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1. PALEOMAGNETISM OF THE JURASSIC ISLAND INTRUSIONS OF VANCOUVER ISLAND, BRITISH COLUMBIA

2. A PALEOMAGNETIC STUDY OF THE NIPISSING DIABASE, BLIND RIVER-ELLIOT LAKE AREA, ONTARIO

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3. MAGNETOCHEMICAL ASPECTS OF THE HEATING OF RED AND GREEN BEDS

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Illustration

PALEOMAGNETISM OF THE JURASSIC ISLAND INTRUSIONS, OF VANCOUVER ISLAND, BRITISH COLUMBIA

D.T.A. Symons

ABSTRACT

Granodioritic batholiths of the mid-Jurassic (159 ± 10 m.y.) Island Intrusions were sampled at 24 sites (218 specimens) along the length of Vancouver Island. After AF demagnetization and statistical consistency tests, 17 sites were judged to have stable primary TRM with 16 sites reflecting a normal mid-Jurassic paleomagnetic field and one site a reversed field. Use of the fold test indicates that the broad Island-spanning anticlinorium found in the Triassic Karmutsen basalts was formed prior to cooling of the Island Intrusions. The calculated geomagnetic pole position for the Island Intrusions of 79°N, 240°E (10°, 11°) is consistent with positions for other North American Jurassic rock formations indicating either no post-intrusion movement of Vancouver Island relative to the North American continental block or at most very little movement. If minor relative movement has occurred it can best be explained by a few degrees ($\approx$15°) of clockwise rotation of Vancouver Island either during the mid-Cretaceous Nevadan Orogeny or during the later Tertiary through sea-floor spreading off the adjacent East Pacific Rise, and by a few degrees ($\leq$5°) of the northeastward tilt of panels of rock between block faults during the Tertiary.

INTRODUCTION

The Island Intrusions outcrop extensively throughout Vancouver Island as irregularly shaped bodies ranging in size from stocks to batholiths of several hundred square miles (Fig. 1). They range from granite to gabbro in composition but are mainly quartz diorite and granodiorite (Jeffrey and Sutherland Brown, 1964). They intrude Lower Jurassic rocks of the Bonanza Subgroup and other older formations, and they are nonconformably overlain by the Late Cretaceous sediments of the Nanaimo Group (Muller and Carson, 1969). They are also probably older than the Late Jurassic sediments on the west coast of Vancouver Island (Jeletzky, 1954). The overlying sediments have dips of generally less than 15 degrees except immediately adjacent to fault scarps. The available K-Ar radiometric age dates indicate a Middle to early Upper Jurassic age (Geological Society of London, 1964) for the Island Intrusions giving an average of 159 ± 10 m.y. from the following values (Fig. 1): 167 ± 10 m.y. (Wanless *et al*., 1966, p. 7); 151 ± 14 m.y., 162 ± 9 m.y., and 166 ± 8 m.y. (Wanless *et al*., 1967, pp. 18-23); 152 ± 7 m.y. and 160 ± 8 m.y. (Wanless *et al*., 1968, pp. 27-33); and 154 ± 8 m.y. (Muller's sample MEKA-68-3, R.K. Wanless, pers. comm.). There are additional replicate dates and dates from units metamorphosed during intrusion which confirm the given values.

The Island Intrusions were selected for study because of the paucity of paleomagnetic data for the Jurassic of North America and because of the need for such data to examine current hypotheses of continental rafting, fault tectonics and pluton emplacement for the Western Cordillera (Wheeler, 1970).

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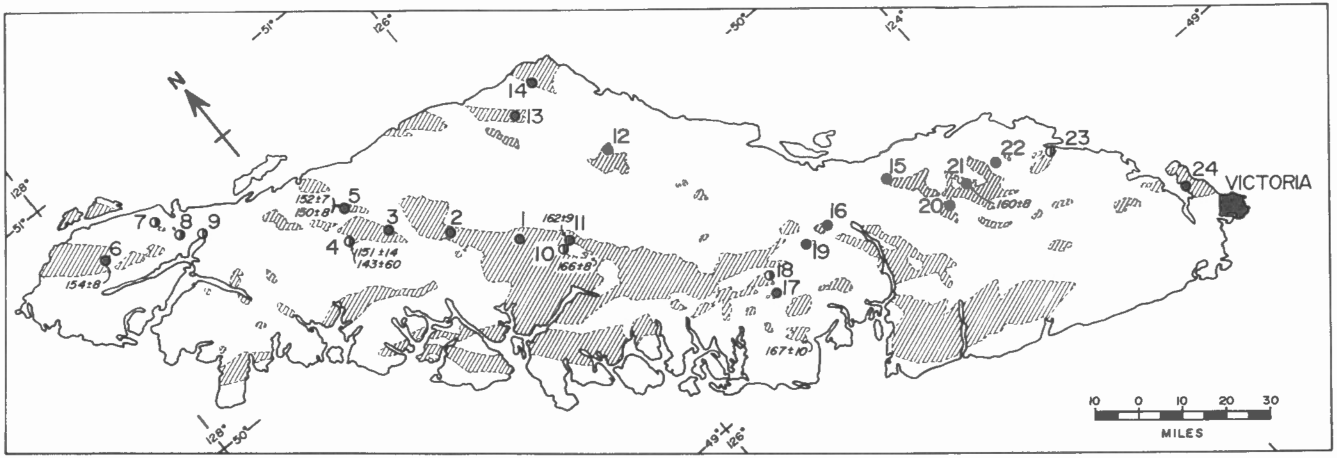


Figure 1: Sketch map of Vancouver Island showing the outcrop area of the Island Intrusions from a map by Muller (1967) by hatching, the 24 sampling sites with accepted sites shown by solid circles and non-accepted sites by semi-solid circles, and the locations of relevant radiometric age dates (my) shown by sloped numerals.

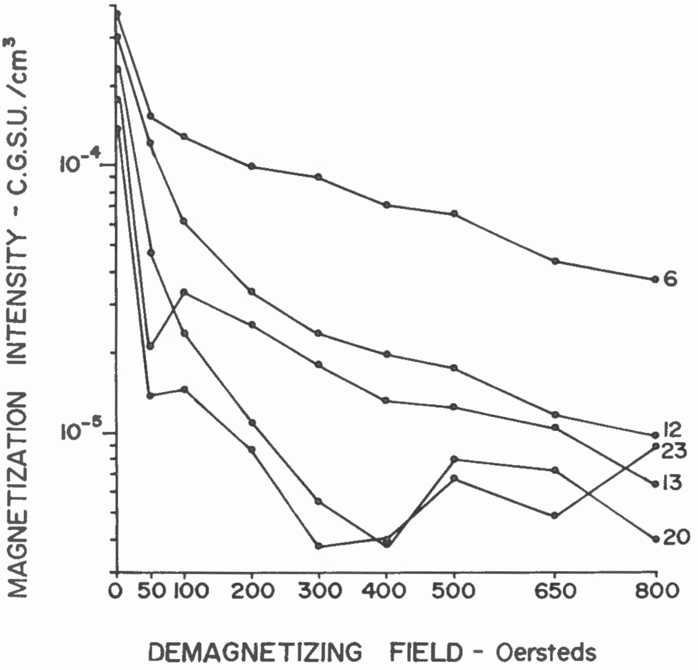


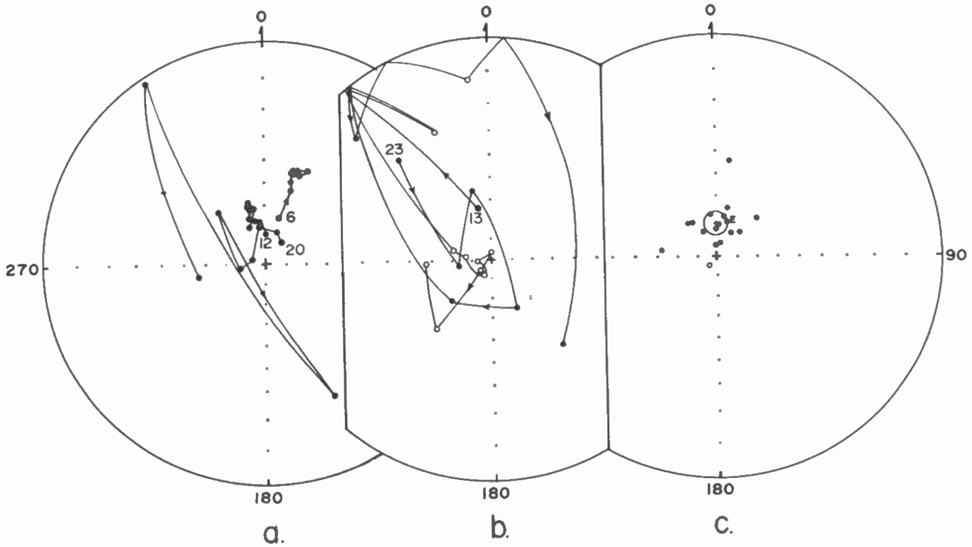
Figure 2: Typical NRM intensity decay curves on AF step demagnetization with the number on the right indicating the site represented.

SAMPLING

One hundred and nine cores were drilled from 24 sites representing 19 separate bodies of the Island Intrusives along the length of Vancouver Island (Fig. 1). Sites with known radiometric dates were sampled wherever possible. The rocks at all sites exhibited massive texture except at site 9 which was subsequently rejected. No evidence of post-intrusive alteration associated with the few centres of weak Tertiary igneous activity were observed. Individual cores at a given site were collected from points several metres apart. All cores were oriented in situ by solar compass with Brunton compass and topographic check orientations. Two specimens, each 3.2 cm in diameter and 2.9 cm in length, were cut from each core.

