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CONTRASTING STUDIES IN PALEOMAGNETISM: QUATERNARY MAGNETOSTRATIGRAPHY AND EARLY PROTEROZOIC PLATE MOTION ANALYSIS

by

MARIA THERESE CIOPPA

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We accept this thesis as conforming to the
required standard.

[redacted]

Dr. E. Irving, Supervisor (School of Earth and Ocean Sciences)

[redacted]

Dr. G. Spence, Committee Member (School of Earth and Ocean Sciences)

[redacted]

Dr. E. Van der Flier-Keller, Outside Member (Department of Geography)

[redacted]

Dr. N. Massey, External Examiner (B.C. Ministry of Energy, Mines, and Petroleum Resources, Geological Survey Branch)

[redacted]

Dr. J. Clague, External Examiner (Geological Survey of Canada)

University of Victoria

Supervisor: Dr. Edward Irving

Abstract

Two projects involving different aspects of paleomagnetism were completed for this thesis.

The magnetostratigraphy of stacked sequences of pre-Wisconsinan diamict (mostly till) and paleosols at three localities in southwestern Alberta and northern Montana was determined in an attempt to resolve conflicting ideas of their age. Sediments and paleosols at the Mokowan Butte locality carried a normal polarity-reversed polarity-normal polarity magnetization sequence, whereas the other localities sampled (Saint Mary Ridge and Two Medicine Ridge) carried only a normal-reversed sequence. It is suggested that the upper normal polarity sediments were probably deposited during the Brunhes Normal Chron, the reversed polarity sediments during the Matuyama Reversed Chron, and the lower normal polarity sediments deposited during the Gauss Normal Polarity Chron. The most likely correlation of the three localities indicates that paleosol 4 at Saint Mary Ridge, paleosol 4 at Mokowan Butte and paleosol 4 at Two Medicine Ridge are the same unit. The paleomagnetic record implies that glaciation of North America could have occurred at least 2.6 Ma ago.

A paleomagnetic determination of the Early Proterozoic (2250 - 1800 Ma) plate motion of the Archean structural provinces of western Laurentia (Slave-Rae-Hearne and Superior) results in information about the formation of the Trans-Hudson Orogen. The use of minimum reliability criteria and the development of a quality index culled that portion of the data set which could not be considered as representative of the geomagnetic field for the time interval under consideration. After relative rotations within a structural province were determined and corrected, paleolatitude curves and apparent polar wander paths were used to estimate motion between the structural provinces. The final amalgamation of the structural provinces seems to have occurred at 1840 Ma, and is characterized by similar paleolatitudes and overlapping APWPs. Certain discrepancies in the paleomagnetic data are resolved by an hypothesis of relative plate motion.

Examiners:

[redacted]

Dr. E. Irving, Supervisor (School of Earth and Ocean Sciences)

[redacted]

Dr. G. Spence, Committee Member (School of Earth and Ocean Sciences)

[redacted]

Dr. E. Van der Flier-Keller, Outside Member (Department of Geography)

[redacted]

Dr. N. Massey, External Examiner (B.C. Ministry of Energy, Mines, and Petroleum Resources, Geological Survey Branch)

[redacted]

Dr. J. Clague, External Examiner (Geological Survey of Canada)

TABLE OF CONTENTS

PART 1 Quaternary Magnetostratigraphy

PART II Early Proterozoic Plate Motion Analysis

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

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First, I would like to thank Dr. E. Irving, my thesis supervisor, who introduced me to the magic of paleomagnetism, for his unfailing patience, knowledge, and support. Dr. Rene Barendregt and Dr. E. Karlstrom introduced me to paleomagnetic field work, and Rick Myers provided much of the "grunt labour" for that expedition. Discussions with the aforementioned workers, as well as with Dr. P. Hoffman and Dr. Ken Buchan helped to clarify the ideas presented in this thesis. Jane Wynne and Judith Baker introduced me to the paleomagnetic lab, and got me out of a lot of problems with the equipment! Computer aid was provided by Guy Marquis. Funding from an NSERC grant to Dr. E. Irving is gratefully acknowledged.

CHAPTER 1

General Introduction

The discipline of paleomagnetism has made two major discoveries in the past few decades. This thesis was designed to explore both. The studies made are relevant to on-going research themes in Canadian earth sciences, and relate to problems that are difficult to solve by normal geologic methods.

The first discovery was the phenomenon of reversals of the geomagnetic field. The subdiscipline of magnetostratigraphy uses these reversals to date and correlate rocks. The second discovery was that the earth's axis of rotation (the mean magnetic pole) moves relative to the lithospheric plates, which is referred to as apparent polar wander. In actuality, this phenomenon records the movement of the plates relative to the axis of rotation. Although both phenomena are related to the geomagnetic field, they have different immediate causes. Reversals of the geomagnetic field are the result of motions in the earth's fluid core. Apparent polar wander is the result of movement of the lithospheric plates upon the surface of the earth. The two phenomena are both affected to some extent by convection in the earth's mantle.

The first part of this thesis is a paleomagnetic study of three stacked sequences of diamicts and paleosols, collectively termed Kennedy Drift, in southwestern Alberta and northwestern Montana. Conflicting ideas regarding the time spanned by formation of the drift may be resolved using magnetostratigraphy. Pedogenic correlation of the paleosols at the three localities has been attempted previously; magnetostratigraphic correlation may corroborate or refute the various hypotheses.

The magnetostratigraphy at various sites across western Canada has been determined (Barendregt *et al*, 1991a; Barendregt *et al*, 1991b; Barendregt and Vincent, 1990; Jackson *et al*, 1990), and can be used to understand climate change and to reconstruct the paleogeography of North America at various times in the past.

The second part of this thesis is a re-evaluation of paleomagnetic data from Early Proterozoic rocks of the Canadian Shield for the purpose of analyzing the relative motion of four Archean structural provinces (Slave, Superior, Rae and Hearne). No new data is generated; instead, the available paleomagnetic data is compiled and its quality is determined. Computational paleomagnetic techniques, including the calculation of paleopoles, relative rotations and paleolatitudes, are applied to those poles which are representative of the paleofield for a specified time interval. These paleopoles are used to determine apparent polar wander paths and consequently, the motion of the structural provinces.

Research in the Canadian Shield has been an on-going theme in Canadian earth sciences for many decades. At the present time, one aspect of LITHOPROBE, the largest project in the earth sciences in Canada, is the study of the origin of the Trans-Hudson Orogen in the western part of the Canadian Shield. This thesis is of direct application to that work.

PART I

QUATERNARY MAGNETOSTRATIGRAPHY

CHAPTER 2

Introduction and Geology

2.0 Introduction

The purpose of this part of the thesis is to describe the paleomagnetism of several pre-Wisconsinan glacial drift sequences (Horberg, 1956), to improve estimates of their age, and to suggest possible correlations among them based on observations of magnetic polarity. Competing suggestions have been made (detailed in section ***2.1.4***) for the age of the sediments and paleosols; they are either predominantly middle Pleistocene or predominantly late Pliocene/early Pleistocene. The competing ideas should be testable paleomagnetically; if the former hypothesis is correct, the sediments and paleosols should be predominantly of normal polarity, whereas if the latter hypothesis is correct, reversed polarity paleosols and sediments should prevail. Paleomagnetic methods have been utilised to solve this problem because of a lack of suitable materials for radiometric dating. The duration of the time interval in which the magnetization was formed is also questionable; the magnetization may be an integrated record of the paleofield over a long time interval, or may represent only a short time interval.

The glacial drift sequences, collectively termed Kennedy Drift, occur as isolated remnants in northern Montana and southwestern Alberta (Fig. 1), along the eastern margin of Waterton-Glacier Park. Paleosols cap the various units included within the Kennedy Drift. These probably formed mainly under interglacial conditions warmer and wetter than the present (Karlstrom, 1987, 1988, 1991). For the purposes of this account a unit is defined as being composed of a diamict (mostly till) and the paleosol developed in it. Each diamict-paleosol unit records at least one glacial and one interglacial interval.

Mokowan Butte, in southwestern Alberta, has the most complete and best preserved sequence of paleosols, and has been studied paleomagnetically by Karlstrom (1987) and Barendregt *et al.* (1991a). They were unable to obtain meaningful data from the lower part of the sequence, which we have therefore resampled. Results are also reported from Saint Mary Ridge and Two Medicine Ridge in Montana, which have good, but less complete sequences. The sediments at Mokowan Butte are not extensively cemented and alternating field (AF) demagnetization only could be carried out. Of special interest in the Montana sections is the greater abundance of cemented diamicts or calcrete, which provided solid specimens that could be thermally demagnetized, allowing the carrier of magnetization to be determined.

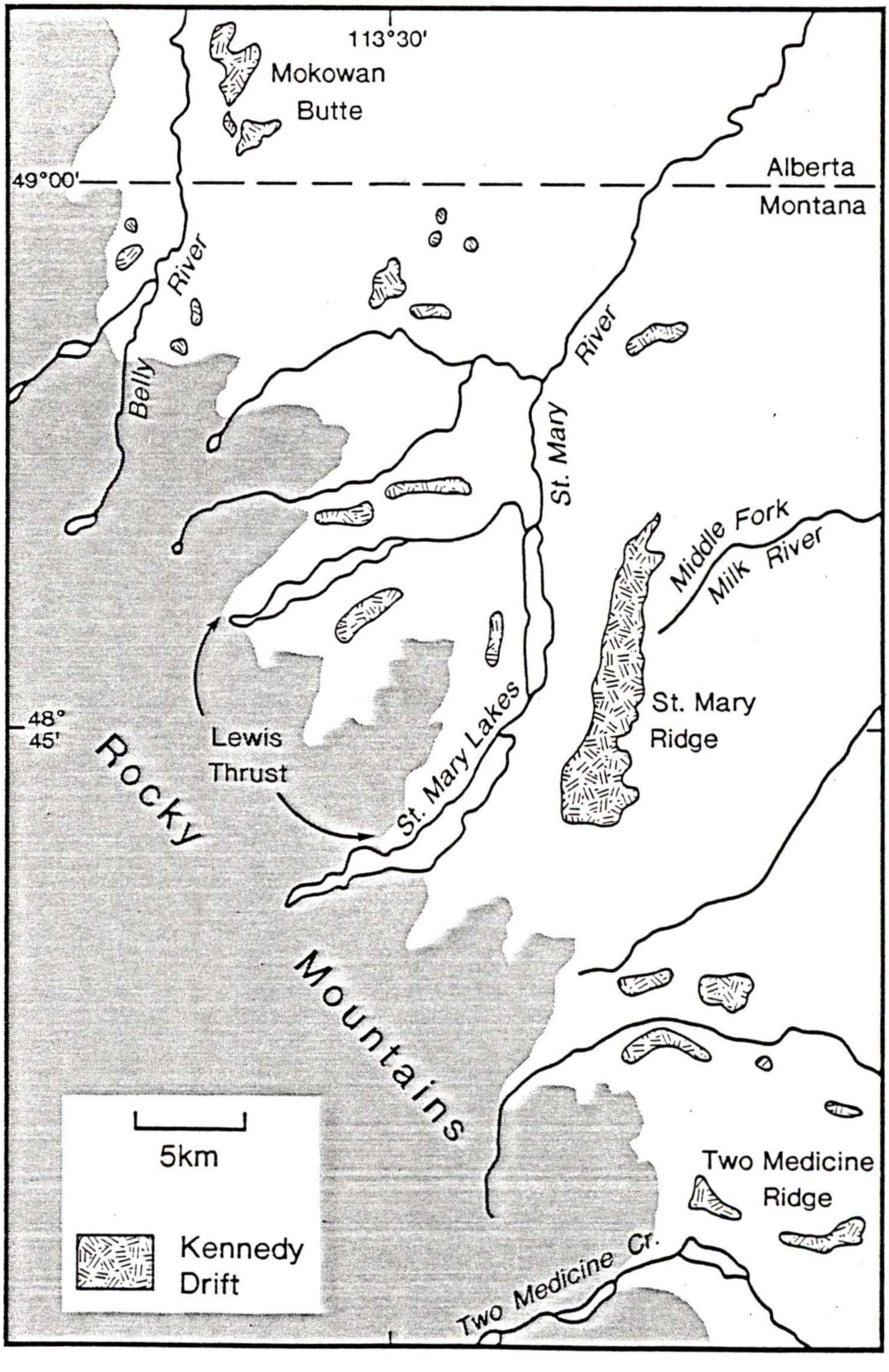

Figure 1. Location of Kennedy Drift in study area. The three localities sampled are Mokowan Butte, Saint Mary Ridge, and Two Medicine Ridge.

2.1 General Geology

2.1.1 Basal erosion surface

A series of erosion surfaces of different ages occur east of the Lewis Range (Alden, 1924). The most prominent of these is the Miocene-Pliocene Flaxville Bench upon which 30 to 70 m of the Kennedy Drift rests (Alden and Stebinger, 1913). Jungerius (1966, 1967), and Karlstrom (1987, 1990), consider this, and other similar surfaces, to be pediments formed by fluvial or glaciofluvial erosion, and/or by cryoplanation under periglacial conditions. In the sampling region, the Flaxville surface bevels Upper Cretaceous sandstone and shale. Rivers flowing through the foothills east of the Lewis Range have formed interfluves which expose the sequences of Kennedy Drift.

2.1.2 Composition and petrography of Kennedy Drift

The diamict is poorly sorted, consisting of about 50% Precambrian Belt-Purcell rock fragments in a sandy loam matrix. When unweathered, the rock fragments are 65-78% greenish and reddish argillite, 20-32% limestone and dolomite, 7-8% quartzite, 1-4% sandstone, and 1-4% diorite and basalt (Karlstrom, 1987). A glacial origin is suggested by the presence of striations on clasts (Alden and Stebinger, 1913; Karlstrom, 1987). Calcrete, or cemented diamict, occurs as distinct layers and was formed mostly by the leaching and reprecipitation of primary carbonates at depth, and in some cases, possibly by lateral movement of groundwater (Karlstrom, 1987; 1988). Calcrete horizons are not present in every unit, and their thickness varies.

Karlstrom (1987, 1988) describes the paleosols as consisting of yellowish-red, clay-rich, leached Bt or Bw horizons overlying leached Bw and/or Bk or Bkm (calcrete) horizons.

In order to explain the above terms, a general soil classification scheme follows (White, 1979). The major horizons of the soils are designated A, B, and E. A is the surface horizon, containing organic material, E is a near-surface horizon from which material has been leached, and B is a subsurface horizon which has been enriched by illuviation from the above horizons. Subscripts indicate the type of material present: k indicates that the horizon contains a relatively high percentage of secondary calcium carbonate, m that the horizon is continuously cemented, w that the parent material shows alteration due to leaching, weathering etc., and t indicates that translocated clay is present (White, 1979). Part or all of the Bkm horizons consists of calcrete. In the unindurated horizons (Bw or Bk) of the diamict (till), pockets of fine sediments which can be sampled exist.

2.1.3 Diamicts and paleosols in Kennedy Drift

Karlstrom (1981, 1988) suggests that as many as five paleosols in five till units occur at Mokowan Butte and Saint Mary Ridge, three paleosols in four tills occur at Two Medicine Ridge, two paleosols in two tills cap Milk River Ridge. Hence, he argues that at least five glacial and five interglacial intervals are recorded. This is probably a minimum, as the units on Mokowan Butte and Saint Mary Ridge, the two most complete sequences, are not directly correlative. The lower levels at Saint Mary Ridge are covered by talus and the total number of units there is unknown.

Diamicts and paleosols are here denoted by ***D*** and ***P*** respectively. The oldest diamict at a particular locality is identified as ***D1***, and its associated paleosol as ***P1***. If, in a unit, an associated paleosol is not present, then that paleosol number is not used. The stratigraphy and sampling sites at the three localities are shown in Fig. 2. Sampling sites are designated by letters, which have little stratigraphic significance.

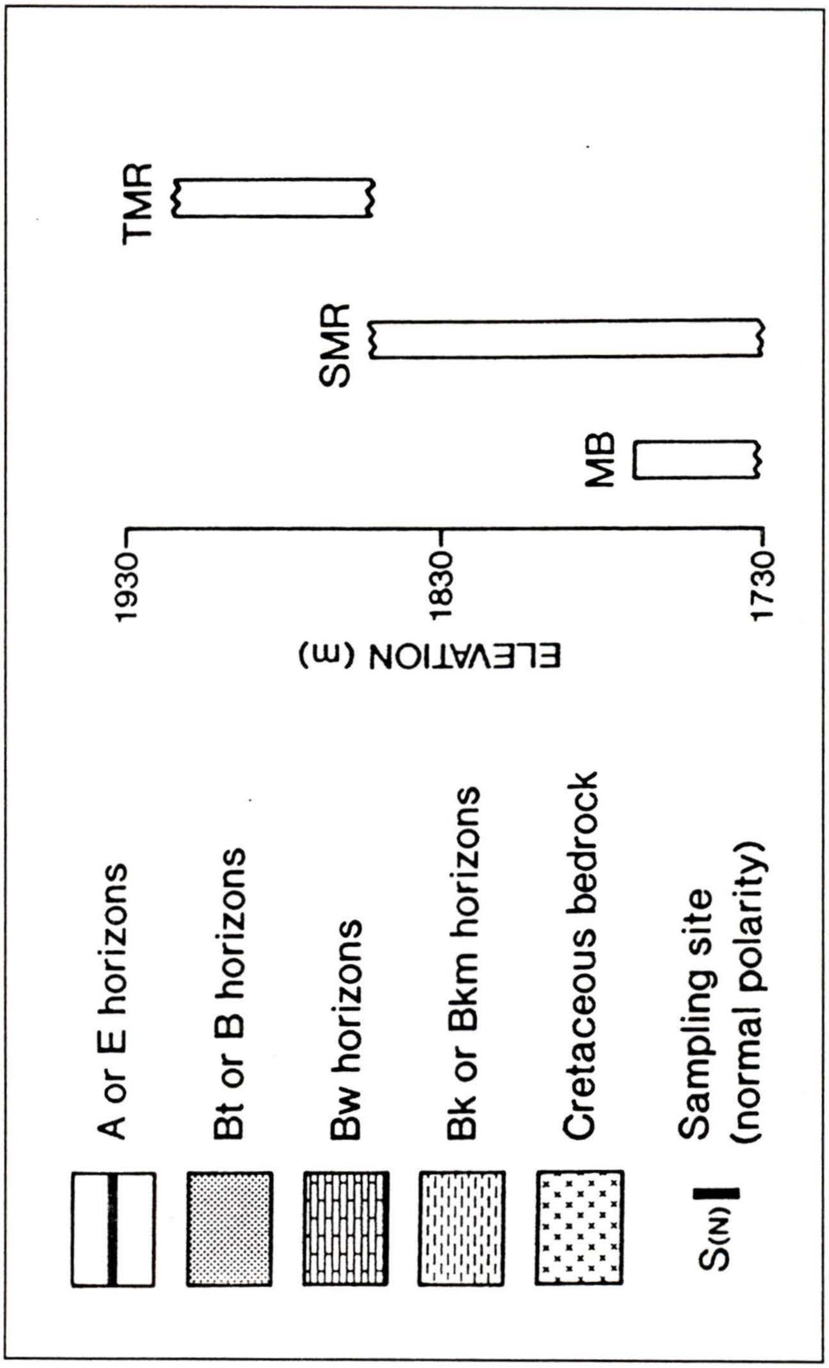

Figure 2. Stratigraphy and sampling sites at three localities. The thickness sampled in indicated by bar height; polarity of each site is also indicated. Relative elevations are shown at right.

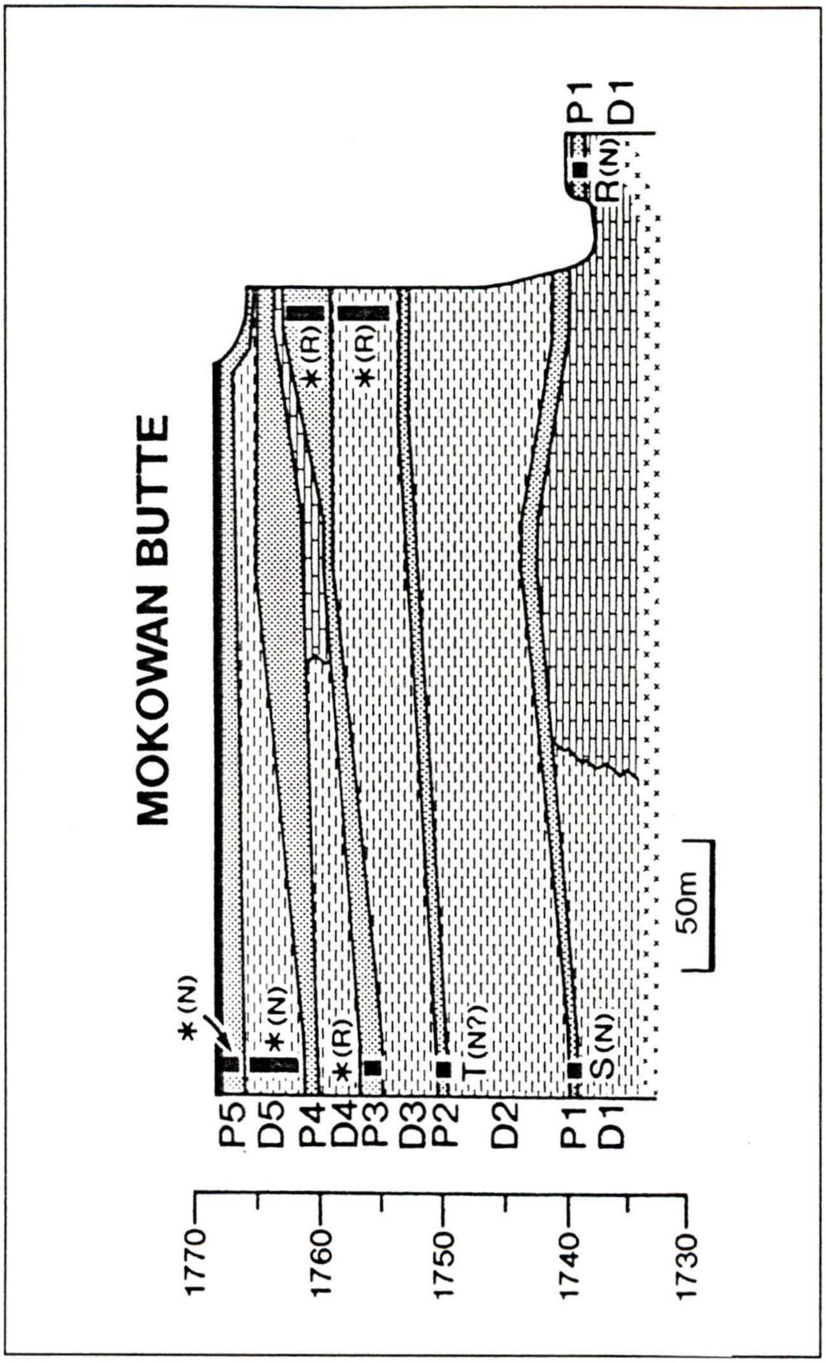

Figure 2a. Stratigraphy and sampling sites at Mokowan Butte, adapted from Karlstrom (1981, 1987). See page 8 for legend.

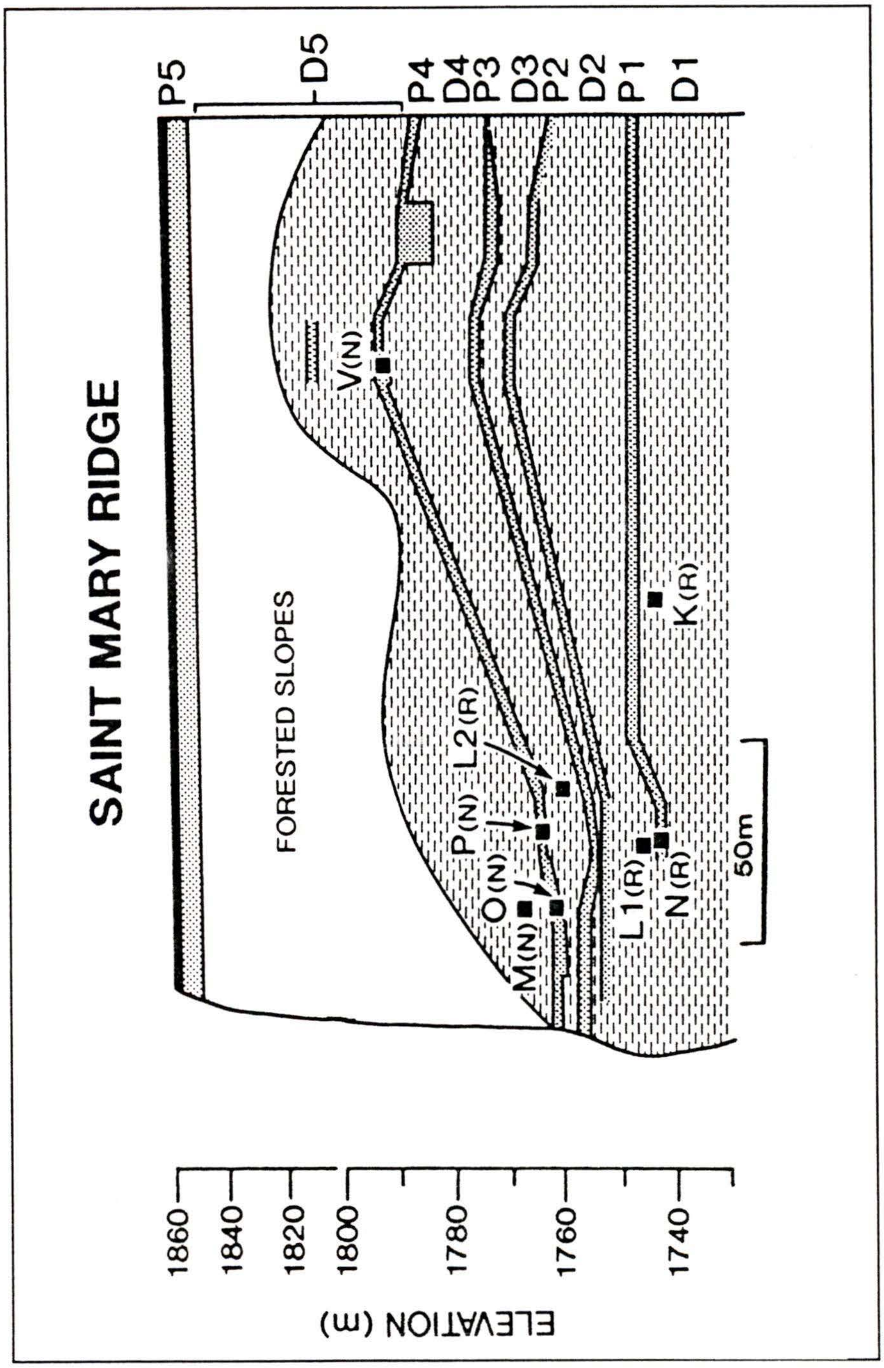

Figure 2b. Stratigraphy and sampling sites at Saint Mary Ridge. Stratigraphy is adapted from Karlstrom (1981, 1987). See page 8 for legend.

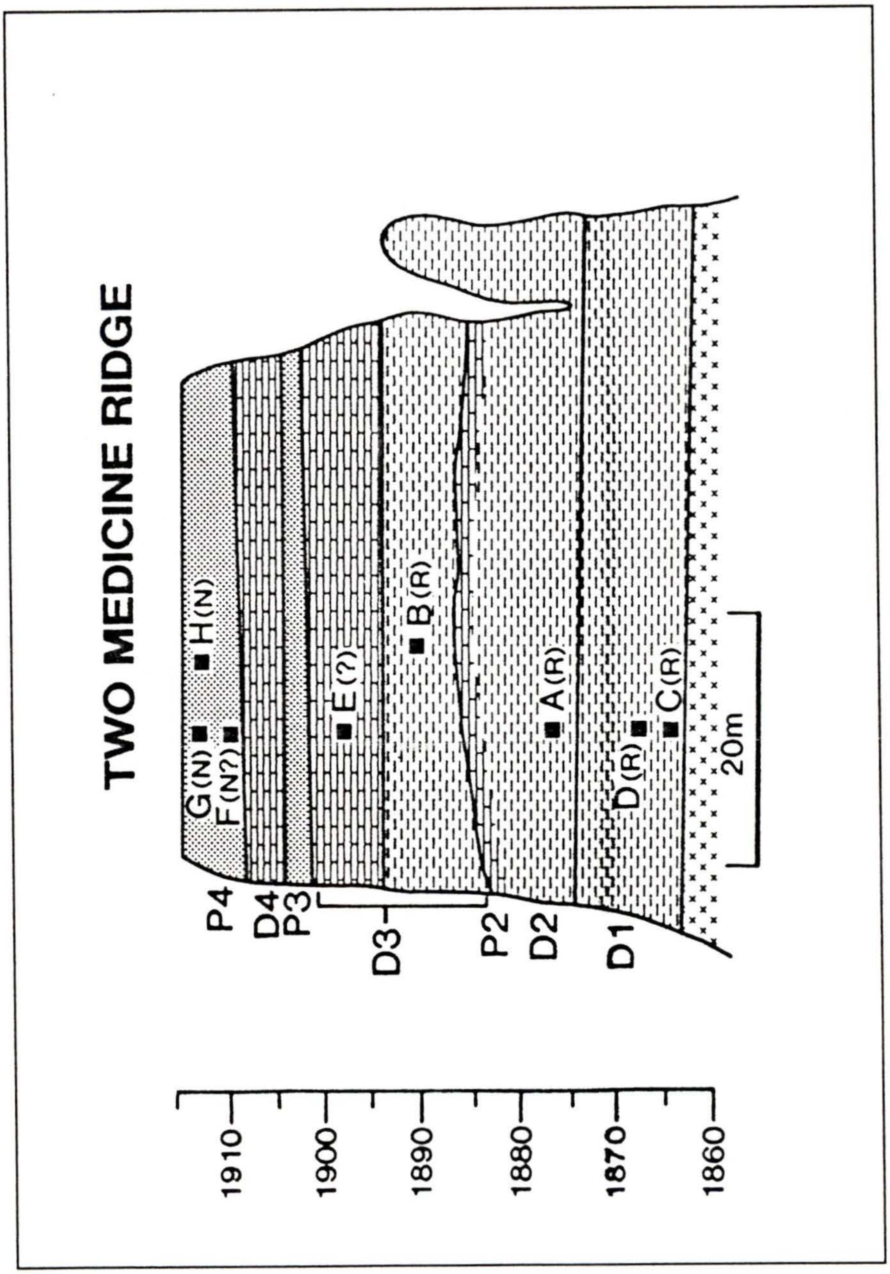

Figure 2c. Stratigraphy and sampling sites at Two Medicine Ridge. Stratigraphy adapted from Karlstrom (1981, 1987). See page 8 for legend.

Of the five superposed paleosols at Mokowan Butte, ***P3***, ***P4***, and ***P5*** are thickest and most strongly developed, and include reddish, clay-rich, argillic (Bt) horizons overlying petrocalcic (Bkm), calcic (Bk), or leached (Bw) horizons (Karlstrom, 1987). ***P1*** and ***P2*** are less developed but also include clayey argillic horizons overlying calcic, petrocalcic or leached horizons. The whole sequence overlies Cretaceous bedrock (Karlstrom, 1987). The lowermost diamict (***D1***) contains rounded clasts, possibly indicative of a fluviatile rather than a glacial origin.

At Saint Mary Ridge there are at least four buried paleosols (Karlstrom, 1981; 1988, Fig. 2b). This locality, unlike the others sampled for this study, did not have Cretaceous bedrock exposed, so older buried paleosols may underlie the exposed section. In general, the paleosols are thinner and less developed than those found elsewhere and consist of yellowish-red, leached, argillic horizons, and / or reddish-brown, leached, Bw horizons overlying 4 to 15 + cm thick calcretes (Karlstrom, 1988). Carbonate-cemented diamict is more common than at Mokowan Butte, and many of the sites were obtained by drilling.

Previous workers thought there was only one paleosol developed in one pre-Wisconsinan till at Two Medicine Ridge (Horberg, 1956). Karlstrom (1981, 1988) suggested that as many as three buried paleosols in up to four tills were present. Fig. 2c is adapted from Karlstrom (1981), and follows his suggested stratigraphic sequence. As at Mokowan Butte, the sequence overlies Cretaceous bedrock.

2.1.4 Age

Flaxville erosion surfaces occur beyond the range of the last (Wisconsinan) glaciation, and this establishes a younger age limit of 65 Ka for the Kennedy drift. Horberg (1956) considered Two Medicine Ridge to be entirely of Kansan age, or about

220 to 440 ka. Richmond (1965) subdivided the drift into three tills which he correlated with the Illinioan (120 to 170 ka), Kansan, and Nebraskan (600 to 860 ka). Later Richmond (1986) reduced his estimate of the time spanned by deposition of Kennedy Drift to between 780 and 428 Ka. Thus, glaciation is considered to have occurred primarily from the Middle Pleistocene to the present.

Much older age estimates have been made by Karlstrom (1987, 1991). His estimates of the age of the paleosols and tills are based on the Harden profile index which is dependent on horizon thickness and degree of soil development (Harden, 1982), on the clay accumulation index which measures argillic horizon development (Levine and Cielkosz, 1983), on paleomagnetic data from eight samples from Mokowan Butte, on a uranium trend date of 440 ± 120 ka from Saint Mary Ridge (Richmond, 1986) and on correlation with dated paleoclimatic sequences elsewhere. He estimated that the length of time of formation of the more strongly developed paleosols was 10^5 to 10^6 years, and for the less well developed paleosols was 10^4 to 10^5 years. On this basis a minimum age of 2.2+ Ma for the oldest diamict at Mokowan Butte is suggested, and glaciation occurred from the Late Pliocene to the present.

Paleomagnetism should discriminate between the two conflicting hypotheses. If Richmond's (1986) age estimate is correct, the sediments and paleosols should have dominantly normal polarity, formed during the Brunhes Normal Chron (780 ka BP to present), with reversed polarity occurring near the bottom of the sequences. If Karlstrom's (1987) age estimate is correct, the sediments and paleosols should have predominantly reversed polarity, formed during the Matuyama Reversed Chron (2 600 - 780 ka BP). Normal polarity would occur near the top of the sequences.

CHAPTER 3

Theory, Techniques, Sampling, and Instrumentation

3.1 Paleomagnetic Theory

The orientation of the earth's geomagnetic field at any point on the earth's surface is represented by two numbers: the declination (***D***), or the angle from north, and the inclination (***I***) or the angle from the horizontal. A magnetic mineral will align itself, insofar as possible, in the direction of the earth's magnetic field.

The magnetization of a rock can be carried by several minerals: magnetite, hematite, pyrrhotite etc., and can be acquired in different ways. The most common is thermal remnant magnetization (TRM). TRM is acquired as a rock cools from a high temperature, where the magnetic minerals can carry no magnetization, through its Curie point, where the minerals can begin to retain a permanent magnetization. At this point randomly oriented magnetic domains in the minerals will orient themselves along the earth's magnetic field. Further cooling 'freezes' this magnetization into the rock.

