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Palaeomagnetism of Memesagamesing Lake and Caribou Lake norites, Parry Sound District Ontario.

Sudhindra Nath. Dey
University of Windsor

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Ottawa, Canada
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PALAEO MAGNETISM OF NEMESAGAMESING LAKE AND
CARIBOU LAKE NORITES, PARRY SOUND DISTRICT
ONTARIO

by

Sudhindra Nath Dey

A Thesis

submitted to the Faculty of Graduate Studies
through the Department of
Geology

in Partial Fulfillment of the requirements
for the Degree of Master of Science at the
University of Windsor.

Windsor, Ontario, Canada.

1981
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ABSTRACT

A palaeomagnetic study was done on the Memesagamesing and Caribou Lake norites in Parry Sound District, Ontario. The object of this study was to determine the age of the norites and to see if they correlate with the economically important Sudbury norites. A total of 32 sites from Memesagamesing Lake and 26 sites from Caribou Lake intrusives were drilled, oriented in situ, cored, and sliced into specimens. The low field susceptibility perpendicular to banding ($k_1$) anomaly maps of the area corresponds closely to the aeromagnetic anomaly maps of the area especially in the central portions. This suggests the presence of rocks of high susceptibility in the central portions and contradicts Friedman's (1957) and Lumbers' (1971) explanation that the intrusives are funnel shaped. The $k_{11}/k_{1}$ ratio of 1.450 for the Memesagamesing and that of 1.195 for the Caribou Lake norites suggests the presence of banding even though banding is not often visible in the field. The magnetic anisotropy study also contradicts Friedman's and Lumbers' explanation that the intrusives suffered compression and tilting subsequent to their intrusion. The baked contact tests on the Memesagamesing Lake norites provide strong evidence that the norites significantly predate intrusion of the granite pegmatite and olivine diabase dikes. The ambient temperature of the norites was calculated to be $\sim 22^\circ$C at the time of the pegmatite dike intrusion.

After AF, thermal and chemical cleaning, the Memesagamesing and Caribou Lake norites yield a stable A remanence component with a mean direction of $\sim 310^\circ$, $-51^\circ$. This gives a pole position of $\sim 32^\circ$W, $-4^\circ$N. The pole indicates an age of about 1760 $\pm$ 40 Ma on the AFW paths for late Archean to Early Helikian times (Irving, 1979; Stupavsky and Symons, 1981). This age differs with the of Sudbury norites by at least 100 Ma and therefore the norites of the study area do not correlate with the Sudbury Intrusive. The palaeomagnetic age for the Memesagamesing and Caribou Lake norites suggests an age of at least 1800 Ma for the formation of the Grenville Front.
ACKNOWLEDGEMENTS

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CHAPTER I
INTRODUCTION

1.1) The Proposal

Palaeomagnetism can often be used to determine the age of magnetization of various rock types, and thereby lead to an understanding of the geologic history of metamorphic terrains such as the Grenville Province. The purpose of this project is to study the palaeomagnetic characteristic of the Memesagamesing and Caribou Lake norites to see if they can be correlated with the Sudbury norites some 90 km away. The correlation of these norite bodies is possible because they show striking petrographic and structural similarities (Friedman, 1957). The Sudbury Irruptive is one of the world's greatest sources of economic minerals providing nickel, copper, platinum, gold, silver, and other valuable metals. If the Memesagamesing and Caribou Lake norites can be correlated with the Sudbury Irruptive, then the intrusive bodies of the study area warrant more through investigation for similar mineralization. Further, if the norites of Sudbury and those of Memesagamesing and Caribou Lake resulted from comagmatic intrusion, this would give a minimum age for the juxtaposition of the Grenville and Southern Province because the Sudbury norites give an isotopic and palaeomagnetic age of $1900 \pm 100$ Ma (Urry and Russell, 1964; Fairbairn et al., 1968; Souch et al., 1968; Huist and Wetherill, 1974; Gibbins and McInnes, 1974; Krogh and Davis, 1974; Irving, 1978).

Most Grenvillian rocks were altered by the Grenville orogeny and have reset magnetization ages. Thus determining the residual primary pole position is often difficult. The norites of the study area were chosen because they appear to be relatively unmetamorphosed and to be very similar petrographically to be Sudbury norites.

1.2) Location of the area

The Memesagamesing Lake stock and the Caribou Lake complex are located in the northwest corner of the exposed part of the Grenville Structural Province in Ontario (Fig. 1a). They are about 60 km south of the Grenville Front. The Sudbury Irruptive is about 30 km north of
the Front in the Southern Structural Province or about 90 km northwest of the study area. The Memesagamesing and Caribou Lake intrusives are about 3 km apart. The Caribou Lake complex is accessible by Highway 522 which passes by the southern part of the lake. A sideroad from Highway 522 ends midway along the west side of the Memesagamesing Lake (Fig. 1b). Outcrops of both intrusive bodies are accessible by boat around the lakes.

1.3) Previous Studies

Satterly (1942) first described the norites in his geological study of the Memesagamesing Lake stock. Later Friedman (1957) mapped the stock and studied the petrology of its intrusive phases. He considered it to be intruded after the 1400-1200 Ma Grenvillian orogeny. Lumbers (1967) examined the mineralization in the norite along the eastern shore of the lake. Later Lumbers (1969, 1971) studied the area more extensively and related the stock to a 1900-1500 Ma intrusive event.

Satterly (1942) first identified the basic igneous rocks of the Caribou Lake complex as norites. Oldham (1954) presented a map of the Caribou Lake area prepared from aerial photographs which defined the foliation patterns. Later, Friedman (1957) published an extensive report on the structure and petrology of the complex.

This is the first palaeomagnetic study done on the norites of the Memesagamesing Lake stock and Caribou Lake complex.
Fig. 1a. Location of the study area.
Fig. 1b. Access to Memesagamesing and Caribou Lake.
CHAPTER II
GEOLOGY AND MINERALOGY

The regional geology of the study area is shown in Fig. 2. The maps and discussion has been taken from Friedman (1957) and Lumbers (1969, 1971a, 1971b, 1975) for the most part. The regional geology is summarized in Table 1 (Lumbers 1971, 1975).

2.1) Regional Geology

The host rocks for both the Memesagamesing and Caribou Lake intrusives form a high rank metamorphic complex of gneissic metasediments and plutonic rocks. The oldest and most abundant rocks are metasediments derived largely from siliceous sandstone and siltstone that probably accumulated to a considerable thickness during Middle Precambrian time (Lumbers, 1971; Brocoum and Dalziel, 1973). Two major sedimentary facies are represented: a) biotite gneiss thought to reflect a eugeosynclinal facies, and b) feldspathic gneiss and muscovitic and quartzose gneiss thought to reflect a miogeosynclinal facies (Lumbers, 1971). Major features of the metasedimentary sequence together with the available geochronological data suggest that the sequence could be the eugeosynclinal and miogeosynclinal facies of the Huronian super-group of the Southern Structural Province which was deposited between 2200 and 2450 Ma ago (Lumbers, 1971; Brocoum and Dalziel, 1973; Symons and O'Leary, 1975).

Most of the plutonic rocks intruding the metasediments are now felsic gneisses forming stocks, sheets and a few batholiths (Lumbers, 1969, 1971). They are mainly granitic and monzonitic rocks. At least three ages of granitic rocks can be recognized (Lumbers, 1971). Geochronological studies (Dalziel, Brown and Warren 1969; Krogh et al, 1971; Henderson, 1972; Card et al, 1972a; Brocoum and Dalziel, 1973) suggest that the granitic rocks are generally older than the monzonitic rocks. Metamorphosed mafic plutons of several ages, some of which may be older than the felsic plutonic rocks, form small sheets, stocks and dikes in both the felsic plutons and the metasediments (Lumbers, 1969).
Fig. 2. Regional geology of the study area.
Table I.

TABLE OF LITHOLOGIC UNITS FOR THE STUDY AREA (LUMBERS, 1971).

F. CENOZOIC

(ii) RECENT - Swamp, Lake and Stream deposits.

(i) PLEISTOCENE - Varved clay, sandy and silty boulder clay, sand, pebble gravel, boulder gravel.

---------------------------------- Unconformity ----------------------------------

E. PALEOZOIC

(iii) UNCLASSIFIED - Sandstone (on Iron Island).

(ii) ORDOVICIAN

(i) MIDDLE ORDOVICIAN - Limestone, dolostone, shale, sandstone, conglomerate.

---------------------------------- Unconformity ----------------------------------

D. CAMBRIAN

(i) ALKALIC AND MAFIC INTRUSIVE ROCKS

Carbonatite and barite veins, lamprophyre and felsite dikes, nepheline and alkaline syenites, fenite, mafic and ultramafic alkalic rocks, carbonatite, silicacarbonatite.

---------------------------------- Unconformity ----------------------------------

C. PRECAMBRIAN

---------------------------------- Unconformity ----------------------------------

B. LATE PRECAMBRIAN (a)

(ii) MAFIC INTRUSIVE ROCKS - Diabase dikes, diabase, quartz diabase.

