PALEOMAGNETIC EVIDENCE FOR TECTONIC ROTATION OF THE BELCHERTOWN PLUTON, WEST CENTRAL MASSACHUSETTS

Lewis D. Ashwal and Robert B. Hargraves

Department of Geological and Geophysical Sciences, Princeton University

Princeton, New Jersey 08540

Abstract. A paleomagnetic study of the Belchertown pluton, a syntectonic Devonian intrusion in the Bronson Hill anticlinorium, Massachusetts, indicates the presence in 23 samples from eight sites in primary quartz monzodiorites of a strong, stable, and consistently oriented remanent magnetization vector ($D = 154.9°$, $I = -13.4°$, $K = 20.8°$ and $\alpha_{95} = 12.4°$) with a high Q value (7.0). The remanence is inferred to be of thermal and/or thermochemical origin acquired during the original crystallization and cooling of the pluton. Recrystallized equivalents of the primary rocks, which occur as a surrounding border zone, yield weak and inconsistent results (four samples from two sites) due to the absence of opaque minerals. The mean Belchertown vector is discordant with respect to the mean North American Devonian vector ($D = 170°$ and $I = +32°$) in such a direction as to suggest that the entire pluton has undergone some 30°-60° of rotation to the northwest about a NE-SW axis. The high Q value of the primary rocks and their isolation from magnetic country rocks by the surrounding non-magnetic border zone allow computer modeling of the three-dimensional shape of the pluton using the measured remanent vector and the total field aeromagnetic anomaly. The resulting model is consistent with the proposed amount and direction of tectonic rotation of a once roughly vertically symmetrical funnel-shaped intrusion.

Introduction

The Belchertown pluton is one of a series of syntectonic Paleozoic intrusions which were emplaced into the Precambrian gneiss dome terrain of the Bronson Hill anticlinorium in west central Massachusetts during the peak of Acadian kyanite zone regional metamorphism (Figure 1a) [Thompson et al., 1968]. As a result of recent petrological and geophysical studies [Ashwal, 1974; Ashwal et al., 1974; Hall, 1973, 1975] the geology of the pluton and its age of emplacement (Lower Devonian) are comparatively well known. The present study adds a detailed paleomagnetic investigation to the increasing understanding of the pluton and its relations with the surrounding country rocks.

General Geology

As presently exposed, the Belchertown pluton covers an area of some 120 km^2 (Figure 1a). Rock near the margins of the pluton has a strong tectonite fabric and amphibolite facies mineralogy, indicating that the outer areas underwent deformation and metamorphism synchronous with kyanite zone regional metamorphism, presumably during the Acadian orogeny [Guthrie, 1972]. Areas in the center of the pluton appear to have escaped the major effects of metamorphism, retaining a weak primary igneous foliation and mineralogy suggestive of crystallization at temperatures between 800° and 1000°C and at an oxygen fugacity between the nickel-nickel oxide and hematite-magnetite buffers [Ashwal, 1974; Ashwal et al., 1974]. Surrounding the areas of unaltered igneous rock is an extensive transition zone in which primary features are in various stages of metamorphic reconstitution. This was achieved via a series of well-documented hydration reactions which took place along pervasive shear zones throughout the entire pluton and converted the primary two-pyroxene quartz monzodiorite to hornblende-biotite quartz monzodiorite gneiss (see International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks [1973] for classification of granitic rocks). The core zone (Figure 1a) thus encompasses the extent of unaltered igneous rocks. Whole rock chemical analyses demonstrate that the plutonic rocks and their metamorphic equivalents are virtually isochemical with respect to all major components except H_2O [Ashwal, 1974]. Radiometric age determinations (R. E. Zartman, unpublished data, 1976) by the U - Pb method give an age of 380 ± 5 m.y. for crystallization of the primary quartz monzodiorite (a more detailed discussion of the general geology of the pluton, including the geochronology, is in preparation). On the basis of gravity and ground and airborne magnetometer studies [Hall, 1975] the pluton was considered to be roughly disc shaped with a thickness between ½ and 1 km; however, this shape must be modified somewhat in order to be compatible with the data presented here.

