73-19

GEOLOGICAL SURVEY OF CANADA

DEPARTMENT OF ENERGY, MINES AND RESOURCES

PAPER 73-19

1. PALEOMAGNETIC RESULTS FROM THE TERTIARY MOUNT BARR AND HOPE PLUTONIC COMPLEXES, BRITISH COLUMBIA

2. UNIT CORRELATIONS AND TECTONIC ROTATION FROM PALEOMAGNETISM OF THE TRIASSIC COPPER MOUNTAIN INTRUSIONS, BRITISH COLUMBIA

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CONTENTS

Page

Paleomagnetic results from the Tertiary
Mount Barr and Hope Plutonic
Complexes, British Columbia

D. T. A. Symons

Illustrations

Unit correlations and tectonic rotation
from paleomagnetism of the Triassic
Copper Mountain Intrusions, British Columbia

D. T. A. Symons

Page

Illustrations

A Ballistic Magnetometer for the measurement of rock magnetic properties

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Illustrations

1. PALEOMAGNETIC RESULTS FROM THE TERTIARY MOUNT BARR AND HOPE PLUTONIC COMPLEXES, BRITISH COLUMBIA

D.T.A. Symons

ABSTRACT

The Hope and Mount Barr felsic plutonic complexes outcrop in the Cascade Mountains in southernmost British Columbia. Intrusive rocks of sialic composition have rarely been studied paleomagnetically because of remanence instability, however, a stable primary remanent magnetization has been isolated in 5 of 7 sites from each complex after alternating field demagnetization. Individual plutons within each complex give coherent clusters of either normal or reversed remanence directions indicating that they were intruded and cooled sequentially rather than concurrently. The upper Eocene to lower Oligocene Hope complex gives a pole position of 151.9°W, 87.7°N (δm 6.1°, δp 5.1°) which is concordant with poles from coeval North American units. The mid-Miocene Mount Barr pole position of 85.8°W, 72.4°N (δm 14.6°, δp 13.3°) is slightly discordant possibly because of non-representative sampling. The results suggest that these complexes have not been rotated relative to the North American craton since their emplacement.

RÉSUMÉ

Les complexes plutoniques felsiques de Hope et du mont Barr affleurent dans les monts Cascades à l'extrême sud de la Colombie-Britannique. On a effectué peu d'études paléomagnétiques sur les roches intrusives de composition sialique en raison de l'instabilité de la rémanence; toutefois, on a réussi à isoler une aimantation rémanente primaire stable dans 5 des 7 sites de chaque complexe après démagnétisation dans un champ alternatif. Les plutons individuels dans chacun des complexes présentent des groupes cohérents de directions de la rémanence qui sont parfois normales, parfois inversées, indiquant une intrusion et un refroidissement en succession plutôt que simultanés. Les calculs relatifs au complexe de Hope, de l'Éocène supérieur à l'Oligocène inférieur, placent le pôle par 151.9° W, 87.7° N (δm 6.1°, δp 5.1°), ce qui correspond à la position du pôle indiquée par des unités nord-américaines de même âge. La position du pôle calculée d'après les données provenant du mont Barr, du Miocène moyen, (85.8° W, 72.4° N (δm 14.6°, δp 13.3°), est légèrement discordante probablement en raison d'un échantillonnage non représentatif. Les résultats semblent signifier que ces complexes n'ont pas pivoté par rapport au craton nord-américain depuis leur mise en place.

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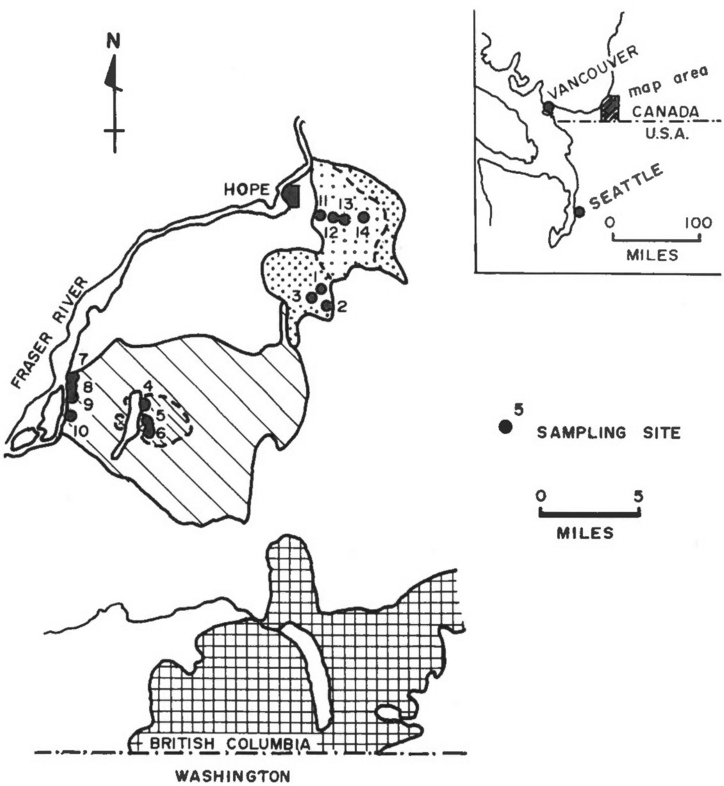

Figure 1-1. Location of sampling sites and general geology simplified from Richards and White (1970).
The geological units are the: Hope plutonic complex (stippled) with the older quartz monzonite pluton (sites 11, 12, 13, and 14) and younger quartz diorite plutons (sites 1, 2, and 3); Chilliwack plutonic complex (cross-hatched); and the Mount Barr plutonic complex (diagonal lines) with older quartz monzonite-quartz diorite pluton (sites 7, 8, 9, and 10), intermediate granodiorite stock (site 4), and younger quartz monzonite stock (sites 5 and 6).

INTRODUCTION

The Chilliwack felsic batholith straddles the Canada - United States border in the Cascade Mountains about 90 miles east of Vancouver, and south of Hope, British Columbia. Based on petrologic and K-Ar radiometric age studies, Richards and White (1970) have subdivided the batholith as mapped by Cairnes (1944) into three complexes. They restrict the term "Chilliwack batholith" to a complex of three plutons (not sampled in the present study) straddling the Canada - U.S.A. border around Chilliwack Lake where Daly (1912) originally defined the unit. Five K-Ar determinations from this complex give upper Oligocene to lower Miocene age of 26 to 29 m.y. The other two units are the Hope and Mount Barr plutonic complexes (Fig. 1-1).

The Hope plutonic complex outcrops a few miles southeast of Hope, B.C. It is composed of a central pluton of leucocratic quartz monzonite giving an age of 41 ± 2 m.y. (Richards and White, 1970). It is in sharp contact on its northeast and southwest sides with two later plutons of biotite hornblende quartz diorite both of which give an age of 35 ± 2 m.y. The complex is therefore considered to be upper Eocene to lower Oligocene in age.

The Mount Barr plutonic complex is centred around Wahleach Lake between the Chilliwack and Hope complexes. The main pluton has a quartz monzonite core grading radially outwards to quartz diorite. Within the core there is a younger stock of biotite hornblende granodiorite and a still younger stock of leucocratic biotite quartz monzonite. An offshoot granophyric dyke is the fourth pluton included in the complex. The K-Ar radiometric ages reported by Richards and White (1970) of 21 ± 1, 18 + 1, and 16 ± 1, by Baadsgaard _et al_. (1961) of 18 and 18 m.y. indicate a mid-Miocene age for the complex.

The Hope and Mount Barr plutonic complexes were sampled during the summer of 1969 as part of an extensive paleomagnetic study of felsic plutons in the Canadian Cordillera. They were sampled as representative of the youngest, least tectonically disturbed and unmetamorphosed felsic plutons known (McTaggart and Thompson, 1967). By comparing their remanence directions with those obtained from contemporaneous units known to have stable remanent magnetization, they provide a test to determine whether felsic plutons can yield reliable paleomagnetic data. Relatively few paleomagnetic studies have been carried out on rocks of this composition and only some of these indicate the retention of a stable primary remanence (Hays and Scharon, 1966; Grommé _et al_., 1967; Symons, 1971a and 1971b; Spall, 1971). Other studies have involved felsic rocks that were remagnetized during metamorphism (Spall, 1970a) or possess unstable remanence only (Spall, 1970b; Yaskawa _et al_., 1966).

SAMPLING

Seven sites were collected from the Hope complex of which four (11-14) represent the older quartz monzonite pluton and three (1-3) the younger southwesterly quartz diorite pluton (Figure 1). Seven sites were also collected from the Mount Barr complex of which four (7-10) represent the main pluton in the outer quartz diorite zone, one (4) the granodiorite stock, and two (5 and 6) the leucocratic quartz monzonite stock.

Five or six cores, oriented in situ by sun compass, were collected at each site. The natural remanent magnetization (NRM) of two specimens from each core was measured using an automated biastatic magnetometer (Larochelle and Christie, 1967). One specimen with an average NRM direction and intensity from each site was partially demagnetized in alternating fields (AF) (Larochelle and Black, 1965) of the following peak intensities: 50, 100, 200, 300, 400, 500, 650, and 800 oersteds. The remanence was remeasured after AF treatment. Using the stability index (SI) method (Tarling and Symons, 1967), a field was selected for each site in which its remaining specimens were AF demagnetized or cleaned prior to remeasuring their remanence. Three sites (6, 10 and 15) were cleaned at two different field intensities. The least successful cleaning in terms of within-site grouping of remanence directions was rejected.

ANALYSIS

The SI values for 8 of 14 step demagnetized specimens gave unstable values (<2.5). Hence the following criteria were used to isolate reliable stable site mean remanence directions.

I) All cores with a remanence intensity of $<1 \times 10^{-6}$ emu/cc were rejected as being too weak to be accurately measured.

II) All cores were rejected as inhomogeneously magnetized in which the remanence directions of the two specimens diverge by more than 23°.

III) After the first and second criteria were applied, if only one core remained to represent the site it was rejected as insufficient evidence of a reliable site direction.

IV) If one core mean remanence direction deviated by more than three times the standard deviation from the mean direction of the remaining three or more cores representing the site, the anomalous direction was rejected.

