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THE RELATIVE AGES OF THE OTTO STOCK AND MATACHEWAN DYKE MAGNETIZATIONS

THE RELATIVE AGES OF THE OTTO STOCK AND MATACHEWAN DYKE MAGNETIZATIONS

by

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ABSTRACT

A baked contact test was carried out between the Otto Stock, dated at 2114 Ma by Bell and Blenkinsop (1976) and its host rock, represented by the magnetically stable, Matachewan Dyke swarm dated at 2690 Ma by Gates and Hurley (1973). Paleomagnetic results from this study confirm the recently revised dating of the Otto Stock and Matachewan dykes at 2680±1 Ma and 2452+3/-2 Ma, resectively (Corfu et.al., 1989; Heaman, 1988).

Matachewan dykes both distant and within the contact aureole of the Otto Stock all carry the same southwesterly shallow characteristic Matachewan direction of magnetization. The absense of an Otto Stock overprint on the Matachewan dykes implies that the intrusion of the Otto Stock must have occurred before the intrusion of the Matachewan Dyke swarm.

The relative ages of the Otto Stock and Matachewan dyke magnetizations are inconsistent with the conventional early Proterzoic apparent polar wander path (APWP) for North America, which decreases in age from the Matachewan dyke pole to the Otto Stock pole. It can be concluded that this part of the APWP is running backwards and must now be redefined.

ACKNOWLEDGEMENTS

I wish to thank Dr. C.J. Hale for discussions, guidance and financial support throughout the writing of this thesis. Dr. Hale is really an outstanding supervisor (when he can be found!). I would also like to thank him for his invaluable advice and encouragement during my studies here at McMaster.

Dr. K.L. Buchan at the Geological Survey of Canada deserves my thanks and appreciation for proposing this study, leading and funding the field trip, providing laboratory facilities and for many helpful discussions throughout this study's duration.

The following list of people are also to be thanked for their contributions to this project: Dr. G.V. Middleton and Jim McAndrew for computer assistance; Larry Heaman at the Royal Ontario Museum for providing the most recent information on the dating of the Matachewan dykes and the Otto Stock; Trudy Chin at the Ontario Geological Survey for sending maps of the study area; Andrew Wiacek for many helpful discussions; and Pete Lloyd just for being there.

I can't forget my family and friends (you all know who you are) for their continuous encouragement and enthusiasium from start to finish.

Finally, I would like to dedicate this thesis to the memory of my father, Dr. Thomas Neilson. Without his encouragement, guidance, and belief in me, my career in science would never be possible.

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CHAPTER 1

INTRODUCTION

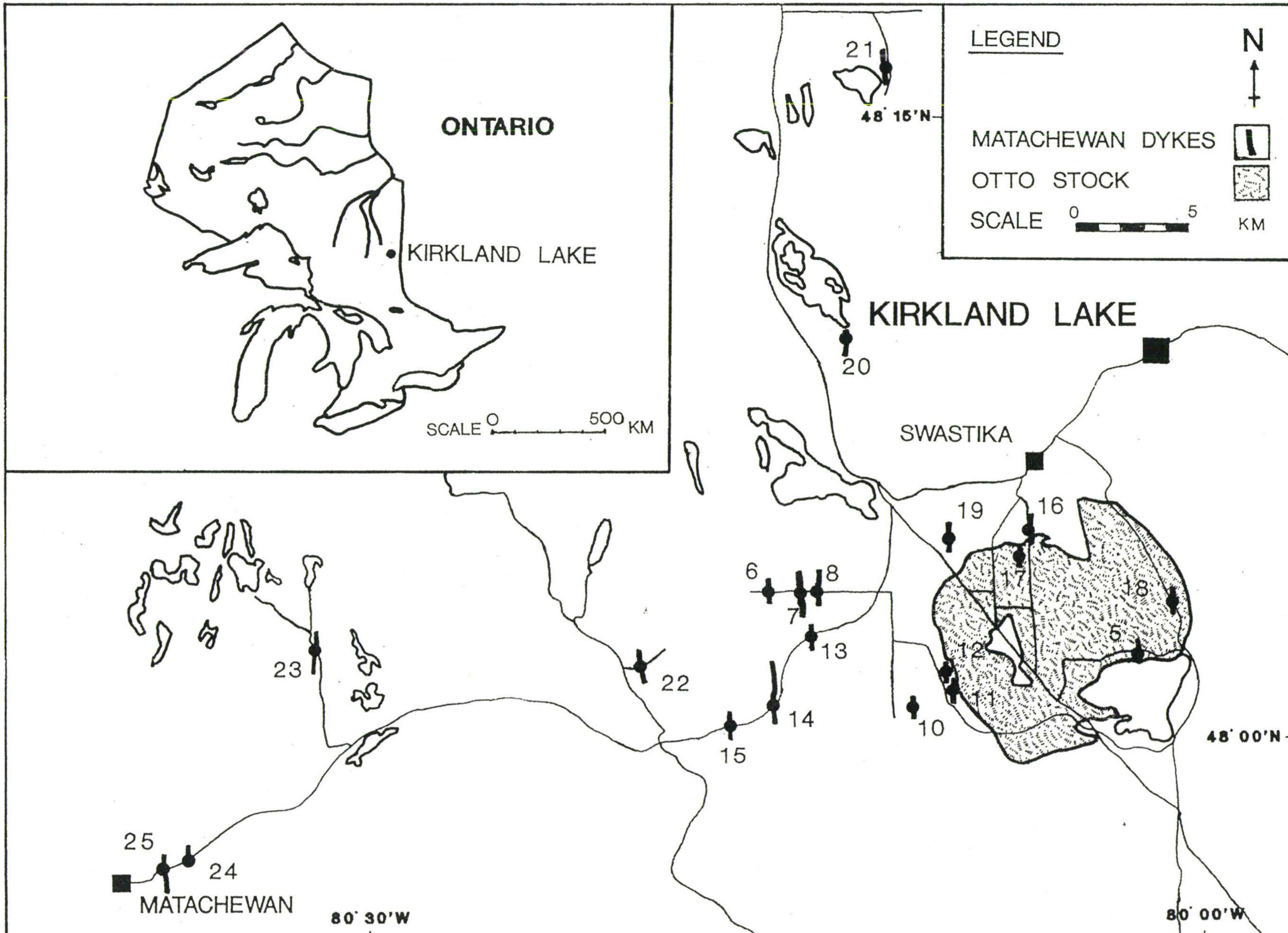
1.1 Location and Geochronology of the Area

The Otto Stock is a syenite intrusion 12 Km in diameter located in the Superior Province about 20 km south-west of Kirkland Lake, Ontario (Figure 1.1). It has been widely believed, from whole rock Rb-Sr dating (Bell and Blenkinsop, 1976), that it intruded the Archean metavolcanic and felsic intrusive country rock at 2114 Ma. However, a more recent Pb-U zircon age determination (Corfu et.al., 1989) dates the Otto Stock at 2680±1 Ma.

Part of the Matachewan Dyke swarm also occurs in the country rock of this area (Figure 1.1), as mapped by Lovell (1967 and 1972). Matachewan dykes are north-south trending diabase dykes that contain characteristic plagioclase phenocrysts. Their age has also been revised recently. Gates and Hurley (1973) used a whole rock Rb-Sr method and obtained an age of 2690 Ma, but a more precise Badeleleyite age determination by Heaman (1988) dates the Hearst-Matachewan dyke swarm at 2452+3/-2 Ma.

In the light of these new dates, the Otto Stock appears to be older than the Matachewan Dyke swarm. This is the opposite to what was believed previously and raises a fundamental question about the relative ages of the Otto

Figure 1.1 Location of the Otto Stock in Ontario. Sampling sites on Matachewan dykes are numbered and marked with dots.


ONTARIO
KIRKLAND LAKE
SCALE 0 500 KM
LEGEND
N
MATACHEWAN DYKES
OTTO STOCK
SCALE 0 5 KM
48° 15'N
KIRKLAND LAKE
SWASTIKA
48° 00'N
80° 30'W
80° 00'W
MATACHEWAN
5
6
7
8
10
11
12
13
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Stock and the Matachewan dyke swarm characteristic magnetization. The paleomagnetic poles implied by these magnetizations are both important tie points for the early Proterzoic Apparent Polar Wander Path for North America.

1.2 Previous Paleomagnetic Studies

Pullaiah and Irving (1975) established the direction of the magnetic remanence in the Otto Stock, declination 330°, and inclination +71°. The Otto Stock syenite was found to be magnetically unstable, for the most part, therefore the direction had to be determined by measuring late-stage lamprophre dykes cutting the stock and basic rocks within its contact aureole. In order to verify that this direction was primary, Irving and Pullaiah measured the magnetic remanence in two Matachewan dykes in the contact aureole of the stock. As it was then believed that the Otto Stock was younger than the Matachewan Dyke swarm, these dykes were expected to be magnetically overprinted with a record of the direction of the ancient field at the time of intrusion of the Otto Stock. The metamorphic grade in the contact aureole reached amphibolite facies, implying reheating of the contact zone to temperatures in excess of 550°C.

Matachewan dykes studied by Strangway (1964) and Fahrig et.al. (1965) revealed a south-westerly shallow direction of remanent magnetization. This direction differs from that of the Otto Stock. A change from the Matachewan direction to the Otto Stock direction during thermal demagnetization of a partially overprinted Matachewan dyke sample would verify that the magnetization in the lamprophyre dykes and in the basic rocks was a primary magnetization. This is in accordance with the baked contact test of Everitt and Clegg (1962).