Paleomagnetic Sampling and Measurement

A series of 27 oriented samples were collected from 10 sites within the pluton (Figure 1a). An attempt was made to sample both the primary igneous lithology and its fully metamorphosed counterpart. Sites 1-7 represent individual localities along an abandoned railroad cut approximately ½ km long which contains fresh exposures of all rock types representative of the pluton. Although the separation between some of the sample sites is small, we believe

Paper number 6B0703.

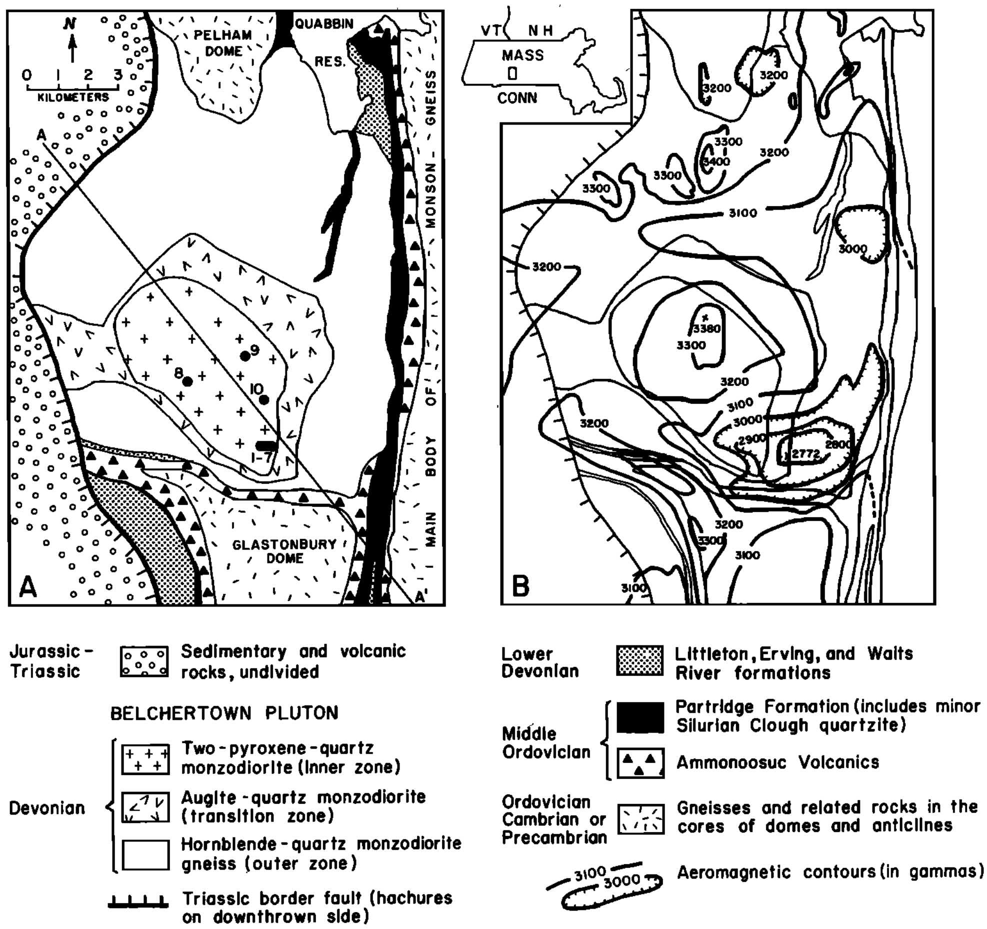


Fig. 1. (a) Geologic map of the Belchertown pluton and related rocks. Numbers indicate paleomagnetic sample sites. A-A' shows orientation of geologic cross section given in Figure 11. (b) Aeromagnetic map of the Belchertown pluton [from Gilbert et al., 1968a, b] showing the total intensity of the magnetic field of the earth in gammas relative to an arbitrary datum. Hachures indicate closed areas of lower magnetic intensity. Contour interval is 100 γ. Contours east of the pluton have been omitted for clarity.

that the site distribution is sufficiently adequate to be representative of the pluton.

