Magnetic signatures of ophiolitic and continental margin pillow lavas from the Quebec Appalachians

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MAGNETIC SIGNATURES OF OPHIOLITIC AND CONTINENTAL MARGIN PILLOW LAVAS FROM THE QUEBEC APPALACHIANS

BY

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SUMMARY

Diagnostic features such as the petrochemical facies and magnetic signatures of pillowed metatholeiites from the Thetford Mines ophiolitic complex and the Late Cambrian — Early Ordovician Caldwell Group are defined on the basis of a detailed examination of their petrological and magnetic properties.

It was found that radial variations of magnetic properties in ophiolitic lavas are similar to the oceanic H-type pillows of Marshall and Cox while, in Caldwell lavas, they are similar to the oceanic L-type pillows. Radial variations of magnetic properties in pillows appear to be independant of compositional zoning but rather to be related to the size and distribution of the NRM carriers, a function of the cooling rate of lavas. Thermomagnetic analyses indicate that magnetite is the principal NRM carrier; α-hematite, pyrrhotite and, in some cases, a small amount of native iron can be associated with magnetite.

Alteration and metamorphism have caused a large lowering of the NRM in both ophiolitic and Caldwell lavas. Four samples have been selected after AF demagnetization for a preliminary paleomagnetic test which gave an approximate Middle Cambrian paleopole position (151°E-25°N, reverse polarity).

RÉSUMÉ

Des caractères diagnostiques tels que le facies pétrochimique et la signature magnétique de métatholeiites en coussins provenant du complexe ophiolitique de Thetford Mines et du groupe d'âge Cambrien supérieur à Ordovicien inférieur de Caldwell sont définis sur la base d'une étude détaillée de leurs propriétés pétrologiques et magnétiques.

Il a été observé que les propriétés magnétiques des laves ophiolitiques varient radialement d'une manière analogue au type H des coussins océaniques de Marshall et Cox, tandis que dans les laves du groupe de Caldwell elles varient d'une manière semblable au type L des coussins océaniques. Ces variations radiales des propriétés magnétiques paraissent ne pas dépendre d'une zonation de la composition des pillows, mais dépendre plutôt de la taille et de la distribution des porteurs de la mémoire magnétique, facteurs qui sont fonction du taux de refroidissement des laves. Les analyses thermomagnétiques indiquent que la magnétite est le principal porteur de la mémoire magnétique; de l'hématite α, de la pyrrhotite et, dans certains cas, un peu de fer natif accompagnent la magnétite.

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Altération et métamorphisme ont causé une réduction considérable de la rémanence magnétique tant dans les laves ophiolitiques que dans celles du groupe de Caldwell. Après démagnétization, quatre échantillons ont été sélectionnés pour un test paléomagnétique préliminaire qui a donné un paléopole approximatif d'âge Cambrien Moyen et de position 151°E-25°N (polarité inverse).

INTRODUCTION

The results of this study relate magnetic properties such as susceptibility, remanent magnetization and Koenigsberger ratio to petrographic and chemical features of volcanic rocks from the Thetford Mines ophiolitic complex and from the Caldwell Group of Late Cambrian to Early Ordovician age. We have selected the least metamorphosed pillow lavas from the Thetford Mines ophiolitic complex and the Caldwell Group in order to obtain the best possible knowledge of their magnetic memory. After presenting a summary of the geological setting, we describe the petrological features and the magnetic properties of the lavas studied. We aim to show how these data can be used to define petrochemical facies and magnetic signatures.

The Thetford Mines area is well within the internal tectonic domain of the Quebec Appalachians (St. Julien and Hubert, 1975). The domain consists of formational units that are believed to represent the continental rise and deep-sea facies of the sedimentary prism that has accumulated along the southeastern margin of the Canadian shield in early Paleozoic time.

The principal lithologic units of the Thetford Mines area (Fig. 1) are: 1) the Lower Cambrian (?) Rosaire Group (Béland, 1957) which occupies the core of Sutton-Notre Dame anticlinorium and consists mainly of orthoquartzites and schists or phyllites; and 2) the Upper Cambrian-Early Ordovician Caldwell Group (Mackay, 1921) which is composed of feldspathic sandstones and slates grading upward into red and greenish shales with intercalations of metabasaltic lava flows. Rocks of this group constitute the southeastern flank of the Sutton-Notre Dame anticlinorium where they are tectonically overlain by the Thetford Mines ophiolitic complex (Laurent, 1975; 1977). The ophiolitic complex is, in turn, unconformably overlapped on the southeast by the early Middle Ordovician (?) breccias and phyllites of the St. Daniel Formation, a mélange which was deposited at the time of the obduction of the ophiolitic complex.

The ophiolites and the St. Daniel mélange extend in a northeast trend for more than 200 kilometers along the southeastern boundary between the Cambrian and Ordovician formations of the internal tectonic domain suggesting the existence of a major regional suture zone. To the southeast, towards the United States the ophiolite-mélange belt is overlain unconformably by the Magog Group, a thick flysch sequence which contains graptolites of the *Nemagraptus gracilis* and *Diplograptus multidens* Zones of Middle Ordovician age (Riva, 1974).

Structural studies have shown that the Cambrian rocks to the northeast of Thetford Mines (Fig. 1) are overturned to the southeast and form the lower flank of a large recumbent fold which originally slid in a southeasterly direction (St. Julien and Hubert, 1975, Fig. 1 and 3). This movement apparently directed towards the

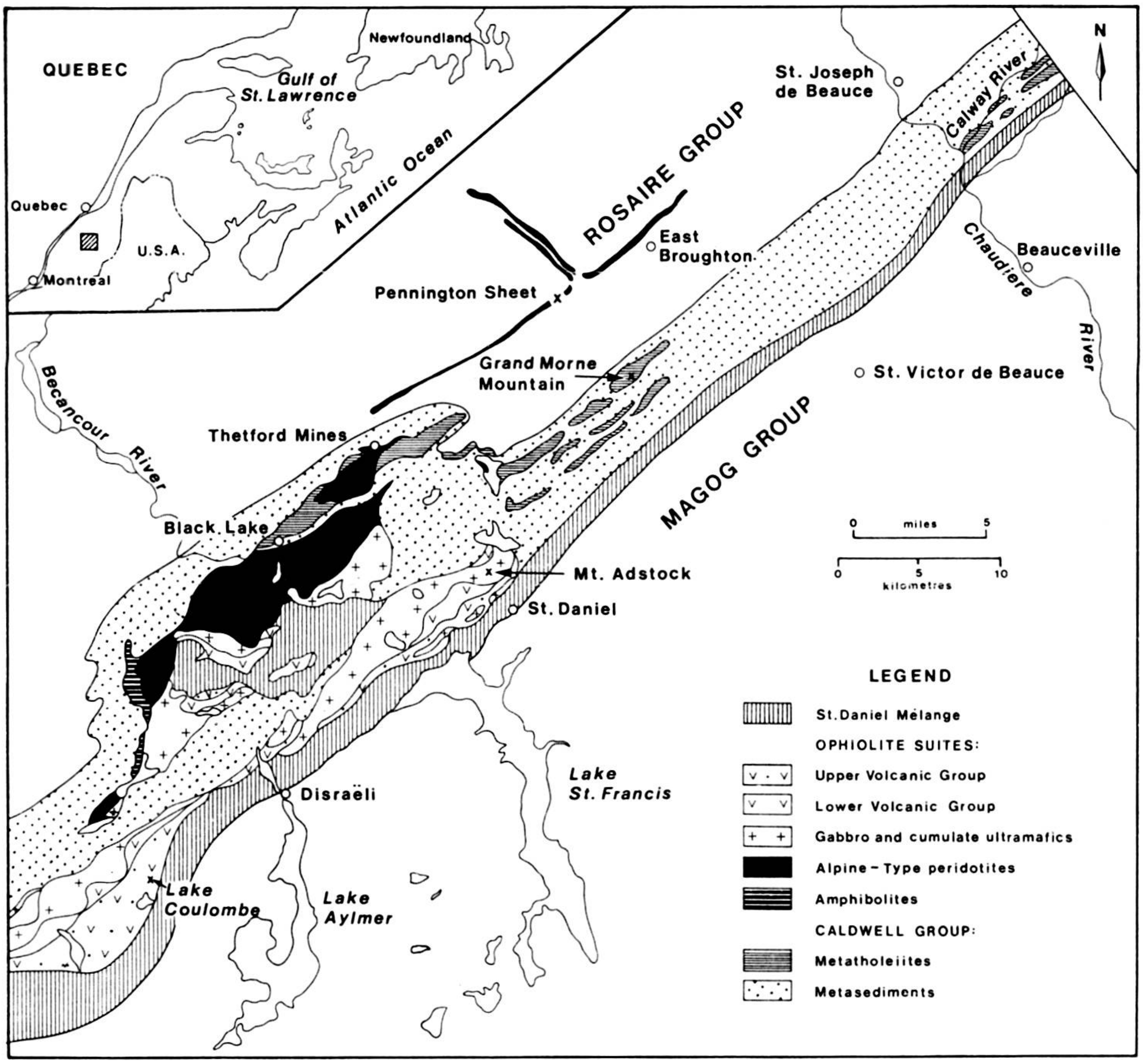

FIGURE 1. — Geological map of the Thetford Mines area.

oceanic basin is believed to have been caused by the subsidence of the continental margin of eastern North America, and in response to the formation of a southeasterly-dipping subduction zone at the western limit of the Proto-Atlantic ocean (Church and Stevens, 1971; Stevens et al., 1974; Williams and Stevens 1974; Norman and Strong, 1975; Laurent, 1975). It is assumed that the subsidence of the cratonic margin led to the obduction of the ophiolites onto the continental margin during the deposition of the St. Daniel mélange and prior to the deposition of the Middle

Ordovician Magog Flysch. Later the Cambro-Ordovician rocks together with the ophiolites were refolded during the Mid- to Late Ordovician Taconian Orogeny.