---------------------------------- Intrusive Contact ----------------------------------

(i) MAFIC STOCKS - Norite, olivine gabbro, uralitized gabbro, metabasalt, uralitized and serpentinized pyroxenite and peridotite.
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A. **METAMORPHIC COMPLEX** (Probably Middle to Late Precambrian).

(iv) **LATE PEGMATITE** - Granite Pegmatite dikes.

---------------------- HIGH RANK REGIONAL METAMORPHISM ----------------------

(iii) **MAFIC PLUTONIC ROCKS**

Metagabbro, metadiorite, metamorphosed ultramafics, fine and medium grained amphibolite dikes, metadiabase dikes.

(ii) **FELSIC PLUTONIC ROCKS**

Monzonitic Rocks - gneissic, garnet-hornblende monzonitic rocks with associated gneissic granitic rocks; gneissic tonalite and gneissic diorite.

Granitic Rocks (b) - Migmatic and gneissic biotite granite; nonmigmatic gneissic biotite granite; migmatitic and gneissic garnet-biotite and hornblende-biotite granite.

---------------------- Intrusive and Metamorphic Contact ----------------------

(i) **METASEDIMENTS**

Calcareous Metasediments, carbonate metasediments, hornblende gneiss.

Clastic Siliceous Metasediments, biotite gneiss, Quartzose and Muscovitic gneiss, feldspathic gneiss.

---

**note:**

(a) Some mafic intrusive rocks may be Early Palaeozoic in age.

(b) Multiple ages represented.
(The youngest rocks of the metamorphic complex are amphibolite dikes which are probably metamorphosed gabbroic hypabyssal intrusions (Lumbers 1971, 1975). The metamorphic complex underwent a complicated history of deformation, plutonism and metamorphism during the Middle and Late Precambrian (Dalziel, Brown and Warren, 1969; Krogh et al, 1971; Lumbers, 1971; Henderson, 1972; Broccoum and Dalziel, 1973.) Following major plutonism, the entire complex was subjected to a late high-rank regional metamorphic event known as Grenville orogeny which culminated between 1400 and 1200 Ma ago. Dikes of massive granite pegmatites were emplaced into all rocks of the metamorphic complex during the waning stages of the orogeny.

Following the Grenville orogeny, the region was subjected to faulting along two major systems (Lumbers, 1971) - a WNW and NE system. During this tectonism, gabbroic stocks and diabase dikes intruded the metamorphic complex (Lumbers, 1971).

By Cambrian time, a westerly trending graben had formed across the central part of the area (Lumbers, 1971). Cambrian alkalic complex and associated lamprophyre dikes were emplaced within this graben.

Middle Ordovician sedimentary rocks, the youngest rocks exposed, were deposited within the graben. At one time, they may have covered most of the earlier rocks outside the graben also (Lumbers, 1971).

Finally the area was subjected to Pleistocene glaciation. When the ice margin of the Wisconsin ice-sheet retreated to the north of the study area about 9500 to 10000 years ago, post glacial lakes inundated parts of the area (Lumbers, 1971). Post glacial uplift of the area drained these large lakes to leave numerous small lakes in depressions and extensive deposits of sand, gravel and varved clay. Recent deposits consist of muskeg accumulations and local fluvial and lacustrine deposits.

2.2a) Geology of the Memesagamesing Lake Stock

The Memesagamesing Lake stock is exposed along the shores and islands of the Memesagamesing Lake (Lumbers, 1971). The stock is crudely elliptical in plan with its long axis trending northwest (Fig. 3.).
Fig. 3. Geology and site locations for the Memesagamesing Lake Stock.
More than one half of the stock is covered by the lake, but the available exposures and airborne magnetics suggest that the stock is about 5 km long and 2 km across (Lumbers, 1969, 1971).

Evidence for the intrusion of the stock into the migmatitic metasédiments and gneissic biotite granite sheets is clearly exposed in only a few places. According to Lumbers (1971) the stock contains mainly layered norites and olivine gabbros. The primary minerals are extensively granulated leading to the alteration of pyroxene to amphibole, and to the development of biotite and garnet. He believes that the granulation was caused by 1900-1500 Ma intrusive event. Friedman (1957) stated that rocks showed little or no deformation and he believes that they were emplaced after the Grenville orogeny.

Dikes and small apophyses of norites are present in the gneisses close to the contact (Lumbers, 1971). In places they are found to be brecciated and recrystallized to yield granoblastic texture. Inclusions of the gneisses are found within the stock near its margin, and some of these inclusions are separated from the surrounding norites by reaction rims rich in garnet.

At least three major fault zones (Fig. 3) cut across the stock without any appreciable lateral displacement (Lumbers, 1971). One of these faults, trending WNW, contains a late 45 m wide dike which is believed to be a member of the Sudbury olivine diabase dike swarm emplaced about 1250 Ma ago (Van Schmus, 1965; Fairbairn and others, 1969; Gates, 1971, 1972; Gates and Hurley, 1973; Palmer et al, 1977; Schwarz, 1977).

2.2b) Geology of the Caribou Lake Complex

The Caribou Lake complex intrudes a belt of high grade metamorphic rocks composed mainly of gneisses, granitic rocks, and granitized sediments (Friedman, 1957). A distinct foliation pattern is observed in the gneisses (Oldham, 1954) with a generally N-S trend. This foliation is attributed to the Grenvillian orogenic movement (Friedman, 1957). The intrusive body is tadpole-shaped with a length of ~8 km and a width of ~3 km. It includes mainly ultrabasics, norites, with a few granite pegmatites (Friedman, 1957). The roof of the intrusive body is exposed
in a triangular fault block on the south shore of the Caribou Lake.

The complex is overlain by an orthopyroxene-bearing rock of granodioritic composition which is considered by Friedman (1957) to be a phase of the intrusive body. This rock is extensively jointed and some of these joints extend into the metasedimentary country rocks. The jointing is less prominent in the eastern part than in the western part (Friedman, 1957). One set of vertical joints roughly parallels the E-W intrusive contacts. Another prominent set of tensional joints trends N to NE and carries some mineralization. There is also a third set of joints present with a westerly trend but it is less common (Friedman, 1957).

Zoned granite pegmatite dikes are found mostly in the complex where they occupy joint planes. The contacts between the dikes and the norites are sharp. Some pegmatites and granitic veins are slightly displaced by faults.

The Caribou Lake intrusive body is cut by several W to NW trending faults (Fig. 4) forming trench-like depressions (Friedman, 1957).

2.3) Petrography of Memesagamesing and Caribou Lake Intrusives

2.3a) Memesagamesing Lake Stock

The Memesagamesing Lake stock consists of norite with minor olivine gabbro zones which have been cut by granite pegmatite and diabase dikes (Lumbers, 1969, 1971).

The norites are medium grained, light grey rocks composed essentially of labradorite, hypersthene, and augite which weather to a light brown colour (Lumbers, 1971). Hypersthene predominates over augite. Microscopically the norites show evidence of cataclastic deformation yielding granulation of the primary minerals and development of mortar structure. Pyroxene grains are partly altered to amphibole, biotite, garnet, epidote, and iron-titanium oxides. Plagioclase ranges in composition from An$_{48}$ to An$_{60}$ and it is clouded in some rocks. Much of the norite is anorthositic. The margin of the stock has more calcic plagioclase and magnesian hypersthene than the core (Lumbers, 1971).

Olivine gabbro, exposed on small islands in the lake, consists of labradorite, clinopyroxene, orthopyroxene and olivine with minor pyrrhotite, iron titanium oxide minerals and greenish spinel. Biotite,
Fig. 4. Geology and site locations for the Caribou Lake Complex.
amphibole, serpentine and garnet are present as secondary minerals (Lumbers, 1971).

The granite pegmatite dikes are emplaced in late fractures after cooling of the stock (Lumbers, 1971, 1975). The norite, adjacent to these dikes, is recrystallized and altered to amphibolite.

The diabase dikes generally have a W to WNW trend in the area. These rocks are massive, grey to black on fresh surface with prominent tabular plagioclase, they also weather to a brown colour.

2.3b) **Caribou Lake Complex**

The Caribou Lake complex consists mainly of ultrabasics, norites and granite pegmatites (Friedman, 1957).

The ultrabasics include picrite, olivine norite and pyroxenite. The picrite is a dark, brownish green, coarse grained rock with the olivine grains enclosed within poikilitic pyroxene plates. The primary minerals are olivine, clinopyroxene, orthopyroxene and plagioclase. The olivine norites have a higher feldspar content than that in picrites. Magnetite, pyrrhotite, pyrite, spinel and their intergrowths are locally enclosed in secondary amphibole or mica. Pyroxenite occurs only on the south shore of the lake.

