PALEOMAGNETISM OF THE KILLARNEY IGNEOUS COMPLEX, ONTARIO

A PALEOMAGNETIC ANALYSIS OF THE DEFORMATION AND HYDROTHERMAL ALTERATION IN THE KILLARNEY IGNEOUS COMPLEX, ONTARIO.

By

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ABSTRACT

The Killarney Igneous Complex lies along the Grenville Front, forming a wedge between the Grenville and Southern Provinces of the Canadian Shield. The complex consists of a granitic pluton and associated felsic volcanic rocks that have been subjected to both mid-Proterozoic and Grenvillian tectonism. This study sought paleomagnetic confirmation of pre-Grenville deformation by carrying out AF and thermal demagnetization experiments on 226 samples representing both the massive and foliated parts of the complex. This was accompanied by an analysis of polished thin-sections to attempt to determine a paragenesis for the remanence carrying minerals.

Sixty-four specimens of foliated and veined, hematite-enriched porphyry carry a stable southwesterly magnetization (Declination = 242.4°, Inclination = -26.4°, K = 17.5, A95 = 11.2°) or its antipole. The paleomagnetic pole implied by this magnetization (Longitude = 19.3°E, Latitude = 29.1°, dp = 9.6°, dm = 10.9°) is consistent with an age of somewhat less than 1100 Ma. This magnetization is a CRM that was acquired during the hydrothermal alteration of the porphyry. As a consistent magnetization is carried by highly sheared rocks as well as the hematite-enriched porphyry, it is

concluded that the shearing must have occurred prior to the hydrothermal event. Thus, the onset of Grenville tectonism in the Killarney region began before 1100 Ma. Sufficient paleomagnetic evidence was not obtained to determine the timing of pre-Grenville tectonism.

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I dedicate this thesis to my father, whose encouragement led me to pursue graduate work. He has had a lifetime interest in geology, but never had the opportunity to pursue that interest.

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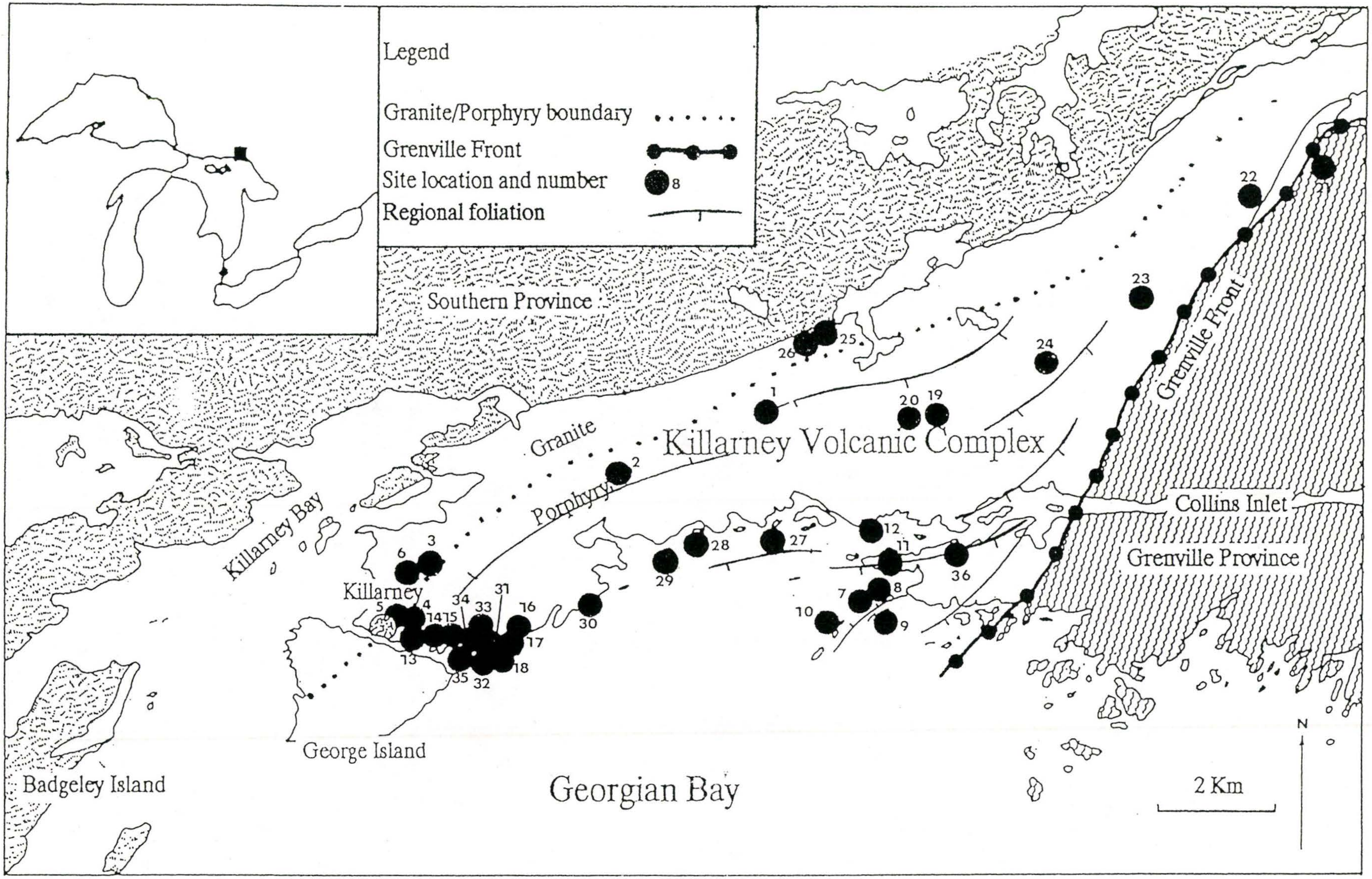
Chapter 1: INTRODUCTION

Location and Access

The Killarney Igneous Complex (KIC) is a wedge-shaped granitic pluton, with associated volcanic rocks, which lies between the Grenville and Southern Provinces of the Canadian Shield, southwest of Sudbury, Ontario (Fig. 1-1). The complex extends from the village of Killarney to Carlyle Lake (about 25 Km to the northeast) and at its widest is 7 Km across. The KIC is just one of a suite of plutons that form a continuous chain from the shore of Georgian Bay northeastwards for approximately 80 Km. These igneous bodies have collectively been called the Killarney batholith (Collins, 1925; Frarey, 1985), batholithic complex (Lumbers, 1975) and the Grenville Front granites (Frarey & Cannon, 1969). The plutons in this suite include the KIC, the Bell Lake granite, the Terry Lake diorite, the Annie Lake complex and the Chief Lake granite.

Access into the Killarney complex is relatively easy along Highway 637, which joins Highway 69 just south of Sudbury. Highway 637 bisects the complex before ending in the village of Killarney. The highway crosses the Grenville Front and into the KIC near the access road to Johnny Lake

Fig. 1-1: Site map of the Killarney Igneous Complex, southwest of Sudbury, Ontario. The map shows the location of the Grenville Front and the site locations (1 to 36). The position of the complex, sandwiched between the Southern and Grenville Provinces, is shown, as well as the distinction between granite and porphyry within the complex. Regional foliations spatially distinct and with oblique orientations to the Front, are also illustrated. After Clifford (1986) and Davidson (1986a).


Legend
Granite/Porphyry boundary
Grenville Front
Site location and number
Regional foliation
Southern Province
Killarney Volcanic Complex
Granite
Porphyry
Killarney Bay
Killarney
Grenville Front
Collins Inlet
Grenville Province
George Island
Badgeley Island
Georgian Bay
2 Km
N

and parallels the contact between the granite and porphyry almost into Killarney.

A base camp was set up at the George Lake campground in Killarney Provincial Park. Well maintained park trails provided valuable access to outcrop. Roadcuts along Highway 637 provided numerous sampling sites that were quickly and easily accessible. The lakeshore immediately east of the village of Killarney was accessible by foot, while the rest of the lakeshore was sampled by boat. Over a period of two weeks, over 200 samples were collected from 36 sites. Sampling localities are shown in Figure 1-1. Most of the samples were taken as blocks and were oriented using a magnetic compass. Hematite-enriched samples from site 31 were field drilled as 2.5 cm by 2.5 cm cores.

General Geology

The KIC consists of granites and related porphyries and pyroclastic rocks (Fig. 1-1) that have been affected to varying degrees by tectonism. The granite makes up the north and west sections of the complex and the contact between the granite and the Huronian sediments to the northwest is usually sharp and easily identified on the islands in Killarney Bay. However, inland it is represented by a small valley, usually filled with small lakes, making it very difficult to see. Nonetheless, the immediate presence of quartzite once the contact is crossed, reflects the proximity of the contact.

Macroscopically, the granite is virtually devoid of any evidence of deformation. A few brittle hairline fractures appear as the contact with the porphyry is approached, but otherwise it is massive, medium-grained, pink in colour, with few mafics present. In outcrop, the granite weathers a pleasant salmon pink, and is found as rounded knolls, commonly referred to as humpbacks. These rises measure from 1 m to about 75 m in height (Fig. 1-2). Other than the lakeshore, these knolls are the only form of outcrop present. Sites sampled in the granite are numbers 3, 5, 6, 25 and 26.

Fig. 1-2: View of the complex, looking south from the Huronian quartzite La Cloche mountains. The topography is relatively flat. Any large, salmon red rises, or humpbacks, are usually extremely weathered, and therefore unsuitable for paleomagnetic analysis.

The map in Figure 1-1 illustrates the approximate boundary between the granite and porphyry. This contact also coincides somewhat with the appearance of an east trending regional foliation. The boundary between the granite and the porphyry is difficult to distinguish, as it is usually gradational and there is limited outcrop, but it has been reported to be distinct in at least one location (Davidson, 1986b). Two major macroscopic differences between the granite and the porphyry are that the porphyry is fine-grained and porphyrytic and that it also has a pervasive foliation.

Two sets of foliations have been identified within the complex (Clifford, 1986; Davidson, 1986a). One set trends northeast and parallels the Grenville Front, but these are only evident when within about 2 Km of it, prompting Clifford (1986) to call this set the mylonitic foliations. The second set of foliations trend eastwards and these he named the regional foliations. The two sets have been interpreted by Clifford (1986) and Davidson (1986a) to be due to two periods of deformation: the mylonitic set related to the Grenvillian Orogeny, and the regional set related to pre-Grenvillian deformation.

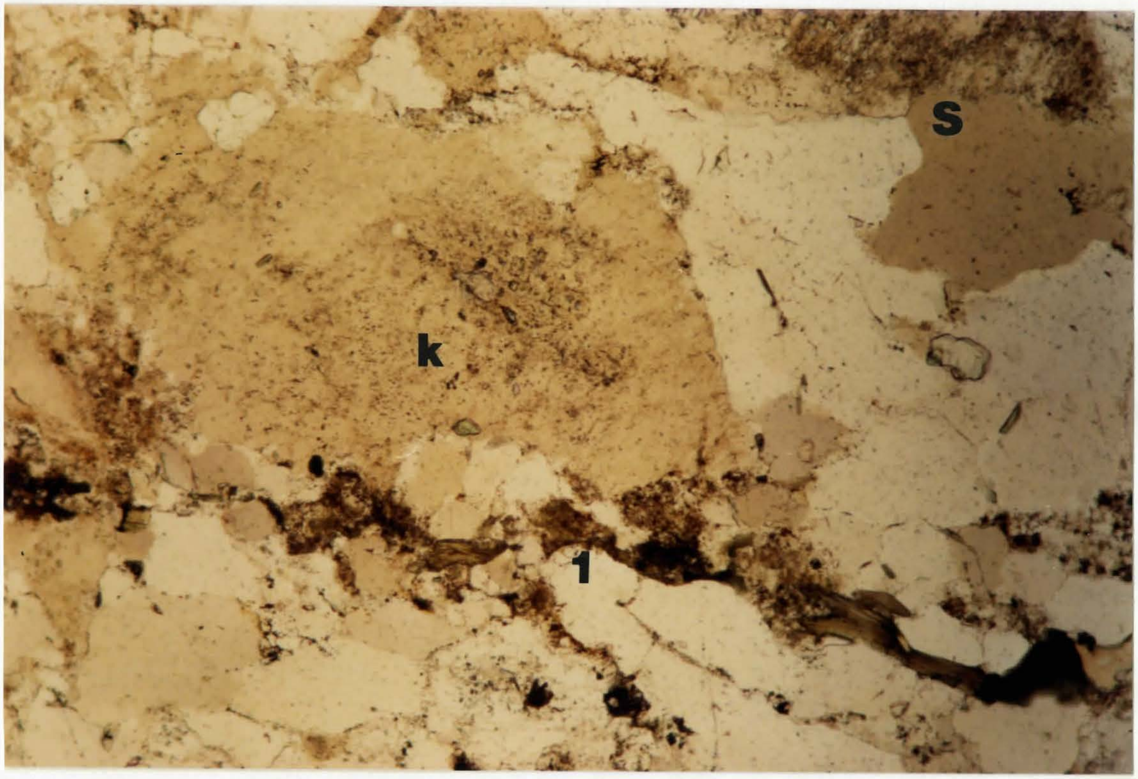
The KIC is presently believed (Van Breeman & Davidson, 1988) to be the northeastern extension of mid-Proterozoic granites and rhyolites found by Van Schmus & Bickford (1981) to underlie the mid-continent of North America. The Killarney complex is of similar composition and age to the rhyolites and granites, which extend west of the Phanerozoic Michigan Basin as far as the Rocky Mountains. If the KIC and the other Grenville Front plutons do belong to this felsic volcanic-plutonic complex, then it is evidence of a widespread orogeny which had no relationship to the Grenville Front or the Grenville Orogeny.

The porphyry is heterogeneous, both structurally and lithologically. Although a pervasive foliation exists and two different orientations have been identified, there are areas of the porphyry that do not show any evidence of either foliation. In other parts of the porphyry, the west end of George Lake and the west end of Phillip Edward Island for example, volcanoclastic rocks are present (Card, 1976; Clifford, 1986; Davidson, 1986a), some of which are identified as pyroclastic. Just east of the village of Killarney, in what is coined the "Lighthouse porphyry" (Frarey, 1985), there are the quartz-rich masses interpreted by Quirke & Collins (1930) and Quirke (1940) as relics of Huronian quartzite. As a traverse is made from these masses towards the village of Killarney, the quartz and muscovite schist (Davidson, 1986a) grades into large quartz and muscovite veins surrounded by large alteration haloes. Further west, closer to the Lighthouse at Red Rock Point, all that remains of these masses are bands, up to 10 cm in width, that are darker in colour than the surrounding porphyry (Fig. 1-3). The edges of these bands consist of two parallel black lines which represent concentrations of hematite flakes as interpreted from the red staining of the porphyry. Hairline fractures, sometimes filled with quartz, can be seen in the middle of a number of these bands. These bands are represented by sites 31 and 32.

These bands produce a crisscrossing pattern, suggesting that more than one generation is present. The bands also cut across the slight foliation in the porphyry in this area. This implies that the foliation was produced prior to the introduction of the hematite-enriched bands. These hematite-enriched veins were first noted by Quirke (1940) and Davidson (1986a) interpreted the phenomenon as the result of diffusion adjacent to the hairline fractures. Clifford (1986) interpreted these bands and quartz masses as a rhyodacite dome/flow plus spall-off breccia. Whatever the interpretation, the timing of this hydrothermal event has not yet been determined.

As mentioned above, the foliation that is persistent throughout the porphyry is also heterogeneous. Over the span of only a few meters at almost any foliated site, the foliation can disappear, leaving the porphyry with no macroscopic evidence that it has been deformed. Only near the Grenville Front, represented by the mylonitic foliations, do the foliations generally persist over entire

Fig. 1-3: Illustration of the "railroad track" veining along the shore of Georgian Bay, east of the village of Killarney. The black lines are concentrations of hematite. These lines parallel a central fracture, which is often filled with quartz. A number of generations of these veins exist as they appear to cross each other.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sites. These mylonitic foliations are represented by sites 7-11, 22 and 23 (Fig. 1-1). The regional foliations are identified in samples from sites 1, 2, 14, 27 and 29.

A number of dykes also cut the complex. Three sets have been identified: 1) pegmatite dykes that are undeformed, except when in close proximity to the Grenville Front, 2) altered diabase dykes that trend northwest (Sudbury swarm; Davidson, 1986a), and 3) fresh diabase dykes that are continuous across the Front, termed the Grenville swarm (Fahrig & West, 1986). The diabase dykes are represented by samples from sites 33-36.

Recently determined ages for the Grenville Front plutons range from 1742 Ma for the KIC to 1471 Ma for the Bell Lake granite (Van Breeman & Davidson, 1988). These ages have provided evidence that the emplacement of the granites was not related to the Grenvillian Orogeny (1160-970 Ma; Rivers *et al*, 1989) as previously suggested (Quirke & Collins, 1930; Quirke, 1940).

The pegmatite dykes have a tentatively assigned age of about 1400 +/- 50 Ma (Van Breeman & Davidson, 1988), while the Sudbury dykes are 1250 Ma (Palmer *et al*, 1977) and the Grenville swarm are dated at 575 Ma (Fahrig & West, 1986).

The Killarney Igneous Complex has been subjected to numerous interpretations since it was first mapped by Bell (1898). Various hypotheses for the KIC have been suggested concerning the age of the complex, to which structural province it belongs, the emplacement and subsequent structural history of the complex, and how, if at all, the complex relates spatially and temporally to the Grenville Front. Many of these problems are still unresolved. Apparently, the region has undergone more than one period of deformation, each one distorting evidence of the former. The Grenville Front is but the manifestation of the last major period of tectonism.

The Grenville Front, as named by Derry (1950), is a tectonic lineament that can be traced for 2000 Km from Georgian Bay to Labrador. It is taken to be the northwest margin of the Grenville Province, but not necessarily the limit of Grenvillian metamorphism or deformation (Wynne-Edwards, 1972; Lumbers, 1978). In the Killarney area the Grenville Front (Lumbers, 1975; Card & Lumbers, 1977; Davidson, 1986a) marks the southeastern boundary of the KIC, although earlier workers placed the Front at the northwest boundary of the complex (Frarey & Cannon, 1969; Frarey, 1985).

Historical Perspective

The KIC was first mapped by Bell (1898), who recognized that the granitic complex intruded the folded Huronian strata. This fact was later confirmed by Collins (1916). Quirke & Collins (1930) and Quirke (1940) placed great emphasis on quartz-rich masses that occur within the complex, interpreting them as relics of the Huronian quartzite. They explained the presence of the granite as a result of large-scale feldspathization (granitization) of the Huronian sediments. The complex was thus interpreted to be part of the Grenville Province, partly because K-Ar determinations on micas gave ages of about 1000 Ma (Stockwell, 1964), even though the complex was made up of reworked Huronian sediments.

The quartz-rich masses found along the shore of Georgian Bay just east of the lighthouse grade into small quartz-filled fractures in the middle of darker coloured porphyry. The edges of these margins are black lines of concentrated hematite flakes. Davidson (1986a) interpreted this phenomenon as resulting from a hydrothermal event which silicified the porphyry, not the reverse. As these bands cut across the faint foliation in this area, the hydrothermal event postdates the regional deformation of the complex.

Rb-Sr and U-Pb dating by Wanless & Loveridge (1972) and Krogh *et al* (1971) illustrated that the emplacement age of the KIC, as well as the other Grenville Front granites, was 500-700 Ma earlier than suggested by the K-Ar dates. This proved that the K-Ar ages were reset during the Grenvillian Orogeny, which had been loosely dated between 1250 Ma and 950 Ma (Wynne-Edwards, 1972). The older dates were used to suggest that the fault zone (the present Grenville Front) was in existence long before the Grenvillian Orogeny (Krogh *et al*, 1971), since the fault was believed to control the location of emplacement of the granites (Lumbers, 1975). This also led to the hypothesis that tectonic activity must have taken place over a long period of time (~600 Ma).

The debate over the positioning of the Grenville Front still continues today. Quirke and Collins (1930) and Quirke (1940) first positioned the Front along the northwestern margin of the KIC, since it was believed that the complex was Grenvillian in age. Frarey & Cannon (1969) and Frarey (1985) also agreed with this positioning. Their argument was that the northwestern margin separated the large-scale, regional structures of the Southern Province from those within the Grenville Province. This included the truncation of the large-scale folds about east-trending anticlines and synclines in the Huronian sediments along the northwest boundary of the KIC, as well as an abrupt change in the lithologies from quartzite to granite. These points satisfy the basic criteria applied to structural province boundaries as defined by Gill (1949) and Stockwell (1961, 1969, 1973, 1982).

Lumbers (1975) was the first to suggest that the Front should be positioned along the southeastern margin of the KIC, which he called the Grenville Front Boundary Fault. This view was later supported by Card & Lumbers (1977), Davidson (1986a) and Clifford (1986). The southeastern margin, characterized by mylonites and ultramylonites, is now favoured because major changes in structural style, orientation and age occur between the KIC and the adjacent Grenville Province. Figure 1-1 illustrates the location of the Front along the southeastern margin of the complex.

The presence of volcanic rocks was first reported by Card (1976), which he tentatively suggested to represent an as yet unrecognized Huronian formation. This led to further field work, after which Clifford (1986) and Davidson (1986a) reinterpreted the rocks in the Killarney area as belonging to a volcanic-plutonic complex emplaced at high crustal levels. They suggested a connection with the mid-continental rhyolitic and granitic suite ranging in age from 1800 Ma to 1350 Ma (Van Schmus & Bickford, 1981; Sims & Peterman, 1986).

An age of 1742 +/- 1.4 Ma for the KIC has been determined using the U/Pb method on zircons (Van Breeman &

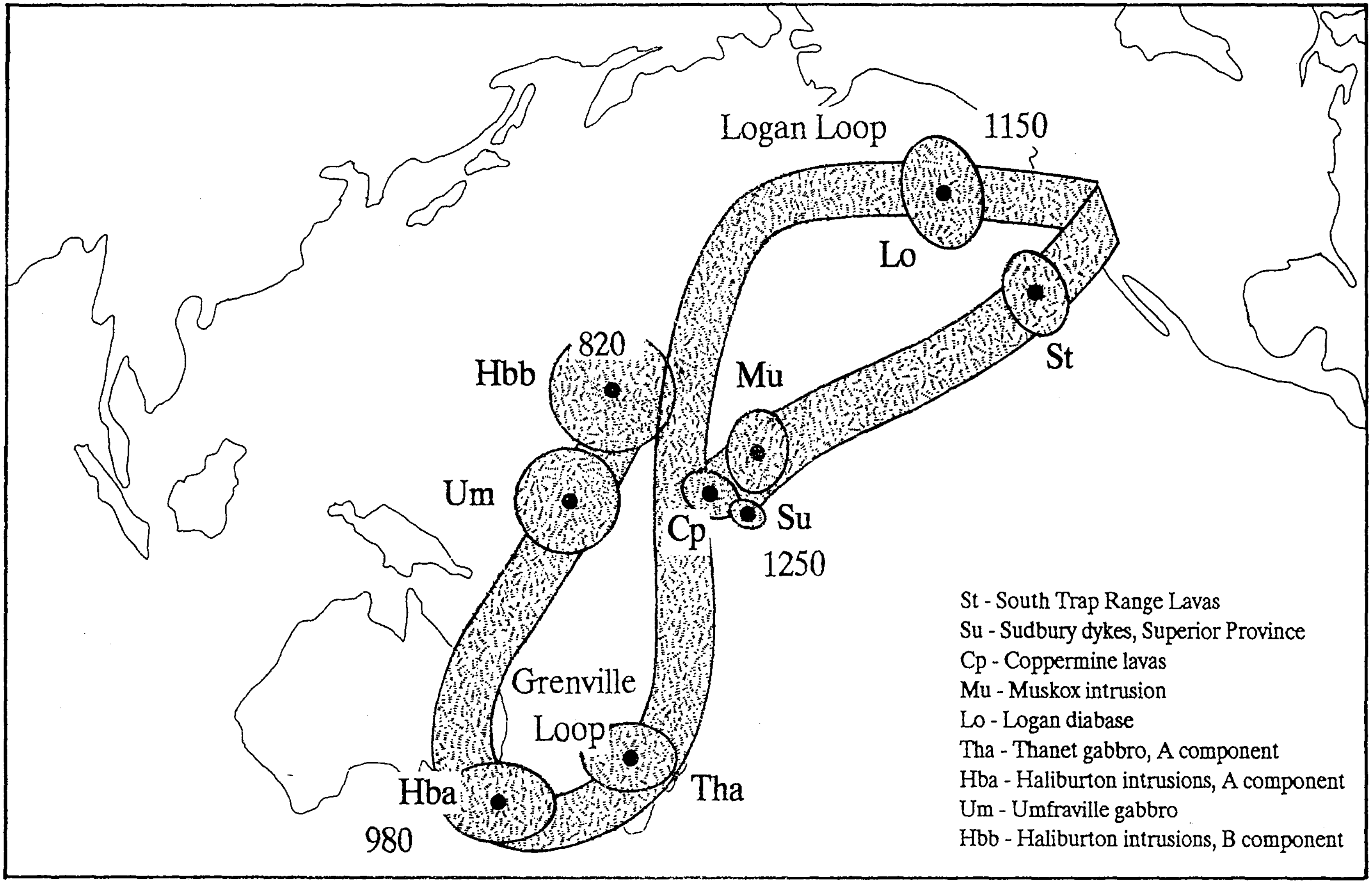
Davidson, 1988). Along with structural evidence, this age has been used to suggest that the occurence of the KIC, and probably the other Grenville Front plutons, is both spatially and temporally distinct from (predates) the Grenvillian Orogeny and the Grenville Front (Van Breeman & Davidson, *op cit*). However, the event responsible for the emplacement of the plutons, if any, and the exact timing of the Grenville Front are as yet unknown.

Paleomagnetism

Many paleomagnetic studies have been undertaken on rocks adjacent to the Grenville Front and within the Grenville Province (see Irving (1979) for a summary of studies), but no such study, until the present one, has yet been undertaken on rocks from any of the Grenville Front granites. Most of the previous studies that concentrated on rocks from within the Grenville Province reported that natural remanent magnetizations (NRMs) were either partially, or totally reset during cooling between 1000 Ma and 900 Ma. These dates were based on K-Ar dating methods, which became particularly useful for paleomagnetism after York (1978) developed a formula describing both magnetic and isotopic blocking temperatures, showing that the two could be related even though their blocking temperatures differed (Dunlop *et al*, 1980). The apparent polar wander path (APWP) for this time period, the Grenville Orogeny, was therefore constructed from these poles and dates. Figure 1-4 illustrates the generally accepted APWP compiled by Dunlop (1981), as well as some well documented poles.

A problem associated with Grenville virtual geomagnetic poles (VGPs) is that no remanence has yet had an age determined that is older than about 1200 Ma (Berger & York,

Fig. 1-4: Apparent polar wander path (APWP) for the Late Proterozoic, spanning from 1250 Ma and 820 Ma. This version was compiled by Dunlop (1981). The Logan Loop represents poles from the Laurentian craton prior to the accretion of Grenvillia in the Sudbury region. The Grenville Loop represents poles from the Grenville Province after the accretion.



After Dunlop (1981)

1981). This means that it is very difficult to piece together the paleomagnetic and structural history of "Grenvillia". The timing of the collision between Grenvillia and Interior Laurentia has not been well defined paleomagnetically, although limits between 1250 Ma and 1150 Ma have been suggested (Dunlop *et al*, 1980). This collision is manifested by the present day location of the Grenville Front. It must be noted that the Grenville loop shown in Figure 1-4 is the APWP for Laurentia, meaning that Grenvillia had already collided with Laurentia. The Logan Loop is defined by poles magnetized during the Keewanawan (1250 Ma-1150 Ma) for a Laurentia without an attached Grenvillia (Irving & McGlynn, 1981).

A number of studies (Ueno & Irving, 1976; Palmer *et al*, 1977; Hyodo *et al*, 1986) have examined the effects of the Grenvillian Orogeny on rocks outside the Grenville Province, ie: adjacent to the Grenville Front. These studies established that the rocks adjacent to the Front did not escape thermal overprinting. Variations in the size of the areas affected have been reported, ranging from 2-30 Km. Ueno & Irving (1976) found the overprinted zone in the Chibougamau greenstone belt, Quebec, to extend up to 30 Km north of the Front, while Palmer *et al* (1977) reported a zone of only 2-8 Km in width. This latter study was performed on Sudbury dykes found just to the northeast of the KIC, and the distances represent the onset of partial remagnetizations. The study by Hyodo *et al* (1986) was performed on samples from around Temagami, Ontario. They concluded that heating and remagnetization only extended 2-3 Km north of the Front and was confined to an area where deformation and metamorphism associated with the Grenville Orogeny were noted.

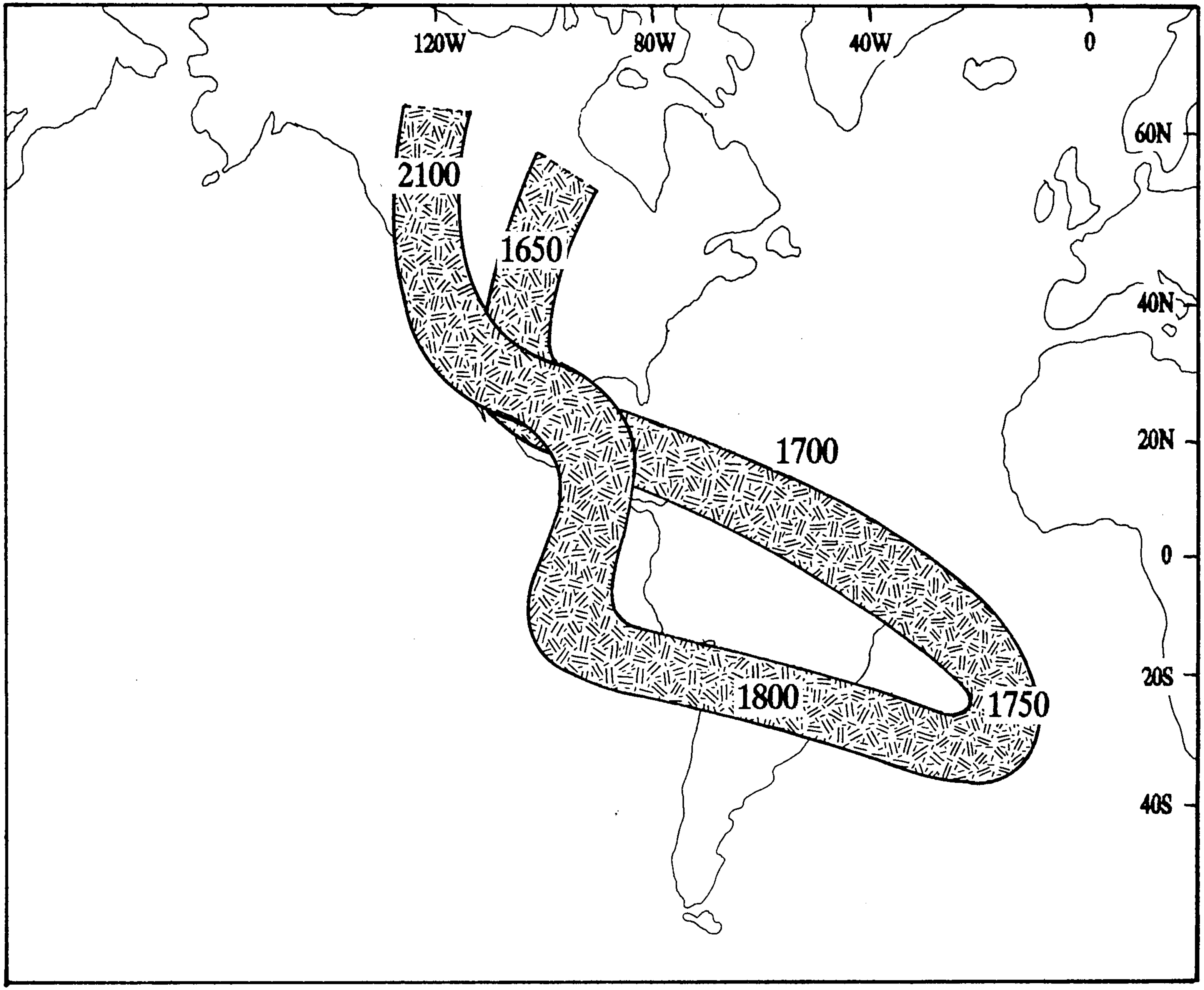
The polar wander path for the middle Proterozoic (2100-1400 Ma) is rather poorly defined as no poles from rocks between the ages of 1650 Ma and 1450 Ma have been reported. A recent version of the APWP for the period 2100-1650 Ma is illustrated in Figure 1-5 (Hyodo & Dunlop, 1989). This track is called the Coronation Loop and it has an inherent problem for this study in that rocks with ages between 1750 Ma and 1700 Ma have antipoles which fall on the Late Grenville path. This makes it very difficult in resolving primary Early Proterozoic poles from primary or secondary Grenville poles.

A problem with Archean paleopoles that has recently been addressed (Hale & Lloyd, 1989), and which might be of importance for some Proterozoic paleopoles, is one associated with high latitude poles. These have usually been discarded and interpreted as Present Earths Field (PEF) overprints. Since it is very difficult to distinguish legitimate pole positions from PEFs if they fall in high latitudes, any poles that fall in this category should be examined carefully, and other information must be used to deduce appropriate interpretations. Figure 1-5 (the Coronation loop) stops short of very high latitudes (ie:>60°), and there is a time gap of 200 Ma to the next accepted APWP (Irving, 1979). For this study, a period of deformation might have occurred during this time gap, indicating the importance of this time period and the possibility of legitimate high latitude poles.

The APWP first described by Morris & Roy (1977) for the Late Hadrynian (~950-800 Ma) was drawn to lie close to the present geomagnetic pole. The path was not widely accepted at that time, but recent arguments in favour of Archean high latitude poles (Hale & Lloyd, 1989) might help reinforce their hypothesis.

