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A PALEOINTENSITY METHOD TO STUDY THE CAUSE OF REVERSAL ASYMMETRY IN LATE PRECAMBRIAN KEWEENAWAN ROCKS

by

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Abstract

A new intensity method is presented for calculating whether the polarity asymmetry in Keweenawan reversals (1200–1000Ma) of the Lake Superior rocks is caused by unremovable secondary component or by apparent polar wander (apw). Three types of theoretical intensity ratios (NRM, relative and absolute) of reversed and normal polarity rocks are calculated for both interpretation models and these ratios are compared with those observed in Keweenawan rocks.

All the three intensity ratios reveal a definite conflict with the secondary component model. On the other hand, the observed intensity ratios are consistent with the geocentric dipole field model and may suggest that the asymmetry represents apparent polar wandering, *i.e.* motion of the North American continent relative to the pole during the reversal crossing (R →N). However, a third model involving a long-term standing non-dipole field component causing the polarity asymmetry cannot be ruled out by intensity and inclination data.

1. *Introduction*

A general procedure in calculating the paleomagnetic poles for rocks units, where both normal (N) and reversed (R) remanent magnetization directions (NRM) are present, is to invert either of the directions by 180° and then to average all directions in order to obtain an overall mean direction. The basic assumption in such calculations is that the two sets of data are caused by the axial geocentric dipole field (AGDF) and that they represent, geologically speaking, the same time. If this is the case, the reversal will be symmetric (180°) (Fig. 1a).

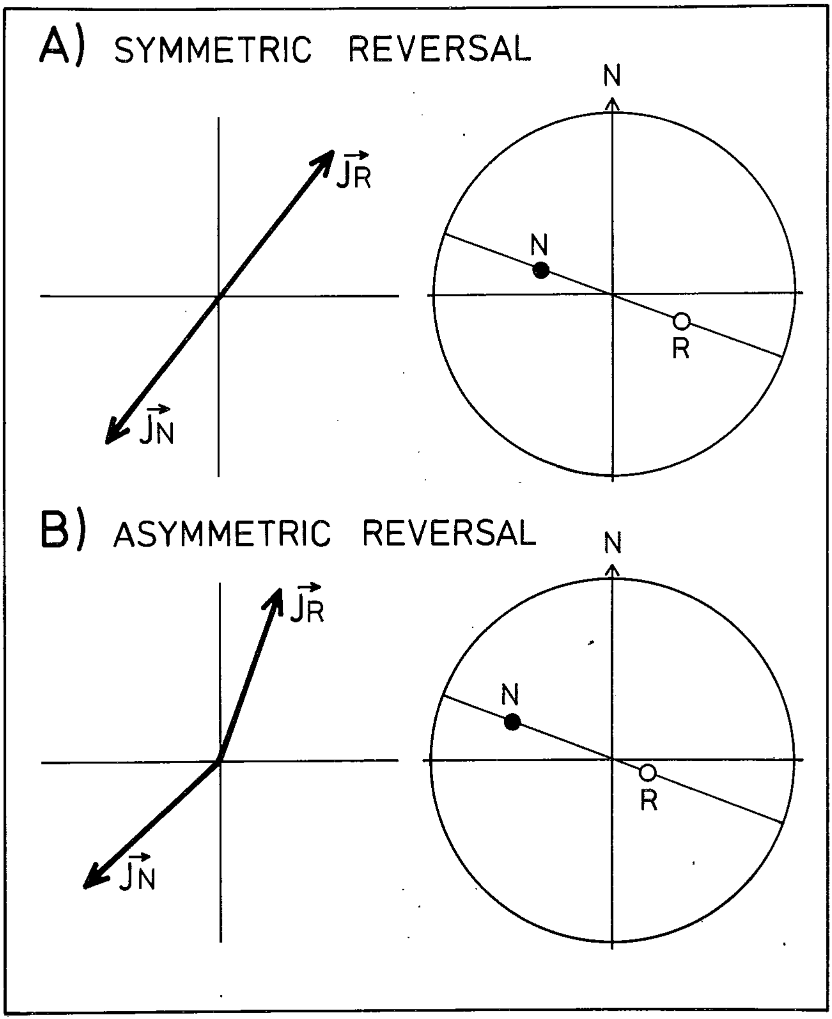

Fig. 1. (A) Symmetric (180°) reversal: *Left:* vector diagram of the remanences in the plane (D_N = 293°/D_R = 113°) containing normal and reversed remanences. *Right:* remanence directions in an equal area stereo projection with open (closed) symbol denoting reversed (normal) direction. (B) asymmetric (not 180°) reversal.

Normal and reversed remanence vectors, however, often differ from the 180° symmetry (Fig. 1b), in which case the averaging procedure would be invalid. For example, the polarities of the Late Tertiary Mull dykes of Scotland (ADE-HALL *et al.*, 1970), of the Late Precambrian Gardar lavas in Greenland (PIPER, 1977), and of the Middle Proterozoic dykes in Finland (PESONEN and NEUVONEN, 1981)