The norites of the complex are typically a light grey, medium to coarse grained rock showing granitoid texture that weather to a brown colour. The essential minerals are labradorite, hypersthene and augite. Magnetite and apatite occur as accessory minerals. Norite pegmatites and aplites cut earlier norites. Granulation and mortar structure in the feldspar and pyroxene grains suggest that the norites were subjected to cataclastic changes. Secondary minerals in the norite include hornblende, biotite, garnet, clinzoisite, scapolite, quartz, apatite, sphene, spinel, pyrite, pyrrhotite, titaniferous magnetite, chalcopyrite and carbonate. Reaction rims of garnet commonly separate pyroxene crystals from feldspar crystals. Occasionally the feldspars are clouded by minute inclusions.

The granite pegmatite dikes which cut the norites are commonly zoned. Their quartz core is surrounded by a feldspar zone which is surrounded in turn by a marginal zone where the feldspar is intergrown with quartz.
and mica. Tourmaline is a rare accessory mineral. The pegmatites may be genetically related to the granite occurring on the NE shore of Caribou Lake (Friedman, 1957).

2.4) Mineralization

2.4a) Memesagamesing Lake Stock

Six poorly exposed zones of disseminated sulphide mineralization are exposed within the norite stock (Lumbers, 1971; Fig. 3.) Most of the mineralization is found in shear zones along the NNW trending fault system. Disseminated pyrrhotite, pyrite, magnetite and chalcopyrite are the main minerals found in order of decreasing abundance (Lumbers, 1971). Potential economic products include copper, nickel, and uranium with traces of gold, silver and molybdenum (Satterly, 1942, p. 34).

2.4b) Caribou Lake Complex

Abundant pyrrhotite, titaniferous magnetite, pyrite and sparse chalcopyrite occur either in stringers or as disseminated crystals in the norite (Friedman, 1957).
CHAPTER III
EXPERIMENTAL METHODS

3.1) Sampling

Specimens were collected from 24 and 26 sites in the Memesagamesing Lake stock (Fig. 3) and Caribou Lake complex (Fig. 4) respectively. The sites were distributed throughout the intrusive bodies. At each of the sites, five or six cores were drilled several metres apart. They were oriented in situ to an accuracy of $\approx 2^\circ$ using both a solar compass and a Brunton compass with topographic sitings. Care was taken to avoid topographically high areas that are susceptible to lightning strikes. Thus, the majority of the sites were collected by boat from outcrops along the shoreline and islands in the lakes.

Eight additional sites were collected from the Memesagamesing Lake stock for baked contact tests (Fig. 3).

3.2) Sample Preparation

The drilled cores are 2.5 cm in diameter. They were sliced to yield a minimum of two conventional cylindrical specimens of 2.5 cm in length. Thus there are at least ten norite specimens from each site. This gives a database of 260 specimens for the Caribou Lake complex and 240 specimens for the Memesagamesing Lake stock. An additional 230 specimens were obtained for performing the baked contact tests on the Memesagamesing Lake stock.

3.3) Sample Treatment

3.3a) Natural Remanent Magnetization (NRM)

The NRM components of all 730 specimens were measured using a Schonstedt SSM-1A spinner magnetometer. A '3-spin' technique was used for all of the cores. The NRM direction and intensity for each specimen were computed from the component measurements using standard computer programmes.

3.3b) Alternating Field (AF) cleaning

One pilot specimen per site with a representative NRM direction and
intensity for that site was step demagnetized in alternating fields with peak intensities of 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90 and 100 mT using a Schonstedt GSD-1 AF demagnetizer.

The palaeomagnetic stability index (PSI) method of Symons and Stuparyk (1974) for directional analysis and the intensity decay curves for each pilot specimen were used to select the optimum AF intensity for demagnetizing the remaining specimens from each site. The PSI values, the corresponding intensities and directions for each cleaning field, and the vector-removed between each demagnetization step were computed using the PSI computer programme for each specimen.

3.3c) Thermal Step Cleaning

AF cleaning of the Caribou Lake specimens revealed that their directions and magnitudes became unstable at moderate fields of about 20 mT. Therefore, they were considered unsuitable for analysis by thermal demagnetization.

One specimen per site from the Memesagamesing Lake stock, having a representative NRM direction and intensity for that site, was thermally step demagnetized at temperatures of 100°, 200°, 300°, 400°, 450°, 500°, 525°, 540°, 555°, 570°, and 580°C. A furnace, having a non-inductive heating element and located in a series of five nested 'mu'-metal shields in a shielded room, was used for the process. The introduction of partial thermoremanent (TRM) components during cooling of the specimens because of incomplete shielding of the Earth's field was checked by orienting the specimens in opposite directions during successive heating steps. The PSI for directional stability and the intensity decay plots were computed.

3.3d) Chemical Cleaning

Chemical cleaning was performed on one representative specimen per site from the Memesagamesing Lake stock to assess the merit of using this process for isolating primary remanence components. The cleaning process lasted for 120 days until the specimens disintegrated. Following the techniques of Park (1970) and Roy and Lapointe (1975), slots were cut in the specimens before commencing the cleaning process.
The specimens were then immersed in 6N HCl at room temperature and stored in 'mu'-metal shields between successive measurements. They were washed in water after each step, allowed to dry and their remanance of the specimens was measured after 5, 10, 15, 20, 25, 30, 45, 60, 90 and 120 days. As before, the variation in direction and intensity was analysed using the PSI index method and intensity decay plots.

3.3e) **Cryogenic Test**

Ozema *et al* (1964) originally noted that supercooling rock specimens, especially those with large magnetite or hematite grains causes them to become demagnetized. They suggested that the anisotropy energy of magnetite decreases thereby causing a partial demagnetization of the NRM as the unstable low coercive force components are randomized. Thus, they suggested that the supercooling treatment of rocks may provide a quick and effective way of magnetic cleaning. Merrill (1970) compared the low temperature and AF cleaning methods for magnetite samples. His results suggest that the combination of both methods may be very useful in separating the magnetic behaviour of the multidomain grains from that of the single domain grains.

One specimen from 19 of the Memesagamesing Lake stock sites was cooled down to liquid nitrogen temperature (-196°C) and then allowed to heat back up to room temperature in a field-free space provided by 'mu'-metal shields. The magnetic remanence of these specimens was then remeasured. Two cycles were repeated in this way. Unfortunately, when the directions were plotted on a stereonet, they gave a random distribution.

3.3f) **Magnetic Bulk Susceptibility**

The low field (≈0.1 mT) magnetic susceptibility perpendicular to banding (K) was measured on a toroid bridge (Christie and Symons, 1969) for all 500 specimens from Memesagamesing and Caribou Lake intrusives. The site mean bulk susceptibility was then calculated for each site.
3.3g) Anisotropy of Magnetic Susceptibility

The toroid bridge was also used to measure the low field magnetic susceptibility along nine directions of all 500 specimens from Caribou Lake complex and the Memesagamesing Lake stock. This data was used to calculate the matrix elements of the anisotropy of susceptibility ellipsoid for each specimen. The principal susceptibilities were calculated by a method of successive approximation. The direction and magnitude of the principal axes, the ratio between the axes (K_int/K_min, K_max/K_min), and Koenigsberger ratio were calculated using an existing laboratory computer program (MFABRIC). Another existing program (MFABRIC Mean) was used to calculated the mean direction and magnitude of principal axes, and the mean Koenigsberger ratio for each site.

3.3h) Baked Contact Test

Baked contact tests were performed to examine the stability of the norite magnetization. The test is based on the fact that when an igneous rock intrudes an older host rock, the intrusion heats the contact margin of the host rock. The host rock margin upon cooling will acquire a remanence in the same magnetic field as that in which the intrusive became magnetized (Everitt and Clegg, 1962). The country rock and the intrusives are generally different rock types with different ferromagnetic mineralogy, and the host rock magnetization must predate intrusion. Therefore, if the dike magnetization has not been reset since intrusion, agreement between the intrusion and host rock margin directions proves the stability of the intrusive magnetization. The test is more conclusive if it can be shown that there are changes in magnetic properties such as the remanence direction and the bulk magnetic susceptibility with increasing distance from the baked contact which correspond to the diminishing heating effects of the intrusion (Everitt and Clegg, 1962).

Granite pegmatite and olivine diabase dikes cut the Memesagamesing Lake stock and surrounding host rock. The age of granite pegmatite dikes (~1050-1100 Ma) are well defined by extensive radiometric dating (Van Schmus, 1965; Krogh and Davis, 1972) and the olivine diabase dikes
are believed to be members of the Sudbury diabase dike swarm (Lumbers, 1971). The Sudbury dikes have radiometrically (Rb-Sr) been dated to be about 1250 Ma old (Fairbairn et al., 1969; Gates, 1971, 1972; Gates and Hurley, 1973; Palmer et al., 1977; Schwarz, 1977). Therefore, several contacts of these dikes with the norites were chosen for the test.
CHAPTER IV
DISCUSSION OF RESULTS

4.1) Natural Remanent Magnetization

4.1a) Memesagamesing Lake Stock

The NRM intensities (Jo) of the 240 Memesagamesing Lake specimens exhibit a lognormal distribution with a broad spectrum of values ranging from $1.61 \times 10^{-6}$ emu cm$^{-3}$ to $4.37 \times 10^{-1}$ emu cm$^{-3}$ which give a lognormal mean of $4.2 \times 10^{-3}$ emu cm$^{-3}$.