All samples were 2.5-cm-diameter cores obtained in the field with a portable gasoline-powered drill [Doell and Cox, 1967] and were oriented by means of a sun compass [Creer, 1967] and/or an astrocompass [LaRochelle, 1961] as well as a magnetic compass. Orientations by these different techniques invariably agreed within 5°, which is considered the maximum error in orientation.

The natural remanent magnetism (NRM) of cylindrical specimens 2.5 cm in diameter by 2.3 cm long was measured on a Princeton Applied Research SM-1 spinner magnetometer. Alternating current and thermal demagnetization was performed on standard apparatus described by McElhinny [1963] and Phillips [1964]. Saturation magnetization measurements and Curie point determinations both in air and in a vacuum were performed on whole rock chips and purified feldspar separates by using a vertical type magnetic balance.

Paleomagnetic Results

At least one specimen from each of the 10 sites was systematically demagnetized in steps in alternating fields up to 500 Oe following NRM measurement.

Samples from 8 of the 10 sites, those representing the primary igneous lithology, yielded stable and highly consistent results; however, the remaining two sites, from the metamorphically hydrated equivalents, were extremely weak and inconsistent (Figure 2) and were omitted from further consideration. The mean vectors of the individual consistent sites, taken at the af steps at which best directional grouping was obtained, are given in Table 1 and Figure 3. Also given is the mean paleomagnetic vector of all eight sites. The value of this mean vector depends upon the confidence with which one can determine (1) when it was acquired, (2) whether the sampling represents a sufficient time interval of acquisition of magnetization to average out secular variation, and (3) whether the orientation of the vector has been disturbed by subsequent tectonic movements.

Magnetic Mineralogy and Source of NRM

Microscopic Observations

The opaque mineral assemblage of the primary igneous lithology is dominated by ilmenohema-

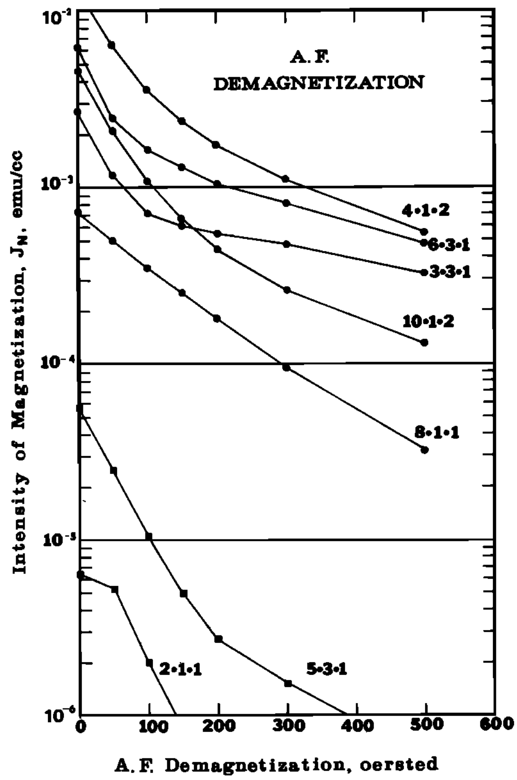


Fig. 2. Alternating field demagnetization curves for primary quartz monzodiorites (circles) and metamorphically hydrated gneisses (squares).

