Anomalous and Reversed Paleomagnetic Field Directions from the Miocene Lovejoy Basalt, Northern California

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Abstract

The Lovejoy formation consists of undeformed basalt flows distributed across the northern Sierra Nevada, California, and has been dated by the potassium-argon method as early Miocene. Measurements of remanent magnetization of 200 specimens collected at 16 widely separated sites have provided 13 independent determinations of paleomagnetic field direction during the relatively short period of eruption. Of these, 5 are not greatly different from the field of a reversed axial dipole, while 8 correspond to virtual geomagnetic north poles ranging in latitude from 60° north to 8° south. Stability of magnetization was established by a.c. and thermal demagnetization. Viscous magnetization, with intensity of the order of 50% of the natural thermoremanent component, was completely removed by peak alternating fields of 75 to 200 oersteds. The mean of the 13 virtual geomagnetic north poles lies at 76° north latitude and 74° east longitude, but the precision parameter k for these directions is only 4. Attempts to relate the degree of divergence of individual poles from the mean (or from the geographic pole) to the apparent relative intensity of the ancient field were unsuccessful because observed irreversible increases up to five-fold in the susceptibilities of specimens heated to 600°C invalidate any comparison of natural T.R.M. to artificial T.R.M. It is concluded that these basalts were erupted during a period of time, about 24 million years ago, in which the earth's field was predominantly reversed but varied in direction to an unusual degree.

1. Introduction

The paleomagnetic evidence for the hypotheses of polar wandering and continental drift depends upon the uniformitarian argument that the earth's magnetic field has always been a dipole nearly parallel to the earth's axis of rotation. For the late Tertiary and Quaternary this argument appears to be well supported by paleomagnetic data, but such data are less abundant for the early Tertiary. There can now be little doubt that reversals of the polarity of the geomagnetic field have occurred, and the chronology of reversals for the last four million years has been established by Cox, Doell, and Dalrymple (1964). It is desirable to extend this chronology back in time as far as the resolution of the dating of rocks will permit; such extension will doubtless be accomplished in the somewhat piecemeal manner inherent in the solution of large-scale geologic problems. The paleomagnetic results reported here are from relatively well-dated volcanic rocks in a tectonically stable area, and have been interpreted in the light of these two questions.

The Lovejoy formation, which consists almost exclusively of basalt flows, is one of the

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Fig. 1 Distribution of Lovejoy basalt in northern California (compiled from Lydon *et al.*, 1960, and Burnett and Jennings, 1962), showing paleomagnetic sampling sites.

older volcanic sequences in the undeformed Cenozoic rocks of the Sierra Nevada, California. The present distribution of the remnants of the basalt is shown in Fig. 1, which also includes the locations of the paleomagnetic sampling sites referred to below. Potassium-argon ages of related rocks (Dalrymple, 1964) have established the age of the Lovejoy formation as early Miocene. These ages are as follows: At site 5 the type section of the basalt (Durrell, 1959) is overlain by the Ingalls andesite, above which is the 22 million-year-old Delleker rhyolite. South of site 16, andesitic tuff-breccia occurs interbedded in the basalt near the base of the flows; plagioclase from this rock gave an age of 24 million years. It is probable that all of the Lovejoy basalt is older than 22 million years but that most of it is younger than 24 million years.

The geologic setting and the petrography of the Lovejoy basalt have been described in detail by Durrell (1959), and only some aspects of this which are pertinent to the paleomagnetic results will be discussed briefly here. The flows are all flat-lying and have been disturbed only by block faulting in the eastern part, as shown in Fig. 1. The basalt is massive and almost entirely non-vesicular, and where well-exposed it is usually fresh and unweathered. There is no visible evidence of autobrecciation of the tops of flows, and flow structures such as alignment of plagioclase laths are uncommon. Interbedded sedimentary material occurs only rarely between flows, and the fossil soils and oxidized zones that are commonly found developed on the tops of basalt flows are absent in these; hence the period of eruption appears to have been short, perhaps 15 flows in a few thousand years.

2. Paleomagnetic Results

Sampling sites

Each sampling site shown in Fig. 1 is in a single flow of basalt; poor exposure and limited accessibility have prevented sampling more than one flow in any single area. Three pairs of sites are in the same three flows; these are sites 3 and 4, sites 5 and 6, and sites 15 and 16. Sites 5 and 15 have been so thoroughly remagnetized by lightning as to give no useful paleomagnetic information. From 5 to 20 oriented cores, distributed over distances ranging from 5 to 50 feet, were obtained at each site.