MEASUREMENT AND DEMAGNETIZATION OF REMANENCE

The direction and intensity of the natural remanent magnetization (NRM) of each specimen was measured using an automated biastatic magnetometer (Larochelle and Christie, 1967). A test specimen with an "average" NRM direction and intensity was selected from each site and demagnetized in steps at successive peak field intensities of 50, 100, 200, 300, 400, 500, 650, and 800 Oe using the alternating field (AF) demagnetizing equipment described by Larochelle and Black (1965). For each test specimen the change in remanence intensity (Fig. 2) and direction (Fig. 3) from step to step was plotted



a and b. AF step demagnetization of test specimens with the site number adjacent to the NRM direction and successive circles indicating the direction after 50, 100, 200, 300, 400, 500, 650 and 800 Oe cleaning.

c. Site mean remanence directions with the cone of 95% confidence about the unit mean direction (+) after normalization of the reversed site, and with the present direction of the earth's magnetic field (E).

Figure 3: Remanence directions plotted on an equal-angle stereonet with solid circles indicating upward (reversed) inclinations.

and its stability index (SI) value calculated (Tarling and Symons, 1967). Using this data, a field intensity was selected for each site (Table 1) at which the remaining specimens were AF demagnetized after which their remanence was remeasured. Several sites were AF demagnetized at two different field intensities in which case the better grouping of remanence directions for the site are reported in Table 1.

DATA SELECTION

The following criteria were preset in order to assure that the data used for statistical analysis were homogeneous and represented stable remanence (Table 1).

a) Cores with remanence intensities of less than 5×10^{-7} c. g. s. v. / cm^3 were considered likely to give unreliable remanence direction because of instrumental errors and were rejected.

b) Cores for which the remanence directions of the two contained specimens diverge by more than 20 degrees were considered inhomogeneous and rejected.

The vectorial average of the remanence directions of the two specimens was used to represent each accepted core. Giving each core unit weight, the site mean angular standard error (δ_{se}) (Larochelle, 1968) was calculated.

c) If one core in a site for which $\delta_{se}>10°$ had an angular deviation from the mean direction of the remaining cores in excess of three times the value of $\sqrt{n}\delta_{se}$ for the remaining n cores, then the deviating core was considered an erratic and rejected.

d) If the value of δ_{se} was greater than 10° for a site after criteria (a), (b) and (c) were applied, then the site was considered insufficiently homogeneous and rejected.

The resulting site statistics for the remanence directions are given in Table 1 along with the mean direction by core and by site unit weight for the Island Intrusives.

REMANENCE STABILITY

Application of the data selection criteria leads to the acceptance of 65 of 109 cores (60 per cent) and 17 of 24 sites (71 per cent). The test specimens for all 7 rejected sites give low SI values ranging from 0.6 to 2.6, and the specimen from site 23 illustrates the typical behaviour of such unstable rocks during AF demagnetization, i.e. a rapid irregular decrease in intensity (Fig. 2) with scattered remanence directions (Fig. 3b) from 0 to 300 Oe, and then an irregular increase in intensity with very scattered directions up to 800 Oe as anhysteretic remanent magnetization (ARM) components are introduced into specimen. ARM is an unstable viscous magnetization which is often produced by instrumental difficulties in the demagnetization process for specimens of low NRM stability (Doell and Cox, 1967).

The specimens from sites 6 and 12 with SI values of 13.1 and 7.3 respectively are typical of the sites having the most stable remanence. On the initial demagnetization step they show a moderate drop in intensity (Fig. 2) and a slight shift in remanence direction (Fig. 3a), followed by a slow regular decrease in intensity and nearly constant remanence direction up to 800 Oe. The specimen from site 20 is typical of sites having lesser but still acceptable remanence stability. It shows a rapid regular decrease in intensity with moderately consistent remanence directions (Fig. 3b) up to 400 Oe AF demagnetization above which the intensity fluctuates and the directions scatter as ARM is introduced.

Site 13 is the sole site to have a stable remanence direction with reversed polarity, and its mean direction is almost antiparallel to the mean of all the normally polarized sites (Fig. 3c). Providing it is established that site 13 has a stable remanence reflecting reversal of the earth's magnetic field at the time of intrusion and not reflecting a mineralogic self-reversal, this site provides strong evidence for the preservation of a primary thermoremanent magnetization (TRM) in the Island Intrusions aligned during the Jurassic by the earth's field. AF demagnetization of the test specimen shows a sharp decrease in remanence intensity (Fig. 2) and an abrupt change from normal to reversed remanence direction (Fig. 3b) by 50 Oe as a "soft" normal viscous remanent magnetization (VRM) component is removed. This is followed by a slight increase in intensity and slight shift to a more perfectly reversed direction produced by treatment in 100 Oe as most of the remaining normal VRM component is removed. Thereafter the intensity drops slowly and regularly and the direction remains constant up to 650 Oe as the stable reversed component is demagnetized. Above 650 Oe the direction starts to

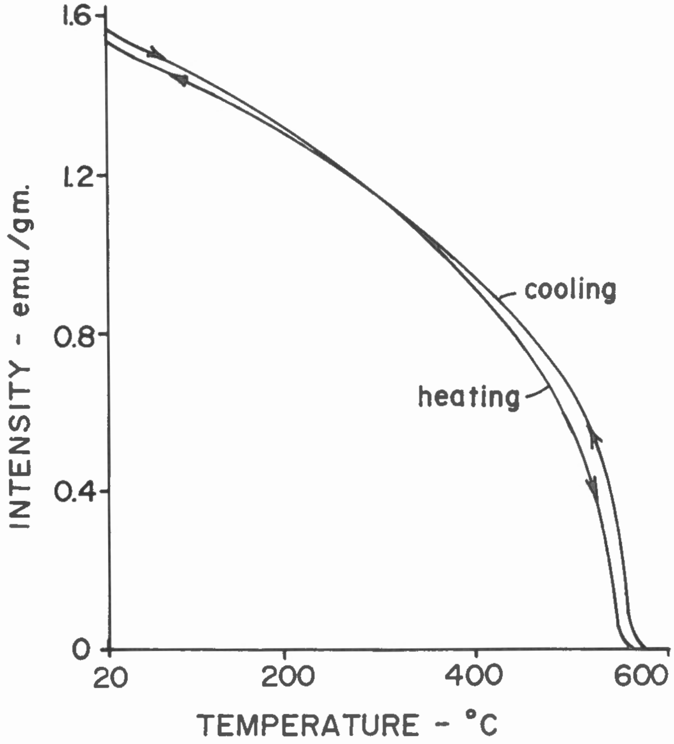


Figure 4: Thermomagnetic curve obtained during heating and cooling of specimen from site 13 using an applied field of 3745 Oe and an air pressure in the instrument of $5x10^{-3}$ torr. The Curie Point is at 552 ± 8°C. The heating and cooling rate was constant at 7.5°C/min.

scatter slightly, probably indicating the emplacement of ARM components in the specimen. Merrill and Grommé (1969) find evidence of a nonreproducible self-reversal in diorite samples from the Jurassic Bucks Batholith in California where samples from the same site may both be normal and reversed polarity. At site 13 all samples behave in the same fashion going from normal to reverse remanence direction upon 50 Oe AF demagnetization. However as an additional test, the response of the intensity of the high-field saturation magnetization to increasing temperature was determined. The resulting curve (Fig. 4) shows no evidence of more than one ferromagnetic component, and it yields a Curie Point temperature of 552 ± 8 °C which indicates that the remanence resides in relatively pure magnetite.

Examination of the site mean remanence directions provides further evidence for the isolation of a primary TRM by AF demagnetization. Using data from accepted cores only and normalizing the reversed remanence of site 13 by rotating it through 180°, the cone of 95% confidence ($\alpha 95$) about the mean remanence direction is decreased from 6.1° for the NRM to 3.6° after demagnetization. Variance ratio analysis (Larochelle, 1968) indicates that this decrease is statistically significant at the 95% confidence level. Further, the cone of 95 % confidence for the NRM encompasses both the earth's present geographic and geomagnetic poles, whereas after demagnetization it does not encompass them.

Thus the evidence suggests that the unstable remanence components in the accepted sites have been removed by AF demagnetization to leave primary remanence components aligned by the earth's field during the Jurassic, and that the remanence is probably a TRM residing in relatively pure magnetite.

DISCUSSION

The Triassic Karmutsen Formation is composed of oceanic basalts with interbedded sediments. It is the most extensively exposed unit on Vancouver Island. Based on regional geological mapping, J.E. Muller (pers. comm.) notes that the basalts have been folded into a broad north-northwest trending anticlinorium (separating sites 1 to 11 from sites 12 to 24), and with dips of 10°-25°SW and 10°-20°NE in the northwest and southeast halves of Vancouver Island respectively. The variance ratio test is used to compare the mean remanence directions of the 6 accepted sites (1-3, 5, 6, and 11) from the northwest to thos of the 11 accepted sites (12-17, 19-22, and 24) from the southeast on applying the fold test (Graham, 1949). Before applying tectonic corrections for the anticlinal folding, the variance ratio $\delta_b^2/\delta_\omega^2$ equals 1.45 for the two groups of remanence directions which is considerably less than the statistic $F_{2,\ 30,\ 0.05}(3.32)$ thereby indicating that they are not nearly statistically significantly different. After applying corrections $\delta_b^2/\delta_\omega^2$ equals 22.3 which is vastly greater than the statistic $F_{2,\ 30,\ 0.05}\ (3.32)$ thereby indicating that they form two very statistically significantly different groups. This result strongly supports the hypothesis that the Karmutsen volcanics were folded into the anticlinorium prior to the mid-Jurassic cooling of the Island Intrusions. Most likely, because the intrusions are most extensively exposed near the axis of the anticlinorium, the folding and intrusion occurred virtually simultaneously.

Using the dipole formula and the formation mean remanence direction found by giving each site unit weight, the resulting pole position and semi-axes of the oval of 95% confidence for the Island Intrusions are 79°N, 240°E (10°, 11°). The available Upper Triassic to Lower Jurassic pole positions for North America are listed in Table 2 and plotted on a polar projection of northern hemisphere in Figure 5. Excluded from this list are the pole positions derived from the Franciscan Formation of California (Grommé and Gluskoter, 1965; Saad, 1969) which may be as young as Late Cretaceous and for which the interpretation of the deviating pole position is still in considerable doubt.