As shown in Table 1-1, criteria I, III and IV led to the rejection of only 1, 3 and 1 core respectively. Criteria II led to the rejection of 23 cores and the majority of these had weak remanence intensities of $<5 \times 10^{-6}$ emu/cc. The usefulness of selection criteria is illustrated by the increase in the average SI values with decreasing rejection of cores - both are independent measures of remanence stability - i.e., the four sites with all cores rejected give an average SI value of 0.85, the four sites with some cores rejected give 2.1, and the six sites with no cores rejected give 5.8. Giving the 3 or more core mean remanence directions unit weight, the site mean remanence directions were calculated for 10 sites. These 10 sites are considered to have homogeneous remanent magnetization because each has a circular standard error about its mean direction of less than 10°.

DISCUSSION

The site mean remanence directions indicate that the subdivision of the batholith into plutonic units as proposed by Richards and White (1970) is correct. As shown in Figure 1-2a, the two valid sites from the older quartz

TABLE 1-1

Site Statistics

SITE	GEOL	LOCATION		AF STEP DEMAGNETIZATION			DATA SELECTION						SITE MEAN REMANENCE					
		Lat.°N	Long.°W	SI	RANGE	FIELD	N	I	II	III	IV	n	R	DECL	INCL	k	α_{95}	SE
1	H-QD	49.31	121.41	4.2	50-300	100	5					5	4.9754	348.0	66.9	162	4.9	2.9
2	H-QD	49.30	121.40	3.0	50-300	200	5		2			3	2.9820	357.6	63.8	111	7.7	4.5
3	H-QD	49.31	121.41	5.4	50-200	100	5					5	4.9859	350.2	69.1	283	3.7	2.2
4	MB-GD	49.24	121.59	1.3	0-300	100	5		1			4	3.8725	61.2	74.1	24	14.5	8.4
5	MB-QM	49.23	121.59	1.1	400-800	200, <u>650</u>	5		4	1		0						
6	MB-QM	49.22	121.59	1.3	100-800	<u>200</u>	5					5	4.8561	217.3	-64.2	28	11.9	6.9
7	MB-QD	49.26	121.67	1.5	0-100	100	6		2		1	3	2.9773	357.1	75.2	88	8.6	5.0
8	MB-QD	49.26	121.67	1.5	0-100	100	5					5	4.9377	19.0	81.2	64	7.8	4.5
9	MB-QD	49.25	121.68	0.8	500-800	100, <u>650</u>	5		4	1		0						
10	MB-QD	49.23	121.68	14.8	50-800	<u>200</u>	5					5	4.9983	348.3	71.9	2321	1.3	0.8
11	H-QM	49.37	121.40	7.3	100-300	200	5					5	4.9583	192.9	-68.5	96	6.4	4.1
12	H-QM	49.36	121.39	2.7	50-500	100	5		2			3	2.9977	183.5	-71.3	882	2.7	1.6
13	H-QM	49.36	121.37	0.8	100-400	300	5		5			0						
14	H-QM	49.37	121.35	0.7	0-100	<u>100</u>, 650	5	1	3	1		0						

GEOL — plutonic complex - Hope (H), Mount Barr (MB); petrology-quartz diorite (QD), granodiorite (GD), quartz monzonite (QM)

LOCATION — the co-ordinates (Lat. °N, Long. °W) are given in degrees

SI, RANGE — stability index value and its minimum and maximum AF demagnetizing field in oersteds

FIELD — selected AF demagnetizing field in oersteds used for site; the underlined value indicates the less successful and omitted field

DATA SECTION — number of cores collected (N); cores rejected because their remanence too weak to measure reliably (I) or internally inhomogeneous (II) or sole remaining core for site (III) or anomalous direction for the site (IV); cores used for site statistics (n)

R — length resultant vector giving each core unit length

DECL, INCL — declination and inclination of mean vector in degrees (+ ve down)

k, α_{95}, SE — Fisher statistic k; radius of cone of 95% confidence in degrees; standard error in degrees

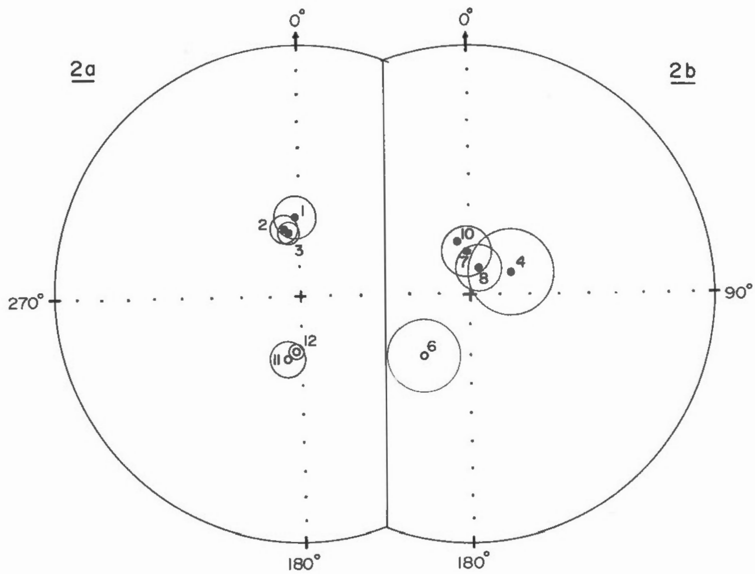

Figure 1-2. Equal-area stereographic projection showing the site mean remanence directions with their circle of 95% confidence for the: (2a) Hope plutonic complex, and (2b) Mount Barr plutonic complex. Individual sites by pluton are as given in Figure 1-1 and in text. Solid (open) symbols indicate normal positive (reverse negative) inclinations.

monzonite pluton in the Hope complex give similar reversed remanent magnetization directions whereas the three sites from the younger quartz diorite pluton give a tight cluster of nearly antiparallel normal remanence directions. The simplest and best explanation of this result is that the monzonite pluton cooled while the earth's magnetic field was reversed, and that the diorite pluton was intruded and cooled a short time later after the field had switched to normal polarity. Similarly for the Mount Barr complex, the three valid sites from the quartz diorite perimeter of the oldest pluton give a tight cluster of normal remanence directions whereas the one site in the younger granodiorite pluton gives a slightly divergent normal direction and the one site in the youngest quartz monzonite pluton gives a nearly antiparallel reversed direction. As before it appears that the Mount Barr plutons were emplaced and cooled at similar but discretely different times. The data are insufficient for rigorous statistical testing of these within-complex (i.e., between-pluton) differences in remanence direction, however, it is significant that each pluton yields a well-grouped characteristic cluster of directions.

From Figure 1-2 it is apparent that the two complexes have different mean remanence directions. After rotating the reversed site mean directions through 180° to the normal position, the Hope complex has a mean direction of 358.2°, 68.2° with a precision parameter (k) of 299 and a cone of 95% confidence (α_{95}) of 3.6° (Fisher, 1953) and the Mount Barr complex of 22.0°, 75.0° ($k = 62$, $\alpha_{95} = 8.0°$). Using the angular variance test, these two direction populations are significantly different at the 95% confidence level. This

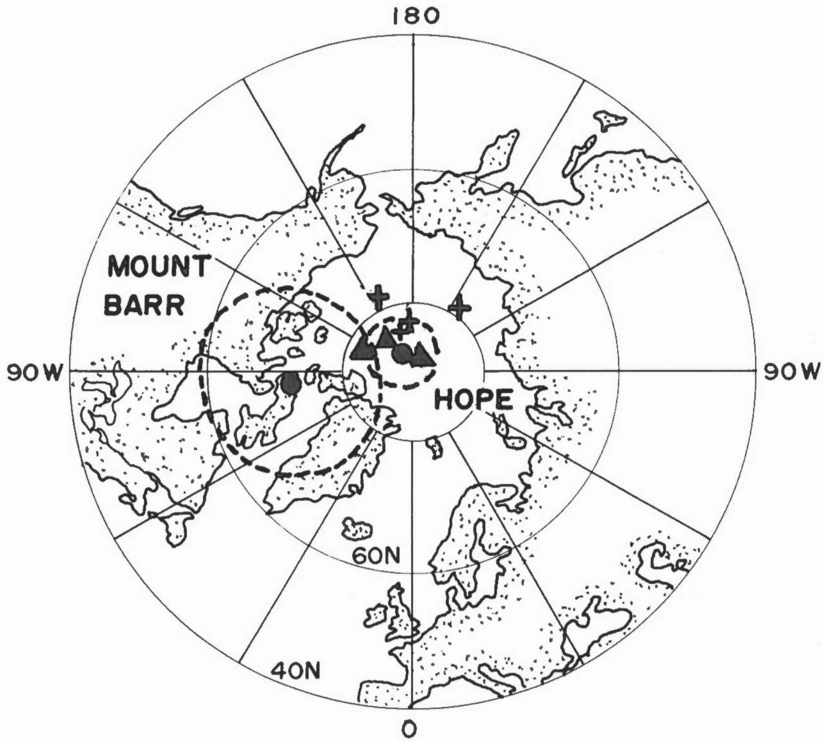

Figure 1-3. Polar projection of the northern hemisphere showing the pole positions of the Hope and Mount Barr plutonic complexes (solid circles) with their oval of 95% confidence and of other North American rocks of Eocene - Oligocene (crosses) and Miocene (triangles) age as given in the text.

result is consistent with the differing mean radiometric ages of 38 ± 3 and 18 + 3 m.y. determined by Richards and White (1970) for the two complexes.

The pole positions calculated from the mean remanence directions for both plutonic complexes are typical for North American Tertiary rock units i.e. within 25° of the present geographic pole and offset towards northwestern Canada or Alaska. The pole position calculated for the Hope complex is 151.9° W, 87.7° N (δm = 6.1°, δp = 5.1°) and for the Mount Barr complex is 85.8° W, 72.4° N (δm = 14.6°, δp = 13.3°) where δm and δp are the semi-axes of the oval of 95% confidence perpendicular to and along the site-pole great circle. The upper Eocene or lower Oligocene Hope pole is close to those found by Torreson et al. (1949) for the Eocene Wasatch sediments (180°, 84° N (27°, 20°)) and for the Green River sediments (158° W, 78° N (7°, 6°)) (168° W, 85° N (9°, 8°)) and by Grommé and McKee (1971) for the Oligocene west-central U.S.A. extrusives (146° E, 78° N (11°, 9°)) (Fig. 1-3). The discordant pole positions reported by Cox (1957) for the Eocene Siletz River volcanics and by Symons (1972) for the Oligocene East Sooke gabbro are attributed to local tectonic rotations (Irving, 1964; Symons, 1972). The discordant position found for the Oligocene Mount Washington dacites is thought to be a virtual pole reflecting a single magmatic pulse in which secular variation is not averaged out (Symons, 1971c). The mid-Miocene Mount Barr pole is not consistent with those found by Watkins (1965) for the Miocene Columbia River basalts (172°E, 87°N (5°, 4°)) excluding the rotated Oregon plateau basalts and by Symons (1969a, 1969b) for the upper Miocene Bella Coola brown dykes (112°W, 82°N (17°, 15°)) and Cariboo plateau basalts (140°W, 84°N (5°, 5°)). Considering the large overlapping radii of the oval of 95% confidence about the Mount Barr pole and the relatively few sampling sites, no tectonic significance is attached to the apparent discordance of its pole. Hence it is concluded that regional tectonic rotation of both the Hope and Mount Barr complexes since their emplacement does not appear likely.