The 240 remanence directions from the specimens were calculated. These directions were plotted on an equal area projections with the upward and downward directions being plotted separately. The directional point desities were then contoured using a 1% smoothing circle. (Stupavsky and Symons, 1980). Most of the downward directions are similar to that of the present Earth's magnetic field. The downward directions showed a well defined concentration at $\sim 150^\circ$, $\sim 60^\circ$, (declination, inclination) (Fig. 5a). Relatively few directions were scattered. The upward remanence directions showed a distinct anomaly at $\sim 300^\circ$, $\sim 55^\circ$ (Fig. 5b) with relatively few scattered directions. The stereoplot of the downward directions suggest that the NRM is dominantly a secondary or viscous remanence (VRM) in origin, and records the ambient Cenozoic magnetic field of the Earth.

The NRM of one specimen per site was remeasured after a storage period of 12 weeks. No significant change in intensity or direction occurred during the storage. This suggests that the NRM components are relatively stable.

4.1b) Caribou Lake Complex

The NRM intensities (Jo) of the 260 Caribou Lake specimens also exhibit a lognormal distribution with values ranging from $7.23 \times 10^{-7}$ emu cm$^{-3}$ to $2.5 \times 10^{-1}$ emu cm$^{-3}$ which give a lognormal mean of $4.9 \times 10^{-4}$ emu cm$^{-3}$.

The 260 NRM directions were calculated, plotted and contoured on equal-area projections, as before. The downward directions form a major anomaly at $\sim 110^\circ$, $\sim 70^\circ$ (Fig. 6a). The upward remanence
Fig. 5a and 5b. Equal area projection showing point density contours of the Memesagamesing Lake NRM directions.
(The contours are in % of the total directions.)
directions were scattered with a minor concentration close to the vertical position of the stereonet. (Fig. 6b).

A storage test lasting 12 weeks was performed on 26 specimens representing each of the 26 sites. The NRM directions were found to be essentially unchanged which suggests that their NRM components are also relatively stable.

4.2) AF Cleaning of Mensesagamesing Lake Specimens

4.2a) Pilot Specimens

Twenty four pilot specimens representing each site were step demagnetized to 100 mT. Fig. 7 shows the intensity decay curves for 3 pilot specimens. These represent 3 of the most stable sites and display the two common types (A & B) of decay behaviour. Fig. 8 shows a plot of radii for circles of 95% confidence ($R_{95}$) about each mean direction with increasing demagnetizing field for the A and B groups decay behaviour found in the pilot specimens. The remanence directions of the 3 specimens at each demagnetizing field representing the A and B groups are shown in Fig. 9. Zijderveld (1967) noted that the intensity decay curves show the magnitude of the vector sum of different magnetizations. Fig. 10 shows Zijderveld diagrams for the progressive AF demagnetization of the 3 pilot specimens. They show the north-south (N-S), east-west (E-W) and vertical (V) components at each demagnetizing step.

Sites 15 and 24 represent group A intensity decay behaviour (Fig. 7). They show an increase in the relative intensity up to ~10 mT, followed by a smooth decay with the curves flattening out in the 50-60 mT range. Thus, they exhibit the rapid removal of significant VRM components up to the 10-15 mT range. Between ~15 mT and ~70 mT the intensity decay rate is low and decreasing which suggests the progressive isolation of a stable remanance component. They are seen to be stable even up to a field of about 100 mT which is recorded by the decay curves which proves that no significant anhysteretic remanence components have apparently been added by the demagnetization process. The Zijderveld plot (Fig. 10) for site 15 shows the removal of a large vertical component in the E-W vs
Fig. 7  Intensity decay curves for AF cleaned pilot specimens from Nemesagamesing Lake Stock
Fig. 8. Radii for circles of 95% confidence for the mean direction at each peak AF demagnetizing field for the Nemesagamesing Lake specimens.
Fig. 9 Equal area projection showing the change in direction on progressive AF cleaning of Memesagamesing pilot specimens.
Fig. 10 Zijderveld plots for AF cleaned Memesagamesing pilot specimens
Fig. 10 (cont.) Zijderveld plots for AF cleaned Memesagamesing plot specimens
vertical component & in the N-S vs E-W horizontal component, the removal of a large horizontal component. Thus, the plots for site 15 show the isolation of a single component up to \( \sim 100 \) mT as evidenced by the fact that the curves pass almost exactly through the origin of the plot. A similar plot (Fig. 10) for site 24 shows the loss of only a small amount of intensity during the whole demagnetization process but the decay curves project to pass near the origin. Their positions at 100 mT are sufficiently far from the origin to suggest the isolation of a very hard primary remanence component. Thus the demagnetization process may have only succeeded in isolating a moderately stable but not a hard stable primary component. The remanence direction of group A, represented by sites 15 and 24 (Fig. 9), show a considerable stability up to \( \sim 100 \) mT. They isolate a direction of \( \sim 280^\circ, -55^\circ \). The plot of \( A_{95} \) for each mean direction for the A group (Fig. 8) show its minima in the 55-70 mT range as the stable component is isolated. The marked increase in \( A_{95} \) at \( \sim 85 \) mT suggests the concept of introduction of randomly directed ARM components during the demagnetizing process.

Site 5 represents the B group of demagnetization behaviour. It shows a continual decrease in relative intensity with increasing intensity of the AF cleaning field from the NRM intensity (Fig. 7) which flattens out in the 50-60 mT range. In other respects, this B group of specimens behave in the same way as the A group. The Zijderveld plot (Fig. 10) for a B group specimen shows the removal of a stable component when the E-W vs vertical component is plotted. Its intensity has decayed considerably by \( \sim 60 \) mT above which the direction becomes erratic suggesting the acquisition of spurious ARM components during high AF demagnetization. The plot of the N-S vs E-W component for the same group shows a stable component being removed to to \( \sim 80 \) mT above which the spurious ARM components appear. Their presence is recorded by the bending of the curve away from the origin of the plot. The remanence directions of the B group at each peak demagnetizing field (Fig. 9) show some instability above \( \sim 80 \) mT. A direction of \( \sim 330^\circ, -58^\circ \) is isolated by the AF demagnetization process. Like the A group, the plot of \( A_{95} \)
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<th>PSI (minima)</th>
<th>Remanance Decl. (degrees)</th>
<th>Direction Incl. (degrees)</th>
<th>Intensity (emu cm$^{-3}$)</th>
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for the mean direction at each AF cleaning field (Fig. 8) for the B group show a minima in the 55-70 mT range as the stable component is isolated. At ~85 mT a marked increase in $A_{g5}$ is observed which suggests the introduction of randomly directed ARM components.

The optimum cleaning fields for the rest of the specimens were selected on the basis of the PSI minima and the degree of coincidence between the vector-removed between successive cleaning steps and the measured vector at each step.

The magnetic coercivity spectrum for a specimen on AF demagnetization may be defined in part by its median destructive field (MDF). The MDF is the AF coercive force ($H_c$) that is required to demagnetize one-half of the NRM intensity. The plots of relative remanance (Fig. 7) intensity against the peak AF demagnetizing field for the Memesagesing Lake Pilot specimens show that they have $H_c$ values of ~10 mT which is a further indication that relatively soft, secondary VRM components are present.

4.2b) Remaining Specimens

The remaining 192 specimens were demagnetized using the optimum AF intensity selected for each site from the pilot specimens (Table II). Three criteria were observed for data screening. First the specimen directions were combined for core means if the mean length of resultant vector $R > 1.88$ After that, a minimum of 3 core means for each site were required to compute the site means and the site means were accepted if the mean radius for their circles of 95% confidence was 10° or less ($A_{g5} < 10°$). The screened specimen directions were combined using conventional tiered statistics to give the mean direction and pole position for the Memesagesing Lake Stock (Table III). Twelve out of the 24 sites survived the screening process. The mean direction was found to be 299°, -51°, 10°, (i.e. declination, inclination, and $A_{g5}$) involving 40 cores in all (Fig. 11). This mean direction gives a pole position of 31.5°W and 3.8°N (longitude and latitude).

A second method of analysis was attempted. All of the AF cleaned specimen directions were plotted and contoured on equal-area stereonets (Fig. 12a and 12b). The upward remanence directions showed a significant
Table III

Summary of the Remanence Directions after AP cleaning for the Memesagamesing Lake Morites.