One of the dykes in the contact aureole gave a direction that was consistent with the results from inside the stock. Thus its magnetization was interpreted to have been overprinted during the intrusion of the Otto Stock. The other dyke was found to be magnetically unstable. As Pullaiah and Irving (1975) did not establish the unbaked host direction, it was assumed to be the characteristic Matachewan direction determined in the earlier studies (Strangway, 1964 and Fahrig et.al., 1965). Irving and Pullaiah's results are inconclusive as evidence that the magnetization is primary because only one dyke was used and the unbaked direction was never established.

1.3 The Purpose of this Study

Dr. K.L. Buchan, of the Geological Survey of Canada, proposed to carry out a proper baked contact test to establish the relativate ages of the Otto Stock and Matachewan dyke magnetizations. A positive baked contact test

(Everitt and Clegg, 1962) would show a swing in magnetic direction from a host direction to the contact direction as the intrusion is approached along a traverse from a distance outside the metamorphic aureole. Observations made in the field called into question the age relationship assumed for the baked contact test.

1.4 Field Work and Sampling

Matachewan dykes were sampled instead of the country rock because they hold a strong stable remanence and they are relatively soft to drill. The country rock is magnetically unstable and difficult to drill, and therefore undesirable for sampling. Two large scale traverses were sampled (Figure 1.1): one along an east-west line and the other along a north-south line. Samples were also taken from north-south trending dykes within the Otto Stock. Typically 5 or 6 samples per site were taken as blocks or diamond-drilled 1 inch cores. The samples were oriented with either the sun compass or magnetic compass, or both.

Field study indicated that dykes within the Otto Stock contain the plagioclase phenocrysts that are characteristic of Matachewan dykes. These dykes are mapped as Nipissing or Keweenawan dykes by Lovell (1972). Further study also indicated that the dyke sampled by Pullaiah and Irving (1975) is probably not Matachewan. It trends northeast-southwest and contains no phenocrysts.

Field work and sampling for the project were done in June 1988 by Dr. K.L. Buchan and D. Neilson. This particular study includes only the samples taken from the east-west traverse and include sites 6, 7, 8, 10, 11, 12, 22, 23, and 24. The other samples in the collection are being analysed by Dr. K.L. Buchan at the Geological Survey of Canada.

CHAPTER 2

LABORATORY EQUIPMENT AND PROCEDURES

2.1 Core Preparation

All samples were prepared as oriented cylinders, 2.5 cm in diameter and 2.2 cm in height, at the Geölogical Survey of Canada in Ottawa. Samples that were drilled in the field were scribed and cut to length. However, samples that were taken as oriented blocks from the field had to first be drilled in the lab.

2.2 Measurement of Magnetic Remanence

Magnetic remanence of the samples was measured using a Spinner Magnetometer (Schonstedt, Model DSM-1) at the Geological Survey of Canada. The function of the spinner magnetometer is to hold a magnetized sample near a fluxgate sensor in order to generate an alterating voltage (Vs). The output of the fuxgate sensor is sent to the processor and can be represented by,

$$Vs = f(p_\perp ,s,z)$$

where $p_\perp$ is the moment perpendicular to the rotation axis and the sample is a distance z from the fluxgate sensor with sensitivity given by s. The spinner magnetometer consists of four basic assemblies. The magnetic shield eliminates the earth's magnetic field around the fluxgate sensor assembly. The carriage assembly holds and rotates the sample close to the fluxgate sensor within the magnetic shield. It also transmits information to the processor about the angular orientation of the sample with respect to the fluxgate sensor axis. The sample is positioned in the spinner magnetometer in six different orientations and two measurements are made per orientation. This is a two-fold redundancy as only six different orientations are required for the calculation. The processor averages all of the measured values to calculate the X, Y, and Z components of the remanent magnetization after a number of spins. The processor then outputs the X, Y and Z components to a computer that calculates the Intensity (I), Declination (Dec) and Inclination (Inc) of the magnetization. With additional inputs of the samples outcrop orientation (strike and dip), the computer recalculates these components to the Declination and Inclination for the samples original position in the field.

2.3 Magnetic Cleaning and Demagnetization

Once the natural remanent magnetization (NRM) was measured the samples were subjected a progression of magnetic cleaning steps. The underlying principle of the routine magnetic cleaning is based on the lower stability of secondary magnetizations relative to those aquired by the primary processes, such as, chemical remanence and thermo-remanence (Collinson, 1983). Secondary magnetizations or viscous remanent magnetism (VRM) can be aquired during an metamorphic event or long exposure to a weak magnetic field, such as, the present earth field (P.E.F.).

Three methods of magnetic cleaning were employed in this study. They were the alternating field (AF) method, the thermal demagnetization method (TH), and the combination alternating field and thermal demagnetization method (AF-TH). AF and TH cleaning were done using methods and apparatus similar to those described by Roy et.al. (1969, 1971, 1973). The AF-TH method was carried out in a similar manner to that described by Park (1975). Details of the magnetic cleaning procedures are outlined in the following sections.

2.3.1 The Alternating Field Method

The AF Method employed the use of a Geophysical Specimen Demagnetizer (Schonstedt, Model GSD-1). This instrument was used to remove the VRM or any other soft secondary magnetization by subjecting the speciment to a 400 Hz alternating magnetic field that decays linearly to zero from a user-specifield inital strength. The samples were demagnetized in the +X direction in the specimen de-magnetizer at the 2.5 mT field-level followed by the measurement of the first and second position on the Spinner Magnetometer. The sample could then be demagnetized in the +Y direction, at the same field level, followed by mesurement of the third and fourth positions. The +Z direction was last to be demagnetized, followed by the measurement of the fifth and sixth positions, thus completing the measurement and demagnetization at the 2.5 mT field level. Demagnetization and measurement at the next level, 5 mT, were done similarly except that demagnetization was done in the negative direction (i.e. -X, -Y, -Z). The procedure of demagnetization and measurement is repeated for the following field levels to ensure careful removal of the secondary magnetization: 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 90 and 100 mT. The direction of demagnetization was flipped back and forth from positive to negative through the sucessive field levels to ensure that the alternating fields did not create any artificial magnetizations. When a second sample from the same core was used, the demagnetization sequence was reversed,

i.e. 1st Sample Core X: 2.5(+), 5(-), 10(+), 15(-), 20(+), 25(-), 30(+), 35(-), 40(+), 50(-), 60(+), 70(-), 80(+), 90(-) and 100(+)

2nd Sample Core X: 2.5(-), 5(+), 10(-), 15(+), 20(-), 25(+), 30(-), 35(+), 40(-), 50(+), 60(-), 70(+), 80(-), 90(+) and 100(-)

where the sign in brackets refers to the relative direction of demagnetization. The change in the postive and negative sequence of demagnetization between samples of the same core was used to ensure that the alternating fields did not create any laboratory magnetizations that would produce anomalous directions.

2.3.2 The Thermal Demagnetization Method

The TH Method employed the use of Thermal Specimen Demagnetizer (Schostedt Model TSD-1). This instrument had been extensively modified for the ease of use and greater precision. The loose fibre insulation between the heating coils and the magnetic shield was replaced by coils of 3/8 inch copper tubing to act as a water jacket. This allows the furnace to reach equilibrium faster, keeps temperature constant over time, and protects the μ-metal magnetic shield from the heat. Aluminum foil was wrapped around some parts of heating coil to ensure an even temperature profile within the furnace.

The Thermal Demagnetizer itself is housed within a 12 ft by 12 ft and 7 ft high (inside dimensions) shielded room which is completely surrounded by 2 layers of electrical steel. The earth's magentic field is reduced to 1000-2000 nT within the room. Further nulling of the earth's field in the room is achieved by adjusting the Helmholtz coils which line the inside of the room. The residual field field can be reduced to <100 nT at the front of the magnetic shield of the Spinner Magnetometer. This nulling of the earth's field is required to prevent the acquisition of secondary TRM's during the thermal demagnetization process.

The TH method begins by first measuring the NRM of the samples with the spinner magnetometer. The thermal demagnetizer can take up to seven samples at a time. Each sample was assigned a place in the furnace that it occupied throughout the sequence of temperatures used during demagnetization. This ensured a repeatable progression of temperatures in sucessive demagnetization steps for each individual sample. The samples were also flipped over end to end and rotated 90^{o} (there are 4 possibe orientations), in a set sequence, between demagnetization steps. This minimized the chance for the samples to acquire secondary magnetizations in the laboratory. The sequence of demagnetization steps used was: 100, 200, 300, 400, 450, 500, 550, 560, 570, 580, 590, 600, 605, and 620^{o}C. This sequence was chosen because the magnetic remanence of the diabase samples is carried by magnetite (see Figure 3.4). The Blocking Temperature of magnetite is known to be about 580^{o}C (Nagata, 1962). The samples were measured on the Spinner Magnetometer in six orientations between demagnetization steps in the same manner as an NRM measurement. The Spinner

Magnetometer is also located within the shielded room. The samples were not exposed to the earth's magnetic field as they were never taken out of the room during their demagnetization procedure. If a sample became unstable before 620°C no further demagnetization steps were required. It could be taken out of the group and replaced by a blank for the subsequent demagnetization of the remaining samples. A blank is an old sample which is used to keep the temperature profile within the furnace constant while other samples continue their demagnetization.