PETROLOGICAL STUDY

LAVAS OF THE OPHIOLITIC SUITES

The volcanic and sedimentary sequence forming the cap of the Thetford Mines ophiolitic complex is divided into two groups: a) a lower group consisting of metabasaltic lavas, pillow breccias and tuffs with a sedimentary cover of cherty red argillite, and b) an upper group more heterogeneous in composition and consisting of basaltic lavas, pyroclastic agglomerates and breccias, siliceous volcaniclastic tuffs and mudstones. The total thickness of the two groups and their sedimentary cover is about 1000 to 1200 meters. The volcanic and sedimentary sequence of the ophiolitic complex resembles the association of basaltic pillow lavas, pelagic red mudstones, basaltic andesites and marine volcaniclastic rocks that form the backbone of present young oceanic island arcs, such as the Tonga Islands and the New Hebrides Islands Arc in the Pacific (Laurent and Hébert, 1977).

The samples of pillows selected for the study of the ophiolitic lavas are metatholeiites which come from both the lower and upper volcanic groups. Their magnetic memory is stored in several mineral phases that have been identified in polished sections and studied by microprobe. Besides magnetite, or hematite in some cases, five other magnetic phases are present in small amounts: sphene with inclusions of ilmenite, an (unknown ?) Fe-Si oxide, pyrrhotite, chromite and native iron. Sphene occurs in bundles of hairy crystals (wiskers) less than 10 microns long (composition: TiO_2 41%; SiO_2 31%; FeO 1%; CaO 27%). The Fe-Si oxide occurs as irregular to oval grains less than 20 microns long and with a rim of slightly different composition than the core (composition of the core: FeO 80%; SiO_2 12%; V_2O_5 1%; CaO 1%; composition of the rim: FeO 73%; SiO_2 14%; V_2O_5 2.5%; CaO 1%). Pyrrhotite and chromite occur as relatively large crystals of irregular shape, about 50 microns long (composition of chromite: Cr_2O_5 67%; FeO 33%). Native iron occurs in particles of lamellar habit less than 5 microns long (Fe 96%), Ni present but not estimated, traces of Cr), which are found in fractures of former olivine phenocrysts that have been entirely pseudomorphosed by magnesian chlorite. Chlorite forms a soft green matrix which apparently has protected the iron particles against oxidation (Deutsch et al., 1977).

a. *Pillow lavas from the lower volcanic group:*

The lower volcanic group is composed of pillowed metabasalts of greenschist metamorphic grade. Their mineral assemblage is actinolite, chlorite, epidote, albite, quartz, calcite and magnetite; relics of calcic plagioclase and clinopyroxene are not uncommon. Two types of lava are distinguished, the first one rich in chlorite and tholeiitic in composition, and the second one rich in actinolite and containing abundant magnesian chlorite pseudomorphs after olivine microphenocrysts and phenocrysts, and with the composition of an olivine tholeiite. The metatholeiite is relatively low in MgO, Cr_2O_3 and NiO, but relatively high in Al_2O_3 and FeO $+ Fe_2O_3 + TiO_2$ (OST, Table I) compared to the olivine metatholeiite (OOT), Table I). Both types of lava are spilitized and metasomatically enriched at various extents in soda and silica.

The pillow lavas are structurally characterized by the association of closely-packed tube-like bodies, up to 2 m in diameter and up to 8 m or more in length, and pillows having the shape of potato bags. Pillow diameters vary from 5 to 90 cm in sections perpendicular to their long axis. The association is alike the outcrops of Mount Chenaillet in the Alps (cf. Vuagnat, 1975). The ophiolitic pillows of the lower group are not homogeneous but can be divided into three concentric zones on the basis of fabric and composition: margin, intermediate zone, and core. From the margin to the core of the pillow, textures vary from originally vitrophyric (?) to arborescent and intersertal porphyritic, while sizes of phenocrysts increase and habits of microlites change from acicular to lath-shaped. The chilled outer zone of olivine metatholeiites shows an arborescent globulitic structure and that of metatholeiites a variolitic structure (Laurent and Hébert, 1977). The pillows contain fine scattered amygdules filled with albite and quartz or carbonates. Radial jointing is absent or poorly developed.

Table 1 gives the chemical composition of a metatholeiitic pillow from Asbestos selected for the study of magnetic properties. The sampling includes analyses from the margin (AS-27A), the intermediate zone (AS-97B) and the core (AS-27C). This pillow is not chemically zoned. Despite abundant amygdules of calcite yielding an excess of lime of secondary origin, analyses show that the metatholeiitic pillow has chemical features common to most of the metabasalts of the Quebec ophiolites, i.e., a high Na_2O/K_2O ratio and low K_2O, TiO_2 and P_2O_5 contents. Table I gives also the average chemical composition of the olivine metatholeiite (OOT) whose petrological features and magnetic properties have previously been described (Seguin and Laurent, 1975).

b. *Pillow lavas from the upper volcanic group:*

The base of the upper volcanic group consists of alternating greenish and grey flows of pillow lava, breccias and agglomerates. The chemical composition of the pillow lavas is close to that of the metabasalts of the lower volcanic group, while the grey volcanics are less mafic and have no analogs in the lower group, their composition being metaandesitic (Laurent and Hébert, 1977). The metamorphic grade of this sequence is lower than that of the lower group and falls in the boundary region

TABLE 1

Chemical composition in wt % of ophiolitic pillow lavas

OXIDES	AS-27A	AS-27B	AS-27C	TM-2A	TM-2B	TM-2C	OOT	OST
SiO_2	49.86	50.09	49.50	43.50	44.51	46.93	51.08	53.35
TiO_2	0.08	0.08	0.08	0.12	0.10	0.12	0.07	1.09
Al_2O_3	8.78	8.12	7.87	11.14	10.57	11.52	11.60	14.50
Fe_2O_3	2.38	2.10	2.32	3.61	3.34	3.32	1.91	3.84
FeO	4.00	3.98	3.96	4.92	4.62	4.58	6.70	6.86
MgO	6.77	6.75	7.87	12.76	12.18	12.40	13.98	5.49
MnO	0.12	0.12	0.12	0.14	0.12	0.12	0.15	0.17
CaO	14.02	14.81	14.82	14.84	14.29	11.60	6.91	4.23
Na_2O	3.46	3.14	2.64	3.23	3.60	4.14	2.21	5.12
K_2O	0.46	0.54	0.84	0.40	0.39	0.27	0.20	0.16
P_2O_5	0.01	0.01	0.01	0.00	0.01	0.01	0.02	0.07
$H_2O\pm$	5.62	5.92	6.02	3.36	3.61	3.05	3.91	3.82
H_2O	0.16	0.12	0.15	0.12	0.17	0.18	0.30	0.20
CO_2	4.05	3.85	3.65	2.50	2.45	1.80	0.42	0.63
TOTAL	99.77	99.63	99.85	100.64	99.96	100.04	99.46	99.53
				Trace elements in PPM				
Cr	600	500	630	1280	1150	1200	1061	119
Ni	113	135	131	241	248	255	277	28
Cu	34	34	52	20	22	20	66	54
Zn	55	50	47	32	34	44	73	83
Sr	100	76	53	271	281	250	60	121

AS-27: Pillow from Asbestos, ophiolitic complex of Asbestos.
TM-2: Pillow from Lake Coulombe. ophiolitic complex of Thetford Mines.
A: Margin of pillow; B: Intermediate zone of pillow; C: Core of pillow.
OOT: Average composition of a pillow of olivine tholeiitic composition from Mount Adstock (Lower volcanic group, ophiolitic complex of Thetford Mines) calculated in using five analyses from the rim to the center of the pillow (for detailed data c.f. Seguin and Laurent 1975).
OST: Average composition of 7 selected analyses of spilitized pillows of tholeiitic composition (Lower volcanic group, ophiolitic complex of Thetford Mines),

between the greenschist and the prehnite-pumpellyite facies. The metamorphic mineral assemblage is similar to that of the lower volcanics, but locally pumpellyite occurs as pseudomorph after pyroxene and also as a cement filling amygdules and veins together with chlorite, epidote, calcite, albite and quartz. In size and shape the pillows are similar to those of the pillowed flows of the lower group. Jointing is also absent or poorly developed. However, in contrast with the pillows of the lower volcanic group, the metabasaltic pillows of the upper group are not structurally zoned and are characteristically amygdaloidal with an intersertal microlitic and porphyritic texture. The microlites are skeletal plagioclases, entirely saussuritized, and the phenocrysts are augitic clinopyroxenes which are sub-idiomorphic, up to 3 mm long, and often well preserved; relics of poorly preserved pigeonite also occur locally in the cryptocrystalline matrix.