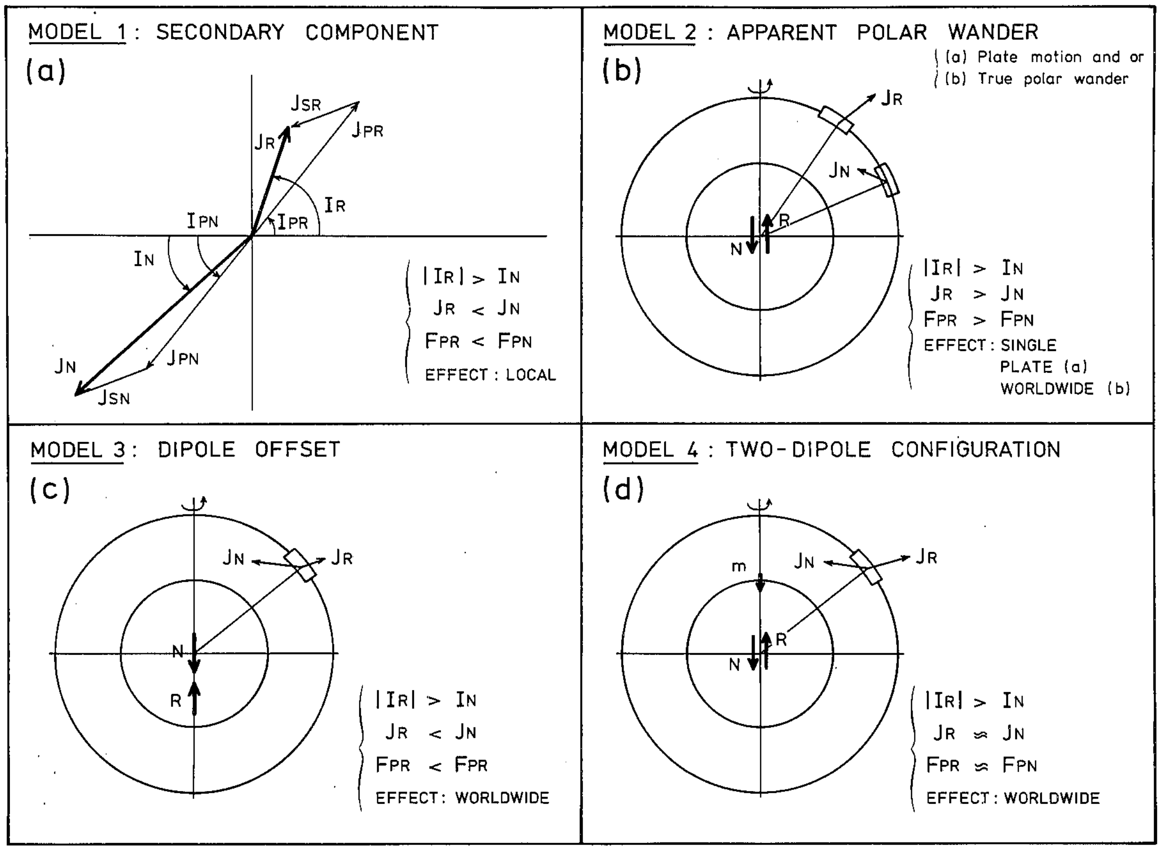

Fig. 2. Four models to explain the Keweenawan asymmetric reversals. (a) secondary component model, (b) apparent polar wander model, (c) single dipole-offset model and (d) two-dipole model. Also shown are the inclinational asymmetries ($/I_R/ > I_N$) observed in Lake Superior region and the sense of the intensity ratio ($J_R >, <, = J_N$) predicted by each model. The areal (colatitudinal) extensions of the asymmetries are also indicated.

are asymmetric. In fact, as shown by WILSON (1972) and MERRIL & MCELHINNY (1979), there is a significant global asymmetry in the pole positions of reversed and normal rocks of Late Tertiary age.

A pronounced asymmetry is present in the Late Precambrian Keweenawan (1200–1000Ma) reversal (R→N) of the Lake Superior region in North America (*e.g.* DUBOIS, 1962; PALMER, 1970; PESONEN and HALLS, 1979). The inclination of the reversely magnetized rocks ($I_R \approx -67°$) is consistently steeper (upward) than the normal (downward) one ($I_N \approx 42°$) (Fig. 1b; *e.g.* PESONEN, 1979). This asymmetry may be caused by (i) secondary overprint (Model 1), (ii) apparent polar wandering (Model 2), (iii) main dipole offset (Model 3) or (iv) persistent non-dipole geomagnetic field component (Model 4). These models are schematically shown in Fig. 2 which also illustrates the inclinational and intensity asymmetries and their areal extends (*e.g.* PALMER *et al.*, 1981; PESONEN and NEVANLINNA, 1981; HALLS and PESONEN, 1982).

The purpose of this paper is to present an intensity method for distinguishing between models 1 and 2 (see also KITAZAWA and KOBAYASHI, 1968; HUBBARD, 1971). In a subsequent papers (PESONEN and NEVANLINNA, 1981; NEVANLINNA and PESONEN, 1983), we describe another intensity method to test the applicability of models 3 and 4 in explaining the Keweenawan reversal asymmetry.

2. *Keweenawan asymmetric reversal*

2.1. Paleodirections

The Middle/Lower Keweenawan (~1200–1000Ma) paleomagnetic data from the Lake Superior region are shown in Table 1. Only the data, that contain both normal and reversed results are included (see HALLS and PESONEN, 1982). The inclinational asymmetry is 30° on the average, while the corresponding declinational asymmetry is less than 5 degrees. The major problem in these reversals arises from the observations (*e.g.* PALMER, 1970; ROBERTSON, 1973; PESONEN, 1979) that neither alternating field nor thermal demagnetization studies on Middle/Lower Keweenawan rocks (except some conglomerate pebbles; see PALMER *et al.*, 1981) show any indications of a secondary component which could explain the polarity asymmetry. Therefore, the secondary overprint (if present at all) must be a so called »unremovable» one (PALMER, 1975). This means that the coercivity and blocking temperature spectra of the secondary and primary remanences must be exactly identical.

The fact that thermal demagnetization method is not capable to separate the two components implies that the secondary overprint is a chemical remanent magnetization (CRM) (PESONEN, 1978; PALMER *et al.*, 1981). In the further calculations

Table 1. Summary of Keweenawan paleodirections and intensity data.

	B/N	$\bar{D}$	$\bar{I}$	$\overline{\Delta D}$	$\overline{\Delta I}$	*NRM*	ARM^b	χ^b
				Group 1: Igneous rocks[a]				
Reversed polarity (*R*)	7/166	115	−67			3824±2680	2698±3605	1500
				1	25			
Normal polarity (*N*)	7/343	294	42			2755±1711	1307±1502	650
Ratio of the means (*R/N*)						1.45	1.58	2.3
				Group 2: Baked rocks[b]				
Reversed polarity (*R*)	1/9	116	−69			10.8	16.0	15
				5	38			
Normal polarity (*N*)	1/5	291	31[c]			9.2	14.0	21
Ratio of the means (*R/N*)						1.17	1.14	0.7

B/N number of studies/total numbers of sites
$\bar{D}, \bar{I}$ mean declination, inclination (in degrees)
$\overline{\Delta D}$ mean declinational asymmetry ($/D_R + 180°/ - D_N$)
$\overline{\Delta I}$ mean inclinational asymmetry (see NEVANLINNA and PESONEN, 1983)
NRM mean intensity of natural remanent magnetization (mAm^{-1})
ARM^b mean intensity of anhysteretic remanence (mAm^{-1})
χ^b mean volume susceptibility (10^{-5} SI)
a data from all over the Lake Superior region
b data available only from Thunder Bay intrusives and baked rocks
c Note: shallow normal inclinations in baked rocks are not the property of baked rocks in general but rather a property of Sibley Peninsula dykes and baked rocks. (see PESONEN, 1978 for details)

we assume that the direction of this chemical remanence is $D_S = 293°$, $I_S = 25°$ which is the average overprint direction isolated from the Copper Harbor and Mamainse Point conglomerates (PALMER *et al.*, 1981). The intensity method described in the following will be used to test the presence of this hypothetical secondary component in Middle/Lower Keweenawan rocks. The test will be made for two different rock groups representing different amount of asymmetries (Table 1). The effect of the variation of the direction of the secondary overprint to the intensity tests will be also investigated. Finally, the possibility to apply the method to a general asymmetric reversal will be discussed.