All the Late Triassic pole positions (poles 1-8, Fig. 5) representing a time interval of 25 m.y. form a consistent cluster in north-central Siberia. Similarly, the Lower Cretaceous pole positions (poles 17-19) representing a time interval of 35 m.y. form a consistent cluster around the Bering Strait. The intervening 55 m.y. of the Jurassic is represented by relatively few reliable and consistent data. The White Mountain igneous complex dated at 180 m.y. provides the most reliable Early Jurassic pole position (pole 11). Currie and Larochelle (1969) consider the Mistastin Lake volcanics which were extruded onto tectonically stable Precambrian Shield to be Jurassic despite a Late

Table 1. Remanence data by sites

Site	Location		AF Demagnetization				Data Selection						After AF Demagnetization				
No.	Long. ° W.	Lat. ° N.	SI	$H_{min.}$	$H_{max.}$	H_{af}	N	a	b	c	d	n	R	D_s	I_s	δ_{se}	α_{95}
1	126.17	49.92	2.2	300	500	300	5		2	1		2	1.9851	336.6	69.8	7.0	
2	126.42	50.08	11.3	100	400	200	5					5	4.8363	276.9	62.7	7.4	
3	126.65	50.22	.7	0	100	100 (400)	5					5	4.8967	333.8	76.4	5.8	
4	126.86	50.28	1.2	0	400	200	3	1	2			0					
5	126.76	50.37	1.8	0	100	100	5		1			4	3.9726	14.4	64.9	3.9	
6	127.88	50.73	13.1	200	400	300	5					5	4.9847	9.2	42.9	2.2	
7	127.56	50.73	2.5	200	800	300	5		2	1	2	0					
8	127.51	50.64	2.0	100	400	300	5		5			0					
9	127.42	50.60	2.6	100	400	200	6		3	1	2	0					
10	126.03	49.80	1.8	0	100	200 500	5		3		2	0					
11	125.98	49.81	1.6	0	200	100 (650)	5		1			4	3.9835	16.0	82.9	3.0	
12	125.53	49.96	7.3	300	650	100 (400)	5					5	4.9931	351.8	69.5	1.5	
13	125.78	50.24	2.9	100	500	300	5		1	1		3	2.9851	212.7	-84.6	4.1	
14	125.61	50.29	1.8	0	200	100	4					4	3.9649	359.5	76.2	4.4	
15	124.55	49.30	10.4	50	200	100	5					5	4.9203	30.8	75.6	5.1	
16	124.92	49.29	3.2	50	200	100	4					4	3.9944	11.9	69.5	1.8	
17	125.36	49.23	8.9	50	400	300	5			1		4	3.9880	353.9	73.6	2.5	
18	125.32	49.29					3	3				0					
19	125.08	49.29	5.2	50	650	100	3					3	2.9600	18.1	71.7	6.7	
20	124.40	49.08	1.4	0	200	200	5		2	1		2	1.9871	1.7	83.7	6.5	
21	124.27	49.10	1.7	0	100	200	5		2			3	2.9902	47.2	61.6	3.3	
22	124.06	49.08	2.1	50	200	100 (400)	5			1		4	3.9675	44.5	73.0	4.2	
23	123.84	48.99	.6	400	650	100 (500)	3		1		2	0					
24	123.47	48.61	3.4	50	800	(200) 500	3					3	2.9833	321.2	68.4	4.3	
Total							109	4	25	7	8	65					
Mc	125.58	49.75										65	62.2878	1.0	73.4	2.1	3.6
Ms	125.46	49.55										17	16.4988	1.9	73.9	3.5	6.0

The co-ordinates (Long. °W, Lat. °N) are given in degrees. The minimum (H_{min}) and maximum (H_{max}) alternating field (AF) demagnetization steps represented in the stability index (SI) value are given in oersteds as is the field (H_{af}) used to "clean" the remaining site specimens. Bracketed field strengths indicate an alternative AF cleaning attempted which gave less reliable remanence directions. Of the number of cores (N) collected of each site, some could be rejected by the data selection criteria (a, b, c, and d) given in the text thereby leaving the number of cores (n) used to calculate the declination (D_s) and inclination (I_s) in degrees of the site mean resultand vector (R) with the radius of its cone of standard error (δ_{se}) in degrees. The mean remanence direction by core unit weight (M_c) and by site unit weight (M_s) for the Island Intrusions is given at the bottom of the table along with the radius of their respective cones of 95% confidence in degrees after normalizing the remanence direction of site 13 by rotating it through 180°.

Table 2. Upper Triassic to Lower Cretaceous (205-100 m.y.) pole positions for North America

	FORMATION	AGE	P	SAMPLING			POLE POSITION				REFERENCE
				B	N	n	Lat. °N	Long. °E	δ_ψ	δ_χ	
1	**Chinle Fm. (redbeds)** Utah and New Mexico, U.S.A..	uTr	M	3*	40	115	55	93	—	—	Collinson & Runcorn (1960) Irving (1964)
2a	North Mountain basalt Nova Scotia, Canada	uTr, 200±10 m.y.	-	17*	28	54	66	113	6	11	Larochelle (1967)
2b	Nova Scotia, Canada	—	-	25*	25	38	73	104	5	7	Carmichael & Palmer (1968)
3	Grand Manan Is. lavas New Brunswick, Canada	uTr	-	4*	4	8	80	100	17	24	Carmichael & Palmer (1968)
4	Great Dyke (diabase) Nova Scotia, Canada	uTr, 197 m.y.	-	2*	11	22	69	98	4	6	Larochelle & Wanless (1966)
5	Meridan Fm., Newark Gp. (lavas) Massachusetts, U.S.A.	uTr	-	5*	16	32	55	88	6	11	Irving & Banks (1961)
6	Connecticut Valley, Newark Gp. (igneous) Connecticut, U.S.A.	uTr, 193±6 m.y.	-	53 7*	313	609	65	87	7	12	de Boer (1968)
7	Newark Gp. (red beds, lavas, diabase) New Jersey, U.S.A.	uTr, ≈190 m.y.	-	29*	78	329	63	108	3	4	Opdyke (1961)
8	Newark Gp. (diabase intrusives) Pennsylvania, U.S.A.	uTr	-	20*	95	—	62	105	2	3	Beck (1965)
9	Mistastin Lake volcanics Labrador, Canada	uTr-J(?)$\left\{\begin{smallmatrix}(1)\\(2)\end{smallmatrix}\right\}$, 202±13 m.y.	+	10*	73	117	86	118	4	4	Currie & Larochelle (1969)
10	Appalachian diabase dykes Eastern U.S.A.	uTr-ℓK	-	74*	121	223	66	145	3	3	de Boer (1967) McElhinny (1968)
11	White Mountain volcanics New Hampshire and Vermont, U.S.A.	ℓJ, ≈180 m.y.	M	12*	130		85	126	5	6	Opdyke & Wensink (1966)
12	Kayenta Fm. (red beds) Arizona, U.S.A.	uTr-ℓJ	-	4*	39	146	83	63	21	21	Collinson & Runcorn (1960) Cox & Doell (1960)
13	Island Intrusions (granodiorite) Vancouver Is., B.C., Canada	mJ - uJ, 159±10 m.y.	M	17*	65	130	79	240	10	11	this paper
14	Carmel Fm. (red beds) Utah, U.S.A.	J (uJ?)	-	1	9	31*	80	200	11	14	Collinson & Runcorn (1960)
15	Bucks Batholith (granodiorite) California, U.S.A.	uJ, 138±6 m.y.	M	9*	—	116	58	195	8	8	Grommé et al. (1967)
16	Guadeloupe Mtn. igneous complex California, U.S.A.	uJ, 136 m.y.	M	4*	—	56	43	171	27	27	Grommé et al. (1967)
17	Mt. Ascutney gabbro Vermont, U.S.A.	ℓK, 130±5 m.y.	+	2*	24	—	64	187	—	—	Opdyke & Wensink (1966)
18	Monteregian Hills (basic intrusives) Quebec, Canada	ℓK, 124±3 m.y.	M	32*	147	294	71	189	3	4	Larochelle (1969)
19	Isachsen diabase Dist. of Franklin, N.W.T., Canada	ℓK, 106±4 m.y.	-	10*	20	40	69	180	14	14	Larochelle & Black (1963) Larochelle et al. (1965)

Under AGE the following abbreviations are used: Upper Triassic (205-190 m.y.) - uTr; Lower Jurassic (189-172 m.y.) - ℓJ; Middle Jurassic (171-162 m.y.) -mJ; Upper Jurassic (161-136 m.y.) - uJ; and Lower Cretaceous (135-100 m.y.) - ℓK. The quoted ages summarize the available radiometric ages. The indicated polarity (P) for the earth's magnetic paleofield is shown as negative (–), mixed (m) or positive (+). Under SAMPLING, the number of sites (B), samples (N), and specimens (n) are given with the asterisk indicating the unit weight basis for the pole position calculation. The co-ordinates of the POLE POSITION in the northern hemisphere are given (Lat.°N, Long.°E) with semi-axes of the oval of 95% confidence with δ_ψ in the colatitude direction and δ_χ perpendicular to it. Comments: (1) the authors consider the paleomagnetic results indicative of a Lower Jurassic age contrary to limited radiometric evidence; (2) the author considers paleomagnetic result indicative of a Jurassic age.