tite (Figure 4a). (The terminology used in describing Fe-Ti oxide minerals is based on the classification proposed by Balsley and Buddington [1958].) Electron microprobe analyses of the exsolved phases gave compositions of $Ilm_{92}Hem_8$ and $Ilm_{25}Hem_{75}$, and the bulk composition before unmixing was estimated to be approximately $Ilm_{33}Hem_{67}$ [Ashwal, 1974]. Also associated with the ilmenohematites are smaller subhedral grains of relatively pure magnetite (TiO_2 $\sim$ 0.8 wt %) which are usually surrounded by a wide rim of ilmenite (Figure 4a). Plagioclase from the primary rock characteristically contains 'submicroscopic 'dustlike' opaque inclusions concentrated in the cores of the grains (Figure 4b). These inclusions impart a pink or reddish coloration to the rock, since plagioclase constitutes nearly 50% of the rock by volume. Microprobe traverses across these feldspars indicate that areas of high dust concentration are also enriched in FeO and TiO_2 and therefore suggest that the particles may be iron or iron-titanium oxide phases [Ashwal, 1974]. This possibility was investigated further in the present study.

With progressive hydration and recrystallization of the primary rocks their opaque mineral assemblage is completely converted to mafic silicates by metamorphic hydration reactions [Ashwal, 1974; Ashwal et al., 1974]. This process also involves destruction of the dustlike opaque inclusions within the feldspars. As a result, metamorphic equivalents of primary igneous rocks possess neither appreciable remanence nor magnetic susceptibility as is borne out by the data given in Table 1.

Bulk Magnetic Properties

The magnetic moment J versus magnetic field H measurements of both a whole rock chip of the primary igneous lithology (Figure 5a) and a purified mineral concentrate of plagioclase containing dustlike opaque inclusions (Figure 5b) are dominated by a magnetic component which is saturated at about 2.5 kG. This is presumably magnetite, since hematite or titanohematite only become saturated in much higher fields [Nagata, 1961]. The saturation moments are equivalent to a pure magnetite (saturation magnetization of approximately 100 emu/g) content of 0.6 and 0.004% by weight in the whole rock specimen and plagioclase concentrate, respectively. The decreasing moment of the feldspar concentrate in high fields (Figure 5b) is presumably due to the intrinsic diamagnetism of the feldspar, which swamps the moment due to the ferrimagnetic and paramagnetic phases present.

The temperature dependence (in air) on saturation magnetization (J_s of 8100 Oe) of the whole rock chip is shown in Figure 6a. Shown in Figure 6b are the results of similar experiments performed (one in air and one in a vacuum of 10^{-5} torr) on the feldspar concentrate. It is clear that the high-field magnetic properties of the whole rock chip are dominated by a phase with a Curie temperature of 580°C, presumably magnetite, although the smaller decline at approximately 450°C may be due to the rhombohedral phase ($Ilm_{25}Hem_{75}$). The decline of the saturation moment J of the plagioclase concentrate between 500° and 600° may well be due to the presence of magnetite (Curie temperature of 580°C, but the sharp decline at 600° suggests the presence of an additional phase with a somewhat higher Curie temperature, such as titanohematite with approximately 10 mol % ilmenite in solid solution.