Table I gives the chemical composition of an olivine metatholeiitic pillow from the Lake Coulombe area selected for the study of magnetic properties. The sampling includes analyses from the margin (TM 2A), the intermediate zone (TM 2B) and the core (TM 2C) showing no chemical zonation. Because of the large number of calcite-filled amygdules results are biased, there is an excess of lime of secondary origin. They show however that contents in major oxides (SiO_2 and CaO excepted) and trace elements of this pillow are very close to those of the olivine metatholeiite of the lower volcanic group (OOT, Table I).

Lavas of the Caldwell Group

The Caldwell rocks of assumed Late Cambrian-Early Ordovician age occupy stratigraphically the upper part of the Early Paleozoic sequence of the internal tectonic domain of the Quebec Appalachians. Their lateral stratigraphic equivalents are the Stowe Formation in Vermont (Cady, 1969) and the upper units of the Fleur de Lys Supergroup in Newfoundland (Church, 1969; Kennedy, 1971). As these rocks are complexly deformed and are faulted their true thickness is not known but can only be estimated to be in the order of several thousand meters in the Thetford Mines area (MacKay, 1921; Tolman, 1936; Cooke, 1937; Riordon, 1953; St. Julien, 1976, oral communication).

The samples of pillows selected for this study come from two main localities (Fig. 1), Grand Morne Mountain and Calway River. The lavas from Grand Morne Mountain are relatively unaltered metatholeiites while those from Calway River are spilites.

a. *Pillow lavas from Grand Morne Mountain*

Grand Morne Mountain, also known as Broughton Mountain, is situated 8 km south of East Broughton (N 46°08'-71°06'W). It is part of metabasalts interbedded in the sandstone — slate lower unit of the Caldwell Group. The volcanic complex of the Grand Morne is more than 300 m thick and is well preserved. The pillows are not deformed and are of low grade metamorphism with pumpellyite as the typical index mineral. Structurally, the sequence is isoclinal; the flows dip vertically or steeply to the southeast and face southeast.

The pillows are porphyritic and homogeneous, dark grey-green to grey-purple in color. The diameter of their sections varies from less than 20 cm to about 1.20 m, and they are closely packed together without traces of sedimentary matrix. Locally they may be finely vesicular, and radial jointing is present, but poorly, or irregularly developed. The mineral assemblage is "pumpellyite-chlorite-epidote-albite-magnetite-leucoxene" which is characteristic of low-grade metamorphism (Coombs, 1954). Prehnite as well as pumpellyite have been identified by X-ray diffraction. Zen (1974) has recently described in other volcanics from the west side of the Appalachians similar occurrences of pumpellyite while Trzcienski (1976) has reported the presence of crossitic amphibole in Early Paleozoic volcanics from the Richmond area.

Table 2 gives the chemical composition of a metatholeiitic pillow from Grand Morne Mountain. The sampling includes analyses from the margin (RCA-8A), the intermediate zone (RCA-8B) and the core (RCA-8C) of the pillow. Except for a slight increase in the MgO content from the margin to the core, this pillow does not present a distinct chemical zoning. The lava is alkalic, poor in potash but relatively rich in soda; it has the composition of a sodic basalt with a low titanium content (Middlemost, 1975, p. 348). The pillow composition compares well with the average composition of other Caldwell lavas and of lavas from the stratigraphic equivalent Stowe Formation of Vermont (see CG and SF, Table 2).

b. *Pillow lavas from Calway River*

Calway River is the type locality for the Caldwell Group as originally defined by MacKay (1921). It is situated in the Chaudière valley, 6 km southeast of St. Joseph de Beauce (N 46°17'-70°47'W). The volcanics are interbedded in the purple shales of the upper unit of the Caldwell Group. The volcanic rocks strike N 30 to 40E and dip to the west at high angles; their thickness is estimated to be about 400 m. As indicated by tops of pillows facing southeast and polarity features of the sedimentary rocks, the unit is structurally isoclinal and overturned to the southeast (MacKay, 1921, p. 20). It consists of massive and pillowed flows of green metabasalt, dark red spilite, and of pillow breccia, hyaloclastic tuff and fine-grained green volcaniclastic rocks together with purple shales and thin layers of red chert and red limestone.

Lithologically the Calway River volcanics are spilitized submarine metabasalts of low-grade metamorphism. Two facies of spilite are distinguished. The first is a greenstone which is similar in mineral assemblage, metamorphic grade, structure and in texture to other Caldwell volcanics such as the Grand Morne rocks. The second facies is a dark red spilite which is rich in hematite, but, otherwise, mineralogically similar to the greenstones. The structure, texture and chemical composition of the hematitic spilite being however markedly different from those of the greenstones, a separate study of this type of pillow is justified.

The hematitic spilites occur as massive and pillowed flows. The pillows are generally aphanitic and homogeneous in composition, and they vary in size from 20 cm to 1 m. The texture of the rock is intersertal microlitic and microporphyritic. Skeletal microphenocrysts of clinopyroxene 0.1 to 0.2 mm long, partly or entirely replaced by pumpellyite and epidote, together with saussuritized plagioclase microlites are scattered in a microcrystalline groundmass of chlorite, epidote, pumpellyite, actinolite, albite, illite, hematite and leucoxene. The rock is cut by numerous veins of epidote, chlorite, quartz, calcite and a small amount of copper sulfide. Radial and concentric jointing is well developped and a brecciated internal structure is characteristic of the pillows. Their matrix is usually composed of hyaloclastic tuff locally replaced by the purple shale.

TABLE 2

Chemical composition in wt % of pillow lavas from the Caldwell Group

OXIDES	RCA-8A	RCA-8B	RCA-8C	RCA-1A	RCA-1B	RCA-1C	CG	SF
SiO_2	46.99	45.53	45.27	49.39	48.30	49.02	47.60	47.68
TiO_2	0.74	0.75	0.76	1.49	1.42	1.27	1.38	1.06
Al_2O_3	16.24	15.67	15.67	19.64	17.53	18.13	13.96	15.35
Fe_2O_3	3.91	4.02	2.41	10.20	16.38	9.87	2.99	5.11
FeO	6.16	6.38	6.88	1.04	1.32	1.82	9.36	6.04
MgO	5.79	6.00	8.76	1.46	1.56	2.35	7.58	7.11
MnO	0.16	0.15	0.15	0.10	0.10	0.12	0.18	0.18
CaO	13.45	15.03	13.86	4.87	3.98	4.75	9.69	10.51
Na_2O	3.05	2.33	3.05	5.32	5.38	5.18	3.18	2.36
K_2O	0.17	0.04	0.05	2.72	1.86	2.40	0.24	0.21
P_2O_5	0.07	0.05	0.05	0.27	0.18	0.12	0.11	0.14
$H_2O\pm$	3.07	3.41	3.48	2.56	2.21	3.47	3.34	2.97
H_2O	0.11	0.10	0.12	0.23	0.21	0.29	0.06	0.06
CO_2	0.19	0.28	0.31	0.18	0.19	0.99	0.19	0.78
TOTAL	100.10	99.73	100.81	99.47	100.62	99.78	99.86	99.56
Trace elements in PPM								
Cr	150	100	100	100	200	270	—	—
Ni	65	68	68	85	100	125	—	—
Cu	137	125	131	350	47	75	—	—
Zn	59	60	63	114	142	158	—	—
Sr	196	100	121	242	242	187	—	—

RCA-8: Pillow from Grand Morne Mountain.
RCA-1: Pillow from Calway River.
A: Margin of pillow; B: Intermediate zone of pillow; C: Core of pillow.
CG: Average of 7 analyses of metatholeiites from the Caldwell Group of southern Quebec (analyses No. D37, D38, D40, D41, D42, D44 of Alsac et al. 1971, annexe 1, and one unpublished analysis from our collection).
SF: Average of 10 analyses of metatholeiites from the Stowe Formation of Vermont (analyses No. 10 to 19 of Cady 1969, pp. 148-149).

