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PALEOMAGNETISM OF THE DUNN POINT FORMATION (NOVA SCOTIA): HIGH PALEOLATITUDES FOR THE AVALON TERRANE IN THE LATE ORDOVICIAN

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Abstract. Volcanic flows of the Late Ordovician Dunn Point Formation contain a generally univectorial magnetization which passes the fold test. Its steep direction (D = 335°, I = -61°, k = 79, α_{95} = 4.2°, paleopole at 2°S, 136°E) is unlike any known for North America or for the Avalon terrane for post-Ordovician time, so that a primary age of the magnetization appears to be very likely. The paleolatitude (42°S) for the Avalon terrane derived from this result is much higher than that predicted for the area on the basis of the cratonic North American apparent polar wander path, and a substantial post-Ordovician displacement (>3500 km) of Avalon with respect to the craton can be deduced. In all likelihood the Avalon terrane did not collide with North America until Middle Devonian time. This collision produced the Acadian orogeny. High Ordovician paleolatitudes have also been obtained for northern Africa and for several localities in Hercynian Europe (the Armorica plate) and it is inferred that these areas may have drifted together until Late Ordovician time.

Introduction

The Ordovician paleomagnetic data base for the Atlantic-bordering continents has been substantially improved in the last few years. New poles have become available for the North American craton (Jackson et al., 1983; Watts and Van der Voo, 1979), Hercynian Europe (Perroud and Van der Voo, 1985) and Gondwana (Bachtadse et al., 1984). In essence these data support previous paleogeographic syntheses, showing that North America (and probably northern Europe as well) was in equatorial paleolatitudes, and that Hercynian Europe (Armorica) and the northern margin of Africa were in near-polar paleolatitudes. This has led Perroud et al. (1984) to refine the Paleozoic plate tectonic models previously proposed by Van der Voo (1982): they conclude that northern Europe (Baltica) and North America collided by latest Silurian time to produce the Caledonian orogenic belt, that Armorica joined this pair shortly thereafter to produce the Acadian orogeny and that Gondwana moved northward rapidly during the Devonian and Early Carboniferous to collide with the combined northern continents during the Middle and Late Carboniferous to produce the Hercynian-Alleghenian orogenic belt.

In this process of assembling a Pangea supercontinent, the role played by the Avalon terrane of northeastern North America is not clear, although various models have been proposed (e.g., Williams and Hatcher, 1983; Neuman, 1984). Dissimilar Early Paleozoic faunas between Avalon and cratonic North America (Wilson, 1966; McKerrow and Ziegler, 1972; Cocks and Fortey, 1982) as well as geologic similarities between Avalon and Europe or Africa (e.g., Schenk, 1971; Rast and Skehan, 1983) have been noted repeatedly and make it quite plausible that Avalon is truly a displaced terrane. This study has been undertaken to quantify this displacement.

Geology and Sampling

The Dunn Point Formation was sampled along the Northumberland coast of mainland Nova Scotia (Figure 1). The stratified rocks of this region, including the Dunn Point Formation, have been described by Boucot et al. (1974). The Dunn Point comprises individual mafic and intermediate flows, from 1 - 4 m thick, which are often laterally discontinuous. These are overlain by silicic volcanics of the McGillivray Brook Formation, which are in turn overlain conformably, or with slight angular unconformity, by fossiliferous Lower Silurian sedimentary strata of the Arisaig Group. A whole-rock Rb-Sr age of 434 ± 15 Ma for the Dunn Point and McGillivray Brook formations (Keppie et al., 1978) is roughly at the boundary between the Ordovician and Silurian periods and is consistent with the Llandovery age for the overlying sediments.

Subaerial exposure of volcanics of the Dunn Point at the time of their deposition is inferred from the occurrence of red soil profiles at the tops of and between individual flows; in the literature, these red soils have been called laterites (Boucot et al., 1974). The interiors of the flows also show reddish hematite staining but in all cases the tops of flows are more extensively oxidized. Incorporation of laterite xenoliths within less oxidized material at the base of some flows reinforces the interpretation that oxidation and formation of these red soils was very early. These observations are important for the interpretation of paleomagnetic results for the volcanics, because they suggest that the magnetically very stable mineral hematite present in these strata is essentially primary. For the purposes of comparison, the interiors as well as the tops of each flow were sampled. Undisturbed laterites were sampled at sites 6 (samples G-L) and 10 (samples H-M); xenoliths of lateritic material (5 to 15 cm in diameter) from site 13' are found in the overlying flow (site 14).