2.2. Magnetic material content

The new method involves comparisons of the NRM intensitites of reversed and normal rocks. However, such a comparison is not very meaningful unless one knows the contents of the magnetic material in the rocks, because the NRM intensities depend on it (*e.g.* BECK, 1970; PESONEN, 1973).

On the basis of magnetic contents, the Keweenawan rocks can be divided into two groups (hereafter called groups 1 and 2). The first group comprises of *igneous rocks* representing the Lake Superior area as a whole. The second group comprises of *baked rocks* from Thunder Bay area in the northern part of the lake. Table 1 summarizes the paleomagnetic and rock magnetic data for these groups. Here we note that the subdivision of the rocks into two groups is made in an order to show that the method applies to all rock types and to any area around the Lake Superior where Keweenawan rocks are exposed.

Weak field susceptibility (χ) and intensity of anhysteretic remanent magnetization (ARM), reveal that the ratios of the magnetic contents of reversed and normal rocks is about 2.0 in group 1 and 1.0 in group 2 (Table 1). Therefore, the ratios (J_{PR}/J_{PN}) of the the primary intensities (*i.e.* before the impartment of the hypothetical secondary overprint) of reversed and normal rocks are assumed to be 2.0 and 1.0, respectively. In further calculations we assume that the subsequent growth of the hypothetical secondary component depends on the similar fashion on the content of the magnetic material. Thus the ratio of the intensities of the secondary components (J_{SR}/J_{SN}) will be also 2.0 (group 1) and 1.0 (group 2).

2.3. Laboratory intensities

The observed NRM intensities (Table 1) are based on more than 1000 NRM determinations of various Middle/Lower Keweenawan rocks of both polarities (PESONEN and HALLS, 1979; PESONEN, 1979). The relative paleointensity data, here measured by the Koenigsberger Q-value and by the NRM/ARM values (*e.g.* LEVI and BANERJEE, 1975; PESONEN, 1978) are based on about 500 determinations of igneous and baked rocks around the Thunder Bay region.

The 54 absolute Thellier paleointensity values were obtained from the same rocks types as the relative paleointensities (PESONEN & HALLS, 1983). A detailed discussion of the intensity determinations, the laboratory methods and the data statistics can be found in PESONEN (1978) and PESONEN and HALLS (1983).

3. *The intensity method*

3.1. Geometry of the reversal

The geometries of the Middle/Lower Keweenawan reversal asymmetries are shown in Fig. 3. In both groups the three vectors (normal, reversed, secondary) lie approximately on the same plane (293°/113°). The following geometrical relationships can be derived:

$$\frac{J_R}{J_{PR}} = \frac{\sin(I_{PR} - I_{SR})}{\sin(I_R - I_{SR})} \tag{1a}$$

$$\frac{J_N}{J_{PR}} = \frac{\sin(I_{PN} - I_{SN})}{\sin(I_N - I_{SN})} \tag{1b}$$

$$\frac{J_{SR}}{J_{PR}} = \frac{\sin(I_R - I_{PR})}{\sin(I_R - I_{SR})} \tag{1c}$$

$$\frac{J_{SN}}{J_{PR}} = \frac{\sin(I_{PN} - I_N)}{\sin(I_N - I_{SN})} \tag{1d}$$

Where I_{PR} $(= I_{PN})$ denotes the inclinations of the primary reversed $(\vec{J}_{PR})$ and normal $(\vec{J}_{PN})$ remanence vectors. I_R and I_N are the inclinations of the observed remanences $(\vec{J}_R, \vec{J}_N)$, and I_{SR} $(= I_{SN})$ is the inclination of the hypothetical secondary component $(\vec{J}_{SR} = \vec{J}_{SN})$ (Fig. 3). For convenience, all the inclinations are given in absolute values and all the remanence intensities are normalized with respect to $/\vec{J}_{PR}/$. In order to simplify the numerical results we choose for convenience a value 1.0 for $/\vec{J}_{PR}/$ in both groups. On the basis of the measured susceptibility and ARM intensity data the corresponding primary normal remanence $/\vec{J}_{PN}/$ will be 0.5 in group 1 and 1.0 in group 2 (Tables 1–2; Fig. 3). Note that in »natural» rocks the true values of the remanence intensities of baked rocks (group 2) would be more than two orders of magnitude lower than those of igneous rocks (group 1) due their much lower magnetic contents (Table 1). Because we are interested only in intensity *ratios* of reversed and normal polarity rocks, the value 1.0 for the reversed primary intensity in both groups is a convenient choise.