Table 2 gives the chemical composition of a spilitic hematiterich pillow from Calway River. Sampling includes analyses from the margin (RCA-1A), the intermediate zone (RCA-1B) and the core (RCA-1C) of the pillow showing alike the Grand Morne pillow, no distinct chemical zoning. Compared to the Grand Morne samples and to the average composition of the Caldwell metatholeiites, the hematitic spilite is rich in alumina and alkalis — the amount of potash varying from about

1.8 to 2.8 percent is notable — but poor in magnesia and lime. It is not possible to tell whether or not these chemical features were caused mainly by spilitization or are partly inherited primary features.

MAGNETIC PROPERTIES OF PILLOW LAVAS

A study of the radial variations in magnetic properties was made on eleven samples of pillow lavas. Two samples were obtained from the same pillow TM-2 in which a sample was oriented along the longitudinal section (direction of flow) and the other along the large diameter of the section perpendicular to the flow direction. Pillows TM-1, TM-2, TM-3 and AS-27 are ophiolitic; the three first ones come from the Lake Coulombe area (upper volcanic group, Thetford Mines ophiolitic complex), and the last one from Asbestos (lower volcanic group, Asbestos ophiolitic complex). Pillows TM-5, RCA-1, RCA-2 and RCA-8 are from the Caldwell Group. TM-5 was collected at Black Lake in the Thetford Mines area, RCA-1 and RCA-2 in the Calway River and RCA-8 at Grand Morne Mountain (Fig. 1). For the purpose of comparison of the magnetic signatures between the different samples two additional pillows were studied. Pillow 41T-20 was collected in a Lower Proterozoic (Aphebian) volcanic sequence of the Labrador Trough, Northern Quebec (age about 1800 m.y.), whereas pillow C-4 belongs to a volcano-sedimentary sequence of Archean age (age about 2800 m.y.) from the Abitibi volcanic belt, Chibougamau region, Quebec.

All pillows were drilled along the large diameter of the section perpendicular to their flow direction and yielded cylinders 2.5 cm in diameter and 2.4 cm in length. The different cylinders were numbered from margin to core and classified in the three zones defined by the geometry of the pillow and its textural features (margin, intermediate zone and core).

The long semi-axis of the elliptic cross-section of the individual pillows investigated ranged from 16 to 22 cm; the thickness of the crust, margin, intermediate zone ane core of the pillows varied between 0.5-1, 1-3, 5-8 and 7-12 cm respectively.

The long axis of flow direction of pillows, which is perpendicular to the section of sampling, was selected as the direction of reference to define the orientation of the NRM vector.

LAVAS OF THE OPHIOLITIC SUITES

The remanent magnetization of each cylindrical sample was measured with a spinner magnetometer and the susceptibility with a low field A.C. bridge. The results of the measurements are available from the authors on reader's request. Values of NRM intensity are low compared to values reported for recent oceanic basalts by Ade-Hall (1964), Irving et al. (1970) and for average DSDP basalts (Lowrie et al. 1973). The susceptibility is relatively large in the crust (zone I) of the ophiolitic pillows but decreases rapidly beneath, within zone II, and occasionally increases slightly towards the center (Fig. 2). In figures 2, 3 and 4, the curves are drawn by connecting 4 points of measurement. Each point represents the geometric mean of the zone considered. The same pattern is observed in the Archean pillow C-4 from Chibouga-

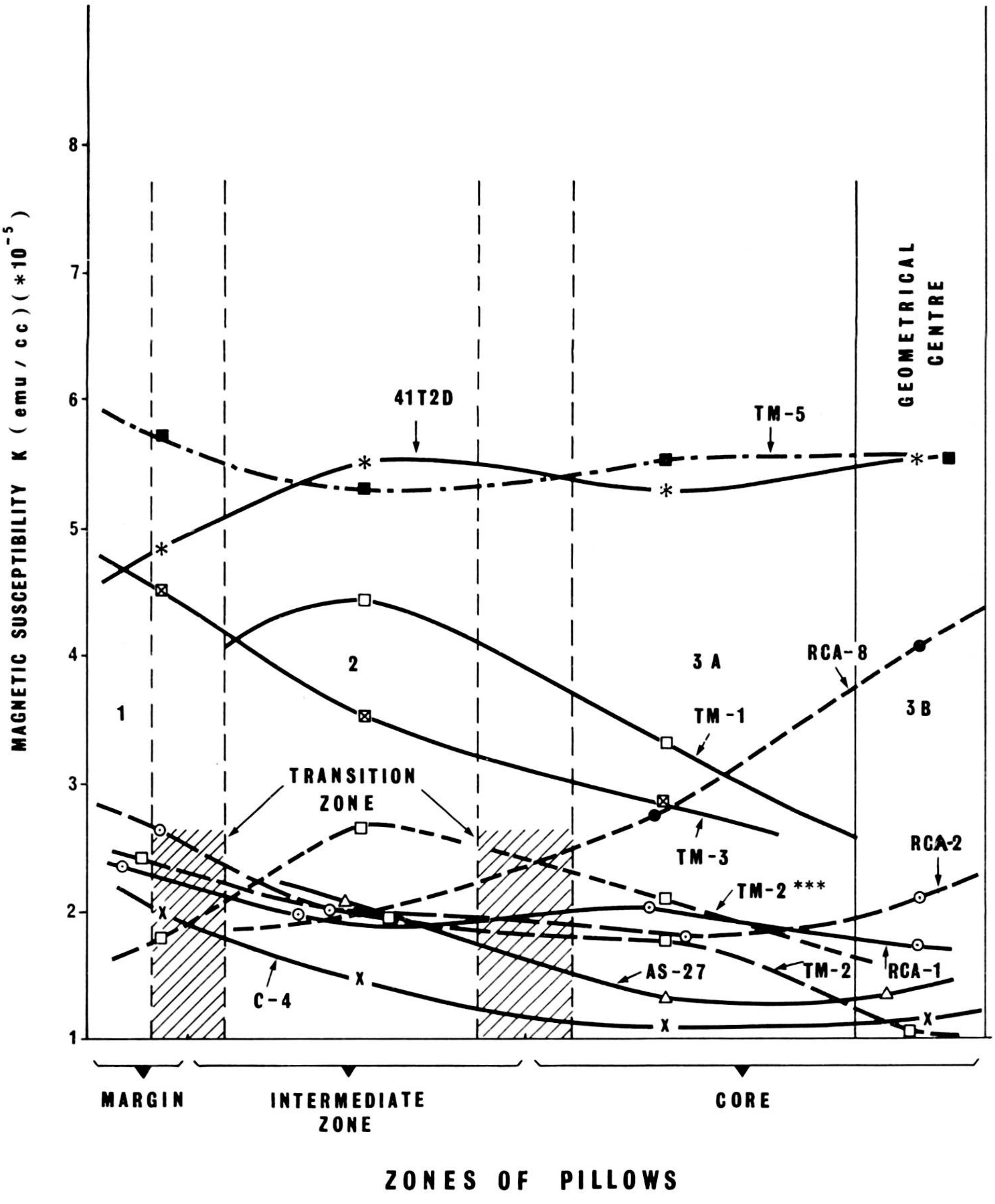

FIGURE 2. — Variation of magnetic susceptibility K with distance from the margin to the center of pillows.

mau. In some ophiolitic pillows the susceptibility is two times smaller in the intermediate zone than in the crust. Most of the susceptibility high in the margin occurs in the outer 2 to 5 cm thick crust. In contrast, the intensity of remanent magnetization is low