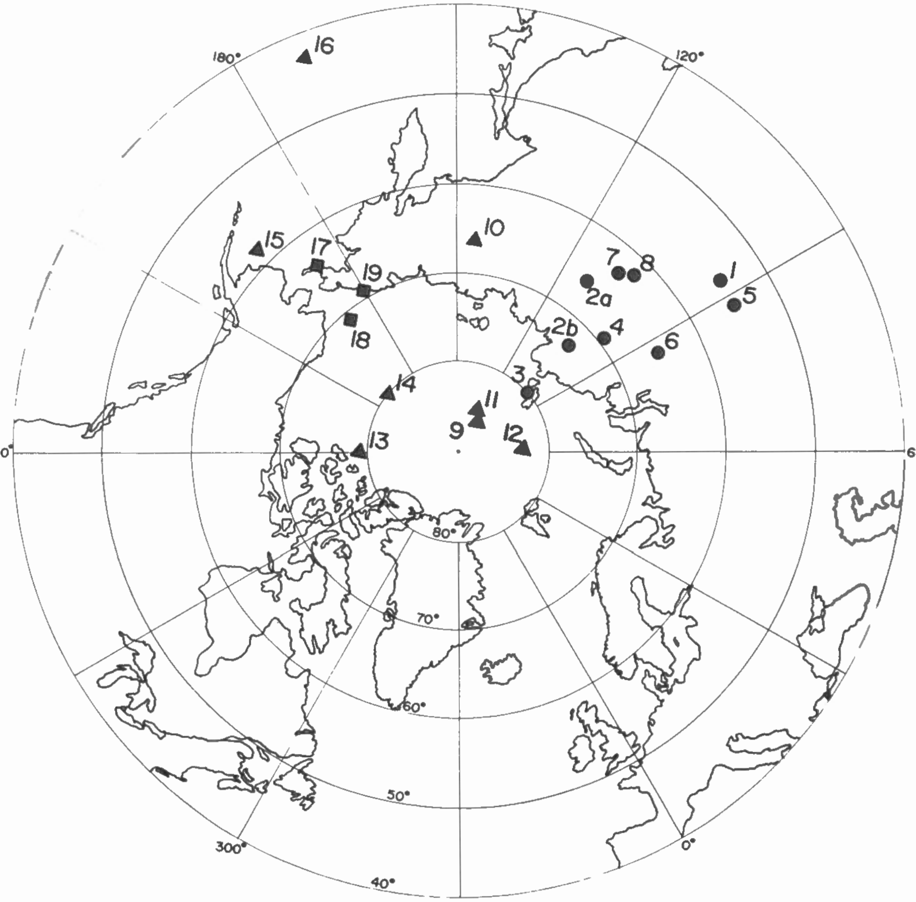


Figure 5: Polar projection of the northern hemisphere showing the pole positions listed on Table 2 for North American formations of Upper Triassic (circles), Jurassic (triangles) and Lower Cretaceous (squares) age.

Triassic K-Ar radiometric age date of 202 ± 13 m.y. because of the coincidence of their pole (pole 9) and the White Mountain complex pole. The Appalachian diabase dykes have usually been considered comagmatic with the Upper Triassic Newark Group (poles 5-8) although they are possibly as young as Early Cretaceous. Because the pole position (pole 10) for these dykes is intermediate between established Upper Triassic and Lower Cretaceous poles, de Boer (1967) believes them to be Jurassic. In the absence of any stability tests Collinson and Runcorn (1960) consider that the remanence in the Upper Triassic or Lower Jurassic Kayenta (pole 12) and the Upper Jurassic Carmel (pole 14) red bed formations is probably a VRM because of the coincidence of their pole positions and the earth's present pole. Maureen B. Steiner (pers. comm.) from work in progress on the Kayenta red beds finds that their NRM is quite stable on thermal demagnetization and that their pole position is probably closer to 80°E, 65°N which is within the Trassic cluster of poles in

Figure 5 and within the cone of confidence about the pole reported by Collinson and Runcorn (1960). It now appears probable that the Kayenta and Carmel poles reflect reliable North American Jurassic magnetic pole locations within the stated experimental confidence limits. The error limits on the radiometric age of the Bucks Batholith (138 ± 6 m.y.) overlap the Jurassic-Cretaceous boundary, and so the batholith's pole position (pole 15) close to the Lower Cretaceous poles is consistent. The Guadeloupe Mountain igneous complex has a similar radiometric age of 136 m.y. Its pole position (pole 16) deviates markedly from the other Jurassic and Early Cretaceous poles which may simply reflect the insufficient sampling of the complex (i.e. 4 sites) as suggested by the large 27° error limits of its oval of 95% confidence.

The Island Intrusives are mid-Jurassic (159 ± 10 m.y.) in age. If they have not been subjected to regional tectonic movement relative to the rest of North America, then they could be expected to reflect a pole position that is approximately intermediate between: a) the Late Triassic cluster and the Early Cretaceous cluster of poles; and b) the Lower Jurassic grouping formed by the White Mountain complex, Mistastin Lake volcanics, and the Kayenta Formation poles, and the Late Jurassic grouping formed by the Bucks Batholith, Carmel Formation, and Appalachian diabase dykes poles. A hypothetical pole at about 170°E, 80°N would be in such an intermediate position. Because this position lies within the oval of 95% confidence for the Island Intrusions, it is reasonable to suggest that the pole position for the intrusions reflects the primary TRM, and that Vancouver Island has been subjected to either no post mid-Jurassic tectonic movement relative to the North American continental block or very little movement at most.

If some relative tectonic movement of Vancouver Island has occurred, limits on the amount and type of movement appear reasonable from the comparison of the established and hypothetical pole positions. The relative declinations of the site-pole directions suggest that any rotation of Vancouver Island in the horizontal plane was clockwise in sense and about 15^o in magnitude (Fig. 6). The relative co-latitudes suggest that the island has been either translated from north to south or the Island Intrusions have been tilted to the north by a few degrees.

Summarizing structural and paleontological evidence Wilson (1968) put forth the hypothesis that a relatively small land mass broke off from the Asian continental block and drifted east relative to a westerly drifting North American continental block. The small land mass first impinged on the offshore island arc and shelf system of the North American block during Upper Devonian or Mississippian time. This collision is reflected in the Antler and equivalent orogenies affecting rocks of the present Rocky Mountains of the eastern Cordillera. Finally the land mass and block were together during the mid-Cretaceous Nevadan Orogeny, as the Coast Range Mountains were being formed. Wilson proposed that a fragment of this land mass now underlies the Interior Plateau of British Columbia. The mid-Jurassic Island Intrusions of Vancouver Island developed in the lee of the fragment on the seaward side of the Coast Range Mountains and could therefore have been significantly rotated or translated after intrusion relative to the continental block. Some evidence for rotation within Vancouver Island appears on the geological and tectonic maps of Canada (Geol. Surv. Can. Maps 1250A and 1251A) which show that formations and faults tend to strike at $N60^o$ W in the southeast corner then they swing clockwise to $N40^oW$ throughout most of the length of the island where nearly all of the sampling was done for this

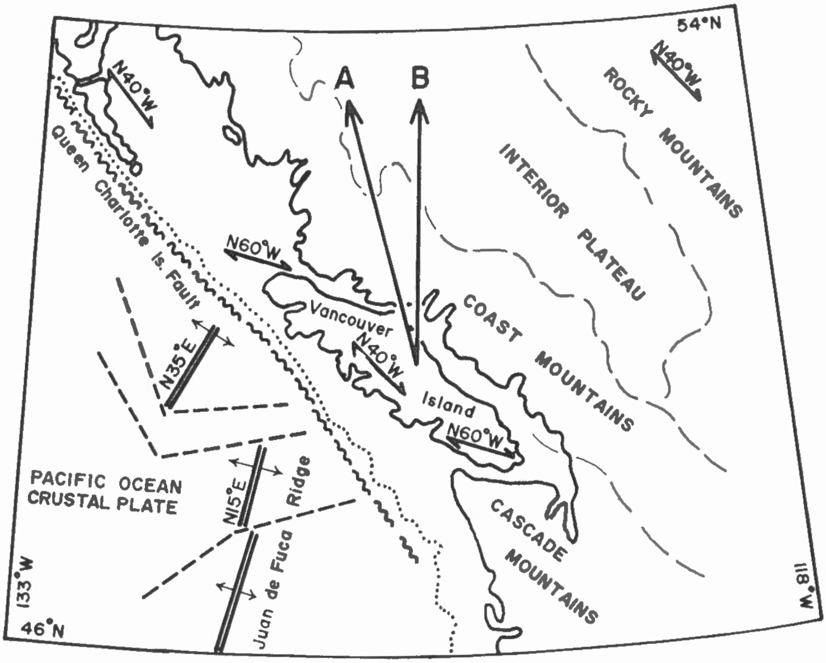


Figure 6: Sketch map of southwestern British Columbia showing major tectonic relationships. Note clockwise rotation of the tectonic trend from N60°W to N40°W in the samples central portion of Vancouver Island, of the Juan de Fuca Ridge (East Pacific Rise) from N15°E to N35°E from south to north, and possibly of the stable remanence declination direction of the Island Intrusions from an "hypothetical average" mid-Jurassic pole position (A) at N13°W to the present measured position (B) at N2°E.

study of the Island Intrusions. J.E. Muller (pers. comm.) noted that the trend swings back to N60°W on the northwest end of Vancouver Island suggesting a zig-zag bending configuration for the Island as a whole. Vine and Wilson (1965) and Vine (1968) interpreted the striped sea-floor magnetic pattern found by Raff and Mason (1961) off Vancouver Island in terms of sea-floor spreading away from the East Pacific Rise. Pavoni (1966) pointed out that the direction of the rise along the Juan de Fuca Ridge is N15°E and that it rotates in a clockwise sense by about 20° just before the rise intersects with the continental margin off the north end of Vancouver Island. The combined effect of sea-floor spreading and the rotation of the oceanic crust could possibly be reflected in a subdued fashion by rotation of Vancouver Island during the Tertiary as the crust slides down underneath the continental margin. Wilson (1965) further proposed that the Pacific crustal plate is moving north relative to North America and that dextral Queen Charlotte Islands fault is the surface expression of the Benioff zone formed at their intersection. Similar parallel dextral transcurrent faults with post Triassic movements of 580 km are reported (Wilson, 1969) in the Cordillera suggesting the possibility of northward movement of Vancouver Island relative to the mainland. The paleomagnetic evidence from the Island Intrusions apparently contradicts this possibility by indicating if anything a southward relative movement. However, Muller and Carson (1969) noted that the panels of rock between major northwest-trending longitudinal faults throughout central Vancouver Island appear to have been tilted to the northeast during the Tertiary. This is entirely consistent with the paleomagnetic evidence from the Island Intrusions.