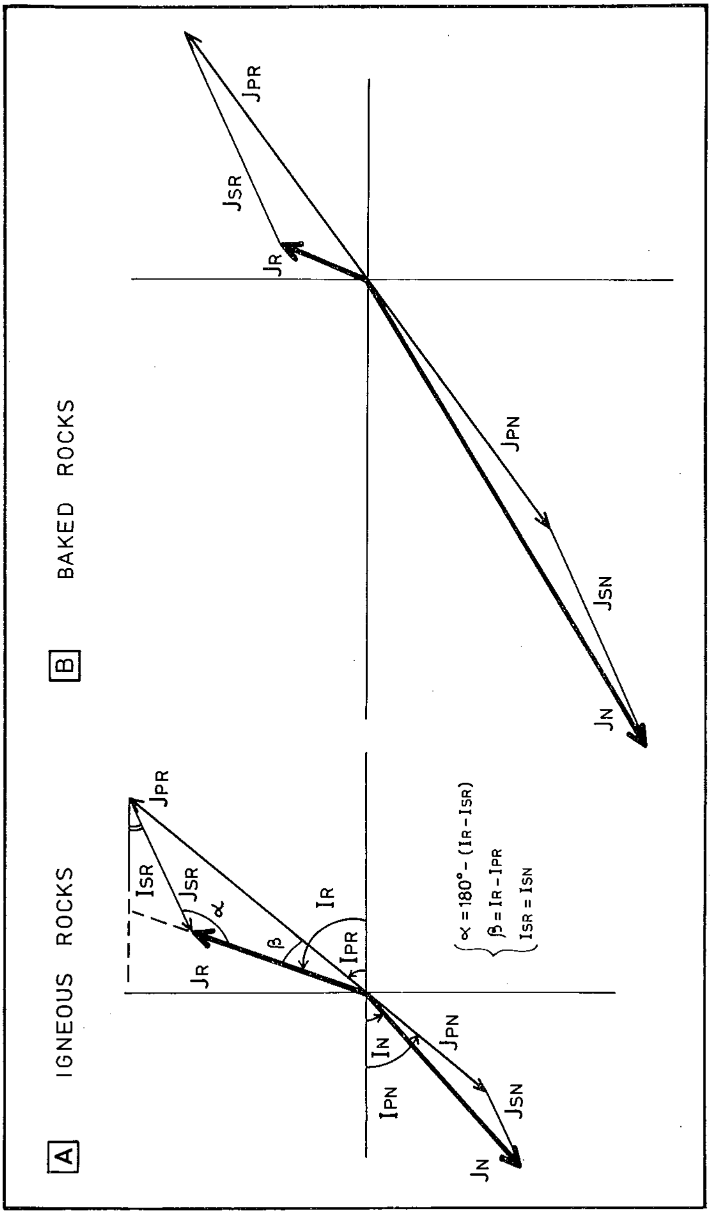

Fig. 3. Vector diagram of the geometries of the Keweenawan reversals. (A) igneous rocks (group 1) of Lake Superior average data, (B) baked rocks (group 2) of the Thunder Bay region. In both groups, the reversed primary remanence has a value 1.0. In (A), the normal primary remanence is 0.5, in (B) 1.0. For other symbols see text.

4. *Results*

4.1. NRM intensity ratios

Substituting the average Keweenawan inclinations ($I_R = -67°$, $I_N = 42°$, $I_{SN} = I_{SR} = 25°$) into equation 1, the primary inclination (I_P) in group 1 was found to be 49.1° (Fig. 3). A similar value has been found previously by PALMER (1970) and HUBBARD (1971) with a slightly different geometrical method. In group 1, the secondary overprint would decrease the reversed NRM intensity from 1.0 to 0.59 and increase the normal intensity from 0.5 to 0.73 (Table 2). The corresponding intensities of the secondary components would be 0.49 (reversed) and 0.25 (normal). Thus, if a hidden »unremovable» secondary component is present in Keweenawan igneous rocks, we should observe about 25 % lower NRM intensities for the reversed rocks than for the normal ones. Table 3 shows that the observed reversed remanences (NRM's) are about 50 % higher than the normal ones.

In baked rocks the inclinations ($I_R = -69°$, $I_N = 31°$) yield a value of 38° for the primary inclination (Fig. 3b). Due to the secondary component, the reversed NRM intensity decreases from 1.0 to 0.27, while the normal one increases from 1.0 to 1.78 (Table 2). The theoretical intensity ratio (J_R/J_N) is therefore 0.15 which is about eight times lower than the observed ratio (=1.17) (Table 3). The NRM intensities in all Keweenawan rock types are therefore in direct conflict with the secondary overprint model as an explanation for the polarity asymmetry. The scatter of NRM intensities (Table 1) is, however, very large and it is of crucial importance to study whether the more sophisticated intensity studies support this conclusion.

4.2. Relative paleointensity ratios

The relative paleointensity ratios, such as the Koenigsberger Q-ratios and NRM/ARM values of Keweenawan rocks can be also used to test the credibility of the secondary overprinting model (see *e.g.* PESONEN, 1978). The main advantage of using relative paleointensity data in testing the model is that the direct (linear) contribution of the amount of magnetic material on intensities will be largely eliminated if the measured remanences are first normalized with respect to the magnetic content. The normalizing can be done for example by the weak field susceptibility (χ), which leads to the Q-value ($J/\chi F$) or by the ARM-value, which leads to a »relative» paleointensity (RF).

The Q-values and NRM/ARM ratios calculated in the secondary component model and those observed in Keweenawan rocks are summarized in Table 3.

In group 1 the secondary component model predicts a value of 0.41 for Q and

RF ratios of reversed and normal rocks. The observed ratios are 1.25 for the *Q*-values and 1.35 for the NRM/ARM-data indicating that also these intensity ratios are in conflict with the overprint idea.

However, the NRM values as well as the relative paleointensities are highly sensitive for variation by such factors as the grain size of the opaques, their blocking temperature spectra and viscous contaminations (*e.g.* LEVI, 1977; THELLIER and THELLIER, 1959; PESONEN, 1978). Therefore, a better approach to study the feasibility of the »unremovable» secondary overprint in Keweenawan rocks is to calculate theoretical Thellier paleointensity ratios and to compare those with the observed Thellier data (PESONEN, 1978). The reason behind this is the fact that the Thellier paleointensities do not depend of the magnetic content (interactions neglected here; see SUGIURA, 1979), of the grain size and of the viscous effects as strongly as do the relative paleointensity data (LEVI, 1977; SUGIURA, 1979).

The main drawback of Thellier procedure is the small amount of determinations (54) so that the resolution to distinguish between the models by Thellier paleointensity data is more limited than in the case of NRM or relative paleointensity data (more than 500 determinations available).

5. *Thellier paleointensity ratios*

5.1. Theoretical Arai-plots

Because the unremovable secondary component model implies that the blocking temperature spectra of the primary and secondary remanences are nearly identical, it follows that the shapes of the normalized thermal demagnetization curves of all the remanences must be similar (PESONEN, 1978). Thus, it is a simply matter to construct the expected paleointensity plots (the so-called Arai-plots; NAGATA *et al.*, 1963) for the normal and reversed rocks in the unremovable secondary component model. The paleointensity ratios can then be directly calculated from the slopes of the Arai-lines (*e.g.* PESONEN, 1978). The credibility of the hypothetical secondary overprint model can be tested by comparing the model paleointensity ratios with those observed in rocks.

For convenience, we arbitraly choose a smooth thermal demagnetization curve to represent a typical (observed) Keweenawan rock sample (Fig. 4). This curve is divided into thirteen demagnetization steps with 50 °C intervals (Table 2). The calculations that follows do not depend on these choises (PESONEN, 1978).