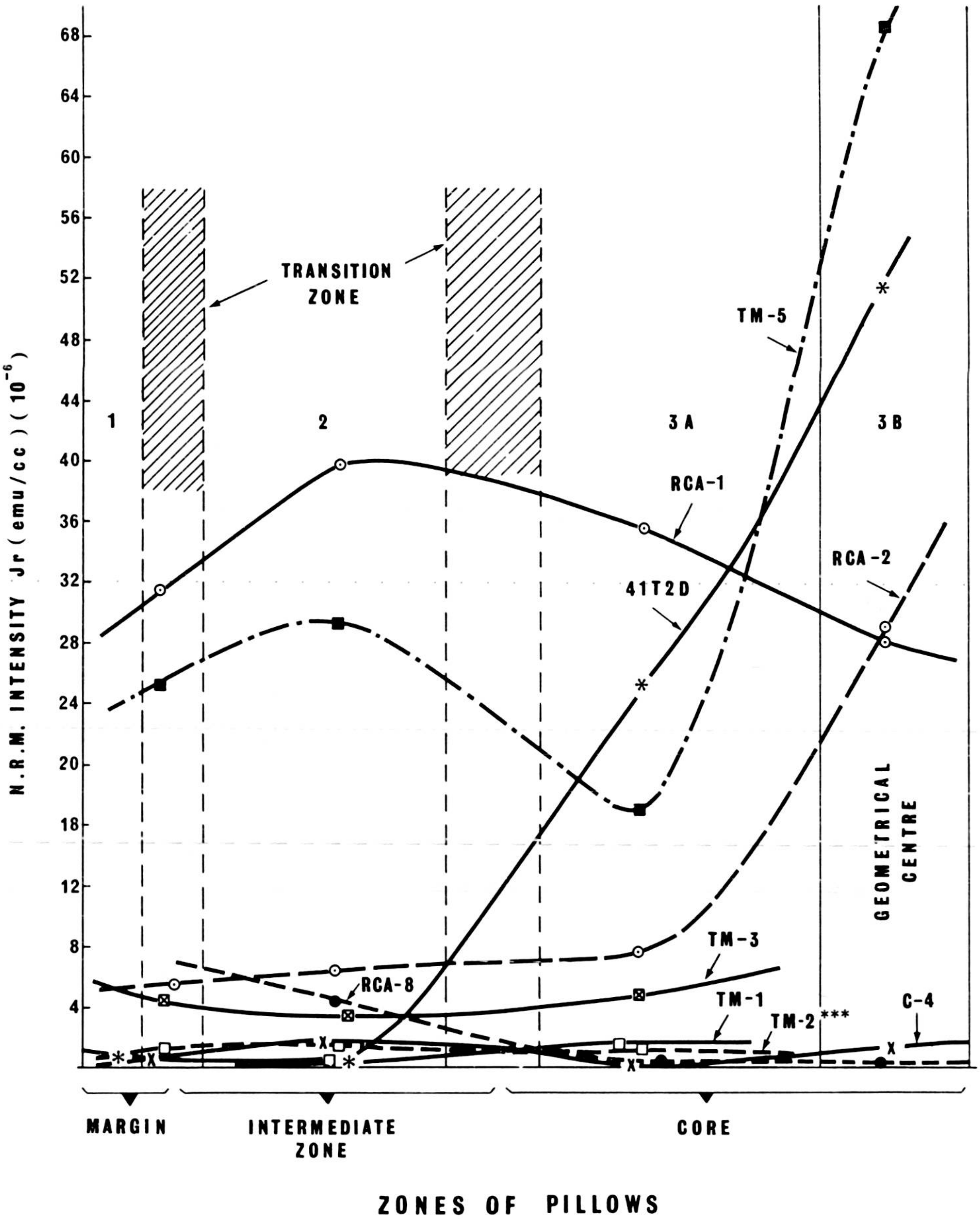

FIGURE 3. — Variation of intensity J of remanent magnetization with distance from the margin to the center of pillows.

in the crust and the intermediate zone and undergoes a further decrease towards the pillow center (Fig. 3). In the pillows studied, the direction of the NRM vector is generally more consistent and constant within the inner part of the intermediate zone II

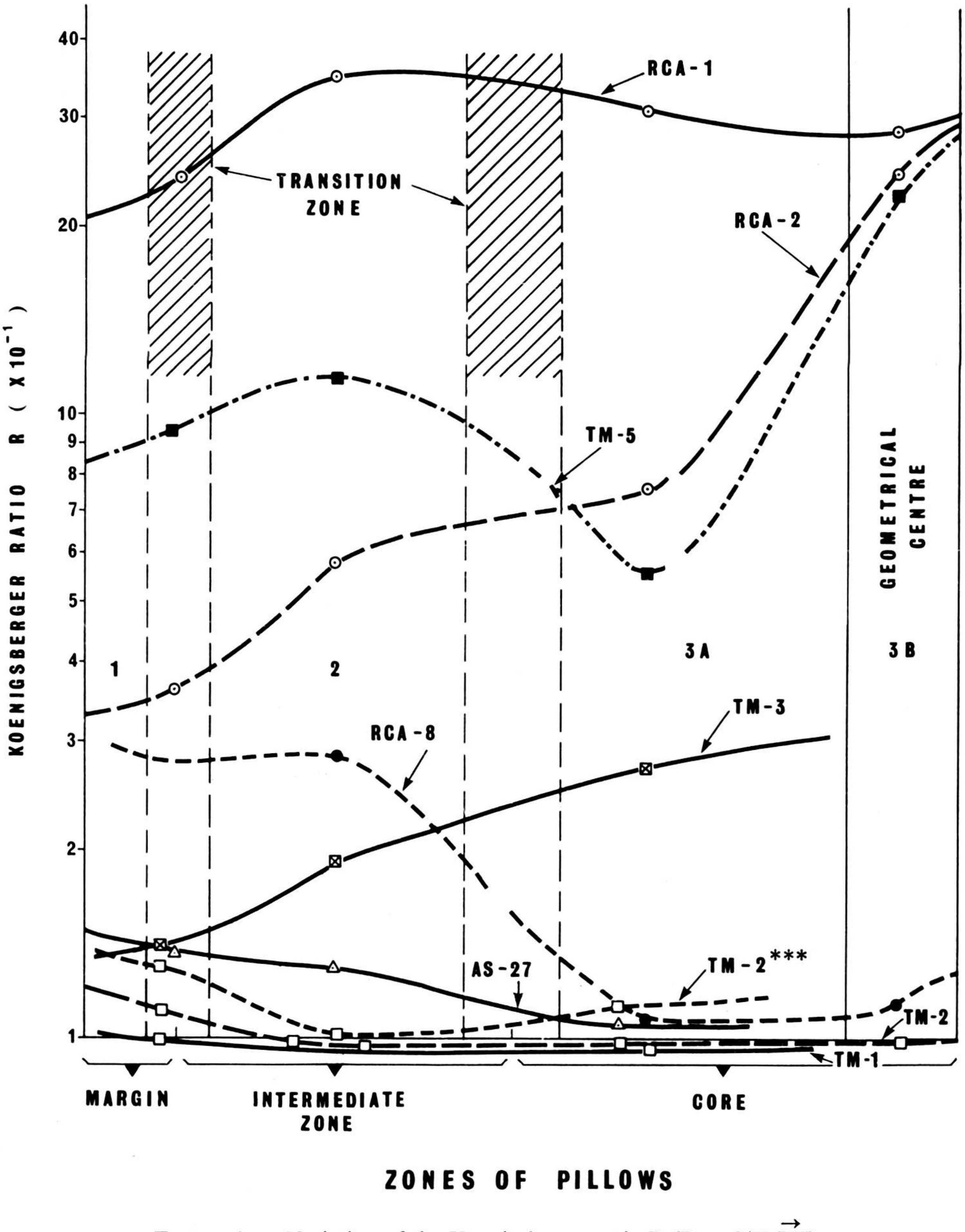

FIGURE 4. — Variation of the Koenigsberger ratio R ($R = J/K\ |\vec{T}|$) with distance from the margin to the center of pillows.

and the external part of the core (zone III A) than within the outer zones. This information concerning the degree of homogeneity or dispersion of the NRM orientation in pillow lavas is necessary before undertaking regional paleomagnetic work.

The variation of the Koenigsberger ratio R ($R = J/K\,|\vec{T}|$) in the different pillow zones is shown in figure 4. The R values are low in the crust, within zone II and in the outer part of the core (zone III A); they are even lower in the pillow geometrical center. The R values are of the order of 0.05 to 0.20 and consequently are 1000 to 2000 times smaller than values obtained by Marshall and Cox (1971) on recent pillow lavas from the Northern Pacific and Central Indian oceans.

Lavas of the Caldwell Group

In the case of the Upper Cambrian — Lower Ordovician pillows belonging to the Caldwell Group the susceptibility values are higher (1.5 to 2 times) than the values obtained for the ophiolitic pillows. Lavas from these two formations can be distinguished to a certain extent on the basis of their susceptibility values alone (Fig. 2). The susceptibility remains relatively constant throughout the different zones of the Caldwell pillows; a slight increase was occasionally observed in the core. This is also true for the Proterozoic pillow 41T2D from the Labrador Trough. The intensity of the remanent magnetization in Caldwell pillows is most commonly higher in the core than in the outer zones, which is the inverse case observed for the ophiolitic pillows. In addition, the NRM intensities of the Caldwell pillows are four to five times higher than those of the ophiolitic pillows (Fig. 3).