2.3.3 The AF-TH Method

The AF-TH Method, as it's name implies, utilizes both the procedures and apparatus of the AF method and the TH method which were described earlier. The NRM of the sample was measured first. Each sample was demagnetized at the first AF level, 2.5 mT, in the X, Y, and Z directions and then measured on the spinner magnetometer in the same manner as NRM measurements. The orientation of the three directions of demagnetization was alternated between positive and negative X, Y, and Z directions, during the demagnetization sequence. Demagnetization and measurement continued using the same field levels as the AF method until the sample began to stabilize, usually between 15 and 25 mT. The sample was then subjected to all necessary thermal demagnetization levels in exactly the same manner and sequence described in the TH method section, starting at 100°C.

2.4 Choosing a Magnetic Cleaning Method

The statistical dependence of paleomagnetic surveys requires that samples be prepared and measured in sufficiently large numbers so that their data can be meaningfully combined. The quality of results is of equal importance. For these reasons the most reliable and fastest method for measurement and demagnetization must be found. Usually two samples per core are measured using the most reliable method. Cores that have been cut into three or more samples are used for preliminary analysis. This ensures that two samples per core were measured constistently.

When the results showed that the AF method or either thermal method gave good (stable) results, the AF method was used for the rest of the site as it tends to be much faster than the thermal demagnetization method. However, if the AF method results were poor or totally unstable a choice was made between the two methods that utilize thermal demagnetization. Sometimes the TH method will yield results that never reach a stable end point, rather they would move along a great circle. The AF-TH method was employed for sites which gave this type of result. According to Park (1975), AF demagnetization removes secondary components created by the present earth field and thermal demagnetization removes other secondary components with much higher stabilities.

CHAPTER 3

RESULTS AND STATISTICAL ANALYSIS

3.1 Data Presentation

Three types of plots are used to present the data. The first type of plot is the demagnetization curve. This plot shows the effect of each demagnetization step on the relative intensity of the remanence as the level applied alternating field or temperature increases. The median demagnetizing field of a sample is shown by the half-value of the intensity on an AF demagnetization plot. This is a commonly used measure of sample stability.

The second type of plot is the stereo net representation. During the demagnetization procedure the field-corrected declination and inclination of the remanence are calculated from the measured components of magnetization using the strike and dip of the sample as it was oriented in the field. This plot displays the corrected direction of the magnetization on a polar Wulff net as the demagnetization progresses.

The third type of plot is an orthogonal vector projection of the magnetization in the sample during demagnetization as described by Zijderfeld (1967). Each of these diagrams contains two separate plots. One shows the projection of the remanence vector in the horizontal plane (north-south and east-west), thus representing a declination of the component(s) of magnetization. The other shows the apparent inclination of the vector in the vertical plane (north-south and up-down).

3.2 Typical Results of the AF Demagnetization Method

The AF Method was chosen to demagnetize sites 7, 8, 10, 11, 22, and 24. Most demagnetization curves for these samples show monotonically falling intensities that approach zero at the higher field levels (Fig. 3.1 A and 3.1 B). Some samples exhibited a slight increase in relative intensity before smoothly falling to zero, at somewhat higher demagnetizing fields (Fig. 3.1 C and 3.1 D). A Few samples exhibited demagnetization curves that did not fall close to zero (Fig 3.1 E and 3.1 B). These samples had high coercivities, as 10 - 25 % of their remanence remained at the 100 mT level, the maximum demagnetizing field.

Stereo plots of the samples demagnetized with the AF Method were quite similar. Of the 59 samples demagnetized by the AF Method, 51 showed stable remanences in a shallow southwesterly direction (Figures 3.2 A, B, and C). The samples had either positive or, more commonly, negative shallow inclinations. These directions are recognised to be characteristic Matachewan directions (Strangway, 1964;

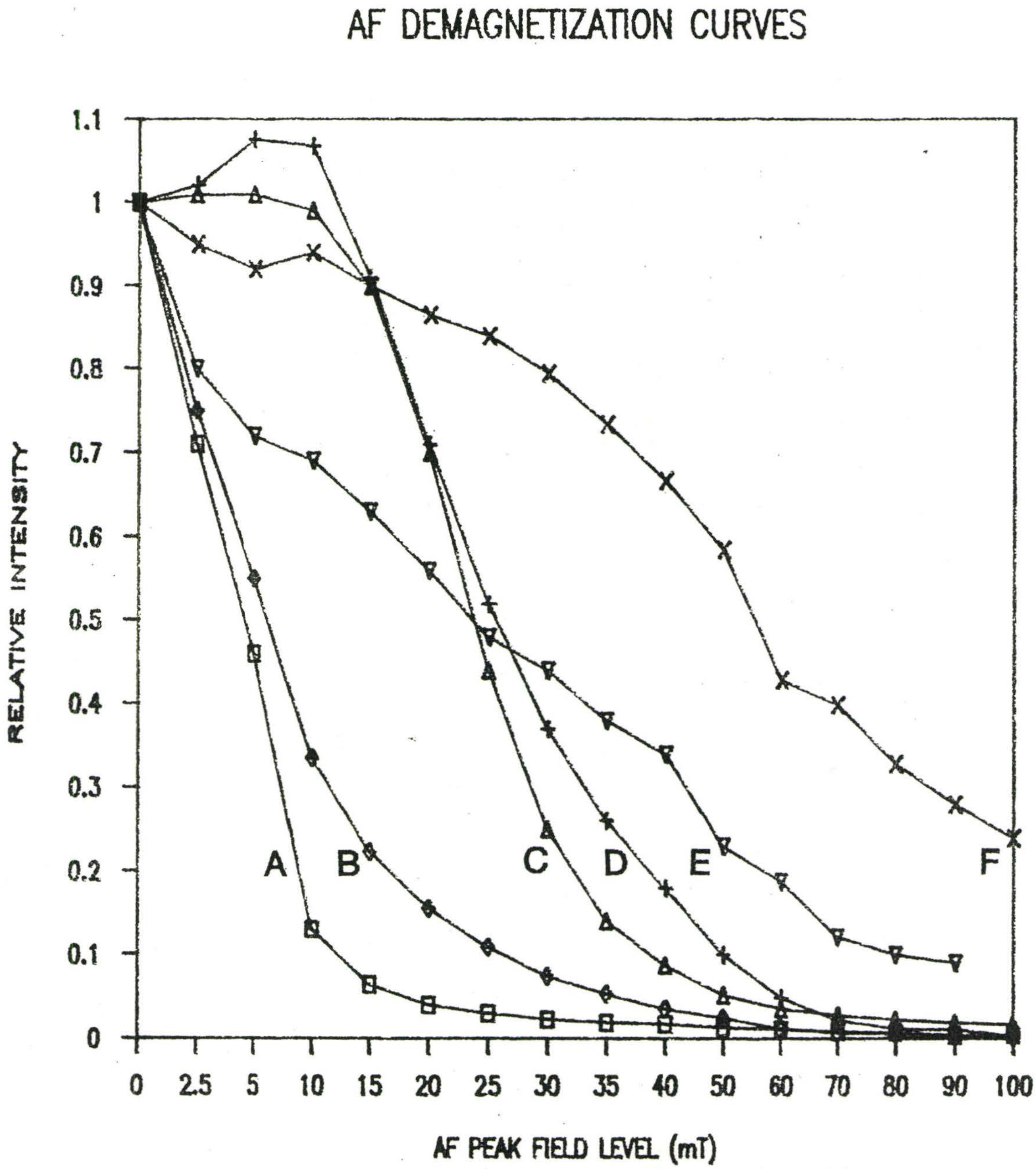

Figure 3.1 Intensity decay during stepwise AF demagnetization, relative to NRM intensity. A) Sample 110101, B) Sample 220403, C) Sample 100402, D) Sample 070202, E) Sample 240202, and F) Sample 080504.