The volcanics exposed along the Arisaig coast all are dipping nearly vertically toward the southeast, as indicated by the vesicular tops of flows. However, there is some variation in the strike (Figure 1), which was exploited for the purpose of a paleomagnetic fold test. Tilting of the Dunn Point Formation apparently occurred at the same time as folding of the overlying Arisaig Group in post-Lower Devonian time, and this has

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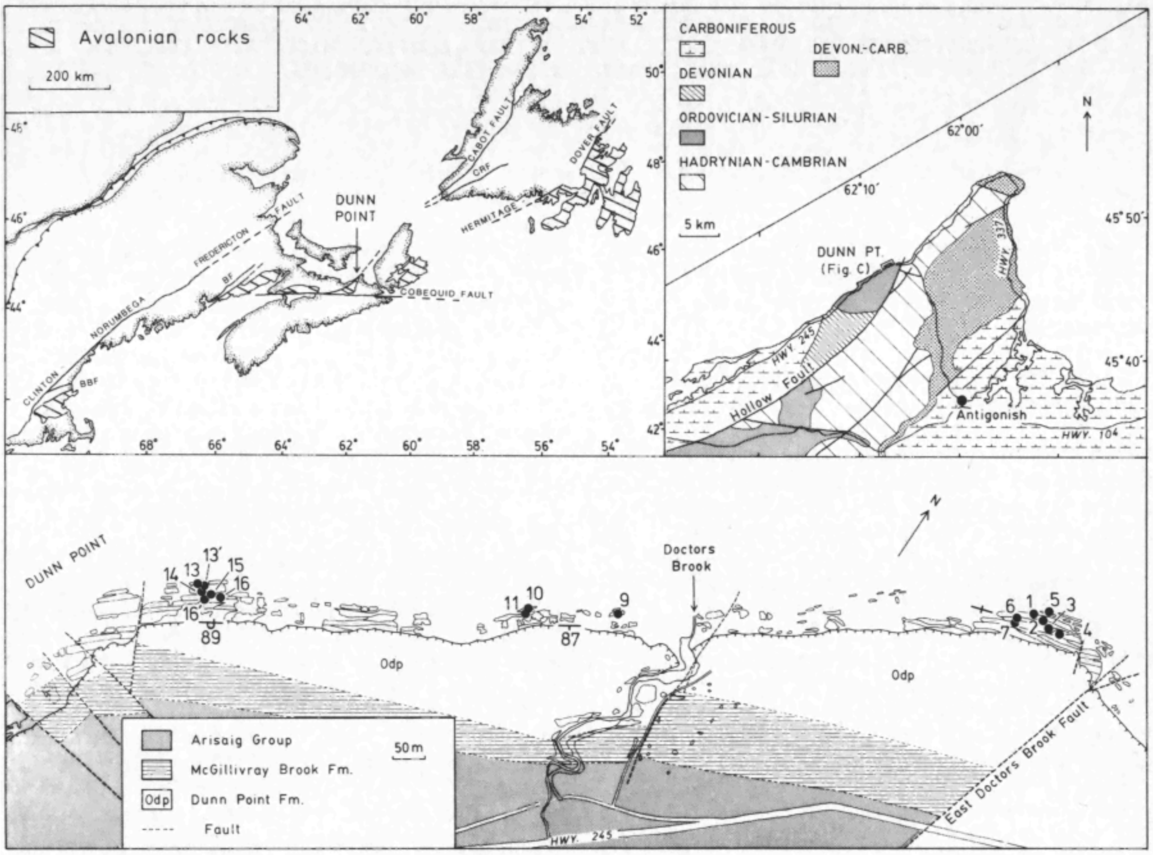

Fig. 1. Regional tectonic setting of Avalonian rocks, and local geologic maps of the Dunn Point Formation (after Keppie, 1979; Keppie et al., 1978). Sampling sites are indicated by black dots.

been correlated with the Acadian orogeny in the northern Appalachians (Boucot et al., 1974).

Paleomagnetic Results

Intensities of the natural remanent magnetizations (NRM's) range between 10^{-1} and 10^{-3} A/m and NRM directions are generally well-grouped. Alternating field demagnetization does not succeed in eliminating the remanence completely, so thermal demagnetization has been used for nearly all samples. Representative examples of vector diagrams are shown in Figure 2, and it can be seen that typically the remanence decays linearly to the origin. In a few cases (20% of all samples), lower blocking-temperature overprints were present in a direction close to that of the present-day field, but these could be readily removed below 550°C in thermal treatment. The maximum blocking temperatures are 680°C, indicating hematite as the carrier of the NRM, which is not surprising given the oxidized nature of these subaerial flows. Samples from interiors and tops of flows have similar remanence characteristics and directions, as do the laterites and volcanics from the same site (the eight red soil samples have directions that form a coherent subset of the overall grouping shown in Figure 3, with a tilt-corrected mean of declination/inclination = 317°/-50°, k = 76, α_{95} = 6.4°).