The variation of the Koenigsberger ratio R in the different zones of the Caldwell pillows is shown in Figure 4. The R values are the highest within zone II and occasionally in the vicinity of the geometrical center (zone III B). The R values are of the order of 0.3 to 3.0 and are approximately 10 times higher than the values obtained for the ophiolitic pillows. In pillow lavas, the relationship of the Koenigsberger ratio to cooling rate is more complex than in other types of igneous bodies because of the occurrence of a relatively thick glassy quenched zone. Marshall and Cox (1971) have found in their L type recent pillows that R increases away from the quenched margin of the pillow towards the interior, whereas in their H type recent pillows R decreases in the same direction. The pillow lavas from the Thetford Mines ophiolitic complex and from Chibougamau are similar to the oceanic H type pillows in spite of the fact that their values of R increase from the outer part of the core to the pillow geometrical center. In contrast, the pillow lavas from the Caldwell Group and from the Labrador Trough are similar to the oceanic L type pillows of Marshall and Cox; in some instances, the R values decrease rapidly from the outer part of the core to the pillow geometrical center. A comparison of the magnetic properties between the Caldwell and ophiolitic lavas shows that the magnetic signature of these two formations is quite different.

The geometric mean of the susceptibilities, NRM intensities and Koenigsberger ratios for the different zones of the pillow lavas studied are presented in Table 3.

TABLE 3

Average variations of magnetic properties

Zone Number	Sample Number	Susceptibility K (emu/cc) $X10^{-5}$	Intensity of N.R.M. Component /J/(emu/cc) $X10^{-6}$	Koenigsberger Ratio R
	Chibougamau — Archean			
	C-4			
I	(3)	2.01	0.61	0.06
II	(4)	1.47	1.63	0.25
IIIA	(4)	1.02	0.54	0.12
IIIB	(Geometrical Center) (1)	1.04	1.08	0.18
	Ophiolites : Eastern Townships — Appalachians			
I	TM-2*** (4)	1.80	1.15	0.13
	TM-3 (2)	4.52	4.24	0.14
	TM-2 (1)	2.43	1.48	0.11
	Average (Zone I):	3.31	2.21	0.12
II	TM-1 (3)	4.41	0.56	0.02
	TM-2*** (15)	2.68	1.34	0.10
	TM-3 (4)	3.50	3.27	0.19
	TM-2 (2)	1.99	0.53	0.04
	AS-27 (4)	2.00	1.53	0.13
	Average (Zone II):	2.96	1.32	0.06
IIIA	TM-1 (5)	3.32	1.17	0.05
	TM-2*** (4)	2.11	1.22	0.11
	TM-3 (3)	2.81	4.42	0.27
	TM-2 (6)	1.77	0.78	0.07
	AS-27 (4)	1.31	0.72	0.10
	Average (Zone IIIA):	2.08	1.78	0.12
IIIB	TM-2 (1)	1.12	0.43	0.07
	AS-27 (1)	1.39	—	—
	Average (Zone IIIB):	1.25	0.43	0.07

TABLE 3 *(fin)*

Average variations of magnetic properties

Zone Number	Sample Number	Susceptibility K (emu/cc) X10−5	Intensity of N.R.M. Component /J/(emu/cc) X10−6	Koenigsberger Ratio R
	Caldwell Formation			
I	TM-5 (2)	5.74	25.3	0.94
	RCA-1 (2)	2.38	31.22	2.40
	RCA-2 (1)	2.69	5.32	0.35
	Average (Zone I):	3.93	8.89	0.92
II	TM-5 (3)	5.30	29.64	1.13
	RCA-1 (3)	1.95	39.88	3.50
	RCA-2 (2)	2.00	6.37	0.58
	RCA-8 (4)	1.99	4.29	0.27
	Average (Zone II):	3.21	13.08	1.03
IIIA	TM-5 (2)	5.52	16.74	0.56
	RCA-1 (4)	2.06	35.89	3.09
	RCA-2 (2)	1.78	7.49	0.76
	RCA-8 (5)	2.74	0.86	0.06
	Average (Zone IIIA):	3.13	5.57	0.44
IIIB	TM-5 (1)	5.56	68.92	2.22
	RCA-1 (1)	1.74	28.06	2.89
	RCA-2 (1)	2.08	28.48	2.45
	RCA-8 (2)	4.05	0.70	0.03
	Average (Zone IIIB):	3.11	6.95	0.33
	Labrador Trough (Proterozoic)			
	41T2D			
	I (1)	4.86	0.79	0.02
	II (2)	5.52	0.63	0.02
	IIIA (3)	5.29	25.2	0.83
	IIIB (1)	5.56	51.6	1.59

AF DEMAGNETIZATION

The specimens were demagnetized progressively in alternating magnetic fields with amplitudes (peak-to-peak) up to 650 Ørsteds. The AF demagnetization results are illustrated in Figure 5 by three typical examples RCA-1, RCA-2 and RCA-8.

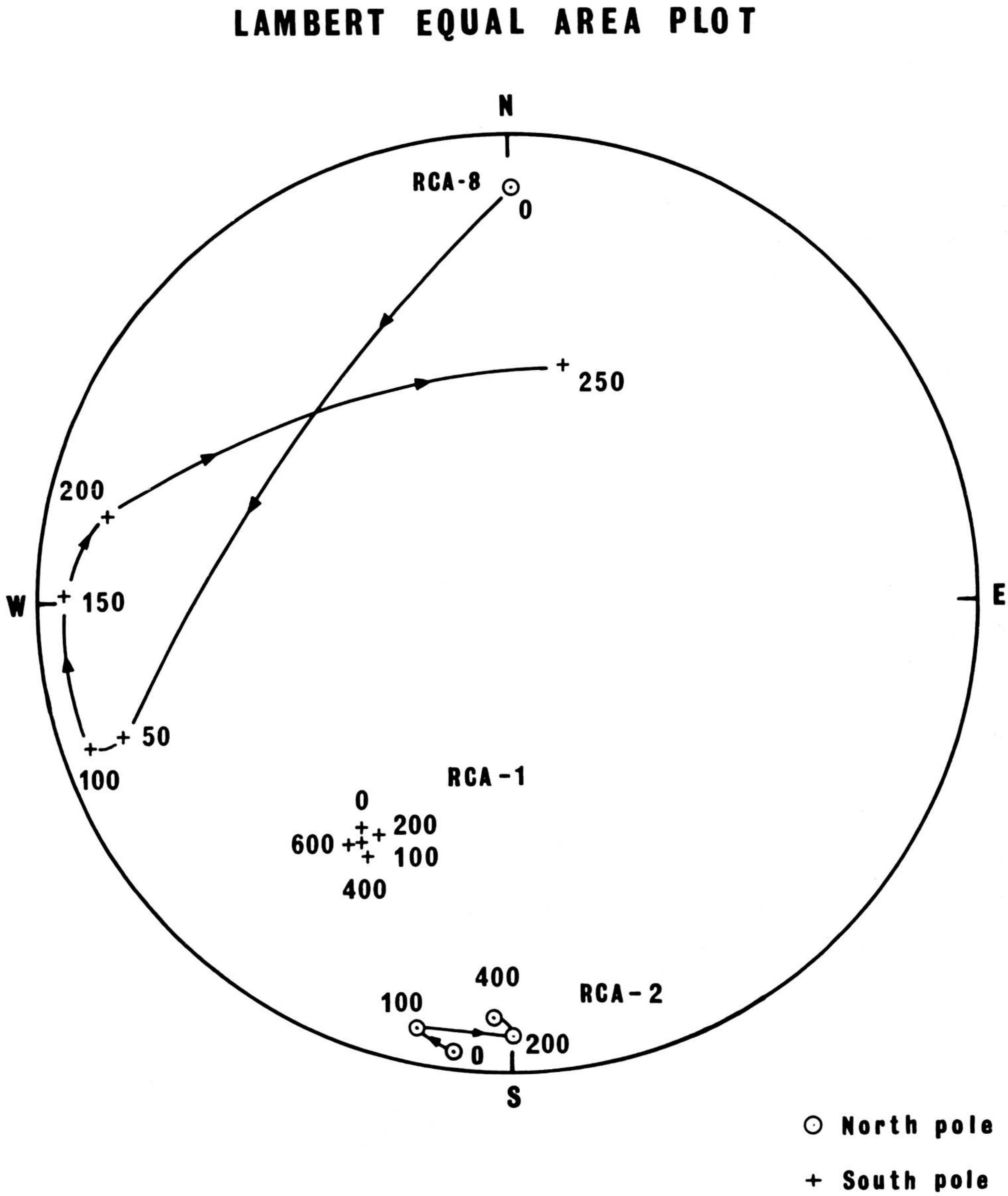

FIGURE 5. — Variation of the direction (D, I) of remanent magnetization in specimens RCA-1-3, RCA-2-1 and RCA-8-1 for different steps of AC demagnetization. The intensities (peak to peak) are expressed in oersteds.