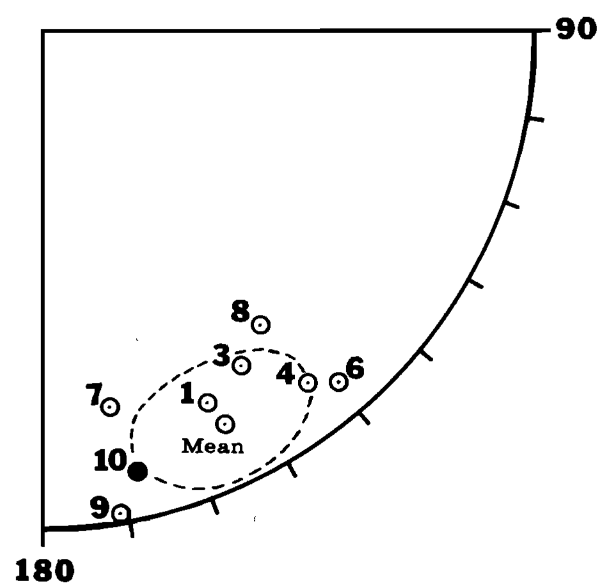
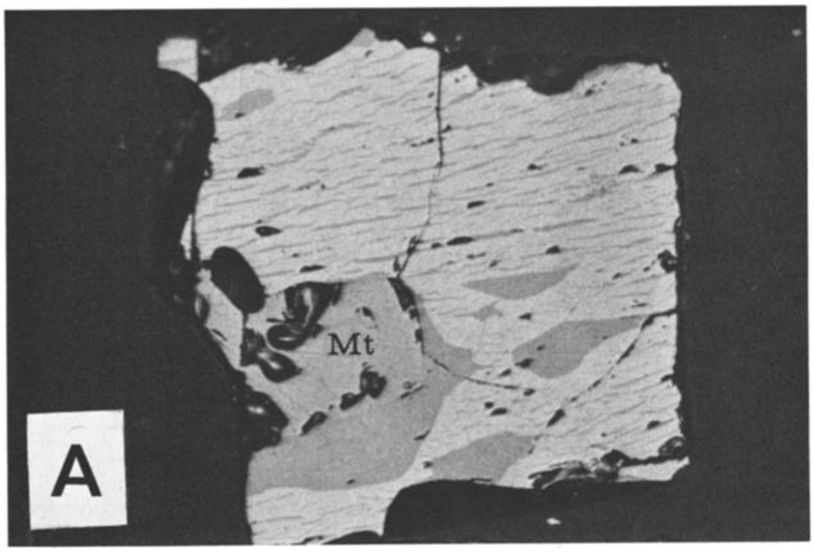


Fig. 3. Equal-area diagram showing orientations of remanent vectors of primary quartz monzodiorites following af demagnetization. Dashed line represents cone of 95% confidence (α_{95}). Circles with dots are on upper hemisphere, and the filled circle is on lower hemisphere.

TABLE 1. Paleomagnetic Results Obtained for the Belchertown Pluton

		Original NRM									Stable Components				Virtual Pole			
Site	N	D,deg	I,deg	k	α_{95},deg	J_N, emu/cc	χ	Q	MDF,Oe	ODF,Oe	D,deg	I,deg	k	α_{95},deg	Lat, °N	Long, °E	α_{lat}, deg	α_{long}, deg
1	2	168.7	-14.0	6.6	90.0	4.5×10^{-3}	5.1×10^{-4}	8.8	~100	300	155.9	-19.3	133.2	21.8	51.4	147.7	11.9	22.8
2	1					6×10^{-6}	1.2×10^{-4}	0.5										
3	3	187.9	-12.7	1.5		1.8×10^{-3}	5.8×10^{-4}	3.1	75-200	200	149.0	-22.1	121.5	11.2	49.0	158.0	6.3	11.8
4	3	139.0	-1.1	105.1	12.1	4.4×10^{-3}	7.4×10^{-4}	6.0	50	200	142.5	-11.6	232.3	8.1	40.7	160.6	4.2	8.2
5	3					3.0×10^{-5}	2.7×10^{-5}	1.1	<50									
6	3	137.6	4.2	3.3	83.2	3.7×10^{-3}	4.6×10^{-4}	8.6	50-100	500	139.8	-7.9	360.0	6.5	37.6	162.0	3.3	6.5
7	3	242.9	-22.2	1.0	90.0	2.9×10^{-3}	4.6×10^{-4}	6.3	50-100	500	169.9	-24.3	8.2	46.3	59.1	127.1	26.5	49.6
8	4	171.5	-37.1	0.8	90.0	1.6×10^{-3}	3.2×10^{-4}	5.0	100	300	143.3	-26.9	18.9	21.7	47.8	167.1	12.8	23.6
9	3	213.0	-29.2	5.4	59.3	5.4×10^{-3}	4.7×10^{-4}	11.5	50	500	171.0	-1.7	300.0	7.1	47.9	120.2	3.6	7.1
10	2	202.4	51.1	1.6	90.0	2.0×10^{-3}	2.5×10^{-4}	8.0	75	500	167.9	9.5	1756.4	6.0	41.6	123.8	12.0	12.0
Mean of 8 sites (excluding 2 and 5)								7.0			154.9	-13.4	20.8	12.4	48.1	146.7	6.5	12.7