To construct the Arai-plots for normal and reversed remanences, two sets of data are needed. The »NRM-remaining» values (first set) after each demagnetization

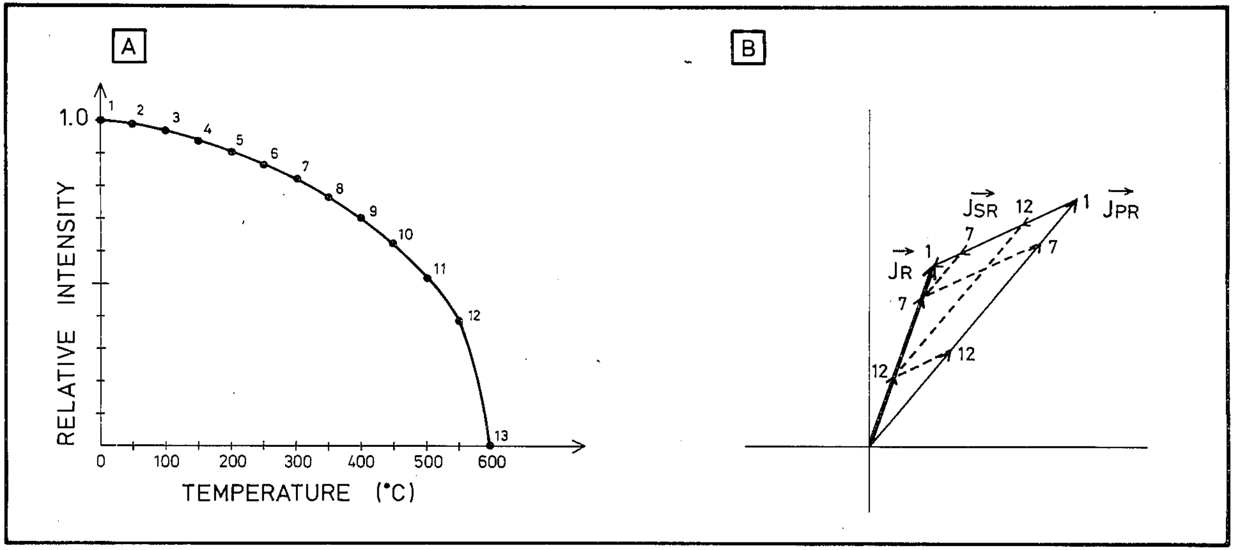

Fig. 4. (A) Hypothetical stepwise thermal demagnetization curve for a typical Keweenawan rock in the case that an »unremovable» secondary component is superimposed into the primary component. (B) vector diagram of stepwise demagnetization treatment of vector (A), where steps »1», »7» and »12» are shown by broken lines. For other symbols, see Fig. 3 and text.

Table 2. Theoretical Thellier paleointensities.

i	T	J_{PR}	J_{PN}	J_R	J_N	J_R/J_N	J_{SR}	J_{SN}	$PTRM_R$	$PTRM_N$	F_{PR}	F_{PN}	F_{PR}/F_{PN}
						(A) Igneous rocks ($J_{PR} = 2J_{PN} = 1.0$)							
1	0	1.000	0.50	0.59	0.73	0.81	0.49	0.25	0.00	0.00	0.40	0.98	0.41
2	50	0.98	0.49	0.59	0.72		0.48	0.24	0.02	0.01			
3	100	0.96	0.48	0.57	0.71		0.47	0.24	0.05	0.03			
4	150	0.94	0.47	0.56	0.69		0.46	0.23	0.09	0.05			
5	200	0.90	0.45	0.54	0.66		0.44	0.22	0.14	0.07			
6	250	0.87	0.43	0.52	0.63		0.42	0.21	0.20	0.10			
7	300	0.83	0.41	0.49	0.60		0.41	0.20	0.26	0.13			
8	350	0.77	0.38	0.46	0.56		0.38	0.19	0.34	0.17			
9	400	0.70	0.35	0.42	0.51		0.35	0.17	0.44	0.22			
10	450	0.63	0.32	0.37	0.46		0.31	0.16	0.55	0.28			
11	500	0.52	0.26	0.31	0.38		0.26	0.13	0.72	0.36			
12	550	0.39	0.20	0.23	0.29		0.19	0.10	0.91	0.46			
13	600	0.00	0.00	0.00	0.00		0.00	0.00	0.49	0.75			
						(B) Baked rocks ($J_{PR} = J_{PN} = 1.0$)							
1	0	1.00	1.00	0.27	1.78	0.15	0.79	0.79	0.00	0.00	0.15	1.00	0.15
2	50	0.98	0.98	0.26	1.75		0.78	0.78	0.02	0.03			
3	100	0.96	0.96	0.26	1.71		0.76	0.76	0.05	0.06			
4	150	0.94	0.94	0.25	1.67		0.74	0.74	0.09	0.11			
5	200	0.90	0.90	0.24	1.61		0.71	0.71	0.14	0.17			
6	250	0.87	0.87	0.23	1.54		0.69	0.69	0.20	0.24			
7	300	0.83	0.83	0.22	1.47		0.65	0.65	0.26	0.31			
8	350	0.77	0.77	0.21	1.37		0.61	0.61	0.34	0.41			
9	400	0.70	0.70	0.19	1.25		0.56	0.56	0.44	0.53			
10	450	0.63	0.63	0.17	1.11		0.50	0.50	0.55	0.66			
11	500	0.52	0.52	0.14	0.92		0.41	0.41	0.72	0.86			
12	550	0.39	0.39	0.10	0.69		0.31	0.31	0.91	1.09			
13	600	0.00	0.00	0.00	0.00		0.00	0.00	1.49	1.78			

i step number
T temperature (°C)
J_{PR}, J_{PN} primary remanence intensities
J_R, J_N resultant remanence intensities
J_{SR}, J_{SN} intensities of secondary components
$PTRM_{R,N}$ acquired thermoremanences (see text)
F_{PR}, F_{PN} Thellier paleointensities (F_{PR} = /Slope of Arai-line/ x F_L, where F_L is the laboratory field (= 1.0))

All remanences relative to $J_{PR} = 1.0$ (arbitrary units) (see PESONEN, 1978 for details) step can be read directly from the normalized demagnetization curve for the observed component (Table 2). The corresponding demagnetization values for the primary and secondary overprint components can then be calculated using Eqs. 1a–1d. The results are summarized in Table 2.

The »TRM-acquired» data (second set) consists of partial thermoremanent magnetizations (*pTRM*'s) acquired by the rock in laboratory heatings under the field F_L. These *pTRM*'s can be split into two components as follows:

$$pTRM = pTRM_1 + pTRM_2 \quad (2)$$

where $pTRM_1$ is the contribution of the demagnetized primary NRM component described earlier and which is be transformed into *pTRM* by the laboratory field F_L during cooling. $PTRM_2$ is the contribution of the demagnetized secondary component which similarly is transformed into a *pTRM* (PESONEN, 1978; ROY, 1977). Eq. 2 can be written as a scalar equation, because the $\overrightarrow{pTRM}_1$ and $\overrightarrow{pTRM}_2$ will be aligned along the laboratory field F_L.

The total *pTRM* after each demagnetization step (i) can now be written:

$$pTRM_R(i) = \lambda[J_{PR}(i-1) - J_{PR}(i)] + \alpha\,[J_{SR}(i-1) - J_{SR}(i)] + \\ + pTRM_R(i-1) \quad (3)$$

where i is the step number (i = 2, 3.....13), and $pTRM_R$ (i=1)=0. λ is the ratio of *CRM/TRM* for the particular mineral in question (ROY, 1977), and α is the ratio of the primary and laboratory field intensities (F_p/F_L). The other symbols have been explained previously. In the case of normal polarity, the index R will be replaced by N.