The second type of magnetization is detrital remnant magnetization (DRM). As clastic sedimentary rocks form, any grains of magnetic minerals will align mechanically with the geomagnetic field. As the rock is lithified, this magnetization is retained, although compaction may cause an apparent shallowing of the inclination.

The third type of magnetization is chemical remnant magnetization (CRM). If a grain of a magnetic mineral is very small, it cannot retain a permanent magnetization. As the grain gets larger (through crystallization), it reaches a critical blocking diameter where a permanent magnetization can be retained in the magnetic domains. It is probably this third type of remanent magnetization (CRM), and possibly the second (DRM) that is found in the sediments sampled.

3.2 Calculation of Magnetization and Fisher Statistics

The magnetometer used takes six measurements, each time measuring the magnetization of two of the three perpendicular axes. A total of twelve measurements, four for each axis, is obtained.

Let the magnetization along the three axes be $\boldsymbol{X}$, $\boldsymbol{Y}$, and $\boldsymbol{Z}$; $\boldsymbol{H}$, the horizontal component of the magnetization, $\boldsymbol{Z}$, the vertical component, and $\boldsymbol{M}$ the vector representing the magnetization. In order to normalize the measurements, a volume correction is necessary:

$$\boldsymbol{M1} = \boldsymbol{M} \times \mathrm{V}, \text{ where } \mathrm{V} = 10.8 \text{ cm}^3$$

Then:

$$\boldsymbol{H} = \sqrt{(\boldsymbol{X}^2 + \boldsymbol{Y}^2)},$$

$$\tan \boldsymbol{D} = \boldsymbol{Y} / \boldsymbol{X},$$

$$\boldsymbol{M1} = \sqrt{(\boldsymbol{X}^2 + \boldsymbol{Y}^2 + \boldsymbol{Z}^2)}$$

$$\tan \boldsymbol{I} = \boldsymbol{Z} / \boldsymbol{H} = \boldsymbol{Z} / \sqrt{(\boldsymbol{X}^2 + \boldsymbol{Y}^2)}$$

From the above formulas the declination and inclination ($\boldsymbol{D,I}$) can be calculated for each of the four sets of measurements ($\boldsymbol{X,Y,Z}$). The average declination and inclination can be calculated as well.

Fisher statistics can be used to calculate the precision and accuracy of the above measurements. We define a right angle triangle; $\boldsymbol{H}$ and $\boldsymbol{Z}$ are the two short sides, $\boldsymbol{T}$ $(=1)$ is the hypotenuse. Therefore, the angle between $\boldsymbol{H}$ and $\boldsymbol{T}$ is the inclination, $\boldsymbol{I}$. Using trigometry:

sin ***I*** = n / 1 where ***Z*** = n

cos ***D*** = l / cos ***I***, where ***X*** = l

sin ***D*** = m / cos ***I***, where ***Y*** = m

Therefore, for each ***D,I*** we can calculate l, m, and n. The declination and inclination of the mean direction are given by:

$$\tan D_m = \sum_{i=1}^{N} m_i \;/\; \sum_{i=1}^{N} l_i$$

$$\sin I_m = \sum_{i=1}^{N} n_i \;/\; R$$

where N is the number of measurements of any single axis, and

$$R^2 = \sum l^2 + \sum m^2 + \sum n^2$$

The best estimate of the precision ***k*** is

$$k = \frac{N - 1}{N - R}$$

The 95% cone of confidence around the mean is given by:

$$\alpha_{95} = \frac{140}{\sqrt{kN}}$$

3.3 Sampling

Sampling was carried out in 1990 at landslide scarps on Mokowan Butte, Saint Mary Ridge, and Two Medicine Ridge, and along a logging road on Mokowan Butte.

In unconsolidated sediments, a vertical face was cut and cylindrical plastic holders 2.54 cm in diameter were inserted into it. In total 121 paleosol or fine-grained diamict specimens were obtained this way: 51 from 6 sites at the Two Medicine Ridge locality, 34 from 4 sites on Saint Mary Ridge, and 36 from 4 sites on Mokowan Butte. In calcrete, cores were taken using a gasoline powered drill. Fifty-seven cores from which 82 cylindrical specimens were cut were drilled: 16 from Two Medicine Ridge and 41 from Saint Mary Ridge. Altogether, including the previous sampling by Barendregt *et al.* (1991a) at Mokowan Butte (125 specimens in plastic holders) a total of 331 specimens have now been collected from the Kennedy Drift: 164 from Mokowan Butte, 85 from Saint Mary Ridge, and 82 from Two Medicine Ridge. Results from Karlstrom (1987) are not included.

The sediment specimens were then cemented with glue to prevent disturbance and preserve the original magnetization. Previous work at Mokowan Butte had indicated the presence of a zone of reversed polarity (Barendregt *et al*, 1991a). In their study the specimens had been demagnetized in an alternating field, and it was possible that thermal demagnetization would improve rather poor results. Specimens collected for thermal demagnetization were dipped into a diluted solution of sodium carbonate (more commonly known as waterglass) and allowed to dry, rather then being cemented by glue. The specimens were then thermally demagnetized. As the polarities of the lower two diamicts and paleosols (units 1 and 2) were not determined by Barendregt *et al* (1991a), sampling was confined to the lowermost levels (***P1*, *P2***, and ***P3***).

3.4 Instrumentation

The paleomagnetic analysis was done at the Pacific Geoscience Centre in Sidney, B.C. Measurements were made on Schonstedt spinner magnetometers which have 'robots' and IBM PC's attached that automate measurements. Batches of 15 specimens can be measured unattended. A Schonstedt SSM-1 was used for AF demagnetization for fields up to 100 mT, whereas for fields above 100 mT and less than 180 mT, a Sapphire Instrument SI-4 was used. A Schonstedt TSD-1 was used for thermal demagnetization. Most specimens were demagnetized using at least three steps, although for a few sites where the pilot specimens showed a unidirectional magnetization, specimens were cleaned at 70 mT only.

The sequences are unlikely to contain a complete record due to reworking and erosion during glacial and interglacial periods. Moreover, the samples obtained did not cover the sequences in a uniform manner because of incomplete exposure, and because the materials exposed were too friable, too coarse-grained, or contained too many pebbles. Therefore the records described below constitute discontinuous spot readings of the geomagnetic field from which an overall interpretation can only be obtained by interpolation.

CHAPTER 4

Results

4.1 Examples of Magnetizations Present

Table 1 lists the site mean directions, and includes the results from Barendregt *et al.* (1991a). Most sites yield acceptable data but several have indeterminate magnetizations, as will be discussed later. Normal and reversed magnetizations occur at all three localities, in both diamicts and paleosols. Examples of each are shown, then the magnetostratigraphy at each locality is detailed.

4.1.1 Examples of normal magnetization

Three examples of the normal magnetization are given in Figs. 3 - 5. Fig. 3 is from paleosol 1 (***P1***), site S, at Mokowan Butte. After removal of a small component along the present earth's field (PEF), there is an excellent end point. Fig. 4 is from ***P4***, site V, at Saint Mary Ridge, and shows a single component magnetization. Fig. 5 is from a thermal demagnetization of calcrete at site M (***D5***) also from Saint Mary Ridge. The decay shows two steps marked by unblocking temperatures (T_{UB}s) of 100-300°C and 600-700°C.

4.1.2 Examples of reversed magnetization

Reversed magnetization occurs at all three localities in both calcretes (Fig. 6) and paleosols (Fig. 7) and are generally more variable than the normal magnetization. The scatter in the individual specimen directions at different sites is widely variable (k ranges from 11 to 113). In the example from site A on Two Medicine Ridge (Fig. 6), the intensity decay during demagnetization was smooth, the orthogonal plots went

Table 1. Site magnetizations

Site	Unit	Polarity	n	D (°)	I (°)	k*	α_{95} (°)
Two Medicine Ridge							
H	**P4**	Normal	5	352	60	60	11
G	**P4**	Normal	5	14	60	64	10
F	**P4**	Transitional?	10	225	84	10	17
E	**D3**	Transitional?	8	176	1	6	24
B	**D3** (Bkm)	Reversed	16	193	-74	58	5
A	**D2** (Bkm)	Reversed	13	167	-63	113	4
D	**D1**	Reversed	13	166	-45	9	15
C	**D1**	Reversed	9	166	-40	19	12
Saint Mary Ridge							
M	**D5** (Bkm)	Normal	10	006	61	483	2
V	**P4**	Normal	12	350	65	152	4
P	**P4**	Normal	4	309	37	74	11
O	**P4**	Normal	4	344	74	84	10
L2	**D4** (Bkm)	Reversed	10	207	-62	29	9
L1	**D2** (Bkm)	Reversed	7	163	-53	16	16
N	**P1**	Reversed	12	156	-53	16	11
K	**D1** (Bkm)	Reversed	9	154	-59	11	16
Mokowan Butte							
*	**6**	Normal	4	348	69	55	13
*	**P5, D5**	Normal	21	356	74	19	7
*	**P3**	Reversed	24	151	-46	6	13
*	**P3, D3**	Reversed	34	149	-57	10	13
T	**P2**	Normal?	11	63	55	3	40
S	**P1**	Normal	5	357	58	56	10
R	**P1**	Normal	6	354	46	10	23

Notes. Sites are grouped by locality. * in the *Site* column indicates results from Barendregt *et al* (1991a); *Bkm* in the *Unit* column indicates calcretes were sampled; α_{95} is the circle of confidence ($P = 0.05$); k is the precision parameter.

Table 2. Mean magnetization directions

Polarity	n	D (°)	I (°)	k*	α_{95}
Normal	65	347	64	27	11
Reversed	131	166	-48	5	30
Normal[1]	5	357	58	56	10

Notes. Only sites with $\alpha_{95} \leq 15$ are included. 1. The mean magnetization direction for the older (Gaussian) normal paleosols.

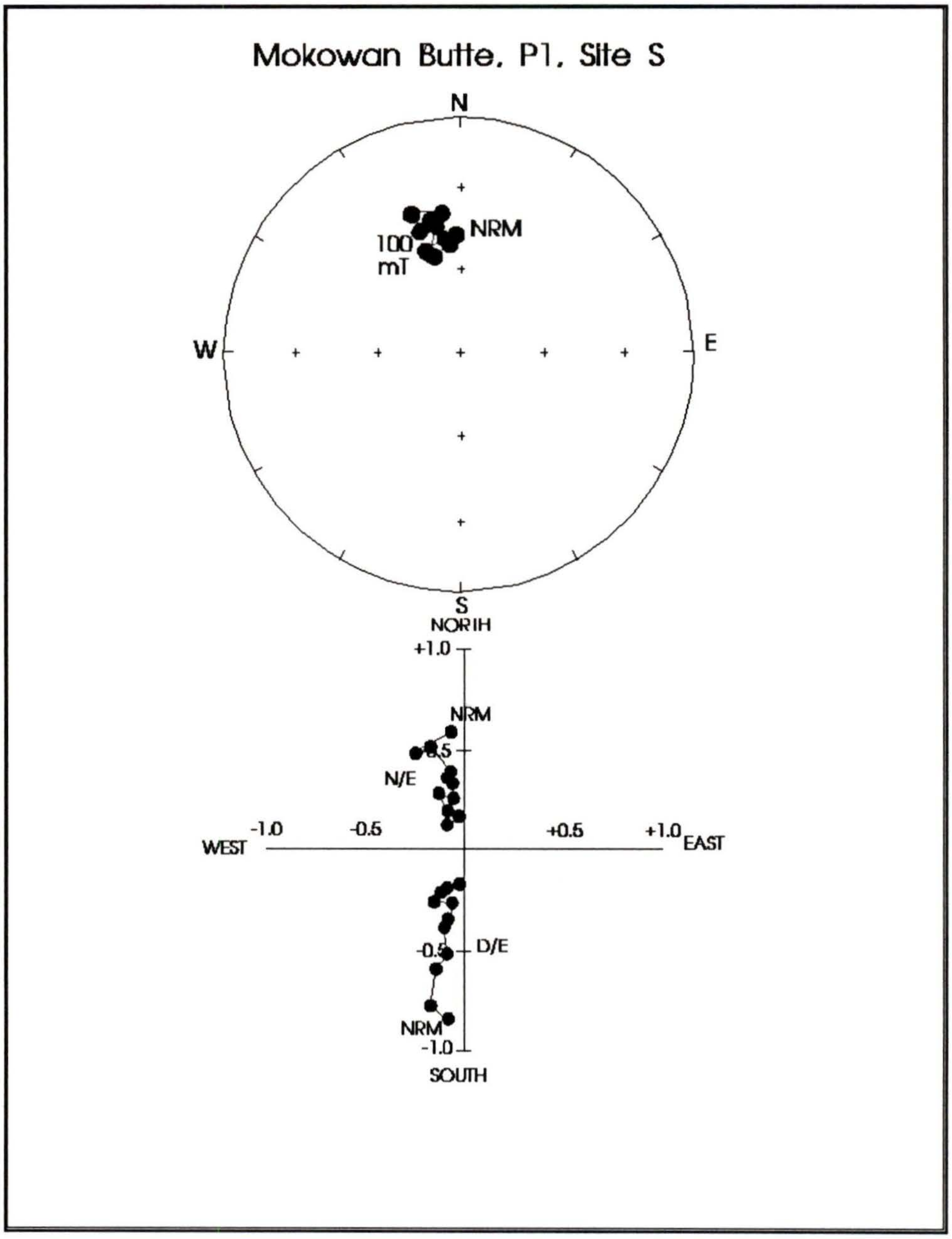

Figure 3. Normal magnetization from site S (***P1***) at Mokowan Butte. Directional change during AF demagnetization and orthogonal plots are shown. A closed symbol on the stereogram indicates downward inclination.

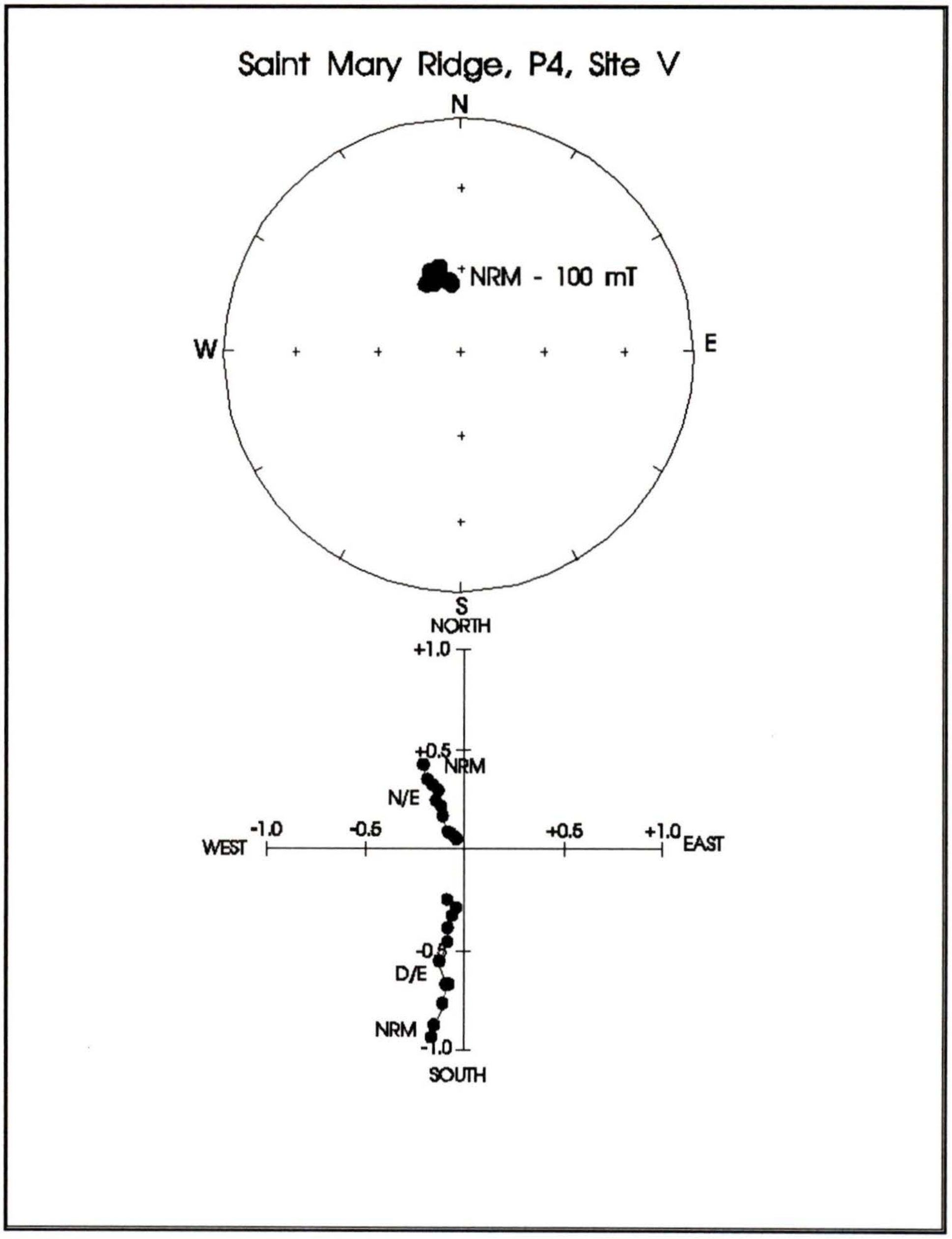

Figure 4. Normal magnetization from site V (***P4***) at Saint Mary Ridge. Symbols as in Fig. 3.

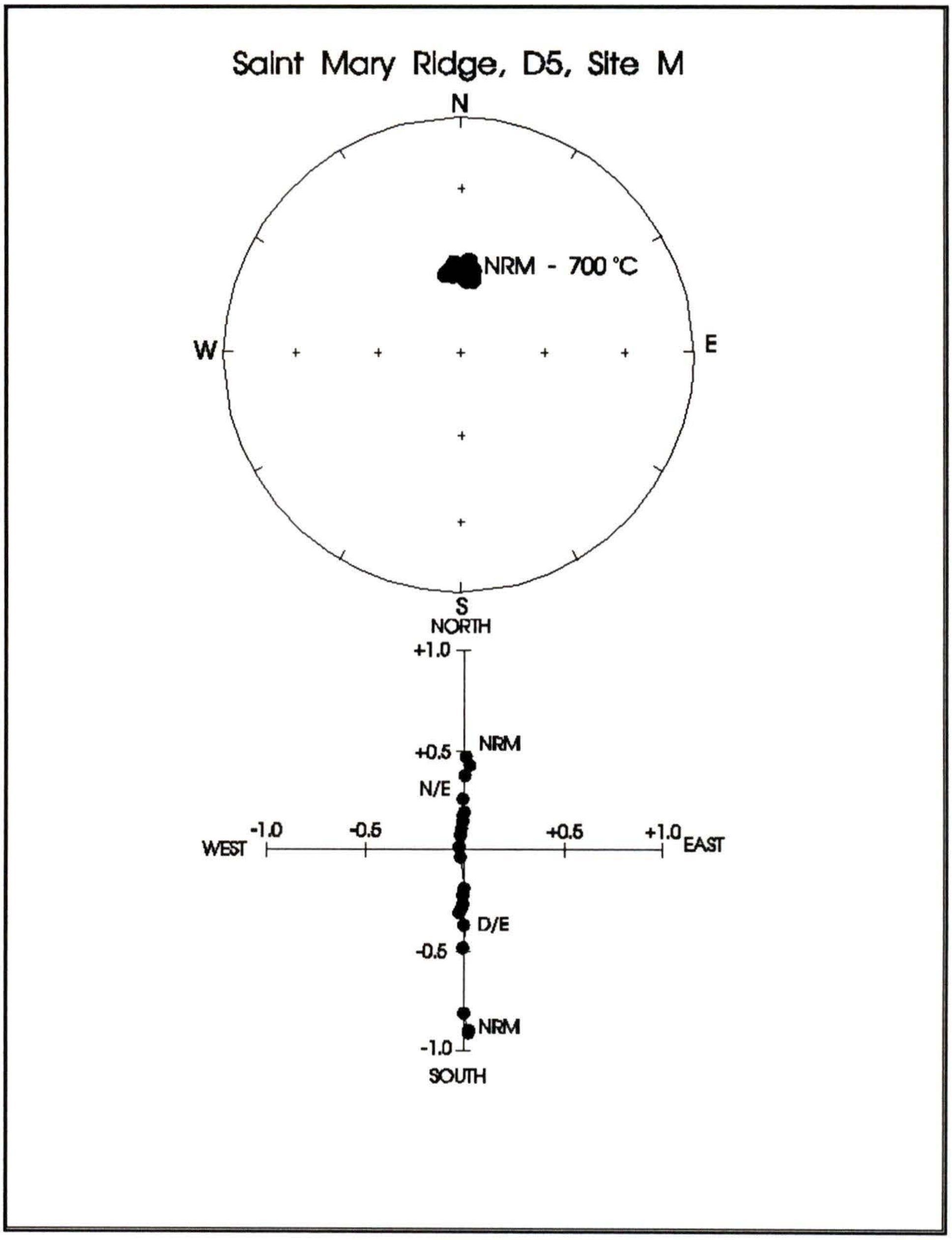

Figure 5. Normal magnetization from site M (***D5***) at Saint Mary Ridge. The calcrete specimen was thermally demagnetized. Symbols as in Fig. 3.

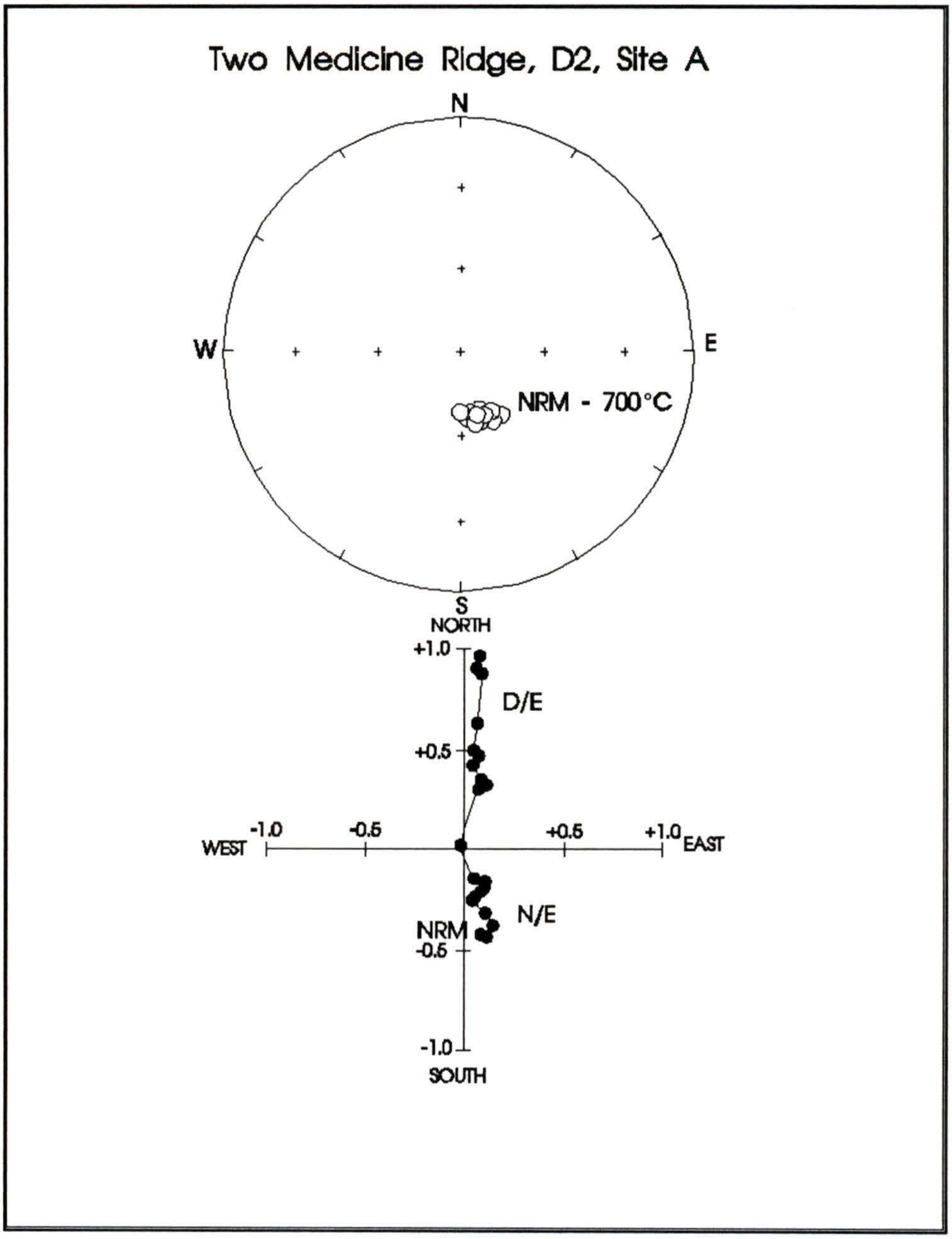

Figure 6. Reversed magnetization from site A (***D2***) at Two Medicine Ridge. Symbols as in Fig. 3; an open circle indicates upwards inclination.

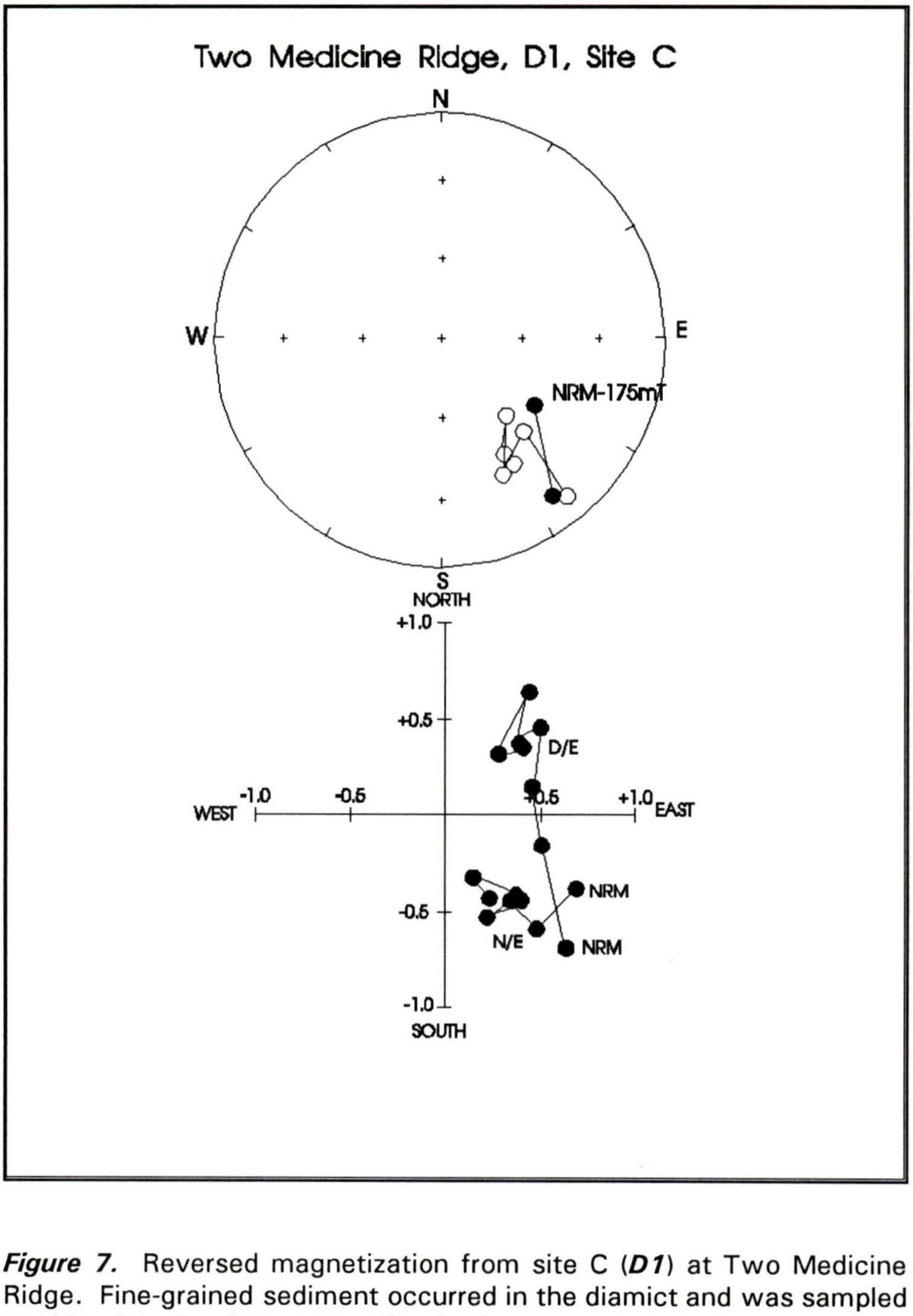

Figure 7. Reversed magnetization from site C (***D1***) at Two Medicine Ridge. Fine-grained sediment occurred in the diamict and was sampled at this site. Symbols as in Fig. 3: the open circle indicates upward inclination.

to the origin, and the individual specimen directions do not change during demagnetization (Fig. 6). At other sites, the orthogonal plots are poor, and the specimen directions variable, although unmistakably reversed (Fig. 7).

4.1.3 Example of oblique magnetization

Two sites at Two Medicine Ridge (E and F) have magnetizations that were neither normal nor reversed. Site E (upper ***D3***) has some specimens with positive inclinations and others with negative inclinations. Upon cleaning in fields of up to 175 mT, little change occurs (Fig. 8). Site F (lower ***P4***) specimen directions are widely scattered.

4.1.4 Thermal summary

Fig. 9 shows the curves obtained from four specimens that were thermally demagnetized. The sharp decline in intensity between 675 and 700°C indicates the presence of hematite. The slow decline in intensity at 200 - 300°C indicates the presence of fine-grained hematite. The directions of magnetization are unchanged throughout.

The inclination of the normally magnetized specimens is similar to, if slightly shallower than, the present earth's field (Table 2). The cause is unknown. At one site (site P, Saint Mary Ridge) a very shallow inclination may be the result of post-magnetization slumping of the sediments.

4.2 Mokowan Butte

Previous work (Barendregt *et al*, 1991a) showed that their Units 1 and 2 (***D1***, ***P1***, ***D2***, ***P2*** in this study) yielded scattered data for which polarity could not be

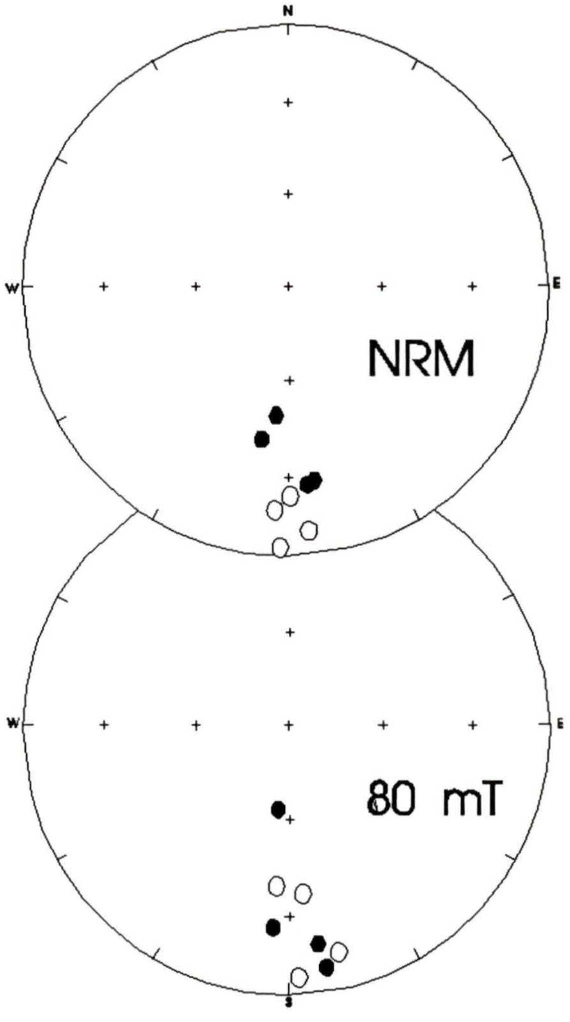

Figure 8. Oblique magnetization from site E (***D3***) at Two Medicine Ridge. After AF demagnetization, positive and negative inclinations were unchanged. Symbols as in Fig. 3.

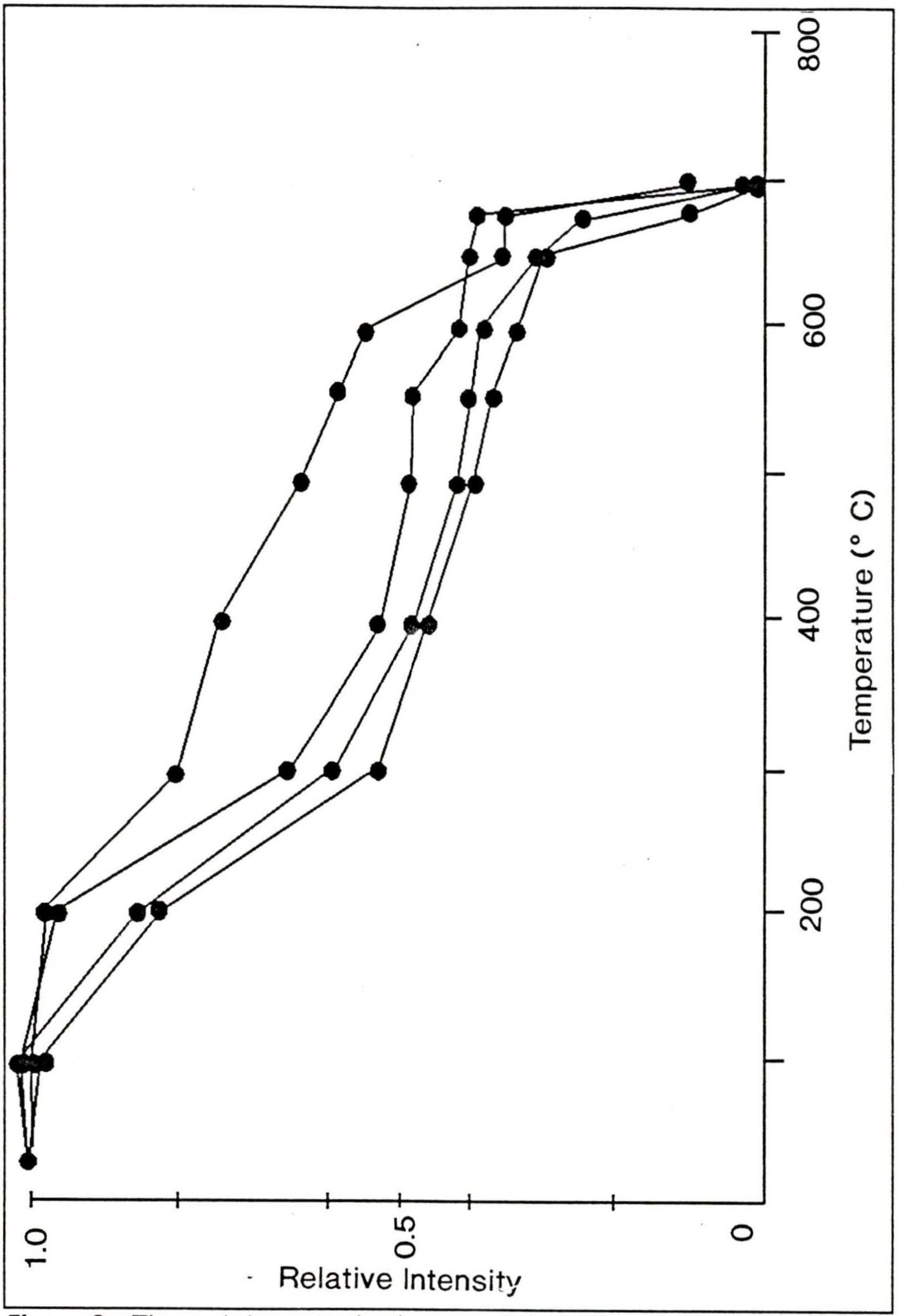

Figure 9. Thermal demagnetization curves from four calcrete specimens. The decline in intensity from 200° to 300° C and from 600° to 700° C indicates the presence of fine-grained hematite.

determined, Unit 3 (***D3***, ***P3***) had reversed polarity, Unit 4 (***D4***, ***P4***) gave rather scattered data, but a generally reversed polarity was indicated, and Unit 5 (***D5***, ***P5***) had normal polarity. As discussed above, only ***P1***, ***P2***, and ***P3*** were sampled.