CONCLUSIONS

From this paleomagnetic study of the mid-Jurassic Island Intrusions of Vancouver Island it is concluded that the rocks possess a stable primary remanence — probably a TRM residing in relatively pure magnetite — which can be isolated by AF demagnetization. The stable remanence direction indicates that the earth's magnetic field was normally directed during intrusion at 16 of the 17 accepted reliable sampling sites and reversely directed at one site. Applying the fold test to the site mean remanence directions shows that the Triassic Karmutsen volcanics were folded into a broad island-spanning anticlinorium before cooling of the Island Intrusions in the mid-Jurassic. The resulting pole position of 79°N, 240°E (10°, 11°) reflects either no post-intrusion movement of Vancouver Island relative to the North American continental block or at most very little movement. If such movement has occurred, it is most likely that most of the island (excluding perhaps the extreme northwestern and southwestern parts) rotated clockwise by about 15° in tectonic response either to the mid-Cretaceous Nevadan Orogeny or to spreading of the Pacific oceanic crustal plate off the East Pacific Rise and under the continental margin during the Tertiary, and that the Island Intrusions were tilted a few degrees to the northeast as a result of block faulting during the Tertiary (Muller and Carson, 1969).

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A PALEOMAGNETIC STUDY OF THE NIPISSING DIABASE BLIND RIVER - ELLIOT LAKE AREA, ONTARIO

D.T.A. Symons

ABSTRACT

This study is based on the paleomagnetic properties of 200 specimens from 11 sites in 3 sill-like sheets and 8 sites in 8 dykes of Nipissing diabase in the Blind River — Elliot Lake area of Ontario. After alternating field demagnetization weak stable remanence components were isolated for 8 sites in the sheets and 6 sites in the dykes. Their remanence directions together with the available radiometric age dates suggest that the Nipissing sheets were emplaced and/or cooled during several polarity intervals of the earth's magnetic field about 2155 m.y. ago while the Aphebian Huronian sedimentary host rocks were being folded, and that the sheets were intruded contemporaneously with the Nipissing sill at Cobalt, Ontario. The "Nipissing" dykes were emplaced after folding of the Huronian sediments and intrusion of the sheets, and probably during a single polarity interval about 1995 m.y. ago. The pole positions for the sheets and dykes are 98°W, 1°S and 131°W, 36°N respectively. Polar wander relative to the Superior Structural Province of the Canadian Shield during the Aphebian Era appears to have occurred at a rate consistent with that found relative to North America during younger eras.

INTRODUCTION

The Nipissing diabase outcrops extensively as sill-like sheets and dykes in the Blind River — Elliot Lake area of Ontario (Fig. 1). The diabase intrudes the Archean basement rocks (>2500 m.y.) and the overlying moderately-folded uraniferous Huronian sediments of the early Aphebian Era (2288 ± 87 m.y., Fairbairn et al., 1969). Roscoe (1969) concluded that the Huronian sediments were folded both before and after intrusion of the diabase.

The Nipissing sheets are often several kilometres long and a few hundred metres thick. The sheets are composed of gabbro with differentiated phases of quartz gabbro, diorite, syenodiorite and granophyre and with chilled diabasic margins (Robertson, 1962, 1963a, 1963b, 1964). In the area of the Quirke Syncline — Chiblow Anticline fold structure (Fig. 1) the sheets are irregular and either in a general way conformable to the Huronian sediments at many stratigraphic levels or cross-cutting the sediments at a low angle. Robertson (1964) interpreted the field relationships to signify that the sheets were intruded either during a lull in the compressive forces forming the fold structure or immediately after folding, and that these essentially syntectonic sheets were emplaced into dilatant areas of the fold structure. Van Schmus (1965) obtained a whole rock Rb-Sr isochron age of 2155 ± 80 m.y. using 9 samples from 7 sheets and a feldspar Rb-Sr isochron age of 1700 ± 50 m.y.; the former he interpreted to be the age of intrusion and the latter a metamorphic event during the Hudsonian Orogeny. There are three whole rock K-Ar age dates reported for 'dykes' in the area which appear concordant with the host Huronian sediments and which would be classified as 'sheets' in this study. Their reported ages of 1465, 1660 and 1400 ± 120 m.y. (Wanless et al., 1965, pp. 91-92; Wanless et al., 1968, p. 96) are probably the minimum age of intrusion and reflect metamorphism during the Hudsonian Orogeny.

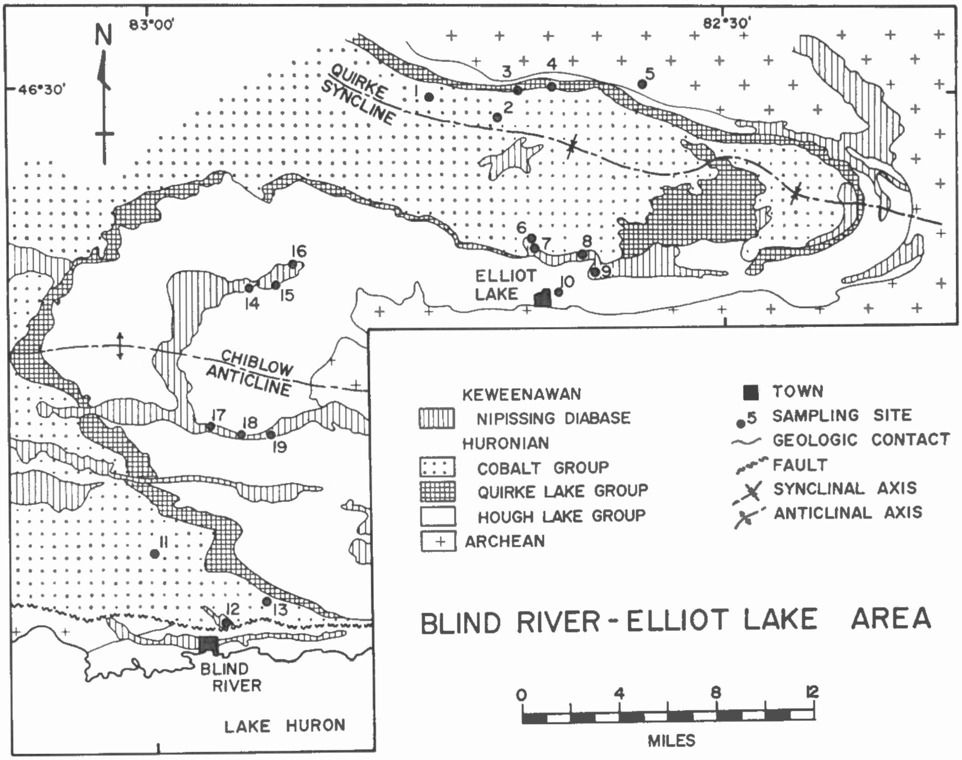

Figure 1: Site location map.

Similar metamorphic overprinting is found in the Huronian sediments immediately to the east in the Espanola-Sudbury district which give a young Rb-Sr isochron age of 1950 ± 100 m. y. (Fairbairn et al., 1969).

The Nipissing dykes strike dominantly northwest-southeast but also east-west and north-south, and are commonly less than 50 metres wide. Although they have diabasic instead of gabbroic texture, they have the same mineralogical composition as the sheets. Robertson (1962, 1963b, 1964) reports instances where the dykes appear to be syntectonic feeders or apophyses of the sheets and instances where the dykes appear to be post-tectonic and cross-cutting the sheets. He suggests that all the dykes were intruded nearly simultaneously into a set of pre-existing fractures and derived from the same magma source as the sheets. There are four whole-rock K-Ar ages of 1995, 1600, 1390 ± 120 and 1340 ± 120 m. y. and one biotite-hornblende K-Ar age of 1660 ± 135 m. y. from Nipissing dykes in or close to the area (Leech et al., 1963, p. 74; Wanless et al., 1968, pp. 97-98; Wanless et al., 1966, pp. 70-71) which probably reflect the minimum age of intrusion.

The Nipissing diabase occurs as a thousand-foot-thick sill in the Cobalt area of Ontario, 120 miles to the northeast of Elliot Lake. The sill gives radiometric age dates of 2180 m. y. using the whole rock Rb-Sr method (Van Schmus, 1965), of 2095 m. y. using the biotite K-Ar method

(Lowdon et al., 1963, p. 92), and of 2162 ± 27 m.y. using the Rb-Sr isochron method at Gowganda nearby (Fairbairn et al., 1969). The sill has a stable primary remanence (Symons, 1967a) and paleomagnetic study of it indicates that the sill was intruded after the enclosing Huronian sediments were folded (Symons, 1970). In this study, the paleomagnetic method is used to examine the tectonic and intrusive evolution of the Nipissing sheets and dykes in the Blind River - Elliot Lake area.

PROCEDURE

Five or six oriented cores were collected at each of 19 sites - 8 sites representing 8 dykes and 11 sites representing 3 sheets of Nipissing diabase - across the Quirke Syncline-Chiblow Anticline structure (Fig. 1, Table 1).

The natural remanent magnetization (NRM) was measured for 2 specimens from each core. One pilot specimen per site for sites 1 to 13 was subjected to stepwise alternating field (AF) demagnetization. The rapid decrease in remanence intensity of most pilot specimens with increasing intensity of AF demagnetization (Fig. 2) and the "unstable" to "poorly stable" stability index values, i.e. SI<2.5 (Tarling and Symons, 1967) of more than half the specimens (Table 1) indicated that most specimens probably had weak stable remanence components dominated by strong unstable components. Accordingly, the remaining specimens at most sites were AF demagnetized at two successive field strengths of which the more homogeneous result in terms of remanence direction was used for analysis. The resulting site mean remanence intensities after AF demagnetization are weak, i.e. 0.12 to 42.2 x 10^{-5} emu/cc (Table 1). The remanence of 5 cores proved too weak (<5 x 10^{-7}emu/cc) to be reliably measured. In 30 cores, the standard error of the core mean remanence direction derived from the 2 specimen vectors exceeded 10°, and so these cores were rejected. A standard error exceeding 10° was taken to indicate an unacceptable inhomogeneity in magnetization at the core and site levels but not at the formation level where secular variation in the paleofield or inter-site tectonic rotations can be expected to cause the remanence directions to be more dispersed. In 9 sites, one core was rejected because it was found to have an anomalous remanence direction deviating by more than three times the standard deviation of the remaining core remanence directions from their mean. For site 3, only one reliable core remained which was regarded as insufficient representation on which to base site mean statistics, and hence this site or core was rejected. After calculation of the site mean remanence direction statistics, the standard error for site 2 was found to exceed 10° and so this was also rejected from further consideration. As a result, 14 sites including 51 per cent of the cores in the collection were considered to yield reliable site mean remanence directions.