To obtain numerical values, the constants λ and α must be known. Experimental (KELLOGG *et al.*, 1970) and theoretical (STACEY and BANERJEE, 1974) studies suggests λ to be equal or slightly less than one. PESONEN (1978) has shown that if λ and α have values different from one, the endpoints »B» on the *pTRM* axis in the theoretical lines (Fig. 4) will go either towards the origin from the point (where $\lambda = \alpha = 1$) or away from it. In the first case the slopes of the theoretical Arai-lines will go relatively steeper and in the latter case shallower. However, the *ratio* of the slopes remains constant whatever value is assigned for λ or α. Because the theoretical paleointensity ratio is obtained from the ratio of the slopes of the Arai-lines, we can assign a value of 1.0 for both λ and α. The Eq. 3 reduces now into simple scalar subtractions of the demagnetized remanence components, and the ratio of the theoretical paleointensities can be easily calculated.

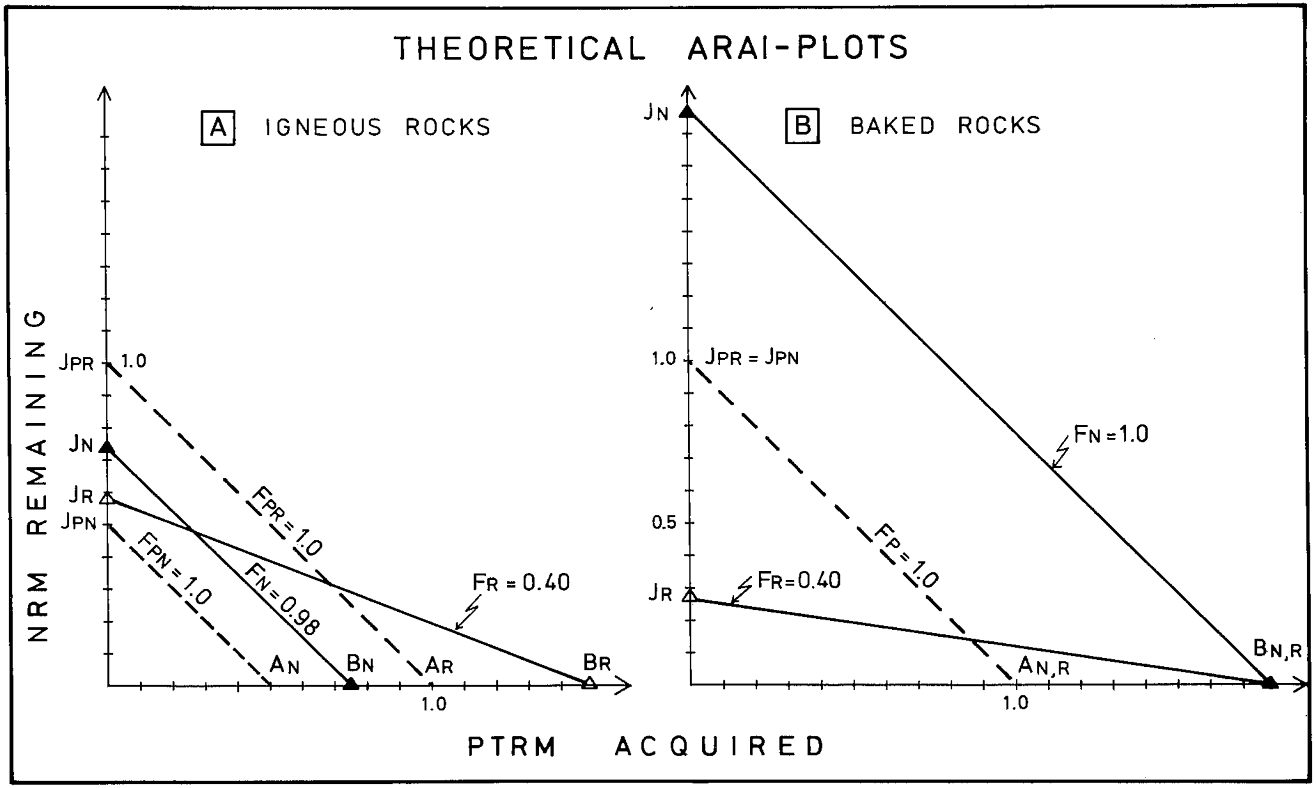

Fig. 5. Construction of theoretical Arai-paleointensity plots in group 1 (A) and group 2 (B) in the case that an »unremovable» secondary component is hidden in the rocks. The predicted Arai-lines for reversed (normal) rocks are shown as lines $J_R - B_R$ and $J_N - B_N$, respectively, where the endpoints B_R, B_N depend on the parameters λ (= CRM/TRM) and α (= F_P/F_L) (see text). In (A) and (B) is illustrated the case when $\lambda = \alpha = 1.0$. Also shown are the primary Arai-lines (*i.e.* lines $J_{PR}(J_{PN}) - A_R(A_N)$) with an assumed primary paleointensity $F_P = 1.0$, although these lines would go unnocticed if the secondary component were real. Vertical axis shows NRM remaining data, and horizontal axis shows the *pTRM* acquired data. Open (closed) symbols for reversed (normal) polarity data. All intensity units are arbitiarily adjusted so that $J_{PR} = 1.0$. Paleointensities (F_R, F_N) can be calculated from the slopes /*s*/ of the Arai-lines ($F_R = /s/_R {}^{\star} F_L$) where F_L (= 1) is the laboratory field in arbitrary units.

Table 3. Comparison of observed Keweenawan intensity ratios with those predicted by the secondary component and apparent polar wander models.