SUMMARY

There are strong arguments to believe that the Hope and Mount Barr felsic plutonic complexes retain a stable primary remanent magnetization that has been successfully isolated in this study. First, neither the cores nor plutons show petrologic evidence of metamorphic events that could produce a stable secondary remanent magnetization. Second, the remanence intensity decay curves and direction paths on AF step demagnetization show that soft secondary remanence components aligned parallel to the earth's present magnetic field are removed by the 100 or 200 oersted step. Third, each pluton yields a distinct cluster of remanence directions. Fourth, both complexes yield approximately antiparallel normal and reverse remanence directions. Fifth, remanence directions of the two complexes are well-grouped and statistically independent. The third, fourth and fifth features would all be unlikely if a stable secondary remanence component had been isolated in the specimens. The slight discordance between the upper Miocene Mount Barr pole and coeval pole positions is not regarded as statistically significant possibly due to insufficient or non-representative sampling. The Eocene Hope granitic complex pole is regarded as concordant with coeval pole positions. These results indicate that regional tectonic rotations of the complexes since their emplacement is unlikely.

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REFERENCES

Baadsgaard, H., Folinsbee, R.E., and Lipson, J.
1961: Potassium-argon dates of biotites from Cordilleran granites; Geol. Soc. Amer., Bull., v. 72, p. 689-702.

Cairnes, C.E.
1944: Hope, British Columbia; Geol. Surv. Can., Map 737A.

Cox, A.
1957: Remanent magnetism of Lower to Middle Eocene basalt flows from Oregon; Nature, v. 179, p. 685-686.

Daly, R.A.
1912: North American Cordillera, Forty-ninth Parallel; Geol. Surv. Can., Mem. 38, 857 p.

Fisher, R.A.
1953: Dispersion on a sphere, Roy. Soc. London, Proc., Ser. A, v. 217, p. 295-305.

Grommé, C.S. and McKee, E.H.
1971: Mid-Tertiary paleomagnetic pole from volcanic rock in the western United States; Amer. Geophys. Union, Trans., v. 52, p. 187.

Grommé, C.S., Merrill, R.T. and Verhoogen, J.
1967: Paleomagnetism of Jurassic and Cretaceous plutonic rocks in the Sierra Nevada, California, and its significance for polar wandering and continental drift; J. Geophys. Res., v. 72, p. 5661-5684.

Hays, W.W. and Scharon, L.
1966: A paleomagnetic investigation of some of the Precambrian rocks of southeast Missouri; J. Geophys. Res., v. 71, p. 553-560.

Irving, E.
1964: Paleomagnetism and its application to geological and geophysical problems; John Wiley & Sons, New York, p. 249.

Larochelle, A. and Black, R.F.
1965: The design and testing of an alternating-field demagnetizing apparatus; Can. J. Earth Sci., v. 2, p. 684-696.

Larochelle, A. and Christie, K.W.
1967: An automatic 3-magnet or biastic magnetometer; Geol. Surv. Can., Paper 67-28, 28 p.

McTaggart, K.C. and Thompson, R.M.
1967: Geology of part of the northern Cascades in southern British Columbia; Can. J. Earth Sci., v. 4, p. 1199-1228.

Richards, T. and White, W.H.
1970: K-Ar ages of plutonic rocks between Hope, British Columbia, and the 49th parallel; Can. J. Earth Sci., v. 7, p. 1203-1207.

Spall, H.
1970a: Paleomagnetism of the PikesPeak granite, Colorado; Roy. Astr. Soc., Geophys. J., v. 21, p. 427-440.

1970b: Paleomagnetism of basement granites in southern Oklahoma: final report; Oklahoma, Geol. Surv., Notes, v. 30, p. 136-150.

1971: Paleomagnetism of Precambrian rocks from El Paso, Texas; Phys. Earth Planet. Interiors, v. 4, p. 329-346.

Symons, D. T. A.
1969a: Geological implications of paleomagnetic studies in the Bella Coola and Laredo Sound map-areas; Geol. Surv. Can., Paper 68-72, 15 p.

1969b: Paleomagnetism of the late Miocene Plateau basalts in the Cariboo region of British Columbia; Geol. Surv. Can., Paper 69-43, 16 p.

1971a: Paleomagnetism of the Jurassic Island Intrusions of Vancouver Island, British Columbia; Geol. Surv. Can., Paper 70-63, p. 1-17.

1971b: Paleomagnetism of the Triassic Guichon batholith and rotation of the southern Interior Plateau, British Columbia; Can. J. Earth Sci., v. 8, p. 1388-1396.

1971c: Paleomagnetic notes on some minor Tertiary igneous bodies on Vancouver Island; Geol. Surv. Can., Paper 71-24, p. 1-8.

1972: Paleomagnetic zones in the Oligocene East Sooke gabbro and tectogenesis of the western Cordillera, British Columbia, in preparation.

Tarling, D.H. and Symons, D. T. A.
1967: A stability index of remanence in paleomagnetism; Roy. Astr. Soc., Geophys. J., v. 12, p. 443-448.

Torreson, O. W., Murphy, T. and Graham, J. W.
1949: Magnetic polarization of sedimentary rocks and the Earth's magnetic history; J. Geophys. Res., v. 54, p. 111-129.

Watkins, N. D.
1965: Paleomagnetism of the Columbia Plateaus; J. Geophys. Res., v. 70, p. 1379-1406.

Yaskawa, K., Vincenz, S. A. and Guja, N.
1966: Thermal investigations of some igneous rocks of Oklahoma; Amer. Geophys. Union, Trans., v. 47, p. 70.

2. UNIT CORRELATIONS AND TECTONIC ROTATION FROM PALEOMAGNETISM OF THE TRIASSIC COPPER MOUNTAIN INTRUSIONS, BRITISH COLUMBIA

D. T. A. Symons

ABSTRACT

The 194 ± 8 m.y. old Copper Mountain intrusions are located at the southern end of the Interior Plateau in south-central British Columbia. Three plutons - the Copper Mountain stock, the Voigt stock, and the Lost Horse Intrusions - were sampled at 21 sites (212 specimens). After AF demagnetization a stable remanent magnetization (RM_s) was isolated for 17 sites. This RM_s is thought to be primary for several reasons including the presence of truly reversed directions and the within-phase and within-pluton clustering of remanence directions. Variance ratio analysis of the RM_s directions supports the hypothesis that the concentric outer diorite and inner monzonite phases of the Copper Mountain stock differentiated and cooled simultaneously. Next the diorite differentiated to concentrate a residual gabbroic magma which cooled in zones within the diorite. Simultaneously, syenitic and perthositic pegmatite was differentiating from the monzonite and cooling to form the core of the stock. During and after emplacement of the gabbro and perthosite phases, the Lost Horse Intrusions were emplaced. The Voigt stock is not coeval with the other units tested, and because it gives a younger average radiometric age of 188 ± 7 m.y. it is thought to be a separate later magmatic pulse. The pole position determined for the Copper Mountain intrusions of 9° W, 68° N is concordant with that reported for the Late Triassic Guichon batholith. Both poles are discordant with those obtained from other North American Triassic rock units. The discordance resulted from a 40° ± 10° clockwise rotation of the southern end of the Interior Plateau during the Columbian Orogeny relative to the rest of the Interior Plateau and to cratonic North America. The rotation of this regional tectonic block is consistent with the available geologic evidence.

RÉSUMÉ

Les intrusions du mont Copper, vieilles de 194 ± 8 millions d'années, sont situées à l'extrémité sud du plateau Intérieur au centre-sud de la Colombie-Britannique. L'auteur a visité trois plutons soit le stock du mont Copper, le stock Voigt et les intrusions Lost Horse, et il a prélevé 212 échantillons en 21 endroits. Après démagnétisation à l'aide de champs alternatifs, une aimantation rémanente stable a été isolée dans le cas d'échantillons provenant de 17 endroits. On croit que cette aimantation rémanente est primaire pour plusieurs raisons, y compris la présence de directions véritablement inversées et les groupements de directions rémanentes à l'intérieur des plutons. L'analyse du taux de variance des directions de l'aimantation rémanente stable vient appuyer l'hypothèse que les phases concentriques de la diorite extérieure et de la monzonite intérieure du stock du

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mont Copper se sont différenciées et refroidies simultanément. Ensuite, la diorite s'est différenciée pour concentrer un magma gabbroïque résiduel qui s'est refroidi en zones à l'intérieur de la diorite. Une pegmatite syénitique et perthositique se différenciait en même temps de la monzonite et se refroidissait pour former le noyau du stock. Pendant et après la mise en place du gabbro et de la perthosite, les intrusions Lost Horse se sont produites. Le stock Voigt n'a pas le même âge que les autres unités étudiées, et parce que son âge radiométrique moyen, qui est 188 ± 7 millions d'années, est moins élevé, on croit qu'il s'agit d'une pulsion magmatique séparée plus tardive. La position du pôle calculée d'après des intrusions du mont Copper, qui est de 9° W et de 68° N, concorde avec celle qui a été rapportée pour le batholite de Guichon du Trias supérieur. Les deux positions ne concordent pas avec celles qui proviennent d'autres unités rocheuses triasiques d'Amérique du Nord. La discordance résulte d'une rotation dans le sens des aiguilles d'une montre de 40° ± 10° de l'extrémité sud du plateau Intérieur pendant l'orogénèse colombienne par rapport au reste du plateau Intérieur et du craton nord-américain. La rotation de cette entité tectonique régionale est conforme aux indices géologiques disponibles.

INTRODUCTION

The Copper Mountain intrusions are located in south-central British Columbia at the southern end of the Interior Plateau. They surround the Copper Mountain mine, just east of site 4 in Figure 2-1, which is about 11 miles south of Princeton, British Columbia, and about 20 miles north of the Canada-United States border.