The studies performed on rocks adjacent to the Grenville Province concluded that varying distances of overprinting occurred into the Southern and Superior Provinces; generally between 2 and 30 Km. These studies, in addition to structural ones (eg: O'Donnell, 1986), also concluded that the collision occurred as Grenvillia was moving in a present day northwesterly direction and was thrust over the older Laurentian craton. Although there is no evidence to suggest that the Archean craton or the Grenville Front granites were buried for any appreciable length of time, the study by O'Donnell (1986), along with pressure estimates on olivine diabases of 600 MPa by Whitney and McLelland (1973), have shown that the adjacent Grenville Province rocks were metamorphosed at a depth of at least 20 Km, showing that this is the minimum vertical offset.

Fig. 1-5: APWP for the Early Proterozoic. The path is called the Coronation Loop, and this compilation is after Hyodo and Dunlop (1989). There is no path defined for the period between 1650 Ma and 1450 Ma.



After Hyodo and Dunlop (1989)

Objectives

The KIC was chosen as the site of a paleomagnetic study because of its strategic location along the Grenville Front and because it shows effects of both Grenville and pre-Grenville deformation. As paleomagnetic remanences can be reset totally or partially by metamorphism resulting from tectonism, the complex could provide valuable clues to the timing of events in this area.

The study was intended to indentify the paleomagnetism associated with one or all of the following: 1) the original emplacement of the complex at 1742 +/- 1.4 Ma (Van Breeman & Davidson, 1988) which would help define the approximate spatial limit of Grenville deformation by the distribution of sites resolving the primary remanences relative to other secondary remanence carrying sites, 2) any effects of mid-Proterozoic tectonism, of which there is structural evidence (Clifford, 1986; Davidson, 1986) and 3) overprinting during the Grenvillian Orogeny.

The granites, in general, have been avoided in previous paleomagnetic studies because of their supposed lack of magnetic minerals. This study relies on the fact that the Killarney granite and porphyry contain enough magnetic constituents to preserve a measurable remanence. This is not a problem in the part of the porphyry that has been affected by hydrothermal alteration.

A second reason for studying the KIC is the hydrothermal vein system. It has been descriptively referred to as the "railroad-track" facies. Hematite, which is thought to have been deposited as a result of the hydrothermal fluids flowing through the porphyry, offers the possibility of recovering stable chemical remanent magnetizations (CRMs). As the timing of this event is unclear, stable remanences could help to date the system, a result that would be of great interest to economic geologists studying the timing of mineralization in vein systems.

Chapter 2: PALEOMAGNETIC RESULTS

Methods and Materials

Five to six samples were collected from 36 sites from across the KIC, representing both strained and unstrained parts of the complex (see Fig. 1-1). Most of these samples, about 226, were taken as oriented blocks. Site 31, from the hematite-enriched porphyry, includes a continous section of 24 field cores across one of these alteration bands, responsible for the introduction of the hematite.

When the samples were in the laboratory, the first procedure was to set the samples in blocks of concrete. The samples were set in such a way that both the strike and dip lines drawn in the field on the samples were horizontal. Lines with arrows parallel to the strike lines were then drawn across the samples. These lines were used to preserve the orientation when the specimen cores were drilled. The cores were then sliced so that each one measured approximately 2.3 cm by 2.3 cm. In this manner, 3 to 6 specimens were obtained from each sample.

The specimens underwent demagnetization experiments to determine the direction, stability and the intensity of remanence carried by each. The two methods employed, Alternating Field (AF) and thermal, both require stepwise demagnetizations with measurements taken between each step. The AF method is usually quick and simple, taking an hour per specimen to complete an experiment. The thermal method is a longer, drawn out procedure as it takes a substantial amount of time to heat the furnace to each specific temperature. For this reason, the thermal method involves heating batches of up to 50 specimens at one time. Each one of these specimens is measured after every heating step.

At least one specimen from each sample was thermally demagnetized. Typically, steps were 50°C up to 500°C and then 25°C up to 675°C. Each specimen was measured after each heating step using a Schonstedt SSM-2 Spinner Magnetometer which was interfaced with a TI microcomputer. The data from the spinner was automatically shown on the screen and if there were no problems with the data, a hardcopy of it was printed as well as being saved on a floppy. A noninductive furnace within a set of three Helmholtz coils, with a residual field of approximately 10^{-8} T, was used to heat the specimens. Each batch took about 4 weeks to complete.

In addition, at least one specimen per sample was AF demagnetized in at least 14 steps to 100 mT using a Schonstedt GSD-1 demagnetizer. After each step, each specimen was measured on the spinner, with the data recorded on floppy disks.

To characterize the minerals carrying the remanence, a number of thermomagnetic experiments were carried out. These experiments require the use of a heating thermomagnetic balance (Schwarz, 1968). A specimen is crushed and ground into a fine powder, placed inside a small quartz-glass bucket and suspended in a vacuated tube between an electromagnet with specially cut pole caps. The force acting on the specimen to keep it stationary within the inhomegeneous magnetic field is continuously recorded as the temperature of the specimen is increased. The force is recorded along the y-axis of a chart recorder, while the temperature is measured on the x-axis. The point at which a strong decrease in the magnetization of the specimen occurs marks the Curie point of the magnetic mineral. This is the temperature above which a mineral cannot retain a magnetic record, or alternatively, it is the temperature below which a mineral can record the direction of the magnetic field it is exposed to. The Curie temperature usually uniquely defines the minerals present. For magnetite it is 575°C, whereas it is 670°C for hematite.

A number of techniques are employed in analyzing paleomagnetic data. The stability of the remanence upon demagnetization is determined by how much of the remanence is destroyed by each successive step and by checking whether the remanence direction remains constant. The next step is to determine the direction of the remanences. Any clustering of points over a particular range of demagnetization steps is referred to as a stable end-point. Usually, the data after demagnetization are scattered when plotted on a stereonet. If a good tight cluster occurs, then the mean direction for the specimen can be calculated directly from the stereonet. However, typical stereonets for specimens are somewhat scattered, so that the data are plotted on an orthogonal vector plot (Zijderveld, 1967). This plot separates the data into two vectors which cover the three dimensions N-S, E-W and Up-Down. The two vectors can be analyzed to determine the declination and inclination of the specimen over a given linear segment. To facilitate this analysis, a computer program originally written by Hyodo (1985) was revised to be IBM compatible.

Not all specimens demagnetize so as to produce stable end-points or linear segments on Zijderveld diagrams; some produce points on a stereonet which "move". These are checked both manually and with a computer program (Bailey and Halls, 1984) to determine whether they follow a great circle path and how close the fit is.

The mean directions for each specimen are then plotted on a stereonet to determine average directions for the sites, which are then plotted to determine the average direction of the sample area. The great circles are also drawn together and their intersection point is calculated to determine whether it closely matches the average remanence direction.

Demagnetization plots are also drawn to illustrate the stability of the remanence(s), and possibly to illustrate any differences between remanences, ie: one remanence is only found above temperatures of 350°C. These plots also help to determine the predominant magnetic carrier.

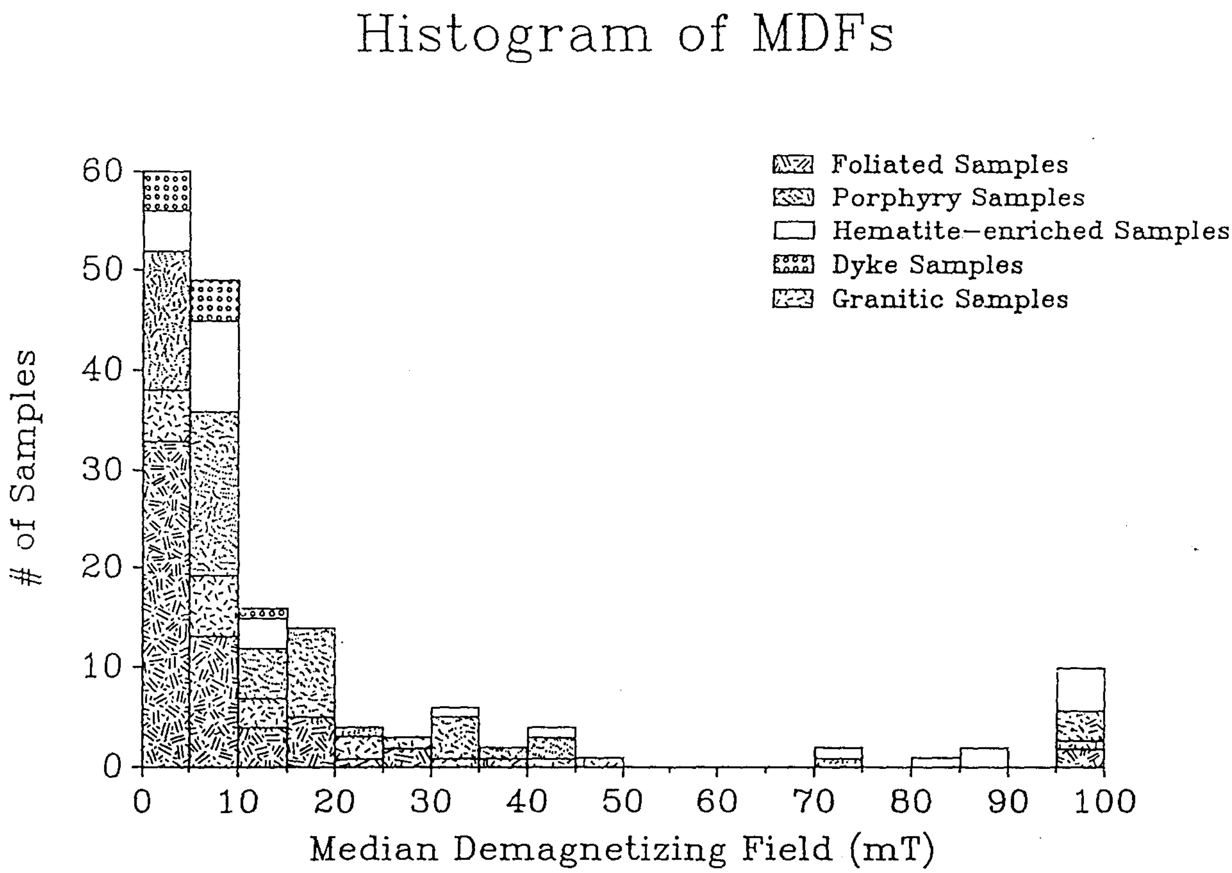
At this point, when average directions have been calculated, the VGP's are calculated. With some constraint on the age of the remanence from other sources, the appropriate polar wander path is used for comparison to determine whether the data is consistent with existing data from that time period. The other alternative is to match the VGP to some polar wander path and infer the age of the rocks in that manner.

Intensity and Stability During Demagnetization

Over 350 specimens were demagnetized over the course of this study, of which 284 specimens provided either stable end-points or linear segments on Zijderveld diagrams which define remanence directions. Figure 2-1 provides a characterization of the behaviour of the Killarney samples during AF demagnetization. This plot illustrates the median demagnetizing fields (MDF's), which are the demagnetizing fields at which 50% of the remanence has been randomized. For clarity, and to determine whether any lithological differences occur, the data are identified with the five lithologies described in the chapter 1 : massive porphyry, hematite-enriched porphyry, foliated porphyry, granite and dyke.

The histogram of MDFs shows that the majority of specimens (about 80%) demagnetize very rapidly, with typical MDFs of less than 20mT. There is also a small tail to the histogram, with MDF's ranging between 70 and 100mT. This tail consists of specimens from the foliated, massive and hematite-enriched porphyry, with the highest coercivity specimens coming primarily from the hematite-enriched porphyry. The dyke specimens are very soft, ie: demagnetize

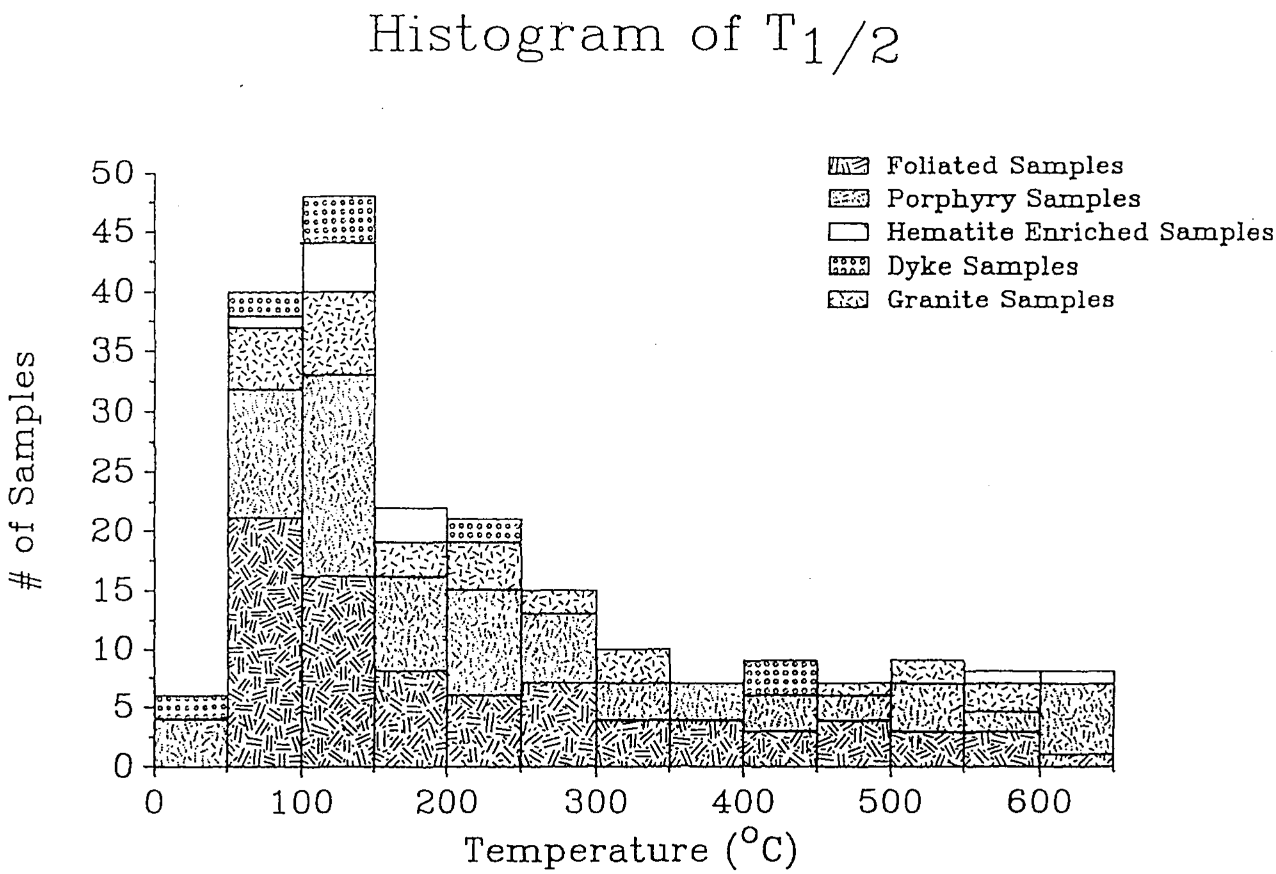
Fig. 2-1: A histogram representing the frequency of median demagnetizing fields (MDF's). More than 70% of the specimens have 50% of their remanence destroyed by 20 mT, illustrating the low coercivity of the specimens. A small number of specimens have coercivities ranging up to 100 mT. The highest coercivity specimens are typically from the hematite-enriched porphyry.


Histogram of MDFs
Foliated Samples
Porphyry Samples
Hematite-enriched Samples
Dyke Samples
Granitic Samples
# of Samples
0
10
20
30
40
50
60
0
10
20
30
40
50
60
70
80
90
100
Median Demagnetizing Field (mT)

very rapidly, while the granite specimens are only slightly harder, with typical coercivities of less than 50 mT.

Figure 2-2 is a histogram depicting the temperature at which 50% of the remanence is destroyed. Again, the majority (about 50%) of the specimens demagnetize rather quickly, at temperatures typically less than 200°C. There is, however, a significant tail to the histogram, showing that some samples demagnetize with unblocking temperatures of up to 670°C. The figure illustrates the wide spectrum of blocking temperatures found in specimens from throughout the entire complex. This suggests that a variety of remanence directions or combinations of directions could exist because any thermal or chemically altering event affecting the complex would result in the overprinting of the remanences already present in the rocks. Bailey and Hale (1981) reported remanence directions intermediate to the NRM originally in the samples and the CRM directions induced into samples. In this case it would be difficult to distinguish valid directions from these partially overprinted remanences. Two other factors that could produce the spectrum of unblocking temperatures deal with the mineralogy. Either a number of different magnetic minerals within the complex carry the remanences, thereby exhibiting a range of unblocking temperatures, or the grain size of the magnetic minerals varies considerably since the unblocking

Fig. 2-2: A histogram representing the frequency of medium demagnetizing temperatures (MDT's), or the temperature at which 50% of the remanence is destroyed. Half of the specimens have very low blocking temperatures (<= 200°C). There is, however, a significant number of specimens that have blocking temperatures up to 670°C. This illustrates the wide spectrum of blocking temperatures present.


Histogram of $T_{1/2}$
Foliated Samples
Porphyry Samples
Hematite Enriched Samples
Dyke Samples
Granite Samples
# of Samples
0
5
10
15
20
25
30
35
40
45
50
0
100
200
300
400
500
600
Temperature (°C)

temperature of a mineral is directly proportional to its grain size (volume) (Stacey and Banerjee, 1974).

The intensity of every specimen is illustrated in a histogram, Figure 2-3. Typical intensities are less than 10^{-1} A/m, which are easily measurable with fluxgate based spinner magnetometers. The lower intensity samples are predominantly the massive samples (porphyry and granite), while the distribution of intensities from foliated specimens peaks higher, at 10^{-1} A/m. The hematite-enriched specimens have a wide spectrum of intensities up to 1 A/m. A few dyke specimens have intensities as high as 10 A/m. Although the frequency of intensities from the massive specimens is roughly constant up to 10^{-1} A/m, the frequency of intensities from the foliated specimens increases, reaching a maximum at 10^{-1} A/m. This suggests an influx of magnetic material into the foliated rocks, which would account for this observation.

A plot of intensity versus MDF (strength versus stability) is illustrated in Figure 2-4. This plot reinforces the point that the majority of the specimens have low intensities coupled with low coercivities. There are, however, a number of specimens with moderate strength that also exhibit high coercivities. Most of these are hematite-enriched specimens. These specimens are prime candidates for paleomagnetic work.

Fig. 2-3: A histogram illustrating the frequency of NRM intensities. Most specimens have intensities of less than 10^{-1} A/m, with dyke and hematite-enriched specimens ranging up to 10 A/m. The massive specimens (granite and massive porphyry) have intensities between 10^{-3} to 10^{-1} A/m, which are relatively constant in frequency over this range. The foliated porphyry specimens have intensities ranging from 10^{-3} to .2 A/m, but their frequency increases to reach a peak at 10^{-2} A/m. This suggests an increase in the magnetic material in the foliated specimens compared with the massive specimens.

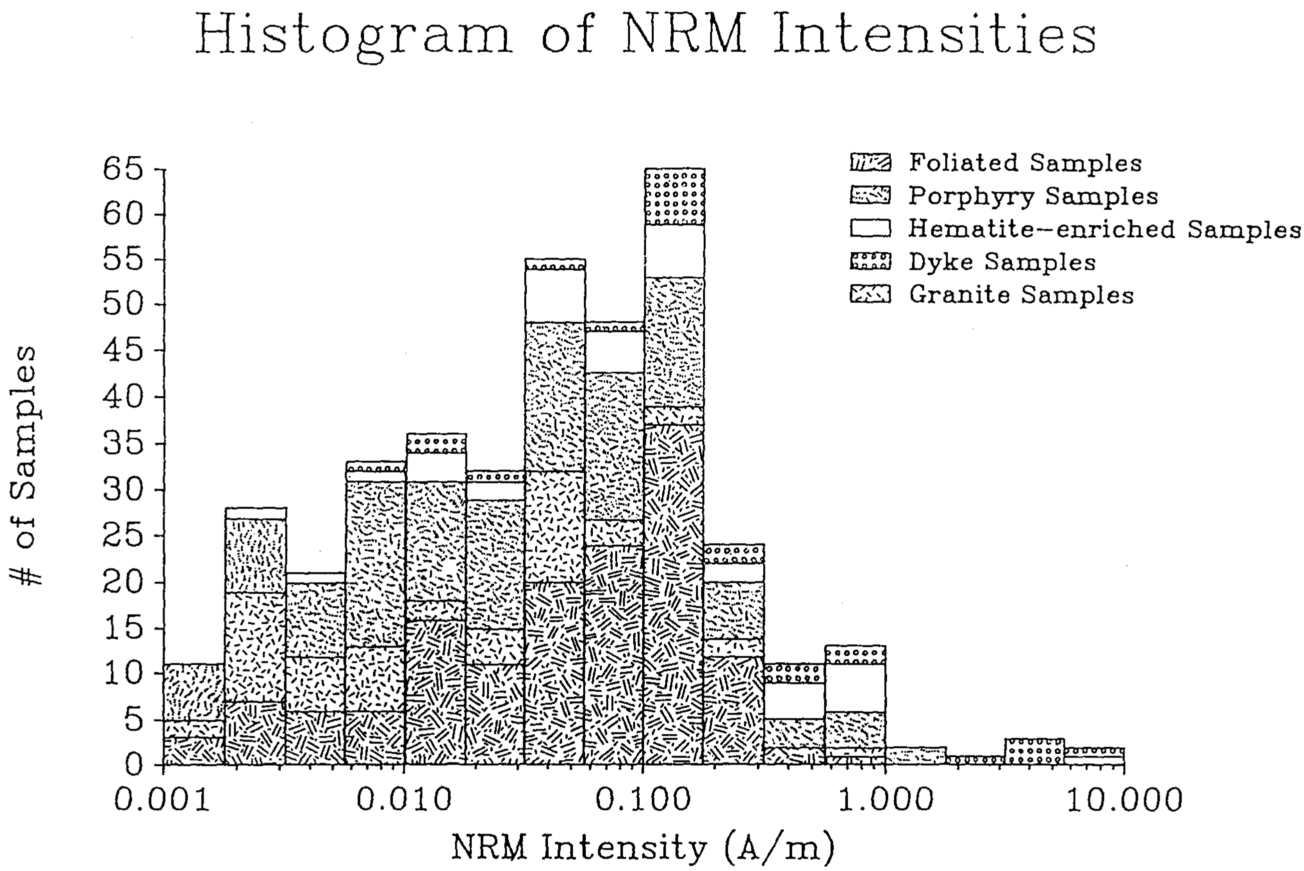
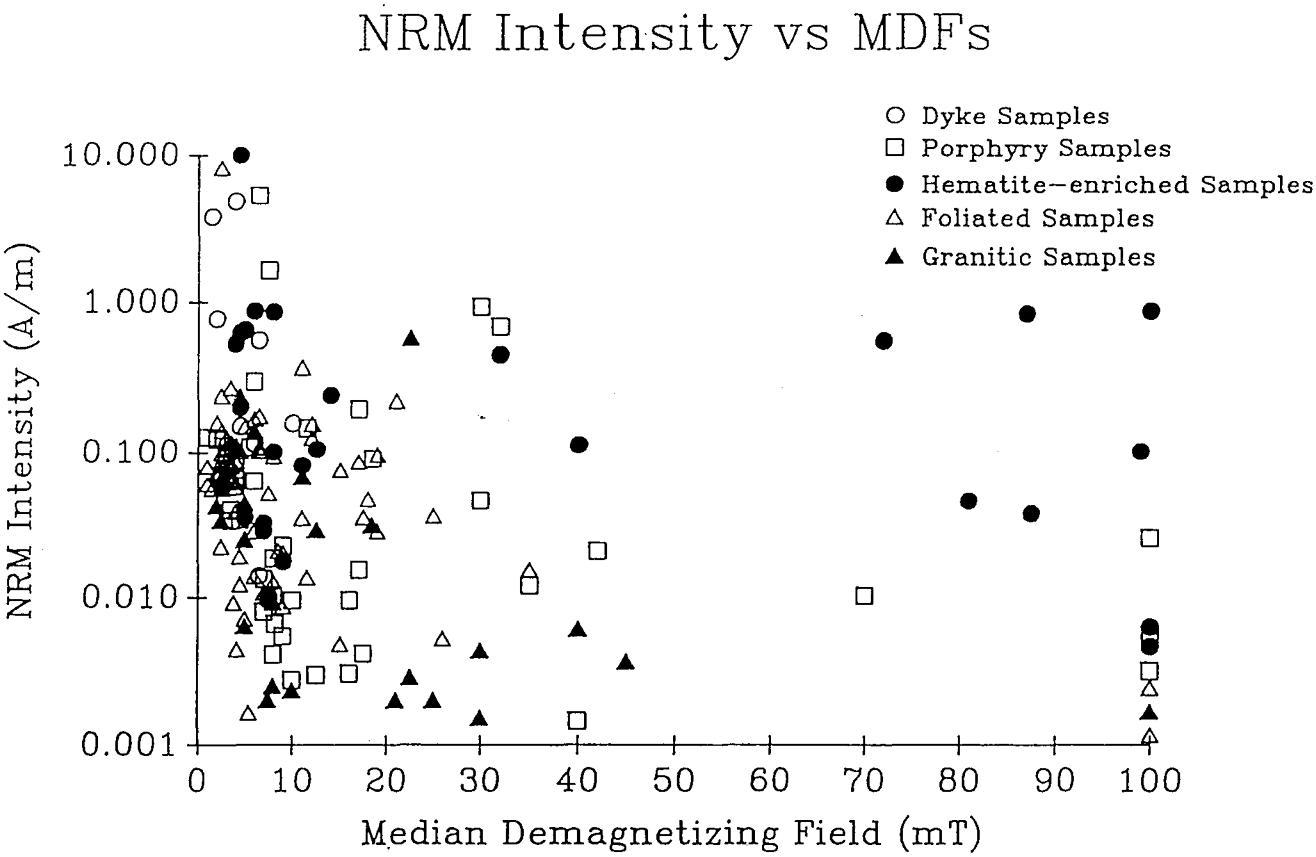

Histogram of NRM Intensities
Foliated Samples
Porphyry Samples
Hematite-enriched Samples
Dyke Samples
Granite Samples
# of Samples
0
5
10
15
20
25
30
35
40
45
50
55
60
65
0.001
0.010
0.100
1.000
10.000
NRM Intensity (A/m)

Fig. 2-4: The NRM intensity of each specimen is plotted against its stability, as represented by MDF's. The massive specimens (massive porphyry and granite) which are unaffected by tectonism, carry comparatively weak NRM's. Some hematite-enriched specimens have both relatively high intensities and high coercivities, suggesting that these specimens will be ideal candidates for paleomagnetic analysis.


NRM Intensity vs MDFs
Dyke Samples
Porphyry Samples
Hematite-enriched Samples
Foliated Samples
Granitic Samples
10.000
1.000
0.100
0.010
0.001
NRM Intensity (A/m)
0
10
20
30
40
50
60
70
80
90
100
Median Demagnetizing Field (mT)

From the demagnetization of the specimens, two key points have arisen: 1) the hematite-enriched specimens are moderately strong and they possess high coercivities which suggest that they will not have their remanences easily overprinted and 2) the foliated porphyry specimens appear to have enhanced intensities compared with the massive parts of the complex. This second point is of importance because it is generally thought that shearing a rock commonly destroys a remanence.

Analysis of Magnetic Constituents

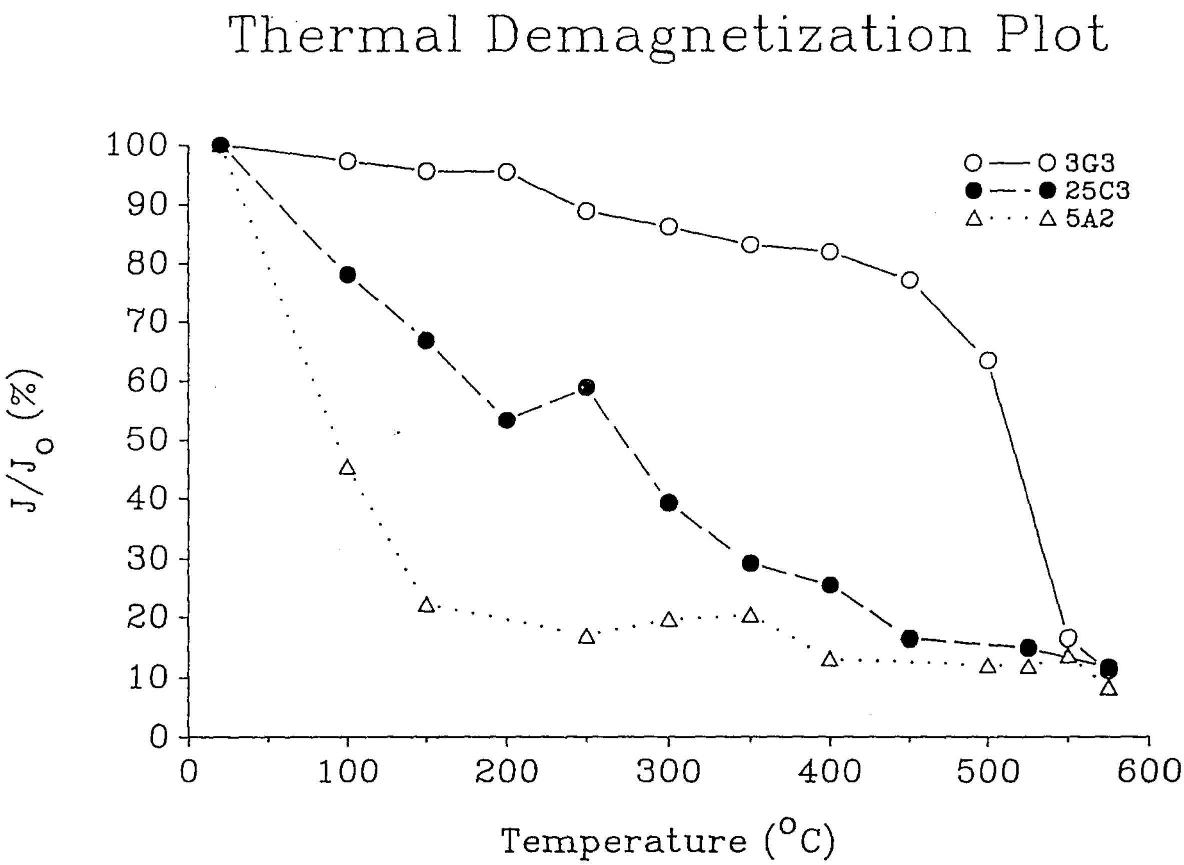
The histogram of median demagnetizing temperatures (Fig. 2-2) illustrates the wide spectrum of blocking temperatures found in the KIC specimens. This results directly from the variation in the magnetic mineralogy found in the specimens. The two magnetic minerals identified under the microscope, hematite and magnetite, have Curie temperatures of 670°C and 575°C respectively. Curie temperatures are the temperatures below which minerals can retain any record of the magnetic field and are very diagnostic of specific minerals when the grains are at the critical diameter between single and multidomain sizes (3.0E-05 mm for magnetite, 0.15 cm for hematite; McElhinny, 1973). Grains that are smaller in size have proportionally lower Curie temperatures until the grain is so small that it cannot acquire a remanence. Particles within the multidomain grain size will have unblocking temperatures much lower than single domain grains (O'Reilly, 1984). Thermal demagnetizations can then be used to determine the dominant remanence carrier, as well as inferring grain size, although other experiments are required to specifically determine grain size.

Alternating Field demagnetizations are not as useful in determining the magnetic mineralogy. If, however, a thermoremanent magnetization (TRM) is carried by the magnetic grains then it might be possible to infer a range of grain sizes if only one mineral is present. This would result in a wide range of resistance to AF demagnetization. In general, magnetite is often relatively easily demagnetized with an alternating field, whereas hematite tends to be more resistant (O'Rielly, 1984).

The decay curves for the thermal demagnetizations have been organized into three typical types (see Fig. 2-5). Type A curves (specimen KV3G3) have square shoulders with unblocking temperatures ranging from 550 to 650°C. The B-type decay curves have blocking temperatures that are more widely distributed (specimen KV25C3). Unblocking temperatures range from 300 to 500°C. Specimen KV5A2 illustrates a type C curve. This curve exhibits much lower unblocking temperatures, generally less than 300°C.