A.C. demagnetization

At all sites the basalt was found to possess secondary magnetization, usually with relatively low coercivity. A.C. demagnetization according to the method described by Cox and Doell (1962) has been used to remove the soft secondary magnetization from all specimens from all sites except one (site 2, see below). An example of the value of a.c. demagnetization is illustrated in Fig. 2. Site 3 appears to have been partially, but not completely, remagnetized by lightning, while at site 4 all but one of the NRM directions are closely grouped. These two sites are about a mile apart in the same flow, and are separated by a fault with the vertical component of displacement about 200 feet. Before a.c. demagnetization the NRM

Fig. 2 Effect of a.c. demagnetization on intensities and directions of NRM at sites 3 and 4. Curves of intensity (J) vs. demagnetizing field are for representative single specimens. Directions are plotted on equal-area projections, with corresponding values of Fisher's precision parameter k .

directions at site 3 were nearly random, but after demagnetization at 200 peak Oe. the dispersion was greatly reduced and the mean direction was not significantly different from that at site 4. This seems to indicate that (1) the stable component of NRM is uniform over a considerable distance and is therefore almost certainly TRM, and (2) movement on the fault was rectilinear.

At sites 5 and 15 the NRM directions were also greatly scattered, but in addition the intensities of NRM in many specimens were anomalously high, being as much 0.3 emu. Although the dispersion of NRM directions at these sites was much reduced by a.c. demagnetization, it could not be reduced sufficiently to provide useful paleomagnetic directions. Thus it appears that in the case of Lovejoy basalt remagnetized by lightning, a.c. demagnetization is effective only if the lightning current passed along the outcrop no closer than a few feet from the specimen locations (*cf.* Cox, 1961).

Most of the sampling sites show no evidence of having been struck by lightning, and at these sites the secondary component is viscous magnetization due to the earth's field. This is illustrated in Fig. 3, in which the great-circle paths followed by the NRM directions during demagnetization are seen to have their common intersection near the present field

Fig. 3 Effect of a.c. demagnetization of NRM at site 6. Curve of intensity (J) *vs.* demagnetizing field is average of all 10 specimens. Great circles are paths along which directions of NRM moved during demagnetization. Equal-area projections; k =Fisher's precision parameter.

direction; this intersection is even closer to the axial dipole field direction. Provided all of the viscous magnetization was removed by the 200 Oe. a.c. field, the fact that these great circles are not all identical indicates that, for site 6 at least, the dispersion of the TRM is greater than that of the viscous component.

During the first stages of a.c. demagnetization of specimens of Lovejoy basalt the NRM directions characteristically move along great circles like those shown in Fig. 3, and the intensities of NRM typically increase and then decrease as illustrated in Figs. 2 and 3. The TRM directions at all sites but one (site 14) make angles greater than 90° with the present field, and many directions are nearly opposite to the field, *i.e.* they are reversed. Thus the change in sign of the slopes of the demagnetization curves simply reflects the preferential removal of the viscous magnetization at low a.c. field strengths. The value of a.c. field sufficient to remove all but an insignificant amount of the viscous component is considered to be that at which the NRM direction ceases to move in a plane and instead starts moving in small and apparently random jumps. This value is usually 2 to 3 times the a.c. field strength that produces maximum resultant intensity of NRM in reversed specimens, and for these particular basalts it is also the field strength for which the dispersion of NRM directions is at a minimum. Since the process of a.c. demagnetization often produces small spurious magnetizations (Irving, Stott, and Ward, 1961), the point at which minimum dispersion occurs may be reached in some rocks before the secondary component has been completely removed. In the case of the Lovejoy basalts this appears to have been true only for sites 5, 14, and 15. A general test for complete removal of soft secondary magnetization is whether the mean NRM direction for several specimens continues to move systematically with further demagnetization even though individual directions appear to change at random (for example, see Currie, Gromme', and Verhoogen, 1963, p. 2272).

