	165.87	1.0	mag > il	80:20
	23	924.60 hornblende vein	2.94	0.06	0.02	0.33	1.29	21.50	763.64	<0.25	mag > py	50:50
	24	1001.10 syeno - granite	2.66	0.52	1.40	2.69	34.00	65.38	114.71	0.75	mag > il	60:40
	25	1094.00 syeno - granite	2.65	0.58	0.40	0.69	34.00	58.62	114.90	0.75	mag > il > mag	70:25:30:2:5

Note: To change cgs/cc to SI units, multiply susceptibility value by 40.
Rock types are based on Au/Fe ratios (Streckeisen, 1967, Table 1).

Table II: Magnetic Properties, Relative Abundance of Magnetic Minerals and Density Measurements in JAL-5

Site No.	Sample depth (metres)	Rock type	Density gm/cc	Susceptibility $\times 10^{-3}$ cgs/cc (Z)	Remanence $\times 10^{-3}$ emu/cc (R)	Koenigsberger ratio (R/Z)	Saturation remanence $\times 10^{-3}$ emu/cc (Jsat)	Jsat/Z	Acquisition coercive force Oe. (H_{CB})	Abundance		Opaque Mineralogy	
										Z	occurrence	Order of	Relative proportions
JAL-5	1	syeno - granite	2.62	0.40	0.27	0.68	21.90	54.75	111.08	0.25-0.50	mag > il > hem		40 30 10
	2	monzo - granite	2.68	0.38	4.81	12.66	55.35	138.38	158.34	0.25	py > il		95 5
	3	granodiorite	2.75	0.03	0.91	0.33	3.57	119.00	1112.25	0.50	py > il		90 10
	4	syeno - granite	2.64	1.80	2.56	1.42	124.00	68.89	468.51	0.50	mag > il > hem > py		60 30 10
	5	syeno - granite	2.62	0.17	0.30	1.76	10.70	60.00	328.07	0.25	hem > il > rt > py		50 40 5-10 3-5
	6	syeno - granite	2.63	0.21	0.89	4.24	33.00	157.00	451.76	<0.25	hem > il > rt		70 25 5
	7	vein	2.62	0.22	0.12	1.45	22.40	101.82	314.89	0.25	mag > hem > rt > il		50 45 3-5
	8	syeno - granite	2.64	0.03	0.25	8.33	26.20	873.33	1400.00	1.0	hem > il > mag		90 35 1-2
	9	syeno - granite	2.65	0.04	0.004	0.10	18.90	422.50	6075	1.50	hem > mag		75 25
	10	syeno - granite	2.77	0.45	0.38	0.84	13.05	29.00	341.32	0.75	mag > hem > rt > py		50 40 5-10
	11	vein	2.70	0.54	0.66	1.22	229.50	425.00	194.46	10-15	py		100%
	12	monzo - granite	2.64	0.14	0.01	0.07	2.53	18.07	890.91	0.25-0.50	mag > hem > il > py		50 45 3 2
	13	syeno - granite	2.64	0.44	1.30	2.95	33.90	77.05	222.00	<0.25	mag > il > py		50 45 5
	14	monzo - granite	2.64	0.78	0.80	1.03	45.60	58.46	260.71	1.0	mag > il > hem		55 40 5
	15	syeno - granite	2.64	0.52	0.32	0.62	32.20	61.92	112.39	0.75	mag > il > hem > rt		80 15-20 3-2
	16	syeno - granite	2.64	0.67	0.18	0.27	23.80	35.52	122.00	0.75	mag > il > hem > py		80 15-20 3-2
	17	granodiorite	2.65	0.01	0.02	10.00	6.71	671.00	2194.44	<0.25	hem > py		75 25
	18	syeno - granite	2.64	0.05	0.04	0.80	26.10	522.00	3600.00	0.25-0.50	hem > mag > rt		55 43 2
	19	syeno - granite	2.64	0.26	0.80	3.08	77.20	294.92	417.81	0.75	mag > hem > il		70 25 5
	20	syeno - granite	2.64	32	0.001	0.05	11.20	590.00	4725.00	0.50	hem > mag > il > rt		80 15 3 2
	21	monzo - granite	2.65	0 1	0.90	1.57	25.50	507.00	105.29	1 0	mag > il > py		90 5-10 2-3
	22	monzo - granite	2.68	0.1	0.03	3.00	3.61	361.00	537.04	0.25	il > py		95 5
	23	monzo - granite	2.67	0.04	0.008	0.20	5.32	133.00	524.21	0.25	il > mag > py		95 2-5 1-2
	24	monzo - granite	2.70	1.03	0.15	0.15	11.00	10.68	246.67	0.75	mag > il		60 40
	25	monzo - granite	2.70	4.50	11.20	2.49	277.50	61.67	154.94	1.5-2.0	mag > il		95 5
	26	monzo - granite	2.65	8.71	0.30	0.42	39.00	54.93	112.61	0.75	mag > il		70 30
	27	vein	2.85	0.08	0.01	0.11	3.83	47.88	325.23	<0.25	py > mag		70 30
	28	granodiorite	2.66	>0.02	0.002	0.10	0.64	32.00	572.73	<0.25	py > il		60 40
	29	monzo - granite	2.66	0.93	1.18	1.27	64.10	68.92	390.00	0.75	mag > il		70 30
	30	monzo - granite	2.66	1.01	0.82	0.81	69.40	68.71	304.56	0 15	mag > il > py		90 5-10 3-5
	31	monzo - granite	2.68	1.01	0.63	0.62	80.05	79.26	122.02	0 15	mag > py		95 5
	32	monzo - granite	2.67	0.90	0.45	0.50	68.00	75.56	120.00	0.75	mag > il > py		90 4-10 3-5