DISCUSSION OF RESULTS

Dykes

All 6 site mean remanence directions derived from the Nipissing dykes are normally polarized (Fig. 3a). Applying the fold test (Graham, 1949) to

Table 1. Site geological and remanence data

SITE		HOST ROCK		AF DEMAGNETIZATION				SAMPLING					MEAN REMANENCE				
I	II	STR	DIP	SI	RANGE	FIELDS	J_{av}	N	I	II	III	n	D_s	I_s	R	δ_{95}	SE
1	D	80	35	2.42	0-100	100, 300	6.4	5		1	1	3	349.8	73.6	2.9576	11.8	6.8
2	D	100	30	17.3	200-400	200	9.9	5		1		4	127.7	76.0	3.5980	25.7	14.8
3	D	80	40	2.48	200-400	300	.76	5		4		1	314.2	60.5			
4	D	95	20	7.31	50-300	200	4.4	5		2	1	2	256.9	64.3	1.9923	8.7	5.0
5	D	100	40	18.4	300-800	300	33.2	5				5	253.7	35.7	4.9958	2.0	1.2
6	S	280	20	14.8	100-300	200	.67	5		2	1	2	250.3	22.8	1.9967	5.7	3.3
7	S	290	15	.36	50-800	200, 400	.50	5		5							
8	S	280	15	.45	0-800	100, 300	1.09	5		5							
9	S	275	20	.77	0-200	100, 300	.12	5		5							
10	D	275	25	.59	0-100	100, 300	6.7	5		2	1	2	293.3	81.0	1.9844	12.4	7.1
11	D	110	20	3.16	200-400	300	1.17	5				5	280.0	72.9	4.8627	11.6	6.7
12	S	85	20	5.97	200-800	300	5.1	5	2			3	294.2	-62.6	2.9500	12.8	7.4
13	D	110	20	1.86	50-200	200, 400	7.5	5			1	4	266.2	68.8	3.9767	6.2	3.6
14	S	265	5			100, 200	42.2	5			1	4	356.8	-44.4	3.9806	5.6	3.3
15	S	255	5			100, 200	31.9	6	1		1	4	358.5	-50.5	3.9953	2.8	1.6
16	S	270	5			100, 200	1.36	6		1	1	4	357.6	34.4	3.9846	5.0	2.9
17	S	95	10			100, 200	17.6	6			1	5	311.4	56.6	4.7345	16.2	9.4
18	S	95	10			100, 200	22.0	6	2			4	359.7	-43.3	3.9948	2.9	1.7
19	S	100	10			100, 200	4.7	6		2		4	262.5	65.7	3.8549	15.4	8.9
MEAN	S											8*	200.8	69.1	6.6272	22.0	12.7
MEAN	D											6*	271.1	69.0	5.6997	14.0	8.1

SITE	I number; II form of diabase sheet - (D) dyke, (S) sill-like sheet
STR, DIP	strike and dip in degrees using the right-hand convention
SI, RANGE	stability index of pilot specimen and range of demagnetization fields (peak) in oersteds it represents
FIELDS	demagnetization fields (peak) in oersteds of all site specimens with the underlined field used for statistics
J_{av}	average intensity in emu x 10^{-5}/cc of 10 specimens after demagnetization
SAMPLING	number of cores collected (N); cores rejected because their remanence proved too weak to measure reliably (I) or internally inhomogeneous (II) or anomalous for the site (III); cores used for statistics (n); sites used for statistics (n*)
D_s, I_s	declination and inclination (+ ve down) in degrees of mean remanence vector
R	resultant giving each core unit weight
α_{95}, SE	radius of the cone of 95 per cent confidence and standard error in degrees

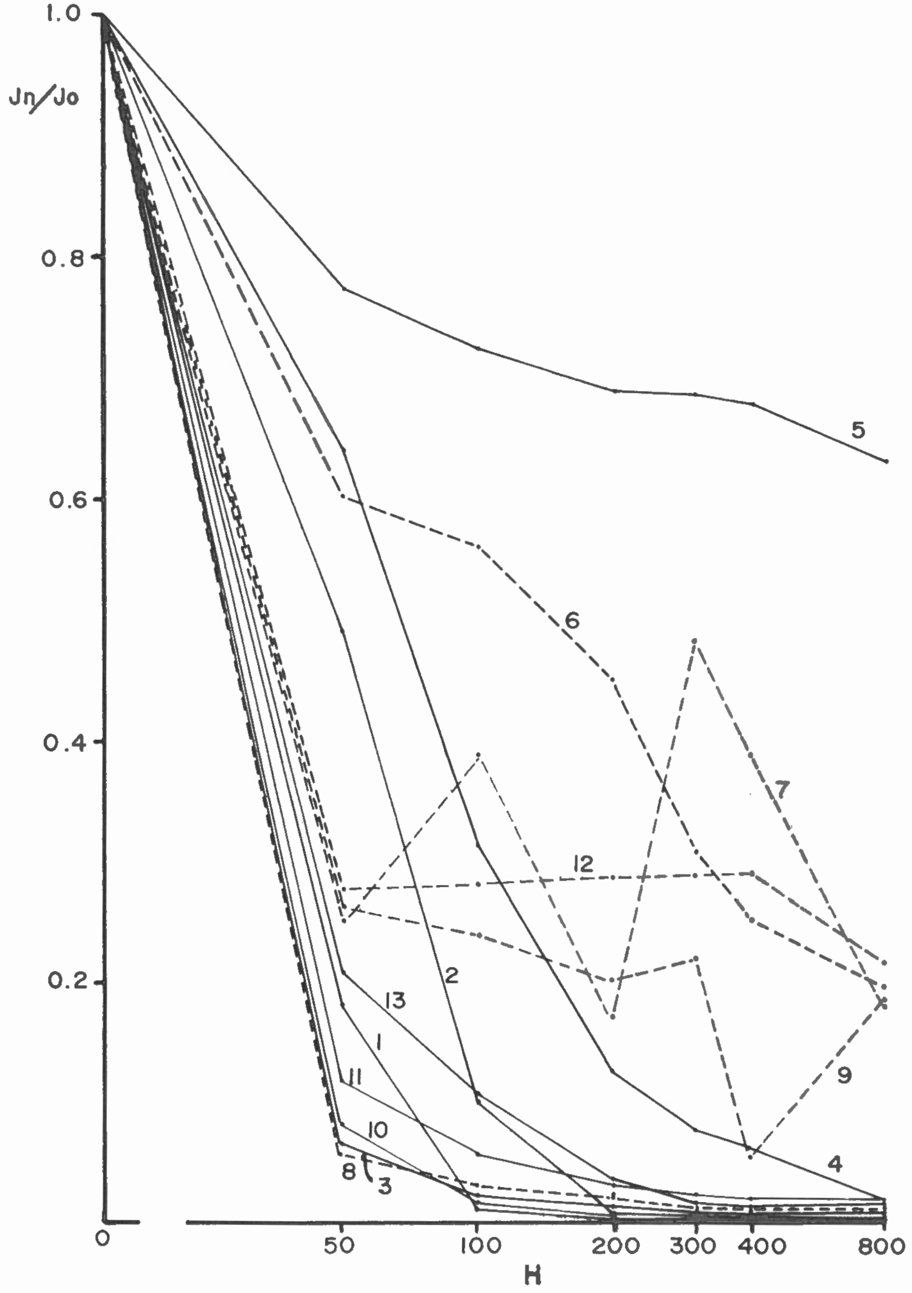

Figure 2. Alternating field demagnetization curves. H is the field strength in oersteds: Jn/Jo is the ratio of the intensity of the measured remanence to the original remanence where Jo for the specimen from site:

1 is 5.15×10^{-2}	4 is 3.89×10^{-4}	7 is 2.16×10^{-5}	11 is 2.95×10^{-4}
2 is 7.12×10^{-2}	5 is 8.80×10^{-4}	8 is 8.56×10^{-4}	12 is 3.24×10^{-4}
3 is 5.33×10^{-3}	6 is 1.87×10^{-5}	9 is 1.07×10^{-5}	13 is 1.96×10^{-3}
		10 is 3.23×10^{-3}	emu/cc.

Nipissing sheets (dykes) are shown as solid (dashed) curves.

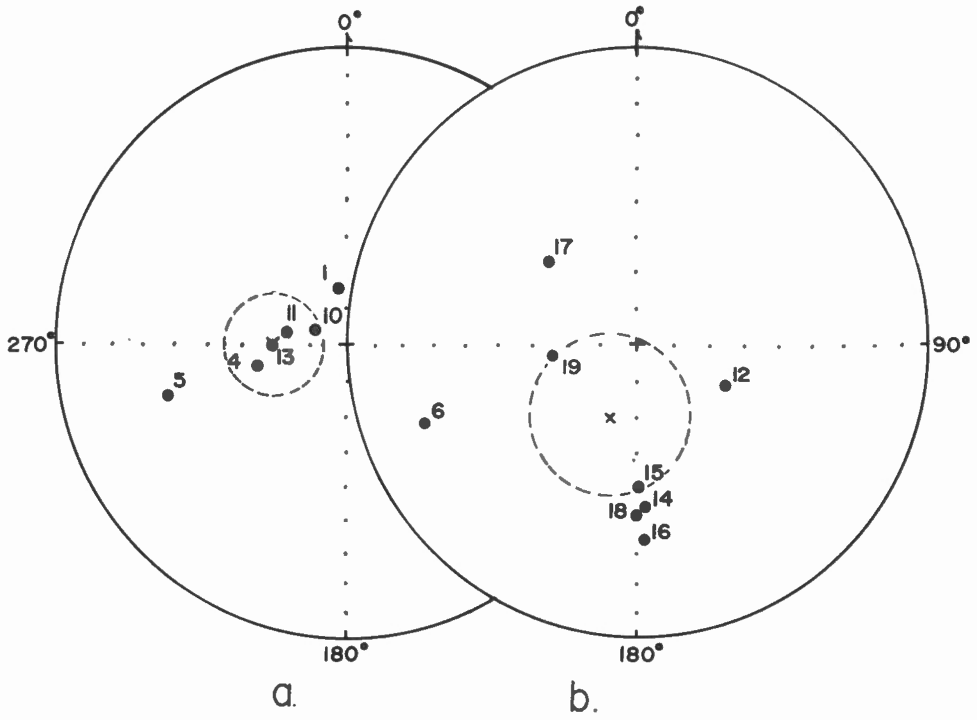

Figure 3: The site mean remanence directions for the Nipissing dykes (a) and sheets (b) are shown in the lower hemisphere of an equal area stereonet. The directions for sites 12, 14-16, and 18 have been rotated through 180°. The dashed circle is cone of 95% confidence about the mean (X).