The intrusions lie within the Princeton map-area and were mapped on a reconnaissance scale by Rice (1947). The geological relationships in the immediate area of the Copper Mountain mine were studied by Dolmage (1934) and Fahrni (1951, 1962, 1966). Montgomery (1967) mapped and studied the intrusions as a unit with emphasis on their structure and petrology. Results of radiometric age determinations have been reported by Sinclair and White (1968) and by Preto et al. (1971).

The initial objectives of this paleomagnetic study were twofold. The first was to see if the petrologic phases could be distinguished within one intrusion and could be correlated between intrusions on the basis of remanent magnetization direction. This method has been reasonably successful in other studies on felsic plutons (Symons, 1972a, 1972b). The second objective was to see if the Copper Mountain intrusions were subjected to a regional rotation about an essentially-vertical adjacent axis relative to the North American Craton similar to that found for the Guichon batholith some 70 miles to the north (Symons 1971, 1972c).

GENERAL GEOLOGY

The oldest rocks in the sampling area (Fig. 2-1) are volcanic and sedimentary strata of the Wolf Creek Formation of the uppermost Nicola Group (Rice, 1947). Except for those immediately adjacent to the later intrusions, they have been only mildly metamorphosed and deformed. They have been dated paleontologically as Upper Triassic.

The Copper Mountain intrusions include several quartz-deficient calcalkalic plutons which cut the Wolf Creek rocks (Montgomery, 1967) of which the Copper Mountain stock is the largest. It is elliptical in plan with a major axis of about 4 miles trending N65° W and a minor axis of about 2 1/2 miles. It is concentrically differentiated with a diorite phase around its perimeter. The diorite contains zones of gabbro. Inside the diorite is a more-or-less concentric ring of monzonite which encloses a core of syenitic and perthositic pegmatite. Sinclair and White (1968) report K-Ar ages on ± biotite of 182 ± 8 m.y. for the gabbro, of 194 ± 8 and 199 ± 7 for the monzonite phase, and of 194 ± 7 for a mineralized veinlet on the margin of the stock. An ore specimen gives a biotite K-Ar age of 189 ± 8 m.y. (Preto et al., 1971). Although the ages do not distinguish between the petrologic phases, it is clear that both the stock and the copper mineralization are of late Upper Triassic age.

The smaller Voigt stock to the northeast and the Smelter Lake stock to the north are satellites of the Copper Mountain stock. They are composed of diorite similar to the outer phase of the Copper Mountain stock. Preto et al. (1971) report K-Ar radiometric ages on biotite of 181 ± 7 and 194 ± 7 m.y. for the Voigt stock and of 197 ± 8 and 200 ± 8 for the Smelter Lake stock. Because of the identical span of K-Ar ages, Preto et al. (1971) agree with previous workers (Montgomery, 1967; Dolmage, 1934) who considered the satelite stocks to be comagmatic with the Copper Mountain stock.

The Lost Horse Intrusions occur in a 3- by 1-mile belt between the Copper Mountain, Voigt and Smelter Lake stocks. They comprise a complex of sills, dykes and irregular bodies of various sizes and shapes whose composition ranges from diorite to syenite. The rocks are commonly porphyritic and their feldspar has generally undergone alteration of variable intensity. Dolmage (1934) considers the Lost Horse rocks to be related to, but slightly older than, the Copper Mountain - Voigt - Smelter Lake rocks. Conversely Montgomery (1967) regarded the Lost Horse complex (which he names the

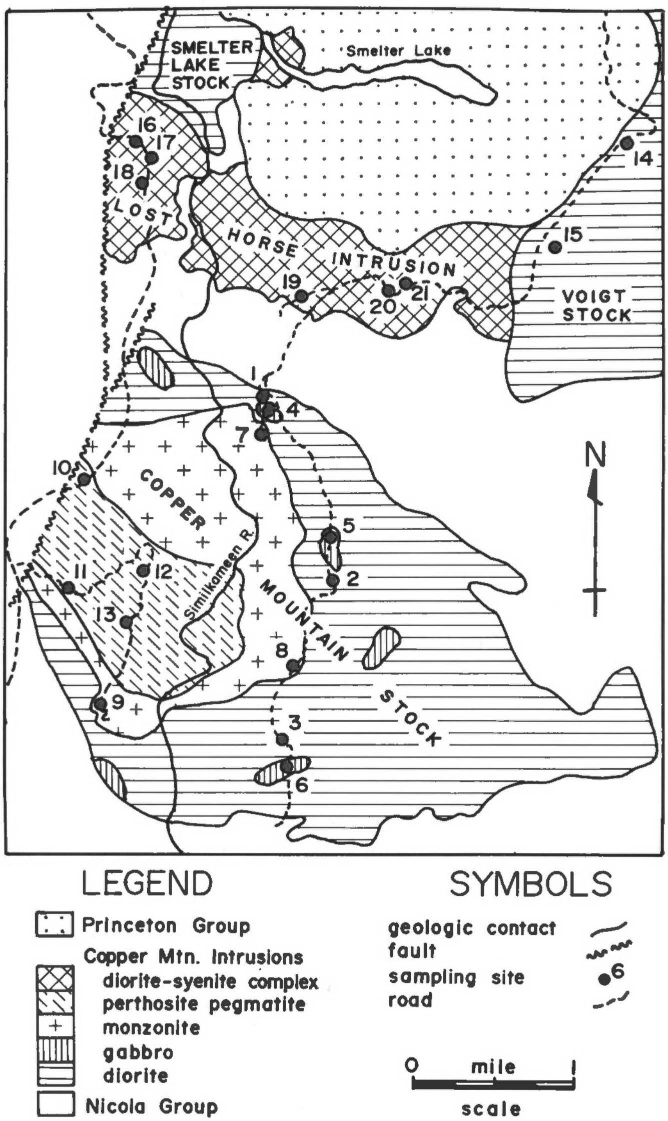

Figure 2-1. Geology of the Copper Mountain intrusions and sampling site locations.

Table 2-1

Summary of sampling and remanent magnetization data.

Site	Geological Unit	Location: Longitude degrees West	Location: Latitude degrees North	AF Demagnetization: Stability Index Value	AF Demagnetization: Stability Index Field (oersteds) Minimum	AF Demagnetization: Stability Index Field (oersteds) Maximum	AF Demagnetization: Field Used oersteds	Sampling: Cores Taken	Sampling: Cores[a] Rejected 1	Sampling: Cores[a] Rejected 2	Sampling: Cores[a] Rejected 3	Sampling: Cores Used	Stable Remanent Magnetization: Length Resultant Vector	Stable Remanent Magnetization: Declination degrees	Stable Remanent Magnetization: Inclination degrees (+ down)	Stable Remanent Magnetization: Precision Parameter k	Stable Remanent Magnetization: α_{95}[b] degrees
	Copper Mountain stock																
1	- diorite phase	120.54	49.33	3.2	0	100	200	5	4		1	0					
2	" "	120.53	49.31	4.8	200	500	300	5				5	4.9821	28.2	43.4	223	4.2
3	" "	120.53	49.30	21.7	300	800	400	5				5	4.9827	28.1	38.6	231	4.1
4	- gabbro phase	120.54	49.33	2.2	50	500	400	5	1			4	3.8752	33.2	53.5	24	14.3
5	" "	120.53	49.32	8.2	50	300	100	5				5	4.9587	23.1	63.9	97	6.4
6	" "	120.53	49.29	6.6	50	200	100, <u>800</u>[c]	5				5	4.9782	36.3	72.6	183	4.6
7	- monzonite phase	120.54	49.33	17.3	500	800	<u>200</u>, 650	5				5	4.9395	27.4	36.7	66	7.7
8	" "	120.53	49.30	15.3	300	800	400	6				6	5.9897	27.6	43.3	487	2.6
9	" "	120.56	49.30	4.1	100	300	200	5				5	4.9625	34.3	42.6	107	6.1
10	- perthosite pegmatite	120.57	49.30	20.4	50	300	200	5				5	4.9927	36.3	57.2	546	2.7
11	" "	120.56	49.31	7.8	50	200	100	5				5	4.9879	33.3	68.1	331	3.5
12	" "	120.55	49.31	3.6	50	300	200	5				5	4.9865	9.0	58.6	296	3.6
13	" "	120.55	49.31	4.0	100	300	200	5				5	4.9664	18.6	53.8	119	5.8
	Voigt stock																
14	- diorite	120.49	49.35	5.9	50	200	100, <u>800</u>	5	1			4	3.9501	69.4	87.8	60	9.0
15	"	120.50	49.34	2.7	0	200	100, <u>650</u>	5				5	4.9679	1.5	76.8	125	5.6
	Lost Horse Intrusions																
16	-diorite syenite complex	120.56	49.35	1.4	400	800	<u>100</u>, 500	5	1			4	3.6937	223.6	-14.3	10	22.4[d]
17	" " "	120.55	49.35	0.8	0	100	<u>300</u>, 500	5	3			2	1.2971	196.3	2.6	1	83.2[d]
18	" " "	120.55	49.35	5.1	300	500	400	5	1	1		3	2.9782	218.5	-47.1	92	8.5
19	" " "	120.53	49.34	2.8	0	300	100, <u>400</u>	5		1		4	3.9512	6.4	67.9	61	9.0
20	" " "	120.52	49.34	3.4	50	200	100	5				5	4.9465	4.3	58.8	75	7.3
21	" " "	120.51	49.34	2.5	200	400	300	5	3			2	1.6011	230.0	-9.4	3	62.7[d]

Note: a) Remanent magnetization data from core rejected as unacceptable because: 1) the two specimens' directions diverged by more than 20°; 2) the direction was anomalous compared to other cores for site; and 3) it was the sole core thereby providing insufficient data.

b) Radius of the core of 95% confidence (Fisher, 1953).

c) Data from underlined cleaning treatment gave increased direction dispersion and hence was not used.

d) Sites rejected as inhomogenously magnetized i.e. $\alpha_{95} > 15^{o}$.

Armstrong Bluffs complex) as being related to, but younger than, the stocks. Preto et al. (1971) obtained four K-Ar dates of 194 ± 8, 194 ± 8 and 197 ± 8 m.y. from the Lost Horse rocks and consider them to be indistinguishable in age from the stocks, but they support geological arguments for considering the Lost Horse rocks to have been emplaced relatively late in the Copper Mountain intrusive sequence.

The Copper Mountain intrusions are cut by the 100 ± 5 m.y. Cretaceous Verde Creek quartz monzonite (Preto et al., 1971) and by the "Mine dykes" (Fahrni, 1951). The Copper Mountain intrusions are unconformably overlain by the Lower Volcanic Formation and the Allenby Formation of the Middle Eocene Princeton Group (Rice, 1947; Rouse and Mathews, 1961).