P1 was sampled at sites R and S (Fig. 2). At site S a normal magnetization was observed (Fig. 3). For R, the specimen directions are scattered, but have an overall direction similar to S. Barendregt *et al* (1991a) in their study of ***P1*** found magnetizations that decreased rapidly in intensity, and concluded that the magnetization observed in ***P1*** was probably a Brunhes-age overprint. For the same paleosol, but at a different location (site S), it is observed that the individual specimens did not decay in the same way; i.e. losing 80% of the intensity after cleaning at 10 mT. Instead, an average of 35% of the intensity isretained after cleaning in fields of 80 mT. Thus it appears that these specimens are normally magnetized, and the magnetization is not an overprint.

P2 was sampled at site T. The NRM specimen directions are widely scattered, and partial demagnetization decreases this scatter somewhat. A normal polarity is seen. While the magnetization direction is systematically different from the present earth's field, the intensity decays more rapidly than that of site S (***P1***).

P3 has been sampled by Barendregt *et al* (1991a), and found to have a reversed polarity. In this study, the initial NRM directions are widely scattered. The specimens were thermally demagnetized, and the results are not clear, and therefore not included in Table 1. However, there does seem to be an indication of reversed polarity.

In summary, the paleomagnetic data indicate that at Mokowan Butte the lower units have normal polarity (paleosol 1 and possibly 2), the middle units have reversed polarity (paleosols 3 and possibly 4), and the upper unit have normal polarity (diamict and paleosol 5).

4.3 Saint Mary Ridge

The paleosol at the surface of Saint Mary Ridge is very strongly developed (Karlstrom, 1991), but was not sampled for paleomagnetic analysis, due to its inaccessibility. Two of the five paleosols (***P1*** and ***P4***) and four of the five diamicts (***D1***, ***D2***, ***D4***, and ***D5***) were sampled (Fig. 2b).

D1 was sampled at site K, ***P1*** at site N, and ***P2*** at site L1. All three sites display reversed polarity, and their site mean directions are virtually indistinguishable (Table 1). However, their k's are low, ranging from about 10 for site K to about 20 for site L1. The decay in intensity during demagnetization is not usually smooth; as well, the direction changes erratically during demagnetization.

D4 (site L2) also displays reversed polarity. Its site mean direction is not the same as at the three previous sites, although its k is higher. Otherwise, it exhibits similar behaviour during demagnetization.

P4 was sampled at sites O, P, and V. All display normal polarity; but site P has a shallower inclination than the others. As the paleosol at site P is not horizontal, it is possible that slumping might have shallowed the site mean direction. All samples exhibit similar behaviour (Fig. 4)

D5, sampled at site M, also exhibits normal magnetization. For all specimens, the decay of intensity during magnetization is smooth, and the magnetization direction does not change (Fig. 4).

At Saint Mary Ridge, sites with a normal polarity have high k values, and the decay of intensity is smooth, whereas the sited with reversed polarity have lower k values, and the decay of intensity is not so smooth. This might be a reflection of the greater frequency of pebbles in the older (reversed) sediments. The difficulty in removing Brunhes-age overprints from the reversed sediments may also be responsible.

In summary, at Saint Mary Ridge reversed polarity beds (***D1***, ***P1***, ***D2***, and ***D4***), underlie normal polarity beds (***P4*** and ***D5***).

4.4 Two Medicine Ridge

Previous paleomagnetic work by Richmond (1986) at this locality indicated that at least part of the succession had reversed polarity. However, the specimens were taken from slumped and tilted beds (Karlstrom, 1988) so their position within the sequence was uncertain. In the present study, 8 sites were sampled in ***D1***, ***D2***, ***D3***, and ***P4***.

The oldest diamict (***D1***) has no associated paleosol, but there were several pockets of sediments with high clay content within it that could be sampled. Two sites (C and D) were sampled. The demagnetization behaviour is not ideal, but reversed polarity is apparent at both sites (Table 1, Fig. 7).

D2 was sampled at site A (Bkm horizon) and ***D3*** at site B (also Bkm horizon). Both had reversed polarity. These sites have a smooth decay in intensity during demagnetization, and the magnetization direction does not change (Fig. 6). The precision for sites A and B is higher than for sites C and D (Table 1).

D3 was also sampled in fine sediments within a leached Bw horizon at site E. It does not have a clearly defined polarity (Fig. 8). Site E includes specimens with both positive and negative inclinations which do not change during AF demagnetization, even in fields of up to 175 mT. The magnetization directions are scattered (Fig. 8), and the inclinations are variable. As the fine sediments occur in a diamict, which was probably deposited in a short time interval, conceivably, this could be a record of the transition between normal and reversed polarities; alternatively, the effect may be a result of incomplete removal of a Brunhes overprint superposed on a reversed polarity. The horizon could have been subject to pedogenetic/diagenetic alterations during either or both the Matuyama and Brunhes epochs.

P4 was sampled at three sites: site F, near the bottom of the paleosol, and sites G and H towards the top. At site F, the individual specimen directions are scattered about a vertical downwards direction. All samples were taken from the same horizon. It is possible that the lower site (F) records a transition in the geomagnetic field, but this is by no means certain. Sites G and H exhibit normal polarity similar to that seen at sites O, P, and V at Saint Mary Ridge (Fig. 5). Little scatter was present in the individual specimen directions.

The reversed calcretes at Two Medicine Ridge (sites A and B) have high precision, whereas those at Saint Mary Ridge (sites K, L1, L2) are lower. This may be caused by the greater abundance of pebbles in the latter.

In summary, at Two Medicine Ridge, sediments with a reversed polarity (diamicts 1 and 2, and part of ***D3***), are overlain by sediments and paleosols with a transitional, overprinted, or uncertain polarity (upper ***D3*** and lower ***P4***), which are in turn overlain by a paleosol with normal polarity (upper ***P4***).

CHAPTER 5

Discussion and Correlations

5.1 Origin of Magnetizations and Length of Time represented by them

The presence of hematite in the paleosols and calcretes is indicated in two ways; the reddish-brown colour, and thermal demagnetization curves which suggest hematite as the carrier of NRM. As the precision, k, was, in general, proportional to the amount of cement present (as the percentage of cement increases, so does the k value) it is likely that the remanent magnetization is carried by the cement, in which hematite was precipitated by groundwater. Hence it is probable that the NRM is a chemical remanent magnetization acquired as the hematite grains grew and exceeded the critical blocking diameter ($\approx 1\mu$ for hematite). At Saint Mary Ridge, a normal polarity paleosol was deposited on a reversely magnetized diamict; therefore, in the diamict, cementation and magnetization probably occurred prior to and was unaffected by the formation of the paleosol. Furthermore, individual calcretes, some with normal and some with reversed magnetizations occur at different localities, indicating several episodes of magnetization acquisition over an extended period of time.

This "extended period of time" can be estimated. Karlstrom (1987, 1988) suggests several hundreds of thousands of years as the time required for the formation of the paleosols. All the hematite present in a paleosol is unlikely to have attained the critical blocking diameter simultaneously (section ***3.1***). It is more likely that the hematite in different parts of the soil attained the blocking diameter at different times. Therefore, it is reasonable to assume, as a first approximation that the paleosols provide an integrated record of the geomagnetic field for periods on the order of 10^5

years. This assumption is referred to as the *integrated record* hypothesis. Under this hypothesis, the polarity of a chron, rather than a subchron is recorded. Alternatively, hematite of the appropriate grain size may have been deposited over a comparatively short interval of time, even though the sediments themselves were deposited over a much longer time interval. In this case, only a short time interval is recorded by the magnetization, which may have been acquired during some stage of sedimentation, or later. This is referred to as the *spot record* hypothesis. The data are discussed in the light of these two hypotheses.

5.2 Integrated Record Hypothesis

The observed polarity sequence is shown in Fig. 10a. The interpretation of the paleomagnetic data consistent with the integrated record hypothesis is set out in Fig. 10b.

A zone of normal polarity occurs at the top of each section (Fig. 10a). It is thickest at Saint Mary Ridge (up to 100 m), and thinnest at Two Medicine Ridge (4 m). The normal deposits grade up into and, at Mokowan Butte, include the present soils which have normal polarity (Barendregt *et al*, 1991a), indicating that late Brunhes magnetizations are present. At Saint Mary Ridge, a uranium trend date of 440 ± 120 Ka for normally magnetized diamict 5 (***D5***) indicated that early Brunhes magnetizations are present. Finally, if Karlstrom (1987, 1988) is correct then soil development occurred over hundreds of thousands of years. Hence it is likely that the upper normally magnetized paleosols and diamict are Brunhes in age (780 Ka BP to present), and span a substantial portion of this chron, as depicted in Fig. 10b.

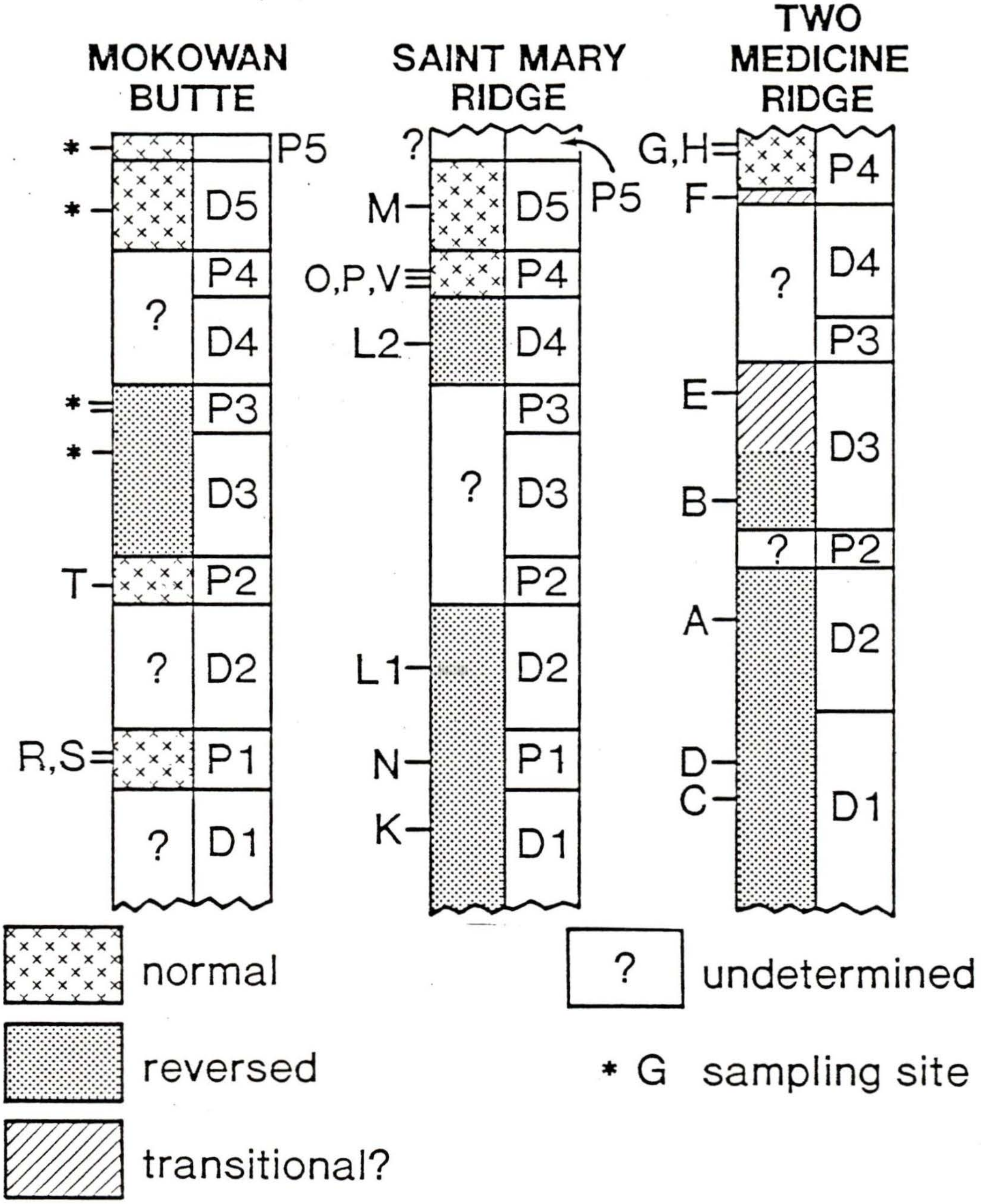

Figure 10a. Summary of polarities at the three localities. Sampling sites are noted to the left. Vertical scales are given in Fig. 2. The polarity for two sites (E and F) at Two Medicine Ridge is uncertain, possibly transitional. *Undetermined* indicates that the sites were either not sampled or the results were inconclusive.

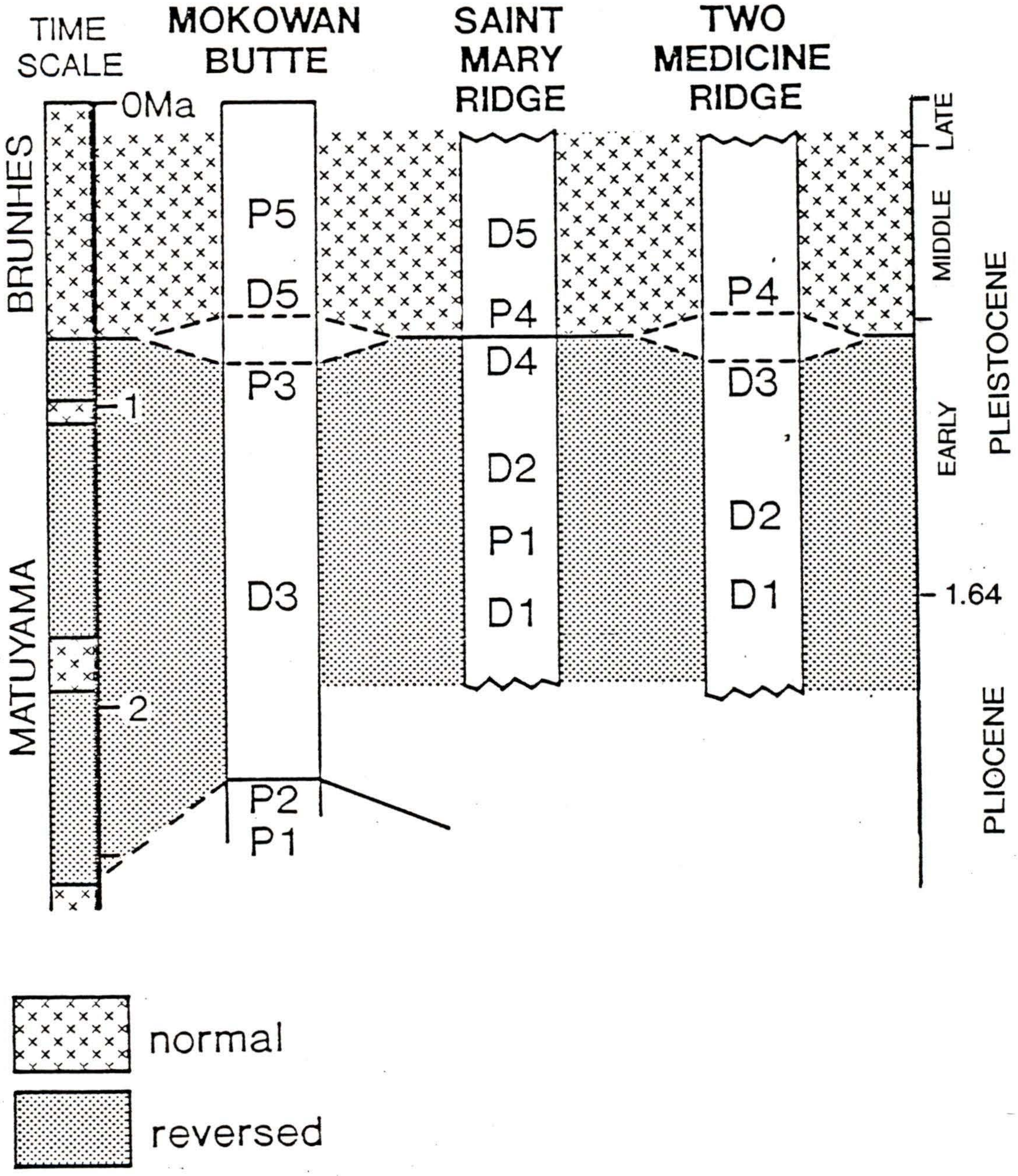

Figure 10b. Correlation of the three localities sampled, based on the integrated record hypothesis. Other options are discussed in the text. At Mokowan Butte and Two Medicine Ridge the Brunhes-Matuyama boundary is not as well constrained as at Saint Mary Ridge. An astronomical time scale is seen to the left.

All three localities record a zone of reversed polarity below the upper normal zone. It is thickest at Saint Mary Ridge (up to 60 m), and thinnest at Mokowan Butte (5-10 m). As this reversed zone directly underlies the normal polarity zone in two sections, and as the age suggested for the (presumed) oldest section is about 2.2 Ma, it is concluded that the reversely magnetized sediments are of Matuyama age (2 600 to 780 Ka BP). An alternative explanation is that the sediments were formed during the prior reversed chron (Gilbert, 3 400 to 5 200 Ka BP). If this were so, a hiatus of several million years would elapse between deposition of the reversed sediments and deposition of the overlying normal (Brunhes) sediments. Glaciations of such antiquity are not known to exist elsewhere in North America, and consequently, this explanation is considered unlikely.

At Saint Mary Ridge, a normal paleosol (***P4***) is developed on a reversed diamict (***D4***), indicating that the field reversed either at the end of a glacial interval or during an interglacial interval. Johnson (1982), using oxygen isotopes and paleomagnetic evidence from deep sea cores, established that the Brunhes-Matuyama boundary occurred in interglacial Stage 19. Therefore, it seems reasonable to place the Brunhes-Matuyama transition at Saint Mary Ridge between ***D4*** and ***P4***. In the same paper, Johnson suggested that the Brunhes-Matuyama reversal occurred at 780 Ka. Recent work by Shackleton *et al* (1990) using astronomical time scales placed the B-M boundary at 790 Ka, supporting Johnson's work.

At Two Medicine Ridge, sediments of uncertain polarity (sites E and F) occurred between sediments of normal polarity and sediments of reversed polarity. One or both of these sites may record the geomagnetic field during the Brunhes-Matuyama transition. However, the presence of both positive and negative inclinations (they are not reversed from one another) at site E (Fig. 8) could be the result of incomplete demagnetization. A Brunhes-age chemical remanent magnetization (CRM) could have formed during weathering, overprinting an older magnetization, and causing the results seen at these sites.

At Mokowan Butte, a zone of normal polarity was observed below the reversed zone. Barendregt *et al* (1991a) suggested that the normal magnetization they observed at the same level could be a Brunhes overprint. The magnetization observed in ***P1*** in this study is stable, and the intensity decay is smooth, unlike the data recorded by Barendregt *et al* (1991a), indicating that this magnetization is not an overprint, but an original magnetization. On the assumption that the paleosols provide an integrated record of the paleofield, the lower paleosols at Mokowan Butte formed during the Gauss Normal Polarity Chron (3 400 to 2 600 Ka), indicating a minimum age of 2 600 Ka for the earliest glaciation at this locality.

5.3 Spot Record Hypothesis

As described above, the magnetization may represent only a short interval of time during the last stages of soil formation, or some later diagenetic process. The arguments for deposition of the upper normal and underlying reversed sediments at Saint Mary Ridge and Two Medicine Ridge during the Brunhes and Matuyama chrons are still valid. However, the magnetization of ***P1*** and ***P2*** at Mokowan Butte may have formed during one of the normal subchrons in the Matuyama Reversed Chron (Jaramillo, 1 070 to 990 Ka; Olduvai, 1 950 to 1 770 Ka).

5.3.1 Magnetization of Jaramillo age

The magnetization of the lower normal paleosols may represent the paleofield of the Jaramillo subchron, and the reversed diamicts and paleosols overlying them (***D3***, ***D4*** at Mokowan Butte, ***D1***, ***P1***, ***D2***, and ***D4*** at Saint Mary Ridge, and ***D1***, ***D2***, and ***D3*** at Two Medicine Ridge) would have formed during a 210 Ka interval between 990 to 780 Ka. On this hypothesis, the glaciations are primarily Middle Pleistocene, as Richmond (1986) suggests. This interpretation requires either that the deposition of diamicts and paleosols during three sequential glacial and interglacial intervals occurred over a period of 210 Ka, or that there was an episode of late cementation and magnetic overprinting of the previously deposited diamicts and paleosols during the time the paleofield was reversed in the late Matuyama. The first alternative is unlikely, because it compresses a complex series of events into a very short time interval. Blanket overprinting of the type suggested by the second alternative is also considered unlikely, as there is no evidence of such overprinting in the data, and because the relationship observed at Saint Mary Ridge (normal ***P4*** overlying reversed ***D4***) shows that in this case at least, overprinting did not occur. Finally, the Jaramillo subchron (80 Ka) is probably not long enough for the formation of two paleosols (***P1*** and ***P2***) developed on two successive diamicts, each representing a separate glaciation. Hence, the possibility that the lower normal paleosols at Mokowan Butte are of Jaramillo age is considered unlikely.

5.3.2 Magnetization of Olduvai age

Alternatively, the magnetization of ***P1*** and ***P2*** at Mokowan Butte may have formed during the Olduvai Subchron, thus giving a minimum age of 1 770 Ka (Late Pliocene) for the earliest glaciation at this locality. The reversed paleosols and diamicts would have formed during the interval 1 770 to 780 Ma (980 Ka), and the lower normal paleosols during the interval 1 950 to 1 770 Ka (180 Ka). Although this provides sufficient time for the reversed sediments to have formed, it is again unlikely that two normal paleosols could form, and the intervening diamict be deposited in the duration of the Olduvai Subchron.

5.4 Preferred Interpretation

Clearly, the polarity sequences observed can be interpreted in several ways. However, the age estimates of Karlstrom (1987, 1988), as well as his estimates of length of time required for soil formation are consistent with consequences of the integrated record hypothesis (Fig. 10b). The hematite of the requisite size is likely to have been formed over a long, rather than a short interval of time (section ***5.1***). The magnetization of the calcretes is likely to have been independent of that of the paleosols, increasing the likelihood that it provides long, rather than brief, records of the paleofield. Thus, the preferred interpretation (Fig. 10b) of the depositional history is as follows: formation of the lower normal paleosols at Mokowan Butte during the Gauss Chron (Late Pliocene), formation of the reversed paleosols and diamicts during the Matuyama Chron (Early Pleistocene), and formation of the upper normal paleosols and diamict during the Brunhes Chron (Middle and Late Pleistocene). However, this interpretation is dependent on the assumption detailed above (section ***5.1***), regarding the length of time that the magnetization records, and cannot be considered conclusive.

5.5 Correlation among localities

In Fig. 10b, I attempt to correlate the three localities. The reversed-normal transition (Brunhes-Matuyama boundary) is best constrained at Saint Mary Ridge, between ***D4*** and ***P4***, and this is chosen as the starting point.

Barendregt *et al* (1991a) found that Unit 5 (***D5*** and ***P5***) at Mokowan Butte are normal. Unfortunately, the data from Unit 4 were not conclusive, but "evidence wouldindicate that it is reversed." (p 1961). Both ***D3*** and ***P3*** are of reversed polarity. Therefore the Brunhes-Matuyama boundary at Mokowan Butte must occur somewhere in Unit 4 (***D4*** and ***P4***). It is unlikely that the almost geologically instantaneous deposition of ***D4*** would coincide exactly with the transition between reversed and normal polarity. The most obvious position for the boundary is between ***D4*** and ***P4***. The reversal then occurs in an interglacial interval, as is suggested by the magnetostratigraphy at Saint Mary Ridge. This placement of the B-M boundary supports Karlstrom's (1988) tentative correlation of ***P5*** and ***P4*** at Mokowan Butte with ***P5*** and ***P4*** at Saint Mary Ridge.

The correlation of Two Medicine Ridge with Saint Mary Ridge is less certain. ***D3*** and ***P4*** were sampled, but ***P3*** and ***D4*** were not (Fig. 2c). The lower part of ***D3*** is reversed, but the upper part, and the lower part of ***P4*** are of uncertain polarity, and may be either transitional or overprinted. Therefore the Brunhes-Matuyama boundary must be between mid-***D3*** and mid-***P4*** (Fig. 10a). The most likely positions of the boundary, based on its location at Saint Mary Ridge are (a) between ***D3*** and ***P3***, (b) between ***D4*** and ***P4*** or (c) somewhere in ***P4***. However, interpretations (b) and (c) could be considered to be the same; as both indicate that the diamict was deposited during the Matuyama, and the paleosol during the Brunhes. Thus ***P4*** at Saint Mary

Ridge is correlated with either ***P3*** or ***P4*** at Two Medicine Ridge. The correlation of ***P4*** (paleosol 3 in his paper) at Two Medicine Ridge, and ***P3*** at Mokowan Butte has been suggested by Karlstrom (1988), but is unlikely, as ***P4*** at Two Medicine Ridge is (mostly) normal, and ***P3*** at Mokowan Butte is reversed.

The older normally magnetized paleosols (***P1*** and ***P2***) at Mokowan Butte cannot be correlated with the other localities on the basis of the information available. It is possible that an unexposed normal paleosol could exist at Saint Mary Ridge, but at Two Medicine Ridge the reversed diamict 1 rests directly on Cretaceous bedrock. Several paleosols and diamicts were not sampled due to lack of suitable material. and if these sediments carry normal magnetizations, the correlation shown in Fig. 10b may be inaccurate. The information available supports the idea that the Mokowan Butte sequence is the oldest of the three localities (Karlstrom, 1981). However, Karlstrom (1991) notes that clasts within ***D1*** at Mokowan Butte are more rounded and better sorted than the overlying units, and may have been deposited during a preglacial fluviatile regime.

PART II

EARLY PROTEROZOIC PLATE MOTIONS ANALYSIS

2250 - 1800 Ma

CHAPTER 6

Introduction and Historical Perspective

6.0 Introduction

The purpose of this part of the thesis is to re-analyze and interpret data from Proterozoic rocks of the western Canadian Shield in order to determine if large-scale relative motions occurred between the Archean structural provinces in the Canadian segment of Laurentia (principally the Slave and Superior provinces). This will aid in understanding the rotations and paleolatitude changes that these structural provinces may have undergone during the period 2250-1800 Ma. The later part of this period coincides with the formation of the Trans-Hudson Orogen, a major collisional orogeny between the Superior and composite Slave-Rae-Hearne structural provinces. The Trans-Hudson Orogen has received much attention in the past decade, and is presently the subject of a LITHOPROBE study. An understanding of the motion of these structural provinces through time may aid in the understanding of the assembly of various elements of the North American craton, as well as increasing our knowledge about the Trans-Hudson Orogen.

6.1 Geology

The North American craton together with Greenland and NW Scotland constitute Laurentia. The North American craton is considered to contain seven Archean structural provinces, separated by younger orogens that apparently formed when the structural provinces or microcontinents collided (Hoffman, 1989). These seven structural provinces are: Slave, Superior, Rae, Hearne, Burwell, Nain, and Grenville (Fig. 11). The Rae, Hearne, and Burwell provinces, recognized by Hoffman (1989) had been previously grouped together into the Churchill structural province (Stockwell, 1961, 1970).

This study deals with paleomagnetic data from four Archean structural provinces; Slave, Superior, Rae, and Hearne. Table 3 summarizes their general geology. However, the data from the Archean provinces is not sufficient to complete this study of rotations and paleolatitude changes. Extensive orogenic systems of Early Proterozoic age separate many of the structural provinces (Fig. 12). The major one is the Trans-Hudson Orogen which separates the Superior and Rae-Hearne provinces (Hoffman, 1981). Others are the Thelon orogen (Hoffman, 1988) separating the Slave and Rae provinces, the Torngat Orogen (Hoffman, 1988) separating the Rae and Nain provinces and enclosing the Burwell province, the Wopmay orogen (Hoffman, 1980) on the western margin of the Slave province, the Penokean Orogen (van Schmus, 1980) on the southern margin of the Superior province, and the Ketilidian Orogen (Allaart, 1976) on the southeastern margin of the Nain province.

6.1.1 Trans-Hudson Orogen geology and problems

The orogen now known as the Trans-Hudson (THO) has been a focus of attention for several decades. The THO is considered to consist of four major

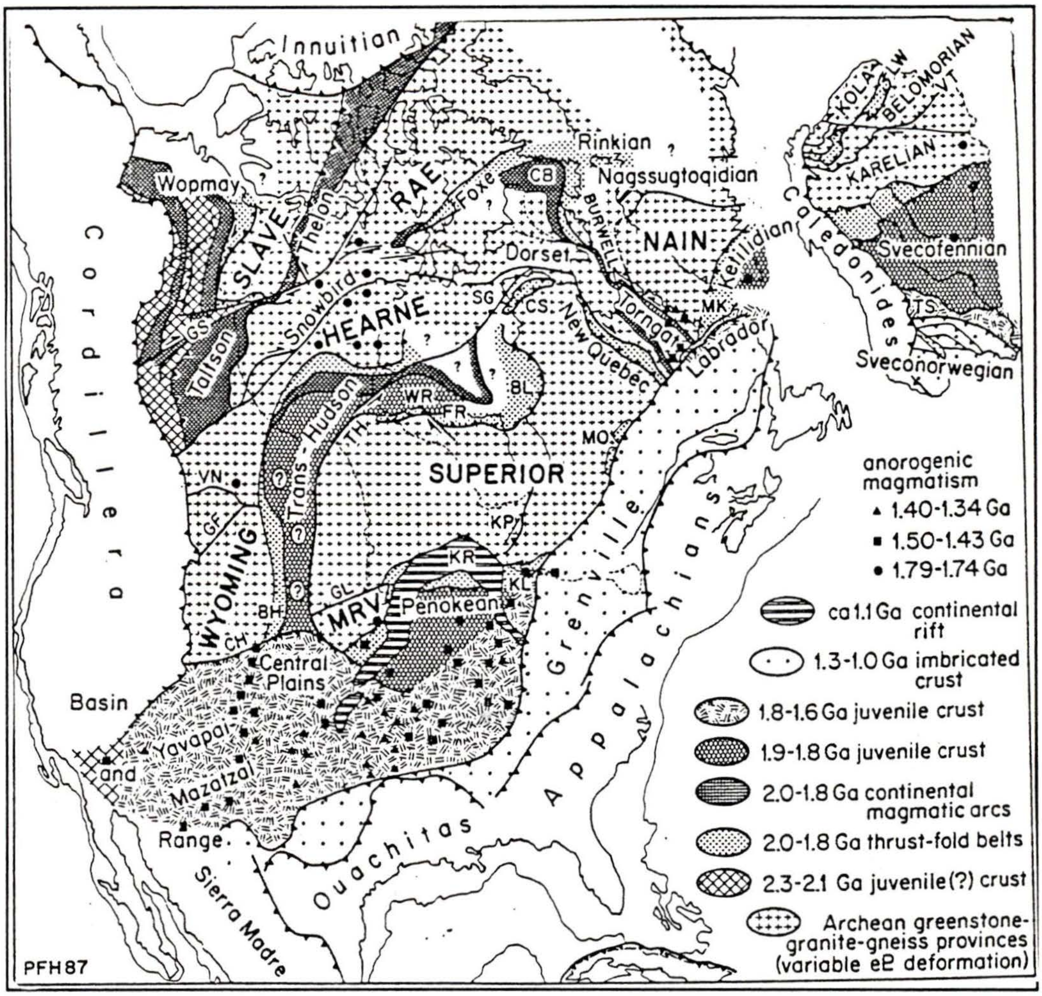

Figure 11. Generalized geology of the North American craton (part of Laurentia). This study deals with the Archean Slave, Superior, Rae, and Hearne structural provinces, and the Trans-Hudson Orogens. From Hoffman (1989).