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<tr>
<th>Site Number</th>
<th>Number of Cores</th>
<th>AP cleaning field (mT)</th>
<th>Site Mean Remanence Decl. (degrees)</th>
<th>Incl. (degrees)</th>
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<th>Aq°</th>
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Mean Values

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<th>Incl.(deg.)</th>
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<th>Aq°</th>
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Mean Pole Position

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* The sites surviving the statistical treatment and used for computing the mean direction and pole position.
Fig. 11 Equal area of projection showing the mean stable direction isolated at 12 sites from Nemesagamesing Lake Stock after AF cleaning.
(The heavy circle denotes the mean.)
Fig. 12a and 12b. Equal area projection showing point density contours for AF cleaned Memesagamesing Lake directions. (The contours are in percentage of the total directions.)
concentration at \( \sim 300^\circ, \sim -54^\circ \) which corresponds closely to the mean direction computed using tiered statistics. The downward remanence directions also show a single concentration at \( \sim 118^\circ, \sim 48^\circ \) which is antiparallel to the upward remanence concentration. If the stereographic plots of the specimen NRM directions (Fig. 5a and 5b) are compared to that of the AF cleaned directions, then it is apparent that declination has changed by \( \sim 50^\circ \) in case of upward remanence and by \( \sim 180^\circ \) in case of downward remanence directions with little change in the inclinations. i.e., both show a shift from the present Earth's magnetic field direction.

4.3) **AF Cleaning of Caribou Lake Specimens**

4.3a) **Pilot Specimens**

Twenty six pilot specimens from the Caribou Lake complex were AF step demagnetized up to 100 mT. A careful study of the directional changes and intensity decay with progressive AF demagnetizing field reveals two contrasting behaviours. Most specimens give remanence directions that are too erratic to analyse, and remanence intensities that lose 60% of their NRM intensity by 100 mT. Conversely, a few specimens give directions that are unchanged up to 100 mT and show only a 30-35% loss of their original NRM intensity.

4.3b) **Remaining Specimens**

The PSI minima determined from the pilot specimens for each site was used as the optimum AF cleaning treatment for the rest of the specimens from the site (Table IV). All the AF cleaned specimen directions were plotted on equal area stereonets and contoured (Fig. 13a and 13b). The upward remanence directions showed several minor concentrations at \( \sim 125^\circ, \sim -80^\circ \), at \( \sim 270^\circ, \sim -30^\circ \) and at \( \sim 320^\circ, \sim -52^\circ \). More than half of the specimen directions were scattered and did not contribute to any of the concentrations. The downward remanence directions defined one concentration of \( \sim 128^\circ, \sim 45^\circ \), although less than half the specimen directions contributed to the concentration. This direction is close to being antiparallel with the remanence concentration of \( 320^\circ \) and \( -52^\circ \). Combining these two antiparallel directions a mean stable direction of \( 310^\circ, -48^\circ \) is observed for the Caribou Lake specimens. The direction at \( \sim 270, -30^\circ \)
# Table IV

**Optimum AF Cleaning Fields of Caribou Lake Specimens Using the PSI Minima**

<table>
<thead>
<tr>
<th>Core Number</th>
<th>Cleaning Field (mT)</th>
<th>PSI (minima)</th>
<th>Remanance Direction Decl. (degrees)</th>
<th>Remanance Direction Incl. (degrees)</th>
<th>Intensity (emu cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA83000401</td>
<td>30</td>
<td>334</td>
<td>23</td>
<td>-19</td>
<td>0.169E-03</td>
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<tr>
<td>10501</td>
<td>40</td>
<td>595</td>
<td>263</td>
<td>32</td>
<td>0.980E-04</td>
</tr>
<tr>
<td>20201</td>
<td>30</td>
<td>957</td>
<td>325</td>
<td>60</td>
<td>0.129E-03</td>
</tr>
<tr>
<td>30201</td>
<td>60</td>
<td>317</td>
<td>123</td>
<td>7</td>
<td>0.559E-04</td>
</tr>
<tr>
<td>40501</td>
<td>30</td>
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<td>315</td>
<td>-41</td>
<td>0.195E-03</td>
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<td>50401</td>
<td>30</td>
<td>24</td>
<td>63</td>
<td>61</td>
<td>0.443E-04</td>
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<td>60301</td>
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<td>380</td>
<td>233</td>
<td>-44</td>
<td>0.352E-03</td>
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<td>70101</td>
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<td>544</td>
<td>249</td>
<td>-31</td>
<td>0.106E-03</td>
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<tr>
<td>80301</td>
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<td>272</td>
<td>329</td>
<td>4</td>
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<tr>
<td>130501</td>
<td>20</td>
<td>704</td>
<td>275</td>
<td>44</td>
<td>0.776E-03</td>
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<td>140301</td>
<td>100</td>
<td>348</td>
<td>281</td>
<td>-60</td>
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<tr>
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<td>220401</td>
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<td>0.206E-03</td>
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<tr>
<td>230301</td>
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<td>69</td>
<td>95</td>
<td>24</td>
<td>0.183E-04</td>
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<td>240101</td>
<td>20</td>
<td>893</td>
<td>333</td>
<td>-5</td>
<td>0.658E-03</td>
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<tr>
<td>250501</td>
<td>40</td>
<td>117</td>
<td>275</td>
<td>-8</td>
<td>0.617E-04</td>
</tr>
</tbody>
</table>
Fig. 13a and 13b. Equal area projection showing point density contours for the AP cleaned Caribou Lake directions.
(The contour increments are in % of the total directions.)
is one of the directions isolated by Sudbury diabase dikes and gives a palaeomagnetic age of \( \sim 1200 \) Ma.

4.4) **Thermal Cleaning**

4.4a) **Caribou Lake Complex**

The Caribou Lake specimens were found to be highly unstable even at a moderate field of \( \sim 20 \) mT. Therefore the collection was not thermally step demagnetized.

4.4b) **Nemesagamesing Lake Stock**

Twenty four pilot specimens were thermally step demagnetized up to \( 580^\circ C \). The pilot specimens show the same multicomponent magnetization during thermal cleaning that was observed during AF step demagnetization. The initial soft secondary VRM components, when present, are removed by \( \sim 300^\circ C \). Most of the specimens show the isolation of a single stable component up to a temperature range of \( 500^\circ C - 550^\circ C \). Above this range the directions became erratic.

The remanence directions of 4 pilot specimens are shown in Fig. 14. They illustrate the three groups of behaviour found in the specimens on thermal demagnetization. Those for sites 5 and 19 represent 12 specimens in one group. They show the isolation of a stable directions at \( \sim 320^\circ C - 55^\circ C \). The site 19 specimen is stable up to a temperature of \( 580^\circ C \). Very few specimens show such high temperature stability.

The specimen from site 9 is typical of 3 specimens that isolate a stable component with a direction of \( \sim 240^\circ C - 80^\circ C \) from room temperature up to \( 530^\circ C - 550^\circ C \) range. The specimen from site 18 represents 6 specimens that show the isolation of a viscous soft component up to \( 300^\circ C \), the isolation of a stable component at \( \sim 145^\circ C - 60^\circ C \) up to \( 540^\circ C \), and scattered directions above \( 540^\circ C \). The \( \sim 320^\circ C - 55^\circ C \) direction shown by the first group of specimens is antiparallel to the \( \sim 145^\circ C - 60^\circ C \) direction shown by the third group. The normal and reversed directions, when combined give a mean direction that is close to the mean direction computed from AF step demagnetization data.
Fig. 14. Equal area projection showing the change in direction on progressive thermal cleaning of mesosagasslinge pilot specimens.
Fig. 15 Intensity decay curves for thermally cleaned Hemesagamesing pilot specimens.
Fig. 16  Equal area projection showing the change in direction on progressive chemical cleaning of Memesagamesing Lake pilot specimens (the closed circles indicate upward directions.)
Fig. 15 shows the thermal decay curves for the example pilot specimens discussed in the preceding paragraph. All of them show a rapid increase in intensity up to \(100^\circ C\) and then a rapid drop of intensity up to \(400^\circ C\) as the secondary VRM components are removed. Above \(400^\circ C\) a stable component is isolated as the curve is seen to take a more typical knee shaped form. The thermal coercivity spectrum of the stable direction is probably carried by multidomain magnetite (Curie temperature \((T_C) = 580^\circ C\)) which is blocked above \(540^\circ C\).

4.5) Chemical Demagnetization

**Memesagamesing Lake Specimens**

Chemical Cleaning on 24 Memesagamesing Lake specimens over the 120 day period was undertaken on a speculative basis. It led to a significant decrease in remanence intensity and marked directional changes in all 24 specimens. Fig. 16 shows the directional changes for the pilot specimens representing the 3 most stable sites. After 35 days, they start to isolate a stable direction. This direction is isolated in 20 of the pilot specimens and gives a mean of \(310^\circ, -45^\circ, 15^\circ\) (Fig. 17). The other 4 pilot specimens behaved in an unstable manner on progressive chemical cleaning.

Fig. 18 shows the intensity decay curve for the same pilot specimens from the 3 of the most stable sites. They are seen to lose 50% of their original intensity within the first 5 days and a further 20% in the next 30 days. The rapid drop in intensity in the first 20 days indicates the removal of VRM components. After this, the curves flatten out, showing the isolation of a single component. The similarity in the decay curves for the 20 specimens indicates that they have the same magnetic mineralogy.