The demagnetization of the granite, whose curves are illustrated in Figure 2-5 representing specimens KV3G3, KV25C3 and KV5A2, can be described by all three types of curves. Specimen 3G3 exhibits a type A curve, with a square-shouldered look, indicating that the specimen does not demagnetize appreciably until a temperature of about 450°C is reached. Although the specimen has an unblocking

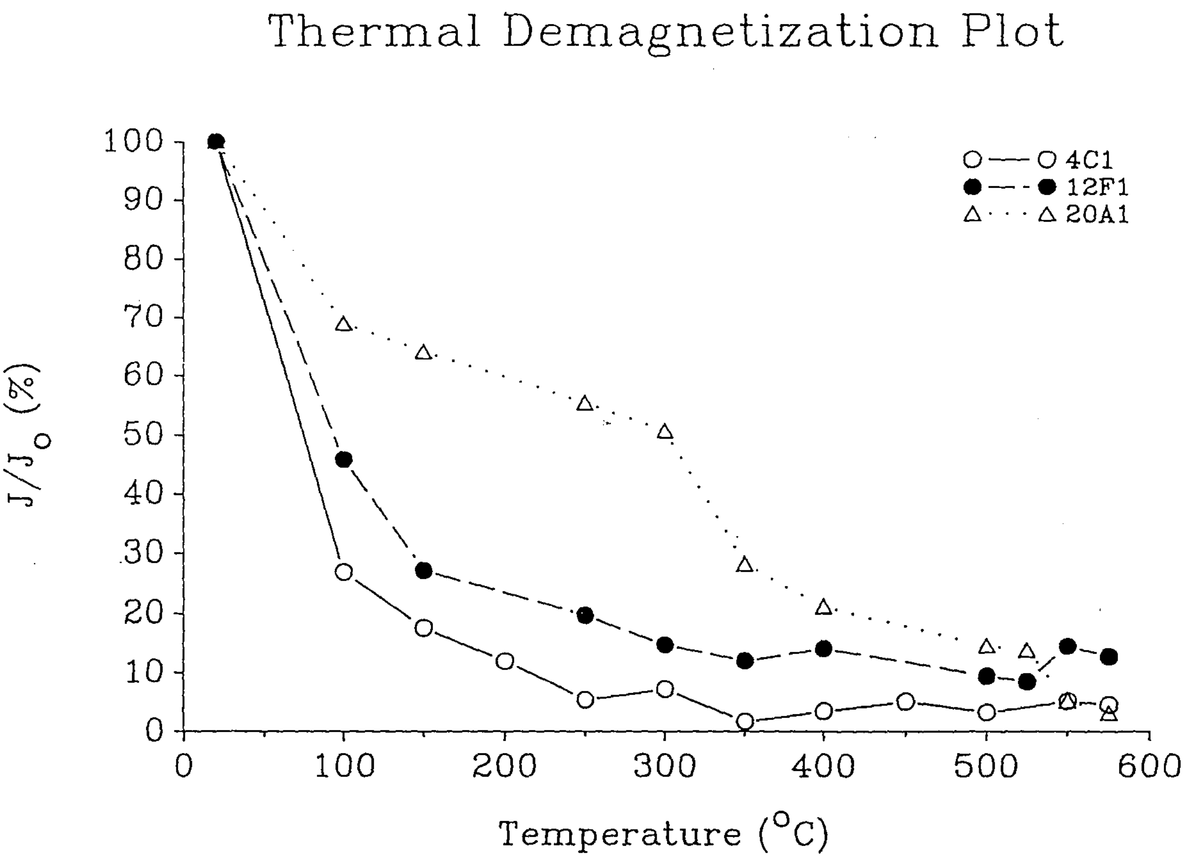
Fig 2-5: Thermal demagnetization plot illustrating the three types of demagnetizations, A, B and C. This plot represents the demagnetization of granite specimens. All three specimens retain 10% of their remanence after heating to 575°C, suggesting that hematite, in part, carries some remanence.


Thermal Demagnetization Plot
100
90
80
70
60
50
40
30
20
10
0
J/J$_o$ (%)
0
100
200
300
400
500
600
Temperature (^oC)
3G3
25C3
5A2

temperature of almost 550°C, about 15% of the remanence still remains at 575°C. A typical type B curve is exhibited by specimen 25C3, which demagnetizes steadily over the complete temperature range and has about 10% of its remanence remaining at 575°C. Specimen 5A2 demagnetizes rapidly, representing a type C curve. However, the curve levels off after 150°C at a remanence of 20% and retains about 10% of its remanence at 575°C. These examples suggest that the granite consists mainly of magnetite with some hematite as indicated by the 10% residual remanence at temperatures over 575°C.

Figure 2-6 illustrates some typical demagnetization curves for the massive porphyry. These examples, taken from sites 4, 12 and 20, typically fit type B and C curves. Specimen 4C1, a type C curve, loses 70% of its remanence after heating to 100°C, but then demagnetizes steadily to a temperature of 350°C retaining 5% of its remanence, which remains at a temperature of 575°C. Specimen 12F1 also demagnetizes rapidly, losing 70% of its remanence after heating to 150°C. This type C curve then demagnetizes slowly but steadily up to 575°C, retaining 15% of its remanence at this temperature. A couple of specimens, represented by KV20A1, exhibit type B curves that demagnetize steadily over the entire range of heating. These generally end up with less than 5% of their remanences at 575°C.

Fig.2-6: Decay curves for the massive porphyry specimens after during thermal demagnetization experiments. Most specimens lose a majority of their remanence after heating to about 400°C.



Thermal Demagnetization Plot
J/J_o (%)
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
Temperature (°C)
4C1
12F1
20A1

Most of the dyke specimens have decay curves that are consistent with type B, although a few type C curves exist. These are illustrated by the curves from specimens KG1-12, KDD6C1 and KDD5A1 in Figure 2-7. Specimens KG1-12 and KDD6C1 illustrate the typical type B demagnetization curves for the dyke specimens. The specimens demagnetize steadily over the entire temperature range, with essentially all of the remanence demagnetized by 575°C. The type C curves, which are exceptions, are represented by specimen KDD5A1. These specimens demagnetize very rapidly, losing 85% of their remanence after heating to 100°C. For the remaining heating steps up to 600°C, a constant remanence level of about 5% is maintained. Magnetite is the primary magnetic mineral carrying the remanence, since virtually no remanence remains at temperatures over 575°C.

The hematite-enriched specimens generally fall into two categories, types A and C. The type A curves come from the specimens from site 32, while the field-drilled cores, site 31, produce all the type C curves. Figure 2-8 illustrates the demagnetization curves for specimens KG3B3 and KV32-7. Specimen KV32-7 comes from the field-cored section consisting of 24 cores. The demagnetization curve shows that the specimen demagnetizes fairly rapidly, losing 80% of its remanence after heating to 250°C. The specimen then demagnetizes only slightly over the rest of the experiment,

Fig. 2-7: Thermal decay curves for dyke specimens. These curves indicate that all the remanence is carried by magnetite as all the remanence is demagnetized after heating to 575°C.

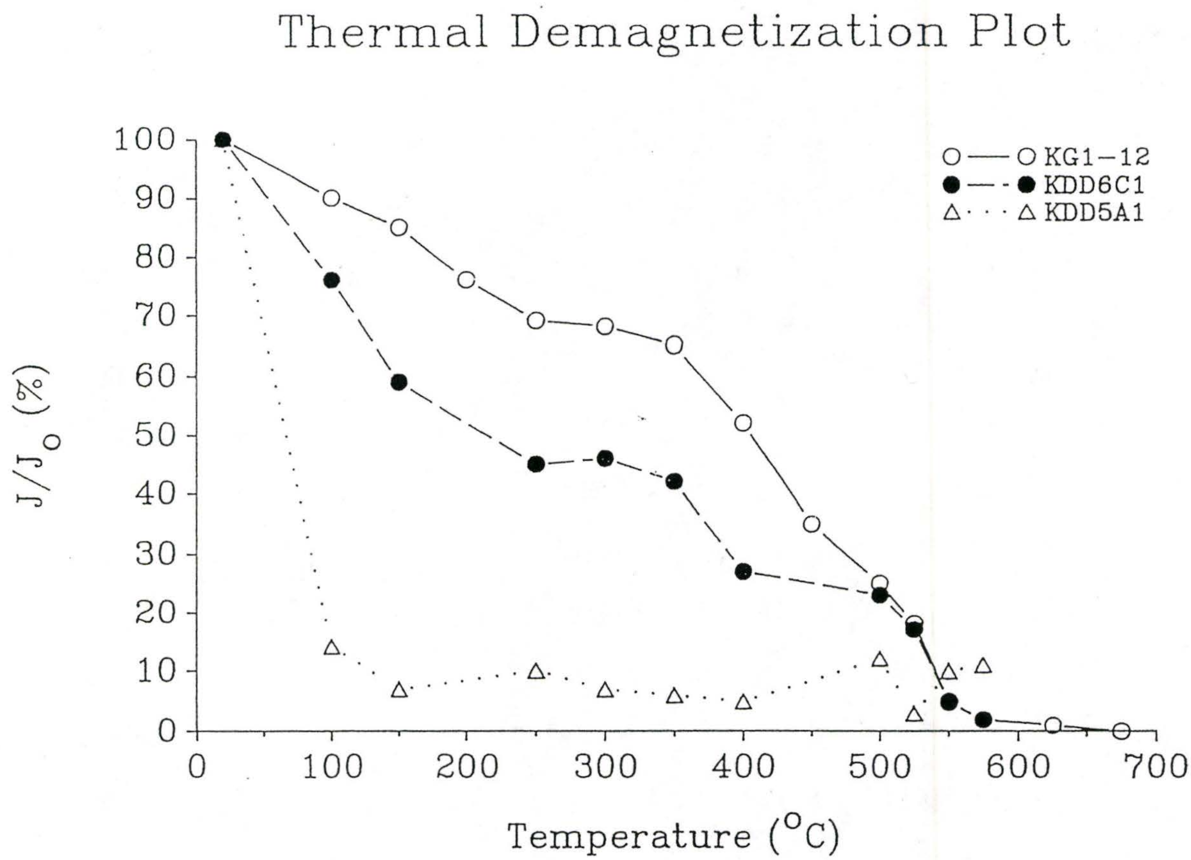
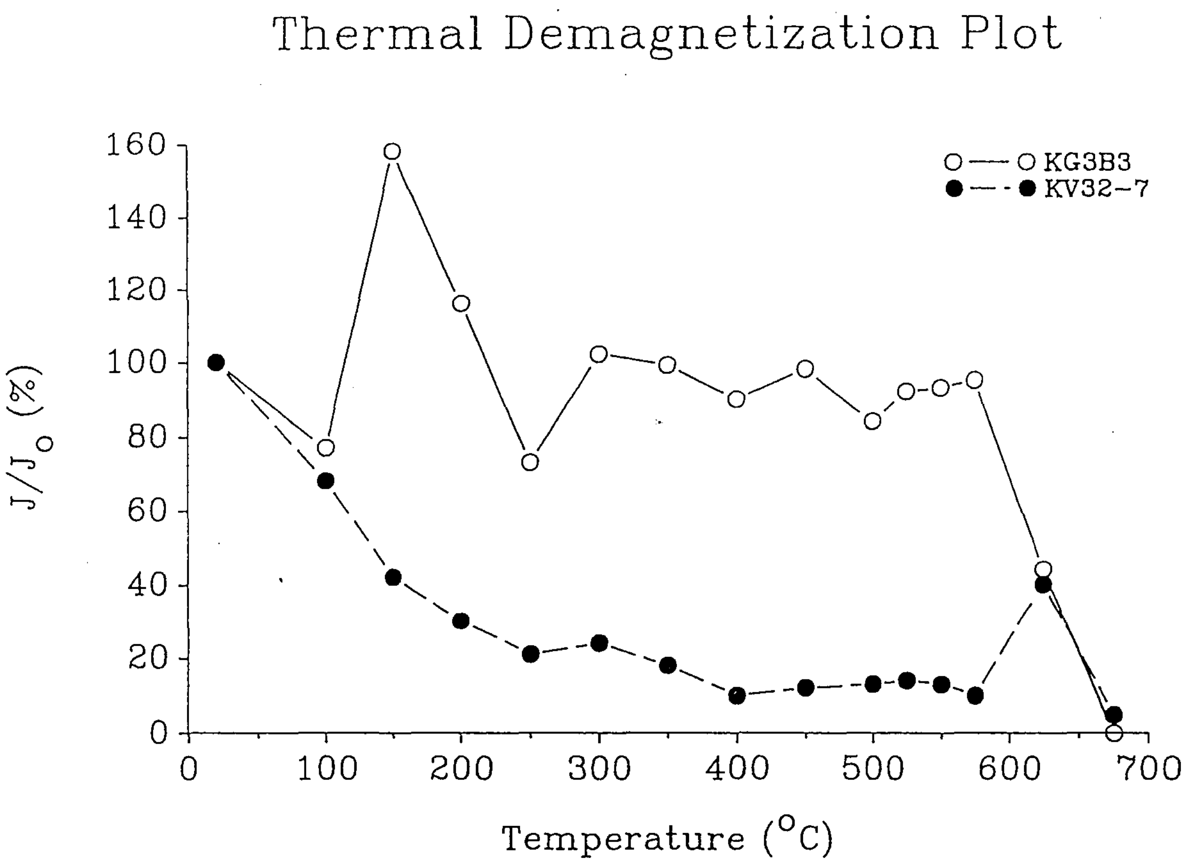

Thermal Demagnetization Plot
100
90
80
70
60
50
40
30
20
10
0
J/J_o (%)
0
100
200
300
400
500
600
700
Temperature (°C)
KG1-12
KDD6C1
KDD5A1

Fig. 2-8: Demagnetization curves for hematite-enriched porphyry specimens after thermal experiments. Hematite is shown to carry a significant portion of the remanence since the remanence is not demagnetized until heating to 670°C.



Thermal Demagnetization Plot
KG3B3
KV32-7
J/J$_o$ (%)
0
20
40
60
80
100
120
140
160
0
100
200
300
400
500
600
700
Temperature (°C)

retaining less than 5% of its remanence after the heating step at 670°C. Specimen KG3B3 represents a type A curve. The specimen does not demagnetize appreciably until about 575°C but essentially all the remanence is demagnetized at 670°C. The type A decay curve example illustrates that the dominant remanence carrier is hematite, since the specimen has a blocking temperature well over 600°C. The type C curve example suggests that both magnetite and hematite are present, as most, but not all, of the remanence is destroyed by 575°C.

It is important to note that there is a slight difference in the decay curves between specimens associated with the regional foliations and specimens associated with the mylonitic foliations. The regionally foliated specimens (shown in Figure 2-9) fall into type B and C curves. The examples illustrated, specimens 14C2 and 27A1, represent the high and low end-members of the demagnetization spectra. Most of the specimens measured demagnetize steadily, losing about 80% of their remanence after heating to 350°C, falling in between the two plotted curves. These specimens retain 10 to 30% of their remanences at 575°C. The specimens that possess the mylonitic foliation have demagnetization curves that not only follow type B and C curves, but there also are specimens that have type A decay curves. These are represented in Figure 2-10 by specimens 7E1, 10A2 and 9E2

Fig. 2-9: Regionally foliated porphyry specimen thermal demagnetization curves. About 20% of their remanence remains after heating to 575°C, suggesting that hematite is carrying some of the remanence.

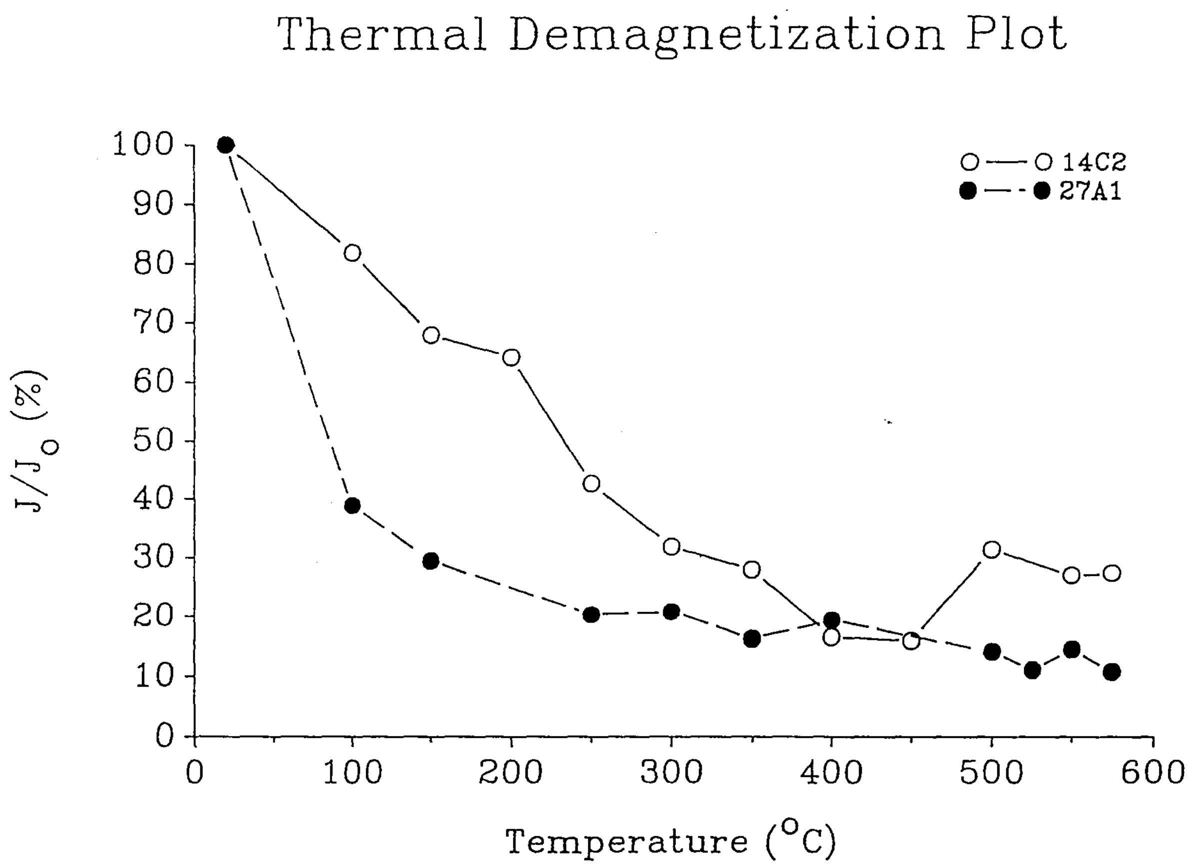
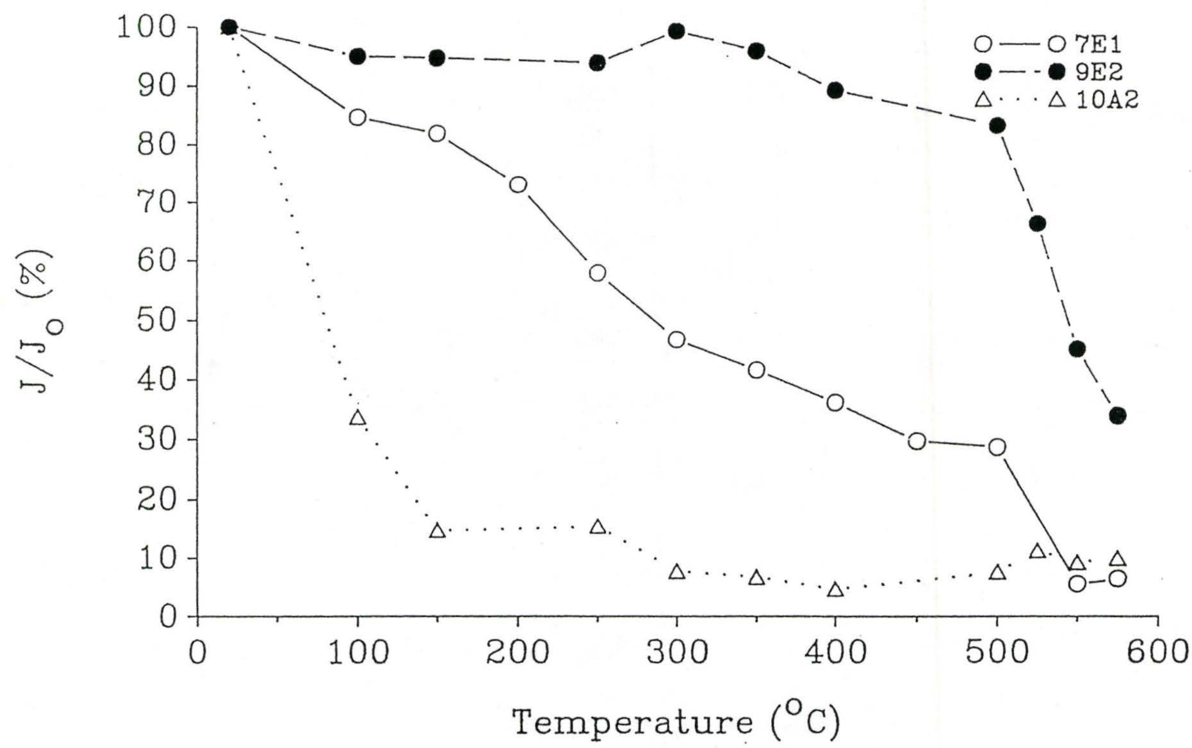

Thermal Demagnetization Plot
100
90
80
70
60
50
40
30
20
10
0
J/Jo (%)
0
100
200
300
400
500
600
Temperature (°C)
14C2
27A1

Fig. 2-10: Thermal demagnetization plot for mylonitically foliated porphyry specimens. These indicate that some of the specimens have hematite carrying the remanence as over 20% of their remanences remain after heating to 575°C.

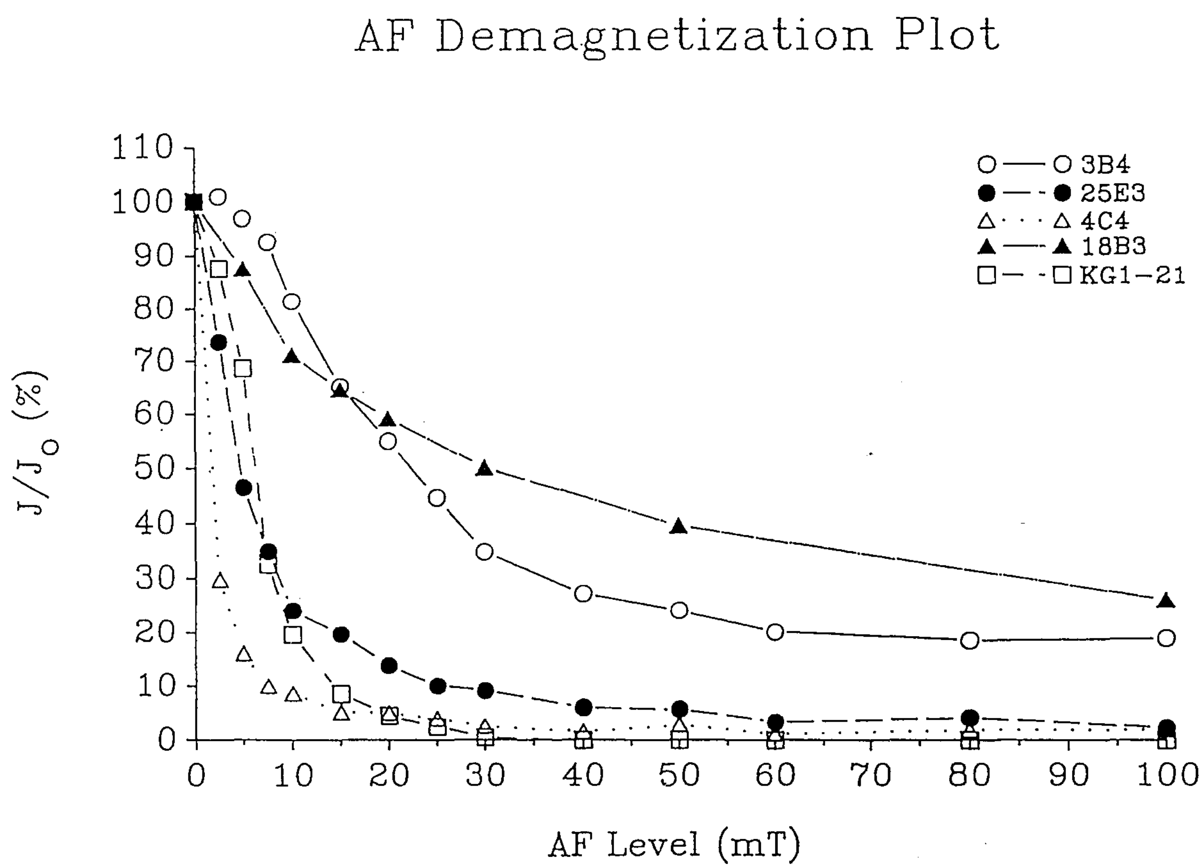
Thermal Demagnetization Plot



respectively. Specimen 10A2 (type C) demagnetizes rapidly, losing 85% of its remanence by 150°C, and retains less than 10% of its remanence at 575°C. The type B curve (specimen 7E1) demagnetizes steadily over the entire temperature range, retaining 5% of its remanence at 575°C. The square-shouldered type A curve (specimen 9E2) begins to demagnetize at 500°C and at 575°C over 30% of its remanence remains. All of these examples show that most of the remanence is carried by magnetite. As a number of specimens retain 10% or more of their remanence at 575°C, especially the type A curve examples, they show that some hematite is present and carrying a portion of the remanence.

AF demagnetizations are not as useful in determining mineralogy as thermal methods. However, it is sometimes possible to distinguish magnetite and hematite. Figure 2-11 illustrates demagnetization plots for the granite, massive porphyry and dykes. The granite is represented by specimens 3B4 and 25E3. The former specimen demagnetizes steadily up to 30mT but then levels out retaining 20% of its remanence at 100mT. Specimen 25E3 demagnetizes very rapidly, losing 90% of its remanence by 30mT. It then levels out, and essentially is totally demagnetized at 100mT. These suggest that magnetite is the dominant remanence carrier. Specimens 4C4 and 18B3 represent the massive porphyry. These essentially show the same characteristics as the two granite

Fig. 2-11: AF demagnetization plot for granite, massive porphyry and dyke specimens. Most specimens are easily demagnetized using an alternating field. The specimens that are resistant to demagnetization either carry hematite or fine-grained magnetite.



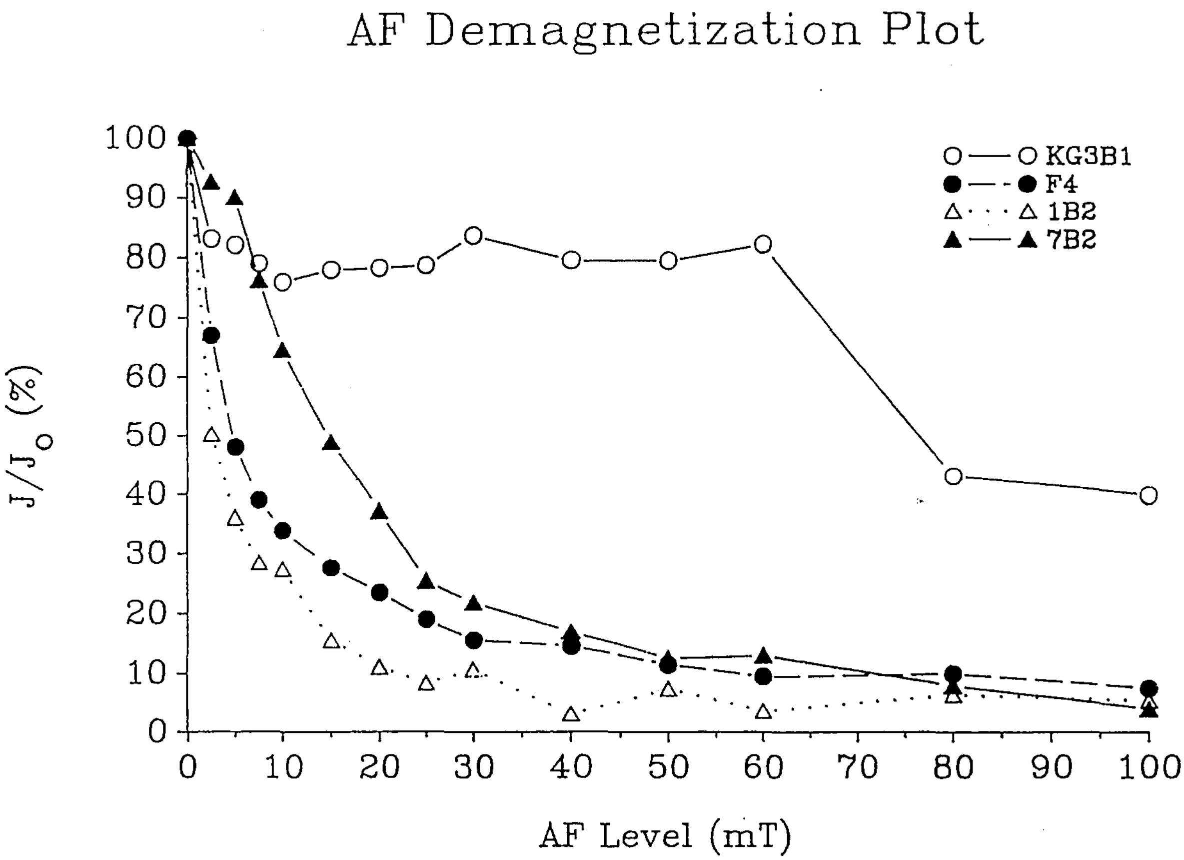
AF Demagnetization Plot
J/J$_o$ (%)
110
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
AF Level (mT)
3B4
25E3
4C4
18B3
KG1-21

samples. All the dyke specimens, represented in Figure 2-11 by KG1-21, demagnetize very rapidly and essentially have all their remanence destroyed by 30mT. This suggests that only magnetite is the magnetic mineral present, as it is in the granite and massive porphyry.

Figure 2-12 shows AF demagnetization plots for the hematite-enriched and foliated specimens. The former group generally demagnetize in two ways, those that do not demagnetize appreciably until 60 or 70mT and those that demagnetize fairly rapidly leaving less than 20% of the remanence by 100mT. These are illustrated by specimens KG3B1 and F4 respectively. The first specimen suggests that either abundant hematite or very fine-grained magnetite is carrying the remanence because the specimen is very resistant to demagnetization. The second specimen suggests magnetite is responsible for the remanence as it demagnetizes rapidly down to almost 0% at 100mT. The foliated specimens show no distinguishable coercivity difference between samples carrying the regional or the mylonitic foliation. Most specimens demagnetize very rapidly leaving less than 15% of the remanence at 100mT. These are illustrated by specimens 1B1 and 7B2. Most of their remanence is carried by magnetite but some hematite is present.

Another method for determining the magnetic mineralogy is through the use of thermomagnetic experiments. Figure 2-

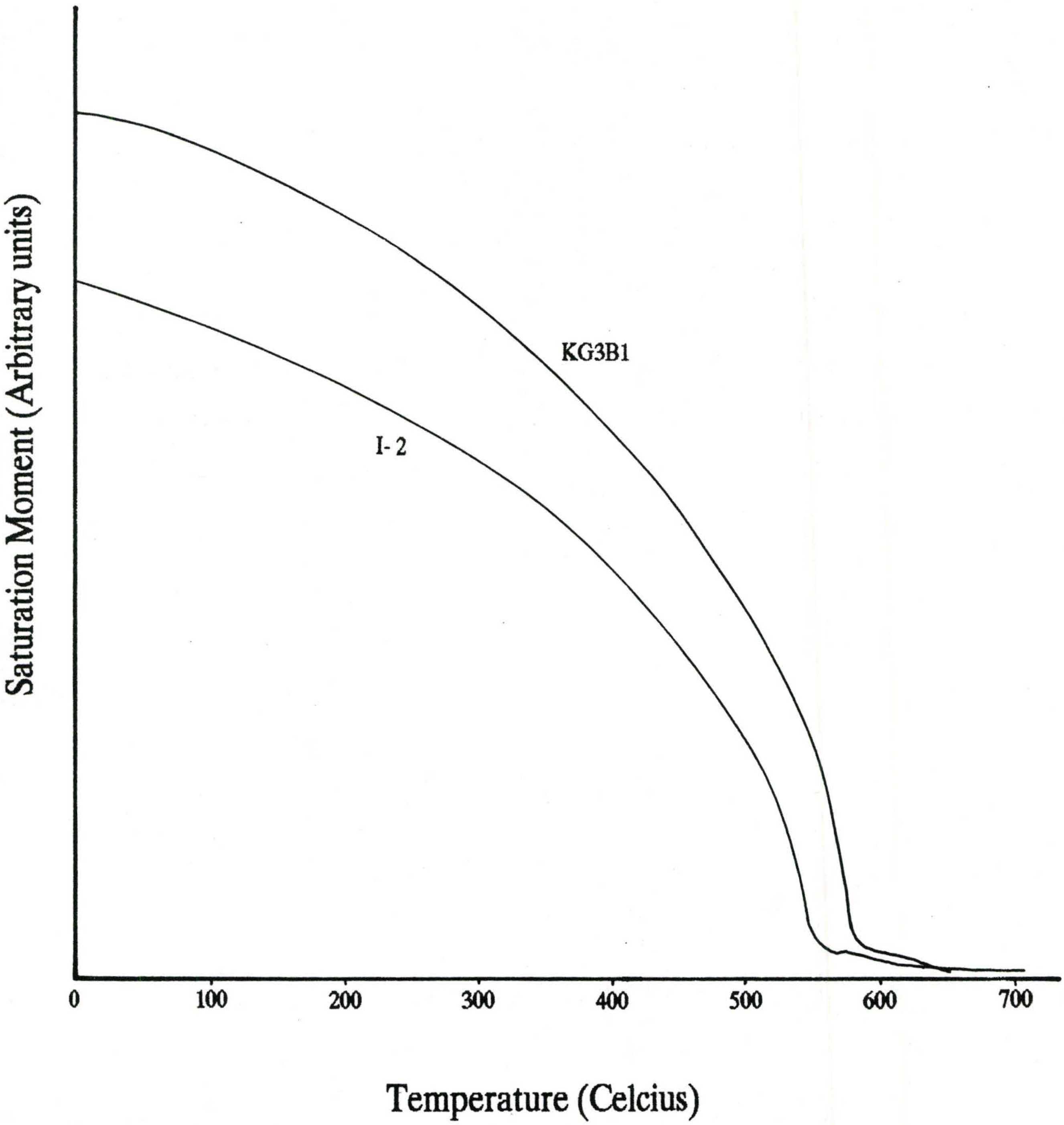
Fig. 2-12: Hematite-enriched and foliated porphyry AF decay curves. Only one of the hematite-enriched specimens is resistant to demagnetization.


AF Demagnetization Plot
KG3B1
F4
1B2
7B2
J/J_o (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
AF Level (mT)

13 illustrates two of these curves obtained for hematite-enriched specimens KB3B1 and I-2. Both of these show that magnetite is the dominant magnetic constituent, because a large decrease in the magnetization of the grains occurs near 575°C. However, the small tail at the end of the curve suggests that some hematite is present, since some magnetization is present at temperatures well above 580°C. If both magnetite and hematite are present, the hematite susceptibility is commonly overshadowed by the magnetite, since the magnetite is a stronger magnetic mineral by a factor near 200 (Stacey and Banerjee, 1974).

Fig. 2-13: Examples of thermomagnetic curves. Both specimens appear to contain magnetite and hematite. A large decrease in magnetization occurs around 575°C, indicating that magnetite is present, but there is also hematite, indicated by the tail at the end of the curve.