Directions of NRM and TRM

Mean directions of magnetization at 13 of the 16 sampling sites in the Lovejoy basalts are given in Table 1. Data from sites 5 and 15 are omitted from this table for the reason given above, and site 3 is also omitted because it is duplicated by site 4 for which the precision is better. For each site the first row in the table corresponds to the first measurements made after collection of specimens, and the second row corresponds to the optimum demagnetization treatment determined in the manner just described. The dispersions of NRM directions at all sites except site 14 were decreased markedly by demagnetization. For site 14, demagnetization beyond 100 Oe. did not continue to move the mean direction away from that of the present field. For site 1 the dispersion of NRM directions prior to demagnetization was too great to permit calculating a mean direction. For site 2 the NRM directions as first measured had a planar distribution, so that the quantity α_{95} is inapplicable. In spite of the large component of viscous magnetization in the NRM, planar distributions of NRM directions were not found at any other site.

The magnitudes of the viscous and thermoremanent components of the NRM in the specimens as first measured can be calculated as follows: We know (1) the direction and (2) the intensity of the NRM as first measured, and (3) the direction of the TRM component.

Table 1. Average NRM at each site in Loyejoy basalt, as first measured and after optimum demagnetization.

Site	Treatment	D	I	N	k	α_{95}	$J \times 10^3$	$J_t \times 10^3$	$J_v \times 10^3$
1	—	—	—	8	4	25	2.8	—	—
	200 oe.	270	-52		186	3.6	2.9		
2	—	186	36	8	35	—	2.6	2.8	1.3
	250°C.	185	10		124	4.4	1.5		
4	—	153	-48	23	13	8.3	5.8	8.6	3.2
	75 oe.	164	-57		595	1.2	6.4		
6	—	161	-31	10	40	7.0	6.3	11.	5.2
	200 oe.	166	-45		231	2.9	7.2		
7	—	274	22	10	8	16	1.8	2.9	2.8
	125 oe.	249	-49		78	5.0	1.9		
8	—	176	2	19	9	11	7.0	7.7	1.3
	200 oe.	178	-7		11	9.6	6.0		
9	—	190	-68	5	430	3.0	6.8	—	—
	100 oe.	179	-72		930	2.0	3.1		
10	—	196	-27	17	53	4.7	4.5	11.	6.8
	100 oe.	201	-46		941	1.1	4.9		
11	—	185	-38	18	72	3.9	8.4	38.	36.
	150 oe.	174	-56		460	1.5	5.6		
12	—	131	-45	9	74	5.4	22.	34.	12.
	200 oe.	137	-43		192	3.4	13.		
13	—	137	14	11	37	6.9	5.2	6.9	3.7
	100 oe.	141	-18		286	2.5	4.9		
14	—	86	72	7	119	4.9	3.0	2.1	1.2
	100 oe.	119	59		106	5.1	1.3		
16	—	120	-40	13	82	4.3	13.	24.	13.
	±200 oe.	148	-43		324	2.2	14.		

(D=declination east of north; I=inclination, negative upward; N=number of specimens; k =precision parameter and α_{95} =radius of 95% confidence interval (Fisher, 1953); J =total measured NRM intensity, J_t =TRM component, and J_v =viscous component, all in emu.)

We can assume (4) the direction of the viscous component to be either along the present field or, as seems to be the case for site 6 (Fig. 3), along the axial dipole field. The lengths of the two remaining sides of the resulting vector triangle are found directly. At all sites except site 1 and site 9, the original NRM direction and the TRM component are more nearly coplanar with the axial dipole field direction than with the present field direction. This may be interpreted to mean that the natural viscous magnetization in these basalts has an extremely long time constant. The calculated intensities of viscous and thermoremanent magnetizations are given in the last two columns of Table 1. On the average the viscous component is about half as large as the natural TRM, and as can be seen in Table 1, this was sufficient to have deflected the NRM directions appreciably.

The mean NRM directions at each site after demagnetization are summarized in Fig. 4. Clearly, all the site-mean directions are significantly different from each other, so that each site listed in Table 1 must be in a separate basalt flow and thus must represent a distinct point in time. This conclusion could not be arrived at from the geologic evidence alone. Although the dispersion of the 13 site-mean directions appears extreme ($k=3.5$), the length of the resultant R is 9.528 and therefore even at the 99% confidence level the distribution is

Fig. 4 Equal-area projection of site-mean NRM directions after demagnetization with associated 95% confidence circles, as given in Table 1.

not random (Watson, 1956). The mean of the site-mean directions has declination 174°E . and inclination 42° upward, but the radius of the 95% confidence interval (α_{95}) is 26° , so that the exact direction has little significance.