SAMPLING AND MEASUREMENT METHODS

Five, and in one case 6, cores were collected from each of 21 sites in the Copper Mountain intrusions after orienting each of the 106 cores in situ using a sun compass (Fig. 2-1, Table 2-1). The four phases of the Copper Mountain stock are represented by 3 or 4 sites each, the Voigt stock by 2 sites, and the Lost Horse Intrusions by 6 sites. Two specimens were cut from each core and their natural remanent magnetizations (n.r.m.) measured on the automated biastatic magnetometer described by Larochelle and Christie (1967). From each site one pilot specimen was selected with an average site n.r.m. direction and intensity. The pilot specimens were demagnetized in steps in alternating field (a.f.) peak intensities of 50, 100, 200, 300, 400, 500, 650, and 800 oersteds (oe.) using the two-axis tumbler apparatus described by Larochelle and Black (1965) with their remanence remeasured after each step. Guided by the stability index (s.i.) data (Tarling and Symons, 1967) and by the remanence intensity decay curve on step demagnetization obtained for each pilot specimen, the remaining specimens from each site were a.f. demagnetized at a selected field intensity (Table 2-1) and their stable remanent magnetization (RM_s) measured. The specimens from 7 of the least stable sites were demagnetized in a second higher field intensity. For these sites the a.f. demagnetization treatment giving the best clustering of RM_s directions was used for statistical analysis.

STATISTICAL ANALYSIS

In 14 cores the angle θ between the RM_s directions of the two specimens exceeds 20°, and so these cores are inhomogeneously magnetized and the data from these cores were rejected (Table 2-1). In 2 sites the RM_s direction of one core deviated by more than 3 times the angular standard deviation of the remaining site cores from their mean direction, and so the RM_s data from these 2 anomalous cores were also rejected. For site 1, only 1 core proved to be homogeneously magnetized, so it was rejected because it provided insufficient data to represent the site. The site mean RM_s directions were calculated along with their precision parameters (k) and the radii of their cones of 95% confidence (α_{95}) (Fisher, 1953). Sites 16, 17 and 21 (Table 2-1) exhibited high α_{95} values ($\alpha_{95} > 15°$). These 3 sites were thought to be inhomogeneously magnetized. The remaining 17 sites (81%) are thought to have a reliable homogeneous RM_s direction.

REMANENCE STABILITY

The soft viscous remanent magnetization (v. r. m.) components forming part of the n.r.m. found in the cores from the 17 remaining sites were successfully removed by a.f. demagnetization. This is evident from the low mean coercivity (a.f. intensity at which the n.r.m. is reduced by one-half) of less than 55 oe for most pilot specimens. Further, the direction of the removed v.r.m. components is towards the present earth's magnetic field direction in all cases. Also the latter direction lies within the cone of 95% confidence of the RM_s directions of only 3 sites (11, 15 and 19). Because the sites are geographically and geologically well separated, the fact that 16 of the 17 sites have small cones of 95% confidence ($\alpha_{95} \leq 9.0°$) about diverging mean RM_s directions is further evidence of the isolation of stable remanence components. There is strong evidence for believing that the stable remanence isolated for these 17 sites is primary. Site 18 has a reversed remanence direction which is antiparallel to the remaining 16 sites' directions. Further, sites 16 and 21 from the Lost Horse Intrusions also appear to retain reversed RM_s directions which have not been successfully isolated. In addition there is no evidence of secondary alteration or metamorphism in hand sample with the possible exception of site 1 which contains sulphide mineralization in the diorite and is close to one of the "Mine dykes". The detailed petrologic reports of Montgomery (1967), Sinclair and White (1968) and Preto et al. (1971) indicate that magnetite is the sole likely remanence carrier. Also it is significant that the only rocks showing notable microscopic evidence of alteration are the Lost Horse Intrusions, and 3 of the 6 sites in this unit do not retain a reliable RM_s. Finally, as will be shown, the consistency of the site directions within petrologic phases and of all site directions to the Guichon batholith directions strongly suggests that the site magnetizations are primary.

Variance Ratio Analysis

The angular variance ratio test method used in this study follows that given by Larochelle (1969). If the ratio of the between-unit to within-unit angular variance is significantly greater than the value of the theoretical statistic F at the 95% confidence level for the appropriate degrees of freedom (i.e. $\delta_b^2/\delta_w^2 > F_{.05}$), then the unit mean remanence directions are independent measures of the paleomagnetic field.

The first test compared the within-site to between-site angular variances (Table 2-2). Because the test result is negative (i.e. $\delta_b^2/\delta_w^2 > F_{.05}$) within the individual phases of the Copper Mountain stock, within the Copper Mountain stock as a whole, within the Voigt stock, within the Lost Horse Intrusions, and within the Copper Mountain intrusions as a whole, it is evident that the site directions are independent measures of the paleomagnetic field for statistical purposes. It would be invalid to use the individual core or specimen directions directly in computing unit mean directions, etc. The geologic explanation for this result is that sufficient time elapsed between cooling of the various sites through their Curie temperatures for secular variation to occur in the earth's paleofield. Time differences sufficient to allow for reversal of the paleofield are indicated by the presence of normal and reversed site directions in the Lost Horse Intrusions. The possibility of tectonic rotation between the sites is discounted because sufficiently large faults are not reported within the batholith, and because as will be shown the site directions are strongly grouped by petrologic phase within the plutons rather than geographic location.

Using the site directions a series of angular variance tests were run to compare the petrologic phases within the Copper Mountain stock (Table 2-3, Fig. 2-2). The diorite and monzonite phases have site RM_s directions which are statistically indistinguishable. Similarly, the gabbro and the perthositic pegmatite core phases have similar directions and they are distinctly different from those of the diorite and monzonite. This suggests that the petrogenesis proposed by Montgomery (1967) for the Copper Mountain stock must be modified as follows. The diorite and monzonite represent the initial cooling and differentiation step from the parent magma. This was followed by a late stage of differentiation with the residual magma in the basic dioritic portion of the stock solidifying 25 gabbroic zones, and in the acidic monzonitic portion of the stock as the syenitic and perthositic pegmatite core. To further test the soundness of this correlation, the basic phases (diorite and gabbro) were compared to the acidic phases (monzonite and perthosite pegmatite) and found to have similar site directions. Conversely, the "older" phases (diorite and monzonite) and the "younger" phases (gabbro and perthosite pegmatite) have distinctly different site RM_s directions.

The two Voigt stock diorite site directions were compared to the directions of the Copper Mountain diorite phase and of the Copper Mountain basic phases. As is obvious from Figure 2-2, the variance test is negative. The geological significance of this result is that, while the two stocks are petrologically comagmatic, they are not coeval and probably represent two distinct intrusive episodes. The alternative of relative tectonic rotation is less likely because it requires the existence of a major rotational fault between the Voigt stock and the Lost Horse Intrusion on which one side has been rotated at about 30° relative to the other.

Finally, the site RM_s directions for the Lost Horse Intrusions were examined. The presence of reversed remanence components indicates clearly that they are not entirely, if at all, coeval with the Copper Mountain phases. The angular variance comparison with the Copper Mountain older phases is negative whereas with younger phases it is positive. Also, the comparison with all the Copper Mountain is positive although not overwhelmingly. Thus these tests oppose the geologic interpretation of Dolmage (1934) and support that of Montgomery (1967) and Preto et al. (1971). Apparently the Lost Horse Intrusions were emplaced during and after the late stages of intrusion of the Copper Mountain stock.

POLE POSITION

The mean pole position calculated for the Copper Mountain intrusions is 9.3° W, 68.4° N with semi-axes (δ_p, δ_m) for its oval of 95% confidence of 7.0° and 9.6° along and perpendicular to the sampling site-pole great circle respectively. In the calculation, the site 18 RM_s direction was reversed and each of the 17 valid site directions were given unit weight. This pole position is clearly discordant with pole positions determined from other Upper Triassic rock units from the "stable" craton of North America (Table 2-4; Fig. 2-3). They cluster about a mean position near 98° E, 66° N. However the position is concordant with that determined for the Upper Triassic Guichon batholith

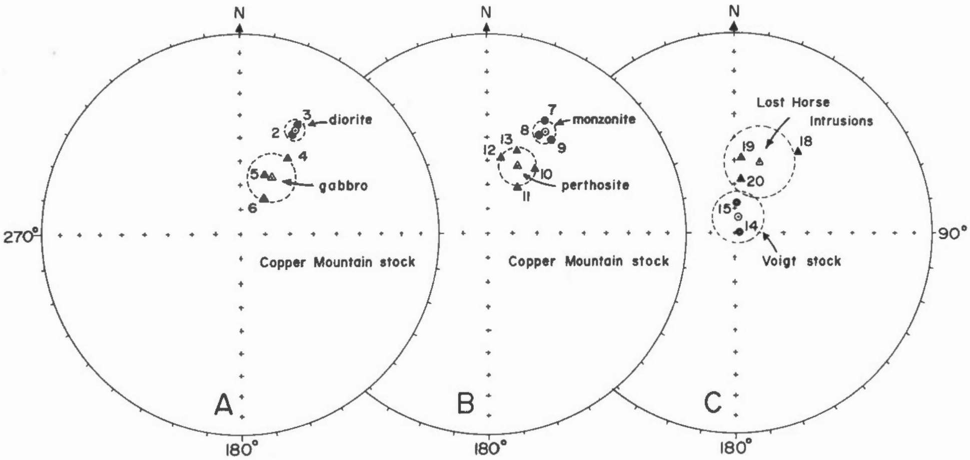

Figure 2-2. Stereographic equal-area projections showing the site mean remanence directions for: A) the Copper Mountain diorite (circle) and gabbro (triangle); B) the Copper Mountain monzonite (circle) and perthositic pegmatite (triangle); and C) the Voigt stock diorite (circle) and Lost Horse Intrusions diorite-syenite complex (triangle). The numbers indicate the site with the direction for site 18 in its antiparallel position so that all directions are in the lower hemisphere. The unit mean position is indicated by a dot in the corresponding circle or triangle symbol, and it is encompassed by its cone of 95% confidence.

some 70 miles north of Copper Mountain. The discordance of the Guichon pole from the North American norm has been discussed in considerable detail in previous papers (Symons 1971, 1972c). Stated simply, the southern end of the Interior Plateau is a tectonic block that has been 'twist' rotated clockwise by 40° ± 10° while most of the Plateau to the north has not moved relative to the North American craton. It is apparent that the Copper Mountain intrusions form part of this block and have been rotated by a similar amount.