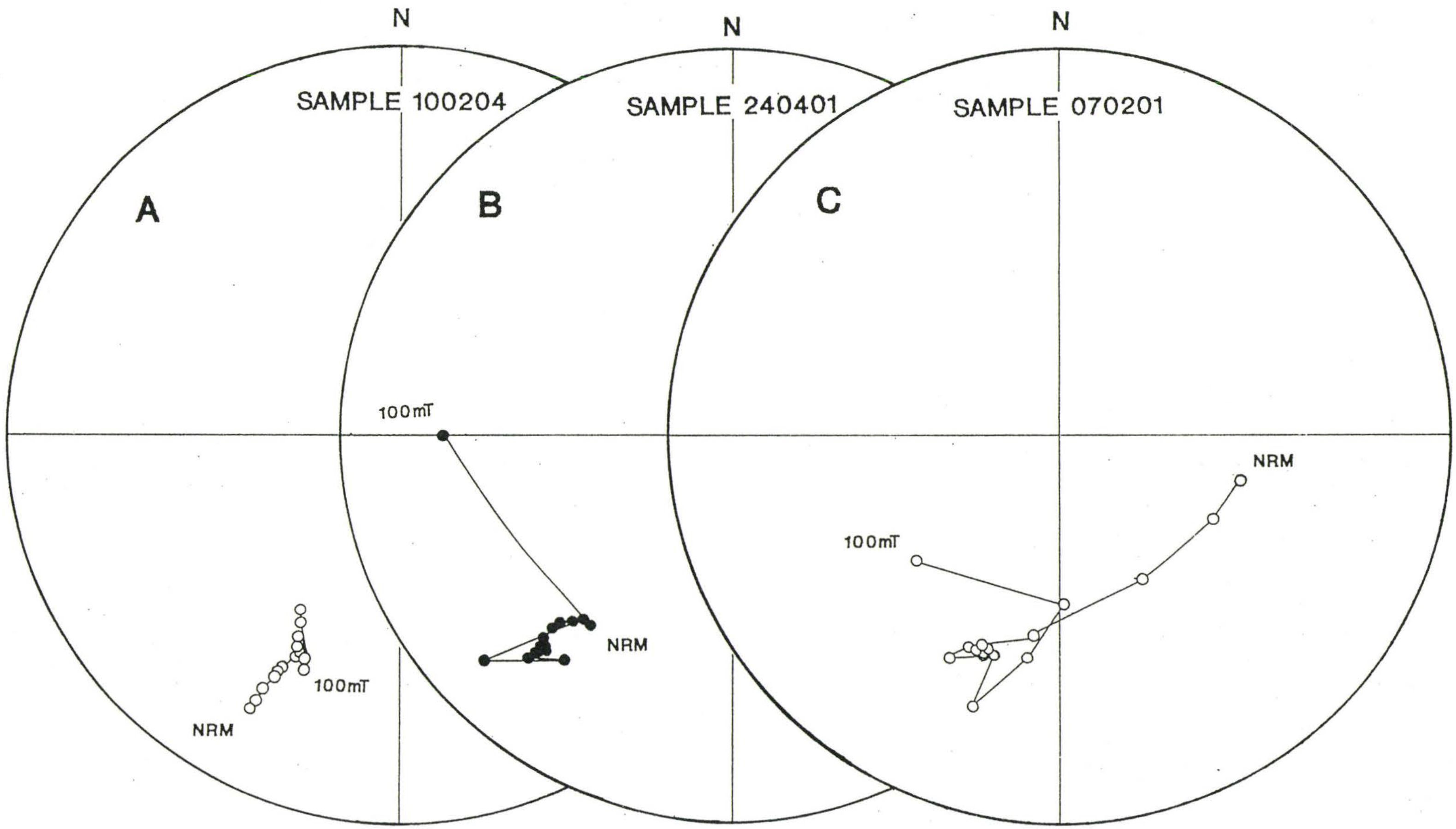

Figure 3.2 Typical stereo plots of samples demagnetized using the AF Method. Dots denote a positive (downward) inclination and circles denote a negative (upward) inclination.

Fahrig et.al., 1965; Irving and Naldrett, 1977). Some samples swung to this stable direction from a different initial direction, while others exhibited this shallow south-westerly direction from the beginning of the demagnetization.

The other 8 samples showed stable but anomalous directions or were unstable.

Orthogonal vector projection plots for most of the samples with the characteristic Matachewan direction revealed two vector components of magnetization (Figures 3.3 A, B, and C). The component that approaches the origin is thought to be the primary component of magnetization, that is, i.e. thermoremanent magnetization (TRM) acquired when the dyke cooled from its Curie temperature after its intrusion. The direction of this component can be determined by a straight line fitted to the data. An estimate of this direction was calculated with a three-dimensional least squares fitting program, utilizing Kirschvink's method (Kirschvink, 1980), and supplied by Mr. H. Hyodo at the University of Toronto. Generally, this direction estimated by the fitting program was comparable to the direction represented by the stable end points on the stereo plots.

The other component of magnetization is most likely a secondary or viscous magnetization (VRM) that was picked up

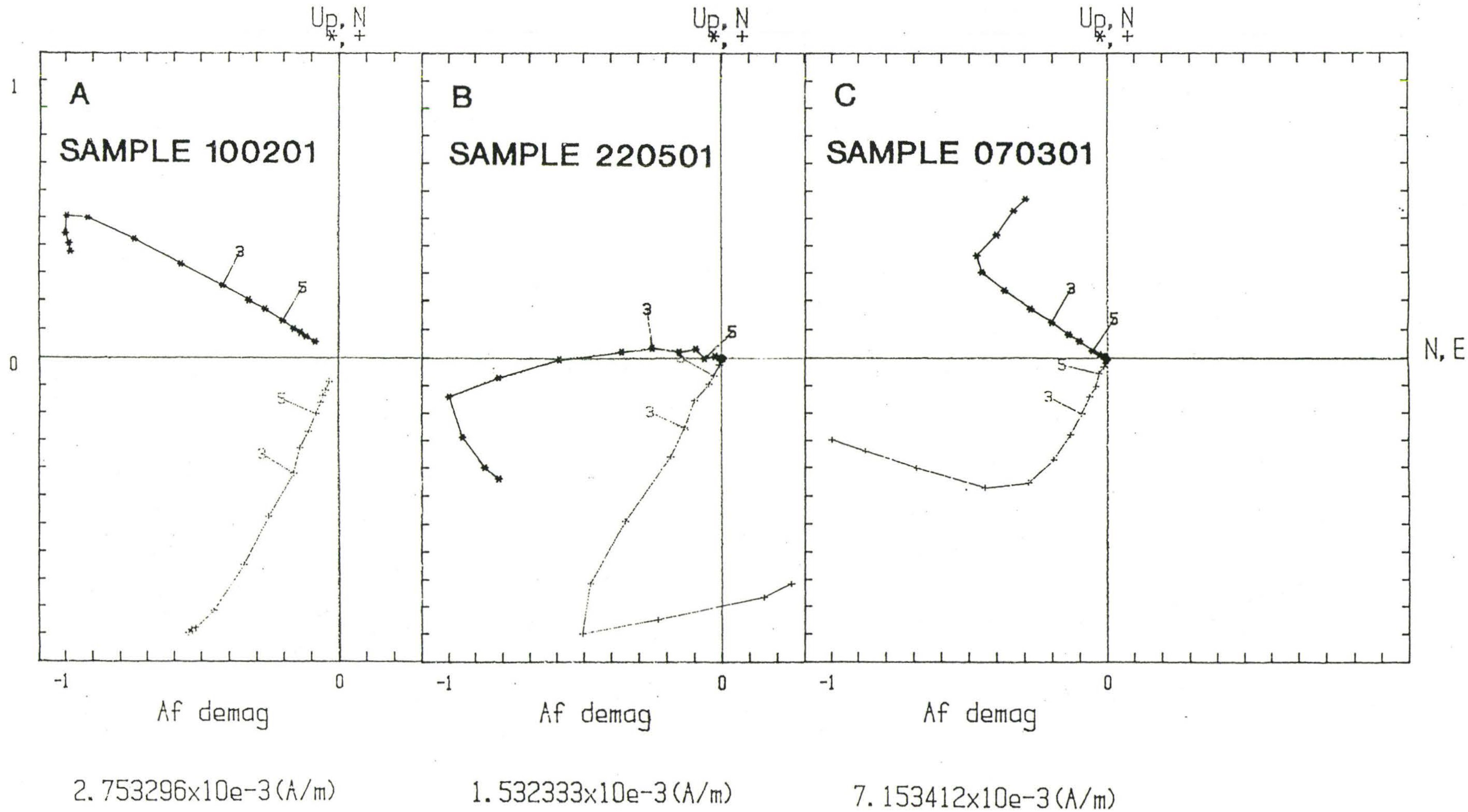

Figure 3.3 Typical orthogonal vector projection plots of samples demagnetized using the AF Method. The intensity of the magnetization is printed under each plot and the vector components are normalized to one. The x's indicate projections on the horizontal plane and the *'s indicate projections on the vertical plane.

in the laboratory or during exposure to the present earth field (P.E.F.). It too can be fitted to a straight line for estimating its direction. The vector sum of these primary and secondary magnetizations is seen on some stereo plots when the initial direction swings toward a stable primary direction.

The transition between the primary and secondary magnetizations on the orthogonal projection plots can tell if the coercity spectra of the two magnetizations are overlapping. Sharp transitions indicate non-overlapping, TRM-like coercity spectrums.

3.3 Typical Results of the AF-TH Demagnetization Method

The AF-TH Method was chosen to demagnetize sites 6, 12, and 23 as the AF procedure alone did not give stable end points for samples from these particular sites. Samples were first demagnetized by AF to about 20 mT to erase soft viscous magnetizations.

Thermal demagnetization curves for most samples exhibit a square-shouldered fall off between about 500 and 570°C (Figures 3.4 A, B, and C). Some samples show a slight increase in relative intensity before the square-shouldered fall off (Figure 3.4 D), while others show a fairly constant decrease in intensity during demagnetization