4.6) Correlation of Stable Directions Isolated by AF, Thermal and Chemical Cleaning

The mean stable direction of \(310^\circ, -45^\circ\) isolated by chemical cleaning was found to be in good agreement with those isolated by AF \(299^\circ, -51^\circ\) and thermal \(322^\circ, -58^\circ\) cleaning using the variance test at the 95% confidence level. The mean directions isolated by AF and
Fig. 17 Equal area projection showing the stable directions isolated at 20 sites from Nemesagamesing Lake Stock on chemical cleaning
Fig. 18 Intensity decay curves for chemically cleaned Hemetegamesing Lake pilot specimens.
<table>
<thead>
<tr>
<th>Populations Compared</th>
<th>No. of specimens, (N)</th>
<th>V</th>
<th>F_{0.05}</th>
<th>Test Results</th>
<th>F_C</th>
<th>F_{0.05}</th>
<th>Test Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Mem. AF vs Caribou AF</td>
<td>125</td>
<td>1.11</td>
<td>1.43</td>
<td>Positive</td>
<td>0.07</td>
<td>3.01</td>
<td>Positive</td>
</tr>
<tr>
<td>2) Mem. AF vs Mem. Thermal</td>
<td>98</td>
<td>1.23</td>
<td>1.57</td>
<td>Positive</td>
<td>0.12</td>
<td>3.09</td>
<td>Positive</td>
</tr>
<tr>
<td>3) Mem. AF vs Mem. Chemical</td>
<td>100</td>
<td>1.33</td>
<td>1.53</td>
<td>Positive</td>
<td>0.09</td>
<td>3.08</td>
<td>Positive</td>
</tr>
<tr>
<td>4) Mem. Thermal vs Mem. Chemical</td>
<td>38</td>
<td>1.34</td>
<td>1.61</td>
<td>Positive</td>
<td>0.15</td>
<td>3.14</td>
<td>Positive</td>
</tr>
</tbody>
</table>

**Table V.**

**VARIANCE TEST BETWEEN THE STABLE REMANENT COMPONENTS ISOLATED BY AF, THERMAL AND CHEMICAL CLEANING**

Note: $V = \text{Variance ratio } \frac{\chi^2_A}{\chi^2_X}$ of the 2 populations being compared.

$F'_{0.05} = \text{Theoretical Statistic } F'_{2} (N_A-1), 2(N_X-1), 0.05$ thereby setting the test at the 95% confidence level.

$F_C = \text{The statistic defined by Watson (1956) } (N-2) x (R_1+R_2-R)/(N-N_1-R_2)$

$F_{0.05} = \text{Theoretical statistic } F_2, 2(N-2), 0.05$ also setting the test at the 95% confidence level.

where $N = \text{No. of specimens, isolating the two populations that are being compared } (N_A+N_X)$.

$R = \text{Length of the vector sum given by the resultants } (R_1, R_2)$ of the two populations.

Caribou AF —— 45 specimens.
Mem. AF —— 80 specimens.
Mem. Thermal —— 18 pilot specimens.
Mem. Chemical —— 20 pilot specimens.
Fig. 19. Equal area projection showing the change in NRM directions after cryogenic testing on the Mmesagamesing Lake specimens.
thermal cleaning were also found to be in fairly good agreement (Table V).

4.7) Cryogenic Test
Memesagamesing Lake Specimens

Low temperature demagnetization was attempted on 19 pilot specimens from the Memesagamesing Lake stock. After 2 cycles of cooling the specimens from room temperature to \(-196^\circ C\) and back to room temperature, no stable component direction could be isolated. Fig. 19 is a plot of the specimen directions after the first and second cycle. However, the specimens lost about 50% of their NRM intensity by the second cycle of cooling.

4.8) Magnetic Susceptibility
4.8a) Memesagamesing Lake Stock

The \(K\) values for the 240 specimens from the Memesagamesing Lake stock show a wide range from \(3 \times 10^{-5}\) to \(912 \times 10^{-5}\) cgs cm\(^{-3}\). The \(K\) values for each site were calculated by taking the mean of the 10 specimens for that site. Fig. 20 shows the site mean \(K\) values plotted on a plan of the stock. The \(K\) values in the centre of the stock are very high compared to the very low values found around the edges of the stock. The \(K\) anomaly pattern for the Memesagamesing Lake stock explains the aeromagnetic anomaly found over the stock (31L4-Nippising Lake, 1487G; 41L1-Noelville, 1499G). The high anomaly magnitudes over the center of the stock simply indicate the presence of rock of high magnetic susceptibility. Thus Lumbers' (1971) explanation that the high central values of the aeromagnetic anomaly are caused by the presence of a thick central pipe of norite, i.e., a funnel-shaped body, extending to the depth is wrong. His interpretation was based on a very few samples which clearly do not represent the stock. The present study indicates that the \(K\) values are consistent with the stock having nearly vertical contacts with the norite in the core having a higher concentration of magnetite.
Fig. 20. $K$ anomaly map of the Memesagamesing Lake Stock.

(Note: The contours are in cgs/cm$^2$ x $10^{-5}$ units.)
Fig. 21. $K_1$ anomaly map of the Caribou Lake Complex.

(Note: The contours are in cgs cm$^{-3} \times 10^{-5}$ units.)
4.8b) **Caribou Lake Complex**

The $K$ values for the 260 specimens from the Caribou Lake complex also show a wide range from $2 \times 10^{-5}$ to $198 \times 10^{-5}$ cgs cm$^{-3}$. The mean $K$ values for each site were calculated from $K$ values for 10 specimens for that site. These are plotted and contoured on a plan of the complex (Fig. 21.) The highest $K$ values are centred along the E-W axis of the complex giving 3 major anomalies. The $K$ anomaly map corresponds to the areomagnetic maps of the area (31E16 - Golden Valley 1486G; 41h13 - Noganosh Lake, 1498G), especially to the anomalies at the western and eastern ends of the E-W axis of the complex. Thus Friedman's (1957) explanation that the complex is a canoe-shaped or funnel-shaped body with a thicker column of rocks extending to depth is also wrong. His interpretation was based on only 5 samples which obviously do not represent the complex.

4.9) **Anisotropy of Magnetic Susceptibility**

4.9a) **Memesagamesing Lake Stock**

Magnetic fabric in the Memesagamesing Lake intrusive results from preferred orientations of magnetite grains. The minimum susceptibility direction ($K_{\text{min}} = K$) is perpendicular to the banding and the intermediate ($K_{\text{int}}$) and maximum ($K_{\text{max}}$) directions lie in the plane of the banding. The mean magnitude ratio for the stock of $K_{\text{int}}/K_{\text{min}}$ is 1.1 and $K_{\text{max}}/K_{\text{min}}$ is 1.2. Thus the mean banding plane susceptibility is:

\[
K_{11} = \frac{(K_{\text{int}} + K_{\text{max}})}{2}
\]

\[= 1.15K\]

The ratio between $K_{11}$ and $K$ suggests that the Memesagamesing Lake norites are distinctly layered even though banding is not commonly observed in the field.

The mean orientations of the maximum - intermediate planes of the susceptibility ellipsoid for each site are plotted on a plan of the stock (Fig. 22). The mean strike and dip of the plane for each site was computed from those of 10 specimens for that site. The
Fig. 22. Plan of the Memesagamesing Lake Stock showing the orientation of the $K_{\text{max}} - K_{\text{int}}$ plane of the susceptibility ellipsoid at each site.

(Note: The arrows and the numbers represent the directions and the amounts of dip respectively of the $K_{\text{max}} - K_{\text{int}}$ plane.)
figure suggests that the trends of the maximum-intermediate planes are subparallel to the contact of the intrusive body with the country rock because an equal numbers of the planes dip towards and away from the contact with no geographical preference. They indicate near-vertical contacts. Thus the plot suggests that neither tilting or compression occurred after the intrusion as suggested by Lumbers (1971).

4.9b) Caribou Lake Complex

The 260 Caribou Lake specimens gave a mean magnitude ratio for the complex of $K_{1}/K_{3}$ of 1.12 and that of $K_{max}/K_{min}$ of 1.27. Thus the mean $K_{11}$ was found to equal 1.195 $K$ which suggests that the Caribou Lake norites are also layered.

The mean orientation of the maximum-intermediate planes for each site is plotted on a plan of the complex (Fig. 23.) They are almost vertical near the E-W axis and are generally steeply dipping around the margins of the complex. Friedman's (1957) suggestion that the complex suffered compression along the N-S direction after intrusion to form a "canoe-shape" is wrong because the maximum-intermediate planes are not oriented perpendicular to the supposed N-S axis of compression. Figure 24 shows the plot of poles of intermediate-maximum planes, all the directions being transferred to the southern hemisphere. From the algebraic sum of the number of positive and negative inclinations, the amount of tilt if any was found out to be $\sim 5^\circ$.

4.10) Baked Contact Test

1) Stability Test

Eight sites of baked contact samples were collected for the test. Also a profile of samples were collected at site 32 (Fig. 3) perpendicular to the contact of a vertical 1.8 m wide pegmatite dike. The first sample was taken at 7.5 cm from the contact, and subsequently at 5 cm intervals up to a distance of 52.5 cm, and finally at 12.5 cm intervals up to a distance of 115 cm.