The Guichon batholith and Copper Mountain intrusions have similar K-Ar radiometric ages of 198 ± 8 m.y. (Northcote, 1969) and 194 ± 8 m.y. (Sinclair and White, 1968; Preto et al., 1971) respectively. Both intrude Nicola Group rocks at the southern end of the Interior Plateau. The geologic evidence in favour of a 40° ± 10° clockwise twist rotation need only be summarized from the previous papers (Symons, 1971, 1972c):

1) The discordant pole positions cannot be explained by a stable secondary remagnetization because, in addition to the previously cited evidence for a stable primary remanence, the Guichon and Copper Mountain poles are remote from reliable post-Triassic North American pole positions. Thus pole positions caused by remagnetization would be centred in Siberia rather than northern Europe.

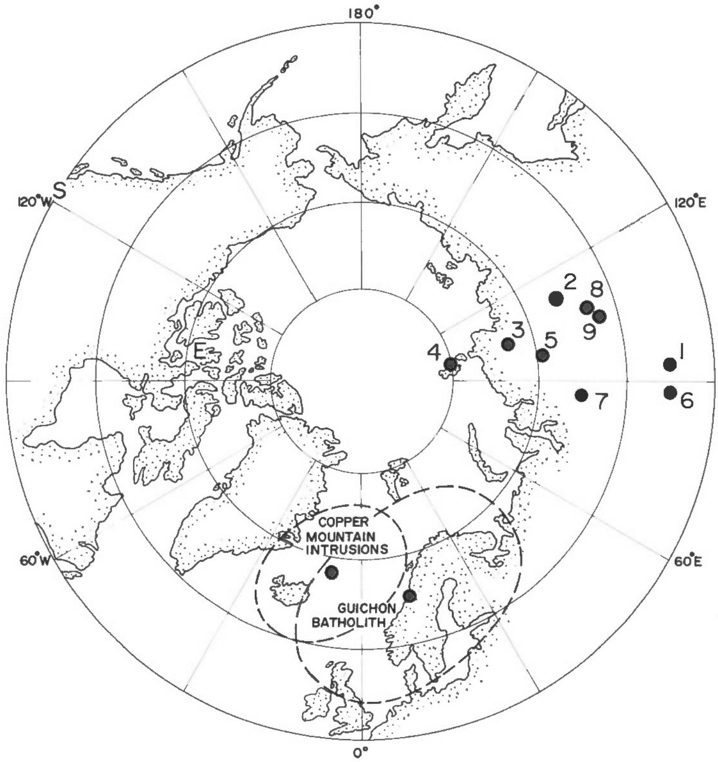

Figure 2-3. Polar projection of the northern hemisphere above 50°N showing pole positions determined from North American rock units of Upper Triassic age. The solid circles are from the North American craton (poles 1-9, Table). The Guichon batholith and Copper Mountain intrusions poles are encompassed by their ovals of 95% confidence and S is the sampling site location. E is the present location of the earth's magnetic pole.

2) The distribution of older and slightly younger strata is consistent with rotation. In the central Interior Plateau they trend N55° W changing to N25° W in the southern Interior Plateau.

3) The physiographic margins of the Interior Plateau swing some 45° clockwise from N55° W and N30° W in the north to N5° W and N10° E in the south.

4) The major faults in the area trend between N55° W and N40° W in the north changing sharply just north of Guichon batholith by some 50° clockwise to N10° W and N10° E in the south.

TABLE 2-2

Angular variance ratio analysis within phases

Unit	Number of cores n	Number of sites B	Characteristic remanent magnetization: Declination degrees	Inclination degrees + down	Length of Unit Vector R	α_{95} degrees	δ_w^2 (radians)^2	δ_b^2 (radians)^2	δ_b^2/δ_w^2	$F_{.05}$	Test Result
Copper Mountain stock											
-diorite phase	10	2	28.2	41.0	1.9983	4.1	0.0088	0.0173	1.96	3.63	positive
-gabbro phase	14	3	30.6	63.5	2.9698	10.0	0.0342	0.1348	3.94	2.82	negative
-monzonite phase	16	3	29.7	40.9	2.9934	4.7	0.0167	0.0344	2.07	2.74	-
-perthosite pegmatite	20	4	23.6	59.9	3.9637	7.7	0.0083	0.1209	14.54	2.40	negative
-all phases	60	12	27.8	52.9	11.7325	6.3	0.0166	0.2454	14.79	1.66	negative
Voigt stock											
-diorite phase	9	2	9.9	82.9	1.9881	10.8	0.0234	0.1059	4.52	3.74	-
Lost Horse Intrusions											
-diorite-syenite complex*	12	3	19.5	59.0	2.9330	14.8	0.0276	0.2299	8.33	2.93	negative
Copper Mountain intrusions											
-all sites*	81	17	25.9	57.5	16.4100	6.5	0.1889	0.3441	18.23	1.54	negative

Notes: α_{95} radius of the cone of 95% confidence;

δ_w^2, δ_b^2 within-site and between-site angular variance;

$F_{.05}$ theoretical value of $F_{2(b-1),\ 2(n-B),\ .05}$;

* polarity of site 18 remanent direction reversed.

Table 2-3.
Angular variance ratio analysis between units.

Unit Pair*	Number of sites B	δ_w^2 (radians)^2	δ_b^2 (radians)^2	δ_b^2/δ_w^2	$F_{.05}$	Correlation Test Result
Copper Mountain stock						
diorite _vs_ gabbro	5	.0215	.1841	8.59	5.14	negative
diorite _vs_ monzonite	5	.0056	.0005	0.09	5.14	positive
diorite _vs_ perthosite peg.	6	.0189	.1477	7.81	4.46	negative
gabbro _vs_ monzonite	6	.0185	.2312	12.48	4.46	negative
gabbro _vs_ perthosite peg.	7	.0266	.0123	0.46	4.10	positive
monzonite _vs_ perthosite peg.	7	.0171	.01951	11.42	4.10	negative
basic _vs_ acidic	12	.0527	.0083	0.16	3.49	positive
older _vs_ younger	12	.0163	.3747	23.06	3.49	negative
Voigt stock diorite vs						
Copper Mtn diorite	4	.0137	.5392	39.33	6.94	negative
Copper Mtn basic	7	.0543	.3618	6.66	4.10	negative
Lost Horse complex[t] vs						
Copper Mtn older	8	.0252	.2065	8.19	3.88	negative
Copper Mtn younger	10	.0349	.0112	0.32	3.63	positive
Copper Mtn all sites	15	.0515	.0430	0.84	3.37	positive

Notes:

δ_w^2, δ_b^2 within-unit and between angular variance

$F_{.05}$ theoretical statistic $F_{2,\ 2(B-2),\ .05}$

* basic (diorite + gabbro), acidic (monzonite + perthosite pegmatite), older (diorite + monzonite), younger (gabbro + perthosite pegmatite).

t polarity of site 18 remanent direction reversed

Table 2-4.
Paleomagnetic pole positions derived from North American rock units of Upper Triassic age.

Pole	Rock Unit	Locality	Number of Site Means	Pole Position	Reference
1	Chinle formation sandstone	Utah and New Mexico	3	$93^{o}E, 55^{o}N$	Collinson and Runcorn (1960)
2	North Mountain basalt	Nova Scotia	17	$113^{o}E, 66^{o}N$	Larochelle (1967)
3	North Mountain basalt	Nova Scotia	25	$104^{o}E, 73^{o}N$	Carmichael and Palmer (1968)
4	Grand Manan lava	New Brunswick	4	$100^{o}E, 80^{o}N$	Carmichael and Palmer (1968)
5	Great Dyke diabase	Nova Scotia	2	$98^{o}E, 69^{o}N$	Larochelle and Wanless (1966)
6	Newark Group lavas	Massachusetts	5	$88^{o}E, 55^{o}N$	Irving and Banks (1961)
7	Newark Group volcanics	Connecticut	53	$87^{o}E, 65^{o}N$	de Boer (1968)
8	Newark Group mixed	New Jersey	29	$108^{o}E, 63^{o}N$	Opdyke (1961)
9	Newark Group diabase	Pennsylvania	20	$105^{o}E, 62^{o}N$	Beck (1965)
10	Guichon felsic batholith	British Columbia	15	$13^{o}E, 66^{o}N$	Symons (1971)
11	Copper Mountain intrusions	British Columbia	17	$9^{o}W, 68^{o}N$	this paper

5) The lack of evidence for the 20 ± 5° W tilt which could also explain the discordant pole positions. There is abundant evidence from the attitudes of foliation planes, shear planes, contacts, and adjacent strata against such a tilt in the case of the Guichon batholith. Similar evidence for the Copper Mountain intrusions is not well documented. Montgomery (1967) noted that the contacts of the stocks are within 15° of vertical except in one area on the northeastern side of the Copper Mountain stock where it dips about 45° SW. Shear zones are uncommon except in the Lost Horse Intrusions where they strike N60° W and dip at 70° S. Foliation planes are confined to the perimeters of the stocks where they are subparallel to the outer contact in plan and dip very steeply. The Nicola strata are gently deformed into broad open folds with low dips (Fahrni, 1951, 1962) except for immediately adjacent to the Copper Mountain intrusions where they are generally conformable and steeply dipping (Montgomery, 1967) and to the major faults (Preto et al., 1971). To explain the discordance of the Copper Mountain intrusions pole position by tilt would require a 25° W tilt about a NNW axis and the available evidence militates against such a tilt.

In summary the paleomagnetic evidence is strongly in favour of a 40° ± 10° clockwise rotation of the southern end of the Interior Plateau. The available geologic evidence is consistent with this hypothesis both on a regional scale of changing trend directions and on a local scale from the attitudes of S planes in the plutons. It is probable that the rotation occurred during the Late Cretaceous to Early Tertiary Nevadan Orogeny.

CONCLUSIONS

1. Most of the rocks of the Late Triassic Copper Mountain intrusions retain a stable primary remanent magnetization.

2. The individual petrologic phases of the differentiated Copper Mountain stock have distinctive remanence directions. Variance ratio analysis of the directions indicates that the parent magma differentiated and cooled to simultaneously form the diorite and monzonite phases. The acidic magma differentiate further differentiated and cooled to form the syenitic and perthositic pegmatite core of the stock while the basic magma differentiate further differentiated and cooled to form zones of gabbro in the diorite.