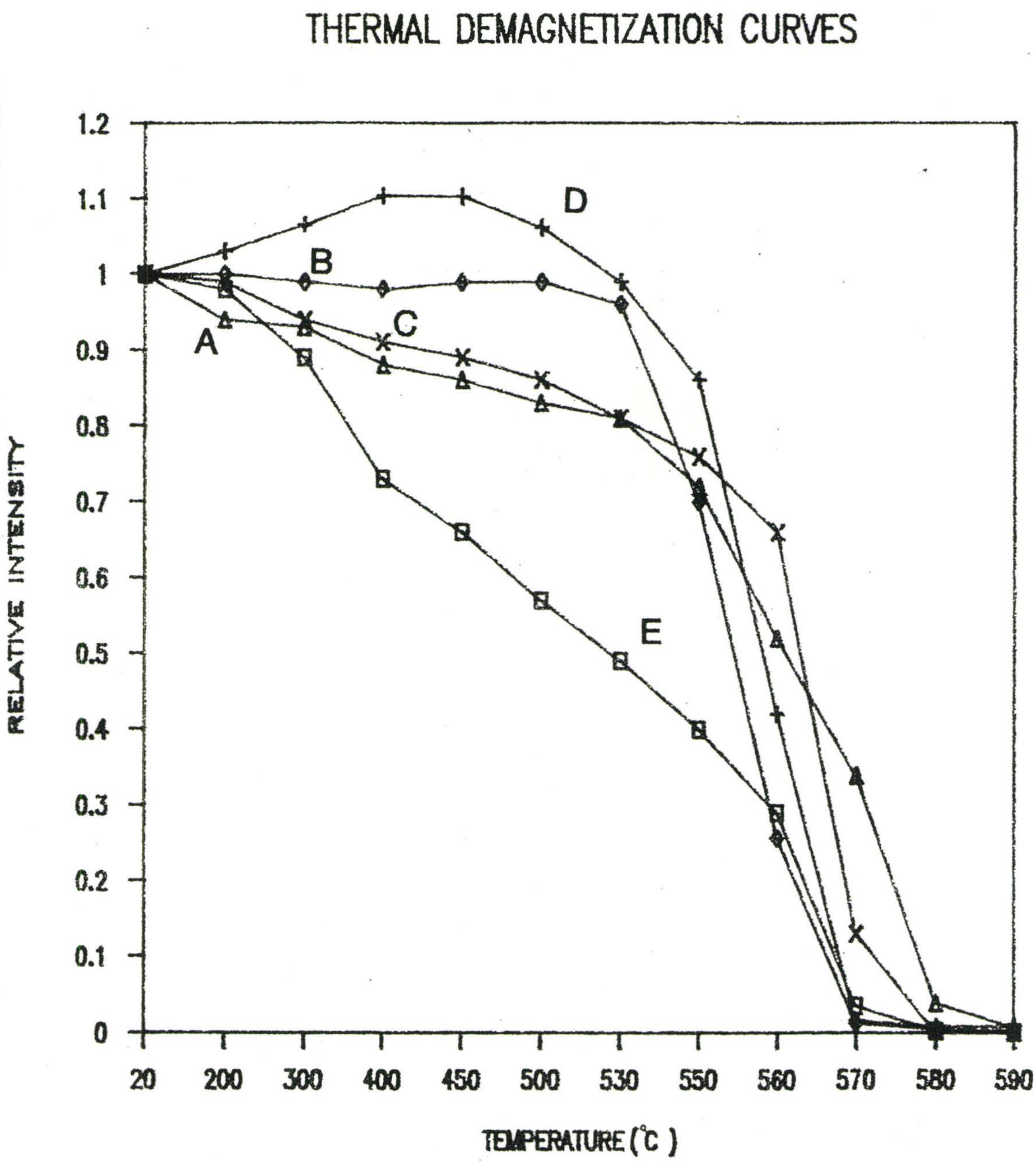

Figure 3.4 Intensity decay during stepwise thermal demagnetization, relative to the intensity measured at the last AF level during the AF-TH Method demagnetization. This indicates that the carrier of the magnetic remanence is magnetite (interval of Blocking Temperatures, 570 to 590°C). A) Sample 060401, B) Sample 070101, C) Sample 100102, D) Sample 120101, and E)Sample 230303.

(Figure 3.4 E). The blocking temperatures of the samples are confined to the interval between 570 and 590°C, indicating that the carrier of the magnetic remanence in the samples is magnetite (Figure 3.4). Two companion samples from the AF Method sites were thermally demagnetized (Figure 3.4 B and C) to demonstrate that the mineral carrying the magnetic remanence in these sites is also magnetite.

Most of the stereo plots for the AF-TH demagnetizations exhibit the characteristic Matachewan direction. Of the 29 samples demagnetized by this method, 26 show stable end point in this characteristic south-west and shallow direction. The other 3 samples were either unstable or had an anomalous direction. Figure 3.5 shows a typical AF demagnetization of a viscous secondary magnetization, as the direction swings to the stable end point and also shows that directional stability is lost at temperatures above 580°C.

Orthogonal vector projections of data from the TH part of the AF-TH demagnetization experiments typically show one straight line component (Figure 3.6 A). Secondary magnetizations, generally were erased by the AF, before the start of the thermal demagnetizations. However, some samples still show a persistant secondary component (Figure 3.6 B) that is erased during the thermal portion of the demagnetization.

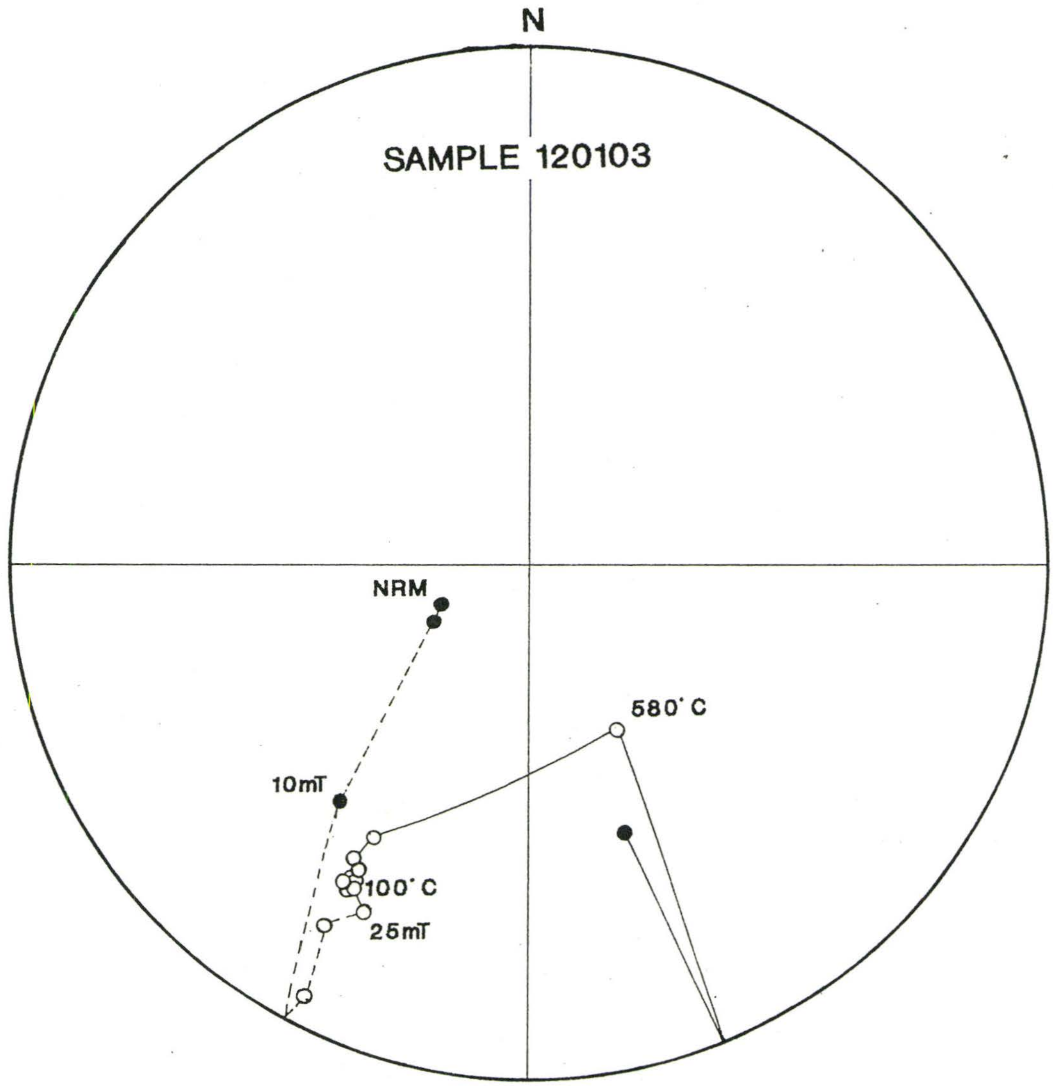

Figure 3.5 Typical stereo plot of during demagnetization by the AF-TH Method. The dashed line represents the AF demagnetization and the solid line represents the thermal demagnetization. Dots denote a positive (downward) inclination and circles denote a negative (upward) inclination.