Js (T) Curves (Heating Portion)



Analysis of Remanence Directions

The previous sections summarized the nature of demagnetization of the specimens, described the quality of the data in terms of their usefulness in a paleomagnetic study, and magnetically determined the magnetic constituents present. There is evidence that the lithology produces differences in NRM intensities, MDF's, thermal demagnetization curves and the dominant remanence carrier, although there are variations in each group. This information can be used to interpret the stereonets in Figures 2-14, 15a&b. Figure 2-14 is a stereonet with all 284 stable end-point directions obtained from the 350 specimens that were demagnetized. The closed circles indicate positive or downwards pointing directions, whereas the open circles indicate negative or upwards pointing ones. The data are scattered along a northeast-southwest axis, around a group with steep positive directions. Figure 2-15a&b illustrate the same data, but they are separated into upper and lower hemispheres. The lower hemisphere stereonet (Fig. 2-15a) shows that the Killarney complex specimens are dominated by a steep positive remanence direction. There are shallow to intermediate directed remanences scattered within the northeast and southwest quadrants. Figure 2-15b shows the

Fig. 2-14: Stereonet of stable end-point directions from 284 specimens. Closed circles represent downward vectors, while open circles represent upwards vectors. The Killarney collection is dominated by a steep downward component.

Killarney Igneous Complex Specimen Directions

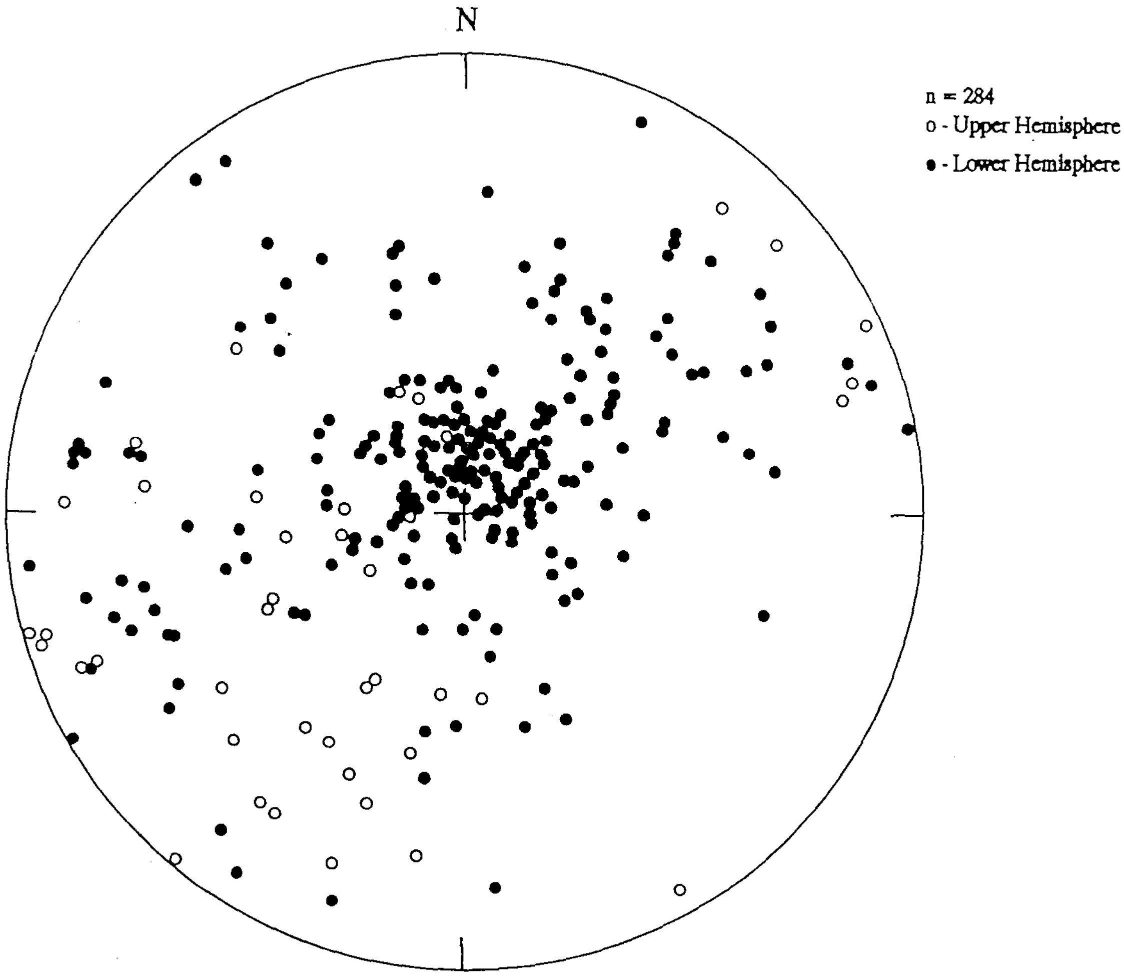
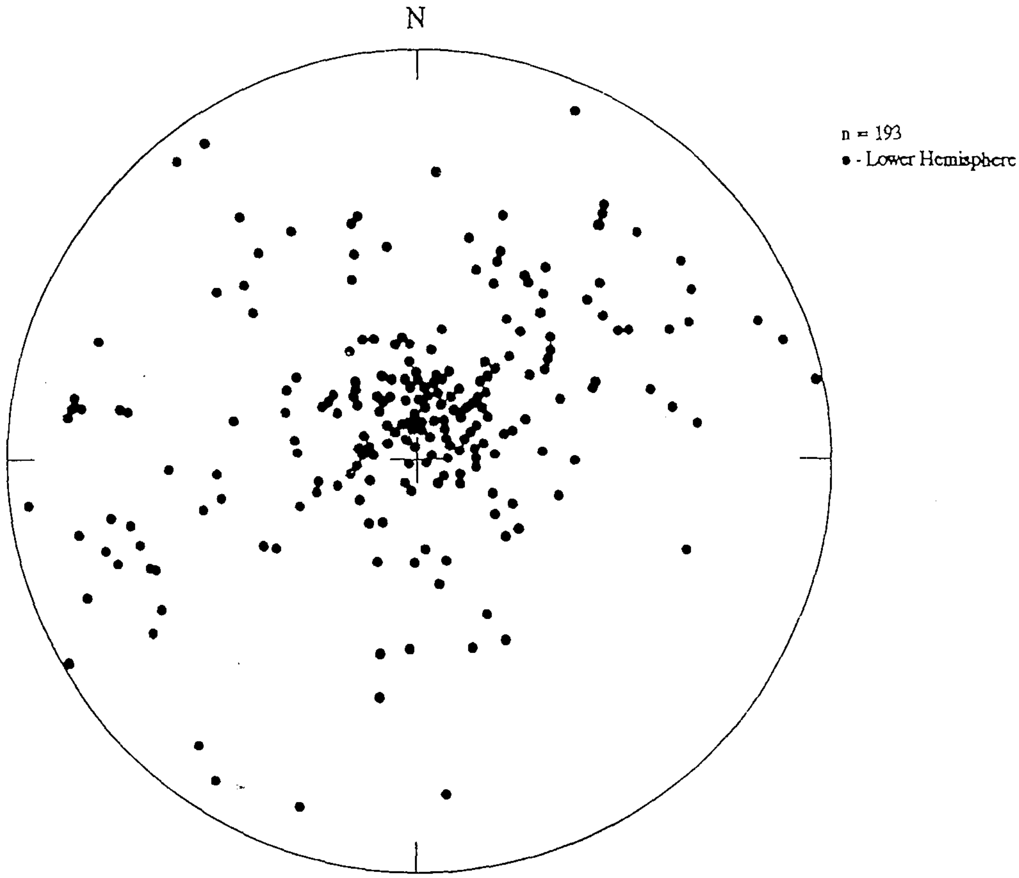


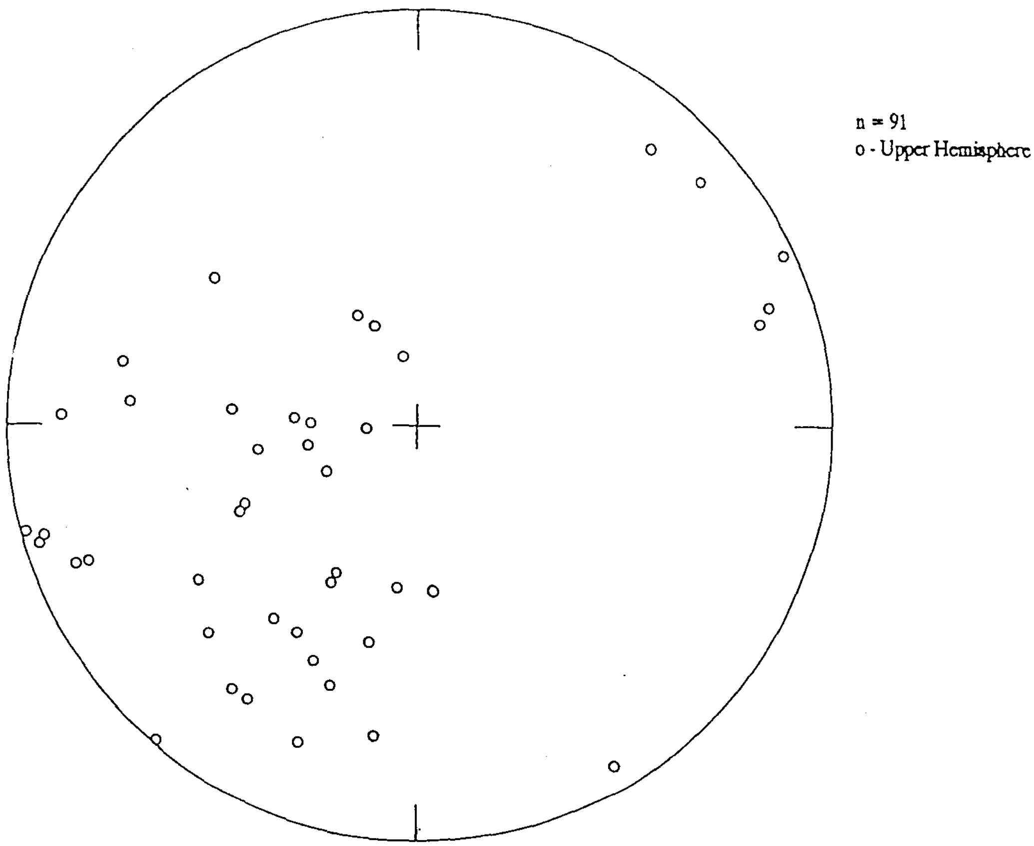
Fig. 2-15: Two stereonets representing the stable end-point directions. (a) A lower hemisphere projection containing 232 specimen directions illustrating the dominance of a steep downward component. (b) Upper hemisphere projection showing that the remaining specimens (52/284) define a southwesterly direction.

Killarney Igneous Complex Specimen Directions

(a)



(b)



upper hemisphere remanence directions. The majority of these are shallow to intermediate in inclination and in the southwest quadrant. A handful of specimens have shallow remanences with northeasterly declinations. The scattering of remanence directions means that the differences observed in the demagnetization properties, as well as in lithology, are of importance in resolving remanence populations.

In a typical paleomagnetic study, the average direction from the specimens from each site would be calculated at this point. However, Table 1 illustrates the statistics associated with all of sites from across the complex. The statistics calculated with these numbers are fairly poor. The Kisher Kappa is a number indicating the degree of scatter to the data, the higher the K the less the scatter. Table 1 shows that most sites have very small K's meaning that the data from each site are very scattered. The other important statistical variable used in paleomagnetism is the Alpha 95. This is the cone of 95% confidence about the calculated average. It is represented on a stereonet by a circle which has a radius equal to the Alpha 95 and means there is a 95% probability of finding the calculated average within that circle. The smaller the Alpha 95, the tighter the cluster of points being averaged. The Alpha 95's from Table 1 are very large, meaning that the data is scattered. These statistics mean that a straightforward averaging of

Table 1: Example of site averages before careful separation of steep component from shallow directions.

Site	N	D(°)	I(°)	K	A95	Lithology
1	7	43.9	49.3	4.8	30.4	Regional foliation
2	11	33.1	48.3	13.2	13.0	Regional Foliation
3	11	257.7	35.6	11.0	14.3	Granite
4	9	218.8	14.2	2.9	36.3	Massive porphyry
5	10	265.6	65.6	2.6	37.5	Granite
6	5	356.1	66.6	3.7	46.0	Granite
7	15	245.0	10.3	2.6	29.2	Mylonitic Foliation
8	6	253.8	-13.7	6.5	15.9	Mylonitic Foliation
9	4	237.7	-42.4	5.1	44.8	Mylonitic foliation
10	8	247.6	-8.4	1.9	54.8	Mylonitic Foliation
11	9	273.9	1.0	2.2	45.8	Mylonitic Foliation
12	6	0.3	47.5	8.1	24.9	Massive porphyry
13	8	46.3	71.5	3.2	36.2	Massive Porphyry
14	6	0.7	79.4	18.2	16.0	Regional Foliation
15	5	57.3	55.9	18.3	18.3	Massive Porphyry
16	10	309.7	57.3	3.0	33.5	Massive porphyry
17	6	347.6	77.1	3.3	43.5	Massive Porphyry
18	5	159.0	77.8	8.7	27.3	Massive Porphyry
19	8	200.4	-15.6	3.1	37.1	Massive Porphyry
20	6	5.4	-7.1	1.4	93.4	Massive Porphyry
21	2	275.7	35.7	---	----	Mylonitic Foliation
22	10	340.0	84.9	3.1	32.8	Mylonitic Foliation
23	12	196.1	64.7	1.4	61.2	Mylonitic Foliation
24	4	340.8	67.8	21.2	20.3	Mylonitic Foliation
25	6	23.3	61.0	13.2	19.1	Granite
26	8	327.2	71.3	15.7	14.3	Granite
27	12	50.1	72.2	10.2	14.2	Regional Foliation
28	9	334.2	61.1	5.9	23.0	Massive Porphyry
29	10	21.4	82.6	25.0	9.8	Regional Foliation
30	11	38.1	73.4	3.2	30.1	Massive Porphyry
KG1	3	209.3	-39.4	99.6	12.4	Dyke
KG2	4	99.4	72.7	11.6	28.1	Dyke
KDD5	6	11.5	75.5	4.1	75.5	Dyke
KDD6	4	38.1	18.3	1.8	99.3	Dyke
31	22	19.3	75.6	35.1	5.3	Hematite-Enriched
32	8	241.7	-5.2	11.1	17.3	Hematite-Enriched

N = number of specimens
D(°) = mean declination
I(°) = mean inclination
K = Fisher Kappa
A95 = Alpha 95

specimen directions cannot be used.

A large number of the specimens in Figure 2-14 that have shallow to intermediate, northeasterly and southwesterly directed remanences come from sites that are foliated and hematite-enriched. However, these sites also contain many specimens that carry steep, upwards pointing remanences (Fig. 2-16). As these steep directions form a tight cluster, an arbitrary cutoff point of +60° can be used to divide the population of steeply directed remanences from the shallow to intermediate remanence population. The steeply directed specimens result in an average direction with a Declination = 343.5° and an Inclination = 79.9° (N = 42, Fisher Kappa = 19.1, Alpha 95 = 5.1°).

The remaining foliated and hematite-enriched data, shown in Figure 2-17, are separated into two groups, one with predominantly upwards directed remanences in the northeastern quadrant, and the other with shallow upwards and intermediate downwards pointing remanences in the southwestern quadrant. As a difference was noted in the previous sections between the mylonitic and regionally foliated specimens, the two were separated and then averaged. Most of the regionally foliated and hematite-enriched specimen directions possess northeasterly remanence directions, whereas most of the mylonitic specimens have

Fig. 2-16: Stereonet illustrating stable end-point directions for the regionally and mylonitically foliated specimens and the hematite-enriched porphyry specimens. A steep downwards component is present, which is marked by the closed circle and its larger circle of 95% confidence. There is also a northeast-southwest trend to the rest of the data.

Foliated and Hematite-Enriched Specimen Directions

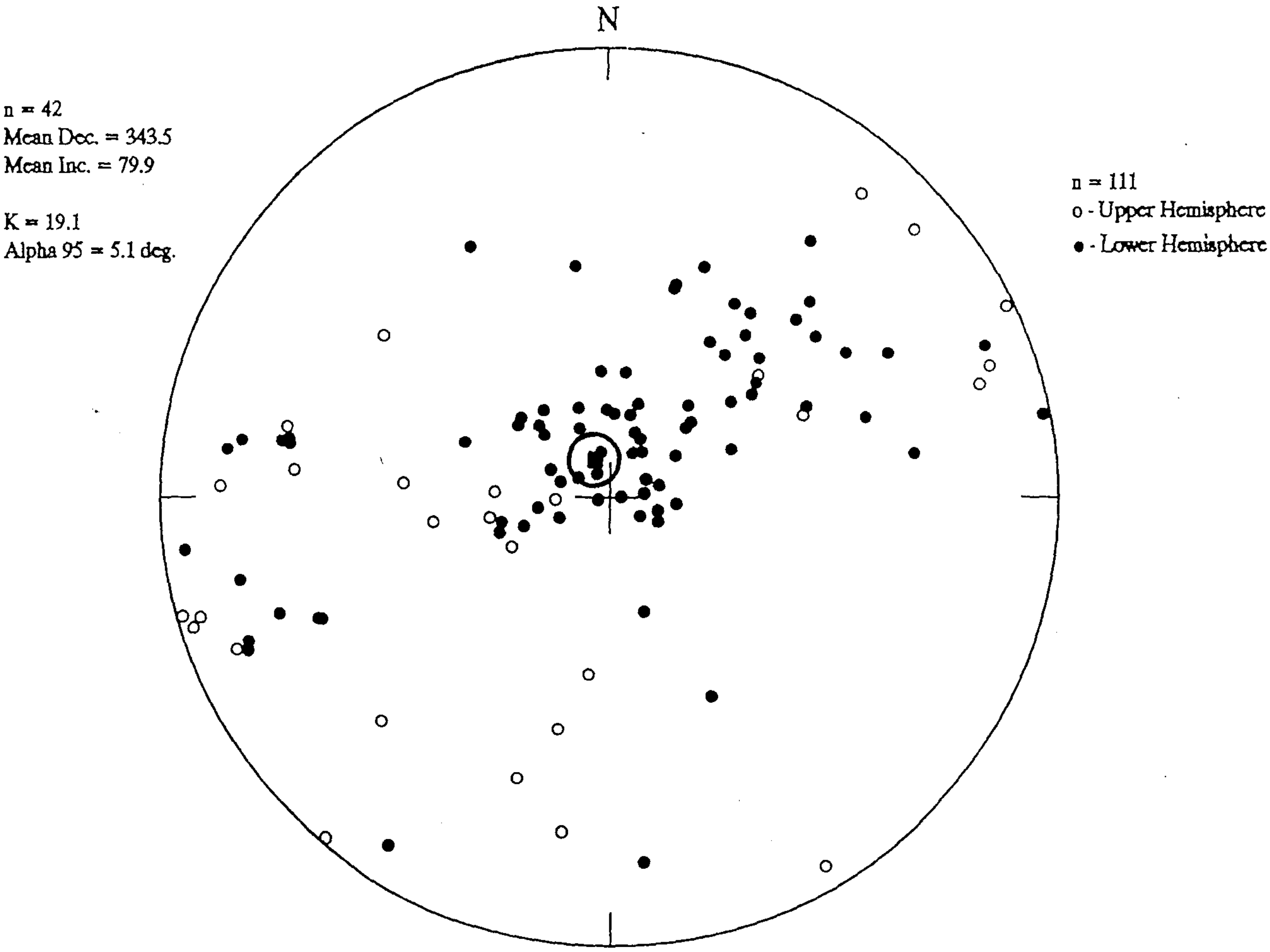
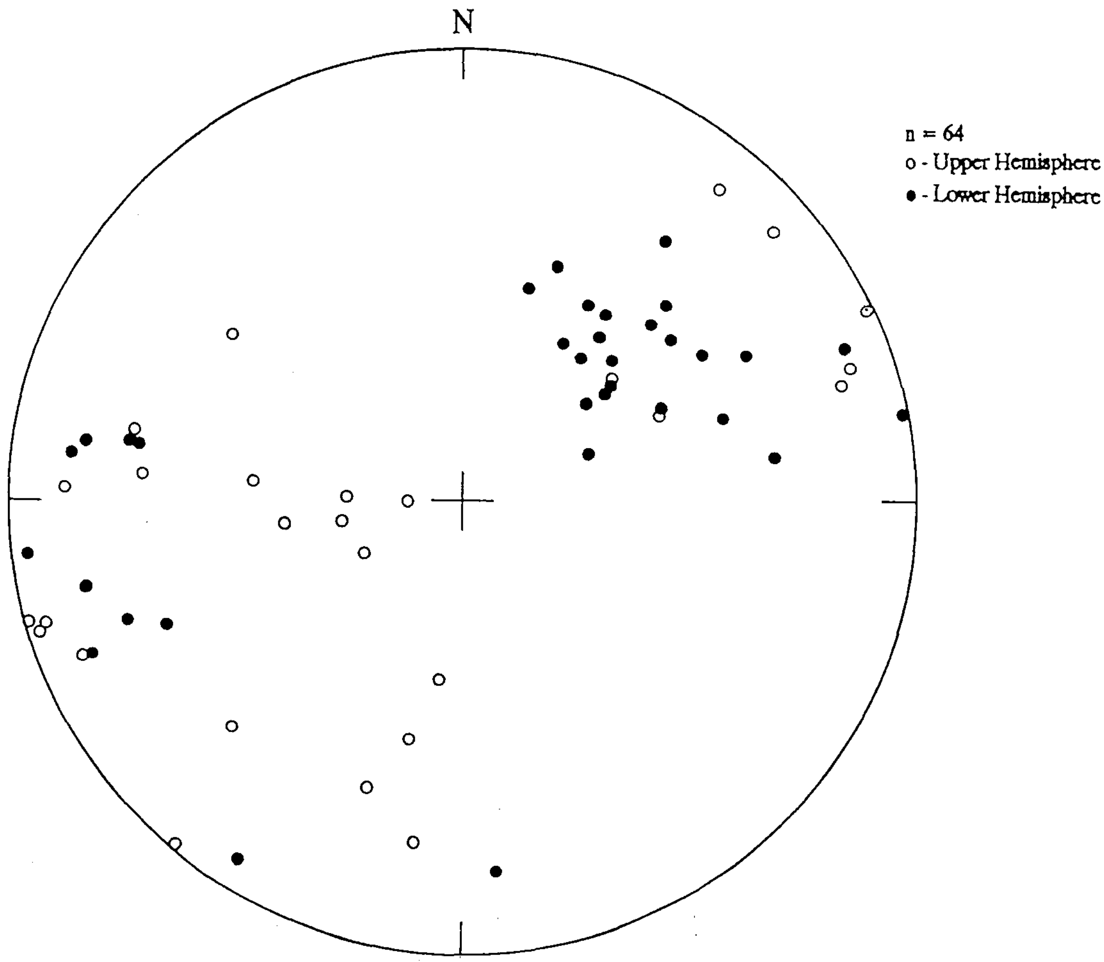


Fig. 2-17: Same as Fig. 2-16, but without the steep downwards component. It better illustrates the northeast-southwest trend.

Foliated and Hematite-Enriched Specimen Directions



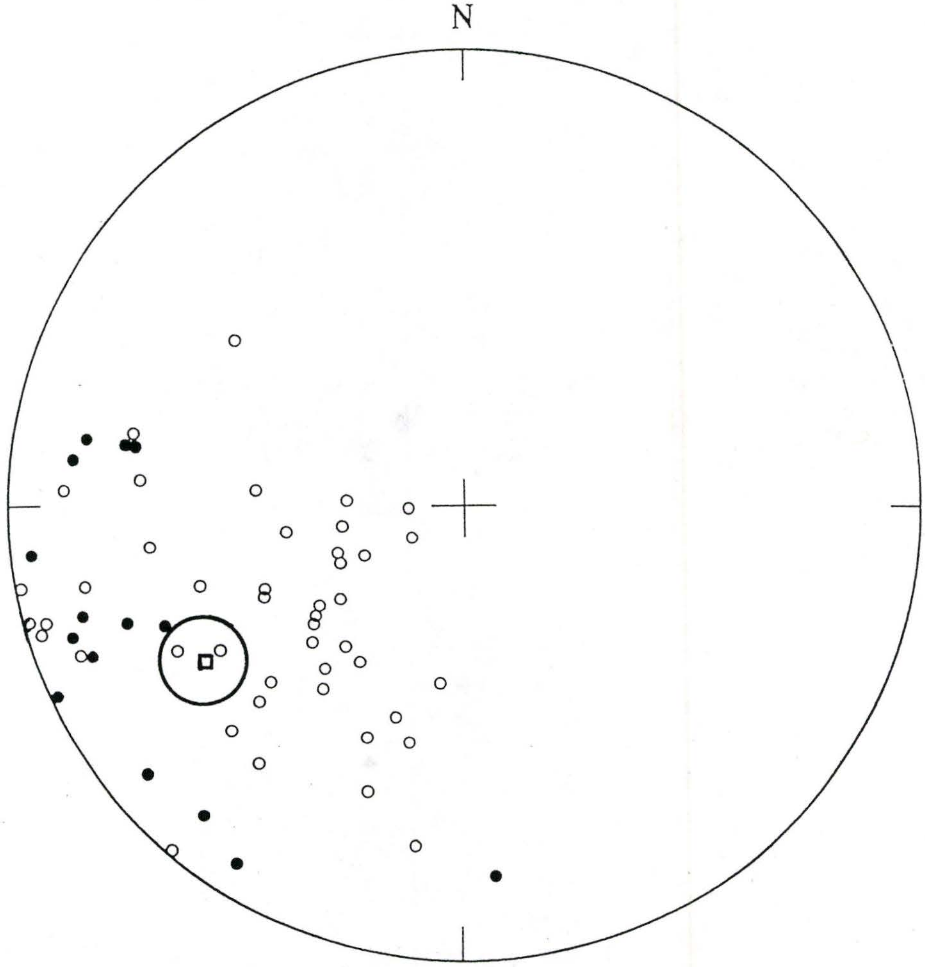
directions in the southwest. The site averages for each group have D = 53.6° (236.6°), I = 28.3° (-28.3°) with N = 4, K = 18.8 and Alpha 95 = 21.7° (regional), and D = 247.3° (67.3°), I = -25.1° (25.1°) with N = 7, K = 17.1 and Alpha 95 = 15° (mylonitic). When the northeasterly directed remanences are reversed (Fig. 2-18a), it results in a more Fisherian distribution of the southwesterly combined population. In this manner, an average direction with a mean Declination = 241.5° and a mean Inclination = -22.7° was calculated (N = 63, Fisher Kappa = 5.1, Alpha 95 = 8.7°). Table 2 illustrates partial site averages for the foliated and hematite-enriched sites, as well as a site average and paleopole. The partial site averages are calculated without the specimens that were separated out by the cutoff of +60°. This produces a two-tiered statistical average direction with a Declination = 242.2° and an Inclination = -27.1° (N = 11, Fisher Kappa = 16.7, Alpha 95 = 11.4°). These site directions, with their average, are illustrated in Figure 2-18b.

Remagnetization circles were also obtained from specimens from the same sites to complement the stable end-point data. In total, 33 of these circles were used and these can be seen in Figure 2-19a. Bailey & Halls (1984) computer program was used to resolve the intersection direction, which is also illustrated in Figure 2-19a. A

Fig. 2-18: Two stereonets illustrating the specimen directions when the northeasterly trending ones are reversed to provide a more Fisherian distribution. (a) Stereonet of the individual specimen directions. A fairly good grouping has a mean direction represented by the open circle and its larger circle of 95% confidence.

Foliated and Hematite-Enriched Specimen Directions

(a)



Mean Dec. = 239.9
Mean Inc. = -22.6

K = 5.8
Alpha 95 = 8.0 deg.

Table 2: Site-mean directions after thermal or AF cleaning of foliated and hematite-enriched sites.

Site	N	D(°)	I(°)	K	A95
1	4	239.3	-29.8	5.7	41.8
2	8	214.9	-38.2	37.6	9.1
7	10	234.8	-0.6	7.0	19.4
8	6	253.8	-13.7	6.5	28.2
9	4	237.7	-42.4	5.1	44.8
10	6	255.6	-18.6	3.0	46.1
11	6	263.4	-30.3	6.1	29.4
22	2	260.4	-41.3	---	----
23	7	227.0	-24.6	5.8	27.1
27	3	235.3	-38.1	21.0	27.5
KG3	8	241.7	-5.2	11.1	17.3
Sample mean	64	239.9	-22.6	5.8	8.0
Site mean	11	242.4	-26.4	17.5	11.2

N = number of specimens used in average
D(°) = mean declination
I(°) = mean inclination
K = Fisher Kappa
A95 = Alpha 95

Fig. 2-18(b). Stereonet illustrating the 11 site means. The open circle and its larger circle of 95% confidence represents the mean of these sites.

Foliated Site Means

(b)

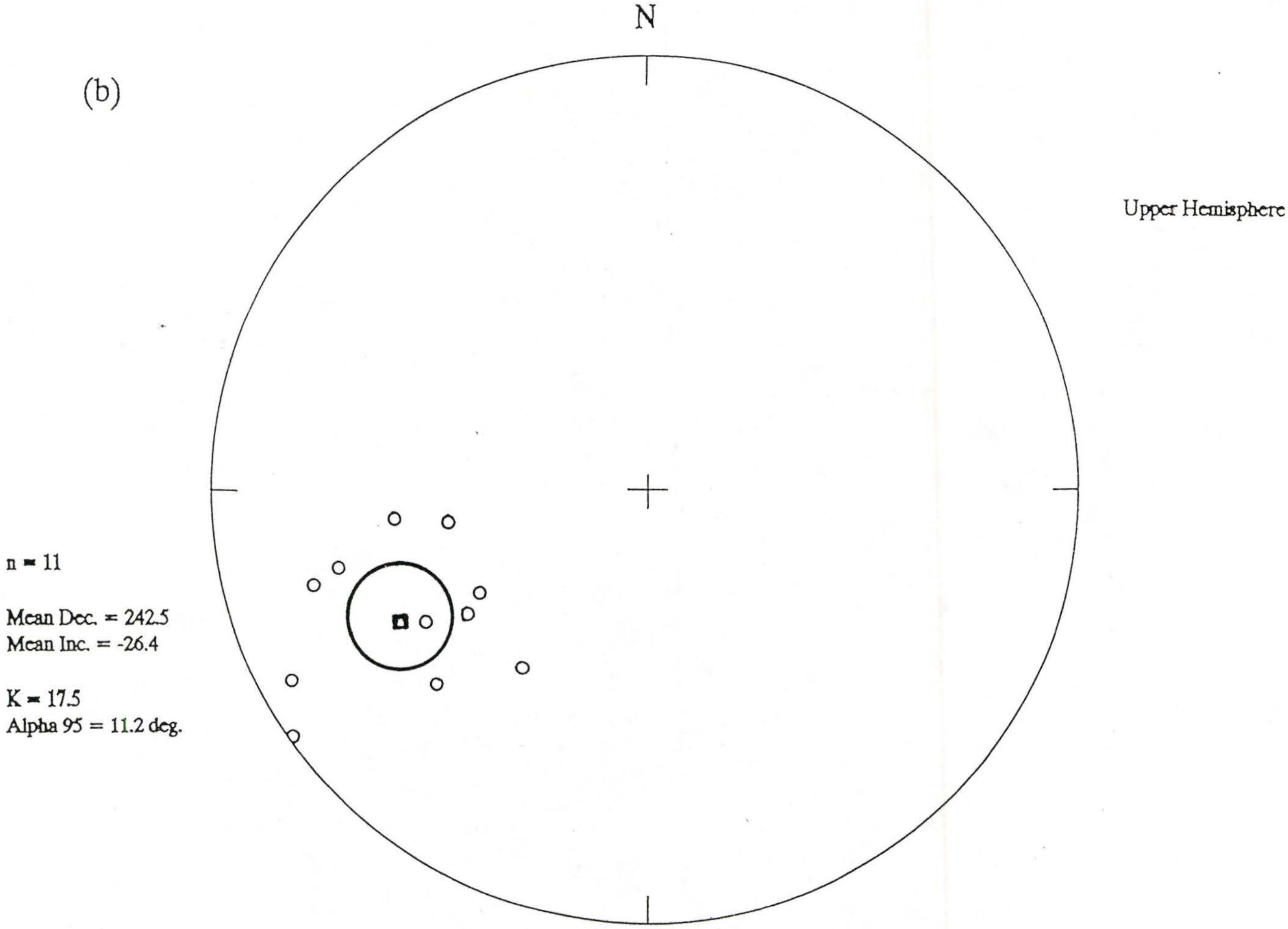
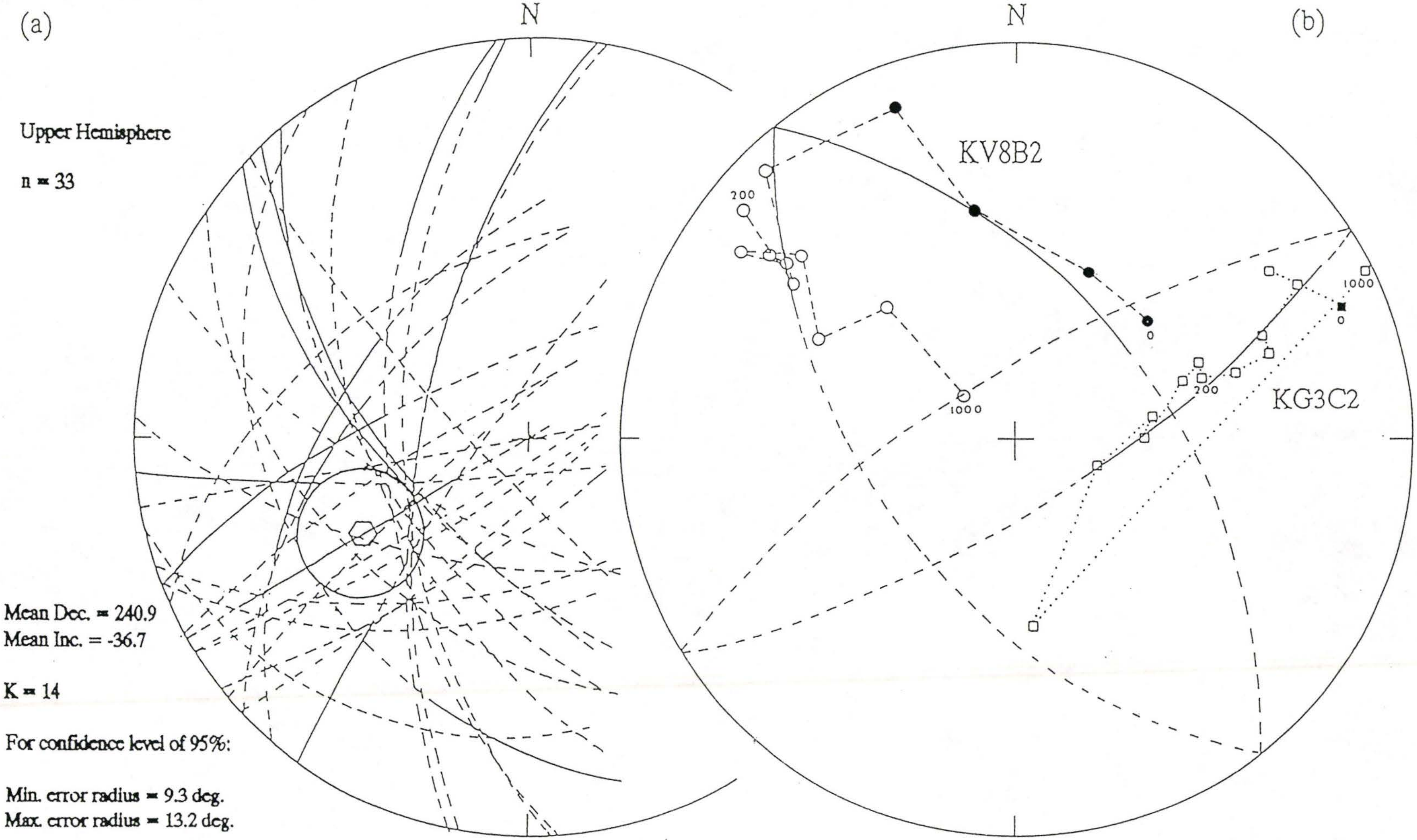


Fig. 2-19: Typical remagnetization circles from foliated and hematite-enriched specimens. (a) Upper hemisphere projection of remagnetization circles. Both AF and thermal demagnetizations are represented. Intersection and minimum and maximum error radii are represented by the open hexagon and ellipse respectively. (b) Polar plot illustrating great circle fit to data for two specimens.