3. Although the Voigt stock is petrologically comagmatic with the Copper Mountain stock, they do not appear to be coeval because they have widely divergent mean remanence directions. The Voigt stock's average radiometric age of 188 ± 7 m.y. is slightly younger than the better established 194 ± 8 m.y. average of the Copper Mountain stock. On this basis the Voigt stock is regarded as somewhat younger than the Copper Mountain stock.

4. The Lost Horse Intrusions give remanent magnetization directions divergent from those of the older diorite and monzonite phases of the Copper Mountain stock and concordant with those of the younger gabbro and perthosite pegmatite. The Lost Horse Intrusions are therefore thought to be comagmatic and in part coeval with the younger phases. Because the Lost Horse rocks retain reversed remanent magnetization components, they must have been emplaced in part after the Copper Mountain stock during an interval when the earth's magnetic field was reversed.

5. The Copper Mountain intrusions have been subjected to a 40° ± 10° clockwise rotation along with the rest of the southern end of the Interior Plateau relative to the rest of the Interior Plateau and North American craton. Included in this rotated block is the Guichon batholith which yields a similar anomalous pole position. The rotation likely occurred during the Columbian Orogeny (Douglas et al., 1970). The discordance of the southern Interior Plateau pole positions cannot be rationally explained by any form of post-Triassic translation of the western Cordillera and Interior Plateau relative to cratonic North America. Such a hypothesis has been proposed to rationalize discordant paleomagnetic poles from western Cordilleran rocks by Beck and Noson (1972) and by Irving and Yole (1972). However their hypothesis is based on meagre data, and more abundant and conclusive data recently analyzed by the author is contrary to the translation hypothesis (Symons, 1972d, 1972e).

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REFERENCES

Beck, M.E.
1965: Paleomagnetic and geological investigations of magnetic properties of the Triassic diabase of southeastern Pennsylvania; J. Geophys. Res., v. 70, p. 2845-2856.

Beck, M.E. and Noson, L.
1972: Anomalous paleolatitudes in Cretaceous granitic rocks; Nature, Phys. Sci., v. 235, p. 11-13.

Carmichael, C.M. and Palmer, H.C.
1968: Paleomagnetism of the Late Triassic, North Mountain basalt of Nova Scotia; J. Geophys. Res., v. 73, p. 2811-2822.

Collinson, D.W. and Runcorn, S.K.
1960: Polar wandering and continental drift: evidence of paleomagnetic observations in the United States; Geol. Soc. Amer. Bull., v. 71, p. 915-958.

de Boer, J.
1968: Paleomagnetic differentiation and correlation of the Late Triassic volcanic rocks in the Central Appalachian (with special reference to the Connecticut Valley); Geol. Soc. Amer. Bull., v. 79, p. 600-626.

Dolmage, V.
1934: Geology and ore deposits of Copper Mountain; Geol. Surv. Can., Mem. 171, 69 p.

Douglas, R.J.W., Gabrielse, H., Wheeler, J.O., Stott, D.F. and Belyea, H.R.
1970: Geology of Western Canada; Chap. 7 in Geology and Economic Minerals of Canada, Geol. Surv. Can., Econ. Geol. Rept. No. 1, 5th ed., p. 367-488.

Fahrni, K.C.
1951: Geology of Copper Mountain; Can. Inst. Mining Met. Bull., v. 44, p. 317-324.

1962: Post-production geology at Copper Mountain; Western Miner and Oil Rev., v. 35, p. 53-54.

1966: Geological relations at Copper Mountain, Phoenix and Granisle Mines; Can. Inst. Mining Met., Spec. Vol. 8, p. 315-320.

Fisher, R.A.
1953: Dispersion on a sphere; Roy. Soc. London, Proc., Ser. A, v. 217, p. 295-305.

Irving, E. and Banks, M.R.
1961: Paleomagnetic results from the Upper Triassic lavas of Massachusetts; J. Geophys. Res., v. 60, p. 1935-1939.

Irving, E. and Yole, R.W.
1972: Paleomagnetism and kinematic history of mafic and ultramafic rocks in fold mountain belts; Can. Earth Physics Br. Publ., v. 42, no. 3, p. 87-95.

Larochelle, A.
1967: Preliminary data on the paleomagnetism of the North Mountain basalt, Nova Scotia; Geol. Surv. Can., Paper 67-39, p. 7-12.

1969: L'application de la statistique au paléomagnétisme; Geol. Surv. Can., Paper 68-59, 19 p.

Larochelle, A. and Black, R.F.
1965: The design and testing of an alternating-field demagnetizing apparatus; Can. J. Earth Sci., v. 2, p. 684-696.

Larochelle, A. and Christie, K.W.
1967: An automatic 3-magnet or biastatic magnetometer; Geol. Surv. Can., Paper 67-28, 28 p.

Larochelle, A. and Wanless, R.K.
1966: The paleomagnetism of a Triassic diabase dike in Nova Scotia; J. Geophys. Res., v. 71, p. 4949-4953.

Montgomery, J.H.
1967: Petrology, structure, and origin of the Copper Mountain Intrusions near Princeton, British Columbia; Univ. Brit. Columbia, unpub. Ph. D. thesis, 172 p.

Northcote, K.
1969: Geology and geochronology of the Guichon Creek Batholith; Brit. Columbia, Dept. Mines Petrol. Resour., Bull. 56, 73 p.

Opdyke, N.D.
1961: The paleomagnetism of the New Jersey Triassic: a field study of the inclination error in sediments; J. Geophys. Res., v. 66, p. 1941-1949.

Preto, V.A.G., White, W.H. and Harakal, J.E.
1971: Further potassium-argon age dating at Copper Mountain, B.C.; Can. Mining Met. Bull., v. 64, p. 58-61.

Rice, H.M.A.
1947: Geology and mineral deposits of the Princeton map-area, British Columbia; Geol. Surv. Can., Mem. 243.

Rouse, G.E. and Mathews, W.H.
1961: Radioactive dating of Tertiary plant-bearing deposits; Science v. 133, p. 1079-1080.

Sinclair, A.J. and White, W.H.
1968: Age of mineralization and post-ore hydrothermal alteration at Copper Mountain, B.C.; Can. Mining Met. Bull., v. 61, p. 633-636.

Symons, D.T.A.
1971: Paleomagnetism of the Triassic Guichon Batholith and rotation in the Interior Plateau, British Columbia; Can. J. Earth Sci., v. 8, p. 1388-1396.

1972a: Paleomagnetic results from the Jurassic Topley Intrusions near Endako, British Columbia; Can. J. Earth Sci., in press.

1972b: Paleomagnetic results from the Tertiary Mount Barr and Hope plutonic complexes, British Columbia; Geol. Surv. Can., Paper, this publ., part 1.

1972c: Paleomagnetism of the Triassic Guichon Batholith and rotation in the Interior Plateau, British Columbia; Reply; Can. J. Earth Sci., v. 9, in press.

1972d: Paleomagnetic zones in the Oligocene East Sooke gabbro, British Columbia; J. Geophys. Res., in press.

Symons, D. T. A. (cont.)
1972e: Concordant Cretaceous paleolatitudes from Coast Range felsic plutons in the Canadian Cordillera; Nature, in press.

Tarling, D. H. and Symons, D. T. A.
1967: A stability index of remanence in paleomagnetism; Roy. Astron. Soc., Geophys. J., v. 12, p. 443-448.

3. A BALLISTIC MAGNETOMETER FOR THE MEASUREMENT OF ROCK MAGNETIC PROPERTIES

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ABSTRACT

The magnetization of a rock sample is measured by moving a sample from the centre of one detection coil to that of another, the coils being co-axial. The field acting on the specimen can be varied between 0 and 1000 oersteds and the temperature of the specimen can be varied between 20° C and 700° C. Furthermore, the remanent magnetization acquired during crystallization of magnetic materials can be investigated using the required compounds in an oxidizing or reducing environment. Results obtained with this instrument for a 25% magnetite (Fe_3O_4), 75% Alundum Cement mixture show the dependence of the coercive force, the intensity of the isothermal magnetization and the thermal remanent magnetization on the grain size of the magnetite which spanned discrete intervals in the range of 2μm to 1600μm in the experiments.

RÉSUMÉ

L'aimantation d'un échantillon de roche est mesurée en déplaçant l'échantillon du centre d'une bobine de détection à celui d'une autre, les bobines ayant le même axe. Le champ agissant sur l'échantillon peut varier de 0 à 1,000 oersteds et la température de l'échantillon peut varier de 20° C à 700° C. De plus, on peut étudier l'aimantation rémanente acquise pendant la cristallisation des matériaux magnétiques en utilisant les composés nécessaires dans un milieu oxydant ou réducteur. Les résultats obtenus sur un mélange à 75% de ciment Alundum et à 25% de magnétite (Fe_3O_4) à l'aide de cet instrument montrent la dépendance du champ coercitif, de l'intensité de l'aimantation isothermique et de l'aimantation rémanente thermique vis-à-vis la grosseur des grains de la magnétite qui couvrait des intervalles discontinus de l'ordre de 2 m à 1,600 m lors de l'expérience.

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INTRODUCTION

In general, the natural magnetization of rocks consists of several components of different types and origins, which have been acquired under different geological conditions. These components are hard to differentiate, but by measuring simultaneously many magnetic parameters, an attempt may be made to distinguish between them. The various types of remanent magnetization acquired under different physical and chemical conditions may be studied in the laboratory by approximating the natural processes of remanence acquisition. If a distinction between stable remanent components in a rock can be made, estimates can then be made of features such as the temperatures to which the rock has been exposed since its formation. This type of study requires the construction of a versatile instrument which allows the measurement of several fundamental magnetic parameters. The design of the various coils used in the instrument was based on conventional theory as discussed, for instance, by Nagata (1967).

Principles of Design

The principle of electromagnetic induction was selected as the basis for measuring the magnetization of the sample (Nagata, 1967). A rock sample 2 1/2 inches in length is moved 3 inches from the centre of one detector coil to the centre of another. These detector coils are mounted in series opposition to obtain good sensitivity while neutralizing the effects of ambient field variations. The change in the magnetic flux through the coils, brought about by the movement of the sample, induces a momentary current in the coils which can be measured with a galvanometer. A shunt across the galvanometer is used to regulate sensitivity.

In order to determine the dependence of magnetization on the magnetic field a field coil is added, and an oven is included for determination of the dependence of magnetization on temperature.

INSTRUMENT DESCRIPTION

The general design of the ballistic magnetometer is shown in Figures 3-1A and 3-1B, and consists of a series of concentric cylindrical components. The innermost cylinder contains the sample which is surrounded by the oven. A cooling jacket surrounds the oven and a set of detector coils fits over the jacket. The field coil envelopes the inner parts of the instrument.