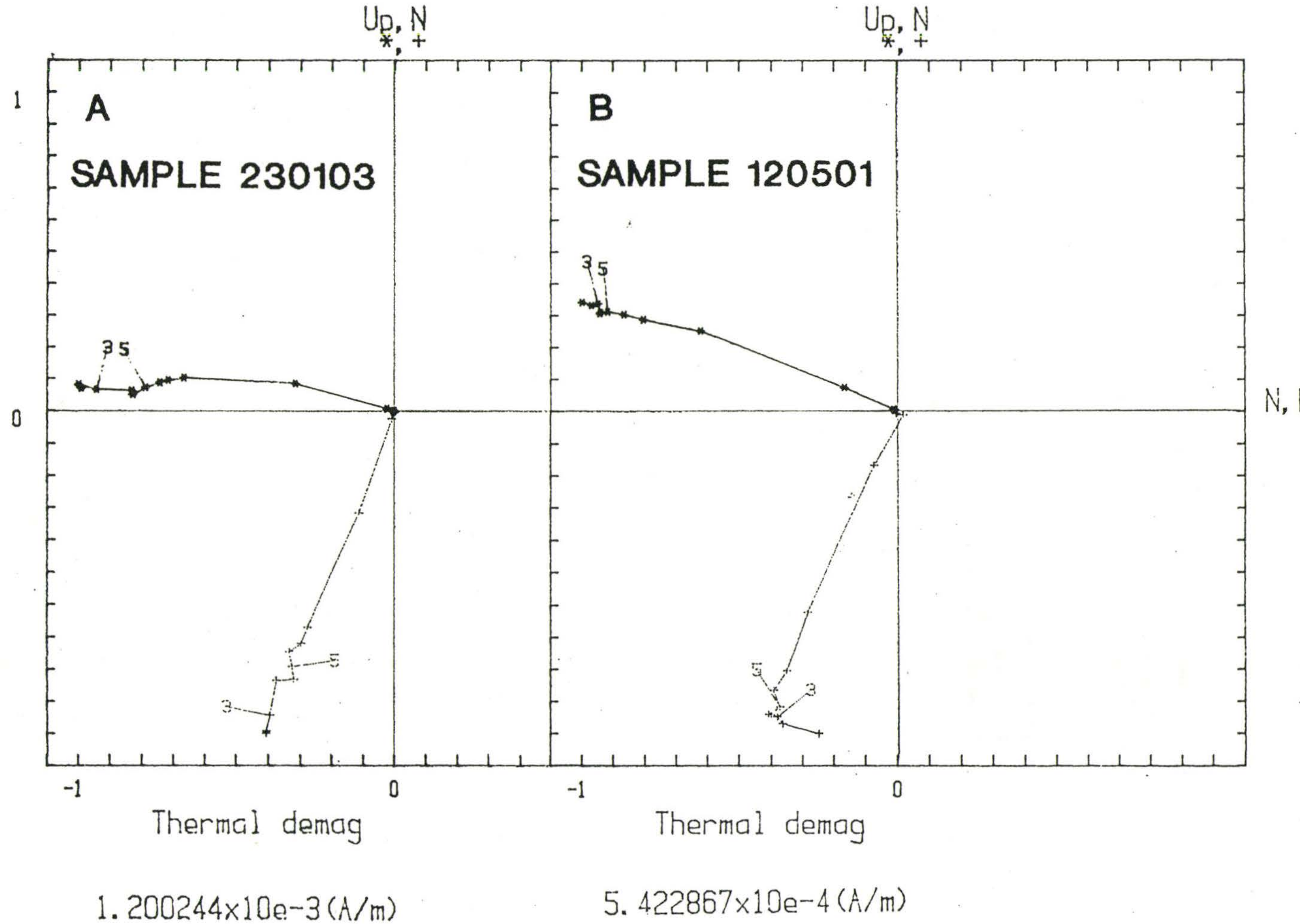

Figure 3.6 Typical orthogonal vector projections of the thermal part of the AF-TH method demagnetization. The intensity of the magnetization is printed under each plot and vector components are normalized to one. The x's indicate projections on the horizontal plane and the *'s indicate projections on the vertical plane.

3.4 Statistical Analysis

Most of the samples measured exhibited the characteristic southwesterly shallow Matachewan direction, thus it was possible to calculate an average direction for these samples and to estimate the precision of the results. This was done using a three tier average of the primary component directions estimated from the orthogonal vector projection plots of field corrected directions.

The first tier of the average was calculated using the data of specimens measured in each core to obtain a core average. Usually, two specimens per core were measured, but some cores had an additional sample.

The second tier for the average used the cores taken at a particular dyke or site. This site average was based on the five or six core averages. The results of this second tier average are displayed in Table 3.1. The precision of this average is given by the Kappa (k) and the Alpha-95 (α_{95}), statistical parameters of Fisher (1953). The Fisher Kappa is a measure of how tighlty grouped a population of vectors is when projected on the surface of a sphere. Greater values of k imply more tightly grouped vectors. The Alpha-95 is the radius of the cone 95 % of confidence about the average vector direction. It is represented on a stereo net by a circle. A smaller radius implies a higher level of

Table 3.1: SUMMARY OF RESULTS

Site	N	Dec°, Inc°	k	α_{95}	Method
06	7	215.0, +0.1	55.3	12.4	AF-TH
07	11	208.0, -29.9	263.6	4.7	AF
08	11	218.8, -27.3	288.6	4.5	AF
10	10	200.0, -25.6	86.6	8.2	AF
11	7	205.2, +0.7	10.1	40.8	AF
12	11	214.8, -10.4	41.2	12.0	AF-TH
22	9	200.0, -4.5	62.2	11.7	AF
23	11	211.6, -1.4	16.5	19.3	AF-TH
24	9	215.0, +8.1	44.5	13.9	AF

Grand Average Direction for 9 Sites:

Dec, Inc: 209.8°, -10.1° Pole Position: 40.1°N, 59.6°E

$k = 27.2$ $\alpha_{95} = 10.0$ $dp = 11.3°$ $dm = 7.8°$

confidence. These statistical parameters were calculated for each site and are also given in Table 3.1. Figure 3.7 shows a graphical representation of the quality of the data in Table 3.1. The quality of the data was quite reasonable, for early Proterzoic samples, as their Alpha-95's were less than 20°. Only site 11 deviated from this standard, achieving a rather poor Alpha-95 of 40.8°.

The third tier of averaging yields the average of all sites. This is known as the Grand average (Figure 3.8). The statistical parameters k and α_{95} are also calculated for this average. This Grand average can be used to calculate the virtual geomagnetic pole position (VGP) when combined with the latitude and longitude of the area where the samples were taken. Formulae for these calculations can be found in Collinson (1983). The results are shown in Table 3.1.

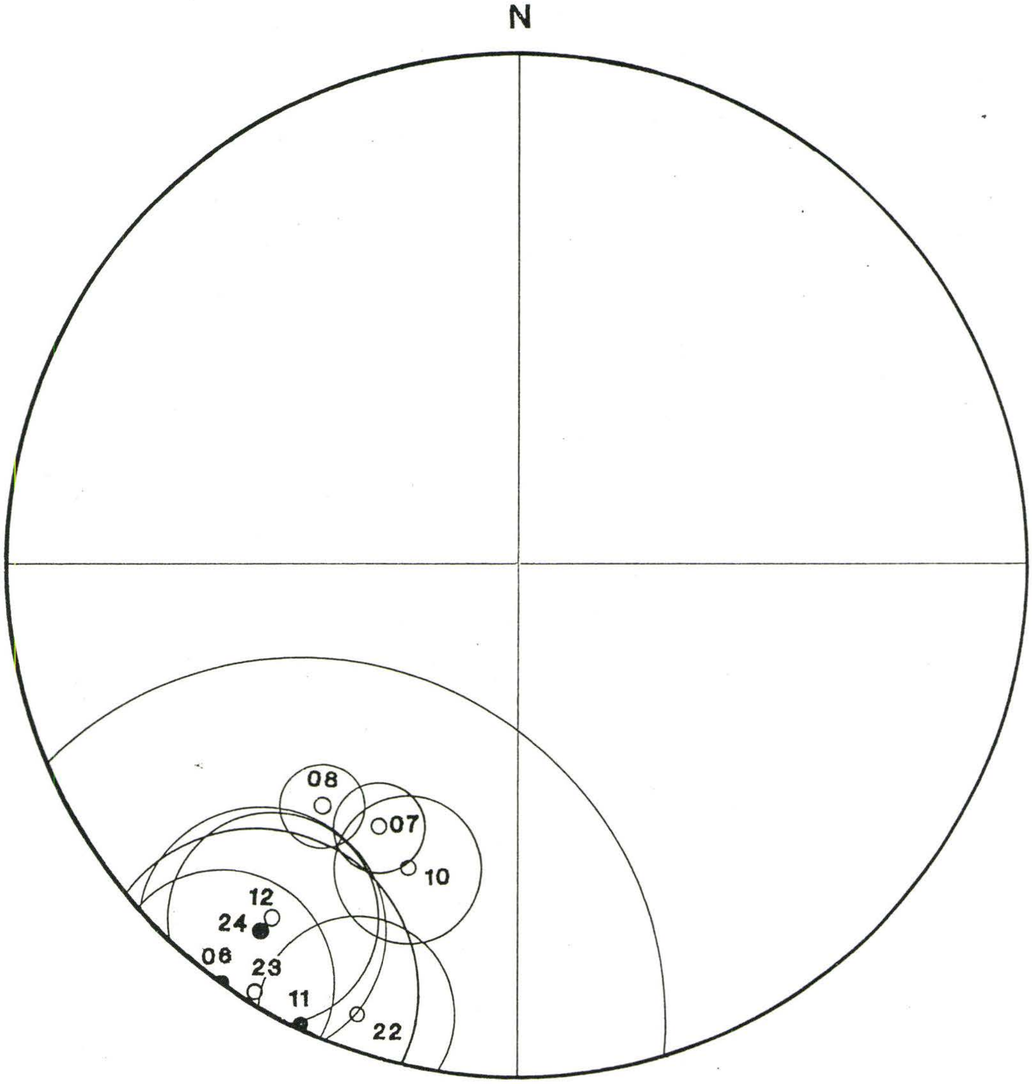

Figure 3.7 A stereo plot showing the average direction calculated for each site and its circle of 95% confidence. Dots denote positive (downward) inclination and circles denote a negative (upward) inclination.