Table 3. Geology of four Archean structural provinces in Western Laurentia

Province	Crustal Age	Structural Trend	Lithology	Bounded by
Superior	Mainly 2700-2800 Ma, small amount > 3500 Ma	east-northeast	1. volcano-plutonic terranes (similar to island arcs) 2. metasedimentary belts (similar to accretionary prisms) 3. plutonic complexes 4. high-grade gneiss complexes	Trans-Hudson Orogen (W, N, E), Grenville Prov (SE), Penokean Orogen (S)
Slave	Mainly 2500-2700 Ma, small amount > 3500 Ma.	north (in SW) northwest (in NE)	plutonic-metamorphic terrane with older gneissic inliers; metasediments intruded by granitic to gabbroic plutons	Thelon Orogen (E) Wopmay Orogen (W)
Rae	Mainly 2600-2900 Ma, small amounts 2900-3100 Ma	northeast	felsic gneisses, metavolcanics, calc-alkaline plutonics	Thelon Orogen (NW) Snowbird Orogen (SE)
Hearne	Late Archean, little geochronologic information available.		metamorphic rocks intruded by plutons; metamorphic grade increases outward from a green-schist core to granulite grade near border with Trans-Hudson Orogen	Snowbird Orogen (NW) Trans-Hudson Orogen (SE)

Notes: Geological information from Hoffman (1989)

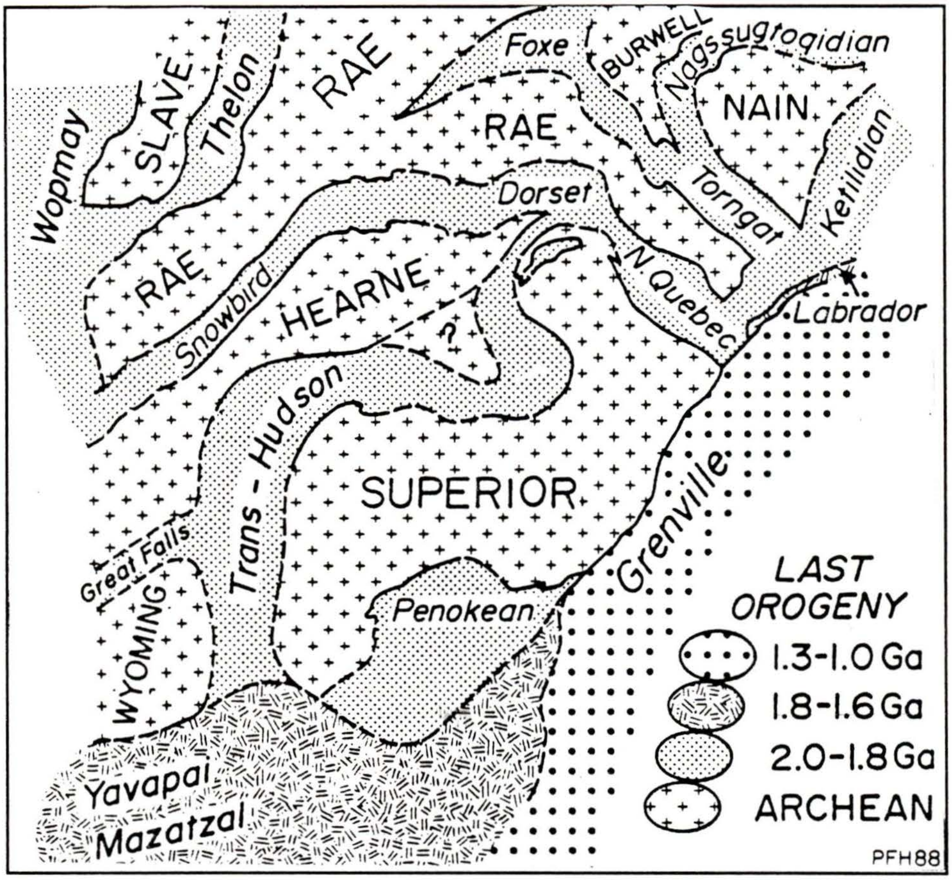

Figure 12. Early Proterozoic orogens of North America. The orogens weld the structural provinces together. See Fig. 11 for relationship to North America. From Hoffman (1989).

segments (Hoffman, 1989): (a) the Northern Quebec segment (also termed the Ungava segment and the New Quebec Orogen); (b) the Hudson Bay segment, extending across Hudson Bay, and exposed only on its eastern side; (c) the Manitoba-Saskatchewan segment which outcrops in the northern part of these provinces; and (d) the Black Hills (Dakota segment), inferred to be part of the THO on the basis of gravity, magnetic and electrical conductivity anomalies (Thomas *et al*, 1987). At present, a multidisciplinary project (LITHOPROBE) is underway to determine the underlying structure of the Manitoba-Saskatchewan segment of the orogen.

There are a number of outstanding questions regarding the THO, which LITHOPROBE is trying to answer. The location and direction of any previous subduction zone(s) are unknown. The amount and the age of Archean crust incorporated into the THO is uncertain. Although much of the THO at the surface is juvenile Proterozoic crust, its thickness is unknown; is it merely a thin covering on underlying Archean basement? Many of the juvenile Proterozoic rocks in the Manitoba-Saskatchewan segment are reminiscent of island arcs; was there an ocean and if so, how wide was it? This has a direct bearing on the question of the possible relative movement of the structural provinces, and thus paleomagnetic data may help provide an answer; a significant latitudinal motion should appear in the paleomagnetic record if a major intervening ocean was present.

6.2 Paleomagnetic Data 1965-1992

Precambrian paleomagnetism has been studied for many years, and many data are available. However, the quality of some, but by no means all, of the earlier paleomagnetic work does not measure up to contemporary standards. Many studies were done on rocks where the age and subsequent history are not well known, and many studies were undertaken with objectives different from those outlined above. Hence, the data have to be ordered according to their applicability to the objectives of this thesis. This ordering will be discussed later, in Chapter 7.

In order to examine motion within and on either side of the Trans-Hudson Orogen (THO), poles from both the interior of the orogen and from the surrounding structural provinces are needed. However, although the Superior province has been, relatively speaking, extensively sampled for paleomagnetic analysis, the Rae and Hearne provinces and the THO itself have received comparatively little attention. However, the Slave province and its bordering orogens (i.e. Wopmay), all of which lie to the northeast of the Rae and Hearne provinces, have undergone more extensive paleomagnetic study. Hence, a comparison of the Slave and Superior APW paths may be expected to produce results relevant to an investigation of motions associated with THO, although such a comparison yields no information about relative motion within the THO.

6.2.1 Slave province

Paleopoles for the time interval 2250 - 1800 Ma are displayed in Fig. 13. All plots of paleopoles were generated on ATLAS (Cambridge Paleomap Services Ltd, 1990).

The Great Slave Supergroup has been extensively studied (paleopoles AR1, AR2, CB, DP, LG, MCD, MCL, PA, PB, PC, PD, SE1, SE2, SE3, STA, TO1, TO2, TO3, and UG in Fig. 13), as has the overlying Et-Then Group (ET). The Goulbourn Supergroup paleopoles are MAR, WR, PH, and GS; and the Coronation Supergroup poles are CAM, TAK and PES. BS1, BS2, BS3, and BS4 are from the Big Spruce

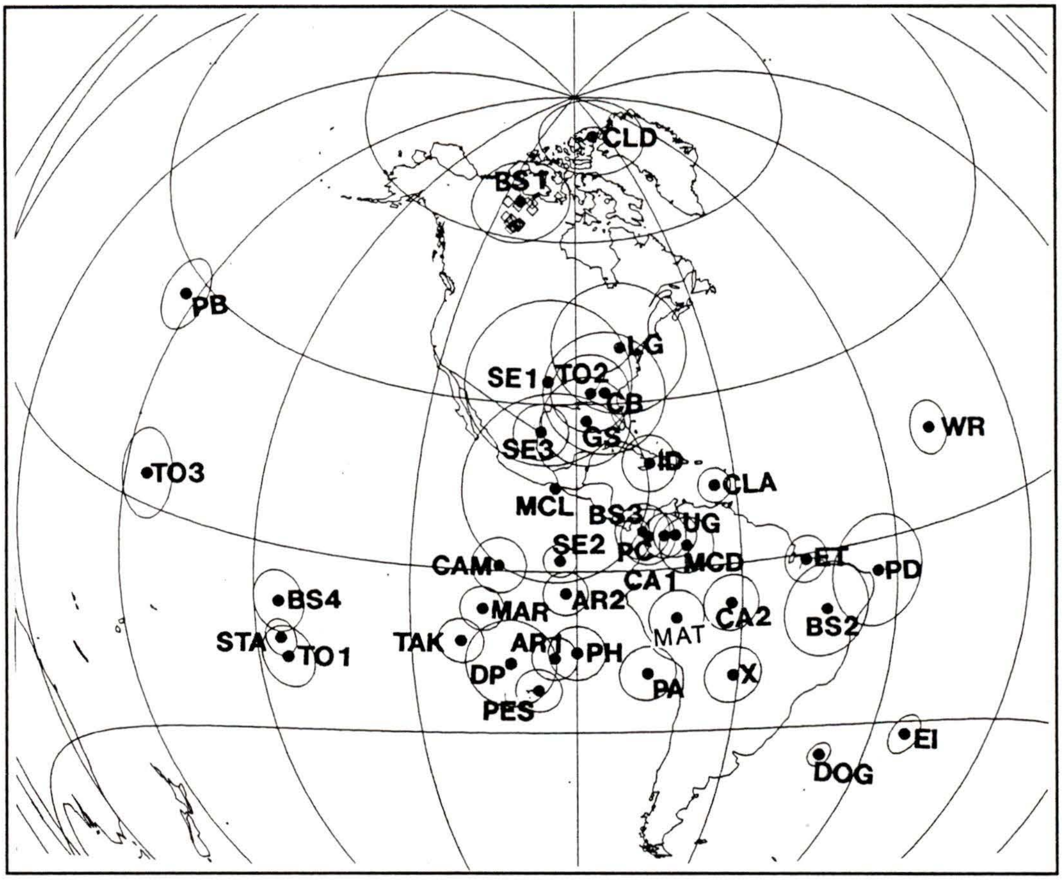

Figure 13. Early Proterozoic paleopoles and sampling sites from the Slave structural province. Circles are α_{63} errors; diamonds are sampling sites. For references, see Appendix 1. AR1 and AR2, Akaitcho River Formation (8); BS1, BS2, BS3, BS4, Big Spruce Complex (17); CA1, Coronation average (5); CA2 Coronation average (7); CAM, Cameron Bay Formation (10); CB, Charlton Bay Formation (5); CLA, CLD, Caribou Lake Gabbro (18); DOG, Dogrib Dykes (19); DP, Douglas Peninsula (6); EI, Easter Island Dykes (18); ET, Et-then Group (1); GS, Gabbro Sill (9); ID, Indin Dykes (19); LG, Lower Gibraltar Formation (5); MAR, Mara Formation (9); MAT, Martin Formation (40); MCD, McLeod Bay Formation (5); MCL, McLean Formation (5); PA, PB, PC, PD, Pearson Formation (2); PES, Peninsular Sill (6); PH, Peacocks Hill Formation (9); SE1, Seton Formation (5); SE2, SE3, Seton Formation (6); STA, Stark Formation (4); TAK, Takiyuak Formation (6); TO1, TO2, TO3, Tochatwi Formation (4); UG, Upper Gibralter Formation (5); WR, Western River Formation (9), X, X Dykes (19).

Complex; CLA and CLD from the Caribou Lake Gabbro. EI, DOG, ID, and X are paleopoles from dyke swarms. CA1 and CA2 are representations of the Coronation overprint pole.

6.2.2 Superior province

The Superior province has yielded the most paleomagnetic data, but much of it is from older rocks not directly relevant to the time interval covered in this study (2250-1800 Ma). Paleopoles are shown in Fig. 14. The Superior Province paleopoles are primarily in the northern hemisphere, whereas the Slave Province paleopoles are grouped close to and south of the equator.

NDA, NDB NDC, NDD, NED, NDF, NDG, NDH, NDI, NDJ, NDK, NDL, NDM, NDN are paleopoles from the Nipissing diabase and sills; HG1, HG2, HGC, and HGF are paleopoles from various parts of the Huronian Gowganda Formation. PRE is from the Preissac Dykes, and NEDD from the Northeast Diabase Dyke. The Sudbury structure poles are represented by SEA (North Range) and SEB (South Range). MD1, MD2, and MD3 are poles from the Molson Dykes; SRA and SRB from the Spanish River Alkali rocks and Dykes; MO from the Marathon Dykes, and FFD from the Fort Frances (Kenora-Kabetogama) Dykes. HI, FV, EV1 and EV2 are paleopoles from the Belcher Islands, while PN, PS, RG, RGL, and QIN are from the Richmond Gulf Group, and NG from the Nastapoka Group.

6.2.3 Rae-Hearne provinces

Relatively little paleomagnetic analysis has been done on 2300 -1800 Ma rocks of the Rae and Hearne provinces (Fig. 15). DU1, DU2, and DU3 are from the Dubawnt Group; NON, the Nonacho Group; and MBA and MBB the Melville-Daly Bay Group. A number of dyke swarms have been analyzed (KAM, KAZ, SPD, and TUL).

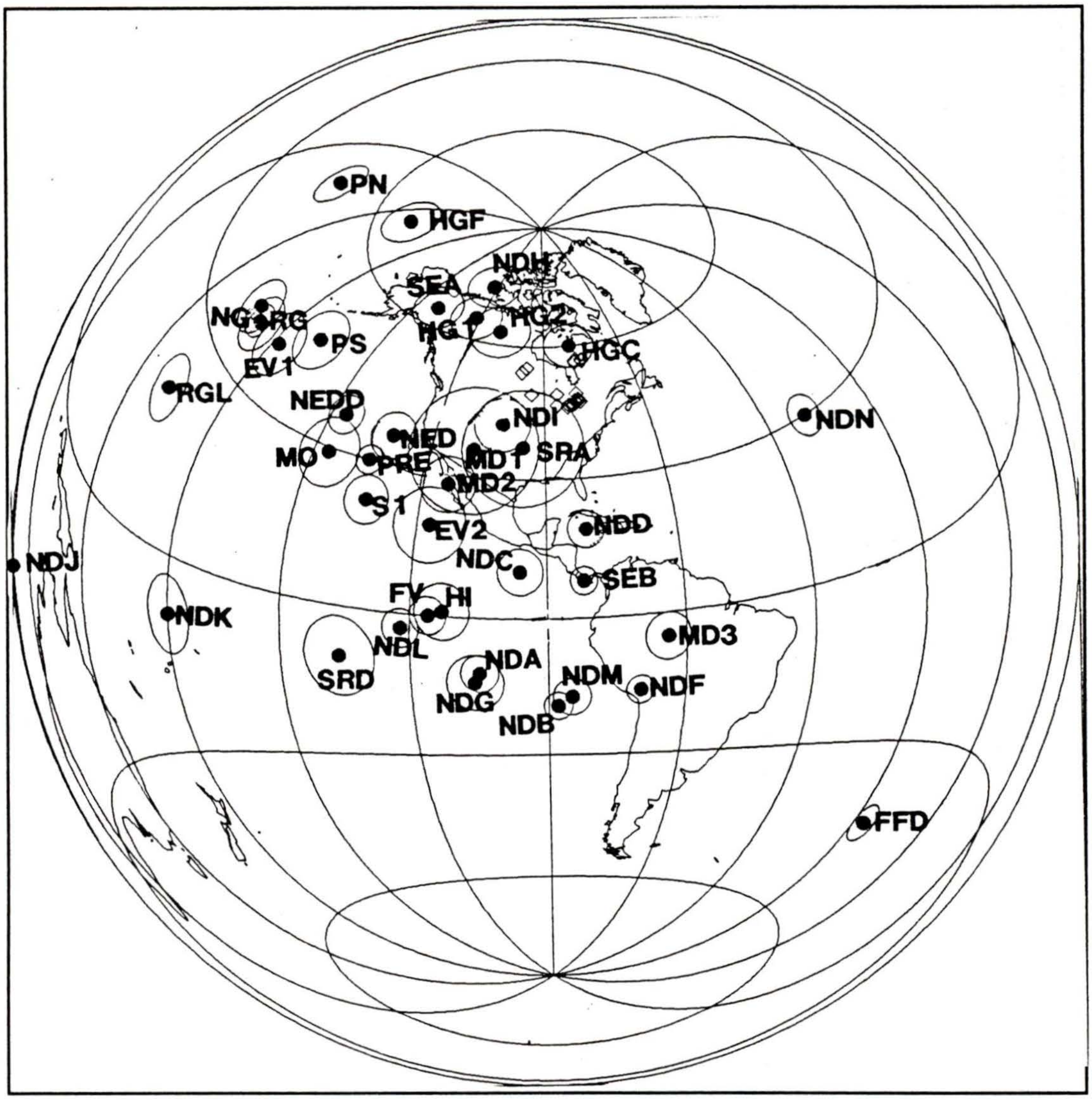

Figure 14. Early Proterozoic paleopoles and sampling sites from the Superior structural province. Circles are α_{63} errors; diamonds are sampling sites. For references, see Appendix 1. EV1, EV2, Eskimo Volcanics (20); FFD, Fort-Frances (Kenora-Kabetogama) Dykes (45): FV, Flaherty Volcanics (20); HG1, Huronian Gowganda Formation (46); HG2, Huronian Gowganda formation (37); HGC, Coleman Member, Gowganda Formation (36); HGF, Firstbrook Member, Gowganda Formation (36); HI, Haig Intrusives (20); MD1, Molson Dykes (28); MD2, MD3, Molson Dykes (29); MO, Marathon Dykes (28); NDA, Nipissing Diabase Sills (31); NDB, Nipissing Diabase Sills (32); NDC, NDD, NED, Nipissing Diabase Sills and Dykes (33); NDF, Nipissing Diabase Sills (34);NDG, NDH, Nipissing Diabase Sills (35); NDI, NDJ, NDK, NDL, Nipissing Diabase Sills (36); NDM, Nipissing Diabase Sills (37); NDN, Nipissing Diabase Sills (38); NEDD, Northeast Diabase Dyke (38); NG, Nastapoka Group (21); PRE, Preissac Dykes (42); PS, PN, Persillon Formation (21); QIN, Qingaaluk Formation (21); RG, Richmond Gulf Group (21); RGL, Richmond Gulf Lavas (22); SEA, SEB, Sudbury Erruptive (43); S1, Sudbury Erruptive (44); SRA, SRD, Spanish River Alkali Rocks and Dykes (30).

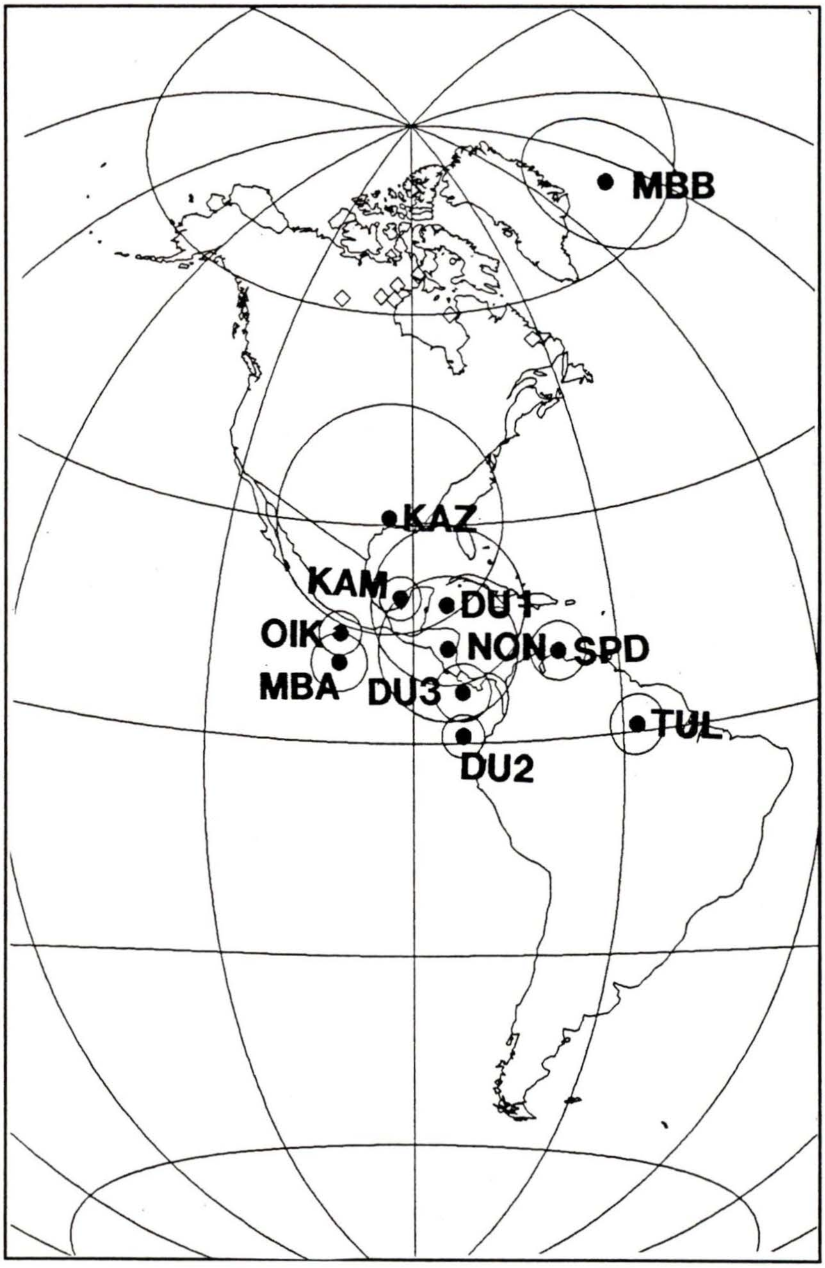

Figure 15. Early Proterozoic paleopoles and sampling sites from the Rae and Hearne structural provinces. Circles are α_{63} errors; diamonds are sampling sites. For references, see Appendix 1. DU1, DU2, DU3, Dubawnt Group (11); KAM, Kaminal Dykes (12): KAZ, Kazan Dykes (13), MBA, MBB, Melville-Daly Bay (14); NON, Nonacho Group (15): OIK Ottawa Island Komatiites (16): SPD, Sparrow Dykes (15), TUL, Tulemalu Dykes (13).

6.2.4 Trans-Hudson Orogen

The 2200 - 1800 Ma paleomagnetic data available from the Trans-Hudson and New Quebec Orogens are shown in Fig. 16. The Trans-Hudson paleopoles are FF1, FF2, FF3, FF4, FFB (Flin-Flon Belt), WB (Wathaman Batholith), CSB (Cape Smith Basalts) and LFL (Lynn Lake-La Ronge Belt). CC (Castignon Complex), DD, MBG, MEA, MG1, MG2, MIR, RPA, RPB, SF1, SF2, SWA, SWB, SWC, and WAG (Labrador Trough) are paleopoles from the New Quebec Orogen.

6.3 Previous APWPs

The construction of apparent polar wander paths (APWPs) is dependent on the assumption that the paleopoles were obtained from rocks of the same rigid plate, and no rotation has occurred. Unfortunately, this assumption is often not valid for Precambrian-age plates, i.e the Laurentian Shield. The present-day configurations of such plates are the result of billions of years of metamorphism, deformation, and recycling of continental crust. The available geologic information must be carefully studied to find areas that may have acted as coherent rigid plates since their formation. It should then be possible to construct APWPs for these areas.

Beginning with the work of Du Bois (1962), there have been many attempts to construct a Precambrian apparent polar wander path for the Laurentian Shield. Du Bois's path is from late Precambrian rocks (1500 - 1000 Ma), and thus is not considered here.

During the first few years of APWP construction little paleomagnetic data were available, and the ages of the rocks and/or magnetizations were uncertain. Ideas were poorly constrained and were subject to major change with the advent of each new

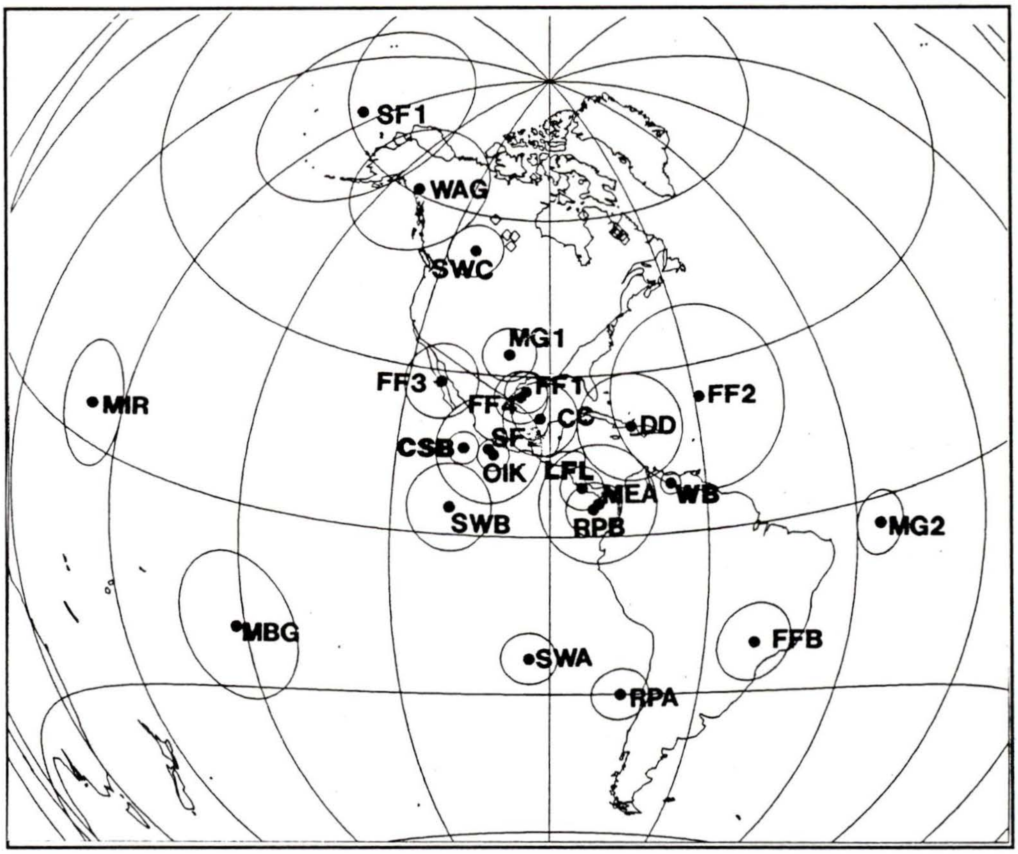

Figure 16. Early Proterozoic paleopoles and sampling sites from the Trans-Hudson Orogen. Circles are α_{63} errors; diamonds are sampling sites. For references, see Appendix 1. CC, Castignon Complex (24); CSB, Cape Smith Basalts (39); DD, Diabase Dykes (25); FF1, FF2, FF3, FF4, FFB, Flin-Flon Intrusives (23); LFL, Lynn Lake-Fraser Lake Gabbros (47); MBG, Matabasalts and Gabbros, Labrador Trough (26); MEA, Menihek Formation (23); MG1, MG2, Montagnais Group (27); MIR, Metaigneous rocks, Labrador trough (25); RPA, RPB, Retty Peridotite A & B (24): OIK, Ottawa Islands Komatiites (16); SF1, SF2, Sokoman iron Formation (25); SWA, SWB, SWC, Seward Formation (24); WAG, Wakuach Gabbro (24); WB, Wathaman Batholith (48).

study. The earliest polar wander paths for the time interval considered in this study indicate that the pole moved northwards from near Antarctica to above the equator during the time interval 2600 - 2000 Ma (Spall, 1972; McGlynn and Irving, 1975). The APW path of the latter authors is shown in Fig. 17. The Slave APWP is based on the sense of relative motion dictated by the known relative ages of the Dogrib Dykes (considered at the time to be 2200 - 2700 Ma) and Indin Dykes (2000 Ma). The Superior APWP is based on data from the Matachewan diabase (the southern hemisphere paleopole was used), then considered to be 2700 Ma, the Nipissing Diabase (2150 Ma), and the Otish Gabbro (2000 Ma). Although the APWPs indicate separate motion, McGlynn and Irving (1975) suggested the possibility that throughout the time interval under consideration, the Slave and Superior provinces were in the same relative position as they are today, and may have acted as one unit, or alternatively, undergone only a small relative rotation. The data allowed no conclusions to be drawn for the time interval after 2000 Ma. As we shall see, their general APW reconstruction for the Slave province has been quite durable. Their APW path reconstruction for the Superior province was soon superseded by other APWPs.

As more paleomagnetic data from Early Proterozoic rocks became available the polar wander paths underwent repeated revisions. Irving and Lapointe (1975), Pullaiah and Irving (1975), and McGlynn *et al* (1975) considered the pole movement during the time interval (2100 -1900 Ma) to be along a north-south path stretching from northern Canada along the western coast of the Americas (Fig. 18). The direction is the opposite of that originally indicated by McGlynn and Irving (1975). Two new pieces of information caused this change: (a) the Big Spruce Complex (Irving and McGlynn, 1976) from the Slave province was found to contain a "D" magnetization which was

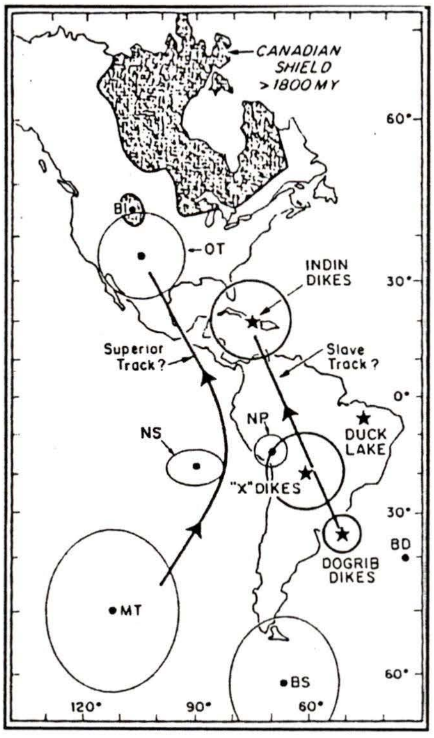

Figure 17. Apparent polar wander path of McGlynn and Irving (1975). Both the Slave and Superior APWPs have northward motion, moving either separately or as one unit.

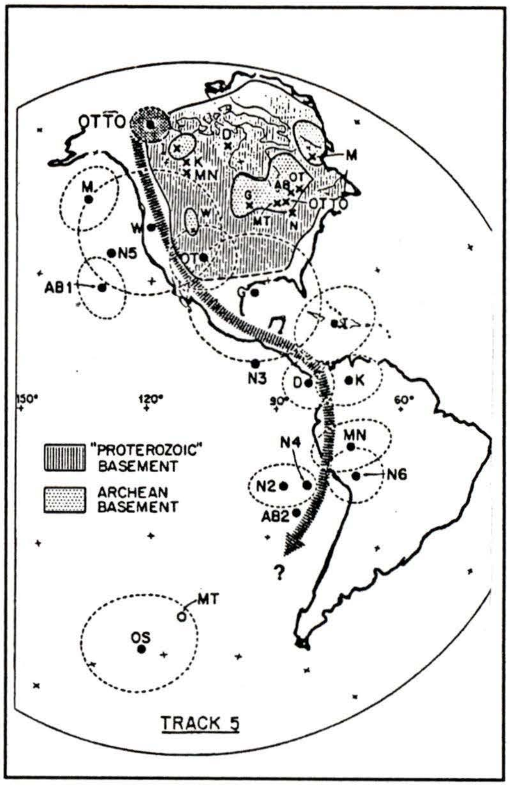

Figure 18. Apparent polar wander path of Pullaiah and Irving (1975). The Slave and Superior provinces acted as one unit. Note the change from a north-moving APWP to a south moving APWP.

considered the original magnetization, based on its high T_{UB}, and (b) the magnetization from the Otto Stock (Pullaiah and Irving, 1975) in the Superior province, based on baked contact studies, yielded a paleopole similar to the "D" magnetization. These magnetizations were thought to be contemporaneous, formed at ≈ 2100 Ma. Most poles from younger rocks of both the Slave and Superior provinces occurred south of the Big Spruce "D" - Otto Stock pole. Thus, the data available were consistent with a single polar wander path for most of the North American craton, and therefore consistent with the hypothesis that there had been little or no relative motion between the structural provinces. This path was initially labelled as Track 5 by Irving and Lapointe (1975), and Pullaiah and Irving (1975).

As more information became available, the younger section of Track 5, and part of Track 4 (the east-west APWP fron 1900-1600 Ma) were redefined as the Coronation Loop (Fig. 19), essentially expressing a change in the paleolatitude of Laurentia (McGlynn and Irving, 1978; Irving and McGlynn, 1979). The path was still considered by most authors to be valid for all structural provinces. The depth of the loop varied from author to author; for example Schmidt (1980) suggested an extremely deep loop, whereas Evans and Hoye (1981) suggested a much shallower loop. The actual form of the Coronation Loop is still a matter of conjecture.

However, although the data were generally consistent with a single polar wander path, enough anomalies were present that it was still possible to construct separate polar wander paths for the Slave and Superior provinces (Fig. 20), as was done by Cavanaugh and Seyfert (1977).

In the early 1980s the polar wander paths again underwent major revisions. Irving and McGlynn (1981) concluded that, contrary to previous work, Track 5

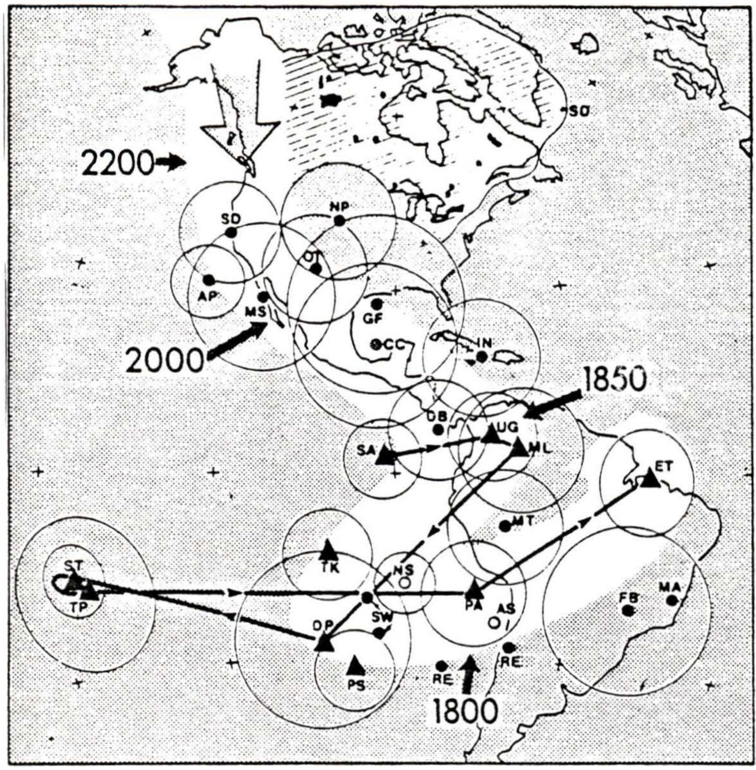

Figure 19. Apparent polar wander path of McGlynn and Irving (1978). The Coronation Loop expresses a paleolatitude shift during the time interval 1900 - 1700 Ma.

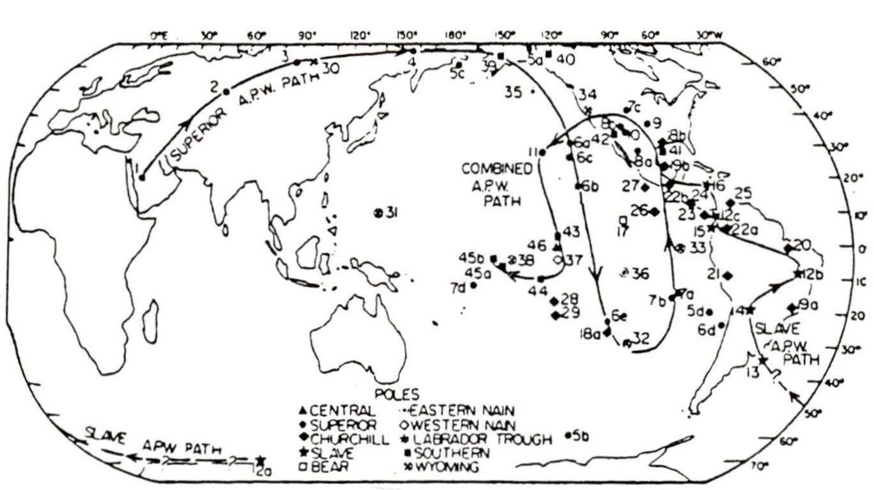

Figure 20. Apparent polar wander path of Cavanaugh and Seyfert (1977). In this interpretation, the Slave and Superior provinces moved separately until amalgamation at ≈ 1800 Ma,

probably did not represent the APWPs of either the Superior or Slave provinces. Reconsideration of the data from the Big Spruce Complex led them to believe that the D magnetization was a Phanerozoic overprint (Cretaceous?, Irving *et al*, 1990), not the original magnetization, as they had first suggested. The uncertainty in the relative and absolute ages of the Nipissing diabase poles were such as to render suspect previous interpretations of a single Track 5 for all of Laurentia.