Note: To change cgs/cc to SI units, multiply susceptibility value by 10^{-6} . Rock types are based on An/Or ratios (Streckeisen, 1967, Table 1).

APPENDIX D:

Table X - Chemical Analyses of URL-1
(in %)

Depth	41.00	68.00	80.00	85.46	100.00	109.00	110.28	129.00
SiO ₂	73.1	73.4	74.1	71.6	69.00	75.1	74.1	75.7
TiO ₂	.18	.22	.19	.15	.72	.18	.13	.07
Al ₂ O ₃	14.7	14.4	14.3	15.4	15.0	13.6	15.2	14.5
Cr ₂ O ₃								
Fe ₂ O ₃	.2	.7	.5	.9	1.3	1.0	1.2	.4
FeO	1.0	1.1	.8	.4	2.1	.5	.3	.4
MnO	.03	.02	.03	.02	.06	.03	.01	.01
MgO	.37	.39	.41	.20	.77	.52	.21	.12
CaO	1.40	1.58	1.36	1.03	1.75	1.35	1.54	2.56
Na ₂ O	3.6	3.2	2.7	2.5	2.3	2.6	3.5	5.1
K ₂ O	4.85	4.20	5.42	6.47	4.51	4.66	3.89	.25
H ₂ O ^T	.4	.5	.5	.5	.8	.2	.7	.1
CO ₂	.1	.2	.2	.1	.2	.1	.1	.1
P ₂ O ₅	.08	.10	.05	.04	0.17	.06	.04	.00
S	0.00	0.00	0.00	0.00	.01	0.00	0.00	0.00
Ba	.074	.062	.084	.109	.087	.069	.046	.006
Rb	.015	.014	.016	.018	.017	.016	.010	.001
Sr	.018	.020	.030	.031	.018	.025	.019	.025
Zr	.014	.022	.021	.016	.059	.024	.007	.006
TOTAL	100.2	100.1	100.9	99.6	98.9	100.2	101.0	99.3

Table X - Chemical Analyses of URL-1
(in %)