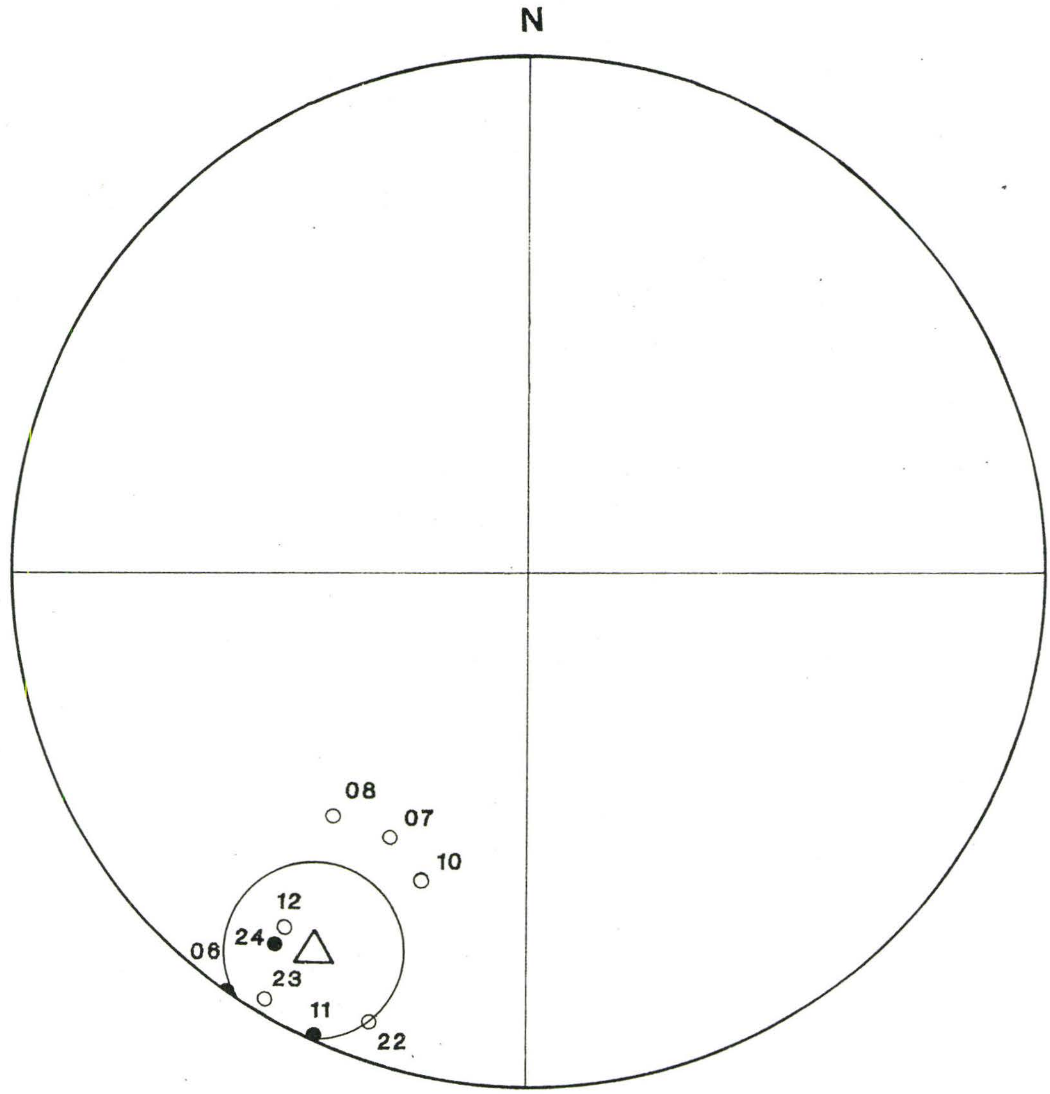

Figure 3.8 A stereo plot showing the site directions and the Grand average direction with its circle of 95% confidence. Dots denote a positive (downward) inclination and circles denote a negative (upward) inclination.

CHAPTER 4

INTERPRETATION

4.1 Comparison of the Matachewan Directions With Previous Results

Data presented in the previous chapter demonstrate that practically all of the samples measured during the course of this study carry a characteristic shallow, south-westerly direction. This has been shown to be statistically indistinguishible from the established Matachewan direction of previous researchers (Strangway, 1964; Fahrig et.al., 1965; Irving and Naldrett, 1977). Table 4.1 compares the data from this study with those from three previous studies. Figure 4.1 shows this comparison diagramatically.

4.2 Scatter of Site Directions

Referring back to Table 3.1, it can be noted that the average site directions are not tightly grouped. The range of declinations is 18.8° and the range of inclinations is 38°. There is no apparent correlation between the site average directions and the position of each site with resect to the Otto Stock, along the east-west traverse. The difference in site averages is most likely due to secular variations in the geomagnetic field. Significant secular variations have been known to occur over a few thousand years (Merrill and McElhinny, 1983). Small differences in

Table 4.1: Comparison of Magnetization Directions

Direction	Dec°	Inc°	k	α_{95}
<u>Matachewan Dykes</u>				
Strangway (1964)	186	-3	6.5	19.2
Fahrig *et.al.* (1965)	211.9	-5.9	4.4	12.4
Irving and Naldrett (1977)	207	-16	97	8
Grand Average (this study)	209.8	-10.1	27.2	10.0
<u>Otto Stock</u>				
Pullaiah and Irving (1975)	330	+71	139	3

Pole Positions	Lat.°	Long.°	dp°	dm°
<u>Matachewan Dykes</u>				
Irving and Naldrett (1977)	44N	60E		
Grand Average (this study)	40.1N	59.6E	11.3	7.8
<u>Otto Stock</u>				
Pullaiah and Irving (1975)	69N	133W		

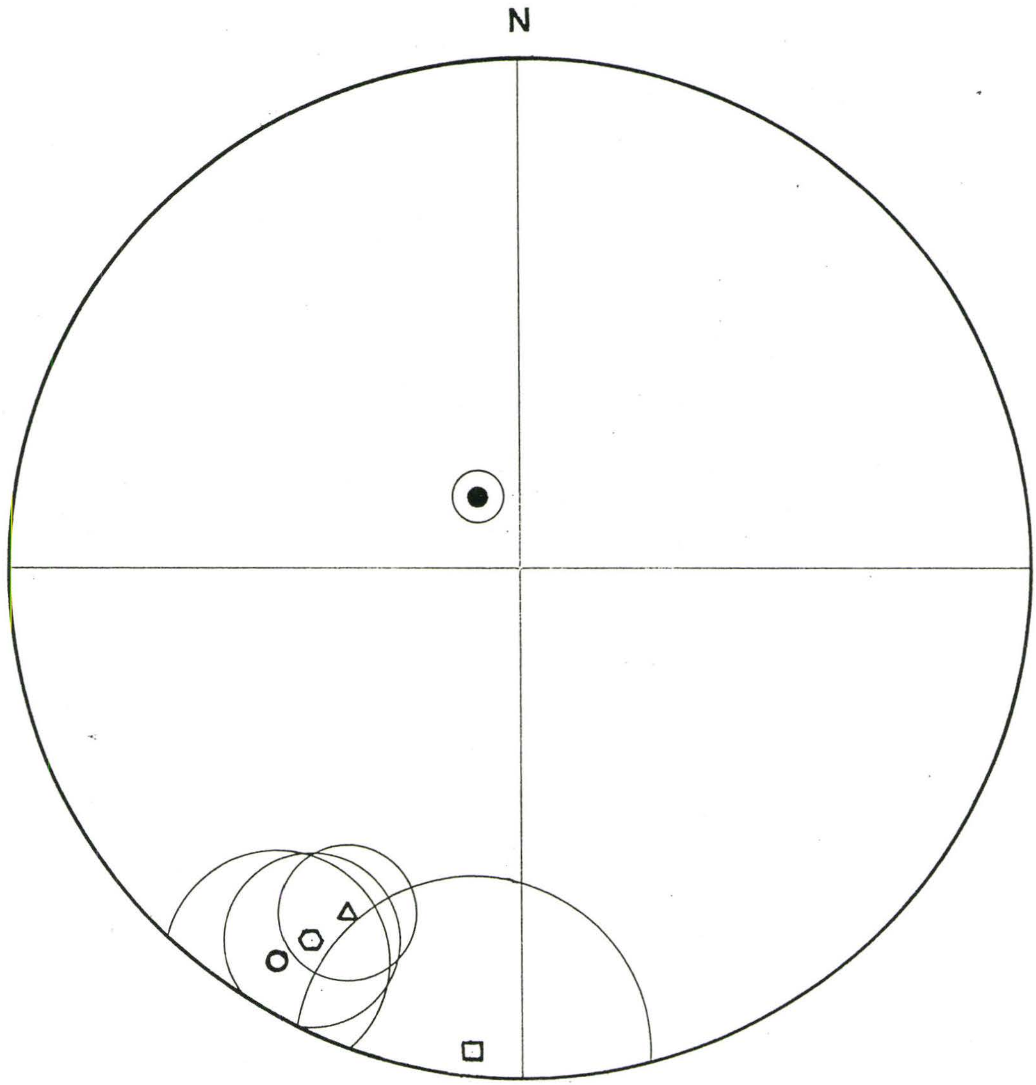

Figure 4.1 A stereo plot showing the Matachewan direction determined in previous studies, (□) Strangway (1964), (○) Fahrig et.al.(1965), (△) Irving and Naldrett (1977) and the direction determined in this study (⬡). The Otto stock direction is also shown, (●) (Pullaiah and Irving, 1975). Solid shapes indicate positive (downward) inclinations and open shapes indicate negative (upward) inclinations.

the time of intrusion of the dykes will therefore cause differences in the direction of the magnetic remanence recorded in the rock.

4.3 Timing of the Matachewan Dyke Intrusions

Some of the samples measured in this study were from Matachewan Dykes that were within the contact aureole of the Otto Stock (sites 11 and 12). These carry a characteristic Matachewan remanence with no evidence of an Otto Stock overprint. The absence of an Otto Stock overprint in these samples implies that the intrusion of the Otto Stock cannot have taken place after the intrusion of the Matachewan Dyke swarm. The Otto Stock is therefore older the Matachewan dykes.