After demagnetization all in-situ directions cluster in the southeast quadrant, with shallow to intermediate upward inclinations (Figure 3). The distribution of directions is non-Fisherian (Fisher, 1953), with a distinct elongation correlating with change in declination. Upon application of the correction for tilt, however, the distribution becomes Fisherian and the clustering increases significantly. This can be seen in the improvement in the statistical parameters upon application of the tilt correction for the site means (Table 1), indicating a positive fold test

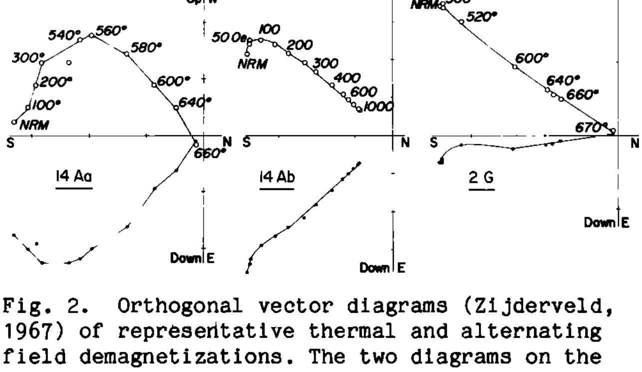

Fig. 2. Orthogonal vector diagrams (Zijderveld, 1967) of representative thermal and alternating field demagnetizations. The two diagrams on the left are for two specimens from the same sample (site 14, sample A). Open (closed) symbols represent projections onto the north-south vertical (horizontal) plane; the tic marks on the axes each represent 0.1 A/m.

at the 99% confidence level (McElhinny, 1964). Thus, the Dunn Point volcanics acquired their magnetization before the Acadian-aged folding.

Discussion

The Dunn Point volcanics present surprisingly non-complex and generally univectorial magnetizations, with a mean direction of declination/inclination = 335°/-61°. This direction is not seen in cratonic North American rocks of Paleozoic or younger age, and in fact is not seen in other studies of Avalonian rocks of post-Ordovician age either. The fold test constrains the age of magnetization to pre-Middle Devonian time. Although the remanence is carried by hematite, the flows are inferred to have undergone early oxidation; a primary age of the magnetization is therefore quite likely. The similarity of the magnetic directions for the red soil samples and the volcanic samples supports this contention. Since there is no doubt about the paleohorizontal for these well-stratified rocks, we can deduce that the mean direction probably represents the Late Ordovician geomagnetic field, and that the calculation of a paleopole is warranted.

More important than the paleopole location, for paleogeographic considerations, is the paleolatitude that can be calculated from this result (42°). Assuming this paleolatitude to be a southerly one, in accordance with the paleolatitudes typically assigned to other Paleozoic rocks from Avalon and similar or neighboring terranes, we can compare our result with those from other continental blocks such as the American craton, Gondwana or Armorica.

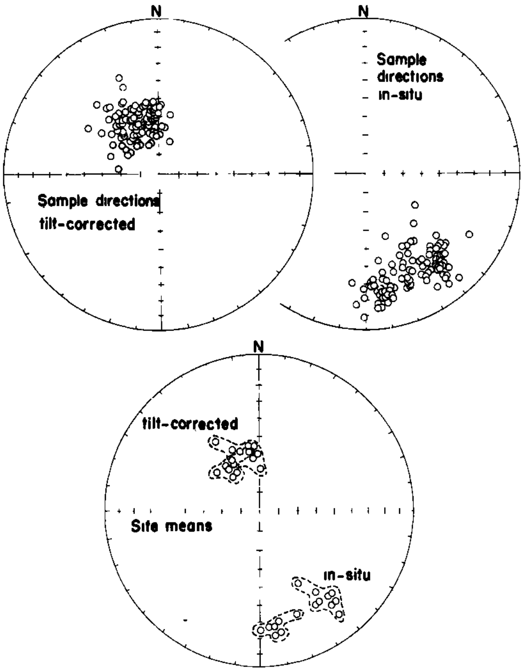

Fig. 3. Equal-area projections of characteristic directions of magnetization for individual samples (after and before correction for the tilt of the strata) and for the site-mean directions (bottom diagram). In the latter diagram, groups of sites with similar tilt correction have been outlined to illustrate the effects of the fold test. All symbols are projections onto the upper hemisphere.