McGlynn and Irving (1981) speculated that the Slave and Superior provinces had moved separately until their collision with the Churchill province at ≈ 2000 Ma (Fig. 21). Evidence supporting this included the paleomagnetic pole from the Easter Island (EI) and Hearne Dykes, ≈ 2200 Ma, in the Slave province (McGlynn and Irving, 1981; Irving *et al*, 1984). This pole is close to the Dogrib dykes pole, DOG (McGlynn and Irving, 1975), which could be the same age. This APWP is thus very similar to that originally proposed by McGlynn and Irving (1975); however, the Superior province APWP is very different.

New information from the Trans-Hudson Orogen was incorporated into the APWP by Dunsmore and Symons (1990) and Symons (1991). Their APWPs are similar to those of McGlynn and Irving (1981) (Fig. 22).

Very recently, Buchan *et al* (1992) have suggested a south to north APWP for the Superior province during the time interval 2220-2100 Ma. This is based on combined geochronologic and paleomagnetic studies of several dyke swarms, including the Nipissing diabase, Senneterre Dykes, Biscoteague Dykes, Kenora-Kabetogama Dykes, and Marathon Dykes.

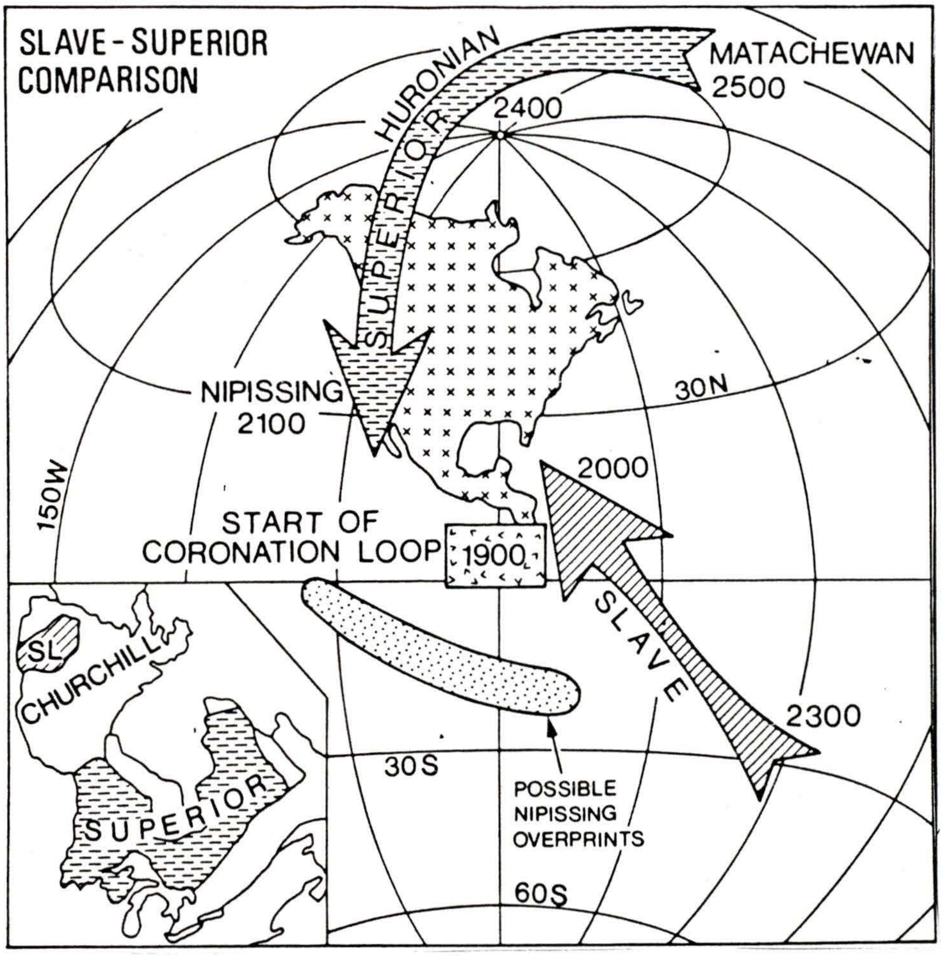

Figure 21. Apparent polar wander path of McGlynn and Irving (1981). The Slave and Superior provinces moved separately until amalgamation at ≈ 2000 Ma. The Slave APWP shows northward motion, the Superior APWP southward motion.

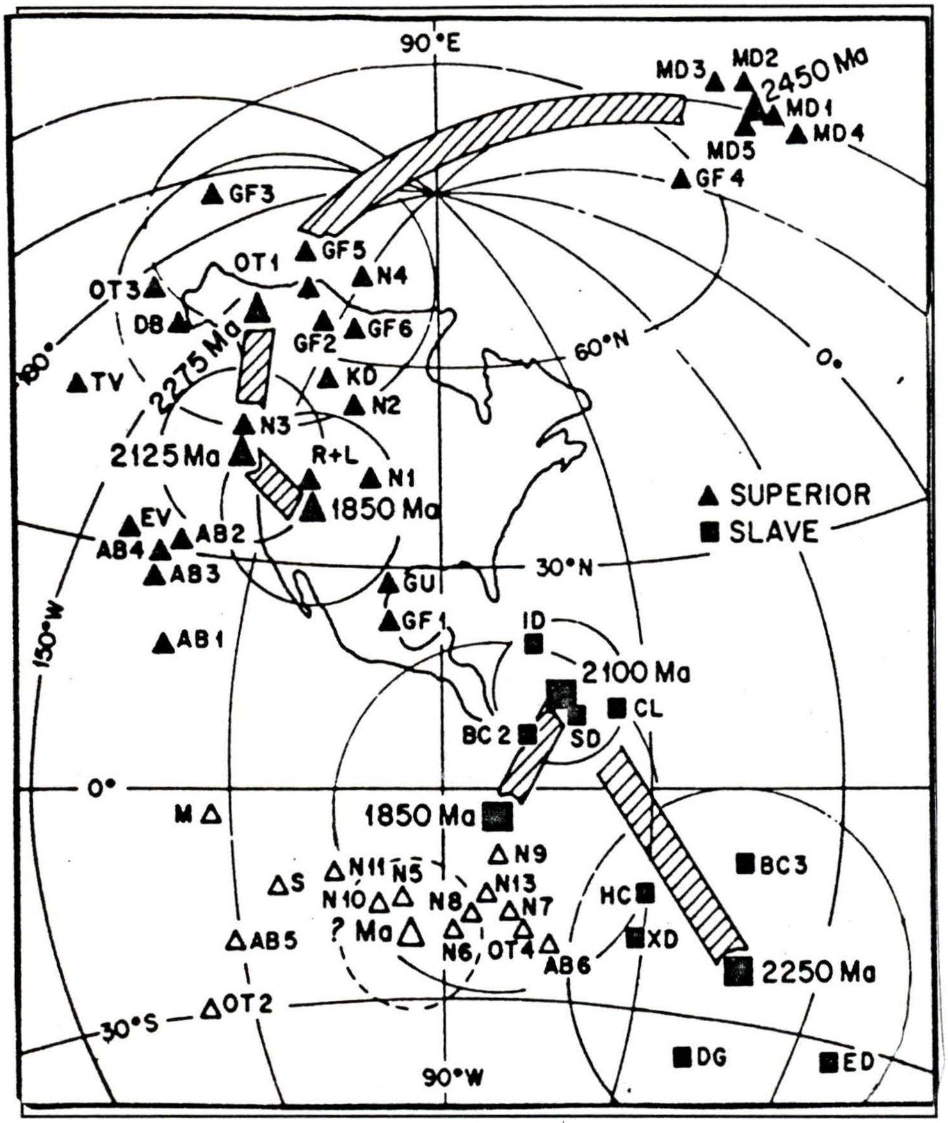

Figure 22. Apparent polar wander path of Dunsmore and Symons (1990). Note the similarity to the APWP of McGlynn and Irving (1981). However, this interpretation considers amalgamation to have occurred at ≈ 1700 Ma.

6.3.1 Timing of Collision

McGlynn and Irving (1981) suggested that the collision between the Slave and Superior structural provinces occurred at 2000 Ma, whereas Dunsmore and Symons (1990) suggest that the collision occurred much later, at ≈ 1700 Ma. Dunsmore and Symons (1990) base their age of collision on: (a) the wide separation (4000 km) between the Slave and Superior provinces at 1850 Ma, implied by the observation that the pre-1800 Slave poles were offset to the south (forming the Coronation Loop), and the pre-1800 Superior poles were offset to the north (merging with older poles); and (b) the proposal by Irving *et al* (1981) that the Slave and Superior provinces had assumed their present relative position by ≈ 1750 Ma.

Geologic and geochronologic evidence suggests that the collision of the Slave-Rae-Hearne composite province and the Superior province occurred between 1890 and 1830 Ma (P. Hoffman, pers comm., 1992). If this is correct then the age suggested by McGlynn and Irving (1981) is too old, and that suggested by Dunsmore and Symons (1990), too young. In Chapters 9 and 10, an attempt is made to reconcile the paleomagnetic data and provide an interpretation that is concordant with the geologically inferred age of collision.

6.4 New information

As more information has become available, the hypothesis that the Slave and Superior provinces were separate has become the most viable option. Some of the more important new information includes:

(a) Precise geochronologic data. One of the most important new radiometric dates came from the Otto Stock. Previously, it had been dated at 2100 Ma, and the pole was assumed to anchor the older section of Track 5. A new U-Pb date indicated that the stock was almost 500 Ma older than previously supposed (Ben Othman *et al*, 1990). This eliminated the possibility that Track 5 represents any part of the 2200-1800 Ma Slave polar wander path and removes the datum from the discussion of the present time interval. Improved geochronologic data have become available from rocks such as the Preissac Dykes (J. Mortenson, from PFH), and the Caribou Lake Gabbro (Bowring *et al*, 1984).

(b) The identification of different ages of magnetizations for the Nipissing diabase (Fig. 23). The initial belief (Symons, 1967) that the southern Nipissing poles (***N1***) were older than the northern Nipissing poles (***N2***) was supplanted by the opposite view (Roy and Lapointe, 1976). Buchan *et al* (1989) suggested that the ***N3*** magnetization was the oldest, acquired at the time of Nipissing diabase intrusion (based on a positive contact test). They suggest that the ***N2*** magnetization in their study area resulted from the intrusion of a crosscutting Preissac (or Abitibi) dyke (based on a baked contact test). The ***N1*** magnetization may have been caused by overprinting during the Penokean orogeny (1800 Ma). The differing magnetizations may be the result of rotations. The Nipissing diabase paleomagnetic data have been used by many workers as key points on APWPs; however, until well determined ages are available for each stage of intrusion, these data should no longer be considered entirely reliable.

(c) The identification of a group of overprinted poles. The overprint has two major characteristics; a paleomagnetic pole in the Caribbean and only normal magnetization. If both normal and reversed magnetizations are present, overprinting, although not impossible, is much less likely. The overprint was described by Reid (1972) and McGlynn *et al* (1974), and quantified and named the "Coronation" overprint by Evans

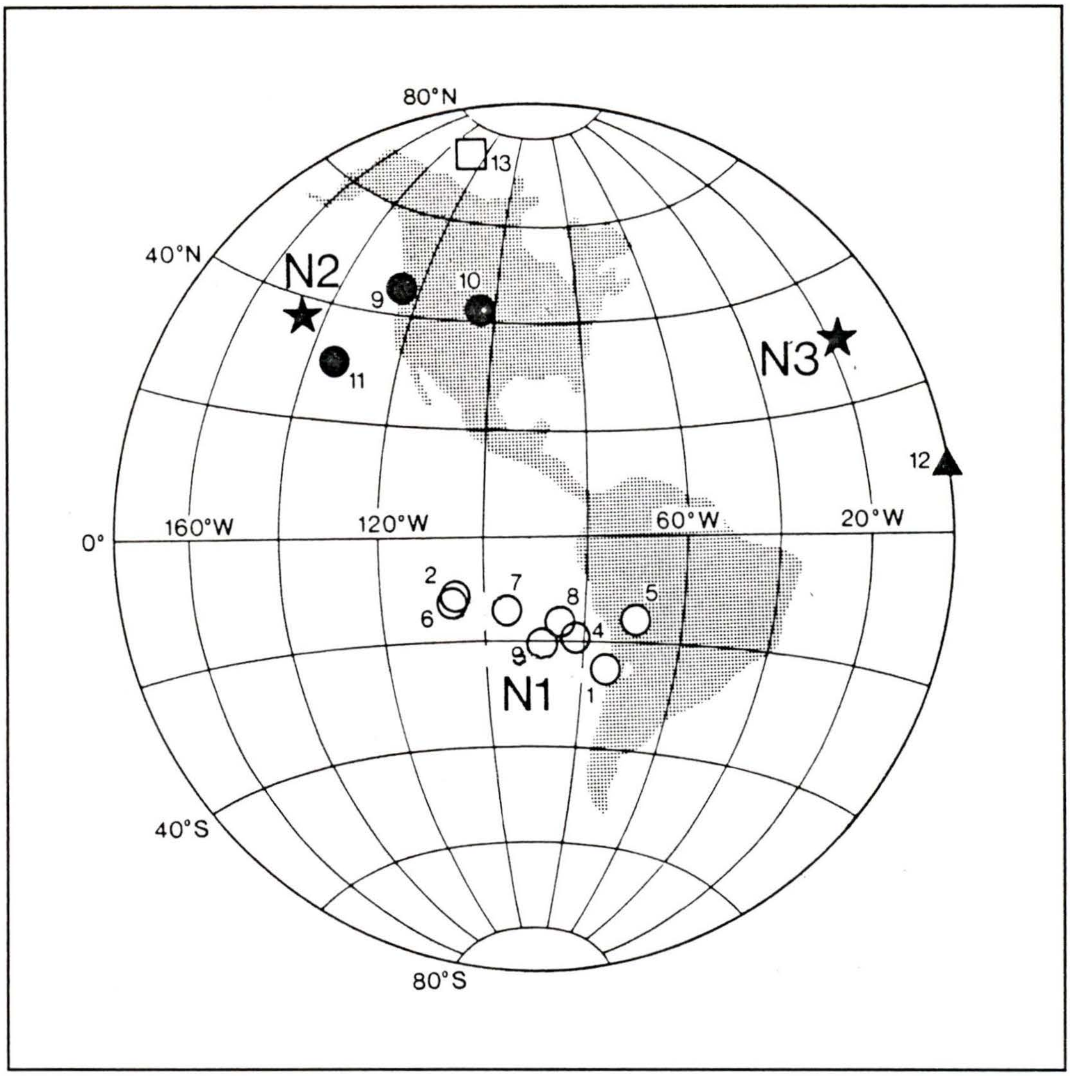

Figure 23. Three magnetizations from the Nipissing Diabase (*N1*, *N2*, and *N3*). The relative ages are still uncertain. From Buchan *et al* (1989).

et al (1980). Recently, a number of poles previously considered original magnetizations have been reclassified as Coronation overprints by Kotzer *et al* (in press). When the paleopoles were considered original magnetizations, they affected the APWPs for the time of rock formation; as overprints, the paleopoles are representative only of the gemagnetic field at the time of overprinting (≈ 1700 - 1650 Ma).

CHAPTER 7

Evaluation of Precambrian paleopoles

7.0 Introduction

The use of any one piece of paleomagnetic data in this study depended on two factors: is it a reliable indicator of the geomagnetic field for a specified time interval, and does it meet the objectives of this study? The paleomagnetic data must be evaluated for quality and applicability.

The compilation of paleomagnetic and geochronologic data for the time interval 2300-1800 Ma produced about 130 paleopoles (Appendix 1).

7.1 Minimum Reliability Criteria

The mere observation of a direction of magnetization and the calculation of a paleopole is not sufficient for it to be considered a reliable recorder of the paleofield. The following minimum reliability criteria are therefore applied:

1. Age of the rock. The age of the rock must be known to better than +/- 100 Ma.
2. Original magnetization. The magnetization must be considered by the authors to be a reasonable estimate of the original magnetization, or an overprint dating from the time interval under consideration.
3. Quantity and precision. Three conditions must be met: $\alpha_{63} \leq 20^\circ$, $k \geq 5$, and n (number of samples) ≥ 15.

Data that pass these minimum reliability criteria are listed in Appendix 2. However, "It is not intended to imply that the results which satisfy them necessarily give the direction of the geomagnetic field at the time of formation of the rocks in question." (Irving, 1964, p. 102).

7.2 Quality Indices

For the present purpose, more stringent conditions must be met for the paleopole to be regarded as useful.

Van der Voo (1989) developed a quality index for Phanerozoic poles. He listed seven conditions, each of which was awarded one point.

(***1***) A well determined age: ± 20 Ma, ***or*** ± 8%, ***or*** (if stratigraphically dated) within a geological period.

(***2***) Sufficient samples and statistical precision; $\alpha_{95} \leq 16^{\circ}$, $k \geq 10$, n (number of samples) > 25.

(***3***) Demagnetization (AF, thermal, or chemical) have been performed and published.

(***4***) Field tests (fold, contact, or conglomerate) were successfully executed,

(***5***) Tectonic coherence; a presumption of coherence with the craton or tectonic block from which the paleopole has been obtained.

(***6***) Presence of reversals.

(***7***) No suspicion of remagnetization (i.e. similarity to a younger pole).

The maximum quality index is seven. The index provides a useful measurement of the quality of Phanerozoic data, but certain problems are present, and additional problems arise when Precambrian data are considered. First, the age uncertainty is usually much greater for Precambrian data than in Phanerozoic; second, an overprinted magnetization, which is often very difficult to recognize in Precambrian rocks, could under the above conditions receive a very quality high index; and third, a pole (either

Phanerozoic or Precambrian) based on a very small number of sites and samples may fail to pass only one criterion, and thus still be awarded a relatively high quality index. To some degree these difficulties are overcome by the application of the minimum reliability criteria above, because all of the criteria must be satisfied. In order to circumvent these difficulties, the following criteria have been developed. They are based on the principles set out by Van der Voo (1989), but are specifically designed for Precambrian paleomagnetic data.

1. *Age of rock unit*. In Precambrian studies, age estimates are generally less precise than in Phanerozoic, although an increasing number of very accurate dates are becoming available. To use an age limit of +/- 20 Ma, as Van der Voo (1989) does, would exclude many poles, some of them well-established paleomagnetically. Three categories with appropriate scores are therefore recognized:

a) 3 points were given to those poles which had a determined age of +/- 20 Ma;

b) 2 points to those poles whose age was known to better than +/- 50 Ma;

c) and 1 point to those poles whose age was not known to better than +/- 50 Ma.

2. *Magnetization characteristics*. Four subcriteria were set, each of which was given a weight of one. They are intended to assess the age of magnetization relative to the age of the rock.

a) The presence of reversals, indicating that enough time has elapsed to remove the effects of secular variation, a systematic bias, or an instantaneous ancient remagnetization (Van der Voo, 1989). However, the presence of reversals may not indicate an original magnetization, as highly metamorphosed rocks which have been heated past their Curie points and then slowly cooled may also display reversals.

b) The execution of field tests (contact, fold, or conglomerate), indicating that the age of magnetization is of great antiquity. This criterion is satisfied if the tests are successful.

c) The execution of laboratory demagnetization sufficient to isolate stable remanent magnetizations, with the successful separation of overprints.

d) No suspicion of remagnetization, or similarity to younger poles.

3. *Quantity and Precision.* In order to average out secular variation, errors due to random sampling, orientation, and bedding measurement, there must be a minimum number of sites and samples, and a minimum degree of confidence in the statistical results. For this criterion, I chose limits similar to those of Van der Voo's (1989). Each subcriterion has unit weight.

a) $\alpha_{95} \leq 16^\circ$;

b) $k \geq 10$;

c) and $n \geq 25$.

4. *Paleohorizontal.* The effects of tilt are difficult to ascertain in many instances, e.g. sills and metamorphosed rocks. However, in certain instances (e.g. subvertical dykes or bedded sediments that pass the tilt test) the paleohorizontal can be considered to have been reasonably estimated. One point is awarded in such cases. A pole is not to be discarded simply on the basis of this criterion.

The maximum score is 11. Poles scoring less than 6 are not considered further. If the score is 5, and no point has been awarded in the paleohorizontal category, then that pole is retained.

The quality index for each pole is given in Appendix 2. Paleopoles with scores $\geq$ 6 are listed in Table 4 and plotted in Fig. 24 (Slave-Rae-Hearne provinces) and Fig. 25 (Superior province).

Table 4. Paleomagnetic poles (QI ≥ 6)

	Name[1]	Pole	QI[2]
Slave-Rae-Hearne Poles 1950+ Ma			
EI	Easter Island Dyke	-32, -22	7
DOG	Dogrib Dykes	-35, -40	6
CLA	Caribou Lk. Gabbro	14, -64	9
ID	Indin Dykes	19, -76	8
WR	Western River Form.	14, -19	10
Slave-Rae-Hearne Poles 1950-1850 Ma			
AR2	Akaitcho River Form.	-4, -92	10
SE2	Seton K-H Form.	2, -93	9
SE1	Seton K-G Form.	34, -96	7
UG	U. Gibralter Form.	6, -74	8
MCD	McLeod Bay Form.	4, -70	9
DP	Douglas Pen.	-17, -102	8
STA	Stark Form.	-15, -145	9
TO1	Tochatwi Form.	-18, -144	10
PA	Pearson A Form.	-19, -77	7
PH	Peacocks Hill Form.	-15, -90	9
MAR	Mara Form.	-7, -107	10
PS	Peninsular Sill	-22, -97	9
TAK	Takiyuak Form.	-13, -111	9
Slave-Rae-Hearne Poles 1850-1800 Ma			
ET	Et-then Group	-1, -48	8
DU3	Dubawnt Group	7, -83	11
SPD	Sparrow Dykes	12, -69	11
MAT	Martin Formation	-9, -72	10

	Name	Pole	QI
Superior Poles 1950 + Ma			
EV1	Eskimo Volcanics	40, -178	8
FFD	Fort Frances Dykes	-43, 4	8
HG1	Huron. Gowg. 546	65, -122	7
HG2	Huron.Gowg.1038	63, -109	8
HGF	Firstbrook Memb.	67, 158	9
MD	Marathon Dykes	29, -146	5
NDB	Nipissing (B) Sills	-19, -88	6
NDG	Nipissing (G) Sills	-14, -106	7
NDH	Nipissing (H) Sills	73, -122	8
NDM	Nipissing (M) Sills	-17, -85	9
NDN	Nipissing (N) Sills	30, -19	8
NEDD	NE Diabase Dyke	37, -146	9
NG	Nastapok Grp.	39, 171	6
PN	Persillon N Form.	49, 134	7
PRE	Preissac Dykes W-2	30, -135	9
PS	Persillon S Form.	46, -168	7
Superior Poles 1950-1850 Ma			
MD2	Molson Dykes 2	28, -114	8
SEB	Sudbury Erupt. B	8, -82	8
Superior Poles 1850-1800 Ma			
FV	Flaherty Volc.	0, -116	9
HI	Haig Intrusives	1, -113	8

	Name	Pole	QI		Name	Pole	QI
Coronation Overprint Poles [3]							
LFL	Lynn Lake -Fraser Lake Gabbros	9,-84	7	FF4	Flin-Flon Intrusives	27, -95	6
NON	Nonacho Group	13, -85	5	MCL	McLean Formation	15, -94	6
OIK	Ottawa Island Komatiites	15, -101	6	CC	Castignon Comples	22, -92	6
EV2	Eskimo Volcanics	19, -117	6	LG	Lower Gibralter Form	40, -80	6
KAM	Kaminak Metamorphosed Dykes	20, -92	5	MBA	Melville-Daly Bay	11. -101	5
CSB	Cape Smith Basalts	16, -107	6	MEA	Menihek Form (A)	6, -81	6

Notes: 1. Name of rock unit sampled. 2. Maximum QI (quality index) is 11. 3. Poles considered to be Coronation overprints are not used further in this study.

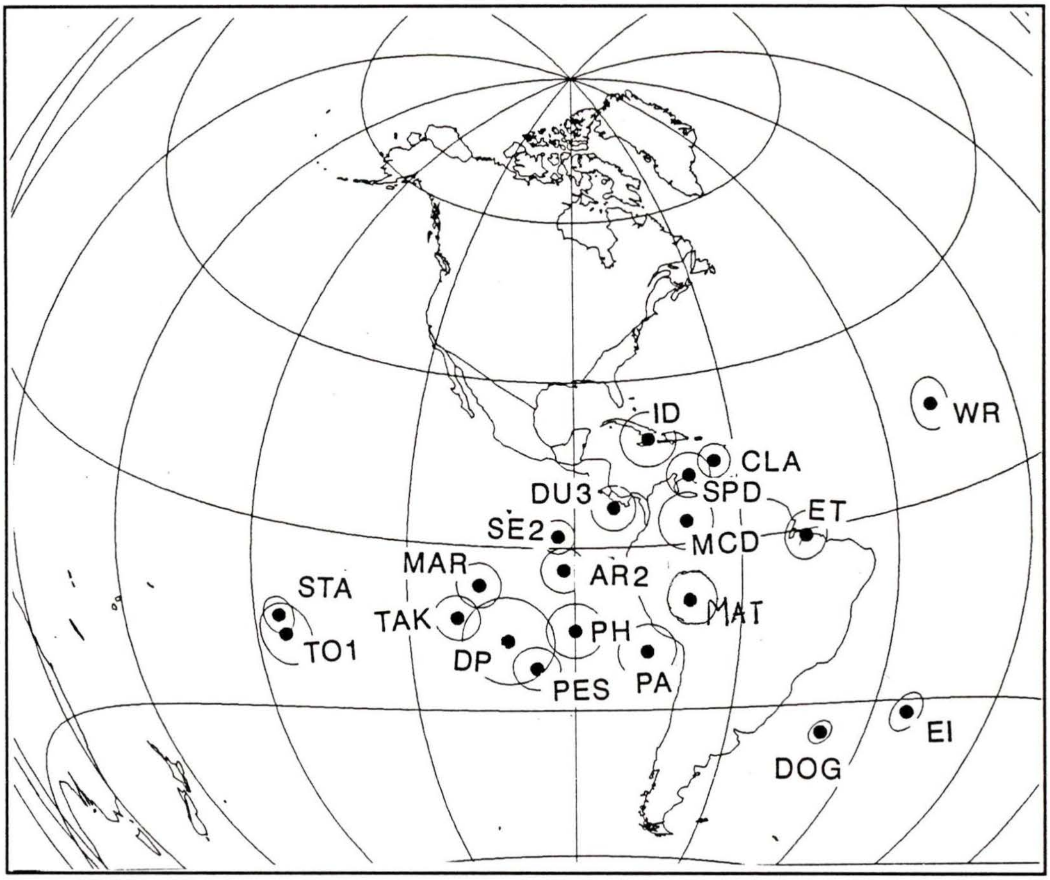

Figure 24. Reliable paleopoles from the Slave-Rae-Hearne composite structural province. Paleopoles score > 5 on the quality index (see section *7.2* and Appendix 2), and are identified in Fig. 13 and Table 4.

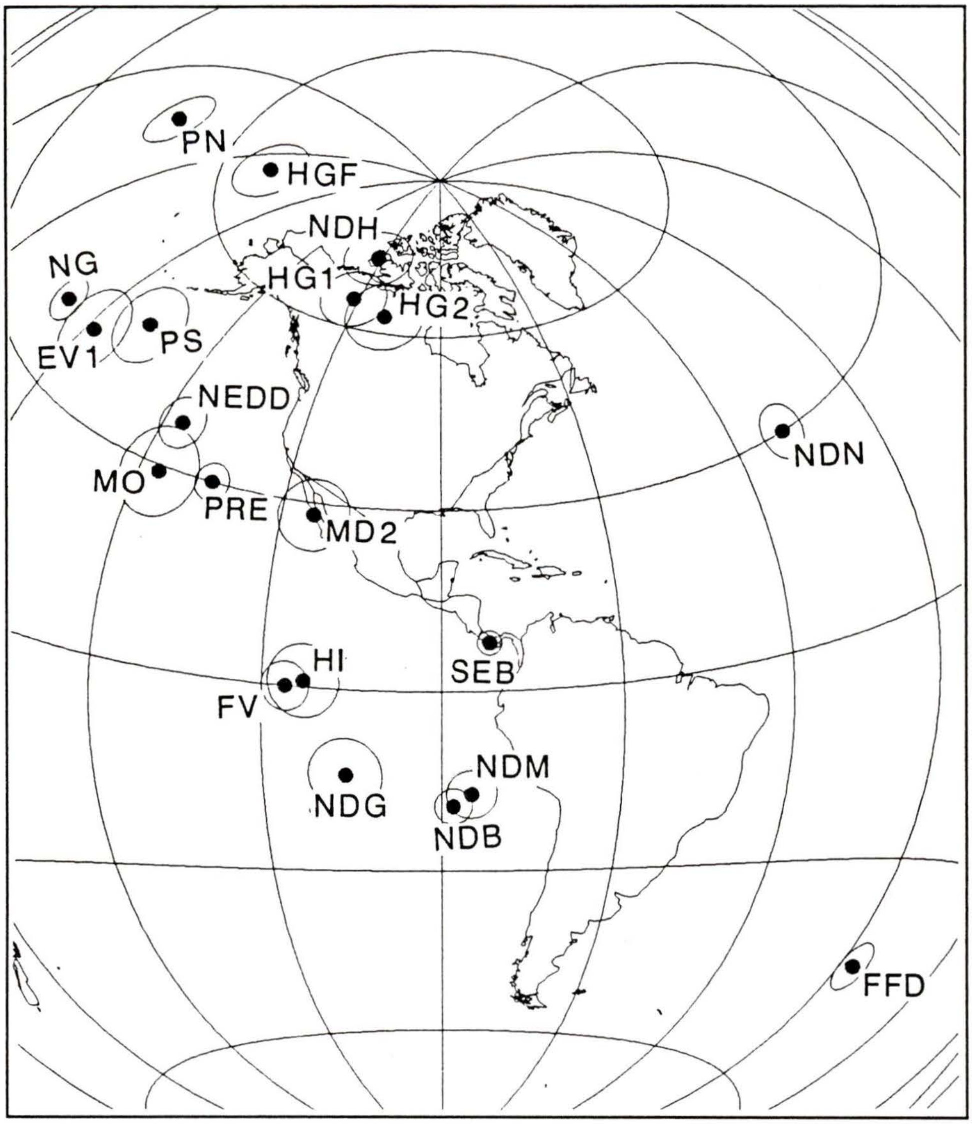

Figure 25. Reliable paleopoles from the Superior structural province. All paleopoles score > 5 on the quality index (see section *7.2* and Appendix 1). Poles are identified in Fig. 14 and Table 4.

CHAPTER 8

Techniques for Data Analysis

8.1 Data Analysis

The principles of spherical trigometry can be used to analyze the magnetization of a rock.

8.1.1 Calculation of paleolatitude

The original latitude of a site can be calculated from the inclination of its magnetization.

$$\tan \lambda_p = \tfrac{1}{2} \tan \boldsymbol{I} \qquad (1)$$

where λ_p is the paleolatitude and $\boldsymbol{I}$ is the inclination of the magnetization.

8.1.2 Calculation of paleopoles

The apparent position of the north pole at the time of rock formation can be calculated from the declination and inclination ($\boldsymbol{D},\boldsymbol{I}$) taking into account its present day latitude and longitude. Fig. 26 shows the spherical triangle formed to solve this problem. The vertices and opposite sides are defined as:

S, the sampling site (λ,ϕ), and **s** its opposing side

P, the pole position (λ',ϕ'), and **p** its opposing side

G, the geographical pole, and **g** its opposing side

such that

$$\boldsymbol{p} = 90 - \lambda$$

$$\boldsymbol{g} = 90 - \lambda_p\text{, where } \lambda_p \text{ is from (1)} \qquad (2)$$

The cos formula and the sin formula are used to define the spherical triangle.

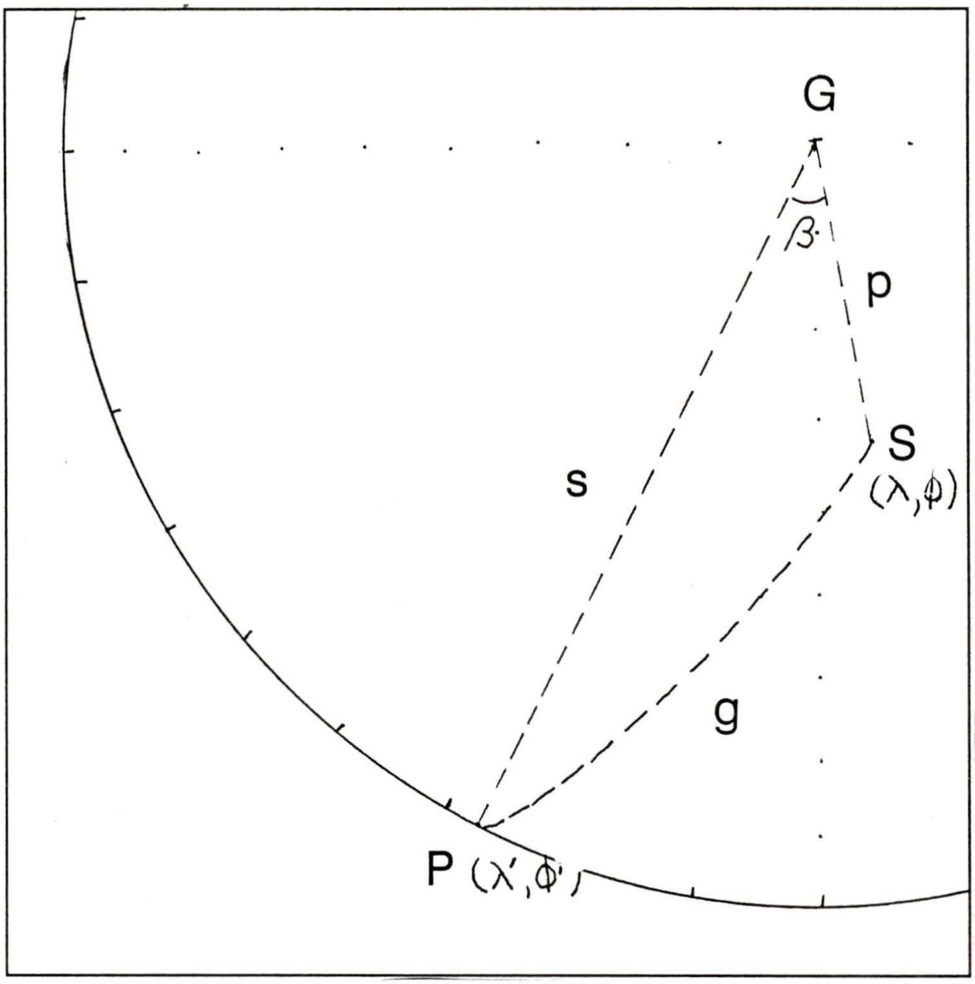

Figure 26. Spherical triangle used in paleopole calculations. ***G*** is geographic north, ***S*** the sampling locality, and ***P*** the paleopole (see ***8.1.1*** for formulas).