This finding is in agreement with recently determined dates for the two intrusions. The Matachewan Dyke swarm is now dated at 2452 +3/-2 Ma by Larry Heaman (1988), of the Royal Ontario Museum, in a Baddeleyite U-Pb age determination. The Otto Stock has been found to be 2680 $\pm$1 Ma by Corfu et.al. (1989), also at the ROM, using the U-Pb Zircon method.

Further evidence that the Matachewan magnetization is younger than the Otto Stock magnetization can be observed in the thermal demagnetization data from lamprophyre dykes presented by Pullaiah and Irving (1975). A few lamprophyre dyke specimens show a characteristic Matachewan overprint before swinging to the Otto Stock direction (Figure 4.2). If it is a partial TRM, then it is a younger component. It probably results from a mild regional heating associated with the intrusion of the Matachewan Dyke swarm.

4.4 Implications for the Archean APWP

The VGP for the Matachewan Dykes (44°N, 60°E) reported by Irving and Naldrett (1977) and the VGP for the Otto Stock (69° N, 133° W) reported by Pullaiah and Irving (1975) are important tie points for the conventional early Proterzoic and late Archean apparent polar wander path (APWP) (Figure 4.3), first proposed by Irving and Naldrett (1977) and later revised by Dunlop (1984). However, this APWP was constructed when the ages of the Matachewan dyke swarm and the Otto Stock were believed to be 2690 Ma and 2114 Ma, respectively (Bell and Blenkinsop, 1976; Gates and Hurley, 1973). As it is conventionally drawn, the path thus shows a decrease in age from the Matachewan Dykes to the Otto Stock. This cannot be reconciled with the results of the present study which demonstrate that the magnetization of the Otto Stock is older than the magnetization of the Matachewan dykes. More precise dating of the Otto Stock, 2680± 1 Ma (Corfu et.al., 1989) and the Matachewan Dyke swarm,

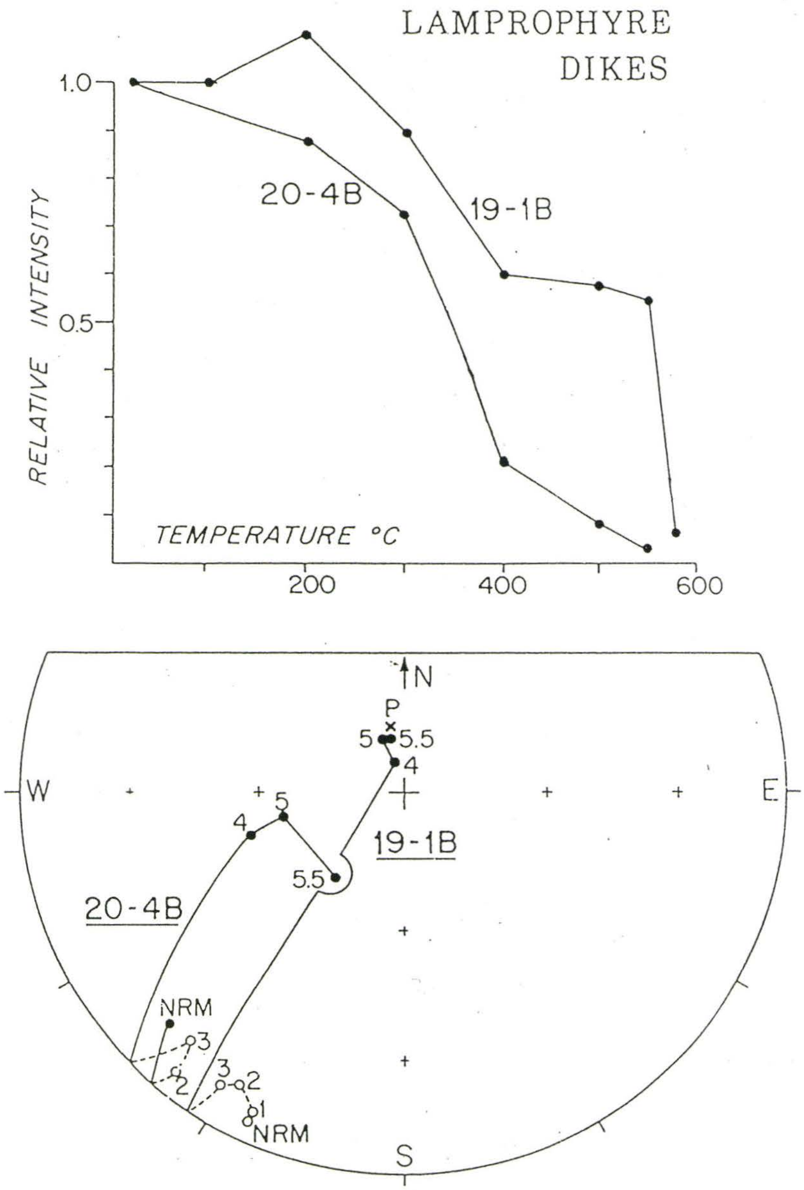

Figure 4.2 This figure is redrawn from Pullaiah and Irving (1975, figure 9). Samples 19-1B and 20-4B show a secondary Matachewan overprint swinging to the primary Otto Stock direction.

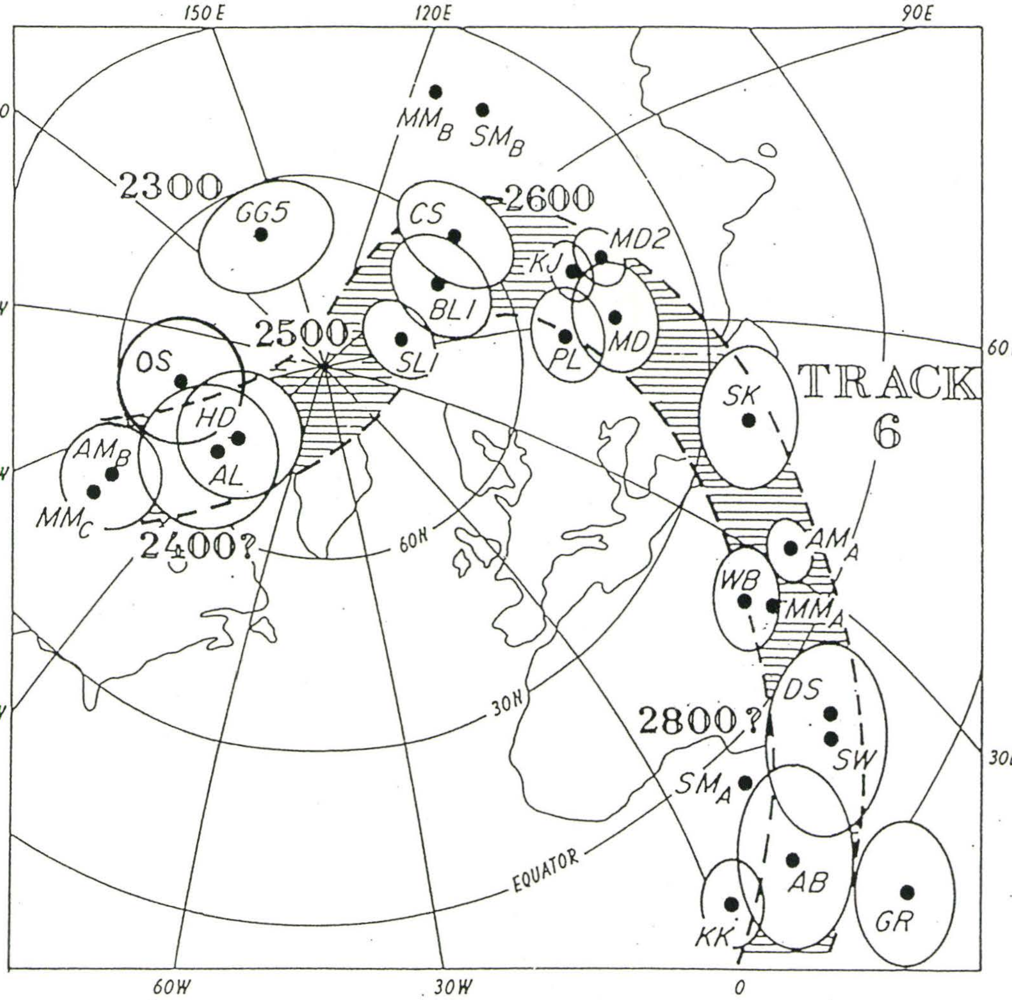

Figure 4.3 Early Proterozoic and late Archean APWP for North America, modified from Dunlop (1984, figure 9). The paleopoles are identified by Irving (1979, figure 11) and Dunlop et.al. (1984, figure 12). This shows that the conventional APWP decreases in age from the Matachewan Dykes (MD) to the Otto Stock (OS).

2452+3/-2 (Heaman, 1988) also lend support to this interpretation. With these new results it can be concluded that the early Proterzoic part of the APWP is running backwards and must now be redefined.

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

The important conclusions of this study may be summarized as follows:

1. Matachewan Dykes in the vicinity of the Otto Stock carry the characteristic Matachewan direction.

2. Matachewan Dykes near the Otto Stock do not show an Otto Stock overprint.

3. The absence of an Otto Stock overprint on the Matachewan Dykes implies that the intrusion of the Otto Stock took place before the intrusion of the Matachewan Dyke swarm.

4. The Otto Stock's steep northwesterly direction is therefore a late Archean direction. This is inconsistent with the conventional apparent polar wander path.

5. The conventional APWP decreases in age from the Matachewan Dyke pole to the Otto Stock pole. Clearly, this part of the polar wander path must now be redefined.

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