The oven was constructed by wrapping two nichrome wires simultaneously around a quartz glass tube which had been covered by a layer of asbestos paper. These windings were connected at one end of the tube so that the electromagnetic field produced at any instant by one set of windings is equal and opposite to that produced by the other. The oven is wrapped in asbestos paper to reduce the effects of excessive heat changes on the glass of the cooling jacket, which is fitted tightly over the oven. A calibrated thermocouple connected to a Temperature Controller is used to regulate the temperature of the sample. The detector coils, which are fitted over the cooling jacket, are wound with #45 insulated copper wire, and have a combined resistance of 60KΩ.

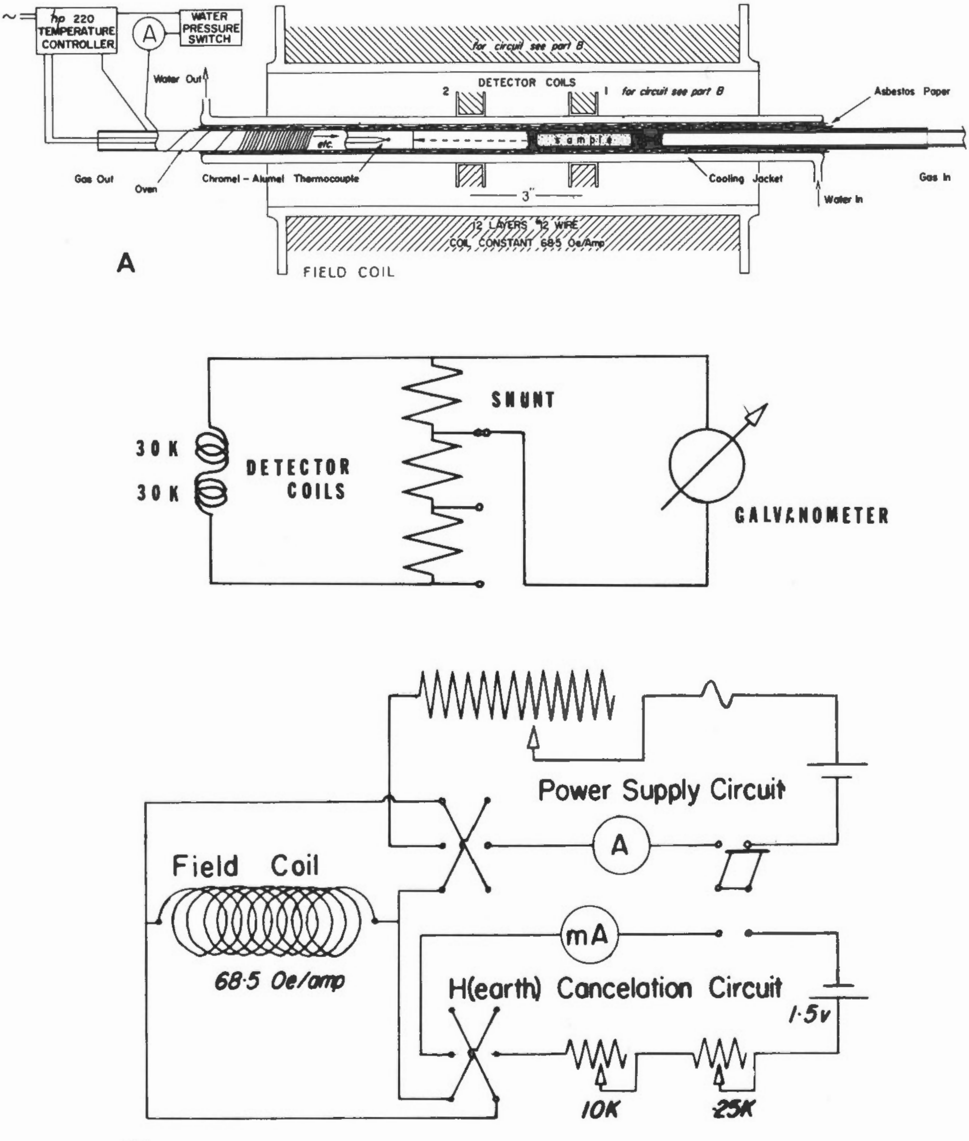

Figure 3-1. Schematic diagrams of the ballistic magnetometer (A) and main electrical circuits (B).

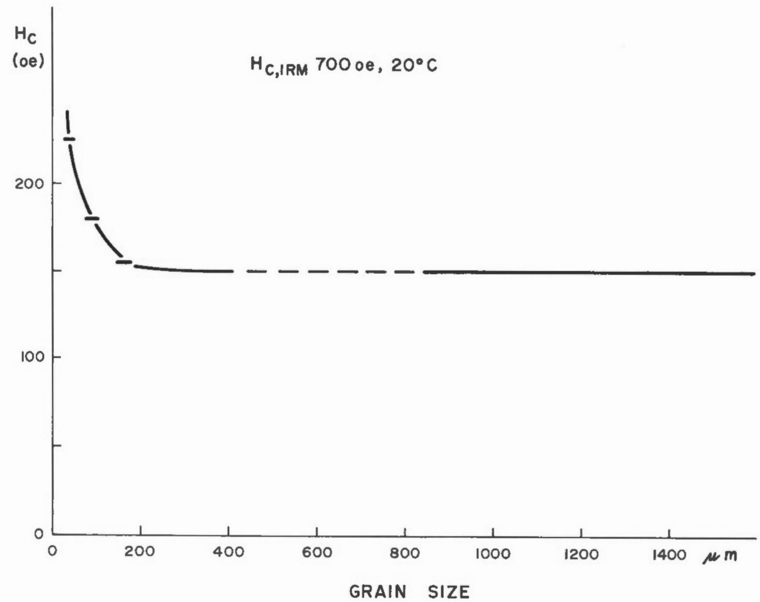

Figure 3-2. Variation of the coercive force (H_C) of the isothermal remanent magnetization (IRM) acquired in a field of 700 oe at 20° C by samples containing magnetite of various grain-size intervals (micrometres, μm).

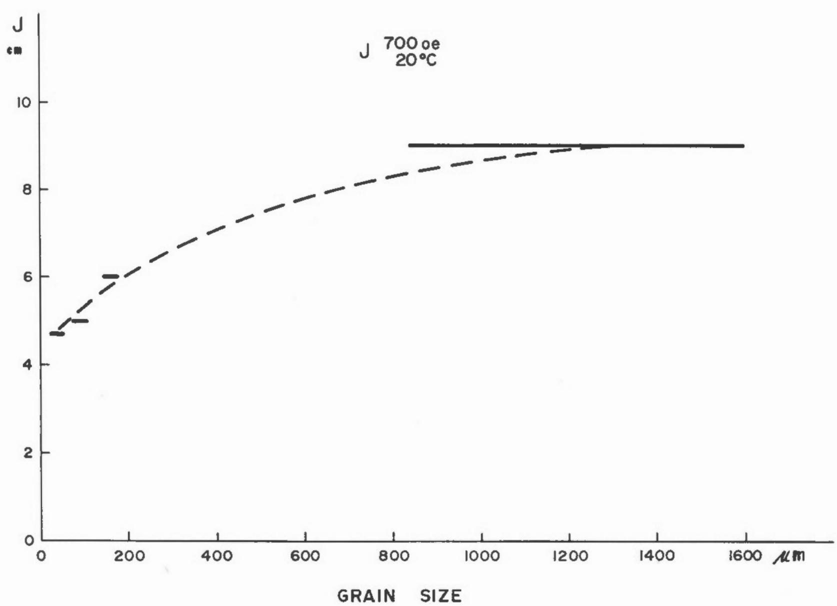

Figure 3-3. Variation in the intensity of total magnetization acquired in a field of 700 oe at 20° C ($J^{700\text{ oe}}_{20°\text{ C}}$) by samples containing magnetite of various grain-size intervals. Grain sizes in micrometres, J in cm scale deflection.

The field coil is operated in two modes as shown schematically in Figure 3-1B; a circuit controlled by a 1.5 volt battery is used to cancel the earth's magnetic field component along the coil axis, and a circuit run by a power supply generates constant fields of up to 1000 oe. Each mode has a switch to reverse the direction of the field. Calibration of the field coil was accomplished with the use of a Hall effect probe.

The unit given for sample magnetization (mm deflection) is not an absolute unit. However, the calibration of the detector coil circuit could be accomplished by using a current-carrying coil in place of the sample.

APPLICATIONS

The ballistic magnetometer allows the determination of the total and remanent magnetization of rock samples and for each of these types of magnetization the dependence on both the applied field and the temperature can be determined. Furthermore, the acquisition of remanent magnetization during crystallization can be measured. This is done in partial vacuum (10^{-3} torr) or in an oxidizing or reducing environment. As an illustration of some of the possibilities of the instrument, some experimental results are discussed in the following.

In order to investigate the effect that grain size has on magnetic properties, tests were conducted with sieved samples of one part magnetite (Fe_3O_4) mixed with 3 parts Alundum Cement (C-218, Fisher Scientific Co.). The cement was used to separate the grains of magnetite thus reducing magnetic interaction. The experimental results are shown on Figures 3-2 and 3-3. Figure 3-2 indicates that the coercive force of isothermal remanence acquired in a field of 700 oe by fine-grained magnetite is substantially higher than that of coarse-grained magnetite. This corresponds to the observation made in many paleomagnetic studies that in general the magnetic stability of coarse-grained plutonic rocks is substantially lower than that of lavas. The stability in terms of the coercive force is expected to decrease to zero for extremely small grains below a certain critical size but this cannot be demonstrated by using sieved magnetite samples. The intensity of the total magnetization in a field of 700 oe ($J^{700\ oe}_{20°\ C}$) also shows a marked dependence on the grain size (Fig. 3-3).

SUMMARY

I. The ballistic magnetometer is a versatile instrument for the low sensitivity measurement of the various magnetic properties of rocks. More specifically the dependence of the acquisition of remanent or total magnetization on the intensity of the applied field and the temperature of the specimen can be investigated.

II. Tests made with 25% magnetite (Fe_3O_4), 75% Alundum Cement mixtures show a strong increase in the coercive force of remanent magnetization towards the smaller grain sizes of magnetite investigated. However, the decrease of the coercive force expected for the extremely small grain sizes within the super-paramagnetic range, was not observed as such grain size fractions could not be isolated by sieving.

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REFERENCE

Nagata: Methods in Paleomagnetism, Edited by Collinson, Greer & Runcorn; Elsevier, 1967.