Depth	130.00	130.90	156.30	176.40	200.70	221.10	221.80	230.10
SiO ₂	75.3	73.7	71.6	72.2	73.9	71.5	68.0	71.6
TiO ₂	.14	0.18	.22	.23	.20	.17	.71	.30
Al ₂ O ₃	13.4	14.7	15.4	14.8	14.3	15.1	15.0	15.2
Cr ₂ O ₃								
Fe ₂ O ₃	.3	.6	.5	.5	.6	.8	1.3	.6
FeO	.6	.4	1.1	1.0	.9	.9	3.5	1.5
MnO	.02	.02	.03	.03	.03	.03	.12	.04
MgO	.22	.38	.45	.40	.25	.47	1.79	.58
CaO	1.03	1.36	1.74	1.50	1.54	1.83	1.78	1.92
Na ₂ O	2.0	2.8	3.7	3.3	2.5	3.6	3.5	3.0
K ₂ O	6.35	5.22	4.51	5.40	5.19	4.40	3.74	4.15
H ₂ O _T	.4	.3	.5	.4	.4	.5	.6	.4
CO ₂	.1	.1	.3	.2	.1	.3	.1	.1
P ₂ O ₅	.05	.06	.05	.09	.07	.06	.04	.12
S	0.00	0.00	0.00	0.00	0.00	0.00	.03	0.00
Ba	.097	.073	.065	.070	.072	.065	.022	0.50
Rb	.017	.015	.014	.016	.017	.016	.029	.015
Sr	.028	.021	.023	.020	.029	.032	.019	.020
Zr	.016	.016	.020	.021	.021	.021	.042	.026
TOTAL	100.1	101.0	100.3	100.2	100.1	99.3	100.4	99.7

Table X - Chemical Analyses of URL-1
(in %)

Depth	240.10	253.90	302.00	356.80	397.20	436.30	442.90	592.00
SiO ₂	73.3	73.0	73.9	74.2	72.0	72.5	72.3	74.8
TiO ₂	.09	.31	.18	.25	.37	.25	.16	.19
Al ₂ O ₃	15.3	14.6	14.2	13.5	14.9	14.4	15.4	13.8
Cr ₂ O ₃								
Fe ₂ O ₃	.2	.9	.4	.7	.4	.5	.4	.9
FeO	.1	.5	.7	1.3	1.8	1.3	.9	.7
MnO	.01	.03	.02	.04	.05	.03	.02	.02
MgO	.10	.44	.45	.43	1.02	.61	.30	.04
CaO	1.44	1.78	1.11	1.53	2.14	1.61	1.35	.87
Na ₂ O	3.0	4.0	2.3	3.0	3.7	3.5	3.1	2.4
K ₂ O	5.44	3.95	6.30	4.05	3.32	4.63	6.13	6.10
H ₂ O _T	.1	.4	.3	.4	.6	.4	.3	.2
CO ₂	.1	.1	.1	.2	.2	.2	.2	.1
P ₂ O ₅	.00	.10	.06	.10	.19	.11	.07	.04
S	0.00	0.00	0.00	0.00	.07	0.00	0.00	0.00
ba	.002	.049	.101	.064	.029	.076	.108	.068
rb	.017	.012	.013	.015	.014	.018	.018	.020
sr	.030	.017	.020	.020	.032	.017	.019	.011
zr	.009	.022	.013	.025	.015	.022	.015	.021
TOTAL	99.3	100.2	100.1	100.0	100.9	100.3	100.3	100.2

Table X - Chemical Analyses of URL-1
(in %)

Depth	599.10	601.90	615.50	648.10	662.00
SiO ₂	73.9	77.9	71.70	71.4	73.9
TiO ₂	.40	.13	.32	.26	.32
Al ₂ O ₃	13.5	11.6	15.0	14.8	14.8
Cr ₂ O ₃					
Fe ₂ O ₃	.6	.7	.3	.7	.9
FeO	.3	.4	1.3	1.0	.5
MnO	.03	.01	.04	.03	.04
MgO	.02	.03	.63	.43	.19
CaO	1.24	.23	1.87	1.58	1.71
Na ₂ O	2.5	.9	3.7	3.1	3.5
K ₂ O	4.99	7.54	3.91	4.76	4.16
H ₂ O _T	.2	.1	.3	.2	.3
CO ₂	.5	.1	.1	.1	.2
P ₂ O ₅	.03	.03	.10	.08	.07
S	.07	0.00	0.00	0.00	.02
Ba	.040	.088	.054	.091	.082
Rb	.017	.026	.017	.021	.016
Sr	.017	.014	.014	.026	.020
Zr	.002	.013	.019	.025	.015
TOTAL	98.5	99.9	99.4	98.8	100.8