Model	*NRM* intensity	Relative paleointensity		Absolute paleo-intensity
	NRM_R/NRM_N	Q_R/Q_N	RF_R/RF_N	F_{PR}/F_{PN}
	(1) Igneous rocks			
Secondary component	0.81	0.41	0.41	0.41
Apparent polar wander	2.70	1.35	1.35	1.35
Observed data	1.50	1.25	1.35	1.22
	(2) Baked rocks			
Secondary component	0.15	0.15	0.15	0.15
Apparent polar wander	1.52	1.52	1.52	1.52
Observed data	1.17	1.0–9.75[a]	1.41	1.72

NRM_R/NRM_N ratio of natural remanent magnetizations (R = reversed, N = normal)
Q_R/Q_N ratio of Koenigsberger-values [= $(J_R/\chi_R F_R)/(J_N/\chi_N F_N)$]
RF_R/RF_N ratio of relative paleointensities [= $(NRM_R/ARM_R)/(NRM_N/ARM_N)$] after 20 mT AF demagnetization
F_{PR}/F_{PN} ratio of Thellier paleointensities
a owing to a large scatter, only the range of values is given (see PESONEN, 1978 for details)

Numerical examples of the data are shown in Table 2. Theoretical Arai-lines for model rocks are shown in Fig. 5. In group 1 the ratio of the theoretical paleointensities (F_R/F_N) would be 0.41 if a secondary component is present in the rocks. This is about three times lower than the observed Thellier paleointensity ratio (= 1.22) (Table 3). In group 2, the secondary component model predicts a paleointensity ratio of about 0.15, which is roughly ten times lower than the observed Thellier ratio (= 1.72) (see Table 3).

5.2. Direction of the secondary component

In the previous calculations it was assumed that the hypothetical secondary component has a direction similar to those observed in Middle Keweenawan conglomerates (Is = 25°, PALMER *et al.*, 1981). Fig. 6 shows the effect on predicted intensity ratios if Is varies from +30° to −30° covering the whole range of values reported for Keweenawan overprints (see HALLS & PESONEN, 1982). Note that in order to keep other variables (*i.e.* observed inclinations) constant when Is varies, the primary inclination (Io) must be always solved at

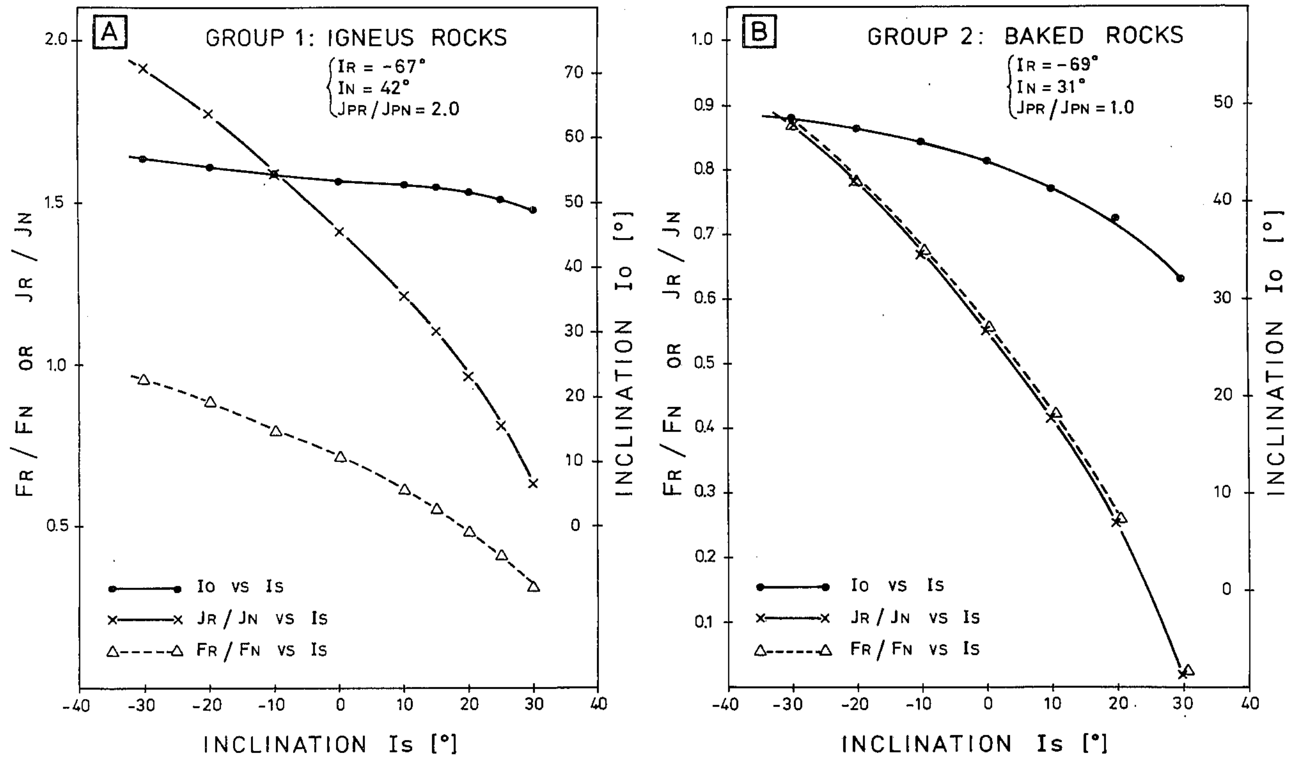

Fig. 6. The effect of variation of *Is* to the primary inclination *Io* and to the NRM (J_R/J_N) and Thellier paleointensity ratios (F_R/F_N) in (A) group 1 rocks, and (B) group 2 rocks. Note in particular that F_R/F_N will always be less than 1.0, when *Is* lies between −30° and +30°.

first by using Eqs. 1a–1d. The variation in Io is, however, quite negligible compared to the variation in the intensity ratios (Fig. 6).

In igneous rocks the ratio of NRM intensities (J_R/J_N) increases from 0.65 to 1.9 when *Is* decreases from +30° to –30°. When *Is* is about 0° the J_R/J_N ratio reaches approximately the value (= 1.4) observed in Keweenawan rocks (Table 3). However, the ratio of Thellier paleointensities (F_R/F_N) always remains less than 1 for the whole range of possible *Is* values in clear contrast with the observed data.

In group 2 (baked rocks) the ratios of F_R/F_N and J_R/J_N are the same and always less than 1.0 for the entire range of *Is* values. Therefore the variation of the value assigned for secondary remanence direction does not explain the observed intensity ratios (always greater than 1).

It can be concluded from these theoretical intensity studies that the unremovable secondary component is not the explanation for the observed polarity asymmetries in Keweenawan rocks.

6. *Model 2: apparent polar wander*

6.1. Geometry

In this model (Fig. 2) we assume that the geomagnetic field is due to the axial geocentric dipole (AGDF) and that the asymmetry in the inclinations results from apparent polar wander (apw) (*e.g.* BECK, 1970; PESONEN and HALLS, 1979). Consider that the North American plate was at high latitudes (high inclinations) during the magnetization of the Keweenawan reversed polarity units, and drifted later to lower latitudes (shallow inclinations) where the normal polarity magnetizations were acquired. An asymmetric reversal produced by this mechanism is shown in Fig. 2b.