these directions and using the attitudes of the enclosing Huronian sediments (Table 1) to make the tectonic corrections, the radius of the core of 95 per cent confidence (α_{95}) increases from 14.0° before to 22.6° after correcting. Analysis of the angular variances (Larochelle, 1968) indicated that the "before" and "after" remanence direction dispersion distributions are significantly different at the 0.07 probability level. The conclusion drawn with 93 per cent confidence is that the remanence directions are dispersed by applying tectonic corrections. This implies that these dykes acquired their remanence after folding of the Huronian sediments. Applying the dipole formula to the uncorrected site mean directions gives a pole position of 131°W, 36°N. Comparing this position to the few available pole positions for North American rock formations of Aphebian age (1700-2500 m. y.) (Table 2; Fig. 4) shows that it agrees most closely with those from the Marathon dykes dated at 1810 m.y. and from the Sudbury Irruptive norite dated at 1704 m.y. (Fairbairn *et al.*, 1968) which were sampled about 200 miles to the northwest and 100 miles to the east respectively. Recalling that the oldest available K-Ar age date for these dykes is 1995 m.y., the simplest and preferred explanation is that the sampled Nipissing dykes were intruded about 2, 000 m. y. ago after the enclosing Huronian sediments were folded, and that they retain a primary remanence acquired during cooling.

Table 2. Pole positions for North American formations of Aphebian age

FORMATION	LOCATION	AGE (b.y.)	REFERENCE	N	n	P	POLE POSITION			
							Lat. (°N)	Long. (°W)	δ_p	δ_m
1 Matachewan dykes (SW)	Timmins, Ontario	2.5	Fahrig *et al.* (1965)	25	39*	M	-37.2	120.8	6.3	12.5
2 Matachewan dykes (NE)	Timmins, Ontario	2.5	Fahrig *et al.* (1965)		15*	+	-62.9	118.8	13.3	21.6
3 Huronian Cobalt sediments	Cobalt, Ontario	2.288	Symons (1967a)	8	8*	-	21.5	97.5	23.8	26.4
4 Gunflint iron-formation	Port Arthur, Ontario	2.5 - 1.8	Symons (1966)	20	20*	M	28	94	9	10
5 Negaunee iron-formation	Marquette, Michigan	2.5 - 1.8	Symons (1967b)	6	6*	+	-33	75	11	21
6 Negaunee hard hematite ore	Marquette, Michigan	2.5 - 1.8	Symons (1967b)	8	8*	+	-8	144	6	11
7 Nipissing diabase sill	Cobalt, Ontario	2.15	Symons (1970)	11*		-	-19.4	88.1	3.9	6.5
8 Nipissing diabase sheets	Elliot Lake, Ontario	2.155	this paper	8*	60	M	-0.8	98.4	25.2	33.3
9 Nipissing diabase dykes	Elliot Lake, Ontario	2.0	this paper	6*	34	+	35.5	131.4	20.3	23.9
10 Marathon dykes	Marathon, Ontario	1.8	Fahrig *et al.* (1965)	4	9*	+	29.0	146.8	12.2	16
11 Sudbury norite, north limb	Sudbury, Ontario	1.7	Sopher (1963)		68*	+	47.0	107.0	8	9

Notes: AGE (b.y.) in 10^9 years; N (n) is the number of sites (specimens) with the asterisk indicating the statistical basis for the pole position; and, P is the remanence polarity shown as positive (+), negative (-) or mixed (M); δ_p and δ_m are the semi-axes of the cone of 95 per cent confidence.

Figure 4: Pole positions for North American rock formations of the Aphebian Era. The formation numbers correspond to those in Table 2 with the age given in slope numbers in 10^9 years. The arrows suggest the trend of the polar wandering curve. The plot is an azimuthal equal-area projection centred on 0° N, 110° W.

An alternative explanation is that these dykes retain a secondary post-folding remanence acquired during a metamorphic event around 2000 m. y. ago. This latter alternative is unlikely because the metamorphic event would have to affect all of the dykes sites while leaving most or all of the sites in the Nipissing sheets unaffected. Finally, it is likely that these dykes were intruded within one normal polarity interval or nearly simultaneously as the geological evidence suggests (Robertson, 1964).

<u>Sheets</u>

The interpretation of the 8 site mean remanence directions from the Nipissing sheets is more complex because of their mixed polarities. Of the

6 directions from the one sheet around the nose of the Chiblow Anticline, 4 are reversely polarized and 2 normally polarized, and of the 2 directions from the other 2 sheets, 1 is reverse and 1 is normal. Sites 14, 15, 16 and 18 yield a cluster of directions that deviate both before and after tectonic correction by only about 8° of arc from the mean remanence direction obtained from the Nipissing sill at Cobalt (Symons, 1970). This agreement supports the radiometric evidence that the sheets and sill were both intruded about 2150 m. y. ago and that the sheets retain a primary remanence. When all 5 reversed site mean directions are rotated through 180° and the 3 normal site mean directions are included (Fig. 3b), a less cohesive group results. Applying a fold test as before causes α_{95} to decrease slightly from 22.0° before to 20.1° after correcting. Variance analysis indicates that the direction distributions are not significantly different and so the data cannot be used to decide whether intrusion occurred dominantly before or after folding of the enclosing Huronian sediments. The test is consistent with the hypothesis suggested by Robertson (1964) that the sheets were intruded during folding as is the fact that applying tectonic corrections caused the sheet mean remanence direction to be displaced by only 2°. Also, the pole position determined for the Nipissing sheets from the mean of the eight site mean remanence directions is 98°W, 1°S which agrees most closely with that of the Nipissing sill at Cobalt (Table 2; Fig. 4). The mixed remanence polarities, the distribution of site mean remanence directions, the results of the fold test, and the pole position are most reasonably explained as follows. The Nipissing sheets have a primary remanence and were intruded over a prolonged period of time (10^6–10^8 years, i.e. sufficient for some polar wander to occur) about 2150 m. y. ago during folding of the Huronian sediments. The remanence of some of the sheet sites, notably site 19 which gives a direction in the midst of the Nipissing dyke directions, may have been affected by intrusion of the Nipissing dykes, but most sites clearly do not show such effects.

Summary

Angular variance comparison of the site-mean remanence directions for the Nipissing dykes and sheets indicates with 94 per cent confidence that the dyke mean and sheet mean directions differ significantly and with 97 per cent confidence that the dispersion distributions about the group mean directions differ significantly. Since 5 of the 8 sheet mean directions have been rotated through 180° into the lower hemisphere to make this analysis, the actual per cent confidence values would be even higher. Clearly it is not valid to combine the two direction populations into one homogeneous population which leads to the geological implication that the dykes and sheets on average acquired their remanence at markedly different times. The pole positions for the dykes and sheets are about 45° apart (Table 2; Fig. 4). Based on known rates of polar wander obtained from younger North American rock formations (Irving, 1964), a reasonable time interval between their remanence acquisitions would be in the order of 3×10^7 to 3×10^8 years. This interval is consistent with the interpretation given above that the sheets were intruded about 2150 m. y. ago and that the dykes were intruded about 2000 m. y. ago. Finally, when the few available pole positions for North American rock formations of the Aphebian Era are plotted on a projection of the earth's surface, despite the imprecision of both the positions and the ages, a generally consistent trend for the polar wander curve can be drawn, and the rate of wander during the 800 m.y. time interval represented in the Aphebian Era appears similar to that found for younger eras (Irving, 1964; Sopher, 1963).

CONCLUSIONS

The results of this initial paleomagnetic study of the Nipissing diabase in the Blind River-Elliot Lake area suggest the following tentative conclusions:

1) Both the Nipissing sheets and dykes contain generally weak but stable primary remanence components which tend to be masked by much stronger unstable components.

2) The sheets were emplaced over the time period of 2 or more polarity intervals, and perhaps as multiple intrusives in some cases although there are no mapped occurrences to date. Intrusion likely occurred during folding of the Huronian sediments as suggested by Robertson (1964) and by Church (1968) in postulating the influence of the Penokean Orogeny (≈2200 m. y. ago) in the area. The pole position for the Nipissing sheets (98°W, 1°S) agrees most closely with that determined for the Nipissing sill at Cobalt, Ontario, and this agreement supports the radiometric age dating evidence of Van Schmus (1965) that both were intruded about 2155 m. y. ago.

3) The sampled dykes appear to have been emplaced within one polarity interval or nearly simultaneously as suggested by Robertson (1964). Intrusion occurred after folding of the Huronian sediments and after intrusion of the sheets by tens of millions of years. The pole position for the dykes (131°W, 36°N) agrees most closely with those of two other formations dated at 1700 to 1800 m. y. which suggests that the oldest radiometric age date of 1995 m. y. available for the dykes closely approximates the date of intrusion.

4) Additional paleomagnetic work is required to establish more rigorously the sheet and dyke pole positions, to examine for more than one age of dyke intrusion, to determine clearly if the sheets were intruded as single or multiple intrusives dominantly before, during, or after intrusion, and to test for regional tectonic rotations as for example between the Elliot Lake and Cobalt areas.

5) If the age difference of some 160 m.y. between intrusion of the sheets and dykes is substantiated by radiometric, geological or geochemical work, then the term "Nipissing" should be retained for the sheets or sills and the dykes should be renamed.