The magnetization directions in many of the Lovejoy basalt flows were quite unexpected and are certainly anomalous in terms of the known behavior of the geomagnetic field during Cenozoic time (for a summary, see Irving, 1964). This is especially true for sites 1, 2, 7, 8, 13, and 14. It has already been shown that the anomalous directions cannot be due to soft secondary magnetization or to remagnetization by lightning, and it is equally certain that tectonic deformation cannot be the cause. For example, at sites 2 and 8 the flows can be seen to be horizontal, and the anomalous nature of the NRM directions at these sites is that they are also nearly horizontal.

The reversed NRM directions at sites 4, 6, 9, 10, 11, 12, and 16 are rather widely dispersed but are not considered anomalous; the probability that they represent a reversed polarity epoch (Cox, Doell, and Dalrymple, 1964) will be discussed in a later section.

Thermal demagnetization

The possibility remains that the anomalous NRM directions are due to uniform hard secondary magnetization, such as partial TRM or chemical magnetization acquired subsequently in the earth's field during a normal polarity epoch. For this reason, thermal demagnetization of NRM was done for a number of specimens. The procedure used was to heat the specimens to a specified temperature in a nitrogen atmosphere and then allow

them to cool to room temperature in the absence of a magnetic field. The remaining NRM and the reversible susceptibility were then measured at room temperature and the heating cycle was repeated using a higher maximum temperature. (The susceptibility was determined in a 1000 cps field of about 1 Oe. peak intensity.)

The results of heating experiments on specimens from site 2 are shown in Fig. 5. The viscous magnetization at this site was found by a.c. demagnetization to have a coercivity less than 150 Oe., but it was completely removed only at 250°C, which is close to the maximum Curie temperature of the rock. The dispersion increased again after heating the specimens to 300°C (Fig. 5), and was even greater after 350°C. There was, however, no indication of further systematic movement of the mean NRM direction after these last two heatings, and the intensities of magnetization had greatly decreased. The significance of the inflection at 200°C in the curve of intensity *vs.* temperature in Fig. 5 is not clear. The inflection may represent the Curie temperature of part of the ferromagnetic minerals, or it may be due to the removal of most of the viscous component, which makes an obtuse angle with the TRM.

Similar results with respect to NRM directions were obtained after heating 3 specimens from site 14 in the same way. These experiments could not be extended to other sites owing to the lack of suitable specimens. There is, however, no indication of any secondary PTRM at either site 2 or site 14, and it seems likely that this is true for the other sites as well.

Note in Fig. 5 the very great increase in susceptibility, on the average almost 4-fold after heating to 350°C. This increase is irreversible with temperature and is not to be confused with the Hopkinson effect. The cause of the increase is obscure, but the weak-field

Fig. 5 Effect of thermal demagnetization of NRM at site 2. Curves of intensity (J) and reversible susceptibility (χ) *vs.* temperature are averages for all 8 specimens. (All measurements were made after cooling from specified temperature to room temperature.) Equal-area projections; k =Fisher's precision parameter.

susceptibility is a highly structure-sensitive property and changes in it may reflect subtle alterations of the magnetic minerals in the basalt.

For the specimens from site 2 the increase in susceptibility after heating does not seem to correspond to the removal of any secondary component of magnetization. Whatever geologic process may have caused the susceptibility to decrease from the higher value it presumably once had could have occurred during the initial cooling of the basalt. Conversely, this process may have been very slow, being completed only at a much later time, and in this case it could possibly have also produced a hard secondary CRM in some unspecified manner.

To pursue this further, specimens from all sites were heated to 600°C and cooled (in the earth's field), the susceptibilities being measured before and after heating. Designating the susceptibility before heating as χ_n and that after heating as χ_t , the ratio χ_t/χ_n was found to range from 1.2 (for site 10) to 12.9 (for site 4). The average value of this ratio is about 3. There is, however, no correlation between the ratio χ_t/χ_n for a site and the degree of divergence of the mean NRM direction from either the mean of site-mean directions or the reversed axial dipole field direction. For example this ratio for site 14 was 1.8, for site 6 it was 6.5, for site 12 it was 2.0, and for site 1 it was 5.5. Thus there is no evidence that the process which affected the susceptibilities also produced any secondary magnetization responsible for the anomalous NRM directions.