Table XI - Chemical Analyses of URL-2

(in %)

Depth	50.77	93.20	115.35	155.60	179.10	179.20	187.20	200.40	256.10
SiO ₂	74.2	74.6	74.9	71.8	73.0	73.7	72.3	74.1	73.3
TiO ₂	.28	.12	.09	.22	.15	.16	.15	.16	.19
Al ₂ O ₃	13.6	14.1	14.0	15.1	15.1	14.8	15.6	14.7	14.5
Cr ₂ O ₃									
Fe ₂ O ₃	.7	.6	.2	.8	.3	.5	.7	.2	.3
FeO	1.1	.4	.4	1.1	.8	.7	.6	.6	1.0
MnO	.03	.04	.01	.04	.03	.03	.03	.02	.03
MgO	.64	.23	.29	.65	.37	.34	.43	.48	.29
CaO	.92	1.52	1.09	1.92	1.48	1.35	1.52	1.60	1.63
Na ₂ O	1.9	3.3	2.7	3.4	3.7	3.2	3.3	2.9	3.8
K ₂ O	5.95	4.36	5.61	4.23	4.66	5.18	5.16	4.90	3.97
H ₂ O _T	.6	.5	.4	.5	.2	.2	.3	.4	.4
CO ₂	.1	.2	.2	.1	.1	.2	.4	.1	.2
P ₂ O ₅	.04	.02	.00	.10	.04	.05	.07	.03	.07
S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	.084	.071	.097	.073	.068	.078	.090	.056	.051
Rb	.021	.017	.019	.020	.019	.021	.021	.019	.018
Sr	.023	.027	.032	.036	.028	.028	.032	.035	.019
F	.011	.015	.012	.029	.015	.016	.019	.018	.014

TOTAL	100.2	100.2	100.0	100.2	100.1	100.5	100.5	100.4	99.9
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Table XI - Chemical Analyses of URL-2
(in %)

Depth	355.40	355.60	397.50	399.20	414.80	447.00	585.00	625.00	705.60
SiO ₂	76.5	75.6	72.6	78.8	76.8	72.3	75.5	69.3	75.9
TiO ₂	.19	.09	.33	.31	.05	.25	.18	.42	.18
Al ₂ O ₃	12.5	14.1	13.6	13.00	13.9	14.6	13.9	15.2	13.6
Cr ₂ O ₃									
Fe ₂ O ₃	1.1	.1	2.1	.2	.0	1.0	.1	1.5	.3
FeO	.8	.2	1.6	.6	.1	.7	.9	2.1	.8
MnO	.03	.01	.09	.03	.01	.03	.03	.08	.02
MgO	.19	.15	.22	.24	.07	.57	.13	.54	.22
CaO	1.17	1.00	1.12	1.75	1.57	1.77	1.28	1.77	1.30
H ₂ O	2.4	2.7	3.1	3.1	3.3	3.7	3.1	4.2	3.3
K ₂ O	4.69	5.93	4.82	2.40	3.76	4.34	4.47	3.81	4.35
H ₂ OT	.2	.1	.2	.3	.2	.5	.3	.3	.3
CO ₂	.1	.2	.1	0.1	.1	.2	.2	.3	.2
P ₂ O ₅	.02	.01	.05	0.02	.00	.11	.06	.11	.07
S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	.046	.061	.061	.023	.067	.097	.057	.051	.064
Rb	.016	.023	.026	.011	.015	.021	.017	.022	.016
Sr	.009	.008	.017	.012	.023	.023	.014	.017	.011
Zr	.032	.004	.060	.006	.000	.020	.015	.040	.015
TOTAL	100.1	100.4	100.1	100.9	100.0	100.4	100.3	99.7	100.7

Table XI - Chemical Analyses of BRL-2
(in %)