Cos Formula

$$\cos \boldsymbol{s} = \cos \boldsymbol{g} \cos \boldsymbol{p} + \sin \boldsymbol{p} \sin g \cos \boldsymbol{\hat{S}} \qquad (3)$$

where $\boldsymbol{\hat{S}}$ is the declination (***D***).

The latitude of the pole is calculated from ***s***.

$$\lambda' = 90 - \boldsymbol{s} \qquad (4)$$

Sin Formula

$$\frac{\sin \boldsymbol{\hat{S}}}{\sin \boldsymbol{s}} = \frac{\sin \boldsymbol{\hat{G}}}{\sin \boldsymbol{g}} = \frac{\sin \boldsymbol{\hat{P}}}{\sin \boldsymbol{p}}$$

and

$$\sin \boldsymbol{\hat{G}} = \frac{\sin \boldsymbol{g} \sin \boldsymbol{\hat{S}}}{\sin \boldsymbol{s}} \qquad (5)$$

where ***g*** is from equation (2), ***s*** is from equation (3), and $\boldsymbol{\hat{S}}$ is the declination (***D***). From this, one can calculate ϕ' (the pole longitude), as

$$\phi' = \boldsymbol{\beta} + \phi$$

where $\boldsymbol{\beta} = \boldsymbol{\hat{G}}$, and ϕ is the longitude of the sampling site.

In many cases, this calculated north pole does not coincide with the present north pole, thus showing the phenomenon of "apparent polar wander".

8.1.3 Use of reference localities

Plots of paleolatitude vs. time are often used to determine the relative motion of different rigid plates. The use of the paleolatitude of the sampling locality can lead to a systematic error in large plates, as the present day latitude of two sampling sites may be degrees apart. This error is minimized by choosing a reference locality for all poles from the same rigid plate, rather than the sampling locality for each pole (Fig. 27). Ideally, once two plates are amalgamated, a single paleolatitude curve will be generated.

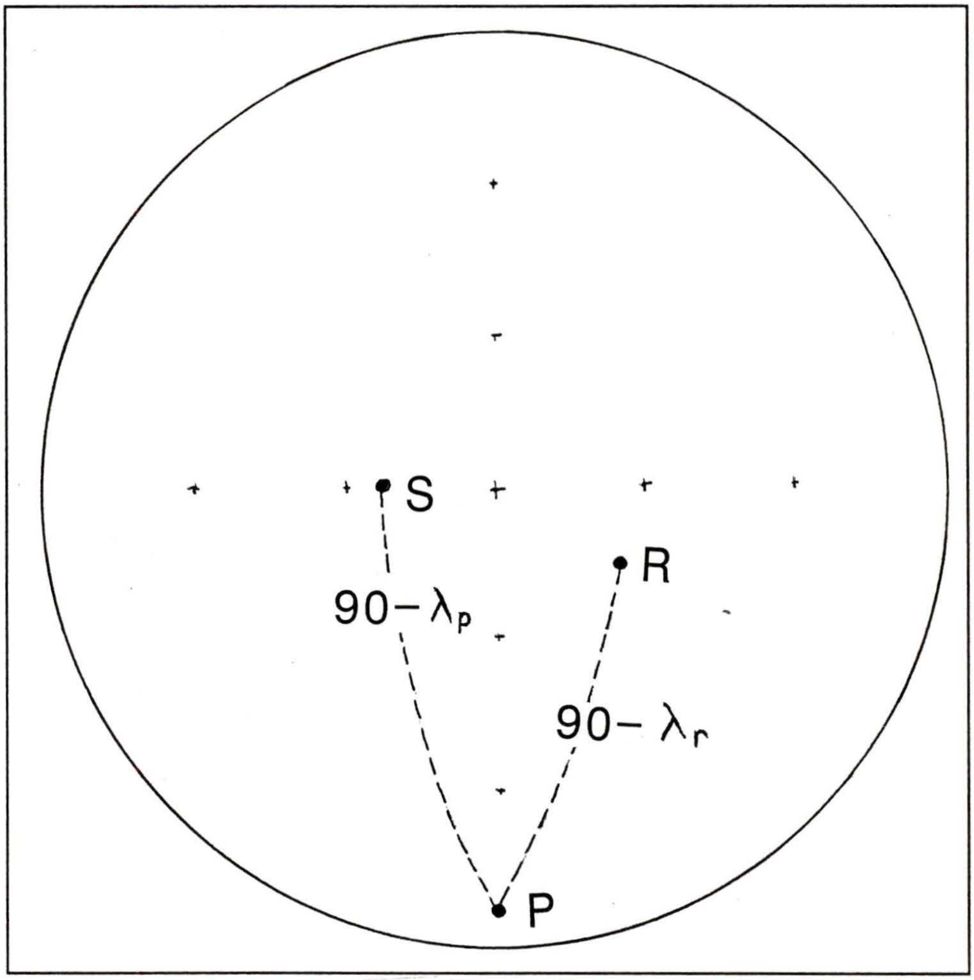

Figure 27. Graphical calculation of the paleolatitude of a reference locality. ***P*** is the paleopole, ***S*** is the sampling locality, and ***R*** is the reference locality. The distance along a great circle between ***P*** and ***S*** is equal to $90 - \lambda_p$. The distance along a great circle between ***P*** and ***R*** is $90 - \lambda_r$ (where λ_r is the paleolatitude of the reference locality).

However, within-plate block rotations introduce another type of error. The change in paleopole position caused by a rotation will not affect the inclination (and therefore paleolatitude) relative to the sampling locality, but may affect it relative to a reference locality and to the plate as a whole (Fig. 28). The error introduced is probably minimal, and is disregarded.

8.1.4 Calculation of rotations

The estimation of the relative rotation of a paleopole requires the use of a reference pole, defined as a pole that represents the field relative to the craton as a whole for a particular time interval. Two assumptions are made: the rocks from which the reference pole has been derived have not rotated relative to the craton, and the reference pole and rotated pole are coeval.

We define four points, and two triangles (Fig. 29)

R (λ_R, ϕ_R) is the reference pole,

T (λ_T, ϕ_T) is the sampling locality for the test site,

AP (λ_{AP}, ϕ_{AP}) is the test pole,

N is geographic north.

The observed paleolatitude at **T** is calculated using section 7.1.2 above. The expected paleolatitude is:

$$\lambda_{P(exp)} = 90 - \boldsymbol{TR} \qquad (6)$$

where

$$\cos \boldsymbol{TR} = \cos \boldsymbol{TN} \cos \boldsymbol{NR} + \sin \boldsymbol{TN} \sin \boldsymbol{NR} \cos \boldsymbol{n}$$

and $\boldsymbol{TN} = 90 - \lambda_T$

$\boldsymbol{NR} = 90 - \lambda_R$

$\boldsymbol{n} = \phi_T - \phi_R.$

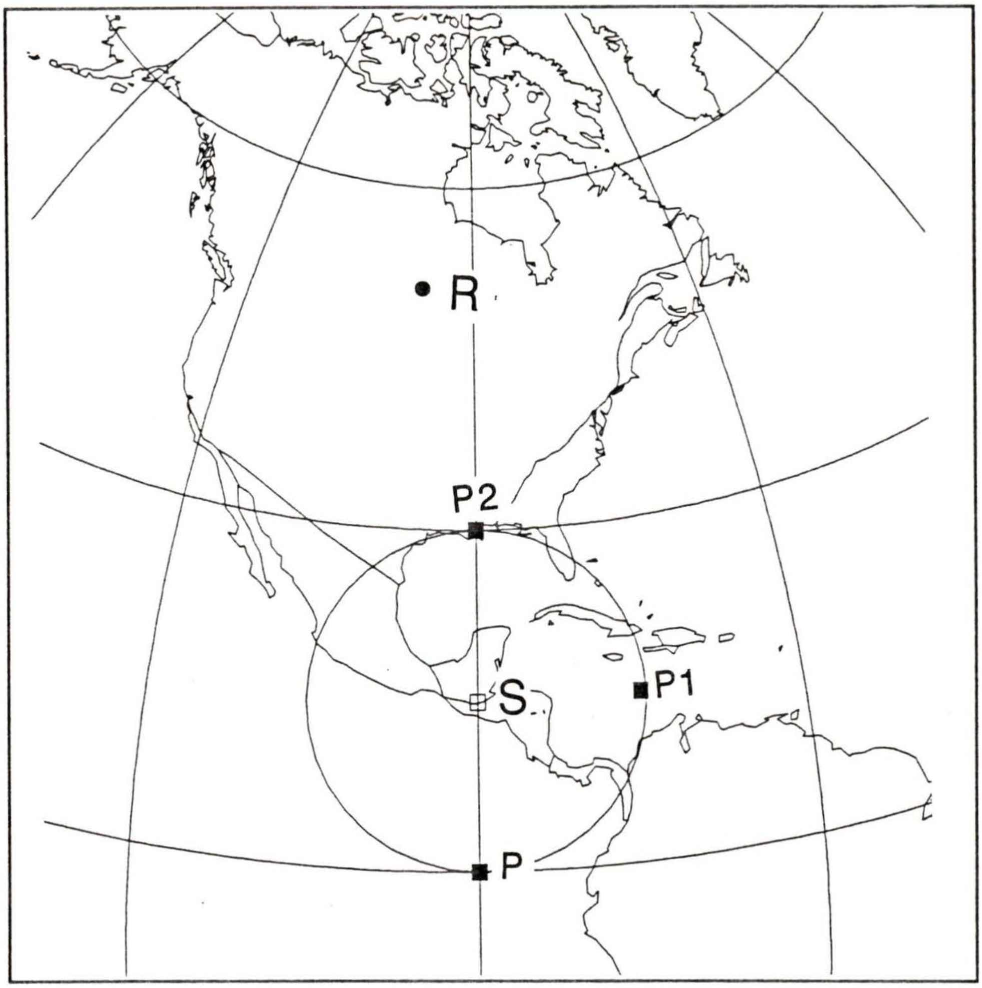

Figure 28. Error caused by the use of a reference locality with a rotated paleopole for the calculation of paleolatitude. The distance from a reference locality (R) to a paleopole will be affected by rotation (P, P1, P2), whereas the distance of the paleopole from the sampling locality (S) remains constant.

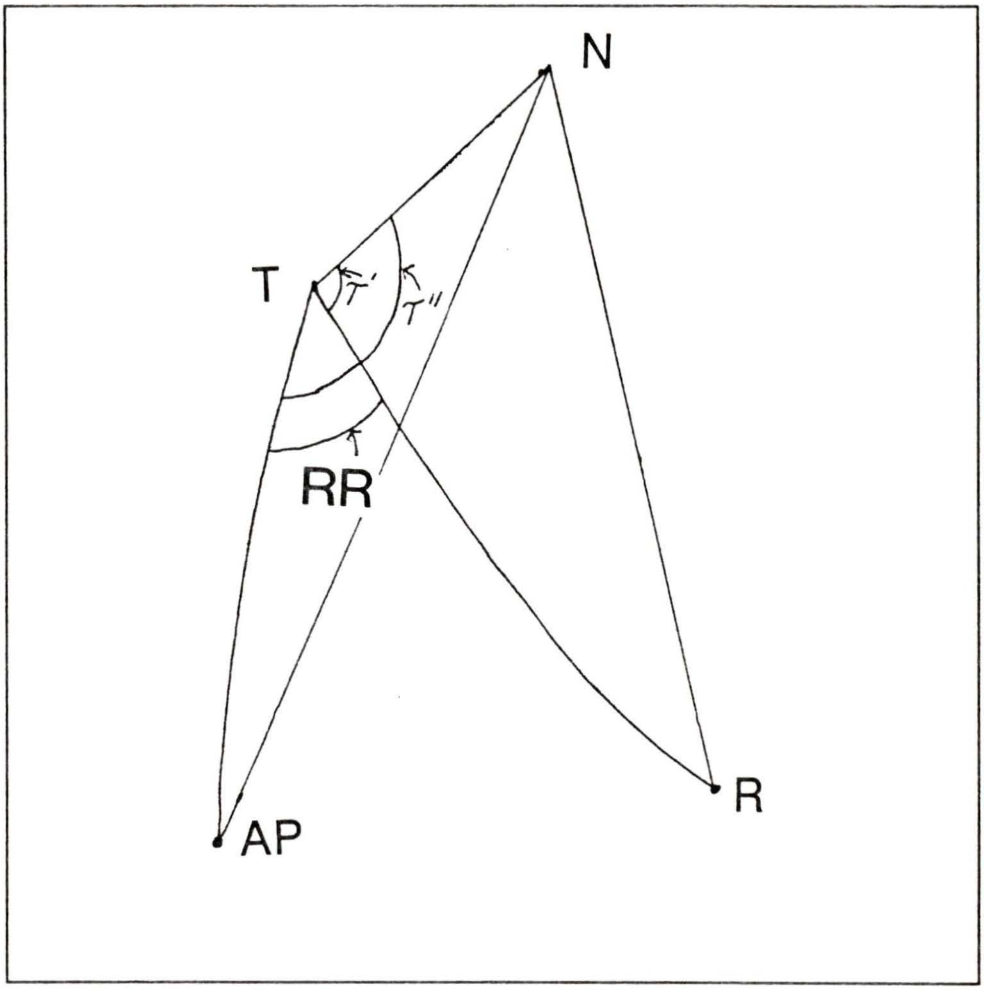

Figure 29. Calculation of the relative rotation between two paleopoles. The difference between the spherical triangle formed by the reference paleopole ***R***, the sampling locality of the rotated paleopole ***T***, and geographic north ***N*** and the spherical triangle formed by ***N***, ***T***, and the rotated pole ***AP*** is the relative rotation.

If the expected paleolatitude is significantly different from the observed paleolatitude, this might affect the calculation of the relative rotation.

As can be seen from Fig. 29, the relative rotation is

$$\boldsymbol{RR} = \angle\, \boldsymbol{NTR}\,(\tau') - \angle\, \boldsymbol{NTAP}\,(\tau'') \tag{7}$$

Using the sin formula, one can calculate τ':

$$\sin \tau' = (\sin \boldsymbol{n} \sin \boldsymbol{RN}) \,/\, \sin \boldsymbol{TR}$$

The observed declination is equal to τ'', and therefore **RR** can be calculated by substitution into equation (7). However, **RR** may be incorrect due to problems encountered in using spherical trigometry. This is easily solved:

$$\tau'_{RR} = 180\text{-}\tau'$$

and τ'_{RR} is substituted into equation (7) in place of τ'.

8.1.5 Effects of rotations and paleolatitude changes

In order to discuss the effects of rotations, tilts, and paleolatitude changes on the declination and inclination of a pole, relative to a reference pole, it is first necessary to define exactly what is meant by these words. A rotation is defined as movement about a vertical axis, whereas a tilt is movement about a horizontal axis. A paleolatitude change is exactly what the name implies, latitudinal movement. In general, a rotation will result in a shift in declination, a paleolatitude change will result in a shift in inclination, and a tilt can result in either or both (Fig. 30)

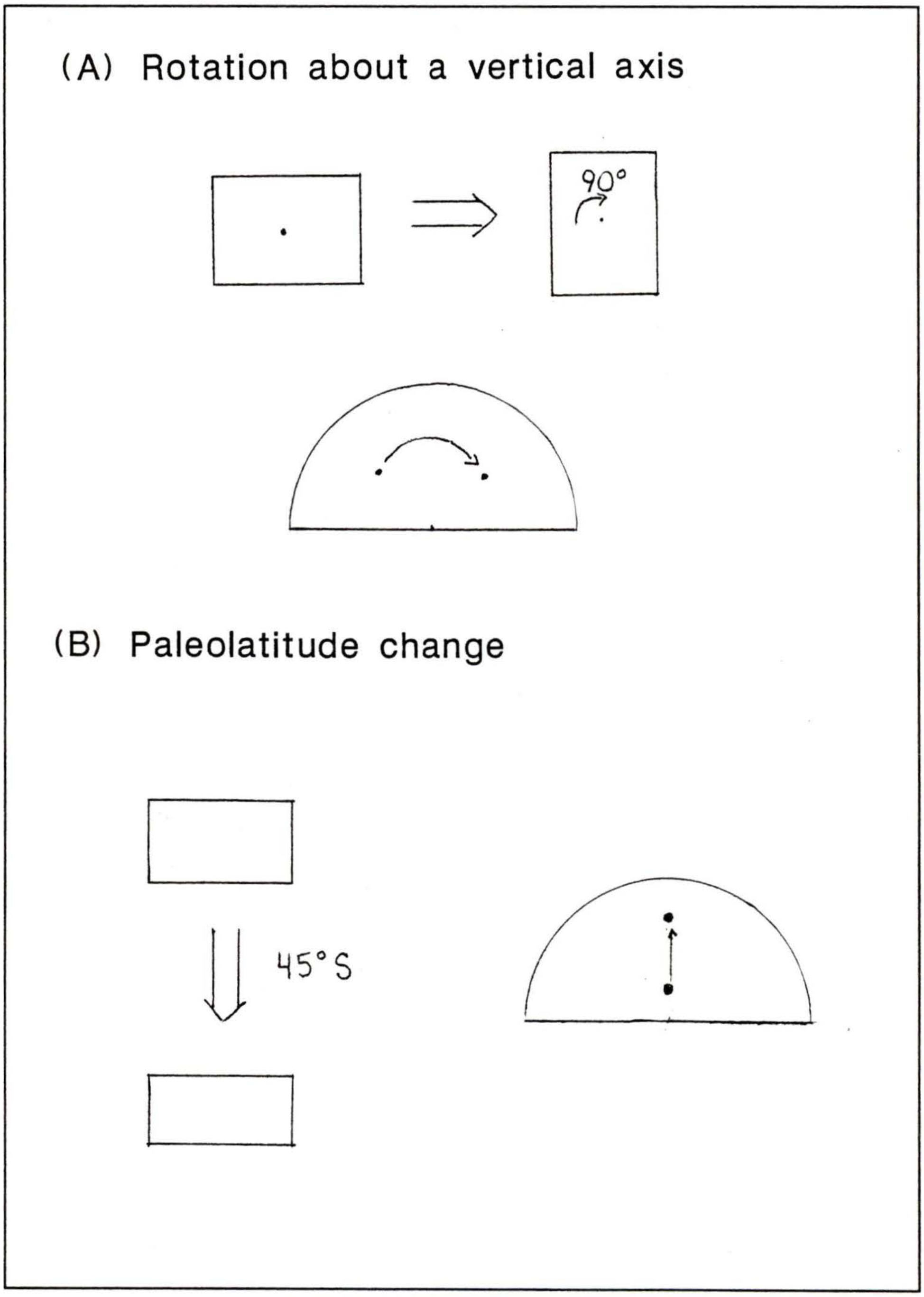

Figure 30. Effects of rotations, paleolatitude changes and tilts on declination and inclination. Rotation about a vertical axis causes changes in declination, but not inclination. A paleolatitude change causes a change in inclination but not declination. However, tilting can cause the same effects.

CHAPTER 9

Rotations and Paleolatitude Curves

9.0 Preamble

Relative rotations within the Slave-Rae-Hearne and Superior provinces must be recognized and an attempt made to correct them prior to making estimates of any paleolatitudinal differences. Paleolatitude curves (described in this chapter), and apparent polar wander paths (described in Chapter 10) were used to determine the relative motion between the structural provinces.

9.1 Relative Rotations and Reference Poles

Estimation of relative rotations (described in ***8.1.4***) necessitates the use of reference paleopoles.

9.1.1 Slave-Rae-Hearne reference poles

Paleomagnetic poles from the Slave-Rae-Hearne composite province were subdivided into three groups: poles older than 1950 Ma, poles between 1950 and 1850 Ma, and poles between 1850 and 1800 Ma (Table 4).

The few pre-1950 poles in the Slave province range in age from 2200 to 1960 Ma, and form a simple track. It is assumed, except in one case, that the poles represent the direction of the geomagnetic field for the Slave province as a whole at the time of formation of the rocks. The single exception is the Western River Formation paleopole (WR), whose considerable offset from the other pre-1950 poles is consistent with rotation of approximately 45° counterclockwise.

Recent geochronologic work has placed tight constraints on most of the 1950-1850 Ma paleopoles. The oldest units in the Great Slave Supergroup (AR2, SE1, DP, MCL, MCD, STA, TO1, PA) are considered to be 1880-1890 Ma. An 1865 Ma batholith intrudes most of the Great Slave Supergroup, with the exception of the upper part of the Christie Bay Group (STA, TO1, PA). However, these units may also be older than 1865 Ma.

The ages of the Mara (MAR) and Peacock Hills (PH) formations of the Kilogihok Basin are constrained by a U-Pb baddelyite age of 1882 +/- 4 on a correlative of the intervening Qadyuk Formation (Bowring and Grotzinger, 1992). The Takiyuak Formation (TAK) of the Coronation Geosyncline has been correlated with the Tochatwi Formation (TO1).

The declination differences in the 1950-1850 Ma paleopoles may be indicative of rotation (Fig. 31). The paleopoles listed above (MCL, MCD, STA, TO1, PA, MAR, PH, SE2, AR2, and TAK) are considered contemporaneous. No known reference pole exists for this time interval; therefore the Seton Formation paleopole will be used. The only difference the choice of reference pole makes is a change is the east-west position ofthis portion of the APWP.

The 1800-1850 Ma paleopoles are from both the Slave and the Rae-Hearne provinces. The Pearson Formation (PA) occurs at the top of the Great Slave Supergroup, which is overlain by the Et-then Group (ET). The maximum age of the latter is probably 1865 Ma, but the minimum age is uncertain. In the Hearne province, the Dubawnt Group (DU1) is 1837 Ma (P.Hoffman, pers. comm, attributed to A. Peterson) and the Sparrow Dykes (SPD) are 1825 Ma (P.Hoffman, pers.comm., attributed to A. Lecheminant). The Martin Formation (MAT) is considered to be 1835

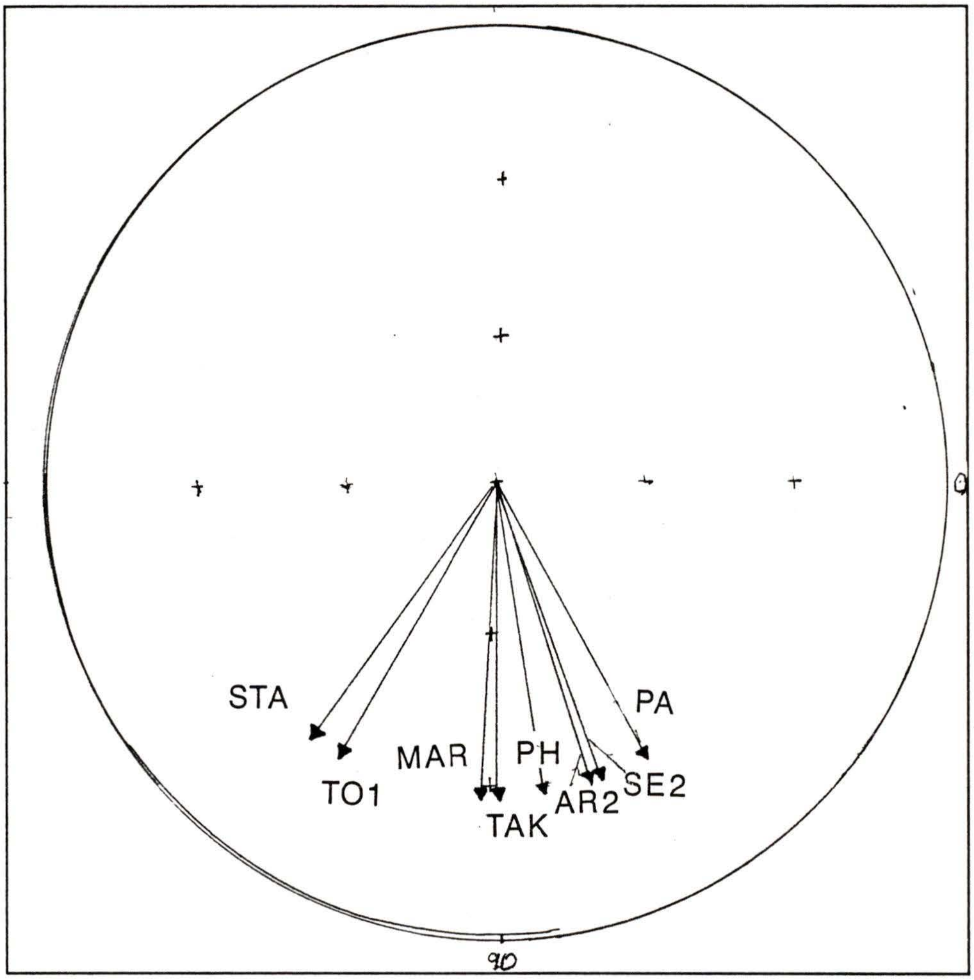

Figure 31. Declination differences in the 1950-1850 Ma Slave province paleopoles. The differences are strong evidence for relative rotations.

Ma. The Dubawnt Group paleopole was used as the reference pole in correcting for possible rotations.

9.1.2 Superior reference poles

Ages for Superior province paleopoles range from 2250 Ma to approximately 1840 Ma. There is much less evidence of relative rotations in the Superior province than in the Slave-Rae-Hearne structural province.

Relative rotations may occur in the Nipissing Diabase, as the ***N1*** paleopoles generally have similar inclinations but different declinations. A known reference pole is not available, but one of the paleopoles could be used. The different ***N1, N2,*** and ***N3*** magnetizations may be the result of rotations; however, that is not considered here.

The 2100-1900 Ma paleopoles (NA, PS, PN, EV1, FFD, MD) are very similar, displaying no evidence of relative rotations. However, the Eskimo Volcanics (EV1) and the overlying younger Flaherty Volcanics (FV) and Haig Intrusives (HI) paleopoles show similar inclinations but very different declinations, perhaps indicating relative rotation. However the Nastapoka Group (NG), which is a correlative of EV1 (Chandler and Parrish, 1989), and whose pole is similar to EV1, rests without structural break on older Archean rock. Thus, for the time being, these poles are considered to be primary and non-rotated.

The FV and HI paleopoles may be coeval with the 1837 Ma Slave province DU3 paleopole . As current theories suggest that the provinces were amalgamated by this time, the similar inclinations and differing declinations may be indicative of relative rotations. Therefore a rotational correction was applied to the HI and FV pole using the DU3 as the reference pole.

The relative rotations were calculated as described in section ***8.1.4***, and are summarized in Table 5. Fig. 32 shows the location of the Slave-Rae Hearne province poles after being rotated to their (presumed) original position, and Fig. 33 the location of the Superior province poles.

9.2 Paleolatitude Curves for the Reference Locality of Winnipeg

After restoring the rotated poles to their original position, a plot of paleolatitude vs. time for the Slave-Rae Hearne composite and Superior structural provinces was constructed (Fig 34), referenced to the present day position of Winnipeg (51N, 97W). The amalgamation of the structural provinces occurred when the two curves overlap. The calculated paleolatitudes are listed in Table 5 .

9.2.1 Slave-Rae-Hearne composite province

The paleolatitude curve for the Slave province (Fig. 34b) indicates rapid northward motion from about 20°S (***1***)to about 50°N during the time interval ≈ 2200 Ma (EI, Easter Island Dykes) to 2167 Ma (CGA, Caribou Lake Gabbro). The province appeared to have stayed at high latitudes (***2***, ***3***) for ≈ 150 Ma (ID, Indin Dykes). It then drifted southward until ≈ 1970 Ma (***3***, WR, Western River Formation). The collision with the Rae and Hearne provinces probably occurred about this time (P.Hoffman, pers. comm., 1992). Slow northward motion resumed until ≈ 1880 Ma (***4***), when the composite province had a paleolatitude of 40°N. During the time interval 1880 - 1825 ma, the composite province drifted south to the equator, and then retraced its path northward. At 1825 Ma, the province had a paleolatitude of ≈ 45°N (***5***).

Table 5. Summary of Rotations and Paleolatitudes

Name		λ_p (°)	α_{63} (°)	Rotation (°)	Reference Pole
Superior Province					
HGF	Huronian Firstbrook Memb.	64	5		
NDB	Nipissing Diabase (B)	30	5		
NDH	Nipissing Diabase (H)	58	5		
PRE	Presisac Dykes	56	4		
PS	Persillon Form. (S)	44	5		
NG	Nastapoka Group	27	4		
EV1	Eskimo Volcanics	34	6		
MD2	Molson Dykes (2)	64	6		
FV	Flaherty Volcanics	38	4	-37 ± 13	Dubawnt
HI	Haig Intrusives	37	3	-35 ± 13	Dubawnt
Slave-Rae-Hearne Provinces					
EI	Easter Island Dykes	-20	3		
CLA	Caribou Lake Gabbro	45	2		
ID	Indin Dykes	54	6		
WR	Western River Formation	19	4	45	arbitrary
AR2	Akaitcho River Formation	36	3		
SE2	Seton Formation	42	3		
PH	Peacock Hills Formation	33	5		Seton
STA	Stark formation	18	3	-54 ± 9	Seton
TO1	Tochatwi Formation	16	6	-50 ± 12	Seton
PA	Pearson Formation (A)	14	5		
DU3	Dubawnt Group	45	4		
ET	Et-Then group	23	4	32 ± 12	Dubawnt
MAT	Martin Formation	24	4		
SPD	Sparrow Dykes	46	4	17 ± 13	Dubawnt
TAK	Takiyuak formation	25	4	-20 ± 10	Seton

Notes. λ_p is the paleolatitude of the reference locality Winnipeg (51N, 97W). α_{63} is the standard error of the pole position. *Rotation* indicates the relative rotation of the named pole with respect to the reference pole; a negative rotation is in an antilockwise rotation.

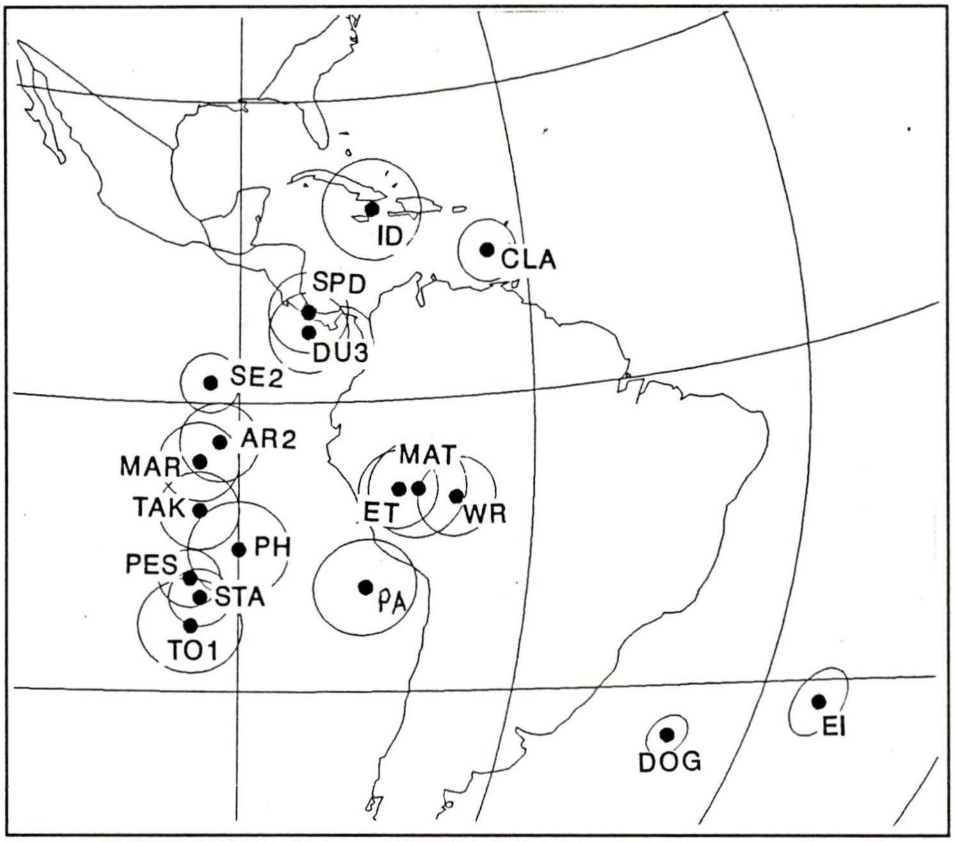

Figure 32. Pre-rotation Slave province paleopoles. The use of reference poles to correct for relative rotations results in a much clearer APWP.

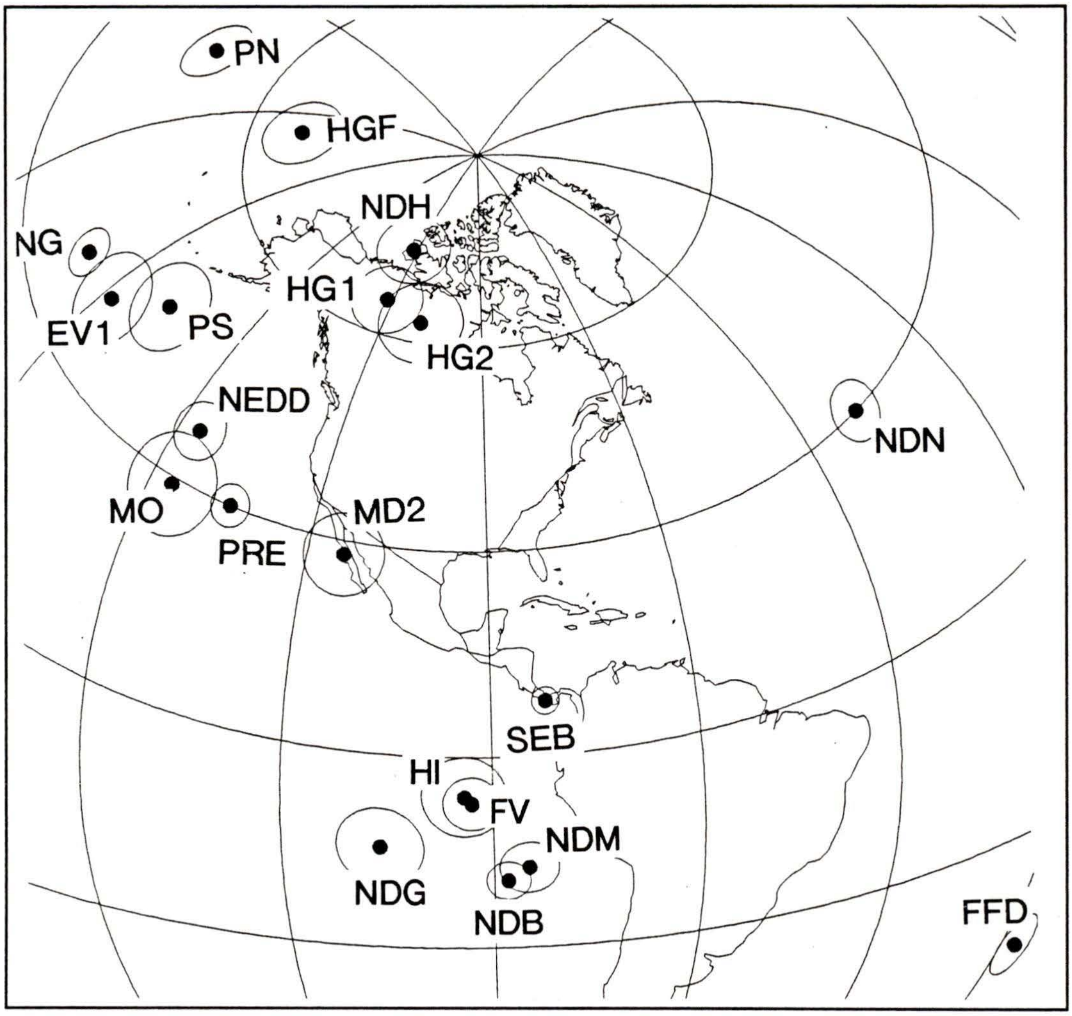

Figure 33. Pre-rotation Superior province paleopoles. Only HI and FV paleopoles have been rotated to their (presumed) original position.