All of these specimens were thermally step demagnetized up to
Fig. 23. Plan of the Caribou Lake Complex showing the orientation of the $K_{\text{max}} - K_{\text{int}}$ plane of the susceptibility ellipsoid at each site.

(Note: The arrows and the numbers represent the directions and the amounts of dip respectively of the $K_{\text{max}} - K_{\text{int}}$ plane.)
Fig. 24  Equal area of projection showing tilt of the Caribou Lake intrusive body.
Fig. 25. Variation of the bulk susceptibility with increasing distance from the intrusive contact before and after heating.
**Fig. 26.** Variation in stable remanence direction of the host rock at increasing distances from the intrusive contact.

(Note: The arrows indicate the remanence directions.)
a temperature of 600°C. Fig. 25 shows the plot of the logarithm of bulk susceptibility with increasing distance from the contact before and after the thermal step cleaning. The plot suggests that heating has caused an increase of bulk susceptibility in the specimens. The irregularities in the curve for the unheated samples are smoothed out in the curve for thermally step cleaned specimens. The variations in susceptibility is large enough to provide evidence that the heating caused by dike intrusion or by the laboratory procedure led to an alteration in the ferromagnetic mineralogy.

Fig. 26 shows a profile of the variation in the stable remanence direction of the host rock at increasing distances from the contact. The host rock retains the dike direction of $\sim 160^\circ$, $30^\circ$ up to a distance of 44.5 cm. Beyond this distance, the dike direction starts to become less prominent, and at a distance of 75 cm from the contact the norite direction ($290^\circ$, $45^\circ$) is seen to prevail. This means that the norites retain a stable remanence which predates the intrusion of the granite pegmatite dike. The olivine diabase dikes and their baked zones showed remanence components with a direction of $\sim 160^\circ$, $30^\circ$. Incidentally, a similar direction is isolated by Sudbury diabase dikes (Palmer et al, 1977).

II) Calculation of $T_{amb}$

The maximum temperature ($T_{max}$) reached at a certain distance from a dike is known from the thermal demagnetization work. The temperature increase attributable to the dike intrusion ($\Delta T$) can be calculated to give the ambient temperature ($T_{amb}$) of the host rock from

$$T_{amb} = T_{max} - \Delta T \quad (i)$$

Directional changes for the hybrid specimens on thermal cleaning were used to calculate $T_{max}$ at a given distance from the dike when it intruded the host rock. This calculation shows that the host rock reached a temperature of $\sim 465^\circ$C at a distance of 22.5 cm from the contact.
Theory of the \( \Delta T \) Calculation

For the purpose of calculating \( \Delta T \), it is assumed that the 1.8 m wide granite pegmatite dike intruded rapidly at its melting point \( (T_{1}) \) of \( \approx 1000^\circ C \). The temperature increases due to the intrusion can be calculated using Fourier's mathematical technique for diffusion problems by assuming the heat transfer by conduction only (Jaeger, 1964; Schwarz, 1977). If the width of the zone of hybrid magnetization is less than 1/4 of the dike width, then this method is inadequate. The critical distance from the contact for the present study is 1/8 of the dike width. Therefore, the more rigorous theoretical approach of Carslaw and Jaeger (1959) is required to compensate for the inward migration from the contact of the dike's cooling front. The method also compensates for the different densities and thermal properties of the granite pegmatite dike and norite host rock.

Density and Thermal Constants

For clarity the subscripts 0 and 1 are assigned to host rock and dike properties respectively.

The mean bulk densities (SG) of 80 host rock and 10 dike specimens were measured using a pycnometer method. They are \( SG_{0} = 2.94 \, g/cc \) and \( SG_{1} = 2.70 \, g/cc \) respectively. The mean specific heats \( (C) \) at 500\(^\circ\)C of the host rock and the dike were assigned as 0.25 cal/g and 0.27 cal/g respectively from Daly (1968). The International Critical Tables (NRC, U.S.A., Vol. 2 and 5) give the thermal conductivity \( (P) \) values at 500\(^\circ\)C for the host rock and the dike of 5.02 \( \times 10^{-3} \) g-cal/cm\(^2\)-sec and 4.50 \( \times 10^{-3} \) g-cal/cm\(^2\)-sec respectively. Thermal diffusivities \( (P') \) were calculated using \( P' = P/(SG \times C) \). The \( P' \) values for host rock and dike were calculated to be 6.83 \( \times 10^{-3} \) cm\(^2\)/sec and 6.40 \( \times 10^{-3} \) cm\(^2\)/sec respectively. The heat generated by the dike during crystallization \( (L) \) is assumed to be 82 cal/g following Schwarz (1977).
Calculation of $\Delta T$

From Carslaw and Jaeger (1959), the temperature increase in the host rock due to the dike intrusion is:

$$T = \frac{P_1 P_0^{1/2} T_1}{P_1 P_0^{1/2} + P_0 P_1^{1/2} \text{erf} \lambda} \left( 1 + \text{erf} \frac{x}{2(P_0 t_m)^{1/2}} \right) \quad -(ii)$$

where $\lambda$ is the root of

$$\lambda \exp \left( \frac{P_1 P_0^{1/2}}{P_0 P_1^{1/2}} \right) + \text{erf} \lambda = \frac{C_1 T_1}{L \Pi^{1/2}} \quad -(iii)$$

The variable $x$ in the equation (ii) is the distance of the hybrid zone specimen from the contact. A negative distance is measured from the contact into the host rock following the convention of Carslaw and Jaeger (1964). The variable $t_m$ is the time taken for the temperature in the host rock to reach $T_{\text{max}}$. That time is given by:

$$x = 2 \lambda (P_1 t_m^{1/2}) \quad -(iv)$$

where $x$ is the position of the surface of separation between the solid and liquid phases of the dike. As the dike cools and solidifies, the surface of separation moves toward the centre of the dike and $x$ increases.

For this study, equation (ii) must be solved for $\Delta T_{\text{max}}$. $\Delta T_{\text{max}}$ is a maximum in the host rock near the contact when the dike first completely solidifies (Jaeger, 1959). This occurs when the separation surface migrates inwards to the midplane of the dike from both contacts. Therefore $t_m$ of maximum $\Delta T$ occurs when $x$ equals half of the dike width ($d$).

For the present study, the right hand side of equation (iii) is 1.98 using the measured $C_1$ value and $T_1 = 1000^\circ C$. Equation (iii) gives the $\lambda$ value to be 0.95 using the determined thermal constants and tabulated values of erf.
(Carslaw and Jaegar, 1959). Using equation (iv), tm is \(3.5 \times 10^5\) seconds by the substitution of \(x = 90\ \text{cm}, \lambda = 0.95\) and of the given \(P_i\) value. Using equation (ii), the \(\Delta T_{\text{max}}\) is calculated to be \(443^\circ\text{C}\) for \(x = -22.5\ \text{cm}, T_i = 1000^\circ\text{C}\) and \(\lambda = 0.95\).

**Calculation of Tamb and Depth of Burial**

Equation (i) is used with \(T_{\text{max}}\) set at \(465^\circ\text{C}\) by thermal step cleaning to calculate the Tamb of the host rock. This results in an ambient temperature of \(22^\circ\text{C}\). The average surface temperature at sea level in this area is estimated at \(25^\circ\text{C}\). Therefore, the present erosion surface was at a depth corresponding to a temperature of \(22^\circ - 25^\circ\text{C} = -3^\circ\text{C}\) below the palaeosurface at the time of dike intrusion. A geothermal gradient of \(35^\circ\text{C}/\text{km}\) is estimated from Hyndman (1976). Therefore, the depth of burial of the present erosion surface was virtually at the surface at the time of dike intrusion. Schwarz (1977) found the Sudbury diabase dikes to be at a depth of several kilometers at \(1250\ \text{Ma}\). Therefore, the present study suggests of a strong uplift in the Grenville Province, between the time of diabase dike intrusion and the intrusion of pegmatite dikes.

4.11) **Magnetic Mineralogy**

Eight polished sections were examined, 4 from the Memesagamesing Lake and 4 from the Caribou Lake norites.

Magnetite and ilmenite occur in about equal abundance and are the most common opaque minerals present in the Memesagamesing Lake norites. Numerous ilmenite lamellae subdivide the magnetite grains into separate groups and thus acts as domain walls. Therefore, their remanence is stable. Hematite, pyrohite, and titano-magnetite are extremely rare (<0.01%) in the Memesagamesing Lake Stock.