The apw model requires that there be a difference between the magnetization age of the reversed and normal rocks. Although the scatter of the ages of Keweenawan rocks (especially those by the K-Ar methods) is often large (from 730Ma to 1300Ma; *e.g.* PESONEN, 1978 and 1979) so that it is impossible to distinguish age differences between reversed and normal units, there appears to be a tendency for the reversed units to be slightly older (~1140Ma) than the normal ones (~1120Ma), consistent with stratigraphic (reversed lavas generally underly normal ones), cross-cutting (normal dykes cut reversed sills) and paleomagnetic results (PESONEN, 1979; SILVER and GREEN, 1972; HALLS and PESONEN, 1982).

6.2. Intensity ratios

If the geomagnetic field during Keweenawan times was due to the axial geocentric dipole (AGD), the ratios of the NRM's, of relative (Q and RF) and of Thellier paleointensities (F) can be calculated as follows:

$$\frac{NRM_R}{NRM_N} = \frac{J_{PR}}{J_{PN}} \cdot C(\theta) \quad (4a)$$

$$\frac{Q_R}{Q_N} = \frac{J_{PR} \cdot \chi_N}{J_{PN} \cdot \chi_R} \cdot C(\theta) \quad (4b)$$

$$\frac{RF_R}{RF_N} = \frac{J_{PR} \cdot ARM_N}{J_{PN} \cdot ARM_R} \cdot C(\theta) \quad (4c)$$

$$\frac{F_R}{F_N} = C(\theta) \quad (4d)$$

where $C(\theta)$ is the axial geocentric dipole function:

$$C(\theta) = [(1+3\cos^2\theta_R)/(1+3\cos^2\theta_N)]^{1/2} \quad (5)$$

and θ_R and θ_N are defined as follows:

$$\tan I_R = 2\cot\theta_R \quad (6a)$$

$$\tan I_N = 2\cot\theta_N \quad (6b)$$

θ_R, θ_N are the colatitudes of the sampling sites during the reversed and normal epochs. Other symbols are explained previously (see Fig. 3 and Tables 1–3). Note that the relative paleointensity ratios (Eq. 4b, 4c) reduce to the value of $C(\theta)$, because the ratio of the primary intensities (J_{PR}/J_{PN}) was assumed to be equal than the ratio of magnetic contents (χ_R/χ_N or ARM_R/ARM_N).

Substituting the average Keweenawan inclinations into Eqs. 4–6, we obtain the intensity ratios in the apw model as shown in Table 3. The results indicate that all the predicted intensity ratios (*i.e.* Q, NRM/ARM and Thellier paleointensity) are consistent with the observed ratios, taking into account the limitations and scatter in the observed data. For example, the theoretical NRM ratios in group 1 and 2 rocks are 2.70 and 1.52, respectively, which are comparable to the observed values of 1.50 and 1.17. Similarly, the theoretical ratios of relative paleointensities (RF_R/RF_N) and Thellier paleointensities (F_{PR}/F_{PN}) are greater than one, consistent with the apw interpretation (Table 3). It must be stressed here, however, that reliable Thellier paleointensity data are so far available only in the northern part of the Lake Superior (Thunder Bay district). Before the apw model can be accepted, it must be shown that the geomagnetic field indeed was that due to axial geocentric dipole and that only one reversal (R→N) took place during the Middle/Lower Keweenawan boundary. If the latter is not true, as it appears in the Mamainse Point area (see MASSEY, 1979, HALLS and PESONEN, 1982), the asymmetry may be caused by a standing non-dipole field component superimposed to the axial geocentric dipole field (see Fig. 2d; PESONEN, 1978). PESONEN and NEVANLINNA (1981) and NEVANLINNA and PESONEN (1983) have recently shown that a co-axial two dipole geomagnetic field configuration can explain the Keweenawan inclination asymmetries. The model predicts approximately equal field strengths for R and N units but has an advantage in being capable to explain the situation (as possible in Mamainse Point area) where several successive asymmetric reversal occur. In order to distinguish between the apw model and the two-dipole model, detailed intensity and paleodirectional data are needed from other Keweenawan units around the Lake Superior to confirm the presently observed trend ($J_R > J_N$) and also from units which are coeval with Keweenawan units (*i.e.* ~1150Ma) but located far away from the Lake Superior region. This is because each model (apw model, two-dipole field model etc.) predicts a testable relationship between inclination and intensity on the colatitude of the area (NEVANLINNA and PESONEN, 1983).

7. *Conclusions and discussions*

The following conclusions can be drawn from the present study:

(1) A new intensity method has been developed to study the cause of the asymmetry of the Late Precambrian Keweenawan reversals. The method requires calculations of NRM, relative and absolute paleointensity ratios of reversed and normal rocks for each theoretical model used to explain the asymmetry. The theoretical intensity ratios are compared with those obtained of the rocks in the laboratory.

(2) All three intensity ratios are in conflict with the secondary component model. In constrast, the observed intensity ratios are consistent with the apw model and suggest that the asymmetry may have been caused by motion of the North American plate (relative to the pole) across the reversal crossing (R→N) and before the onset of the igneous activity in N polarity times. However, intensity ratios are not alone sufficient to prove the apw interpretation. Other models, like a standing non-dipole field model (a two-dipole model) may also prove to be useful in explaining the

asymmetries. Paleointensity and paleodirectional data are needed from units which are coeval with the Keweenawan units (*i.e.* ~1150Ma) but located (in a co-latitudinal sense) far away from the Lake Superior area (*e.g.* the Grand Canyon province or the Gardar province in Greenland).

(3) Although the new method was developed mainly to investigate the Keweenawan reversals, it can be used to study any other reversal asymmetry by varying the input parameters in model calculations. Because the calculations are performed in vector form, the three remanences in question (primary, secondary and resultant) do not have to lie in the same plane as in the case of the Keweenawan data. However, the geometry of the asymmetry must be solved first. Therefore, in addition of the observed remanence vectors, *either* the hypothetical secondary (as in this work) *or* the primary remanence direction must be assumed. A value for the secondary component may be assigned from conglomerate data (as in this work) or by other methods (see *e.g.* EVANS *et al.*, 1980). The direction for the primary remanence components may be found, if a rock unit is found in the investigation area that has not suffered secondary events and that shows the 180° symmetry of reversal.

(4) The present method was used in an order to study the reality of a hypothetical secondary component, the direction of which was assumed to be the one isolated from conglomerate pebbles. The method could also be used to solve the »inverse» type of problem: to find a direction for the secondary component which is causing a perfect reversal to become an asymmetric one. This possibility could be of considerable use in paleomagnetism as the reversals very rarely are symmetric and truly hidden secondary components may be present (eventhough this appears not to be the case in the present study).

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