6) Polar wander occurred during the Aphebian Era (2.5-1.7 b.y.) relative to North America at a rate which appears to be consistent with that found for younger eras.

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MAGNETOCHEMICAL ASPECTS OF THE HEATING OF RED AND GREEN BEDS

E.J. Schwarz

ABSTRACT

Thermomagnetic analyses of Paleozoic red sandstones containing green inclusions of sandstone collected in New Brunswick, Canada, show that a significant amount of Fe_3O_4 is generated in the red matrix if heated in air of low pressure or in nitrogen atmosphere although no magnetite is generated in the green inclusions. Microscopic investigation of thin sections of the red and green sediments revealed only minor mineralogical differences with the exception of the pigment. Moreover, the X-ray diffractograms of the red and green sediments essentially match peak by peak. Hence, it is concluded that the pigment minerals in the red sediments were involved in the production of magnetite. The thermomagnetic records showed that hematite (a pigment mineral) was present in the red matrix only, and consequently a part of it may have been reduced to magnetite. Organic compounds may be supposed to serve as reducing agents. Such compounds tend to be oxydized rapidly during heating of the specimens in air at atmospheric pressure. Dehydration of iron (oxy-) hydroxides probably did not play a significant role in the production of magnetite as such compounds should be present in the green inclusions as well.

INTRODUCTION

Thermomagnetic analyses of red sediments have shown that a significant amount of magnetite tends to be generated above 400°C during heating in air of low pressure or in nitrogen atmosphere (Kobayashi and Schwarz, 1966; Schwarz, 1969; see also Stephenson, 1967). The magnetic signal due to the generated magnetite after cooling to 20°C was found to be up to about 20 times larger than that of the original specimen. The agents active in the generation of magnetite could not be identified but it was tentatively suggested that a minor part (up to 10 per cent) of the αFe_2O_3 present in the specimens was reduced to magnetite (Fe_3O_4). The reducing agent would be inactive during heating of the specimens in air of atmospheric pressure before the temperature of the specimens reached 400°C. Because many paleomagnetic studies are based on the results obtained by thermal demagnetization of red beds for which the generation of magnetite is undesirable, it appeared worthwhile to investigate the matter further.

In many series of detrital red beds, green inclusions and intercalations of green detrital sediments are observed. The red pigment, which may consist of hematite, goethite, maghemite, and limonite (e. g. van Houten, 1968) evidently is absent from these inclusions. Consequently, thermomagnetic analyses of the green inclusions and the red matrix should show whether these ferric oxides were involved in the generation of magnetite.

EXPERIMENTAL RESULTS

The samples (15) selected for the present study come from New Brunswick and are of Paleozoic age. These samples consist of green inclusions

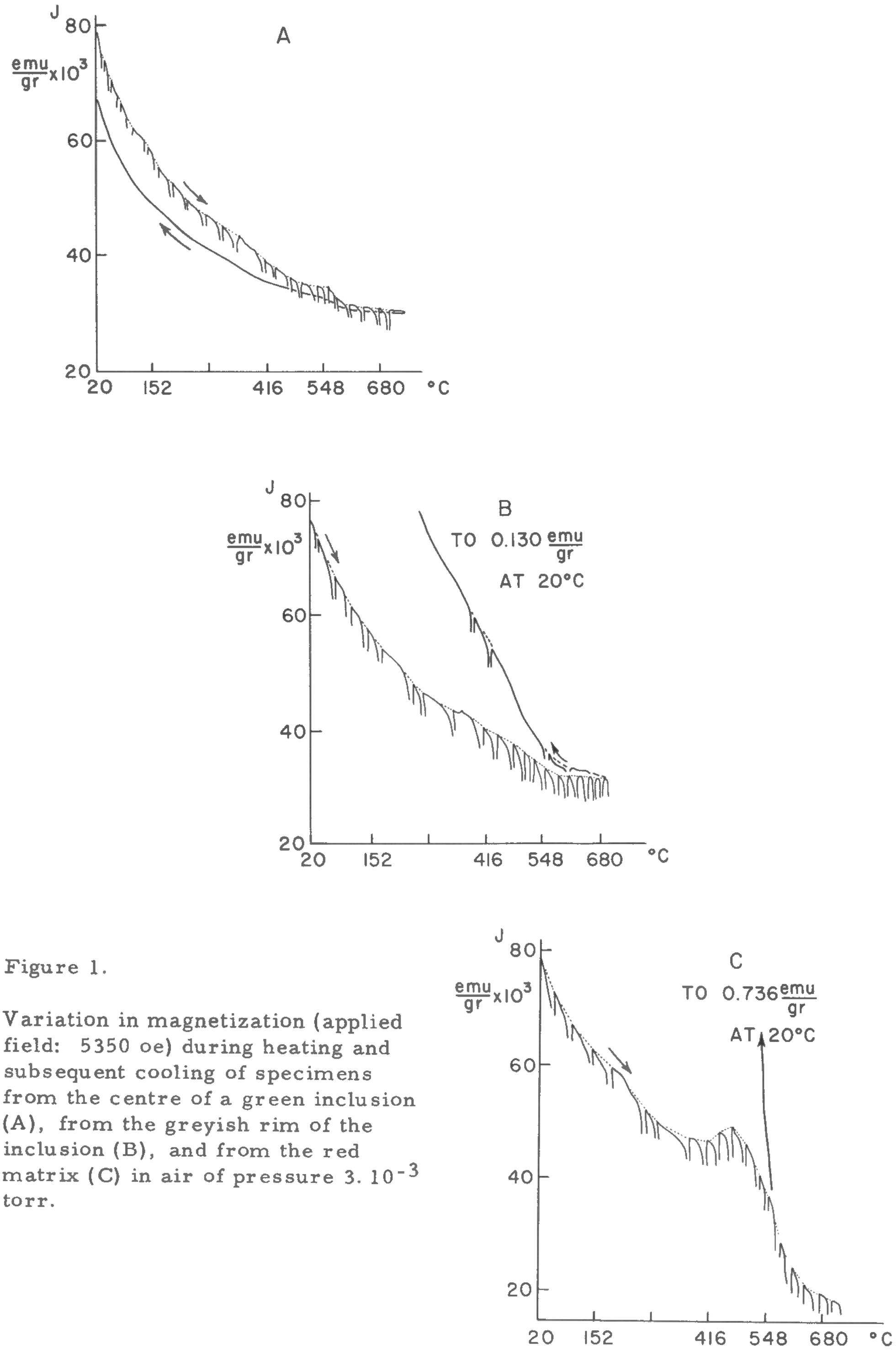

Figure 1.

Variation in magnetization (applied field: 5350 oe) during heating and subsequent cooling of specimens from the centre of a green inclusion (A), from the greyish rim of the inclusion (B), and from the red matrix (C) in air of pressure 3.10^{-3} torr.

of sandstone in a red sandstone matrix. A microscopic study of thin sections of the red and green sandstones did not reveal significant differences with the exception of the pigment. Moreover, X-ray diffractograms of the red and green parts of individual samples match essentially peak by peak but obvious differences were observed between the samples. Quartz, micas, chlorite, and in many cases feldspar and calcite were identified. Consequently, it appears that the pigment minerals constitute the only conspicuous difference between the green inclusions and the red matrix within each sample.

The thermomagnetic experiments were done with a recording magnetic balance (Schwarz, 1968). Single pieces cut from the samples and weighing between 25 and 40 milligrams were used. These specimens were heated either in air of low pressure (10^{-2} to 10^{-3} torr) or in rather pure nitrogen of approximately atmospheric pressure while the force exerted on each specimen by an inhomogeneous magnetic field was recorded continuously.

Figures 1 A, B, and C depict a set of representative results as traced from the records. The interruptions in the curves are due to checking the specimen weights and to correcting for any change in weight. The specimen cut from the green coloured inclusion probably contains a small amount of magnetite with a Curie point of about 580°C (Fig. 1A). There is no indication of the presence of hematite, and the cooling curve does not differ greatly from the heating curve. Heating in air at atmospheric pressure yielded similar results. The specimen cut from the greyish outer rim of the inclusion probably contains small amounts of magnetite and hematite as suggested by the relatively rapid changes in magnetization just below 580 and 680°C (Fig. 1B). However, on cooling below 580°C a relatively strong signal was observed which is probably due to an increase in the magnetite content. No such increase occurred if a specimen was heated in air at atmospheric pressure. The specimen cut from the red matrix exhibits an anomalous increase in magnetization during heating from 400 to 450°C (Fig. 1C). Both magnetite and hematite probably are present. The cooling curve differs strongly from the heating curve below 580°C. Thus, a large amount of magnetite probably is generated in the red matrix in contrast to the green inclusions if heated in air of low pressure or in nitrogen atmosphere. Little or no magnetite is produced if matrix specimens are heated in air of atmospheric pressure (Schwarz, 1969). Heating of pure synthetic αFe_2O_3 at low air pressure did not result in the production of Fe_3O_4.

CONCLUSIONS

1. Both magnetite and hematite were detected in the red matrix. The green nodules in the red matrix appear to contain only some magnetite.

2. A significant amount of Fe_3O_4 is generated during heating of red bed samples in vacuum or in nitrogen atmosphere. On the other hand, no Fe_3O_4 is produced in the green inclusions under the same conditions. Thus, it appears that α Fe_2O_3 (pigment) and possibly Fe (oxy-) hydroxides are involved in the generation of fine-grained Fe_3O_4 in red beds. The agent responsible for this reduction could not be identified. It may be that organic compounds which tend to be oxydized below 400°C in air of atmospheric pressure were operative. Such compounds may be expected to occur in particular the green inclusions in which, however, α Fe_2O_3 was not observed.

3. The high degree of reversibility of the heating and cooling curves for specimens of the green inclusions suggests that it may be advantageous to sample such rocks if present in a red bed sequence for paleomagnetic studies employing thermal demagnetization. On the other hand, the stability spectrum of the natural remanent magnetization of the green sediments may well be inferior to that of red sediments, as reported by Runcorn (1957) for green beds from England. An obvious reason for this is the absence of hematite in the green sediments.

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