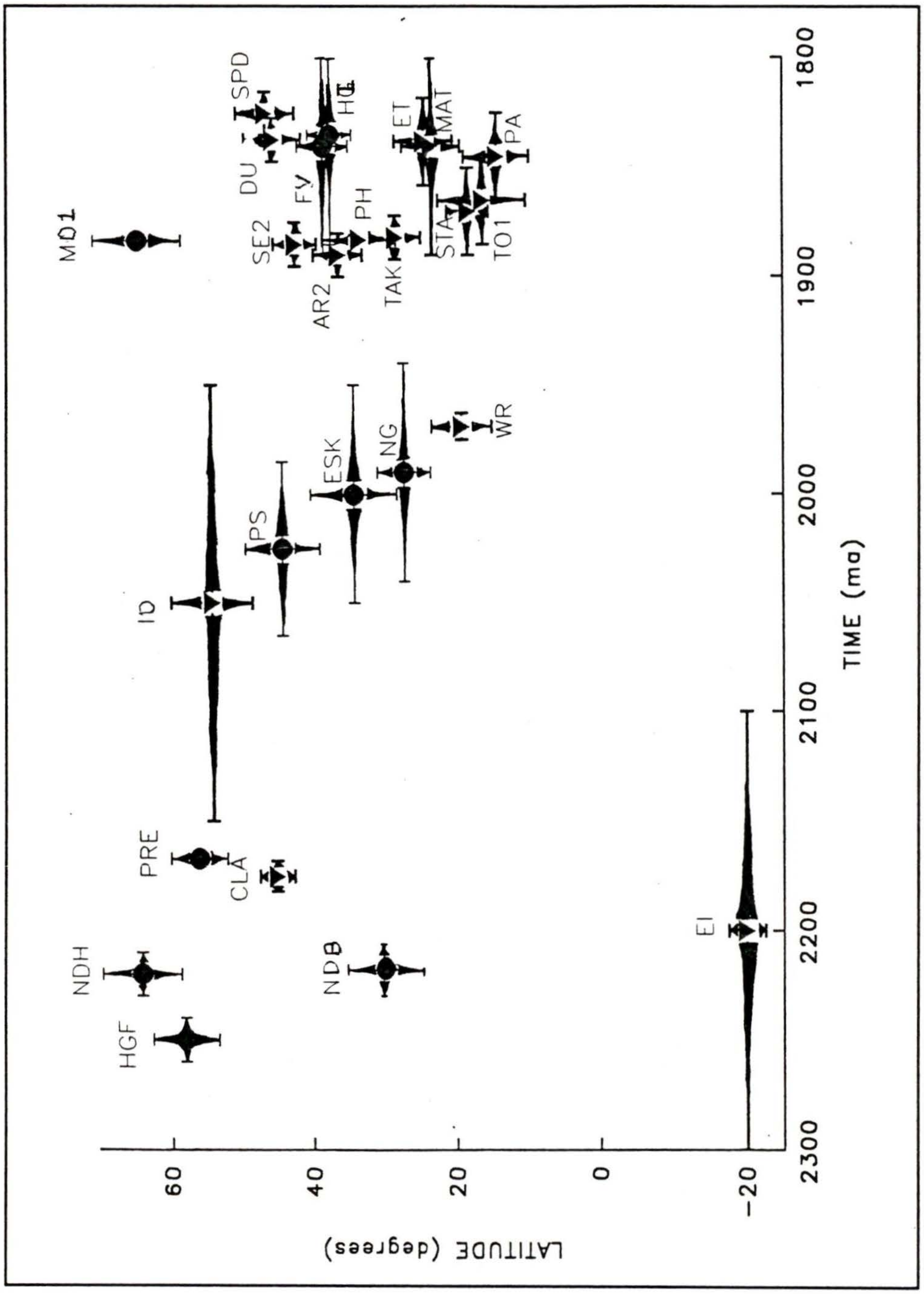

Figure 34a. Paleolatitude of a reference locality (Winnipeg) for each paleopole. Errors in age and paleolatitude are shown. For identification of poles, see Table 4.

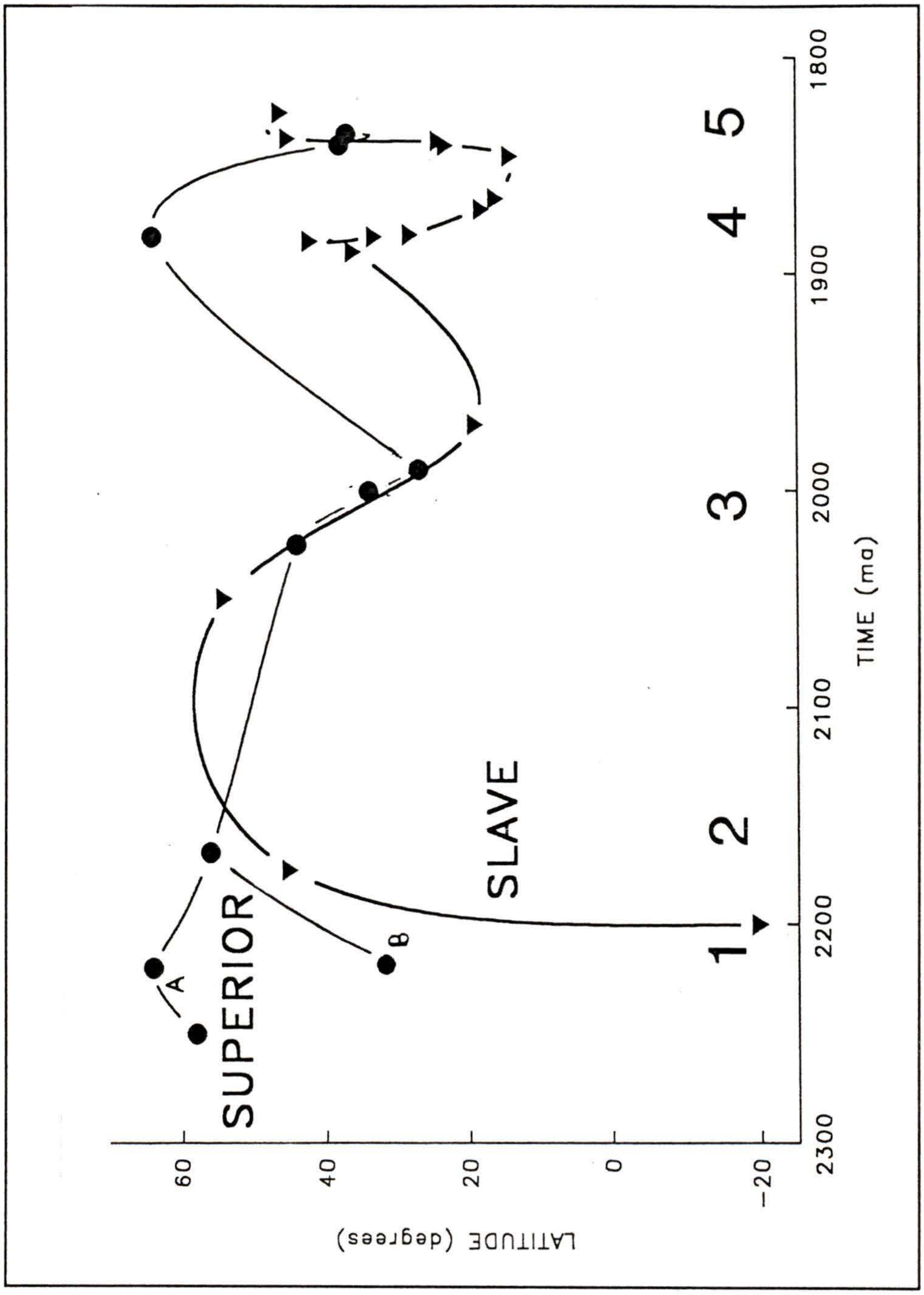

Figure 34b. Paleolatitude curves of a reference locality (Winnipeg; 57N, 91W) for the Slave and Superior structural provinces. A_{SI} and similar marks are identified in the text.

9.2.2 Superior province

The pre-2175 Ma Superior paleolatitude curve (Fig. 34b) has two possible forms. The first (A) assumes that the ***N2*** magnetization is older than ***N1***. The reference locality drifts slowly southward from high latitudes during the interval 2220 to 2175 Ma (HGF, Firstbrook Member; NDH, Nipissing diabase). The second (B) assumes the opposite (***N1*** older than ***N2***), and the resultant motion is northward during the interval 2250-2175 Ma (NDA, NDM, Nipissing diabase). During the interval 2175-2050 Ma (***2***, ***3***) the reference locality remained at high latitudes, then drifted southwards until 1990 Ma (***3***). Thereafter, northward motion occurred until ≈ 1880 Ma (***4***), when it was at a paleolatitude of 65°N (Molson Dykes). Southward motion resumed until 1840 Ma (***5***), when the reference locality seems to have been at a paleolatitude of 40°N.

9.2.3 Summary and Discussion

At 2200 Ma, the provinces were as much as 80° apart (***1***; numbers references to Fig. 34b). The Slave province moved rapidly northward, while the Superior moved either slowly south (option A) or slowly north (option B). Both were at 50° N at 2150 Ma (***2***). Subsequent southward movement of the Superior province contrasted with the north, then south, movement of the Slave province. Similar latitudes are recorded from 2025 to 1975 Ma (***3***). Both the Slave and Superior provinces then moved northward, the Slave more slowly than the Superior. At 1880 Ma, there was 20° of separation, which rapidly increased to ≈ 50° as a result of a rapid southward motion of the Slave province (***4***). This separation then decreased, as the Slave province moved northward. Both provinces were at 40°N latitude at ≈ 1840 Ma (***5***).

The two paleolatitude curves overlap at three different times: ***2*** at ≈ 2150 Ma; ***3*** at ≈ 2000 Ma; and ***5*** at ≈ 1840 Ma. Similar paleolatitudes may be indicative of a collisional event. However, there is no known orogeny at the time of the earliest overlap (≈ 2150 Ma). The second overlap (≈ 2000 Ma) occurred at approximately the same time as the collision of the Slave and Rae-Hearne provinces, and may be the first indication of the assembly of Laurentia. These intervals of similar paleolatitude are discussed further in section ***10.3.1***.

Geological evidence suggests that the collision of the Slave-Rae-Hearne composite province and Superior province occurred at about 1890-1830 Ma (P.Hoffman, pers.comm., 1992). The third period of similar paleolatitudes was around 1840 Ma, and therefore may represent this collision. The lack of paleomagnetic data from 1800-1500 Ma impedes any test for a single paleolatitude curve indicative of an single craton after amalgamation. The 1700- 1650 Ma Coronation overprinting event should provide proof, however, Kotzer *et al* (in press) suggest that large rotations may have occurred, producing errors in the reference locality paleolatitude curve (***8.1.3***).

CHAPTER 10

Proposed Apparent Polar Wander Paths

10.0 Introduction

The construction of APWPs for the Slave-Rae-Hearne and Superior structural provinces has been complicated by the presence of relative rotations. Sections ***9.1.1*** and ***9.1.2*** detailed the rotational corrections made.

10.1 Slave-Rae-Hearne APWP

Fig. 35 displays the Slave-Rae-Hearne composite province APWP.

Irving and McGlynn's (1975) pre-2000 Ma Slave province APWP has been remarkably durable, although still not well constrained. Paleopoles from the Easter Island Dykes (EI), the Dogrib Dykes (DOG), the Caribou Lake Gabbro (CGA), and the Indin Dykes (IND) indicate a north-northwesterly direction from ≈ 2200 Ma to ≈ 2000 Ma. The single paleopole for 2000 - 1900 Ma (WR) suggests southward motion, followed by northward motion during this period; however, an interpolation between the 2200-2000 Ma APWP and the 1900-1800 Ma APWP results in a westerly track. At 1900 Ma, the APWP starts to move almost directly south (SE2, AR2, TAK, MAR, PH, STA, TO1). At ≈ 1860 Ma, it loops back on itself, moving northward (PA, MAT, ET, DU3, SPD). The shape of this loop is dependent on the reconstructions of the rotations of TAK, MAR, TO1, STA, PH, ET, and SPD.

Although the loop bears some similarities to the Coronation loop of McGlynn and Irving (1978), the latter was partially based on poles from the Superior province and Trans-Hudson Orogen, which now must be excluded. Radiometric dating

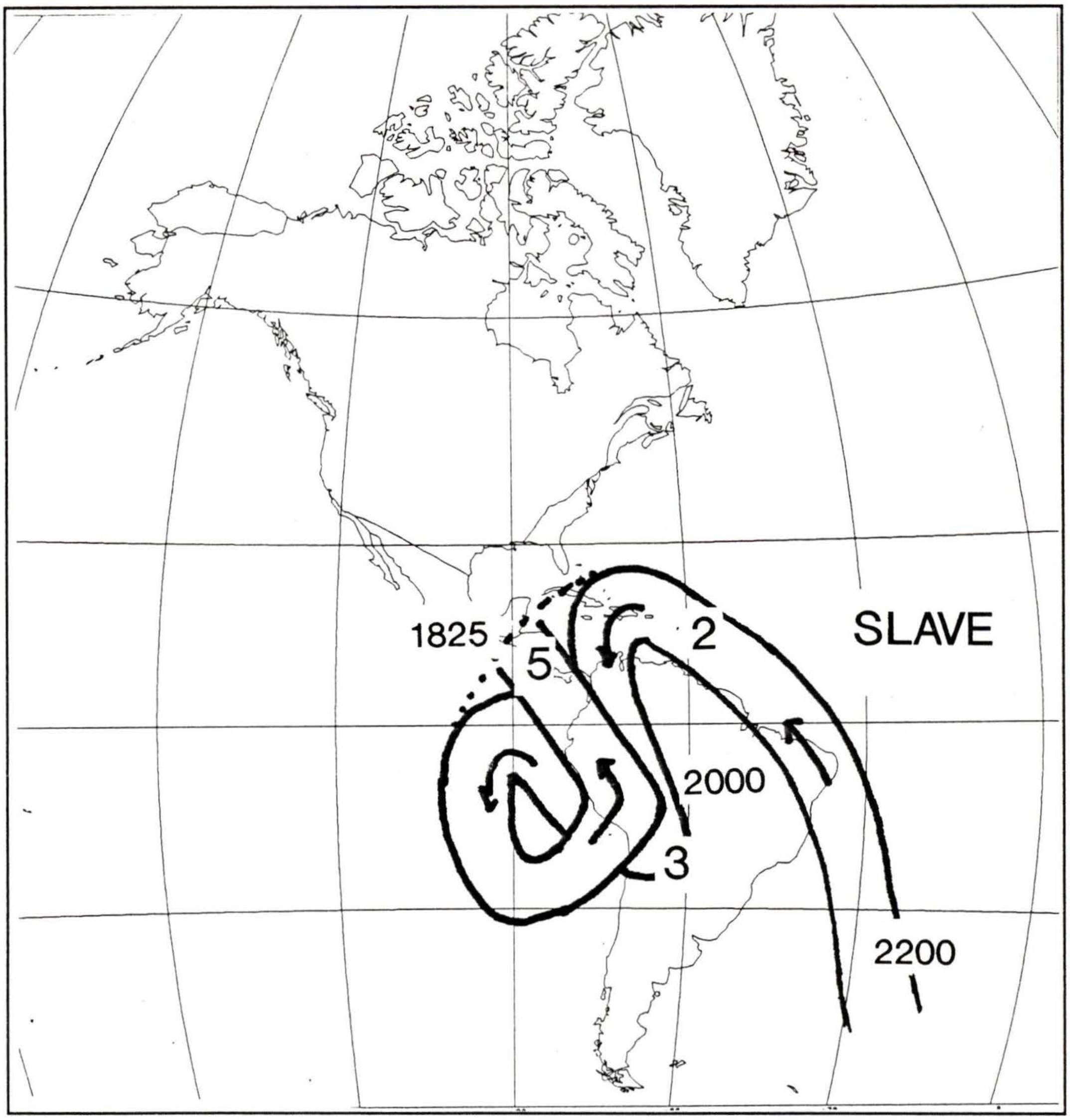

Figure 35. Apparent polar wander path for the Slave-Rae-Hearne composite structural province, 2250-1800 Ma. The dashed portion of the path excludes the WR paleopole. The APWP is based on the rotated paleopoles in Fig. 32. Intervals of similar paleolatitude to the Superior Province (see Fig. 34b) are indicated by ***2*** (2150 Ma), ***3*** (2025-1990 Ma) and ***5*** (1840 Ma).

of the oldest (SE2), and youngest (SPD) units in the loop limits its time span to about 60 Ma, rather than the original estimate of 200 Ma.

10.2 Superior APWP

Fig. 36 displays the Superior province APWP.

The difficulty in understanding the different magnetizations in the Nipissing diabase and associated sills makes construction of the pre-2175 Ma Superior APWP almost impossible. The less reliable poles were culled by the indices, but the original dichotomy remains; is the ***N1*** or ***N2*** pole grouping older? Recent work on mafic dyke swarms (K.L. Buchan 1992, pers. comm) suggests that the ***N1*** magnetization is older. However, the magnetization from sediments intruded by the diabase (HG1, HG2, HGC, HGF) is similar to the ***N2*** magnetization, and previously has been considered coeval. Both possibilities are shown on the APWP.

The 2175-2050 Ma interval is represented by only three poles (PRE, FFD antipole, and MO). A northwesterly trend off the west coast of North America is indicated by their relative ages.

A U-Pb date of 2025 +/- 25 Ma on diagenetic apatite from the basal formation of the Richmond Gulf Group (Chandler and Parrish, 1989) constrains the age of the next group of paleopoles (PS, PN, EV1, and NA). Their similarity to the older FFD and MD paleopoles may indicate a constant latitude during the interval 2100-1950 Ma. However, a counterclockwise rotation may have occurred (see ***9.1.2***).

The 1950 - 1800 Ma interval is represented by only four poles; MD1 and MD2, dated at 1883 Ma, and FV and HI, which are assumed to be ≈ 1840 Ma. The APWP motion is southeasterly throughout this interval.

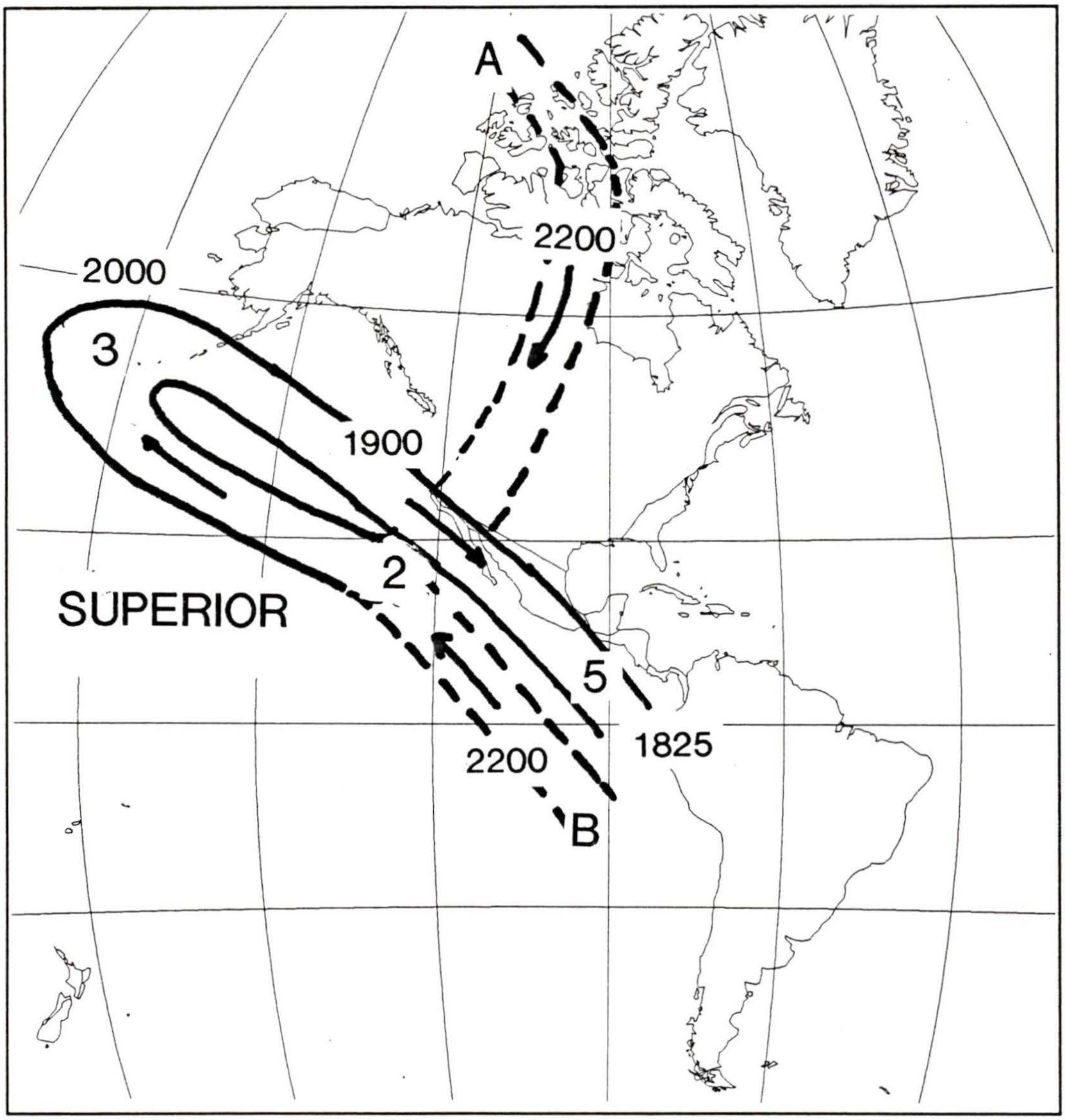

Figure 36. Apparent polar wander path for the Superior structural province, 2250-1800 Ma. The APWP is based on the rotated poles shown in Fig. 33. Two possible pre-2175 Ma APWP are shown by dashed lines. Option A assumes ***N2*** older than ***N1***, Option B the reverse. The three intervals of similar paleolatitude to the Slave Province (see Fig. 34b) are indicated by ***2*** (2150 Ma), ***3*** (2025-1990 Ma) and ***5*** (1840 Ma).

10.3 Amalgamation and Closure of Superior and Slave-Rae-Hearne Provinces

As discussed in section ***9.2.3***, there have been three intervals in which the paleolatitude of the Slave-Rae-Hearne and Superior provinces is approximately the same.

10.3.1 2200 - 1900 Ma

The two earlier intervals of similar paleolatitude (***2, 2150 Ma,*** and ***3***, 2025-1990 Ma) are not overtly expressed as geologically recognizable collisional events on the APWPs for the provinces. However, the assumption that the 2025-1990 Ma interval of similar paleolatitudes is the result of a collision between the provinces can be used to explain the paleomagnetic data. On this assumption, one sequence of events is presented in Fig. 37.

1. The Slave and Superior provinces were separate prior about 2150 Ma.

2/3. The structural provinces could either have been separate or amalgamated during the interval 2150-2025 Ma.

3. The Slave and Superior provinces were amalgamated by ≈ 2025 Ma (and possibly much earlier).

4. Separation of the Slave and Superior provinces occurred after ≈ 1990 Ma, and the Superior province rotated with respect to the Slave province by about approximately 120° about an Euler pole of 55N, 85W.

5. Convergence and amalgamation occurred at 1840 Ma.

The separation of the provinces prior to 2150 Ma explains the different paleolatitudes seen at 2220 Ma (Fig. 34b, Fig. 37, ***1***). As the paleolatitudes move towards each other, and finally meet at 2150 Ma (Fig. 34b, Fig. 37, ***2*** and ***3***), the

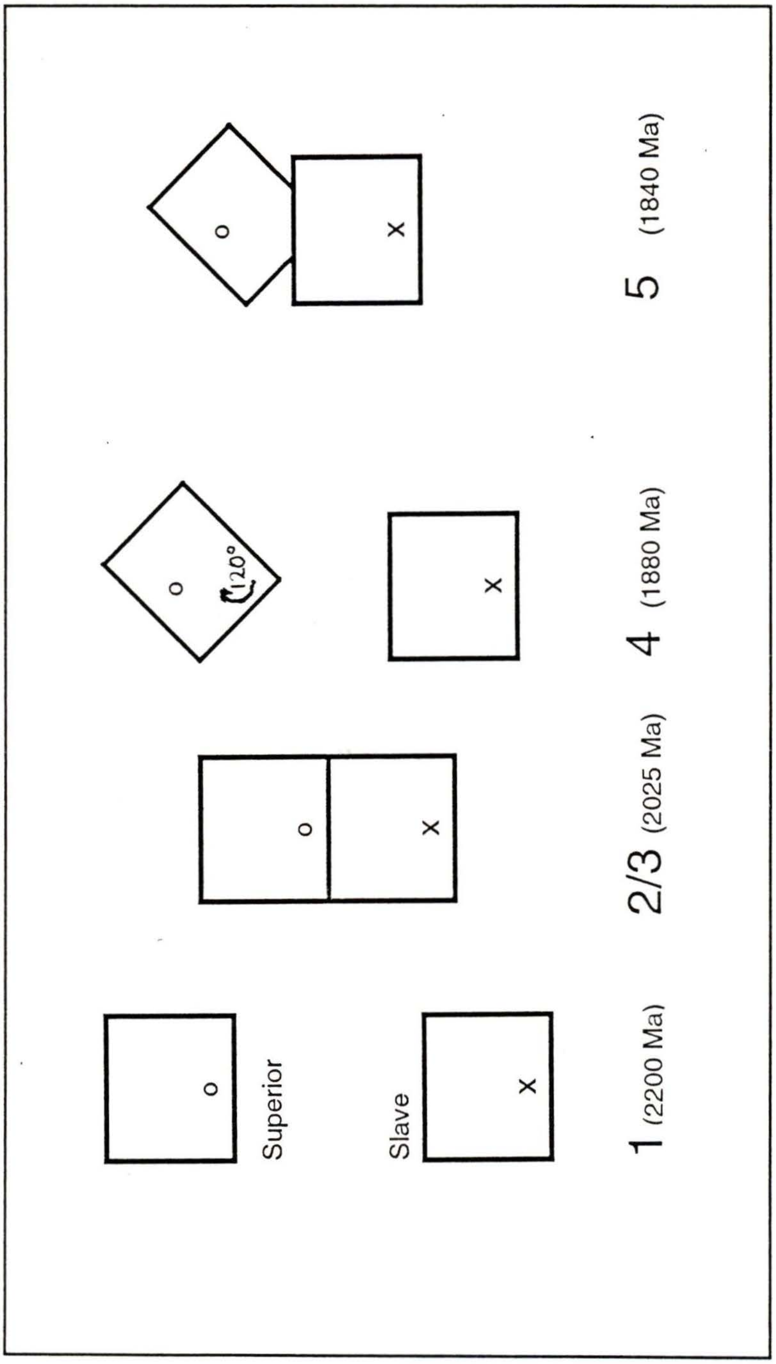

Figure 37. A scenario for the motions of the Slave and Superior structural provinces during the interval 2250-1800 Ma. Numbers correspond to Fig. 34b. Description and explanations are in the text (section ***10.3.1***).

Slave and Superior provinces are also moving closer together. The Preissac Dykes and Caribou Lake Gabbro paleopoles (PRE and CLA) are almost identical after the Superior province has been rotated to its presumed original position (Fig. 38), providing evidence for a collisional event at this time. The interval 2150-2025 Ma is characterized by similar, but not identical paleolatitudes. However, there are no paleopoles from the Superior province during this interval, so the relative motion of the provinces is difficult to determine. Between 2025 and 1990 Ma, the paleolatitudes are almost identical. Separation of the provinces in the interval 1990-1890 Ma explains the different paleolatitudes seen (Fig. 34b, ***4***). If, during this period the Superior province was rotated 120° clockwise about an Euler pole of 55N, 85W, the pre-1990 ma paleopoles would be rotated to their present day positions. By 1880 ma, the Superior must have been fully rotated, in order to produce the Molson Dykes paleopole. Fig. 39 shows the pre-rotation APWP.

The rotated ***N1*** Nipissing diabase paleopoles from the Superior province (NDB, NDG, NDM) become coincident with a non-rotated ***N3*** paleopole from the Southern province (NDN). However, this implies that the Superior province rotated with respect to the Southern province, as well as with respect to the Slave province in the interval 1990-1880 Ma. The difference in declination and similarity in inclinations between the 2100-1900 Ma Superior province paleopoles and the 1840 Ma Superior province paleopoles (***9.2.2***) is explained as the result of this province-wide rotation, rather then the result of smaller block rotations as occur in the Slave province.

This scenario is based solely on paleomagnetic data. It is assumed that the 2025-1990 Ma interval of similar paleolatitude represents a'period when the two

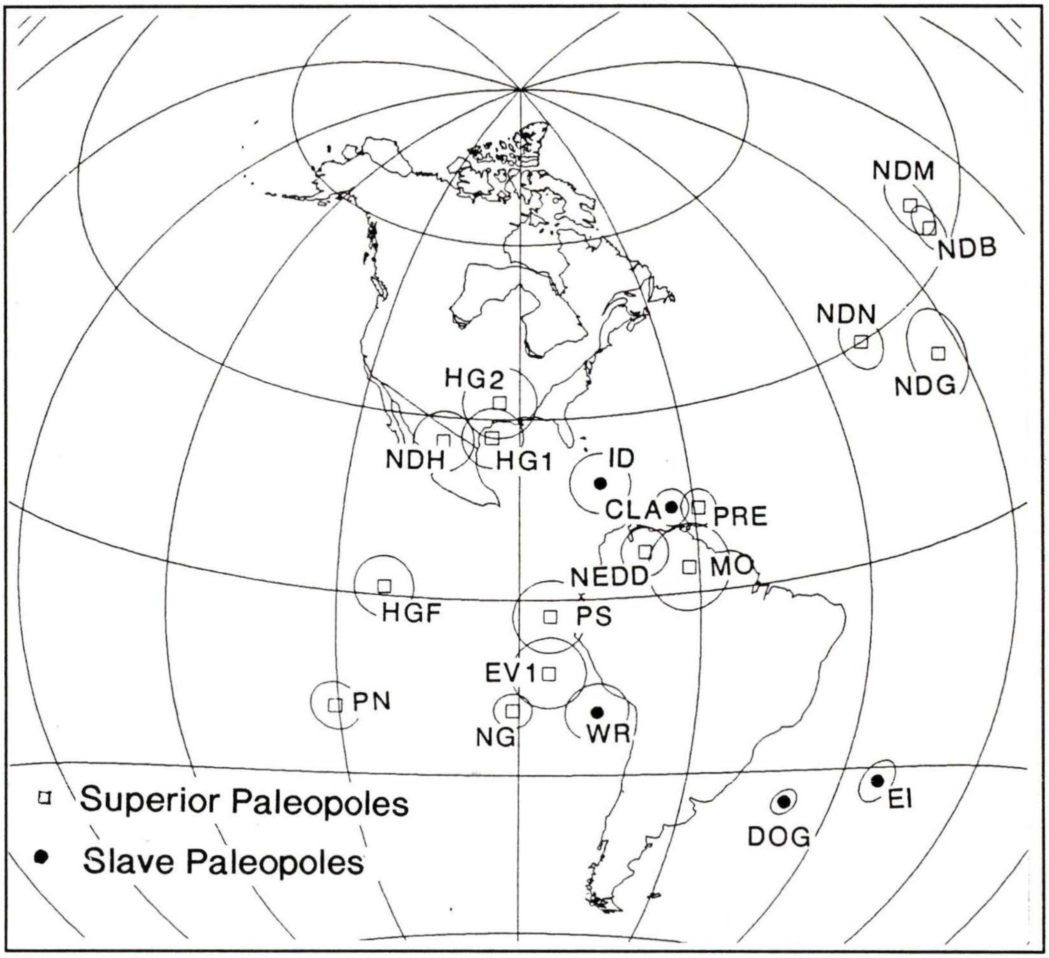

Figure 38. Rotation of the pre-1950 Ma Superior province paleopoles by 120° counterclockwise. The coeval Slave province paleopoles and Southern province (NDN) are retained in their present day position.

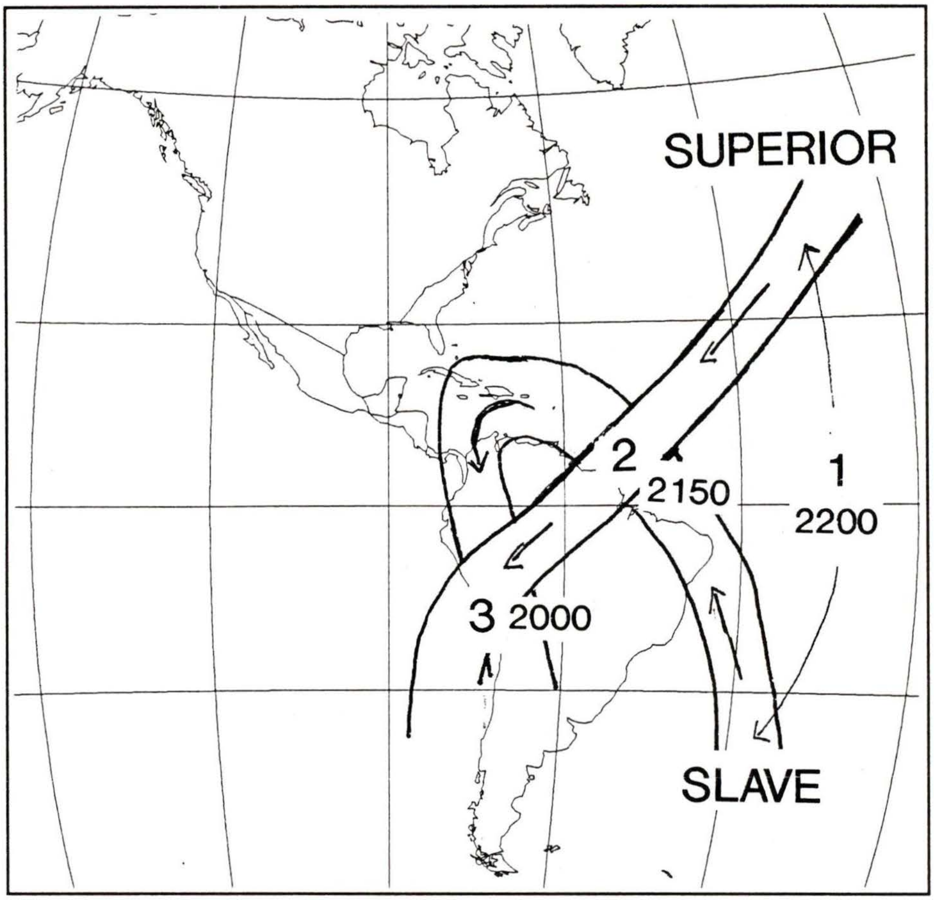

Figure 39. Theoretical apparent polar wander path for the Slave and Superior structural provinces. The Superior province (and pre-1990 Ma APWP) has been rotated 120° clockwise. Note the overlaps at 2150 Ma and at 2025-1990 Ma. The Superior province 2150-2025 Ma APWP is not supported by any paleopoles; it could therefore be the same as the Slave APWP for that interval. Numbers correspond to those of Fig. 34b and Fig. 37.

provinces were amalgamated . There may be no geological basis for it, but the scenario provides a hypothesis which is testable geologically.