The figure shows that the remanent magnetization of specimen RCA-8 is relatively unstable in the 50 to 250 Øersteds range while RCA-1 and RCA-2 are stable. The NRM intensity of specimen RCA-8 decreases very rapidly when increasing the intensity of AF demagnetization and, above 300 Øersteds, its NRM orientations become rapidly scattered. The directional stability shown for the samples RCA-1 and RCA-2 could be indicative of the presence of α-hematite (Fe_2O_3) as summarized in Table 4. Some pillows such as TM-1 could not be demagnetized in an AF because their initial NRM intensities were too low to permit reliable measurements. Others could be cleaned only at relatively low steps (e.g. 50 Øersteds for zones 1 and II A of TM-2, or 250 Øersteds for zone II of RCA-8) for the same reason. A knowledge of the degree of stability of the NRM component is essential before undertaking a regional paleomagnetic study and our results indicate that the intermediate zone II and the outer part of the pillow core (zone III A) have the best stability index in the different pillow lavas studied. While the magnetic properties of the two types of lavas are H (for ophiolitic) and L (Caldwell Group) type of Marshall and Cox (1971), both have the best stability index in approximately the same zones II and III A of the pillow sections.

Thermomagnetic study

The samples were cut with a diamond saw inserted in a brass mount (to avoid possible contamination of the samples by metallic iron). Small fragments from each specimen were coarsely crushed in a tungsten carbide crusher and then pulverized in an agate mortar to make 10 mg powdered rock samples for thermomagnetic analyses. High-field (2000 Øersteds) thermomagnetic curves were obtained with an electromagnetic balance recording the variation of high-field magnetization J with increasing temperature. Fast heating rates were used to raise the temperature from 20° to 900° in approximately 15 minutes. A synopsis of the results is presented in Table 4.

Pure magnetite was found in all the pillows analyzed. In addition, α-hematite ($\theta c = 683° \pm 7°C$) was detected in pillows RCA-1 and RCA-2 from Calway River (Caldwell Group) and a small amount of pyrrhotite ($\theta c = 318° \pm 5°C$) in pillows TM-1 and AS-27 from the ophiolitic suites. In summary, the thermomagnetic curves indicate the presence of a major magnetic mineral having its Curie point in the range 566° to 582°C, with an average at 572°C. This is the Curie temperature of magnetite, which suggests that the main magnetic memory in the pillow lavas studied is present as magnetite with the exception of the hematite-rich pillowed spilites RCA-1 and RCA-2 from Calway River (Fig. 6). Some native iron was detected by the thermomagnetic method in samples from the inner core of TM-3 and the intermediate zone of RCA-8. Detailed petrographic study and microprobe analyses have confirmed the presence of a small amount of native iron which was also observed in a similar geological context in Newfoundland (Deutsch and Rao, 1973). It may be argued that magnetite is not necessarily the main carrier of NRM, since this

Thermomagnetic analyses — Summary of Results

Pillow Sample No.:	ZONE (s)	Region	Quantity of Magnetic Material	Grain size	Fe_3O_4	Fe	Fe_2O_3	Ratio Fe: Fe_3O_4	Others	T-Magcurve
Ophiolites										
TM-1	II -IIIA	Thetford Mines	Very little	Fine	Mainly	None	None	0	Pyrrhotite (little)	Reversible
TM-2	IIIA-IIIB	Thetford Mines	Relatively little	Fine	Only	None	None	0		Reversible ?
TM-3	IIIA-IIIB	Thetford Mines	Relatively much	Fine	Fair amount	Less	None	1 : 2		Reversible
AS-27	IIIA-IIIB	Asbestos	Relatively little	Very Fine	Mainly	None	None	0	Pyrrhotite (little)	Reversible
CALDWELL										
RCA1	IIIA-IIIB	Calway River	Much	Fine	Fair amount	None	Much	0		Reversible
RCA2	IIIA-IIIB	Calway River	Much	Fine	Fair amount	None	Much	0		Reversible
CA8	II	Grand Morne	Much	Fine	Fair amount	Less	None	1 : 8		Reversible
CA8	IIIA-IIIB	Grand Morne	Relatively little	Very Fine	Only	None	None	0		Reversible
TM-5	IIIA-IIIB	Black Lake	Very little	Very Fine	Only	None	None	0		Reversible
ARCHEAN										
C-4	IIIA-IIIB	Chibouga-mau	Very little	Fine	Only	None	None	0		Reversible

Fine 5-10 μm. Very fine < 5 μm.

phase which has the highest saturation magnetization and which dominates the J_{SAT}-T curve may be in the (largely) demagnetized state in nature. However, the NRM intensity and direction is not significantly different in the specimens containing pure magnetite from those containing differing phases.

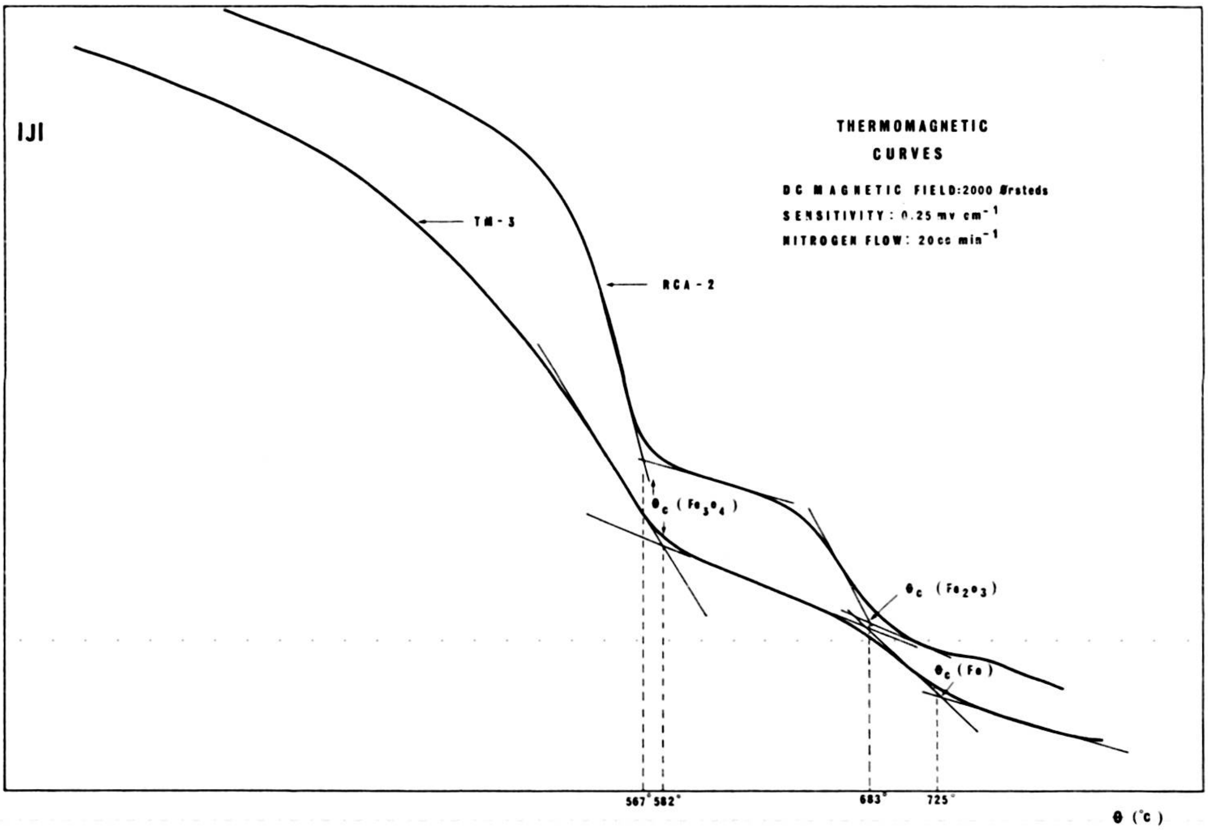

FIGURE 6. — Thermomagnetic curves for a specimen from the core (zone III A) of pillow TM-3, and for a specimen from the core (zone III B) of pillow RCA-2.

PALEOMAGNETIC STUDY

Among the nine pillow lavas collected in the Thetford Mines area four samples (TM-2, AS-27, RCA-1 and RCA-2), which were well oriented and located in a known structural setting, were selected to attempt to determine a common paleomagnetic pole position and to obtain an age. It must be pointed out that the pole and the age obtained are only preliminary since we assume that the samples selected, which are both from the Caldwell Group and the ophiolitic suites, have the same age and since the paleomagnetic data do not fulfill all the criteria for reliability of paleomagnetic results listed by Irving (1964). In particular, it is generally admitted that no result is considered adequate unless it is based on consistent observations from eight or more samples. Our results are based on four samples only and in this respect should be regarded as inadequate in spite of the fact that 59 specimens were drilled from these four samples (Table 5). This, however, was not the main purpose of our present study (see Seguin, 1976). Figure 6 indicates that after bringing the formations to the horizontal position through a double rotation, the paleopole is situated at 151°E, 25°N (reverse polarity). The coverage of the geological time scale with paleomagnetic results of North American Phanerozoic rocks is fairly good except for the Lower Paleozoic and in particular for the Cambrian and the Ordovician. The north paleopole position for the Cambrian is given as 140°E, 07°N and for the Ordovician as 192°E, 28°N (McElhinny, 1973). Our pole position falls roughly a third of the way between the Cambrian (585 m.y.) and the Ordovician (480 m.y.) poles. Assuming a linear apparent polar wandering path between these two points, this yields a Middle Cambrian age of 550 m.y. For the reasons given above, this pole and age determination is preliminary and remains uncertain. The available geological data suggest a Late Cambrian — Early Ordovician age for the Caldwell Group and a probably similar age for the lavas of the Thetford Mines ophiolitic complex. We know that blocks of ophiolitic and Caldwell rocks are found in the breccias of the St. Daniel Formation which is not precisely dated but is assumed to be of early Middle Ordovician age. This provides only a constraint for the upper limit of the age of the pillow lavas studied, the lower limit remaining unknown.