Depth	736.43	851.10	871.60	903.71	904.60	1001.10	1094.00
SiO ₂	68.5	76.1	74.5	75.8	59.5	73.3	74.4
TiO ₂	.18	.17	.21	.29	.41	.23	.17
Al ₂ O ₃	16.3	13.1	13.7	12.5	13.0	14.2	14.0
Cr ₂ O ₃							
Fe ₂ O ₃	1.4	.5	.6	1.6	2.2	.7	0.0
FeO	.9	.5	.9	1.4	5.8	.8	1.2
MnO	.03	.02	.03	.04	.20	.03	.02
MgO	.26	.22	.25	.15	3.69	.39	.26
CaO	.88	1.45	1.46	1.44	9.47	1.56	1.30
Na ₂ O	3.0	2.7	3.3	2.6	3.0	3.5	3.2
K ₂ O	8.10	3.55	4.33	3.86	.67	4.52	4.88
H ₂ O _T	.3	.1	.4	.2	.3	.4	.3
CO ₂	.1	.1	.3	.1	.1	.2	.1
P ₂ O ₅	.01	.03	.06	.05	.21	.10	.04
S	.01	0.00	0.00	0.00	0.00	0.00	0.00
Ba	.121	.083	.118	.146	.074	.092	.150
Rb	.028	.017	.017	.015	.004	.019	.019
Sr	.017	.021	.014	.019	.043	.015	.015
Zr	.007	.019	.016	.047	.004	.017	.014
TOTAL	100.2	98.7	100.2	100.2	98.8	100.2	100.1

Table XII - Chemical Analyses of URL-5
(in %)

Depth	16.00	21.10	28.90	76.00	81.80	90.50	92.00	99.44	103.00
SiO ₂	74.00	70.4	64.9	71.7	77.3	74.0	78.0	73.1	72.2
TiO ₂	.16	.43	.99	.34	.08	.08	.08	.23	.20
Al ₂ O ₃	14.7	15.5	16.1	14.4	12.8	15.2	13.6	14.5	14.7
Cr ₂ O ₃									
Fe ₂ O ₃	0.4	.6	1.2	0.8	.6	.4	.6	.8	1.3
FeO	.7	2.0	4.1	1.6	0.0	.1	.1	.8	.6
MnO	.02	.05	.11	.05	.01	.01	.01	.03	.03
MgO	.22	1.03	2.29	.50	.19	.15	.11	.34	.39
CaO	1.50	2.49	2.85	1.11	.92	1.37	2.23	1.48	1.19
Na ₂ O	3.5	4.0	3.4	3.0	2.4	3.7	4.4	3.1	2.8
K ₂ O	4.57	2.83	2.67	5.71	5.32	4.54	.45	4.60	5.28
H ₂ O _T	.3	.4	1.1	.5	.32	.1	.3	.5	.3
Cu ₂	0.1	.2	.1	0.2	.1	.1	.1	.2	.1
P ₂ O ₅	.05	.19	.27	.12	.03	0.00	.00	.06	.03
	0.00	.07	.06	0.00	.01	0.00	0.00	.01	0.00
Ba	.081	.044	.017	.070	.073	.048	.006	.053	.070
Rb	.014	.014	.023	.024	.020	.017	.008	.019	.021
Sr	.026	.032	.032	.018	.020	.023	.024	.023	.024
Zr	.018	.021	.033	.030	.006	.005	.011	.021	.019
TOTAL	100.3	100.5	100.3	99.2	100.2	99.9	100.1	100.0	99.2

Table XII - Chemical Analyses of URL-5
(in %)

Depth	103.49	105.50	112.40	113.00	120.70	126.00	157.00	190.40	216.90
SiO ₂	71.6	77.3	75.5	75.1	73.0	73.9	73.1	79.7	71.9
TiO ₂	.17	.35	.14	.14	.33	.19	.18	.06	.22
Al ₂ O ₃	15.7	5.4	14.1	13.5	14.3	14.6	14.6	12.5	15.2
Cr ₂ O ₃									
Fe ₂ O ₃	.4	7.7	.3	.2	.8	1.2	.5	.2	1.3
FeO	.7	0.0	.6	.6	1.0	0.0	.7	.1	0.0
MnO	.02	.09	.02	.02	.05	.02	.02	.01	.02
MgO	.28	2.01	.16	.28	.57	.26	.30	.16	.44
CaO	1.39	.51	1.67	1.27	1.67	1.44	1.43	1.79	1.59
Na ₂ O	3.2	.6	3.7	2.8	3.1	3.1	3.2	3.4	3.6
K ₂ O	5.76	1.62	3.11	4.90	4.34	5.13	4.57	1.73	5.14
H ₂ O _T	.4	1.7	.2	.3	.4	.4	.3	.3	.2
CO ₂	.3	.1	.1	.1	.1	.2	.1	.1	.3
P ₂ O ₅	.04	.04	.03	.02	.10	.07	.07	0.00	.07
S	.01	1.94	.04	.02	.01	0.00	0.00	0.00	0.00
		.73							
Ba	.086	.009	.042	.065	.053	.072	.063	.022	.076
Rb	.017	.015	.012	.018	.017	.015	.015	.005	.017
Sr	.028	.004	.023	.025	.025	.018	.019	.021	.024
Zr	.014	.004	.012	.009	.031	.014	.014	.023	.023
TOTAL	100.1	98.7	99.8	99.4	100.0	100.7	99.8	100.2	100.2