Intersection of Remagnetization Circles

Foliated and Hematite-Enriched Sites

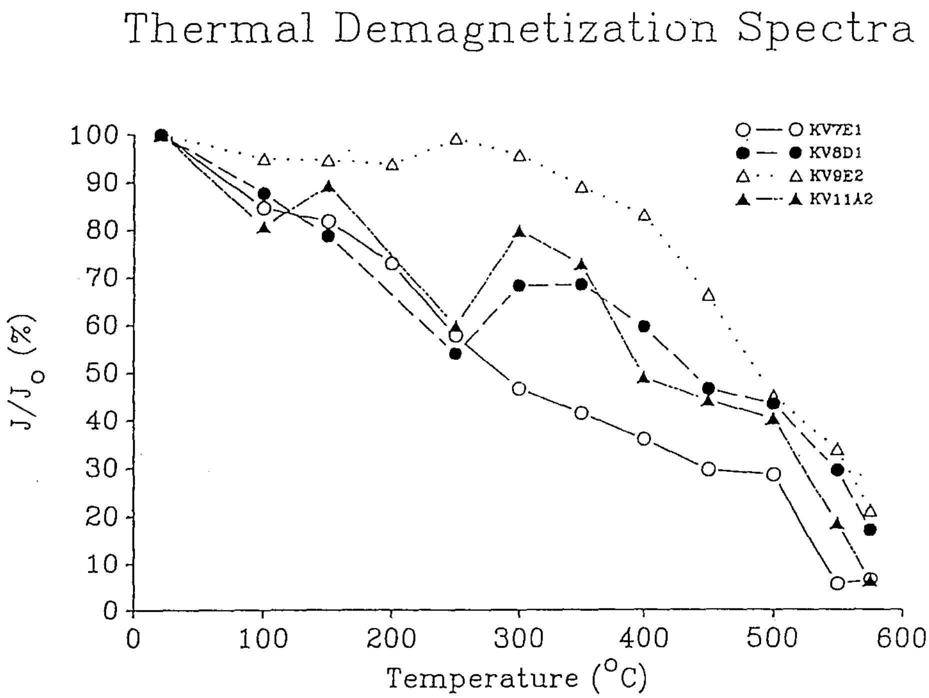


Declination of 240.9° and an Inclination of -36.7° was obtained, with N = 33, Fisher Kappa = 14 and minimum and maximum error radii of 9.3° and 13.2° respectively for a 95% confidence level. This direction supports the stable end-point average, as the two directions are not significantly different from each other. Figure 2-19b illustrates the actual data used to determine the remagnetization circles, with the best fit great circle drawn in. The computer program (Bailey & Halls, *op cit*) was also used to determine the best fit for each specimen, which were used as long as the angular standard deviation calculated within the program was less than 5°.

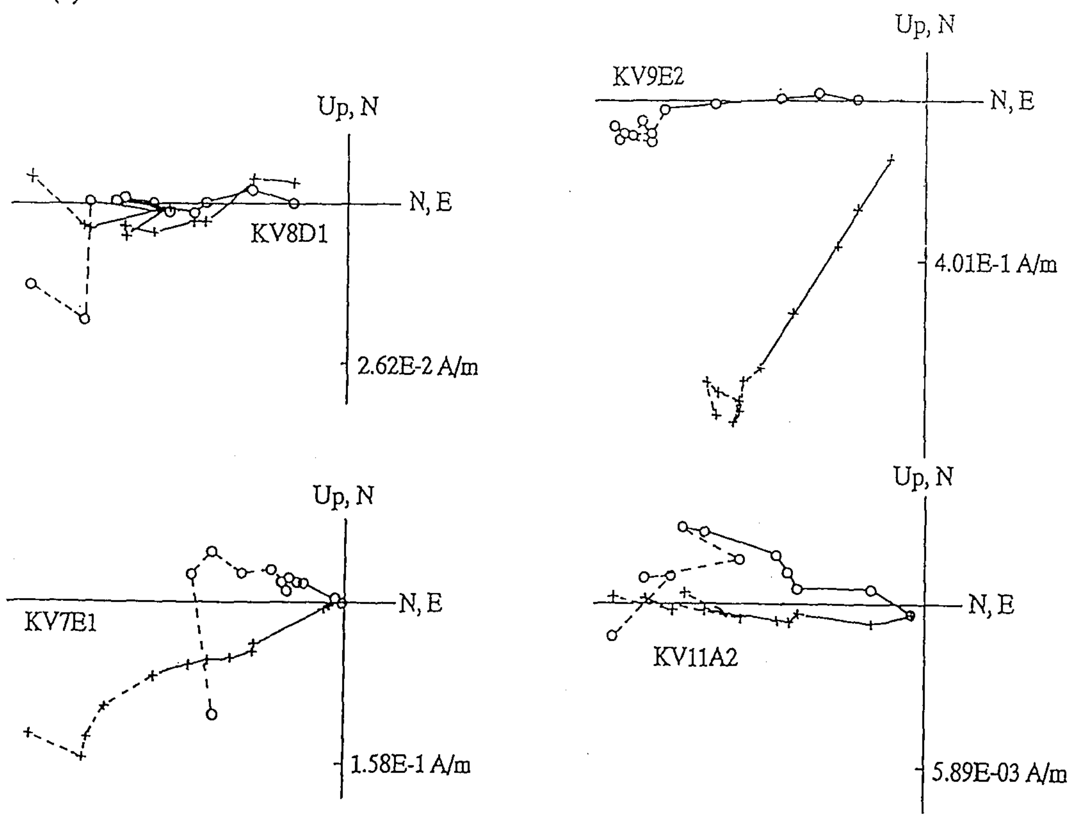
Thermal data from the mylonitically foliated sites are illustrated in Figures 2-20a&b. The demagnetization curves for specimens from sites 7, 8, 9 and 11 (Fig. 2-20a) show that the remanences demagnetize steadily, exhibiting a wide spectrum of blocking temperatures. Figure 2-20b illustrates the orthogonal vector plots for the same specimens. A line is drawn through the points to approximate the best fit. All of these examples resolve into westerly declinations with shallow negative inclinations. The stable remanence direction is determined by the interval over which the data approximates a linear segment. The principle component analysis (Kirschvink, 1980) was used to resolve the directions from these segments.

Fig. 2-20: Behaviour of foliated specimens during thermal demagnetization. (a) Demagnetization plot showing percentage of remanence after stepwise thermal cleaning. Note the wide blocking temperature spectra. (b) Orthogonal vector plots. Open circles denote points on the vertical-plane projection, while crosses denote horizontal-plane projection. The southwesterly declinations with shallow to intermediate inclinations given by some of the foliated specimens are resolved in all the plots.

(a)


Thermal Demagnetization Spectra
J/J$_o$ (%)
Temperature (^{o}C)
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
KV7E1
KV8D1
KV9E2
KV11A2

(b)

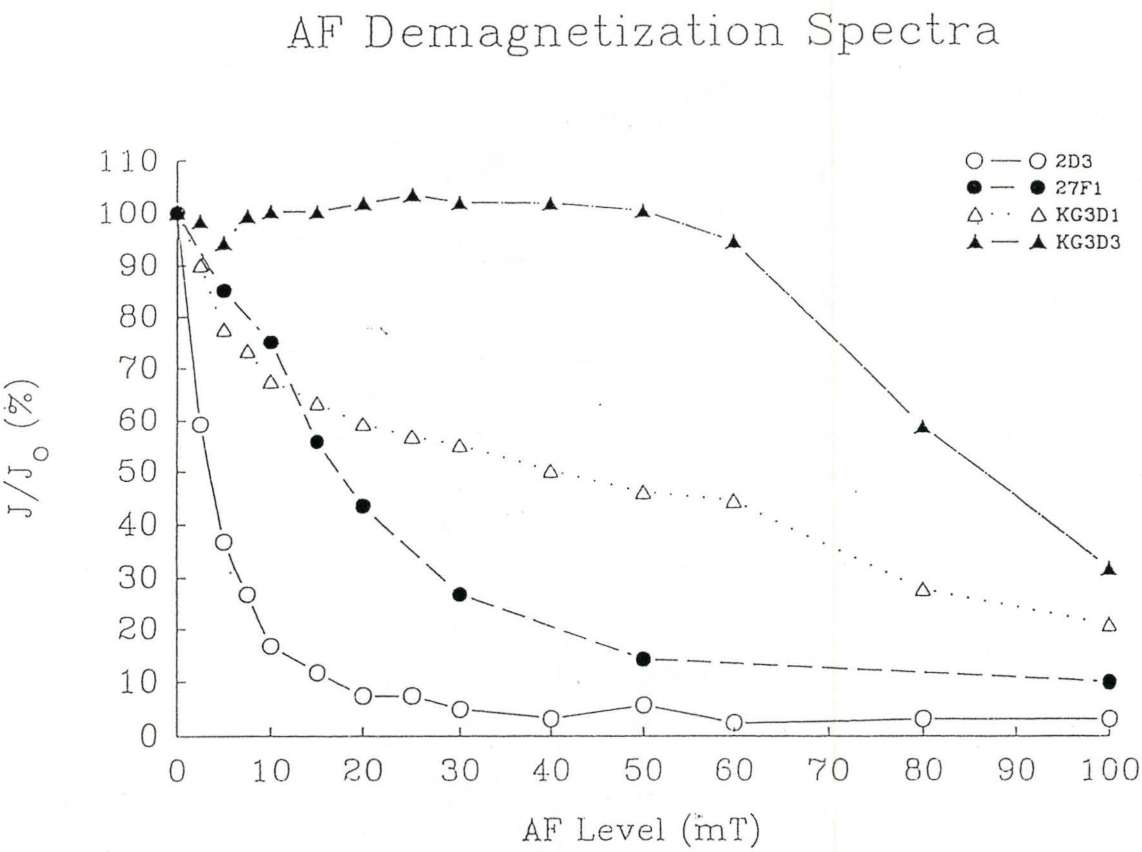

Up, N
N, E
KV8D1
2.62E-2 A/m
Up, N
KV9E2
N, E
4.01E-1 A/m
Up, N
N, E
KV7E1
1.58E-1 A/m
Up, N
N, E
KV11A2
5.89E-03 A/m

The quality of directional data from AF demagnetizations are illustrated in Figures 2-21a&b. These specimens are from regionally foliated and hematite-enriched sites, including KV2D3, KV27F1, KG3D1 and KG3D3. Figure 2-21a shows the demagnetization behaviour of these specimens. Specimen 2D3 demagnetizes rapidly, 27F1 is slightly more resistant to demagnetization, KG3D1 demagnetizes steadily, while specimen KG3D3 does not begin to demagnetize until about 60mT. All these specimens produce typical orthogonal vector plots, as illustrated in Figure 2-21b, which resolve vectors with intermediate to shallow positive inclinations and northeasterly directed declinations.

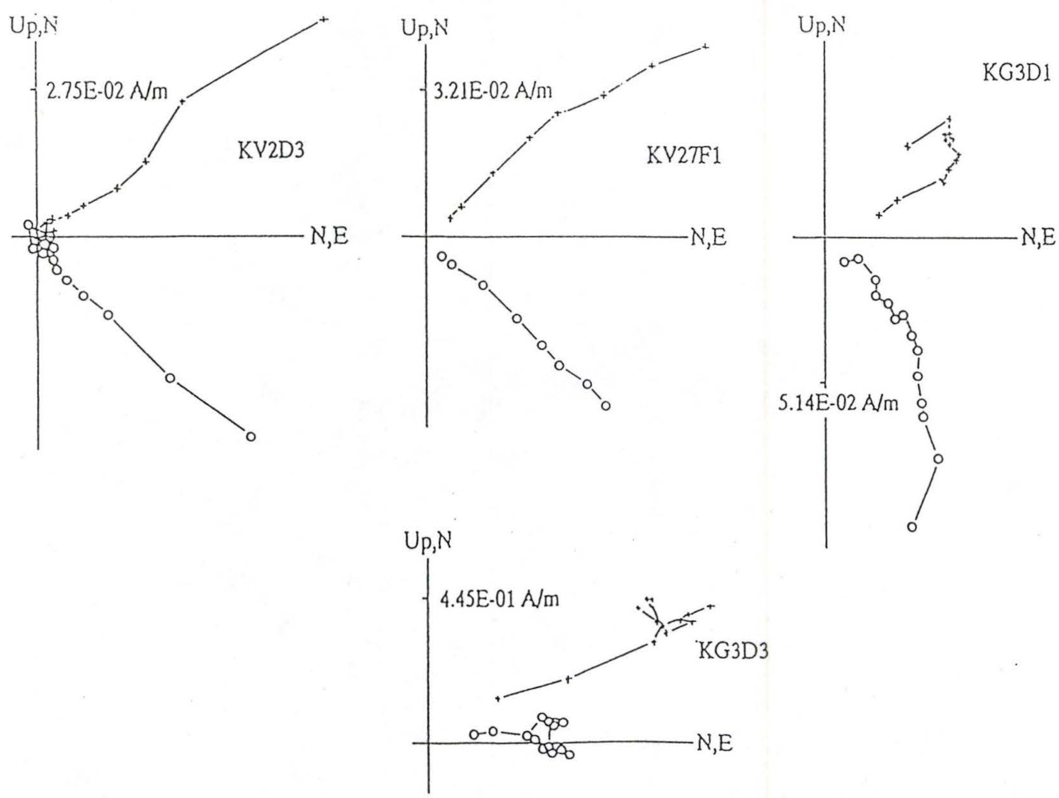
The remanence types described so far comprise about a third (105/284) of the stable directions. The majority of the remaining specimens with intermediate to shallow positive inclinations have westerly declinations. A large number of these come from granitic samples. However, again, these sites include a number of specimens that have steep positive inclinations. The problem with this group of directions is that the very steep positive directions cannot easily be separated from the shallower positive directions. When no directions are separated from the granite population, it results in a Declination = 280.8° and an Inclination = 67.9° (N = 39, K = 4.8 and Alpha 95 = 11.7°) from individual specimens and a Declination = 298.5° and an

Fig. 2-21: Behaviour of foliated and hematite-enriched specimens during AF demagnetization. (a) Demagnetization plot showing percentage of remanence after stepwise AF cleaning. Note the variability in coercivities. (b) Orthogonal vector plots. Symbols as for Fig. 2-20b. The northeasterly declinations with shallow to intermediate inclinations given by some of the foliated and hematite-enriched specimens are resolved in all the plots.

(a)


AF Demagnetization Spectra
J/J$_o$ (%)
AF Level (mT)
2D3
27F1
KG3D1
KG3D3
0
10
20
30
40
50
60
70
80
90
100
110

(b)


Up,N
2.75E-02 A/m
KV2D3
N,E
Up,N
3.21E-02 A/m
KV27F1
N,E
Up,N
KG3D1
N,E
5.14E-02 A/m
Up,N
4.45E-01 A/m
KG3D3
N,E

Inclination = 72.5° (N = 5, K = 10.1 and Alpha 95 = 25.2°) from the site averages.

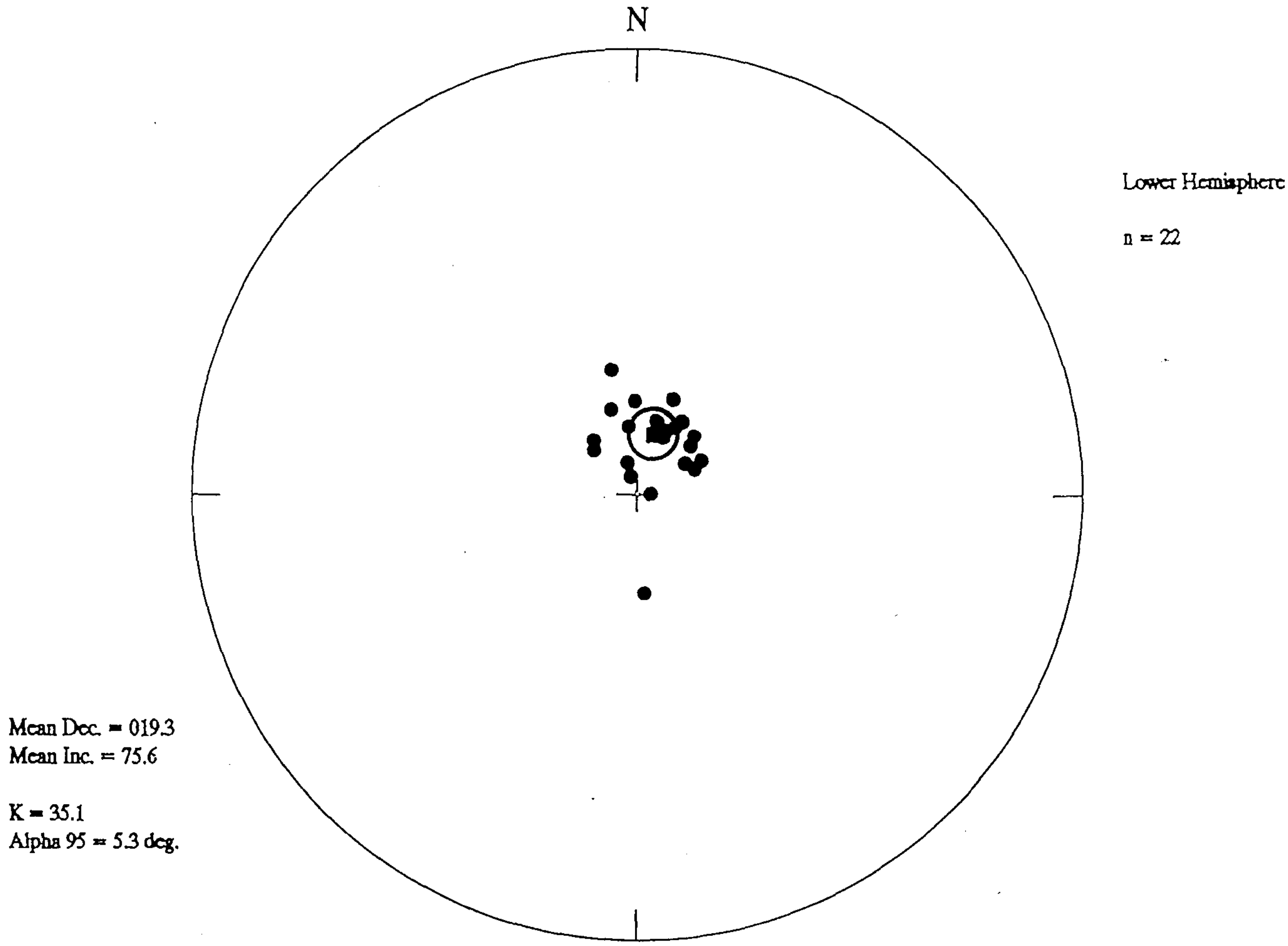
The dykes provide the only other samples that carry directions that are shallow. These also have numerous specimens with steep, positive directions that cannot be easily removed. These specimens give average directions with a mean Declination = 49.8° and a mean Inclination = 62.6° (N = 18, K = 4.9 and Alpha 95 = 17.2°) for all the specimens and a Declination = 50.7° and an Inclination = 54.1° (N = 5, K = 9.3 and Alpha 95 = 26.1°) for the site averages.

The hematite-enriched porphyry specimens averaged with the foliated sites come from one of the two field-cored sites. The other specimens all carry steep positive components (Fig. 2-22). Their average direction has a mean Declination = 19.3° and a mean Inclination = 75.6° with N = 22, K = 35.1 and Alpha 95 = 5.3°. This average direction is also shown in Figure 2-22.

The remaining lithology, the massive porphyry, is represented by about 90 specimens, half of which have inclinations of greater than 60°. These directions cannot easily be separated from the population carrying the shallower directions. The average direction for the massive porphyry calculated from site averages has a Declination = 13.5° and an Inclination = 67.3° (N = 12, K = 12 and Alpha 95 = 13°).

Fig. 2-22: Stereonet of stable end-point directions from the hematite-enriched specimens that produced steep remanence directions. Their mean direction and circle of 95% confidence are represented by the closed circle and larger open circle respectively.

Hematite-Enriched Specimen Directions



A summary table of all the average directions for the various lithologies can be found in Table 3. Figure 2-23 is the same stereonet as in Figure 2-14, but the mean directions from Table 3 are also illustrated.

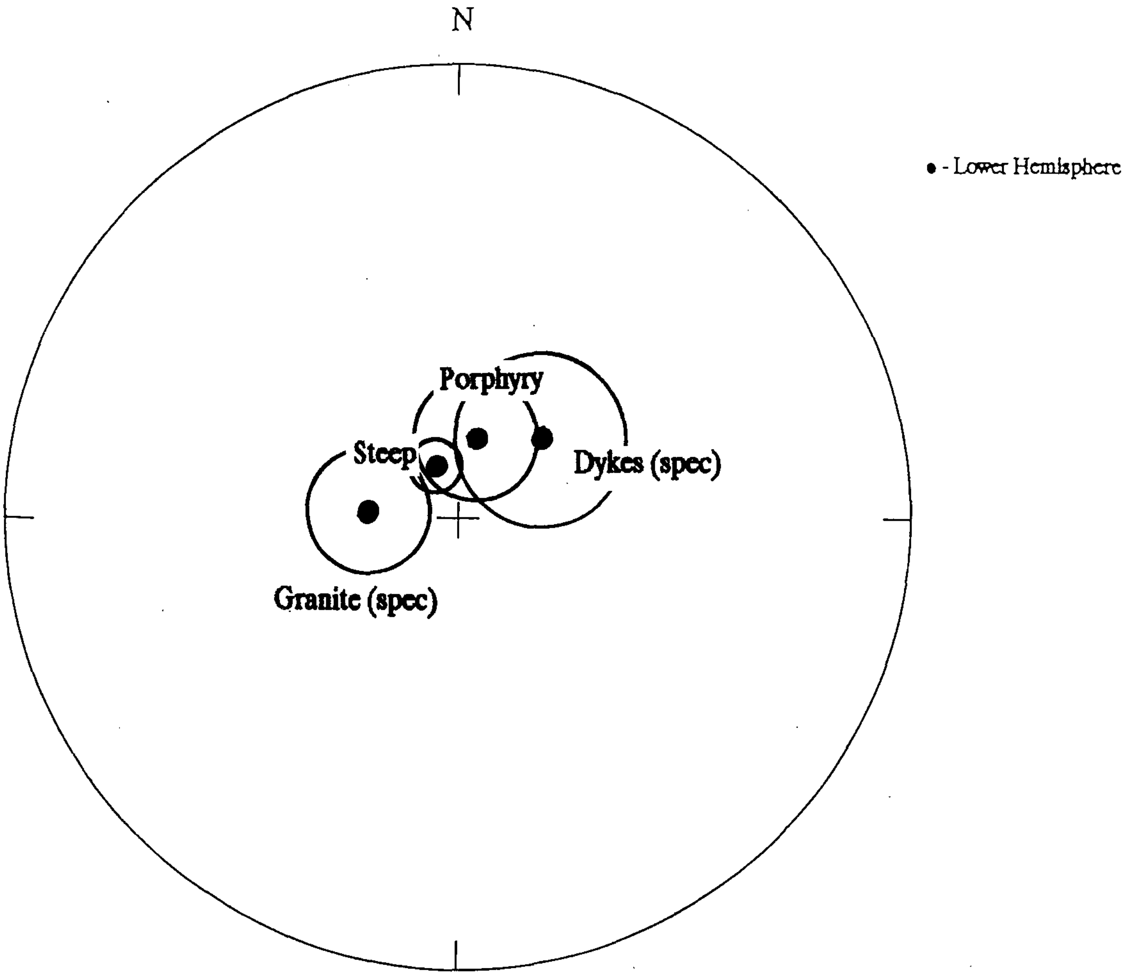
Table 3: Summary of averages for all lithologies

Lithology	N	D(°)	I(°)	K	A95
Reg. Fol. (site)	4	53.6	28.3	18.8	21.7
Myl. Fol. (site)	7	247.3	-25.1	17.1	15.0
Granite (spec)	39	280.8	67.9	4.8	11.7
Granite (site)	5	298.5	72.5	10.1	25.2
Dykes (spec)	18	49.8	62.6	4.9	17.2
Dykes (site)	5	50.7	54.1	9.3	26.1
Hematite	22	19.3	75.6	35.1	5.3
Porphyry	12	13.5	67.3	12.0	13.0
Fol. steep	42	343.5	79.9	19.1	5.1
Steep	193	346.4	77.2	5.0	5.0

Reg. Fol. = Regional Foliation
Myl. Fol. = Mylonitic Foliation
Hematite = Hematite-Enriched Porphyry
Porphyry = Massive Porphyry
Fol. Steep = Steep component from Foliated Porphyry
Steep = Steep component from all specimens
site = average using site averages
spec = average using individual specimens
N = Number of sites or specimens used for average
D(°) = mean declination
I(°) = mean inclination
K = Fisher Kappa
A95 = Alpha 95

Fig. 2-23: Same as Fig. 2-1, but means of all lithologies are represented by the various symbols.

Killarney Igneous Complex Specimen Directions



Chapter 3: PETROGRAPHIC DESCRIPTIONS

Methods

Thin-sections, both polished and regular, were made from specimens representing the granite, the porphyry, the foliated porphyry, the hematite-enriched porphyry and the dykes. The slides were analyzed for mineralogy, both transluscent minerals and opaques, the effects of deformation, including the effects of any hydrothermal alteration and finally, to determine the paragenesis of the samples to attempt to relate the history of deformation to the remanences recovered by the paleomagnetic experiments.

The representative thin-sections for each lithology were chosen because of their location in the complex and because macroscopically they appeared to best represent the respective lithologies. The slides are intended to illustrate the variability in texture and deformation throughout the complex.

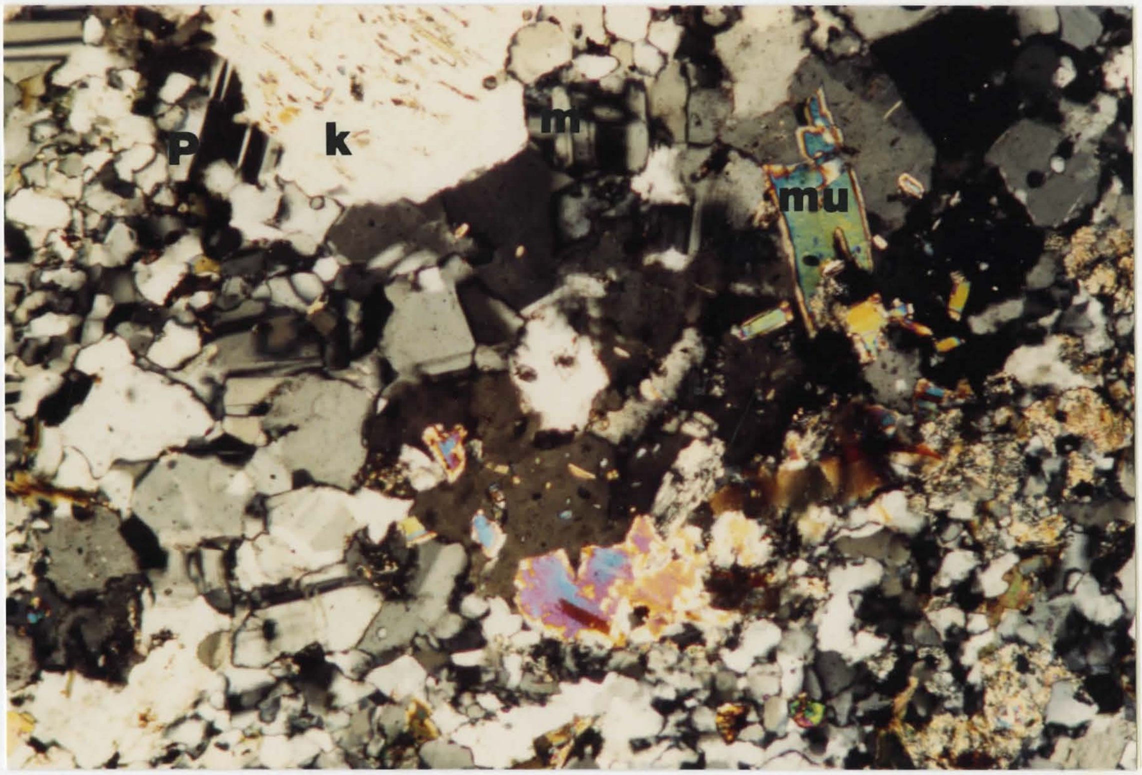
Granite

Representative thin-sections of the granite are taken from samples from sites 5 and 25 (See Fig. 1-1). Both specimens from the granite consist mainly of microcline, orthoclase, plagioclase, quartz and varying amounts of biotite, muscovite, chlorite and hornblende. Accessory minerals include calcite, allanite, opaques, sphene and zircon. However, the two specimens differ texturally.

Figure 3-1 show specimen KV25C4, representing site 25, which is very close to the contact with the Huronian sediments. The microcline and orthoclase are anhedral and usually found as phenocrysts. They range in size up to 0.7 mm, giving the rock a subporphyritic texture. The alkali feldspars are variably sericitized, with some of the orthoclase exhibiting a perthitic, as well as a poikilitic, texture. These orthoclase grains enclose usually randomly oriented lathes of muscovite. The plagioclase is typically oligoclase, with a few grains forming phenocrysts that also poikilitically enclose muscovite. However, the majority of the oligoclase forms anherdral grains usually less than 0.2 mm in size. These are slightly saussuritized.

The groundmass is composed of quartz, biotite, hornblende, muscovite and opaques, with minor amounts of allanite, sphene and zircon. The quartz grains are anhedral

Fig. 3-1: Subporphyritic and poikilitic texture in the granite. Illustrates muscovite lathes within k-feldspar phenocrysts (K) and variable grain size of matrix. Also shows plagioclase (P), microcline (M) and muscovite (mu). Specimen KV25A2. Field of view 1.0 by 1.5 mm.


p
k
m
mu

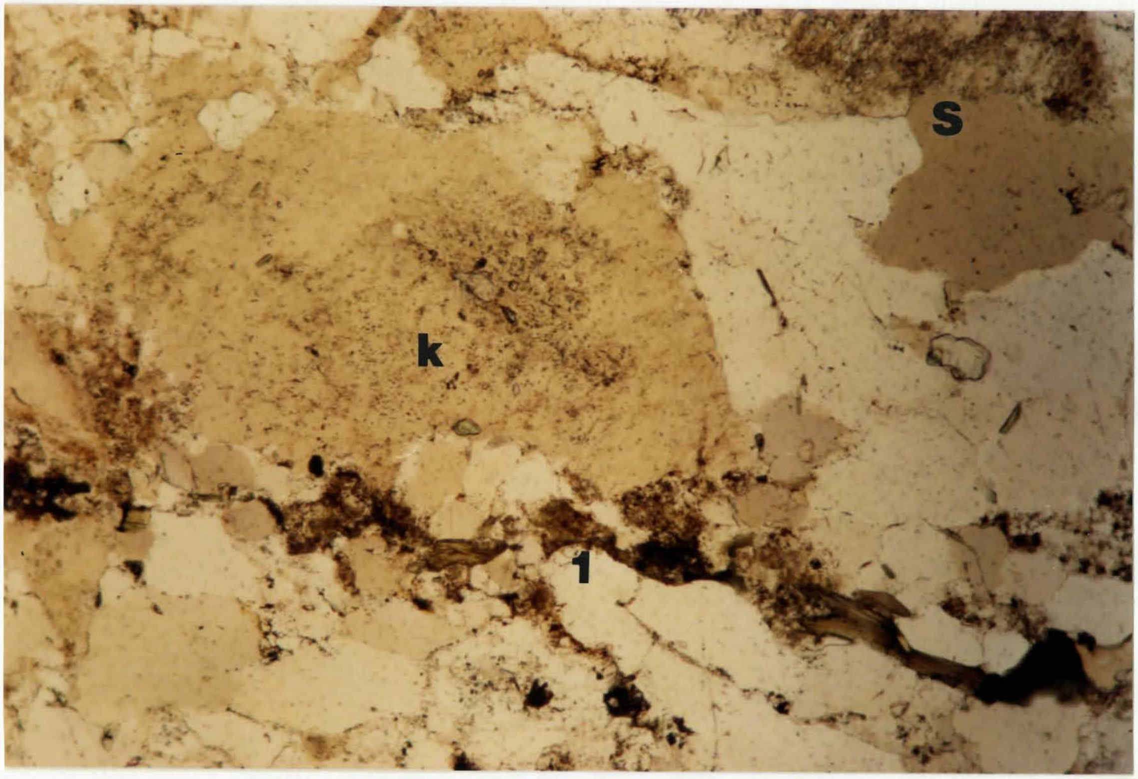
and are less than 0.1 mm in size. They show no evidence of deformation, displaying uniform extinction. Biotite is interspersed with the hornblende, muscovite and opaques. No preferred orientation of the phyllosilicates is apparent. The intensity of sericitization in the alkali feldspars appears to be greater around concentrations of mafics, which include the anhedral to subhedral opaque grains.