10.3.2 1900 - 1800 Ma

The APWPs and the paleolatitude curves indicate that the Slave-Rae-Hearne and Superior provinces were separated by about 20° paleolatitude at ≈ 1880 Ma. At ≈ 1865 Ma, the two continents were ≈ 50° apart. From ≈ 1865 Ma to 1830 Ma, this separation decreased rapidly. The time of closure is indicated by the age and paleolatitudes of the Dubawnt pole (Slave-Rae-Hearne), and Flaherty-Haig poles (Superior) which coincide at ≈ 1840 Ma.

The separation of the structural provinces increases and then decreases very rapidly. Simple calculations can be made to determine the minimum rates of separation and closure. These are the minimum rate as only the latitudinal separation is accounted for.

$$\boldsymbol{R}_s = \Delta d / \Delta t$$

where $\boldsymbol{R}_s$ = separation rate (cm/yr)

d = distance (cm)

t = time (yr)

The calculations indicate that the minimum separation rate of the two provinces during the interval 1880-1865 Ma was approximately 24 cm/yr. The rate of closure for the interval 1865-1840 Ma was the same. The maximum separation rate for plates today is about 18 cm/yr (Windley, 1984). Bickle (1986) predicted that mid-oceanic rift separation rates in the Archean were probably 2-3 times today's rates. If the separation rate changed continuously from the Archean to the present, then the calculated rate is well within the realm of possibility for separation rates in the Early Proterozoic.

10.4 Overprint Poles

A number of paleopoles which passed the reliability index were excluded from the construction of APWPs because of the certainty or likelihood that they were Coronation-type overprints (CSB, OIK, NON, FF4, CC, LFL). The poles are listed in Table 4. The exclusion was based on various factors, including post-folding magnetizations, position near a known younger pole, and lack of normal and reversed magnetizations. The overprinting probably occurred at ≈ 1700-1650 Ma (U-Pb age from diagenetic apatite), as a result of post-Hudsonian deformation (Kotzer *et al*, in press).

At the time of overprinting, complete amalgamation of the structural provinces had already occurred, and therefore, only a single APWP and paleolatitude curve is expected. The broad swath of the overprinted paleopoles may result from rotations about vertical axes after the main period of deformation and magnetization (Kotzer *et al*, in press). The paleolatitudes with respect to Winnipeg also form a broad band, but in most cases there is no significant difference (the α_{63} overlap).

10.5 Comparison with recent discussions of APWPs

As mentioned in section ***6.4***, several other APWPs for the Slave-Rae-Hearne and Superior provinces have been published recently. The similarities and differences to Ma APWP are discussed below.

10.5.1 Symons (1991) and Dunsmore and Symons (1990)

Symons (1991) and Dunsmore and Symons (1990) have a different interpretation of the closure of the Slave and Superior microcontinents, based upon much the same paleomagnetic data as I have used. Their interpretation has the Slave-Rae-Hearne and Superior provinces separated by a 5000 km ocean (the Manikewan Ocean) at 1865 Ma (Fig. 22), similar to the separation on my APWP at the same time. The Proterozoic juvenile island arcs terranes within the Trans-Hudson Orogen (Lynn Lake-La Ronge, Flin-Flon belt) occur at intervals within this ocean. Dunsmore and Symons (1990) indicate that final closure was not complete until 1700 Ma (Fig. 22).

The differences in the APWP are based on the different interpretation and choice of paleomagnetic data. The causes of the differences are summarized below.

1. A number of the poles used by Symons (1991) were excluded from my data set, either not fulfilling the minimum reliability criteria (SRA, MD1) or not having a high enough quality index (SEA). Poles such as CC, LFL, and FF4, regarded by Symons as "primary" may be overprints related to fluid flow at 1650-1700 Ma (Kotzer *et al*, in press).
2. Symons (1991) groups together and averages poles with associated ages up to 60 Ma apart, particularly in the case of the Slave province. I have argued that the age difference is significant, and therefore did not average the poles.
3. Data from the Belcher Islands and Richmond Gulf are incorporated in this study, whereas Symons (1991) and Dunsmore and Symons (1990) do not use it.

Geological and geochronologic information places constraints on the paleomagnetic interpretation. However, with the many differing views on the origin and formation of the Trans-Hudson Orogen, at this time it is difficult to say which, if either, interpretation is more correct. It is interesting to note that at a recent workshop on the Trans-Hudson Orogen in Saskatoon, Saskatchewan, evidence was presented that indicated that the final closure of the Trans-Hudson Orogen occurred at ≈ 1825 Ma (Machado and Bleeker, 1992; M. Bickford, pers. comm. 1992).

10.5.2 Buchan et al (1992)

Concurrent paleomagnetic and geochronologic studies of mafic dyke swarms in the Superior province have led Buchan *et al* (1992) to suggest that the 2220-2100 Ma APWP had northward motion. This is based on the belief that the ***N1*** Nipissing diabase magnetization is the oldest, and on the recognition of several dyke swarms that were previously considered the same (Senneterre, Biscoteague, Preissac) for which radiometric ages have been determined. Unfortunately, these poles cannot be tested for reliability at the present time, and this interpretation cannot be critically discussed.

Buchan *et al* (1992) also suggest that the geochronologic information from mafic dykes in the Slave province is so poorly constrained that it is almost useless in constructing an APWP. However, the available geochronologic and stratigraphic information is sufficient to allow the above reconstructions (***10.1*** and ***10.2)*** to be tentatively made.

CHAPTER 11

Conclusions

11.1 Part I Quaternary Magnetostratigraphy

1. The paleomagnetic record at Mokowan Butte, Saint Mary Ridge, and Two Medicine Ridge implies that periodic glaciation of North America could have occurred as long ago as 2 600 Ka. At the very least, glaciation must have occurred well back into the Matuyama Chron, as several reversed diamicts and paleosols are found at all three localities.

2. The integrated record hypothesis suggests that the magnetizations observed record long rather than brief intervals of time, On this basis, the polarity sequence and the inferred magnetostratigraphy can be used to correlate the deposits at Mokowan Butte, Saint Mary Ridge and Two Medicine Ridge. A normal (Brunhes)-reversed (Matuyama)-normal (probably Gauss) sequence was found at Mokowan Butte, whereas only a normal-reversed sequece was discovered at Two Medicine Ridge and Saint Mary Ridge. The Brunhes-Matuyama transition is mostly closely constrained at Saint Mary Ridge, where a normal paleosol is developed on a reversed diamict. This places the transition either late in a glacial episode or in an interglacial interval; the latter is supported by oxygen isotope and paleomagnetic work on deep sea cores. The most likely correlation is ***D4*** and ***P4*** of Saint Mary Ridge with ***D4*** and ***P4*** at Mokowan Butte. The correlation with Two Medicine Ridge is less certain; either ***D3*** and ***P3*** or ***D4*** and ***P4*** are correlated with ***D4*** and ***P4*** at Saint Mary Ridge.

3. The cemented diamicts (tills) that were sampled for paleomagnetic analysis were found to be good recorders of the geomagnetic field. The magnetization carrier

is probably hematite. Cementation of the diamicts seems to have occurred soon after deposition. Both normal and reversed magnetizations are present, suggesting several episodes of cementation. If only one episode of cementation had occurred, then all the cemented diamicts would retain the same magnetization direction.

11.2 Part II Early Proterozoic Plate Motion Analysis

1. The development of an eleven point quality index for Precambrian paleopoles eliminated data that are not considered to be representative of the paleofield for the interval under consideration. Of the original 117 paleopoles, only 41 met the stringent criteria. The four major criteria used were age, magnetization characteristics, quantity and precision of samples, and known paleohorizontal. In general, only those poles with a score of six or more (out of eleven) were included in the study.
2. Paleomagnetic evidence indicates that the Slave-Rae-Hearne and Superior provinces were not one unit throughout their history. Separate apparent polar wander paths and paleolatitude curves can be constructed. However, relative rotations must be corrected if an accurate idea of the relative motions is to be obtained.
3. Paleolatitude curves for a reference locality (Winnipeg) were constructed. Three intervals of similar paleolatitude occurred: at 2150 Ma, 2025-1990 Ma, and 1840 Ma. The first and second intervals may not represent intervals of amalgamation, as they are not seen on the APWPs. However, the possibility that they represent times of amalgamation cannot be ruled out. On the assumption that the intervals of similar latitude result from amalgamation, a series of events which includes the rotation of the Superior province by 120° clockwise about an Euler pole of 55N, 85W during the interval 1990-1880 Ma has been constructed. The hypothesis of rotation could be

proved or disproved by geological information. If rotation did occur, its cause is still uncertain. While it has been explained here as a simple rotation of the whole Superior province, there could be many other explanations.

4. The third interval of similar paleolatitude is expressed by the coincidence of the Slave-Rae-Hearne and Superior province APWPs, and represents their convergence into the present day configuration. The Coronation Loop, which in this interpretation is significantly smaller form than the usual form, may represent the opening and closing of an ocean containing elements of the Trans-Hudson Orogen.

5. The paucity of useful paleomagnetic data limits the amount of information about relative motion during the interval 2250-1800 Ma. Future work that would be ff particular value in determining the relative motion of the structural provinces is pre-1900 Ma data from the Slave province, and post-2000 Ma data from the Superior province.

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Appendix 1. Paleomagnetic data from western Laurentia: 2250-1800 Ma

	Name	Lat, Long	B	N	D.I	α_{95}	Pole	A_{95}	Age	Method	Assn. age	Ref
AR1	Akaitcho River S-A	62.3,-110.4	35	106	162, 21	9	-16, -94	8				8
AR2	Akaitcho River S-B	62.3,-110.4	35	120	160, 36	7	-4, -92	7			1885-95	8
BS1	Big Spruce D	63.6,-115.9	19	85	22, 88	8	67, -113	15	2170	Rb-Sr	Cret. ovp.	17
BS2	Big Spruce NW	63.6,-115.9	4	16	291, 2	26	-10, -44	16	2170	Rb-Sr		17
BS3	Big Spruce SE	63.6,-115.9	5	25	137, 46	9	7, -78	10	2170	Rb-Sr		17
BS4	Big Spruce SW	63.6,-115.9	2	9	210, 27	0	-9, -145	?	2170	Rb-Sr		17
CAM	Cameron Bay CG	66.5,-117.8	1	3	165, 41	0	1, -104	?	1770	Rb_Sr		10
CSB	Cape Smith Basalts	60.8,-78.2	30	300	218, 60	4	16, -107	5			1700	39
CLA	Caribou Lake Gabbro	62.1,-112.6	12	81	119, 50	5	14, -64	5	2186	U-Pb		18
CLD	Caribou Lk. Gabbro D	62.1,-112.6	12	19	15 ,79	9	81, -73	18				18
CB	Charlton Bay K-A	62.1,-111.9	3	12	136, 71	14	32, -84	22			1875?	5
CA1	Coronation Avg.	62.1,-111.9	22	80	135, 45	7	6, -72	8			1700	5
CA2	Coronation Avg.	62.1,-111.9	18	69	129, 21	10	-7, -62	9			1700	7
DOG	Dogrib Dykes	62.7,-113.9	16	83	309, 37	4	35, 140	4	2150?		2200	19
DP	Douglas Pen. P-B	62.8,-110.3	6	43	172, 18	19	-17, -102	16			1875	6
	Douglas Pen. P-C	62.8,-110.3	10	54	233, 41	4	?	4				6
DU1	Dubawnt Group 479	64.1,-94.4	9	56	347, -63	16	19, -85	22				11
DU2	Dubawnt Group 480	64.1,-94.4	20	70	347, -45	6	1, -83	6				11
DU3	Dubawnt Group 481	64.1,-94.4	30	130	347, -50	7	7, -83	8	1837		1830-40	11
	Dubawnt Group 478	64.1,-94.4	1	4	338, -51	0	?	?				11
EI	Easter Is. Dyke	61.7,-112.8	15	146	288, 46	5	-32, -22	5	2200	K-Ar	2200	18
EV1	Eskimo Volcanics 1	56.0,-79.0	7	29	119, -46	10	-40, 2	12	1693	K-Ar	2000	20
EV2	Eskimo Volcanics 2	56.4,-79.0	7	23	234, 60	12	19, -117	15			1700	20
ET	Et-then Group	62.3,-111.6	14	37	294, -21	10	-1, -48	8			1840	1
FFD	FF (Kenora-Kabe.) Dykes	49.0,-94.0	31	143	116, -56	5	-43, 4	6	2120	Rb-Sr	2100	45
FV	Flaherty Volcanics	56.5,-79.0	11	35	42, -44	7	0, -116	7	1625	K-Ar	1830	20
FF1	Flin-Flon A1	54.8,-101.9	33	24	171, 73	6	26, -96	9				23
FF2	Flin-Flon A2	54.8,-101.9	4	19	117, 62	23	24, -59	33				23
FF3	Flin-Flon A3	54.8,-101.9	6	25	201, 74	8	28, -113	13				23
FF4	Flin-Flon A4	54.8,-101.9	43	73	168, 73	5	27, -95	8	1650		1700	23
FFB	Flin-Flon B	54.8,-101.9	7	110	129, 4	18	-21, -50	13	1800		?	23
GS	Gabbro Sill Kil-1	65.8,-107.1	3	9	346, 7	19	27, -88	15				9

	Name	Lat, Long	B	N	D, I	α_{95}	Pole	A_{95}	Age	Method	Assn. Age	Ref
HI	Haig Intusives	56.4,-79.0	10	47	40, -46	6	1, -113	6	1620	K-Ar	1830	20
HG1	Hur. Gowg. 1038	46.8,-80.3	8	35	327, 78	10	63, -109	15			2250	37
HG2	Hur. Gowg. 546	46.5,-82.8	17	58	326, 75	6	65, -122	10	2290	Rb-Sr		46
HGC	Hur. Gowg. Coleman	47.4,-79.7	1	7	10, 19	?	60, -80	-				36
HGF	Hur. Gowg. Firstbrook	47.4,-79.7	8	56	337, 52	8	67, 158	10	2288	Rb-Sr	2250	36
ID	Indin Dykes	63.3,-113.6	13	72	131, 58	8	19, -76	10	2093	Rb-Sr	2050	19
KAM	Kaminak Meta Dykes	62.2,-95.0	22	94	176, 65	4	20, -92	6				12
KAZ	kazan Dykes	62.5,-99.0	6	29	171, 72	19	31, -94	31	1900	K-Ar	1700?	13
LG	L. Gilbralter K-D	62.1,-111.9	6	24	124, 75	14	40, -80	24			1870	5
CC	LT Castignon Complex	56.5,-68.7	5	24	217, 67	9	22, -92	14	1880	U-Pb	1700	24
DD	LT Diabase Dykes	55.1,-67.0	?	19	187, 74		20, -74	20				25
MEA	LT Menihek (A)	56.8,-69.3	5	25	195, 57	16	6, -81	21				23
MBG	LT Meta-bas & gabb	56.8,-69.1	40	110	119, -11	30	-20, -152	24	1873	K-Ar		26
MIR	LT Meta-igneous rcks	56.0,-67.0	24	73	285, -9	20	5, 172	16				25
MG1	LT Montagnais Grp	57.0,-68.0	5	25	240, 73	26	34, -99	-				27
MG2	LT Montagnais Grp	57.0,-68.0	14	81	136, 36	13	-4, -25	-				27
RPA	LT Retty Peridotite A	56.5,-69.0	2	7	185, 7	-	-30, -76	-				24
RPB	LT Retty Peridotite B	56.5,-69.0	1	5	199, 56	-	5, -82	-				24
SWA	LT Seward A	56.3,-68.5	2	8	203, 15	-	-23, -94	-				24
SWB	LT Seward B	56.3,-68.5	5	22	227, 47	17	5, -109	16			1700?	24
SWC	LT Seward C	56.3,-68.5	6	-	281, 77	5	53, -112	9				24
SF1	LT Sokoman IF 1	55.1,-67.0	-	32	?, ?	?	62, 175	34				25
SF2	LT Sokoman IF 1	55.1,-67.0	-	42	228, 59	15	16, -102	20				25
WAK	LT Wakauch Gabb.	56.5,-68.4	5	18	305, 67	16	61, -140	24				24
LFL	Lynn Lk-Fraser Lk. Gab	56.5,-101.1	42	493	158, 60	5	9, -84	7	1890	est.	1700?	47
MAR	Mara Kil-3	67.1,-107.8	28	104	179, 29	8	-7, -107	7	1882	minimum	1885	9
MO	Marathon Dykes	49.0,-86.0	5	9	268, 61	11	29, -146	14	1800	K-Ar	2100	28
MAT	Martin Formation	59.6,-108.6	15	55	323, -29	10	-9, -72	9	1835	K-Ar	1835	40
MCL	McLean P-A	62.1,-111.9	4	16	157, 60	26	15, -94	33				5
MCD	McLeod Bay K-B	62.1,-111.9	9	27	133, 42	10	4, -70	10				5
MBA	Melville Daly Bay A	66.0,-88.0	16	63	196, 55	6	11, -101	7	1622	K-Ar	1700?	14
MBB	Melville Daly Bay B	54.5,-62.0	8	32	55, 72	13	67, -9	19				14
MD!	Molson Dykes 1	55.0,-96.0	4	5	210, 80	15	36, -109	28	1882	U-Pb		28
MD2	Molson Dykes 2	54.0,-97.5	10	50	213, 75	?	28, -114	12	1882	U-Pb	1880	29
MD3	Molson Dykes 3	54.0,-97.5	1	6	143, 42	?	-5, -64	-				29

	Name	Lat, Long	B	N	D, I	α_{95}	Pole	A_{95}	Age	Method	Assn. Age	Ref
NG	Nastapok Group	56.3,-76.3	5	24	-40, -22	5	-39, -9	5	1750	K-Ar	2000	21
NEDD	NE Diabase Dyke	47.8,-79.7	14	63	282, 61	6	37, -146	8	2150?			38
NDA	Nipissing (A) Sill	47.0,-79.0	1	12	29, -45	7	-12, -105	7	2095	K-Ar		31
NDB	Nipissing (B) Sill	47.3,-79.5	11	39	9, -40	5	-19, -88	5	2180	Rb-Sr	2220	32
NDC	Nipissing (C) Sills	46.0,-83.0	8	25	201, 69	27	10, -96	-	2155	Rb-Sr		33
NDD	Nipissing (D) Sills	46.0,-83.0	4	16	358, -43	8	19, -81	8				33
NED	Nipissing (E) Dykes	46.0,-83.0	6	18	271, 69	17	36, -131	-	1995	K-Ar		33
NDF	Nipissing (F) Sills	46.0,-83.0	5	21	346, -45	6	-16, -70	6	2095	K-AR		34
NDG	Nipissing (G) Sills	47.5,-80.7	10	47	27, -42	11	-14, -106	11	2162	Rb-Sr		35
NDH	Nipissing (H) Sills	47.5,-80.7	9	39	339, 73	6	73, -122	10	2219	U-Pb	2220	35
NDI	Nipissing (I) Sills	47.4,-79.7	18	110	259, 82	5	42, -102	11				36
NDJ	Nipissing (J) Sills	47.4,-79.7	3	18	17, -44	6	-15, 96	5				36
NDK	Nipissing (K) Sills	47.4,-79.7	9	45	271, -26	14	-9, 180	12				36
NDL	Nipissing (L) Dyke	46.5,-86.2	3	0	226, 49	7	-3, -122	7				36
NDM	Nipissing (M) Sills	46.9,-80.2	22	94	186, 44	8	-17, -85	8	2165			37
NDN	Nipissing (N) Sills	47.7,-79.7	15	72	268, -59	6	30, -19	8	2100			38
NON	Nonacho Group	61.6,-109.8	12	40	148, 57	14	13, -85	19	2100?		1700	15
OIK	Ottawa Is. Komatiites	59.8,-80.1	10	46	208, 62	4	15, -101	5	1900		1700	16
PH	Peacocks Hill Kil-2	67.1,-107.8	15	24	342, -12	12	-15, -90	10	1882	maximum	1880	9
PA	Pearson CBG-A	62.6,-110.5	12	52	329, -8	10	-19, -77	9			1850	2
PB	Pearson CBG-B	62.6,-110.5	10	43	269, -9	10	27, 177	10				2
PC	Pearson CBG-C	62.6,-110.5	7	23	321, -48	8	6, -77	9				2
PD	Pearson CBG-D	62.6,-110.5	2	8	284, -3	32	-5, -34	17				2
PES	Peninsular Sill CG	66.2,-113.0	7	32	345, -2	8	-22, -97	7	1800	Rb-Sr	1865	6
PRE	Preissac Dykes	49.0,-80.0	12	115	267, 63	4	30, -135	6	2166	U-Pb	2165	42
RGG	RG Andesites & Redbed	?,?					-39, -8	?				21
PN	RGG Persillon N	56.5,-76.3	11	46	160, -33	3	-49, -46	3	1750	K-Ar	2000	21
PS	RGG Persillon S	56.2,-76.3	4	25	122, -55	8	-46, 12	11	1750	K-Ar	2000	21
QIN	RGG Qingaaluk	56.5,-76.3	3	12	135, -41	10	-40, -13	9			2000	21
RGL	Richmond Gulf Lavas	?,?					-20, -18	?				22
SE1	Seton K-G	62.1,-111.9	5	20	151, 74	14	34, -96	30				5
SE2	Seton K-H	62.0,-112.1	19	154	159, 46	7	2, -93	6	1885	U-Pb	1885	6
SE3	Seton K-I	62.0,-112.1	14	99	158, 68	7	25, -97	10				6
	Slave Overprint	63.3,-113.6	8	13	139, 47	9	7, -78	10				19
SRA	Span. River Alk. Rcks	46.5,-81.6	8	21	234, 83	13	37, -96	25	1790	Rb-Sr	1850?	30

	Name	Lat, Long	B	N	D, I	α_{95}	Pole	A_{95}	Age	Method	Assn. Age	Ref
SRD	Span. River Dykes	46.5,-81.6	4	14	56, -29	19	-10, -136	16	1790	Rb-Sr		30
SPD	Sparrow Dykes	61.6,-109.8	10	54	131, 51	7	12, -69	8	1825		1825	15
STA	Stark CBG-H	62.4,-110.7	39	120	214, 15	7	-15, -145	6			1865	4
S1	Sudbury 1 of 10	46.5,-81.5	5	10	258, 61	-	22, -133	-				44
SEA	Sudbury Eruptive A	46.6,-81.4	0	14	320, 70	5	64, -141	9	1800?			43
SEB	Sudbury Eruptive B	46.5,-81.0	0	33	183, 68	2	8, -82	3				43
TAK	Takiyuak CG	66.1,-113.1	17	111	178, 19	10	-13, -111	7			1880?	6
TO1	Tochatwi CBG-E	62.4,-110.7	8	28	210, 11	15	-18, -144	10			1865	3
TO2	Tochatwi CBG-F	62.4,-110.7	13	35	147, 71	9	32, -87	14				3
TO3	Tochatwi CBG-G	62.4,-110.7	5	12	249, 29	13	4, -175	11				3
TUL	Tulemalu Dykes	62.5,-99.0	18	98	136, 36	9	1, -58	7	2270	K-Ar		13
UG	U. Gilbralter K-C	62.1,-111.9	13	60	137, 46	7	6, -74	7				5
WB	Wathaman Batholith	56.9. -103.7	19	156	135, 54	4	9, -67	4	1854	U-Pb		48
WR	Western River Kil-4	65.9,-107.1	22	65	86, 25	9	-14, -19	8	1969	U-Pb		9
X	X Dykes	63.3,-113.8	3	11	132, -5	12	-20, -61	9	2200	est.		19

Notes: A blank indicates lack of information. Initial compilation from Irving *et al*, 1990. **Name** of rock unit sampled, **Lat, Long** of sampling site, **B**, number of sites sampled, **N**, number of samples used, **D**eclination and **I**nclination of magnetization, α_{95}, paleomagnetic **Pole**, A_{95}, **Age** of rock unit, **Method** by which age was determined, **Assigned age** of magnetization, and **Reference** from which the data was obtained. (1) Irving *et al*, 1972b (2) McGlynn and Irving, 1978 (3) Evans and Bingham, 1976 (4) Bingham and Evans, 1976 (5) Reid, 1972 (6) Irving and McGlynn, 1979 (7) Reid *et al*, 1981 (8) Evans *et al*, 1980 (9) Evans and Hoye, 1981 (10) Irving *et al*, 1972a (11) Park *et al*, 1973 (12) Christie *et al*, 1975 (13) Fahrig *et al*, 1984 (14) Park, 1973 (15) McGlynn *et al*, 1974 (16) Buchan and Baragar, 1985 (17) Irving and McGlynn, 1976 (18) Irving *et al*, 1984 (19) McGlynn and Irving, 1975 (20) Schmidt, 1980 (21) Schwarz and Fujiwara, 1981 (22) Schwarz, 1977 (23) Park, 1975 (24) Park, 1977 (25) Seguin, 1976a (26) Seguin, 1976b (27) Seguin, 1977 (28) Fahrig *et al*, 1965 (29) Ermanovics and Fahrig, 1975 (30) Robertson and Watkinson, 1975 (31) Symons, 1967 (32) Symons, 1970 (33) Symons, 1971 (34) Patel and Palmer, 1974 (35) Symons and Londry, 1975 (36) Roy and Lapointe, 1976 (37) Stupavsky and Symons, 1982 (38) Buchan *et al*, 1989 (39) Fujiwara and Schwarz, 1975 (40) Evans and Bingham, 1973 (42) Irving and Naldrett, 1977 (43) Hood, 1961 (44) Larochelle, 1969 (45) Halls, 1986 (46) Symons, 1975a (47) Dunsmore and Symons, 1990 (48) Symons, 1991.

APPENDIX 2. Determination of Quality Index

Name	1	2a	2b	2c	2d	3a	3b	3c	4a	QI
Akaitcho River S-A	xxx	x	-	x	-	x	-	x	x	8
Akaitcho River S-B	xxx	x	-	x	x	x	x	x	x	10
Cape Smith Basalts	xx	-	-	x	o	x	x	x	-	6o
Caribou Lake Gabbro	xxx	x	-	x	x	x	x	x	-	9
Coronation Avg. 1	xx	-	-	x	x?	x	x	x	x	8
Coronation Avg. 2	xx	x	-	x	x	x	x	x	x	9
Dogrib Dykes	x	-	-	x	x	x	x	x	-	6
Douglas Pen. P-B	xx	x	-	x	x	-	x	x	x	8
Douglas Pen. P-C	?	-	-	x	o	x	x	x	-	4
Dubawnt Group 479	?	x	x	x	x	-	x	x	x	7
Dubawnt Group 480	:	x	-	x	x	x	x	x	x	7
Dubawnt Group 481	xxx	x	x	x	x	x	x	x	x	11
Easter Is. Dyke	x	-	-	x	x	x	x	x	x	7
Eskimo Volcanics 1	x	-	x	x	x	x	x	x	x	8
Eskimo Volcanics 2	x	-	x	x	o	x	x	-	-	5o
Et-then Group	x	x	-	x	x	x	x	x	x	8
FF (Kenora-Kabe.) Dykes	xx	-	x	x	x	x	x	x	-	8
Flaherty Volcanics	x	x	x	x	x	x	x	x	x	9
Flin-Flon A4	x	x	-	x	o	x	x	x	-	6o
Flin-Flon B	x	x	-	x	o?	-	x	x	-	5o
Haig Intusives	x	-	x	x	x	x	x	x	x	8
Hur. Gowg. 1038	xx	-	x	x	x	x	x	x	-	8
Hur. Gowg. 546	xx	-	-	x	x	x	-	x	x	7
Hur. Gowg. Firstbrook	xxx	-	-	x	x	x	x	x	x	10
Indin Dykes	x	x	x	x	x	x	x	x	-	8
Kaminak Meta Dykes	?	-	-	x	o	x	x	x	-	4o
kazan Dykes	x	-	-	x	?	-	x	x	-	4
LT Castignon Complex	xxx	-	-	x	o	x	x	-	-	6o
LT Diabase Dykes	?	-	-	x	?	x	x	-	-	3
LT Menihek (A)	x	x	-	x	o	x	x	x	-	6o
LT Montagnais Grp	?	-	-	x	?	x	-	x	x	4
LT Seward B	?	-	-	x	o	-	x	-	-	2o
LT Sokoman IF 1	?	x	-	x	x	-	-	x	x	5
LT Sokoman IF 1	?	-	-	x	o	x	x	x	-	4o
Lynn Lake- FL gabbros	xx	-	x	x	o	x	x	x		7o
Mara Kil-3	xxx	x	-	x	x	x	x	x	x	10
Marathon Dykes	x	-	-	x	x	x	x	-	-	5
Martin Formation	xxx	x	-	x	x	x	x	x	x	10
McLean P-A	xx	-	-	x	?o	-	x	-	x	5o
McLeod Bay K-B	xx	x	-	x	x	x	x	x	x	9
Melville Daly Bay A	x	-	-	x	o	x	x	x	-	5o
Melville Daly Bay B	?	-	-	x	o	x	x	x	-	4o
Molson Dykes 2	xxx	x	-	x	x	-	x	x	-	8
Nastapok Group	x	-	-	x	x	x	x	-	x	6
NE Diabase Dyke	xxx	-	x	x	x	x	x	x	-	9
Nipissing (B) Sill	xx	-	-	x	?	x	x	x	-	6

Name	1a	2a	2b	2c	2d	3a	3b	3c	4a	QI
Nipissing (D) Sills	xx	-	-	x	?	x	x	-	-	5
Nipissing (E) Dykes	xx	-	-	x	?	-	x	-	-	4
Nipissing (F) Sills	xx	-	-	x	?	x	x	-	-	5
Nipissing (G) Sills	xx	x	-	x	?	x	x	x	-	7
Nipissing (H) Sills	xxx	-	-	x	x	x	x	x	-	8
Nipissing (I) Sills	?	-	x	x	?	x	x	x	-	5
Nipissing (J) Sills	?	-	-	x	o	x	x	-	-	3o
Nipissing (K) Sills	?	-	-	x	o	x	x	x	-	4o
Nipissing (M) Sills	xx	x	x	x	x	x	x	x	-	9
Nipissing (N) Sills	xx	-	x	x	x	x	x	x	-	8
Nonacho Group	?x	-	-	x	o	x	x	x	-	5o
Ottawa Is. Komatiites	xx	-	-	x	o	x	x	x	-	6o
Peacocks Hill Kil-2	xxx	x	-	x	x	x	x	-	x	9
Pearson CBG-A	xx	-	-	x	x	x	x	x	-	7
Peninsular Sill CG	xx	x	-	x	x	x	x	x	x	9
Preissac Dykes	xxx	-	x	x	x	x	x	x	-	9
RGG Persillon N	x	-	-	x	x	x	x	x	x	7
RGG Persillon S	x	-	-	x	x	x	x	x	x	7
Seton K-G	xxx	-	x	x	-	x	x	-	-	7
Seton K-H	xxx	-	-	x	x	x	x	x	x	9
Span. River Alk. Rcks	xx?	-	-	x	x	x	-	-	-	5
Sparrow Dykes	xxx	x	x	x	x	x	x	x	-	11
Stark CBG-H	xx	x	-	x	x	x	x	x	x	9
Sudbury Eruptive B	xx	-	-	x?	x	x	x	x	-	7
Takiyuak CG	xx	x	-	x	x	x	x	x	x	9
Tochatwi CBG-E	xx	x	x	x	x	x	x	x	x	10
Tulemalu Dykes	x	x	-	x	x	x	x	x	-	7
U. Gilbralter K-C	xx	-	-	x	x	x	x	x	x	8
Wathaman Batholith	xxx	-	x	x	x	x	x	x	?	9
Western River Kil-4	xxx	x	-	x	x	x	x	x	x	10

Notes: The criteria are fully described in section **7.1.2.** ***(1)*** Age of the rock; xxx indicates the age is known to better than +/- 20 Ma, xx to +/- 50 Ma, x +/- 100 Ma ***(2)*** Magnetization characteristics **a.** presence of reversals, **b**. execution of a field test, **c**. execution of demagnetization, **d**. non-similarity to a younger magnetization; ***(3)*** Quality and Precision **a.** $\alpha_{95} < 16°$, **b.** k>10, **c**. n (number of specimens) > 25; ***(4)*** Known paleohorizontal. The quality index (out of 11) is in the last column; o in the same column indicates a probable Coronation overprint. Poles with a QI ≥6 pass the index.

VITA

Surname: Cioppa	Given Names: Maria Therese
Place of Birth: Bethel, Alaska, U.S.A.	Date of Birth: March 5, 1968

Educational Institutions Attended:

University of Victoria	1990 to 1992
Carleton University	1986 to 1990

Degrees Awarded:

B.Sc. (Honours)	1990

Honours and Awards:

President's Scholarship	1986 to 1989
J.P Bickell Foundation Scholarship	1987 to 1990
Ottawa Section of the Petroleum Society of CIM	1988 to 1989
Hyman Soloway Scholarship	1989 to 1990
Chevron Canada Resources Ltd. Scholarship in Geology	1989 to 1990
CSPG Undergraduate Student Award	1989 to 1990
Senate Medal for Outstanding Academic Achievement	1990

Publications:

Cioppa, M.T., Irving, E., Karlstrom, E.T., and Barendregt, R. 1991. Paleomagnetism of three Quaternary Sequences, Southern Alberta and Northern Montana. Canadian Geophysical Union Program and Abstracts, v. 17, #49.

Thomas, M.D., Tanczyk, E. I., Cioppa, M., and O'Dowd, D.V. 1991. Ground magnetic and rock magnetism studies near the Appalachian Dunnage-Gander terrane boundary, northern New Brunswick. Geological Survey of Canada, Current Research Part D, Paper 91-1D: 169-178.

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Author [redacted]

Maria Therese Cioppa

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