The polished sections from Caribou Lake norites similarly show magnetite and ilmenite occurring in equal abundance. The magnetite grains are large in size. The ilmenite occurs as separate grains and hence the magnetite domain walls are free to move. Titanomagnetites are also observed. Some hematite occurs in the Caribou Lake norites as a secondary or metamorphic alteration on the edges of the magnetite
crystals. Small amounts of pyrrhotite are also observed. The unstable remanence in the Caribou Lake norites results from the presence of multidomain titanomagnetite or magnetite and pyrrhotite grains.
CHAPTER V
POLE POSITION AND AGE OF THE NORITES

The Caribou Lake norites on AF step cleaning yield a stable A component with a direction of $300^\circ, -42^\circ, 18^\circ$. The Memesagamesing Lake norites yield stable A components with a mean direction of $299^\circ$, $-50^\circ$, $10^\circ$ on AF cleaning, of $322^\circ$, $-58^\circ$, $12^\circ$ on thermal cleaning, and of $310^\circ$, $-45^\circ$, $15^\circ$ on chemical cleaning. All these A directions are found to be statistically same at the 95% confidence level using a variance test. Figure 27 shows the directions of A components isolated by Caribou Lake norites on AF cleaning and Memesagamesing Lake norites on AF, thermal and chemical cleaning with their respective A95. The mean direction of these A components yield a pole position of $32^\circ W$, $4^\circ N$, ($dp = 5^\circ$, $dm = 70^\circ$).

The determined pole position suggests an age of $975 \pm 50$ Ma on the APW path for Neoheikian and Early Hadrynian times (Fig. 28a, Irving, 1979). But the olivine diabase and granite pegmatite dike give Rb-Sr radiometric ages of $1250 \pm 100$ Ma (Gates and Hurley, 1973; Palmer, et al., 1977) and $1200 \pm 100$ Ma (Krogh et al., 1968; Krogh and Davis, 1969; Broccou and Dalziel, 1974) respectively. Also they clearly crosscut the norites meaning that they postdate the norites. Further the baked contact test also demonstrates that they were emplaced and unmetamorphosed prior to $1250$ Ma. Therefore, the post $1250$ Ma portion of the APW path of Irving, 1979 (Fig. 27a) cannot be used to determine the age of the norites, so that an age of $975$ Ma for them is not valid.

The determined pole falls on an age of $1725 \pm 50$ Ma on the APW path (Fig. 28b) for Late Aphelian to Early Helikian times (Irving, 1979) and an age of $1800$ Ma on the revised APW path (Fig. 28c) suggested by Stupavsky and Symons (1981).

The Sudbury norites give a Rb-Sr radiometric age of $1956 \pm 98$ Ma (Gibbins and McNutt, 1975). The Sudbury norite pole indicates an age of $2050$ Ma on the APW path of Irving (1979). It is $70^\circ$ of arc from the Memesagamesing and Caribou Lake norite pole. Both factors imply that there is a considerable difference in ages of the norites of the study area & the Sudbury norites which suggests that they are not co-
Fig. 27. The mean remanence directions isolated by Caribou Lake norites on AF cleaning and by the Memesagamesing Lake norites on AF, thermal, and chemical cleaning with their respective A.
(A=Caribou Lake norites on AF cleaning; B=Memesagamesing Lake norites on AF cleaning; C=Memesagamesing norites on thermal cleaning; D=Memesagamesing norites on chemical cleaning.)
Fig. 28a. APW path for Neohelikan and Early Hadrynian times as suggested by Irving, 1975. (The solid triangle represents the determined pole.)

Fig. 28b. APW path for Late Aphebian to Early Helikan times as suggested by Irving, 1975. (The solid triangle represents the determined pole.)
Fig. 28c. The AFW path for Late Aptian to Early Barremian times as suggested by Stupavsky and Symons, 1981. (The solid triangle represents the determined pole.)
maggmatic. The pole position of the Memesagamesing and Caribou norites is also divergent from the Nippissing diabase $N_1$ and $N_2$ poles which indicates that the norites do not retain a primary residual Nippissing component. No vertical-axis rotation or translation for the Grenville Province compared to the Southern Province appears to be feasible. Therefore, the evident conclusion is that the norites were emplaced in the terminal stages of the Hudsonian Orogeny almost corresponding to the Rb-Sr reset ages of $1700 \pm 100$ Ma determined for the host rocks of the area.

This age of $1760 \pm 40$ for the Memesagamesing and Caribou Lake norites also suggest an age of at least $1800$ Ma for the Grenville Front. This conclusion contradicts the explanation of Irving et al. (1972) that the Grenville Province was thousands of kilometres away from the older Canadian Shield at the time of metamorphism of Grenville rocks and that the Grenville Front formed $1200-1500$ Ma ago as a suture between the two orogens. The older age for the Grenville Front can be supported by the works of Quirke and Collins (1930) who traced the Huronian Formation across the Grenville Front and of Fairbairn et al. (1969) who suggested an age of $\sim 2300$ Ma for the Huronian Formation.

The age of $1760 \pm 40$ Ma for the Memesagamesing and Caribou Lake norites also suggests an older age for the Whitestone anorthosites which have been assigned an age of $\sim 1100-1000$ Ma by Irving et al. (1975). The older age is suggested because palaeomagnetic studies on the anorthosites isolate a stable component with a direction of $-290^\circ$, $-56^\circ, 8^\circ$ which is very similar to that isolated for the Memesagamesing and Caribou Lake norites.
CHAPTER VI
CONCLUSIONS

From the study of the palaeomagnetic and magnetic properties of the Memesagamesing Lake and Caribou Lake norites, the following conclusions can be drawn.

(i) The bulk susceptibility anomaly maps for the intrusive bodies correspond to the areomagnetic anomaly maps of the area. The presence of rocks of high magnetic susceptibility in the central areas of the stocks explains the intense airborne magnetic anomaly highs. This contradicts Friedman’s (1957) and Lumbers’ (1971) explanation that the intrusives are funnel-shaped bodies.

(ii) The $K_{11}/K$ ratios of 1.15 and 1.19 for Memesagamesing and Caribou Lake norites respectively suggest that the norites are distinctly layered even though banding is not commonly observed in the field.

(iii) The orientation of maximum - intermediate planes of the susceptibility ellipsoid contradicts Friedman’s (1957) and Lumbers’ (1971) explanation that the intrusive bodies suffered compression and tilting subsequent to their intrusion.

(iv) The norites from the Memesagamesing Lake contain mainly magnetite with the ilmenite lamellae subdividing the magnetite grains into approximately pseudo single domain size. Hence, they retain a very stable remanence. The Caribou Lake norites contain mainly magnetite, ilmenite, and titanomagnetite as discrete grains with some secondary hematite and pyrrhotite. Hence, they retain a much less stable remanence.

(v) The baked contact tests on the Memesagamesing Lake norite suggest that the norite significantly predates the intrusion of the granite pegmatite and olivine diabase dikes. The ambient temperature of the norites when the pegmatite dike intruded is calculated to be $-22^\circ$C, and the depth of the burial during the dike intrusion is calculated to be $\sim 0.5$
km. This implies a strong uplift in the Grenville Province between the time of diabase dike intrusion (1250 Ma) and the intrusion of pegmatite dikes (∼1100 Ma)

(vi) The Memesagamesing Lake stock isolated a stable A component with a mean direction ∼310°, -51°, 12° on AF, thermal and chemical cleaning. The Caribou Lake complex yielded a stable A component with a direction of 300°, -42°, 18°. Both the A directions are the same at the 95% confidence level. The Caribou Lake norites were found to be relatively unstable at moderate fields and therefore thermal and chemical cleaning was not done on them.

(vii) The cryogenic test on the Memesagamesing Lake stock was unsuccessful because the directions isolated at the end of the test were rather randomly scattered.

(viii) The isolated A component yielded a pole position of ∼32°W, ∼4°N, (dp = 5°; dm = 7°). The pole suggests an age of ∼1725 Ma on the APW path for Late Aphelian to Early Helikian Times (Irving, 1979) and of ∼1800 Ma on the revised APW path of Stupavský and Symons, (1981).

(ix) The difference in Rb-Sr radiometric age and pole position on the APW path for Late Aphelian to Early Helikian times between the norites of Sudbury and the study area eliminates the possibility of them being comagmatic.

(x) The facts that the Sudbury norites give a Rb-Sr radiometric age of ∼1956 ± 98 Ma and that its pole is 70° of arc from the Memesagamesing and Caribou norite pole, implies that there is a considerable difference in the ages of Sudbury norites and the norites of the study area. This suggests that they are not comagmatic. Therefore, it can be concluded that the Memesagamesing and Caribou Lake norites were emplaced in the terminal stages of the Hudsonian Orogeny.
(xi) The age of $1760 \pm 40$ Ma for the Memesagamesing and Caribou Lake norites suggests an age of at least $1800$ Ma for formation of the Grenville Front which contradicts the age of $1200-1050$ Ma suggested by Irving et al (1972).

(xii) The Whitestone anorthosite is thought to be older than the $1100-1000$ Ma age assigned by Irving et al (1975) because of the similarity in its pole to that isolated for norites of the study area.
REFERENCES


VITAE AUCTORIS

Born: October 5th., 1958, in Calcutta, India. Son of Dr. and Mrs. (Dr.) S.K. Dey.

Education:

Secondary School:
Hindi High School, Calcutta, India.

University:
Jadavpur University, Calcutta, India.
Bachelor of Science in Geology, 1979.

University of Windsor, Windsor, Ontario, Canada.
Master of Science in Geology, 1981.