TABLE 1. Summary of Site-Mean Directions

Site	n/n_0	Before TC Decl, Incl	After TC Decl, Incl	k_2	α_{95}	k_2/k_1
1	6/6	159, -31	348, -59	151	5.5	
2	6/6	174, -27	320, -61	77	7.7	
3	3/3	172, -20	318, -68	113	11.7	
4	6/7	173, -25	321, -63	321	3.7	
5	6/6	169, -21	325, -68	224	4.5	
6	8/12	169, -29	329, -61	63	7.0	
7	5/5	179, -24	309, -60	75	8.9	
9	5/6	147, -31	327, -62	45	11.5	
10	10/11	151, -47	325, -47	53	6.7	
11	5/5	144, -37	334, -56	111	7.3	
13	7/7	138, -25	355, -61	136	5.2	
13'	9/9	140, -31	348, -57	248	3.3	
14	5/6	138, -30	352, -56	224	5.1	
15	6/6	141, -18	359, -69	99	6.8	
16	6/6	146, -31	340, -58	105	6.6	
16'	4/4	141, -25	351, -63	223	6.2	
Mean	16/16	155, -29	335, -61	79	4.2	2.7

n/n_0 is the ratio of samples used for the computation of the mean to the samples demagnetized; TC is the correction for the tilt of the strata; Decl and Incl are declination and inclination, in degrees; k_2 (k_1) is the precision parameter of the mean direction after (before) correction for the tilt of the strata, and α_{95} describes the cone of 95% confidence about the mean (Fisher, 1953). The ratio k_2/k_1 is significant at the 99% confidence level for a positive fold test.

North American Late Ordovician paleopoles (Proko and Hargraves, 1973; Van der Voo and French, 1977; Watts and Van der Voo, 1979) indicate a paleolatitude of about 10°S for the present location of our sampling area. Thus, a minimum separation and subsequent relative displacement of about 3500 km is indicated between the Avalon terrane and the North American craton. On the other hand, as discussed by Perroud et al. (1984), Late Ordovician paleomagnetic latitudes as well as paleogeographic indicators (glacial relicts, faunal considerations) indicate near-polar conditions for northern Africa and Hercynian Europe. The latter, assumed to have behaved as a separate plate (Armorica) in Early to Middle Paleozoic times, has provided Late Ordovician paleolatitudes ranging from 46°S to 76°S. This range of paleolatitudes is larger than usual, but can be explained by a spread in ages of magnetization during rapid apparent polar wander. It is geologically plausible and paleomagnetically permissible to infer that Avalon and Hercynian Europe were together at that time, and that jointly they constituted the Armorica plate (Figure 4).

Given that Avalon was still in fairly high paleolatitudes in Late Ordovician time, a collision between Avalon and the equatorial North American craton, as previously postulated by Van der Voo (1979) to explain the Late Ordovician Taconic

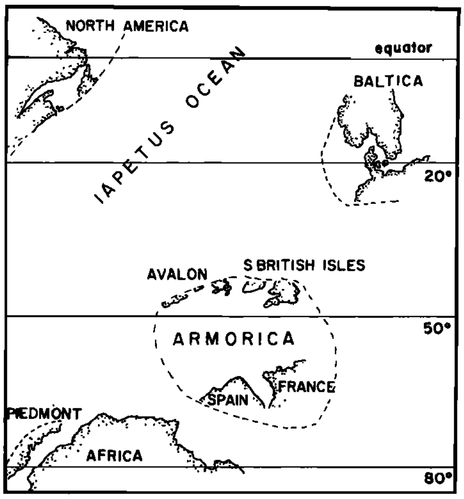

Fig. 4. Late Ordovician paleogeographic map according to paleomagnetic data (modified from Neuman, 1984; Perroud et al., 1984).

orogeny, must be ruled out. Instead, a younger collision time must be envisioned, resulting in either the Acadian or the Alleghenian orogeny. Considering that Devonian paleomagnetic results from the area (Johnson and Van der Voo, 1983) indicate a position of Avalon near to that of the North American craton, and that there are no geologic indicators (deep-water sediments, ophiolites, etc.) for any post-Acadian oceans separating Avalon and the craton, an Early to Middle Devonian collision resulting in the Acadian orogeny is highly preferred.