TABLE 5

Statistical study of the paleopole of pillows *

Pillow No.:	Before tilting				After tilting		
	N	D_1 (°)	I_1 (°)	$\alpha_{0.95}$ (°)	D_2 (°)	I_2 (°)	$\alpha_{0.95}$ (°)
TM-2		152	55	32	135	—32	19
AS-27		036	—06	41	077	48	46
RCA1		175	06	05	208	—39	04
RCA8		231	—02	21	239	—07	20
Pole position:	158° E 36° N				151° E 25° N		

* After AF demagnetization.

CONCLUSIONS

Because of the close association in the field of the ophiolitic and Caldwell Group lavas, the geologists who have mapped the area of Thetford Mines (Cooke, 1937; Riordon, 1953; Alsac *et. al.* 1971; Lamarche, 1972) have had difficulties in recognizing and separating these rocks from one another. This study allows us to show that several features such as the occurrence, structure, metamorphic grade, chemical composition and magnetic signature of these lavas are different and, when considered together, are diagnostic of one or the other formation. This should permit in future work to avoid errors of mapping and interpretation. Hereafter we summarize the features and differences of the ophiolitic and Caldwell lavas.

The ophiolitic lavas form the volcanic cap of ultramafic-mafic plutonic slabs while the lavas of the Caldwell Group occur within a thick sandstone or shale sequence. The ophiolitic pillowed lavas are structurally characterized by the association of pillows with tube-like bodies. Lava tubes have not been observed in Caldwell flows. The ophiolitic pillows are texturally zoned and their chilled outer zones show either an arborescent globulitic or a variolitic structure, radial jointing is absent or poorly developed. In contrast the Caldwell pillows are homogeneous and usually porphyritic, radial and concentric jointing is present and locally well developed. The volcanics of the lower ophiolitic volcanic group have been metamorphosed in the greenschist facies under a regime of low pressure, moderate temperature, and in the presence of water but absence of significant stress. Structures, textures and locally morphologies of quenched microphenocrysts of olivine and plagioclase are well preserved. The same is true for the volcanics of the upper ophiolitic volcanic group whose metamorphic grade is lower than that of the lower group and falls in the boundary region between the greenschist and the prehnite-pumpellyite facies. In areas where the Caldwell Group is not overlain by the ophiolites, the Caldwell volcanic rocks are metamorphosed in the prehnite-pumpellyite facies and their structures and textures are well preserved (e.g. Grand Morne Mountain, Calway River). On the other hand the Caldwell volcanics are metamorphosed in the greenschist facies and characterized by a strong schistosity in areas where they have been tectonically overlain by the ophiolites. This is for example the case of the Caldwell lavas bordering the northwestern front of the Thetford Mines ophiolitic complex between the localities of Thetford Mines and Black Lake (Fig. 1). The ophiolitic olivine metatholeiites (OOT, Table I) are much richer in MgO, Cr_2O_3 and NiO and poorer in Al_2O_3, TiO_2 and FeO + Fe_2O_3 than the ophiolitic and Caldwell metatholeiites (OST, Table 1; CG, Table 2). The ophiolitic metatholeiites can be chemically distinguished from the Caldwell metatholeiites by their higher content of SiO_2 and Na_2O and lower content of CaO. Both ophiolitic and Caldwell lavas are relatively poor in TiO_2 and very poor in K_2O with the exception of the Caldwell hematite-rich spilites from Calway River.

In spite of the fact that one should be cautious in comparing qualitatively the present titanomagnetite bearing oceanic pillows with magnetite bearing Lower Paleozoic pillows, we have observed that the magnetic susceptibility of the ophiolitic pillow lavas is relatively high in the crust and low in the intermediate and core zones. The intensity of their remanent magnetization as well as their Koenigsberger ratio decrease from the margin towards the center of pillows in a fashion similar to the oceanic H type pillows described by Marshall and Cox (1971). In the case of the pillows of the Caldwell Group, the susceptibility, and the intensity of the remanent magnetization, as well as the Koenigsberger ratio tend to increase from the margin towards the core of pillows in a fashion similar to the oceanic L type pillows of Marshall and Cox. The values of the susceptibility, NRM intensity and Koenigsberger ratio of the Caldwell pillows are always much higher than those of the ophiolitic pillows. The origin of these two different magnetic signatures is difficult to explain because it is likely to result from the combined effect of differences in original magmatic composition and cooling conditions and in the history of alteration and metamorphism of these lavas. The susceptibility values show that the concentration of the magnetic carriers of NRM, mainly magnetite with or without hematite, is higher in the pillows of the Caldwell Group than in the ophiolitic pillows. This is verified by the chemical data (Table 1 and 2) which show that the Caldwell lavas are richer in iron than the ophiolitic lavas and that the total amount of iron usually decreases slightly from the margin to the core of pillows. The ratio Fe_2O_3/FeO is either constant or decreases from the margin to the center of pillows, the margin being more oxydized than the internal zones and the core. Alteration and metamorphism have caused a considerable lowering of the remanent magnetization in both Caldwell and ophiolitic lavas. Recent studies of oceanic lavas (Marshall and Cox, 1972; Ryall and Ade-Hall, 1975) have shown that an increase in low temperature oxidation yields a corresponding decrease in intensity of magnetization. However, Ryall and Ade-Hall (1975) note that during this oxidation and lowering of the remanent magnetization there is no change in NRM direction, so that weathered samples may still reliably be used for paleomagnetic work. Comparison of petrographic descriptions with magnetic properties suggest that the H or L type radial variations of the magnetic properties observed in the pillows studied are neither dependent of the presence or absence of a variolitic or globulitic chilled outer zone nor of a mineralogical and chemical zoning of the pillows. Consequently, the ophiolitic or H type and the Caldwell or L type radial variations of the magnetic properties appear to be independent of compositional zoning but rather to be strongly related to the size and distribution of the NRM carriers, an observation in agreement with the works of Dunlop (1973). Size and distribution of the magnetic components in pillows are controlled by the cooling rate of the lava (Lowrie, 1975). Lavas which cool rapidly are homogeneous and partly glassy and partly finely crystalline while lavas which cool less rapidly are more heterogeneous, under a relatively thick glassy crust they can have an intermediate zone and a core more coarsely crystalline than the quickly cooled lavas. In the pillows of the ophiolite suites the decrease in NRM intensity from the margin to the core apparently corresponds to an increase in grain size of the mineral components and in particular of the magnetite grains. The increase in grain size towards the center is not significant in the pillows of the Caldwell Group, and their NRM intensity does not decrease from the margin to the core. This confirms this conclusion of Ryall and Ade-Hall (1975) that grain size plays an important role in determining the characteristics of the remanence in pillow lavas. We can conclude that the ophiolitic and Caldwell lavas differ not only in composition but they also have different cooling histories. When they were extruded in the submarine environment the Caldwell lavas have solidified much faster than the ophiolitic lavas.

An accurate model for magnetic source(s) of oceanic linear anomalies is not yet available. Paleomagnetic studies of pillowed metabasalts and particularly of ophiolitic lavas of oceanic origin (Vine and Moores, 1972; Wagner, 1971; Cogulu et al., 1975) may significantly contribute to refine our knowledge of the relationship existing between the magnetic anomaly, the magnetization vector and the orientation of the magnetic lineations. It might also contribute to our understanding of the problems related to the decrease in intensity of magnetization with time.

Our study of the variation of the NRM directions within the different pillow zones provides evidence on the inhomogeneity of the magnetic properties within pillows and lava flows. Because of the low metamorphic grade of the samples studied, we can assume that the NRM directions obtained after AF demagnetization are primary and correspond to the original magnetic memory of the rocks. A preliminary paleomagnetic test gave a Middle Cambrian paleopole position (151°E, 25°N, reverse polarity), although a Late Cambrian to Early Ordovician age for these lavas is generally assumed on the basis of the available geological evidence.

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