In contrast, specimen KV5C4 from site 5, which is close to the granite-porphyry contact, is much coarser-grained (Fig. 3-2). The perthitic microcline and orthoclase form phenocrysts up to 3 mm in size. These also poikilitically enclose randomly oriented lathes of muscovite. Plagioclase grains form a few phenocrysts, but it is more prevalent in the matrix as anhedral grains. All of the felspars are moderately altered.

Quartz is more common (35% versus 25%) and coarser-grained than in the specimen from site 25. The anhedral grains reach a size of 0.4 mm. A few of the larger grains exhibit undulatory extinction. The quartz, along with the plagioclase, is generally interstitial to the alkali feldspar phenocrysts. The plagioclase and quartz, however, usually do not intersperse.

The biotite lathes, up to 0.5 mm in length, are randomly oriented and are commonly partially or totally altered to chlorite. Allanite, sphene and zircon are usually

Fig.3-2: Coarser-grained granite. Porphyritic texture to k-feldspar is shown (K) as well as sericitization of feldspar grains (S). Fracture through granite with associated chlorite, muscovite and sericitization of feldspars is indicated by (1). Specimen KV5C4. Field of view 1.0 by 1.5 mm.


S
k
1

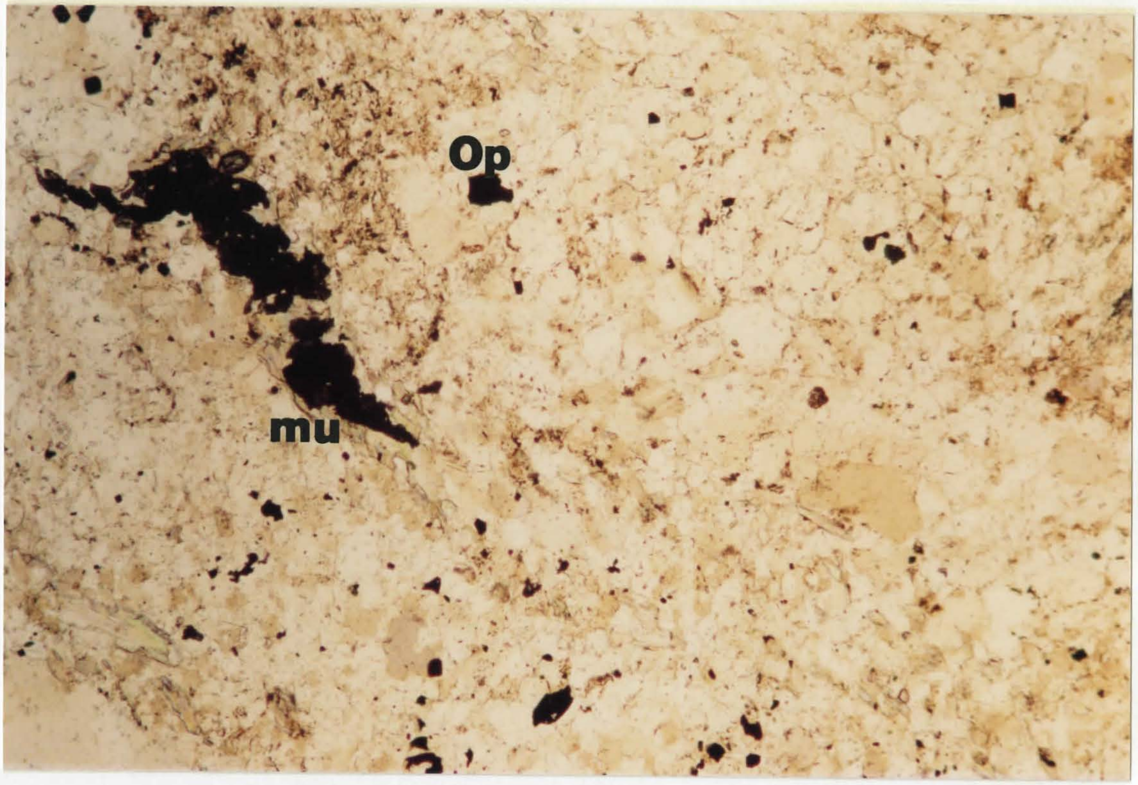
found in close proximity to the phyllosilicates, as well as any opaque grains that are visible. These opaques make up less than 2% of the slide.

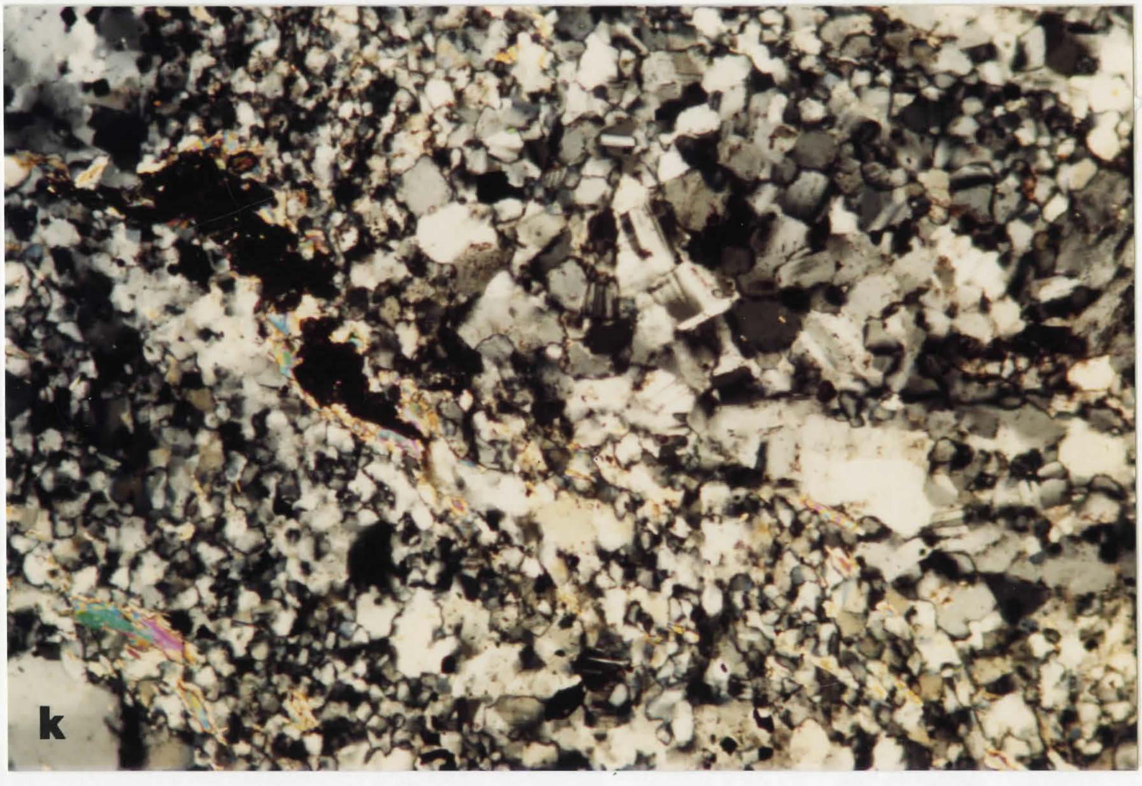
Massive Porphyry

Specimen KV16D1 from site 16 was chosen to represent the massive porphyry. Figures 3-3a&b illustrate the varying grain size of the porphyry. The phenocrysts consist mainly of perthitic orthoclase and a few grains of plagioclase. These grains range in size up to 2 mm and a few phenocrysts poikilitically enclose randomly oriented lathes of muscovite, as well as small grains of quartz, apatite, zircon, sphene and opaques. All of the feldspars are moderately sericitized. Quartz grains also form a few phenocrysts and exhibit undulose extinction. Some of the quartz phenocrysts consist of a few quartz grains clumped together producing a glomeroporphyritic texture.

The groundmass is generally composed of a mixture of anhedral grains of alkali feldspar, plagioclase, quartz and muscovite, with minor amounts of sphene, zircon, apatite and opaques. No preferred orientation is evident to the muscovite, although these grains tend to concentrate in elongated blobs, together with some opaques and sphene.

Fig. 3-3: Examples of massive porphyry. (a) Illustrates the increase in opaque material (Op) and association with muscovite (mu). (b) Shows fine-grained groundmass of muscovite, k-feldspar, plagioclase and quartz, as weel as a few phenocrysts (K). Specimen KV16D1. Field of view 1.0 by 1.5 mm.


Op
mu


k

Sericitization of the feldspars tends to increase in intensity close to the concentrations of muscovite and opaques. The muscovite also appears to fill fractures throughout the slide, which again is associated with an increase in sericitization of the feldspars. This suggests a link between the presence of muscovite, sericite and opaque material such as the influx of hydrothermal fluids depositing these minerals along the fractures in the porphyry. A notable feature of this slide is the increase in the amount of opaque material as compared with the examples of the granite. The granite is made up of less than 2% opaque material, whereas the porphyry contains closer to 8% opaques.

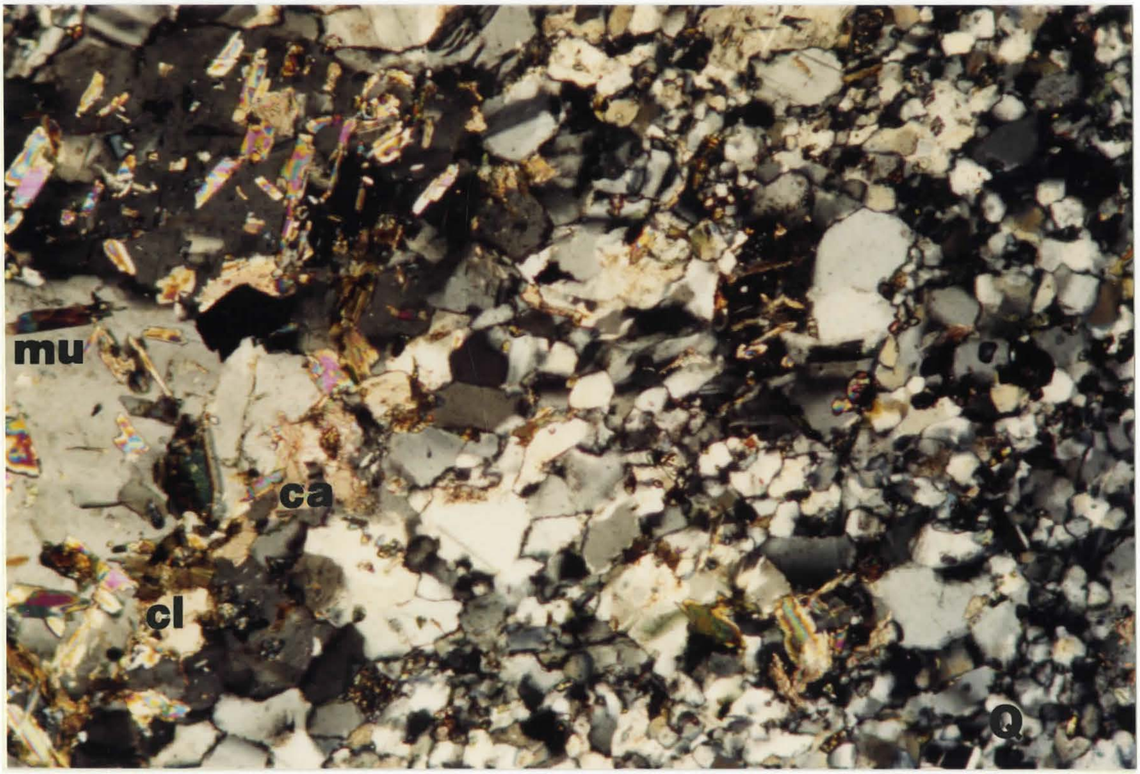
Foliated Porphyry

The mineralogy of the foliated porphyry is essentially the same as that of the massive porphyry. The examples chosen represent both the regional and mylonitic foliation trends, with the mylonitic samples taken within 2 km of the Grenville Front. Specimens representing sites 1, 7, 8 and 11 are illustrated in Figures 3-4 to 3-7. Sample KV1A1 from site 1, located just west of the Provincial Park along Highway 637, is foliated parallel to the east trending regional foliation, while the other three examples, specimens KV7A2, KV8A2 and KV11F2, are taken from the islands just west of the Grenville Front.

Specimen KV7A2 from site 7 (Fig. 3-4) still contains phenocrysts, but these are smaller, generally less than 2 mm in size, and fewer in number than in the massive porphyry. The phenocrysts also poikilitically enclose muscovite lathes, but these are somewhat larger than noted in the massive porphyry. The enclosed muscovite grains are aligned in a sub-parallel manner and it is interesting to note that the orientation of the lathes within the phenocrysts is not consistent throughout the slide. The variability to the orientation of the muscovite between k-feldspar grains is probably due to rotation of the k-feldspar grains during deformation. This suggests that either the muscovite formed as sub-parallel lathes during a period of deformation within the k-feldspar, or it was already aligned in a sub-parallel manner by the time it was enclosed by the k-feldspar grains. In either case, the feldspar grains were subsequently rotated to varying degrees during deformation. The overall size of the feldspars is smaller than in both the granite and massive porphyry, and the intensity of sericitization is low. Quartz is present only in the fine-grained groundmass.

Within the groundmass, both muscovite and biotite are aligned to produce the foliation. The biotite is altered slightly in places to chlorite. The phyllosilicates are aligned, producing chains of lathes, but the biotite and

Fig. 3-4: Subparallel alignment of muscovite lathes in k-feldspar phenocrysts (mu). Also shows fine-grained recrystallized quartz (Q) and association of calcite (ca) with chlorite (cl). Specimen KV7A2. Field of view 1.0 by 1.5 mm.


mu
ca
cl
Q

muscovite tend to generally form separate chains, ie: they are usually found exclusive of each other, although this is by no means a steadfast rule. The opaques, zircon, sphene and allanite seem to concentrate in the chains of biotite. Some of the opaques appear to form as the result of alteration of the biotite.

The foliated porphyry from site 11, represented by specimen KV11F2 (Fig. 3-5), differs only slightly mineralogically and texturally from specimen KV7A2. The only differences that occur are an increase in the intensity of sericitization of the feldspars and that the foliation is marked only by the parallel alignment of muscovite lathes because no biotite is present. There also appears to be a partial segregation of some of the minerals. Quartz forms ribbons which parallel bands of sericitized k-feldspar and unaltered plagioclase. Both sets of bands parallel the foliation exhibited by the muscovite. There is also a hint of alignment of the opaques parallel to the foliation.

A very notable difference in mineralogy and texture can be seen in specimen KV8A2 from site 8 (Fig. 3-6a,b&c). This section contains coarse grains of plagioclase and orthoclase (some perthitic) up to 4 mm in size. Many of the orthoclase grains show evidence of undulose extinction, while the plagioclase grains are commonly cracked and the albite twins bent. Some of the areas interstitial to the feldspar grains

Fig. 3-5: Illustrates parallel alignment of muscovite grains (mu). Fine-grained quartz (Q), plagioclase (P), biotite (B) and k-feldspar (K) are also shown. Specimen KV11F2. Field of view 1.0 by 1.5 mm.

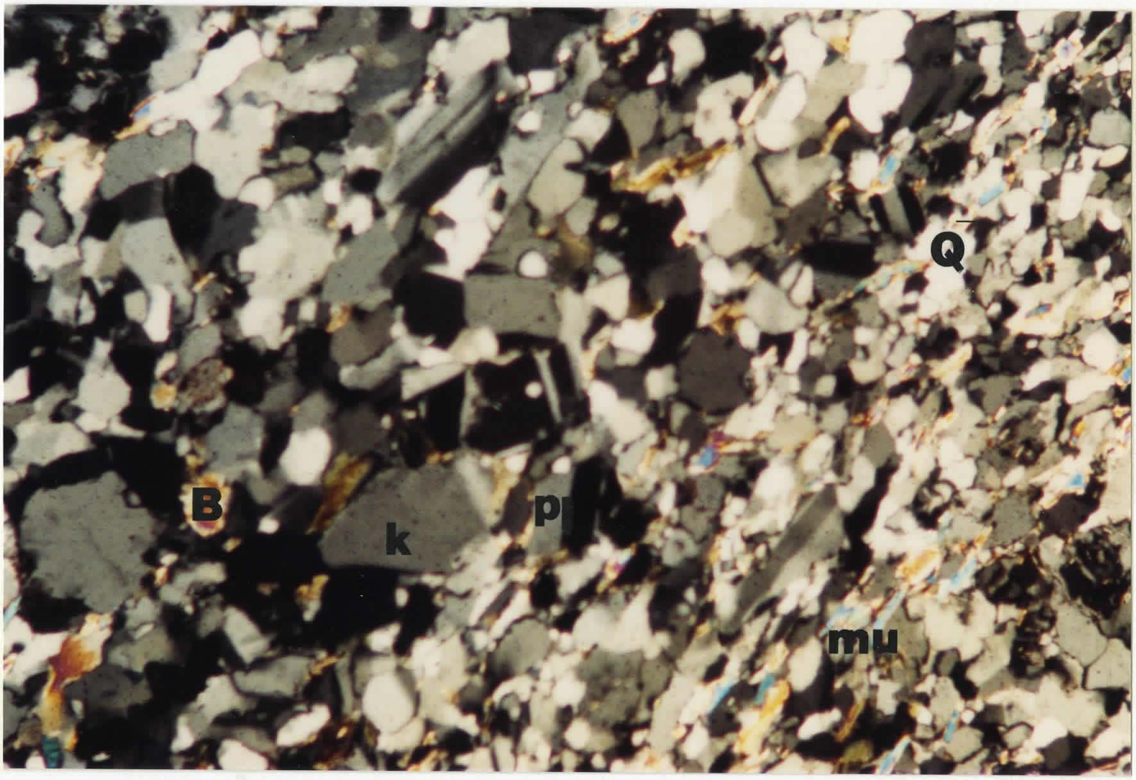
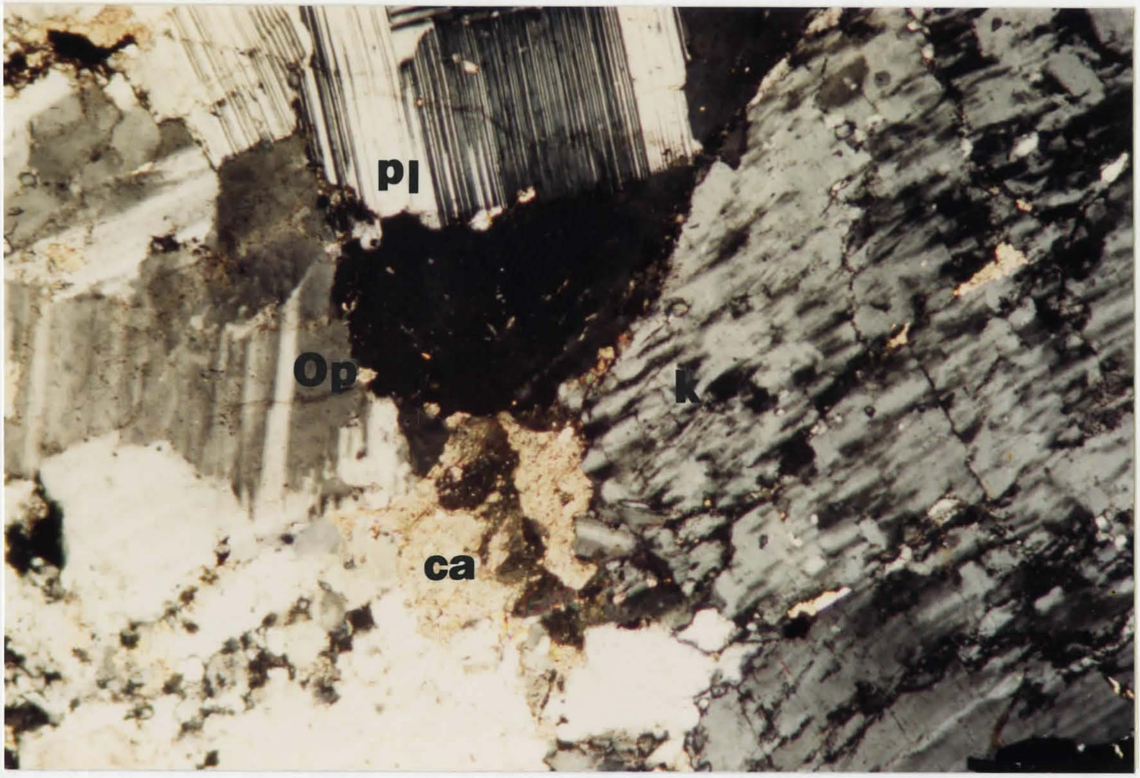

Q
B
k
pp
mu

Fig. 3-6: Example of hydrothermal alteration. (a) Illustrates opaques (Op) and calcite (ca) in the area interstitial to plagioclase (P) and cracked k-feldspar grains (K). (b) Sericite and minute opaque grains (S) along feldspar grain boundaries and cracks with interstitial calcite (ca). Specimen KV8A2. Field of view 1.0 by 1.5 mm.


pl
Op
k
ca

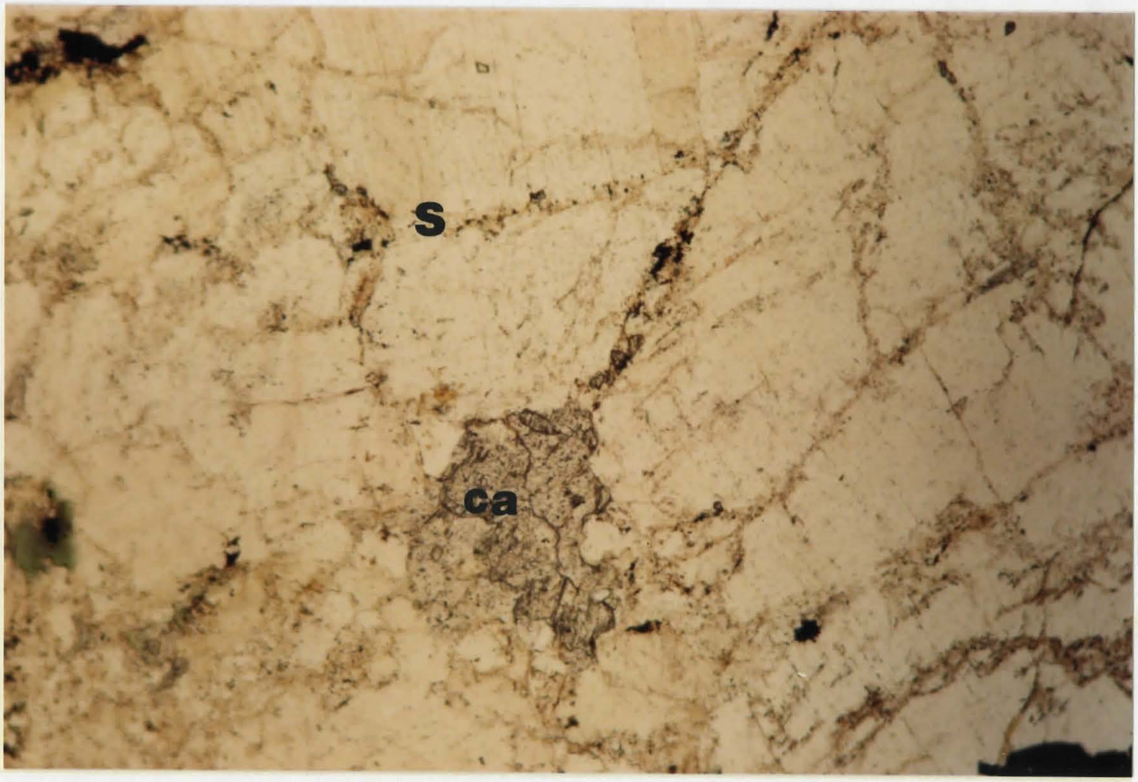
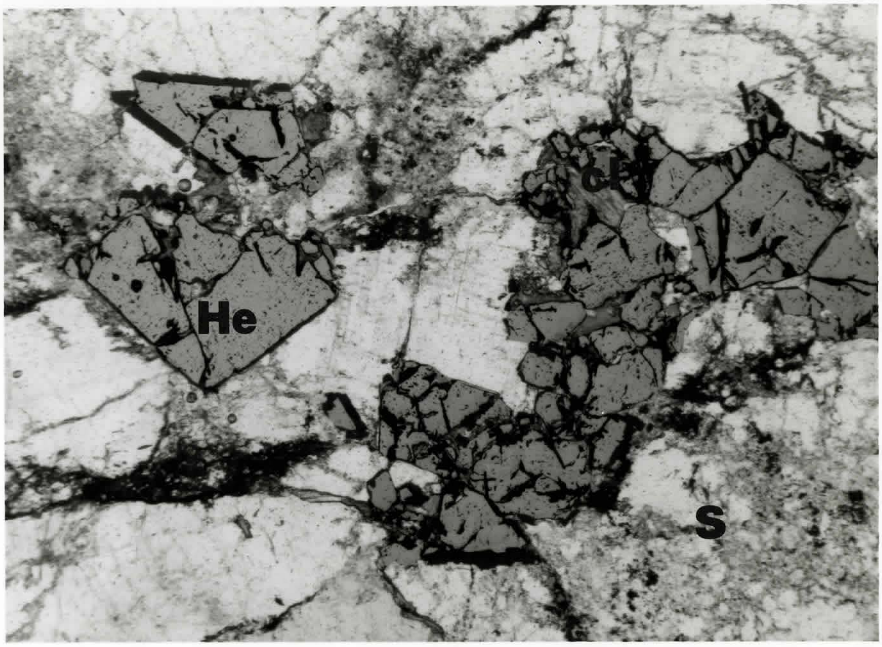

S
ca

Fig. 3-6 (c): Reflected and transmitted picture showing euhedral hematite grains (He) with chlorite (cl) and sericitization of feldspars (S). Specimen KV8A2. Field of view 2.0 by 2.7 mm.

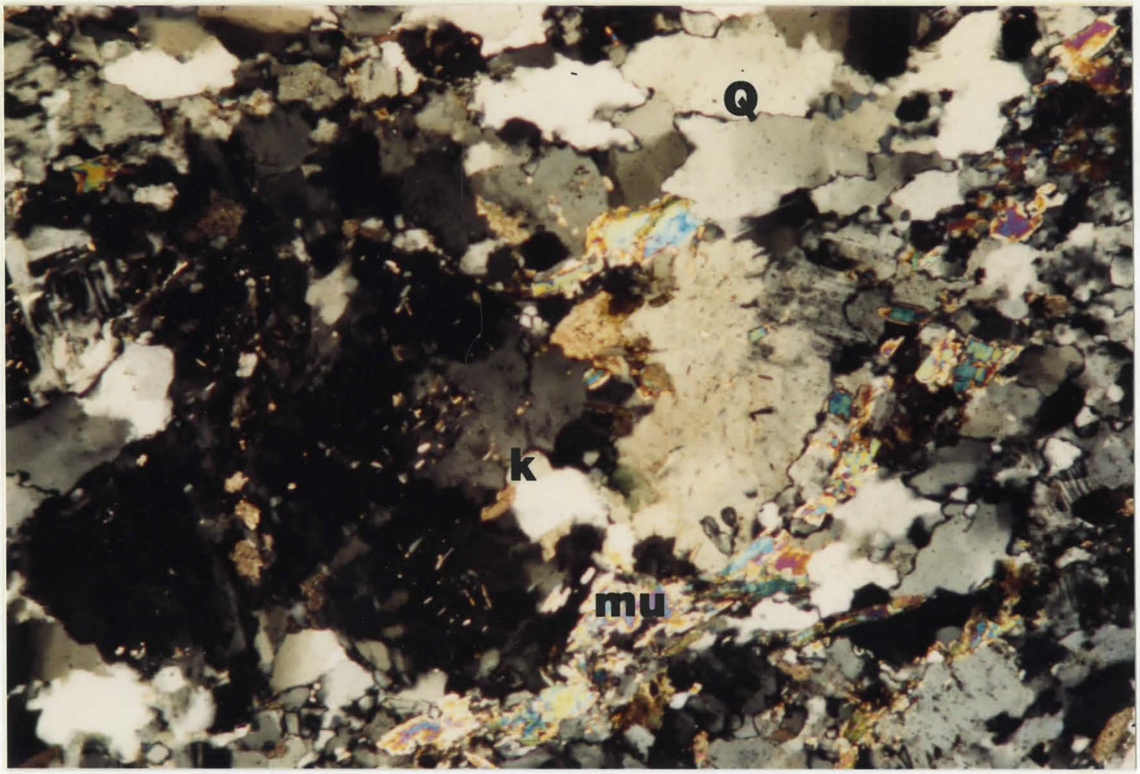

He
cl
S

are filled with finer-grained feldspars. These textures suggests an intense period of deformation that cracked and bent these feldspar grains as well as grinding and recrystallizing some of the grain edges to fill the interstices.

Some interesting features in this slide are found along the feldspar grain boundaries and along many of the cracks within the feldspars. In these areas, the feldspars are moderately to intensely sericitized, with fine-grained opaque material sometimes interspersed with the sericite. The sericite is secondary, suggesting that the associated opaque material is also secondary. Large euhedral to subhedral grains of opaques (Fig. 3-6c), usually closely associated with calcite and chlorite, are typically found in the areas interstitial to the feldspar grains. Both the calcite and chlorite are typical secondary minerals. These, along with the sericite and opaques, strongly suggest a period of hydrothermal alteration has affected this specimen. It is also clear that the fluids must have passed through the rock after it had been deformed since the secondary minerals are found along cracks within the feldspars.

The effects of the regional foliation can be seen in specimen KV1A1 (Fig. 3-7), which is from site 1. The foliation is primarily formed by the sub-parallel alignment

Fig. 3-7: Regionally foliated porphyry showing small lathes enclosed within k-feldspar (K). Ribbons of muscovite (mu) and deformed quartz (Q) showing undulose extinction are also shown. Specimen KV1A1. Field of view 1.0 by 1.5 mm.


Q
k
mu

of muscovite grains. The muscovite tends to form thin ribbons consisting of small grains. These ribbons appear to flow around a number of feldspar phenocrysts. This is different from the mylonitic foliation where the muscovite grains generally do not form ribbons, but remain as discreet grains. The biotite grains are present as larger lathes that are not as intensely aligned as the muscovite. However, the biotite does sometimes form elongated clumps.

Feldspar phenocrysts, usually microcline and orthoclase up to 2 mm in size, are subhedral to anhedral in shape. The orthoclase grains poikilitically enclose small lathes of muscovite which are randomly oriented.

The groundmass consists of fine-grained microcline, orthoclase, quartz, biotite, muscovite and calcite. Minor amounts of apatite, sphene, zircon and opaques are also present. There is a tendency for the accessory zircon, sphene and opaques to be associated with the biotite clumps. It also appears that some of the zircons seem to be altered, forming opaque material.

Hematite-enriched Porphyry

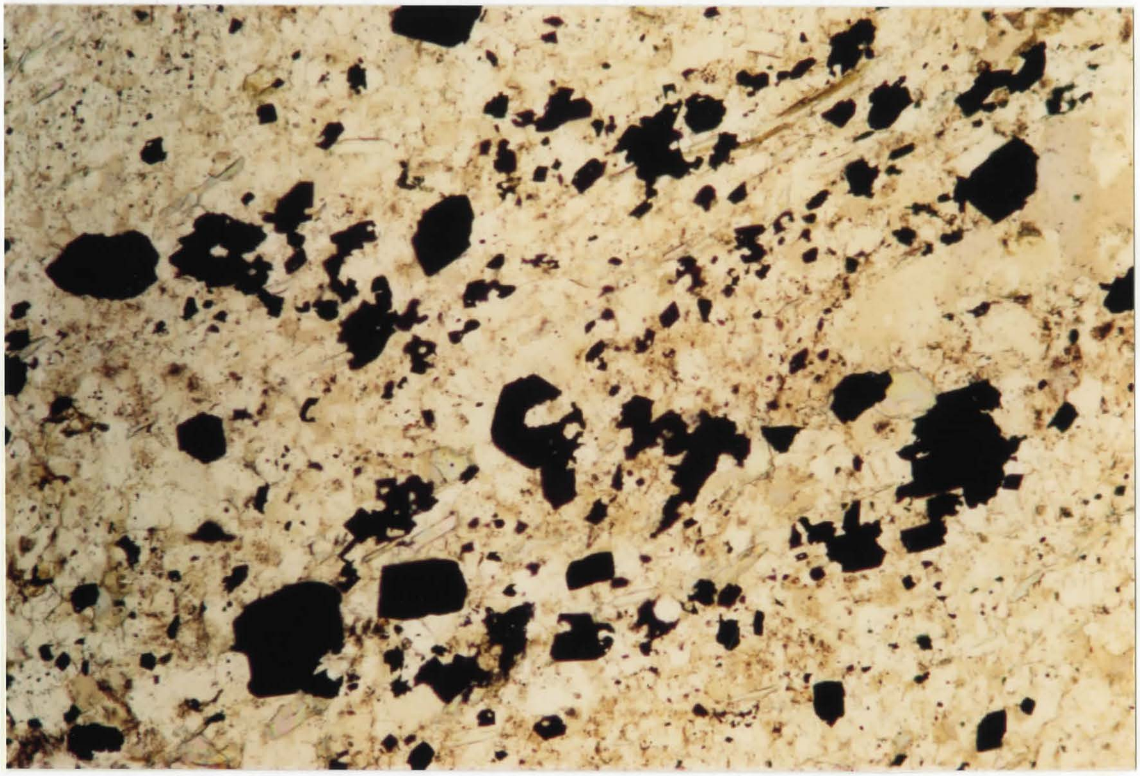
These specimens appear to be microscopically consistent with the massive porphyry in terms of mineralogy and texture. The example chosen, specimen KG3A1, to represent the hematite-enriched rocks comes from site 32 and is illustrated in Figures 3-8a&b. Phenocrysts of alkali feldspar up to 2.1 mm in size and of quartz up to 1.5 mm in size are contained within a fine-grained groundmass of quartz, plagioclase, feldspar, muscovite and opaques. The feldspar phenocrysts are moderately sericitized and poikilitically enclose tiny, randomly oriented grains of muscovite, apatite and opaques. The quartz phenocrysts exhibit undulose extinction and many of them are cracked.