4. Ferromagnetic Minerals

Description

In order to identify the ferromagnetic minerals responsible for the NRM, representative polished sections of the basalt flows have been examined in reflected light at magnifications up to 1000 X. The only opaque mineral that was found is titanomagnetite or a similar isotropic oxide; no rhombohedral oxides (ilmenite-hematite) are present in any of the sections. The limited Curie temperature data available for these rocks, together with a preliminary investigation of mineral compositions using an electron probe micro-analyzer, indicate that these titanomagnetites range in composition from 40% to 70% of the ulvöspinel end-member. Most grains, however, contain only 40% to 50% of the ulvöspinel component. The electron probe has also provided the following preliminary estimates of the minor constituents present in the titanomagnetites (weight per cent): MgO, 1 to 4; Al₂O₃, 2 to 2.5; Cr₂O₃, 0.3 to 3; MnO, 0.2 to 0.5; cadmium and cobalt, traces only. This work is being continued.

Most of the titanomagnetite is homogeneous and is not oxidized or otherwise altered, but in some of the polished sections the oxide grains present a peculiar mottled appearance. This texture consists of light colored or white patches with high reflectivity set in a matrix of normal-appearing titanomagnetite. The light patches are optically isotropic (as is the unaltered titanomagnetite). Scanning with the electron probe has shown no significant variation in Fe/Ti ratio between the light patches and the normal-appearing matrix, so that

this texture cannot represent magnetite-ulvöspinel exsolution. From measurements of the relative intensity of electron back-scattering, however, it was found that the light-colored patches have a lower mean atomic number than the unaltered areas of the same oxide grains. This texture must therefore be the result of partial oxidation of titanomagnetite to titanomaghemite (Akimoto and Kushiro, 1960), which has occurred without partitioning of Fe and Ti between the two phases. An illustration of an oxidation texture identical to that found in the Lovejoy basalts has been published by Kobayashi (1959, p. 109, plate 2), and similar textures have also been illustrated by Akimoto and Kushiro (1960, p. 103).

Discussion

If the anomalous directions of NRM in some Lovejoy basalt flows are due to a hard secondary magnetization, this might possibly be CRM resulting from the partial oxidation of the titanomagnetite. There appears to be no correlation between divergence of NRM direction at a site and the degree of alteration of the oxide minerals, but the number of polished sections available is insufficient to make this certain.

Kobayashi (1959) has shown that oxidation of magnetite to maghemite may produce a strong CRM which, however, is not thermally stable owing to the rapid inversion of metastable maghemite to hematite at moderately high temperatures. In the case of titanomaghemite this inversion is suppressed (Akimoto and Katsura, 1959), so that such a CRM in the Lovejoy basalt might be thermally stable. Furthermore, Kobayashi (1959) has shown that both TRM and CRM in identical material (magnetite) have closely similar thermal demagnetization characteristics. Because oxidation of titanomagnetite without change of Fe/Ti ratio causes a rise in Curie temperature (Akimoto, Katsura, and Yoshida, 1957; Akimoto and Katsura, 1959), it follows that a secondary CRM due to oxidation might have a higher range of blocking temperatures than the primary TRM. At least for site 2, however, the thermal demagnetization results shown in Fig. 5 provide no evidence favoring such a condition.

Kobayashi (1959) has also shown that both TRM and CRM in the same magnetite give the same a.c. demagnetization curves. Since in the Lovejoy basalt the TRM and the hypothetical CRM would be in different materials, Kobayashi's result might imply that the CRM could have a higher range of coercivity than the TRM. Again, all of the a.c. demagnetization experiments have shown that this is not the case, since if it were true the anomalously divergent NRM directions should have moved back away from the mean or from the reversed axial dipole direction at high demagnetizing field strengths.

Akimoto and Kushiro (1960) have found that in some rocks the occurrence of very unstable NRM (apparently viscous magnetization) could be correlated with the presence of titanomaghemite as an oxidation product of titanomagnetite. They found in those rocks no indication of CRM resulting from the oxidation. Its absence may be attributed to the relatively large grain size of the titanomaghemite (greater than 1 micron) (Kobayashi, 1961); this appears to be true also for the Lovejoy basalt. In the basalt, however, there is no apparent correlation of the presence of titanomaghemite with the relative magnitude of the

viscous component of NRM, and no specimens of the basalt had viscous magnetization with as short a time constant as the dolerite described by Akimoto and Kushiro (1960).