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References

Bachtadse, V., R. Van der Voo and A. Kröner, Paleomagnetic results from the Lower Devonian part of the Table Mountain Group, S. Africa, Eos Trans. AGU, 65, 863, 1984.

Boucot, A. J., J. F. Dewey, D. L. Dineley, R. Fletcher, W. K. Fyson, J. G. Griffin, C. F. Hickox, W. S. McKerrow and A. M. Ziegler, Geology of the Arisaig Area, Antigonish County, Nova Scotia, Geol. Soc. Am. Spec. Paper, 139, 191 pp., 1974.

Cocks, L. R. M. and R. A. Fortey, Faunal evidence for oceanic separation in the Paleozoic of Britain, Geol. Soc. London, 139, 465-478,1982.

Fisher, R. A., Dispersion on a sphere, Proc. R. Soc. London, A217, 295-305, 1953.

Jackson, M., R. Van der Voo and D. R. Watts, Paleomagnetism of the Lower Ordovician Oneota Dolomite, Upper Mississippi River Valley, Eos Trans. AGU, 64, 216, 1983.

Johnson, R. J. and R. Van der Voo, Paleomagnetism of the Mid-Devonian Fisset Brook Formation, Cape Breton Island, Nova Scotia, Eos Trans. AGU, 64, 216, 1983.

Keppie, J. D., Geologic map of the province of Nova Scotia, Nova Scotia Department of Mines and Energy, 1979.

Keppie, J. D., J. Dostal and M. Zentilli, Petrology of the Early Silurian Dunn Point & McGillivray Brook formations, Arisaig, Nova Scotia, Nova Scotia Department of Mines, Halifax, Paper 78-5, 20 pp., 1978.

McElhinny, M. W., Statistical significance of the fold test in paleomagnetism, Geophys. Jour. R. Astron. Soc., 8, 338-340, 1964.

McKerrow, W. S. and A. M. Ziegler, Paleozoic oceans, Nature, 240, 92-94, 1972.

Neuman, R. B., Geology and paleobiology of islands in the Ordovician Iapetus Ocean: review and implications, Geol. Soc. Am. Bull., 95, 1188-1201, 1984.

Perroud, H. and R. Van der Voo, Paleomagnetism of the Late Ordovician Thouars Massif, Vendée Province, France, J. Geophys. Res., 90, in press, 1985.

Perroud, H., R. Van der Voo and N. Bonhommet, Paleozoic evolution of the Armorica plate on the basis of paleomagnetic data, Geology, 12, 579-582, 1984.

Proko, M. S. and R. B. Hargraves, Paleomagnetism of the Beemerville (New Jersey) alkaline complex, Geology, 1, 185-186, 1973.

Rast, N. and J. W. Skehan, The evolution of the Avalonian plate, Tectonophysics, 100, 257-286, 1983.

Schenk, P. E., Southeastern Atlantic Canada, northwestern Africa, and continental drift, Can. J. Earth Sci., 8, 1218-1251, 1971.

Van der Voo, R., Paleozoic assembly of Pangea: a new plate tectonic model for the Taconic, Caledonian and Hercynian orogenies, Eos Trans. AGU, 60, 241, 1979.

Van der Voo, R., Pre-Mesozoic paleomagnetism and plate tectonics, Ann. Rev. Earth Planet. Sci., 10, 191-220, 1982.

Van der Voo, R. and French, R. B., Paleomagnetism of the Late Ordovician Juniata Formation and the remagnetization hypothesis, J.Geophys. Res., 82, 5796-5802, 1977.

Watts, D. R. and R. Van der Voo, Paleomagnetic results from the Ordovician Moccasin, Bays and Chapman Ridge formations of the Valley and Ridge Province, eastern Tennessee, J.Geophys. Res., 84, 645-655, 1979.

Williams, H. and R. D. Hatcher, Jr., Appalachian suspect terranes, Contributions to the Tectonics and Geophysics of Mountain Chains, Geol. Soc. Am., Mem. 158, edited by R. D. Hatcher, H. Williams and I. Zietz, 33-54, 1983.

Wilson, J. T., Did the Atlantic close and then reopen ? Nature, 211, 676-681, 1966.

Zijderveld, J. D. A., AC demagnetization of rocks: analysis of results, Methods in Paleomagnetism, edited by D. W. Collinson, K. M. Creer, and S. K. Runcorn, Elsevier, Amsterdam, 254-286, 1967.

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