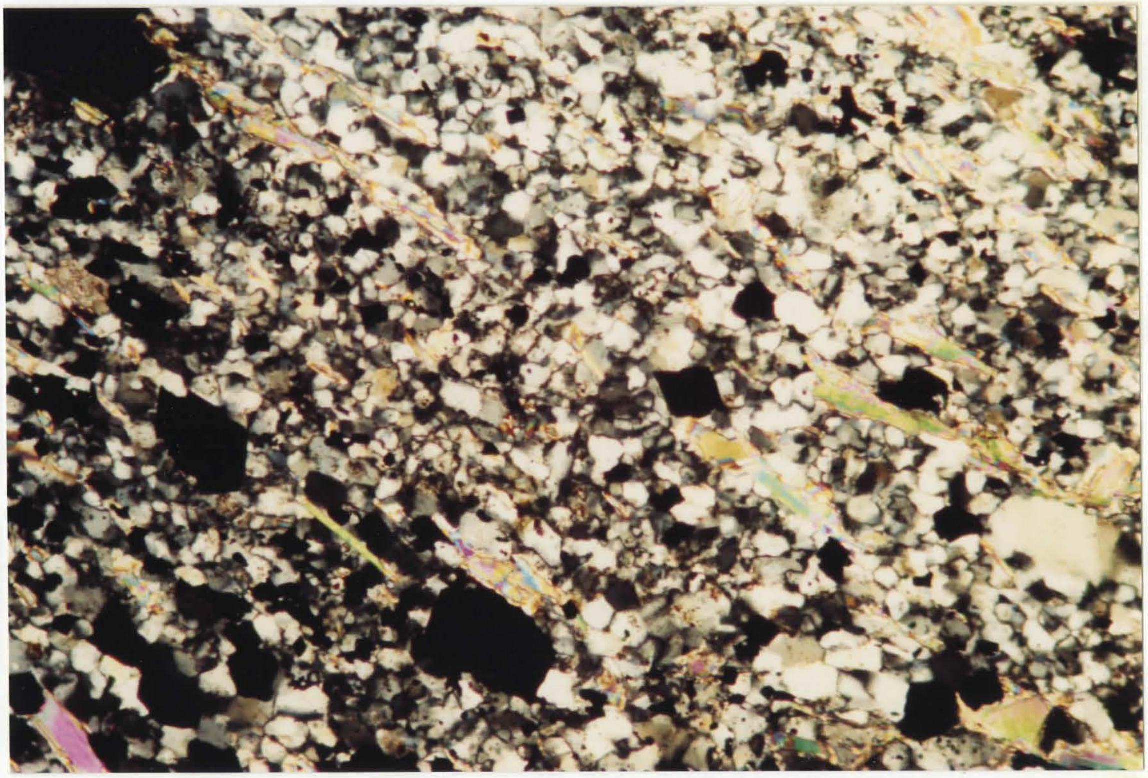
The major difference between these rocks and the other lithologies contained within the complex is that there is a substantial amount of opaque material in the hematite-enriched specimens. The majority of opaque grains in specimen KG3A1 are contained within two bands, which are about 2 mm in width and contain euhedral to anhedral grains of opaques ranging in size from tiny to 0.4 mm (Fig. 3-8a). A slight foliation is visible, imparted by the parallel alignment of muscovite lathes. The orientation of the opaque bands is slightly oblique to the foliation.

Diabase Dykes

The majority of dykes sampled in the complex were deformed, with the exception of the dyke from site 34. The deformed dykes are represented by specimen KV14G from site

Fig. 3-8: Hematite-enriched porphyry. (a) Opaques within diffusion band. (b) Muscovite foliation. Specimen KG3A1. Field of view 1.0 by 1.5 mm.





14 (Fig. 3-9) while the undeformed dykes are represented by specimen KG1-21 from site 34, which is illustrated in Figure 3-10.

The deformed dyke, specimen KV14G, contains abundant amphibole, typically hornblende but sometimes tremolite-actinolite, biotite, a little plagioclase, extremely deformed quartz, chlorite, epidote, apatite, zoisite and opaques. Very little, if any, pyroxenes are present and there is no trace of olivine. There is a preferred orientation to the biotite and any amphiboles that occur as lathes. There is the occasional grain or group of grains of calcite. The opaques are generally subhedral and are sometimes found within biotite lathes.

The undeformed dyke, specimen KG1-21, exhibits typical diabase textures. The dyke consists of abundant lathes of plagioclase, typically labradorite, some biotite, serpentine, phenocrysts of augite with cores of pigeonite, which ophitically enclose lathes of labradorite. Interstitial material is generally chloritic in composition and is fine-grained. Subhedral to anhedral grains of opaque material are also present.

Fig. 3-9: Deformed dyke. Shows fine-grained biotite and chlorite groundmass, with bent biotite lathes (B) and an elongated blob of deformed quartz (Q). Specimen KV14G1. Field of view 1.0 by 1.5 mm.


Q
B

Fig. 3-10: Undeformed dyke. Plagioclase lathes (Pl), pyroxene crystals (Px) with opaques and epidote matrix. Specimen KG1-21. Field of view 1.0 by 1.5 mm.


Pl
Px

Opaque Mineralogy

The opaque mineralogy is of importance when discussing the paleomagnetism of these rocks. Although it is possible magnetically to determine what the magnetic constituents are, an optical analysis of the opaque mineralogy is important in determining the effects of deformation or hydrothermal alteration on the magnetic minerals which in turn can be used to help interpret how and when the remanence was acquired.

The two opaque minerals recognized are hematite and magnetite. The hematite is easily distinguished by its anisotropy and blood red internal reflections. The magnetite is distinguished from the hematite by its lack of internal reflections, its grey colour when compared with the white of hematite and its isotropism.

Polished sections were made of the granite (specimen KV25A2), the massive porphyry (specimen KV16B4), the foliated porphyry (specimens KV7A2, KV8A2 and KV11F2) and the hematite-enriched porphyry (specimen KG3A1). The granite contains few opaques, but any present are subhedral to anhedral, cracked grains of magnetite, which show evidence of irregular martitization. This is the hydrothermal alteration of magnetite to hematite lamellae (Ade-Hall *et al*, 1971) and is illustrated in Figure 3-11.

The porphyry, whether foliated, massive or hematite-enriched, generally contains both magnetite and hematite, many of the grains being composed of the two. Some of the grains exhibit cores of magnetite remaining as a few isolated islands within the hematite, whereas other grains show hematite present only along grain boundaries, fractures and/or along a preferred cleavage plane (111) of the magnetite crystals. This texture is evidence of hematite pseudomorphing after magnetite. The grains are generally less than 0.5 mm in size.

The foliated specimens KV7A2, KV8A2 and KV11F2 which are illustrated in Figures 3-12, 3-13 and 3-14, consist of anhedral to subhedral grains ranging in size from less than 0.008 mm to 1 mm. Most of the larger grains are cracked, and sometimes broken apart. These grains are typically composed of both magnetite and hematite, with the hematite occurring as an alteration product along grain boundaries and cracks within the magnetite grains. There is no evidence of alteration along cleavage planes within the magnetite. The smaller grains in each specimen can be either hematite, magnetite or combinations of the two. A few hematite grains contain small anhedral grains of pyrite.

Fig. 3-11: Example of martization (high temperature alteration) of magnetite (Ma) to hematite (He) in granite. Alteration is along grain boundaries, cracks and cleavage plane (111). Specimen KV25A2. Field of view 0.25 by 0.34 mm.

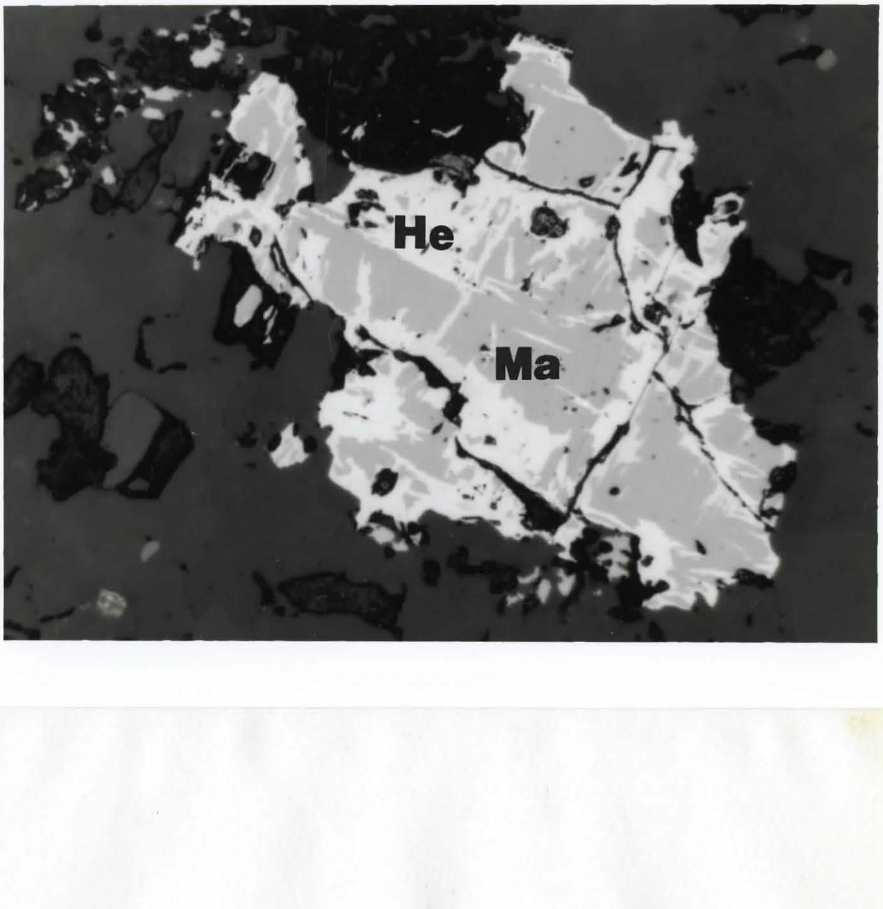

He
Ma

Fig. 3-12: Mylonitically foliated porphyry. Euhedral magnetite grain altered to hematite along grain boundaries. Specimen KV7A2. Field of view 0.51 by 0.67 mm.

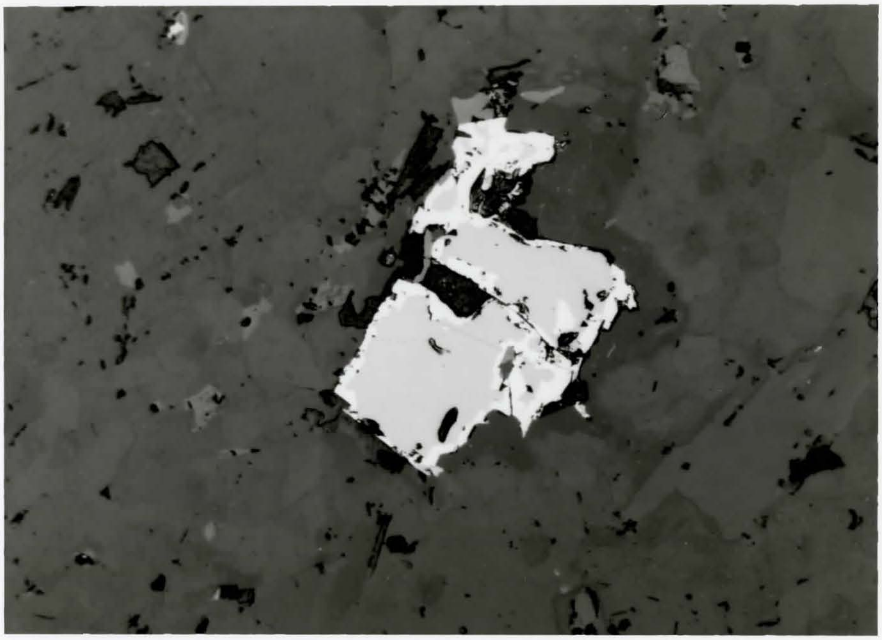
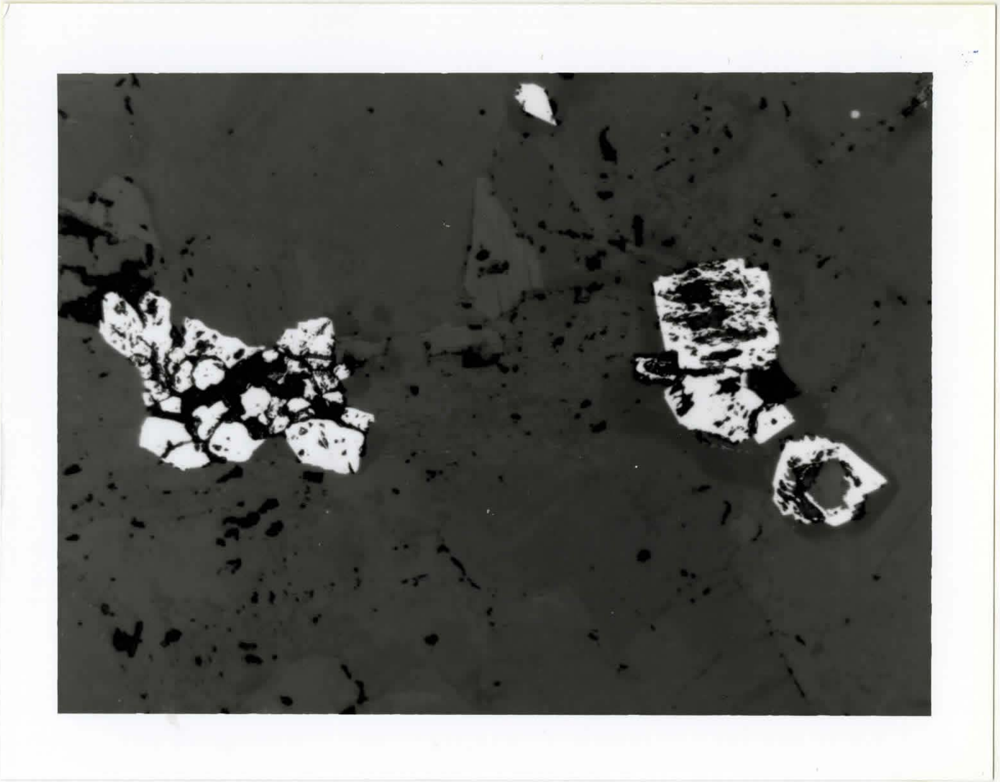


Fig. 3-13: Euhedral hematite crystals that have pseudomorphed magnetite in a mylonitically foliated porphyry. These grains are interstitial to sericitized feldspar grains. Specimen KV8A2. Field of view 2.03 by 2.69 mm.

Fig. 3-14: Mylonitically foliated porphyry showing tattered subhedral hematite crystals. Specimen KV11F2. Field of view 0.41 by 0.54 mm.



The massive porphyry, specimen KV16B4, contains subhedral to anhedral crystals predominantly of hematite. These grains are generally less than 0.2 mm in size. Only isolated grains are magnetite and even fewer grains consist of both hematite and magnetite (Fig. 3-15). A number of hematite grains include anhedral grains of pyrite.

The samples classified as hematite-enriched are certainly enriched in opaques, especially in the bands (Fig. 3-16). Grain size within these bands is extremely variably, ranging from 0.4 mm to less than 0.008 mm. However, the larger grains are generally subhedral to euhedral magnetite which contain some gangue material. Only a few of these grains exhibit any alteration to hematite. The smaller grains, which are anhedral plates, are hematite. These are aligned in a subparallel manner to the trend of the band. Some of the hematite grains include anhedral grains of pyrite.

Fig. 3-15: Massive porphyry. Magnetite crystals altering to hematite along grain boundaries and cracks. Specimen KV16B4. Field of view 0.51 by 0.67 mm.

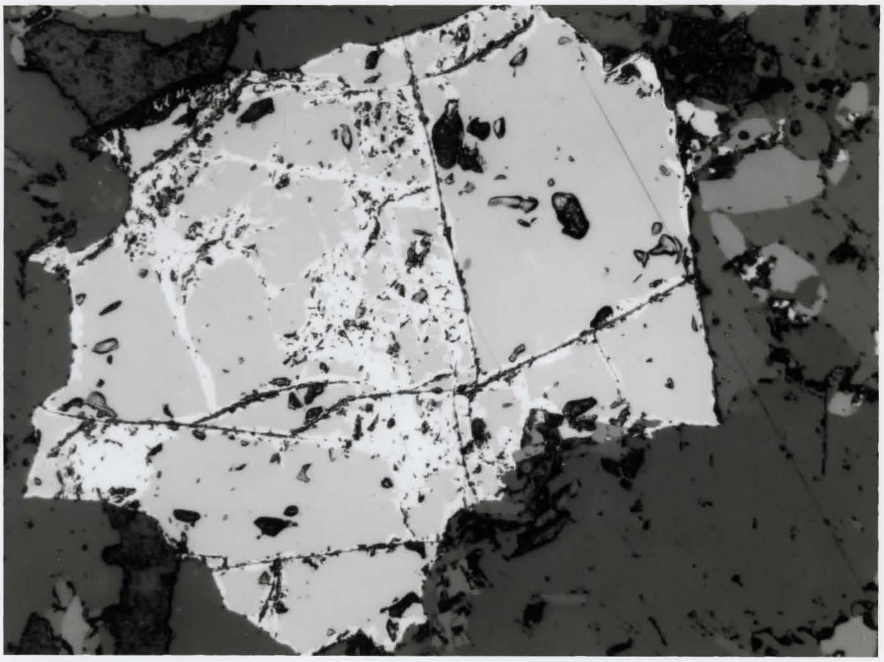
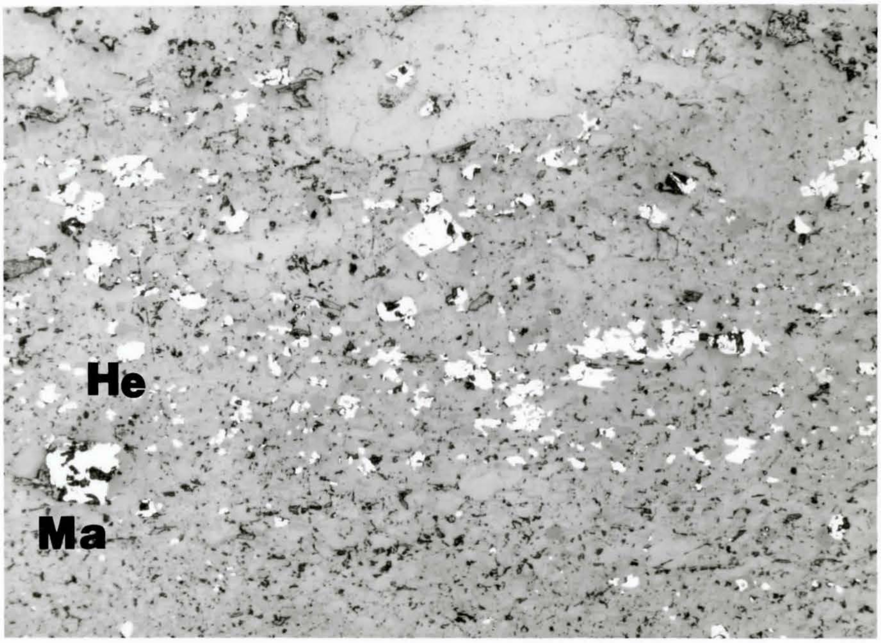


Fig. 3-16: Hematite-enriched porphyry. Magnetite (Ma) and hematite (He) grains in opaque diffusion band. Specimen KG3A1. Field of view 2.03 by 2.69 mm.


He
Ma

Discussion

The key word so far used to describe the KIC is heterogeneous. The effects of deformation have been illustrated to be variable, as well the lithologies present. This is also shown to be true by the textures exhibited by the thin-sections. The most consistent factor shown to be present throughout the complex is the mineralogy of the complex, which is made up of k-feldspar, plagioclase, quartz, biotite, muscovite and some hornblende. Although this does exclude the diabase dykes, it is not always foolproof, as specimen KV8A2 from site 8 (Fig. 3-6a,b&c) is made up of coarse grains of k-feldspar and plagioclase, with some sericite, opaques, chlorite and calcite.

The granite shows little evidence macroscopically that it was subjected to any deformation and/or metamorphism. Microscopically, however, there is some sericitization of the feldspars and locally chloritized biotites. These factors suggest metamorphism, although these can also be caused by an influx of hydrothermal and/or meteoric water (Deer et al, 1966). The granite shows some local concentrations of muscovite and since the granite is slightly peraluminous (Jones, 1930), most of the muscovite probably occurs as a primary mineral, although it is also diagnostic of metamorphism. This point raises the question of whether the k-feldspar megacrysts are phenocrysts or porphyroblasts, ie: did the k-feldspar grow during cooling or is it a result of metamorphism. The muscovite is primary and the small flakes of muscovite within the feldspar can be formed as a result of low temperature leaching of the feldspar (Deer *et al*, 1966). It is also, however, possible to explain the enclosure of muscovite by having the k-feldspar growing after the muscovite, suggesting a porphyroblastic origin for the k-feldspar. I believe that the k-feldspar megacrysts are phenocrysts on the basis that the granite is peraluminous, which easily explains the small muscovite lathes within the k-feldspar. The remainder of the interstitial muscovite is probably composed of both primary and secondary grains as there is other evidence suggesting metamorphism.

Evidence of alteration due to the presence of water is also provided by the opaque mineralogy. The martitization of magnetite grains is evidence of elevated temperatures associated with water (Ade-Hall *et al*, 1971). All of these observations point to the fact that the granite did not totally escape alteration, especially in areas close to the porphyry, although the effects are not very intense. That the granite has been altered is not surprising since the complex, being volcanic-plutonic in origin, would have formed with the granite underlying the porphyry. The present structure of the complex suggests simple tilting of the complex took place in a southeasterly direction, which would result in the granite lying to the northwest of the porphyry. There are, unfortunately, no structures to use as markers to reconstruct the event or series of events responsible. A problem exists with the story of southeasterly tilting exactly for the reason that the granite lies to the northwest of the porphyry. The only thrusting event that has been determined for the area around the Grenville Front plutons is associated with the Grenville Orogeny, and it could not have easily brought about the current structural situation because the thrusting has been interpreted to be towards the northwest, producing an overthrust. If this overthrusting resulted in tilting the complex, this would structurally cause the porphyry to lie to the northwest of the granite. This means that another explanation is required since it is improbable that the complex would have been totally overturned as a result of the Grenvillian thrusting. It is more likely that the complex would have either been buried under the uplifted Grenville Province or only part of the complex would would have been buried causing the complex to tilt towards the southeast. Both of these situations still do not explain how the present structural geometry of the complex was formed. This suggests the possibility of a period of deformation prior to the Grenville Orogeny, which is supported by the regional foliations found in the complex. Since there are no structural markers to help determine the direction of tilting, a southeasterly directed thrust along the Grenville Front could explain the geometry of the complex, suggesting that the northwest thrusting associated with the Grenville Orogeny did not result in any appreciable rotation of the KIC.

Effects of deformation and metamorphism appear to be more variable in intensity and location throughout the porphyry than the granite. The parts of the porphyry classified as massive exhibit much the same effects as the granite. These include sericitization of the feldspars and the presence of associated muscovite. The opaque mineralogy also suggests some type of alteration. The common opaque mineral in the granite, magnetite, is virtually non-existant; instead, the massive porphyry contains numerous grains of hematite. The amount of hematite suggests that fluid deposited hematite while altering any magnetite already present. This means that magnetite was generally the primary opaque mineral in the porphyry and that hematite was introduced by hydrothermal fluids. This event might have been contemporaneous with the episode of pre-Grenville deformation that appears to have been variable in location as shown by the location of the regionally foliated rocks.

The foliations described in the complex have been interpreted as regional and mylonitic. The two have distinct trends, the former being easterly and the latter being northeasterly. However, very little difference is evident microscopically that can be used to distinguish the two. Typically, the mylonitic foliation exhibits higher intensity deformation than the regionally foliated samples even though no true mylonite is represented. This is indicated by smaller grain size due to recrystallization and the bending of crystal lattices causing undulatory extinction in quartz and k-feldspar as well as the bending of albite twins in plagioclase and a more intense alignment of phyllosilicates, especially the muscovite. Specimens representing both foliations still retain phenocrysts, although the most severely foliated specimen, KV11F2 from site 11, contains phenocrysts that are smaller and fewer in number. Site 11 is of interest because it is a protomylonite which Frarey & Cannon (1969) and Frarey (1985) suggested was the southeastern margin of the KIC, but not the Grenville Front. However, petrographically, it does not differ much from the other foliated specimens.

A major anomaly associated with the foliated specimens is seen in specimen KV8A2. This specimen is made up of primarily k-feldspar and plagioclase, which are cracked and bent. The notable feature of this sample is that of the association of large, interstitial hematite crystals with chlorite, calcite and intense sericitization of all the feldspars (Fig. 3-6c). The hematite grains have euhedral shapes that are very characteristic of magnetite implying that hematite totally pseudemorphs the magnetite. This suggests water flowed through this rock, producing these characteristic minerals, either by deposition or alteration. However, it is difficult to determine the exact timing of the alteration as it relates to the deformation. The circulation of water is probably enhanced along foliation planes relative to flow through massive granite. It is then a question of whether the fluid flowed through the complex before or after the Grenvillian Orogeny, which is responsible for the mylonitic foliations.

The regionally foliated specimens show similar microscopic characteristics to the mylonitically foliated specimens, although the alignment of the phyllosilicates is less and the feldspars and quartz grains are not as deformed. The opaque mineralogy also exhibits similar characteristics of alteration, such as magnetite altering to hematite associated with typical hydrothermal alteration minerals such as chlorite, calcite and sericite. The timing of the alteration is not known, as well as whether the same event is responsible for the alteration in both regional and mylonitic foliation trends. If the flow of fluids is enhanced through rocks that possess a foliation as opposed to massive rocks, then it is probable that the regional foliation occurred prior to the hydrothermal alteration. This is the same argument as for the mylonitic foliation, suggesting that all the fluid flow took place throughout the entire complex during or after the Grenville Orogeny.

There is not, however, reason to rule out a number of generations of hydrothermal fluid flow through the complex as suggested by the hematite-enriched porphyry. The hematite-enriched samples exhibit only slight effects from deformation in the form of a foliation associated with muscovite lathes, but the bands of hematite and magnetite must have been produced by hydrothermal alteration, possibly two generations. This is suggested because the magnetite appears to be the primary opaque mineral deposited, which has been subsequently altered to hematite. The porphyry probably was not formed with the parallel bands of opaques to either side of a central fracture already present. This means that the porphyry underwent a period of hydrothermal alteration which resulted in the deposition of predominantly magnetite grains. Since the bands cut the foliation present, this first episode of alteration took place after a period of deformation that was responsible for the regional foliation. A second episode of fluid influx resulted in the alteration of the already present magnetite to hematite. The smaller grains have mainly been altered totally or are hematite grains deposited by the second influx of fluid. The larger grains of magnetite only slightly altered to hematite along grain boundaries and fractures within the magnetite crystals.

The porphyry as a whole exhibits evidence of variable deformation hydrothermal alteration. Both the regionally and mylonitically foliated specimens are generally more altered by water (as shown by the sericitiation of feldspars, the alteration of magnetite to hematite, chlorite, calcite) than the massive porphyry and granite. This suggests that fluid flowed along foliation planes and altered the porphyry in these areas, while only slightly affecting the rest of the complex.

The diabase dykes were emplaced after the deformational event responsible for the structure of the complex, because all the dykes are essentially vertical. Various studies (Bethune and Davidson, 1988; Palmer *et al*, 1977) on the dykes in this region have concluded that the dykes trending northwest are typically of the Sudbury swarm, while the east trending dykes usually belong to the Grenville swarm. However, since most of the dykes are deformed, it is difficult to distinguish if both swarms are represented using microscopic evidence. This does suggest, however, that the deformed dykes belong to the Sudbury swarm as no deformation has apparently occurred in the KIC since the Grenville Orogeny. This means that only the older dykes (the Sudbury swarm) would have been present by the time the Grenvillian Orogeny began and thus would have been affected by the deformation. This is not the case with the younger Grenville swarm, which Bethune and Davidson (1988) have identified to cross the Grenville Front without deflection or deformation. The mineralogy of the undeformed dyke does match that reported for the Grenville dykes (Bethune and Davidson, 1988), suggesting that it does indeed belong to the Grenville swarm. It is important to note that the undeformed dyke trends NW, which has been associated with the Sudbury dykes, whereas the E-W trending dykes have been identified as post-Grenville. The E-W trending dykes from the KIC, however, show evidence of deformation, which means they cannot belong to the younger swarm unless a much younger episode of deformation can be reasoned. This suggests that simply identifying the trends of the dykes within the complex is not sufficient to identify the swarm.

A petrogenesis can be drawn from the geological analysis. The complex was emplaced at about 1742 Ma (Van Breeman and Davidson, 1988) as a volcanic-plutonic body consisting of granite, porphyry and volcanoclastics. A period of hydrothermal fluid flow took place shortly after the cooling of the complex, probably centered at the quartz-muscovite schist along the shore of Georgian Bay, which has been interpreted as a rhyodacite dome/flow (Clifford, 1986). A regional foliation was imparted on the complex, which was possibly associated with a deformational event responsible for tilting the complex in a southeasterly direction. This resulted in another influx of hydrothermal fluid which, through deposition or diffusion, produced the bands of magnetite crystals. The Sudbury dykes were then emplaced around 1250 Ma (Palmer *et al*, 1977). A very intense deformational event subsequently followed associated with the Grenville Orogeny, lasting between 1160 Ma and 970 Ma (Rivers *et al*, 1989). Another episode of hydrothermal alteration occurred either during or shortly after the orogeny, which altered the pre-existing magnetite grains to hematite. The last major event to affect the region was the emplacement of the Grenville diabase dykes around 575 Ma (Fahrig and West, 1986).

Chapter 4: GENERAL DISCUSSION

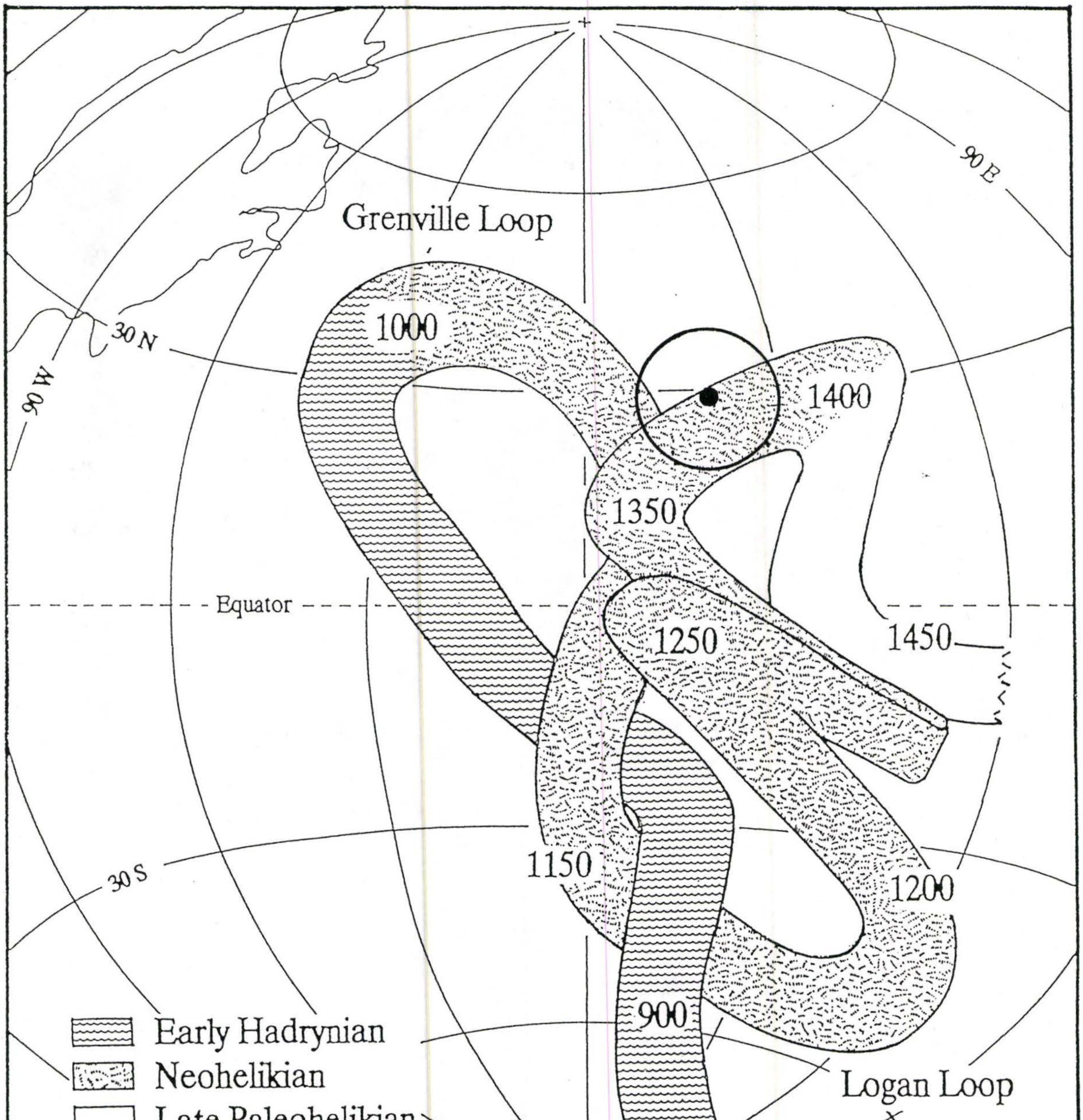
The Southwesterly Remanence

The Killarney complex collection is dominated by a steep positive remanence (Fig. 2-14). However, it was shown that with careful selection of lithologies, an average direction with a southwesterly declination and shallow negative inclination could be determined. This direction is found predominantly in the mylonitically foliated porphyry specimens, and the regionally foliated specimens and one of the hematite-enriched sites when their directions are reversed.