A polished section made from one of the specimens from site 2 which had been heated and had shown the large increase in susceptibility was compared with a polished section from an unheated specimen. A well-developed oxidation texture was present in the titanomagnetite in the unheated specimen, but was completely absent in the heated specimen. This may be an indication that the irreversible increase in susceptibility is due to homogenization and perhaps reduction of titanomagnetite-titanomaghemite intergrowths. There is no apparent correlation of increase in susceptibility with degree of oxidation of titanomagnetite from one site to another, and this matter is also being investigated further.

From the foregoing discussion it seem safe to conclude that partial oxidation of titanomagnetite in Lovejoy basalt has produced no hard secondary magnetization, and that the component of NRM remaining after a.c. or thermal demagnetization is almost exclusively primary TRM. The stable NRM directions at all sites as given in Table 1 must therefore represent the directions of the geomagnetic field at the instants of geologic time during which the different basalt flows cooled.

5. Summary and Conclusions

The NRM data from the Lovejoy basalt are summarized in Fig. 6 in the form of virtual geomagnetic north poles, which are the antipoles of those calculated directly from the mean

Fig. 6 Positions of virtual geomagnetic north poles calculated from mean directions of NRM after demagnetization (Table 1) with 95% confidence ovals. Equal-area map of northern hemisphere. (Pole 14 is in southern hemisphere.)

NRM directions given in Table 1. These fictive dipoles are merely a convenient way of considering the dispersion; no implication that they represent real magnetic poles is intended. Fisher's k for these virtual poles is 3.7, and although the mean pole is 15° away from the geographic pole, the value of α_{95} for it is 25° so that, as already stated, little can be concluded from its exact position. (Note that these statistics differ slightly from those for the mean magnetization direction, but for this general paleomagnetic latitude the difference is too small to be important.)

None of the spontaneous self-reversal mechanisms proposed for titanomagnetite and titanomaghemite (Verhoogen, 1962) are applicable to the cubic oxides in the Lovejoy basalt because these particular ones contain insufficient titanium or other materials in solid solution. As mentioned above, rhombohedral oxides are absent from these basalts. It is therefore probable that the eruptions of most of the flows took place during a reversed polarity epoch.

It is tempting to speculate that the geomagnetic polarity was in the process of changing during the eruption of the basalt flows having anomalous NRM directions (for example, see Momose, 1963). Reconstruction of the time sequence of the NRM directions is uncertain because the relative stratigraphic positions of the sampling sites are not well known. Site 1 is at the top of a section consisting of about 15 basalt flows, and is therefore probably the youngest. The position of site 7 is not certain but it may also be young. Sites 2 and 8, also with divergent directions, are near the bottoms of their respective stratigraphic sections and may be among the oldest basalt flows. On the other hand, sites 9 and 10 do not have anomalous NRM directions but these two flows rest on pre-Tertiary bedrock and are also among the oldest. Site 14, which has the most divergent NRM direction, is in a flow resting on bedrock; for petrological reasons this flow is very likely the oldest of these sampled. The relative ages of the other sites are unknown. Thus if the divergent NRM directions actually record polarity transitions, they represent both the beginning and the end of a comparatively short polarity epoch. This is a hypothesis rather than a conclusion; it cannot be demonstrated from the evidence at hand.

In this regard, it would be interesting if estimates of relative field paleo-intensity could be obtained from these rocks, and especially to compare the divergent results with those from the other sites, as was done by Momose (1963). Unfortunately, in spite of the deceptively simple magnetic mineralogy in these basalts, such a comparison would not be valid because whatever process caused the apparent decrease, in susceptibility since the flows first cooled must surely have also affected the intensity of TRM as now measured.

Figure 6 shows that even a selection of the least anomalous NRM directions will not give a mean paleomagnetic pole located near the geographic pole. This may be because only a relatively small number of flows was sampled, or it may have a common cause with the divergence of the anomalous directions. It is reasonable to conclude that the Lovejoy basalts were erupted during a period of time, about 24 million years ago, in which the earth's magnetic field was predominantly reversed but varied in direction to an unusual degree. Comparable paleomagnetic results from rocks of the same age in other localities would be highly desirable.

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