Table XII - Chemical Analyses of URL-5
(in %)

Depth	218.37	246.32	289.60	322.30	324.60	324.70	324.80	369.00	385.80
SiO ₂	72.9	74.6	73.5	67.9	69.4	68.3	67.8	73.9	63.2
TiO ₂	.21	.24	.21	.44	.36	.44	.29	.23	.68
Al ₂ O ₃	14.4	14.4	14.6	15.4	15.0	15.4	15.9	14.5	15.5
Cr ₂ O ₃	.7	.8	.0	.5	.6	.8	1.6	.8	1.1
Fe ₂ O ₃	.8	.5	1.2	2.0	1.6	2.2	1.6	.9	4.3
FeO	.02	.02	.03	.07	.05	.07	.05	.03	.11
MnO	.48	.52	.50	1.42	1.16	1.32	.68	.26	3.24
CaO	1.55	1.38	1.93	2.43	2.25	2.33	2.07	1.64	3.62
Na ₂ O	3.1	2.8	3.8	4.0	3.7	3.7	3.8	3.1	3.3
K ₂ O	4.88	4.75	3.63	3.23	3.52	3.58	4.64	4.68	2.71
H ₂ O _T	.5	.5	.4	.6	.3	.4	.2	.4	1.0
CO ₂	.2	.1	.2	.2	.2	.1	.3	.1	.2
P ₂ O ₅	.07	.05	.00	.22	.18	.20	.12	.09	.20
S	.01	0.00	0.00	.01	.02	.01	0.00	.01	.01
Ba	.071	.072	.051	.042	.052	.049	.076	.082	.029
Rb	.017	.017	.012	.018	.017	.021	.016	.016	.023
Sr	.024	.026	.023	.041	.038	.032	.034	.018	.022
Zr	.019	.022	.015	.009	.011	.011	.035	.023	.019
TOTAL	100.0	100.9	100.2	98.6	98.5	98.9	99.3	100.8	99.3

Table XII - Chemical Analyses of URL-5

(in %)

Depth	386.10	413.50	449.20	451.00	496.00
SiO ₂	66.9	71.3	70.1	72.3	71.2
TiO ₂	.65	.41	.52	.50	.51
Al ₂ O ₃	15.0	14.8	14.4	13.8	14.2
Cr ₂ O ₃					
Fe ₂ O ₃	1.0	.8	.7	1.5	1.5
FeO	4.0	1.6	2.0	1.4	1.2
MnO	.09	.04	.04	.04	.03
MgO	2.31	.56	.61	.49	.48
CaO	2.71	1.83	1.82	1.74	1.89
Na ₂ O	3.7	2.6	2.4	2.3	3.0
K ₂ O	2.39	5.33	5.17	4.96	5.02
H ₂ O ^T	1.0	.3	.3	.6	.4
CO ₂	.1	.1	.1	.1	.1
P ₂ O ₅	.12	.09	.13	.12	.15
S	.03	.01	.01	0.00	.01
Ba	.016	.123	.120	.109	.119
Rb	.021	.017	.017	.016	.015
Sr	.022	.022	.022	.017	.017
Zr	.036	.048	.056	.045	.051
TOTAL	100.1	100.0	98.7	100.1	100.0

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