The Virtual Geomagnetic Pole (VGP) resolved for the southwesterly directed remanence is plotted on the Late Proterozoic APWP after Irving (1979) (Fig. 4-1). The longitude is 19.3°E, the latitude is 29.1°N and the major and minor radii of the error ellipse (dp & dm) are 9.6° and 10.9° respectively. This pole was calculated using the site averages; the pole calculated using the specimen average is listed in Table 4. This VGP corresponds to an age of about 1350 Ma, a position significantly younger than the 1742 Ma emplacement age of the complex determined by Van Breeman and Davidson (1988). The younger age is not surprising if the

Fig. 4-1: Virtual geomagnetic pole for the southwesterly remanece direction plotted on the Late Proterozoic APWP.

Apparent Polar Wander Path (-1450 to -800 Ma)



After Irving (1979)

remanence is carried by material introduced after the emplacement of the complex. Figure 2-3, a histogram of intensities, showed that there may have been an addition of magnetic material into the foliated parts of the porphyry, although an alternative explanation for this increase is a grain size reduction. The presence of similarly-directed stable remanences in both the foliated and hematite-enriched specimens suggests that the hydrothermal event responsible for the secondary hematite in the "railroad track" facies may also have been responsible at the same time for the increase in magnetic material in the porphyry.

In the foliated and hematite-enriched specimens, at least some of the remanence is carried by the hematite as indicated by the tail in the median demagnetizing temperature histogram in Figure 2-2. The thermal demagnetization data indicate that even though a wide spectrum of blocking temperatures are present, a fraction of the intensity is still present at temperatures above the Curie point of magnetite. At these temperatures, the northeasterly and southwesterly remanence directions can still be resolved. This means that the northeasterly and southwesterly directed remanences were acquired at temperatures higher than the blocking temperature of hematite, suggesting that the remanence is, in part, carried by the hematite. The remanence is a CRM because at high temperatures, hematite can easily form through the alteration of magnetite (see Figures 3-11 to 3-16).

The younger age of 1350 Ma for the foliated porphyry agrees reasonably well with the tentative age of 1400 +/- 50 Ma, assigned to undeformed pegmatite dykes which cut the regional foliation (Van Breeman and Davidson, 1988). The Bell Lake Granite, another granitic pluton which abuts the KIC to the northeast, has a precise emplacement age of 1471 +/- 3 Ma (Van Breeman and Davidson, *op cit*). It is not known whether the pegmatites are related to a post-emplacement thermal event or the final stage of cooling of the Bell Lake Granite, but the paleomagnetic data suggest that a hydrothermal event resulted in the emplacement of both the pegmatites and veins at sometime after about 1400 Ma.

There is evidence (Davidson, 1986b) that deformation occurred in the complex prior to the emplacement of pegmatites at 1400 Ma and diabase dykes of the Sudbury swarm (ca. 1250 Ma; Palmer *et al*, 1977). Of the two foliation trends present in the complex, the regional one is cut by both the "railroad track" facies veins and the pegmatite dykes, indicating that deformation must have occurred prior to the hydrothermal system and the emplacement of the pegmatites at 1400 Ma (Van Breeman and Davidson, 1988). Tectonism can commonly randomize the remanence in specimens (Hale and Lloyd, 1989), but the same southwesterly remanence is carried by both the relatively undeformed hydrothermal system which deposited secondary hematite carrying a CRM and the foliated sites, which include both regionally and mylonitically foliated specimens. This suggests a second option; that the chemical remanence must be younger than the tectonism responsible for both the "regional" and "mylonitic" fabrics. This Grenville or post-Grenville remanence is carried by secondary hematite.

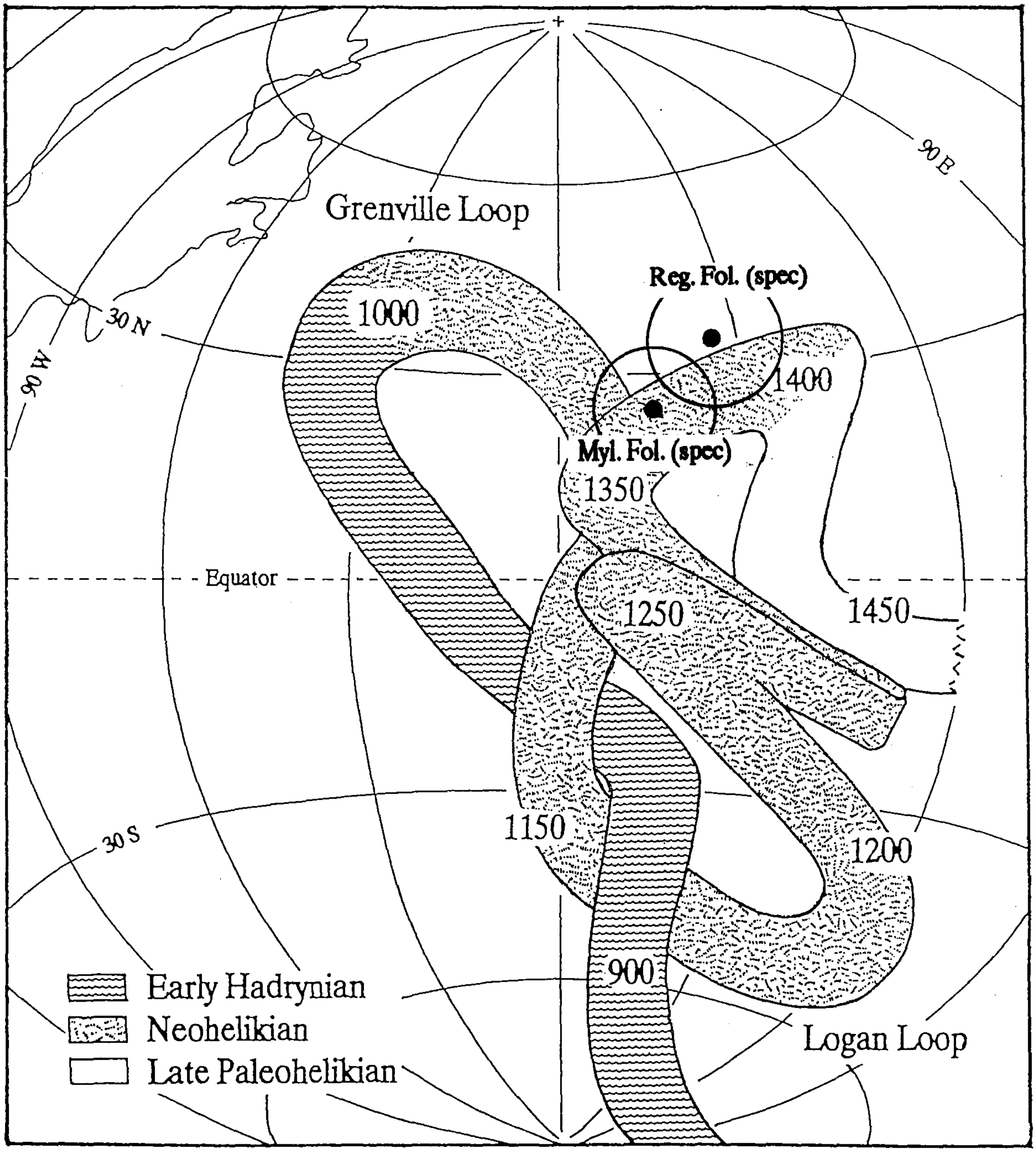
The position of the VGP for the southwesterly directed remanence therefore suggests two explanations. The first is that the VGP is Grenville, with an age around 1050 Ma. This means that the northeasterly directed remanences were acquired during a field reversal, justifying the use of their antipoles in the calculation of the average. The pegmatite dykes and the Bell Lake granite emplacement, therefore, have no connection with the acquisition of the remanence. Any hydrothermal activity responsible for the CRM occurred shortly after the onset of Grenville tectonism. The second explanation is that the age of the remanence is 1350 Ma, implying that the Grenville Orogeny began well before present estimates because rocks used in the averaging are foliated from Grenville tectonism. This case suggests that the emplacement of the pegmatites and Bell Lake granite resulted in hydrothermal activity that produced the CRM, and that the porphyry had already acquired its mylonitic foliation.

Figure 2-17, a stereonet showing the stable end-points for the foliated and hematite-enriched specimens after the steep upwards population had been removed, illustrates a southwesterly and a northeasterly population. The two populations can be easily separated, as most northeasterly directed remanences come from regionally foliated and hematite-enriched porphyry specimens, and the southwesterly ones from mylonitically foliated porphyry specimens. When each population is averaged separately, the following specimen VGP's are calculated: Longitude = 28.2°E, Latitude = 36.0°N, N = 23, dp = 11.1° and dm = 9.8° (regional foliation) and Longitude = 20.3°E, Latitude = 25.0°N, N = 41, dp = 8.5° and dm = 10.7° (mylonitic foliation). These are plotted on Figure 4-2, while the site VGP's can be found in Table 4.

The two populations, when averaged separately, produce pole positions that suggest ages of 1400 Ma and 1075 Ma respectively. These VGP's imply that more than one episode of hydrothermal alteration took place. If the hematite-enrichment in the porphyry resulted in the CRM in the regionally foliated porphyry, then another period of hydrothermal activity resulted in the addition of magnetic material to the mylonitically foliated porphyry. Two problems exist with trying to argue these two separate ages. The first is that only a small number of specimens (23 and 41) are used to calculate these poles, and secondly, that

Fig. 4-2: Late Proterozoic APWP with the VGP's for separated NE and SW remanence directions with their error ellipses.

Apparent Polar Wander Path (-1450 to -800 Ma)



After Irving (1979)

the two poles are very close to each other and almost have their error ellipses touching. This makes the two poles statistically indistinguishable.

In summary, the southwesterly and northwesterly directed remanences from the foliated and hematite-enriched porphyry can be explained by a number of events. However, using all the geologic and paleomagnetic evidence, the most plausible interpretation is that the complex underwent two periods of deformation and two or three periods of hydrothermal activity. Only the most recent hydrothermal event can be resolved, with an age of about 1050 Ma. The remanence is a CRM, as evidence of hematite pseudomorphing magnetite is widespread (Fig. 3-6a,b&c).

Table 4: Summary of VGPs for all lithologies

Lithology	Long(°E)	Lat(°N)	dp(°)	dm(°)
Foliated (site)	19.3	29.1	9.6	10.9
Foliated steep	266.3	64.3	8.9	12.8
Reg. Fol. (site)	25.6	35.8	22.1	20.0
Myl. Fol. (site)	16.1	25.2	11.6	15.0
Granite (spec)	225.2	39.8	17.2	23.1
Granite (site)	229.8	51.5	35.8	52.2
Dykes (spec)	353.9	55.3	26.2	21.4
Dykes (site)	7.2	50.4	36.4	28.5
Hematite	305.0	69.9	9.7	7.3
Porphyry	339.6	80.1	5.5	5.8
Steep	263.1	69.1	9.1	8.1

Foliated = combined NE-SW remanences
Foliated steep = steep component from Foliated Porphyry
Reg. Fol. = Regional Foliation
Myl. Fol. = Mylonitic Foliation
Hematite = Hematite-Enriched Porphyry
Porphyry = Massive Porphyry
Steep = steep component from all specimens
site = average using site averages
spec = average using individual specimens
Long(°E) = longitude in degrees East
Lat(°N) = latitude in degrees North
dp(°) = major radius of error ellipse
dm(°) = minor radius of error ellipse

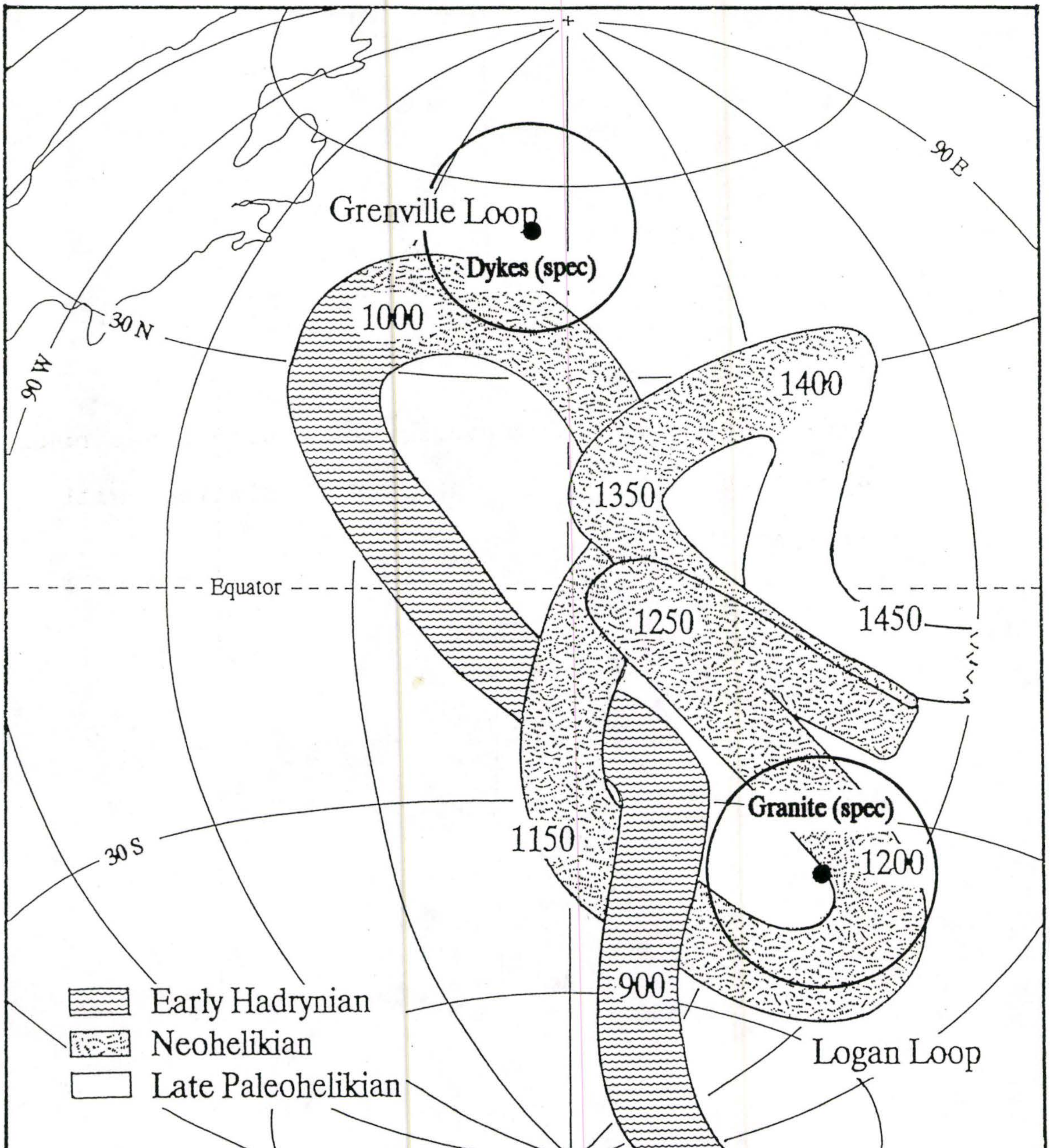
The Steep, Upwards Remanence

The steep, upwards remanence directions that dominate the Killarney collection, are resolved for specimens from all the lithologies. These directions are also resolved for specimens that were demagnetized using either AF or thermal methods, whether they had high or low coercivities or unblocking temperatures. This suggests a widespread overprinting of remanences in the complex. The VGP's calculated for all the steep remanences are listed in Table 4.

The steep positive remanence direction resolved for the foliated specimen population is illustrated in Figure 4-3b, the APWP first described by Morris and Roy (1977) and redrawn here after Irving (1979). No distinction was made between regional and mylonitic foliations to calculate this pole. The longitude = 266.3°E (86.3°E), the latitude = 64.3°N (64.3°S) with major and minor radii (dp & dm) of the error ellipse of 8.9° and 12.8° respectively. At a first glance, this pole lies close to the present geomagnetic pole, and the error ellipse does indeed include the present geomagnetic pole. This means that the steep remanence might represent contamination from the present geomagnetic field, and that the hematite carries a hard viscous remanent

Fig. 4-3a: Late Proterozoic APWP with steep remanence direction VGP's or antipoles plotted with error ellipses for dyke and granite sites.

Apparent Polar Wander Path (-1450 to -800 Ma)



After Irving (1979)

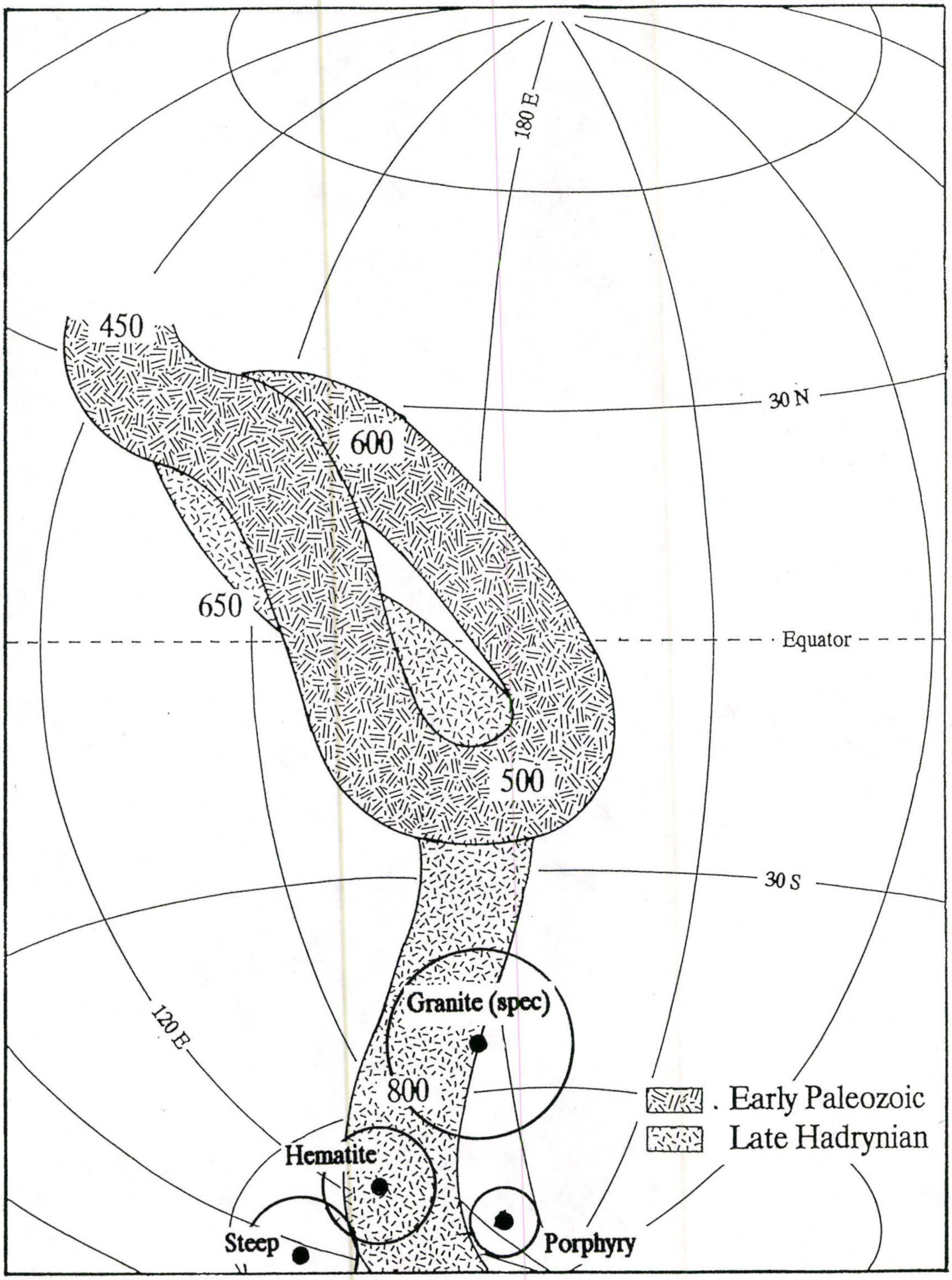
magnetization (VRM). Alternative explanations are possible. The antipole (in brackets) for the Killarney steep direction plots near the Jacobsville (J2) pole on the Hadrynian APWP (Morris and Roy,1977). This corresponds to an age around 800 Ma, a little young for the Grenville Orogeny (1160 to 970 Ma; Rivers *et al*, 1989), but still possible. Another alternative is shown in Figure 7-3c. The VGP falls on the end of the Coronation Loop, redrawn after Irving (1979), suggesting an age of about 1650 Ma. This implies that this steep remanence is primary, representing the end of the cooling of the complex. This is unlikely as this study has shown thatthe entire complex has been affected by tectonism and hydrothermal alteration. These examples do illustrate the problem of assigning dates to VGP's in an area such as the KIC, where VGP's can fall on a number of APWPs.

Although a number of the other lithologies produced average directions, their statistics are much worse than for the foliated specimens. The granite remanence directions contain both steep and intermediate to shallow directions, but the two do not form distinct populations. The individual specimen pole has a longitude of 225.2°E (45.2°E), a latitude of 39.8°N (39.8°S) and major and minor error radii of 17.2° and 23.1° respectively. The pole calculated from the site average is listed in Table 4. The granite antipole plots near an age of 1200 Ma on the Early Proterozoic APWP

Fig. 4-3b: Hadrynian APWP with steep remanence direction VGP's or antipoles with error ellipses for the granite, massive and hematite-enriched porphyry and all steep specimens.

(b)

Apparent Polar Wander Path (-800 to -450 Ma)



After Irving (1979)

while the VGP plots just off the late part of the Coronation Loop at an age of about 1650 Ma (see Figs. 4-3a&c). The 1650 Ma plot, although wrong, again shows the problem with assigning ages to VGP's. The age for the antipole suggests the interesting idea that the first hydrothermal event occurred around 1200 Ma, but this pole is probably contaminated by the present geomagnetic field.

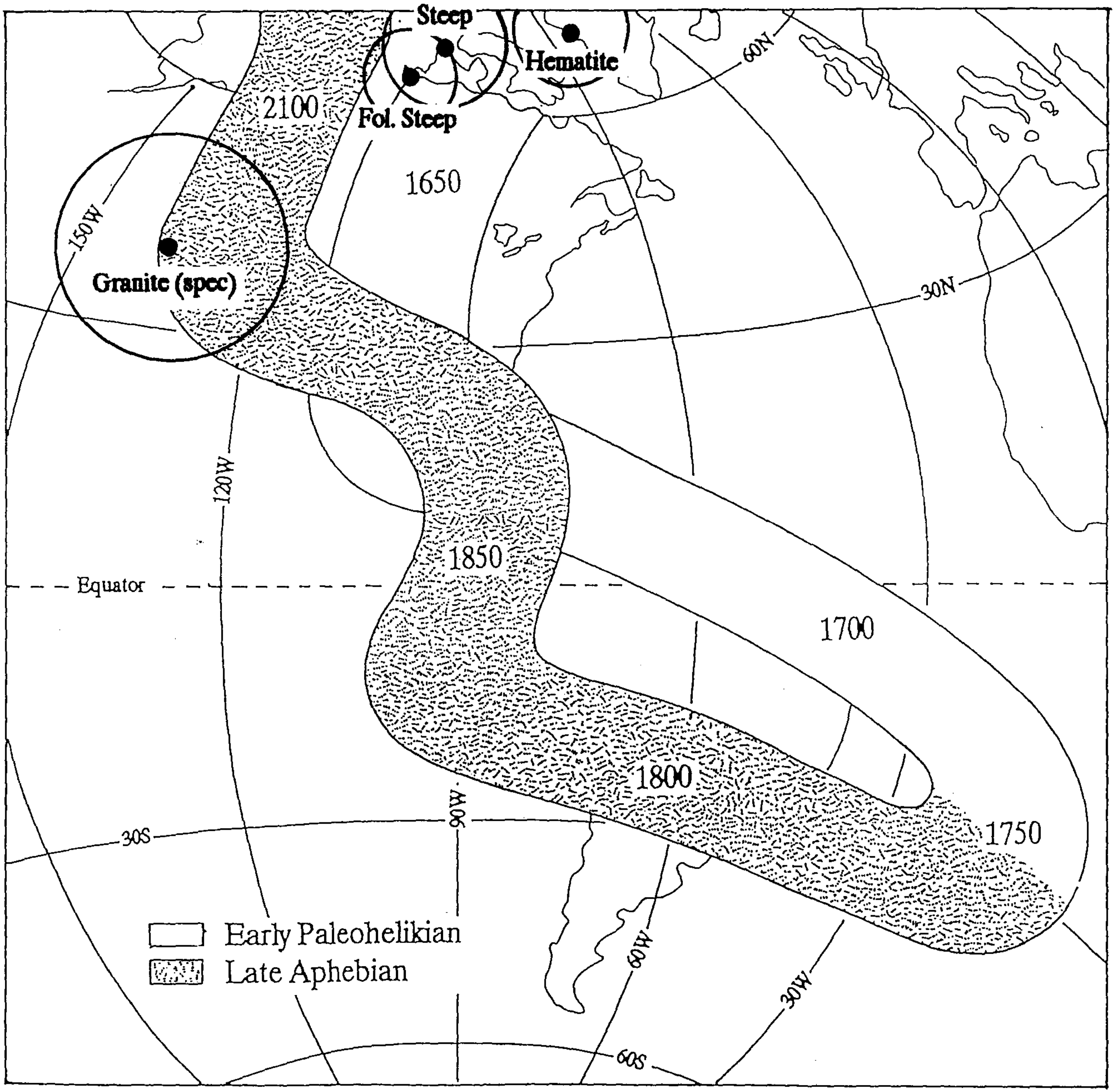
The dykes provide remanence directions that vary from specimen to specimen. The steep component present in a few specimens cannot be separated from the shallower population, so the pole calculated using the specimen average has a longitude of 353.9°E and a latitude of 55.3°N (dp = 26.2°, dm = 21.4°). The pole calculated from the site average is listed in Table 4. The pole and antipole fall close to two different APWPs (Fig. 4-3a&b). One possibility suggests an age of about 1000 Ma, although the pole falls just off the Late Proterozoic path. The second possibility, using the antipole, suggests an age of 800 Ma on the Late Hadrynian path. Both of these ages imply that the dykes, affected by Grenville metamorphism, belong to the Grenville swarm.

The second hematite-enriched site provides a very good statistical average, although, again, not far removed from the present geomagnetic pole. The VGP has a longitude of 305°E (125°E) and a latitude of 69.9°N (69.9°S), with dp = 9.7° and dm = 7.3°. The antipole lies on the Late Hadrynian

Fig. 4-3c: Early Proterozoic APWP with VGP's or antipoles from steep remanence direction carrying lithologies are plotted. Includes granite, hematite-enriched porphyry, steep foliated specimens and all steep specimens.

(c)

Apparent Polar Wander Path (-2100 to -1650)



After Irving (1979)

path suggesting an age of 800 Ma (Fig. 4-3b), while the VGP lies near the Early Proterozoic path near an age of 1600 Ma. These two possibilities imply that the hydrothermal system occurred in this area very early in the history of the complex or evidence of the hydrothermal event is overprinted by a late Grenville event. However, the hematite probably carries a hard VRM, representing contamination by the present geomagnetic field.

The VGP for the massive porphyry has a longitude of 339.6°E (159.6°E) and a latitude of 80.1°N (80.1°S) with dp = 5.5° and dm = 5.8°. This VGP suggests an age near 1600 Ma when plotted on the Late Proterozoic path (Fig. 4-3c), while the antipole falls on the Early Proterozoic path suggesting an age near 800 Ma. The problem of assigning ages for VGP's is again illustrated, although the remanence is probably contaminated by the present geomagnetic field.

The average of all the specimens that carry the steep remanence direction results in a pole position with a longitude of 263.1°E (83.1°E) and a latitude of 69.1°N (69.1°S) (N = 193, dp = 9.1° and dm = 8.1°). This position suggests an age of either about 800 Ma or 1600 Ma (Figs. 4-3b&c), but it also lies close to the present geomagnetic pole.

The steep remanence direction that is pervasive throughout all the lithologies illustrates the problem of assigning ages to poles resolved for the Killarney complex. If some of these poles in fact are legitimate, their proximity to the present geomagnetic pole makes it very difficult to distinguish them from present geomagnetic field overprints. In the case of the Killarney complex, the hematite probably carry a hard VRM.

Chapter 5: CONCLUSIONS AND FURTHER STUDY

Conclusions

This study of the Killarney Igneous Complex has determined that the collection is dominated by a steep, upwards directed remanence. About a third of the specimens measured resolved shallow to intermediate remanences along a northeast-southwest axis. When the northeasterly directed remanences are reversed to produce a Fisherian distribution, the average direction results in a VGP with a longitude of 19.3°E and a latitude of 29.1°N (dp = 9.6°, dm = 10.9°). The pole, when plotted on the Late Proterozoic APWP compiled by Irving (1979), suggests an age of about 1350 Ma. However, with other data suggesting that if the remanence carried in these specimens is a CRM in the hematite, then the remanence must have been acquired after the Grenville tectonism that produced the mylonitic foliations. This means that the pole suggests an age closer to 1050 Ma.

Another plausible explanation for the remanences is possible. When the regional and mylonitic specimens are averaged separately, the poles have the following positions; a longitude of 28.2°E and a longitude of 36.0°N (dp = 11.1°, dm = 9.8°) and a longitude of 20.3°E and a latitude of

25.0°N (dp = 8.5°, dm = 10.7°) respectively. The first consists of the regionally foliated sites and the moderately intense and extremely stable hematite-enriched specimens. This remanence has a shallow to intermediate positive inclination in the northeast. The pole associated with this group lies just off the Late Proterozoic APWP suggesting an age of 1400 Ma. This is tentatively related to the hydrothermal event that resulted in the emplacement of undeformed pegmatites in the vicinity of the hematite-enriched porphyry. As this remanence is a CRM that must have been acquired after earlier tectonism of the complex, it can be concluded that the tectonism must have occurred before 1400 Ma, perhaps along a proto-Grenville Front.

The second direction comes from the specimens from the mylonitically foliated sites. The pole position is slightly different from that calculated for the regional foliation, and the remanence direction is in the southwest and negative. This pole position lies just off the Late Proterozoic APWP near an age of about 1100 Ma. This is related to the Grenville Orogeny. These two poles do not offer evidence as strong as for the 1050 Ma Grenville pole because of the fewer number of specimens used to calculate each average and that the two poles have error ellipses that almost touch, suggesting that they do not differ significantly from each other.

The most dominant cluster of points has a steep positive inclination. These directions are found in specimens from all lithologies. The pole for these specimens falls close to an age of 800 Ma, but it is very difficult to distinguish this position from a PEF.

Suggestions for Further Study

The study of the Killarney Igneous Complex has illustrated that there is valuable data to be collected paleomagnetically from granitic lithologies. To fully understand the role of the Grenville Orogeny along the Grenville Front, it is necessary to undertake studies within the other Grenville Front granites. Since most of these are substantially younger than the KIC, they should have simpler tectonic histories and remanences should be categorized more easily.

Within the complex itself, the dykes and granite should be studied in detail. The dykes are good paleomagnetic lithologies and can be used to determine the timing of the pre-Grenville deformation within the complex. The granite is the least deformed part of the complex and a detailed study could determine a primary pole for it or possibly the role tilting has had in the history of the KIC. A specific study should be undertaken to determine whether the two foliation trends were really formed by two different episodes of deformation. A paleomagnetic study to determine the effect of changing the magnetic susceptibity ellispoid has on the remanance should be undertaken to determine whether the remanence direction is influenced by the shearing during tectonism.

A number of points have to be clarified, such as whether all the steep directions resolved are present geomagnetic field overprints or not. One way to do this is to find rocks, possibly from the mid-continental rhyolitic belt in Wisconsin or westwards, that have ages between 1650 Ma and 1450 Ma and resolve their VGPs. Another manner in which this can be determined is by taking the hematite-enriched specimens and leaving them for 6 months to 1 year in a known orientation after measuring their remanences. This will suggest whether they acquire a viscous remanent magnetization from the Earths field.

A rock body that has been unaffected by tectonism, is spatially removed from the Grenville Front and has an age similar to the KIC is needed to determine the exact pole position for rocks that have ages around 1750 Ma. Such rocks occur in northern Wisconsin. This would pinpoint the location of the primary VGP for the complex.

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