N is the number of samples; D is the eastward declination from north; I is the inclination, downward positive; k is Fisher's precision parameter; α_{95} is the semiangle of cone of 95% confidence; J_N is the intensity of remanent magnetization; χ is the magnetic susceptibility; Q is the Koenigsberger ratio; MDF is median demagnetizing field; and ODF is optimum demagnetizing field.



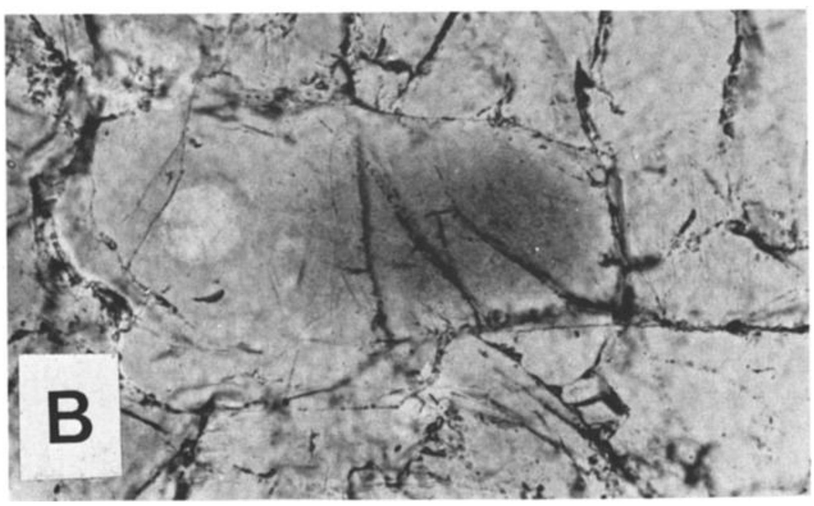


Fig. 4. (a) Photomicrograph showing opaque mineral assemblage in the primary quartz monzodiorite. Titanohematite (white) contains ferri-ilmenite exsolution lamellae (gray). Note small grain of magnetite (Mt) surrounded by ferri-ilmenite. Entire grain is approximately 0.2 mm in length. Light is reflected. (b) Photomicrograph illustrating fine dustlike opaque inclusions in plagioclase from the primary quartz monzodiorite. Note concentration of particles in center of central grain. Photograph shows an area approximately 2.5 mm across. Light is transmitted.

The presence of hematite or titanohematite in the plagioclase is strongly suggested by the marked increase in the saturation moment J_s during the hard vacuum cooling cycle (Figure 6b). Presumably, at least some of the rhombohedral phase was reduced to magnetite under these experimental conditions. Conversely, the decrease of J_s during cooling in air suggests oxidation of coexisting magnetite.

These microscopic and magnetic property data indicate the presence of both titanohematite and relatively pure magnetite in the primary igneous rock. In order to determine which (or whether both) of these phases carry remanent magnetism, thermal demagnetization of NRM in field-free space (< 25 γ) was carried out. The results are shown in Figure 7. Of the four specimens thermally demagnetized, three showed a precipitous decrease in the intensity of remanence between 550° and 625°C, suggesting that the remanence does indeed reside in magnetite and/or titanohematite, as was revealed by the Curie point determinations (Figure 6).

The migrations of the remanent vectors with thermal and af demagnetization are compared in Figure 8. Thermal demagnetization to 450°C and af demagnetization to 300 Oe are more or less equally effective in removing viscous magnetization.

The remanent vector in one sample (9-1-3) remained constant in orientation, but declined steadily in intensity, with demagnetization 'thermally distributed' [Irving and Opdyke, 1965]. The orientation, however, is quite distinct from that revealed by af demagnetization of another specimen from this sample. The

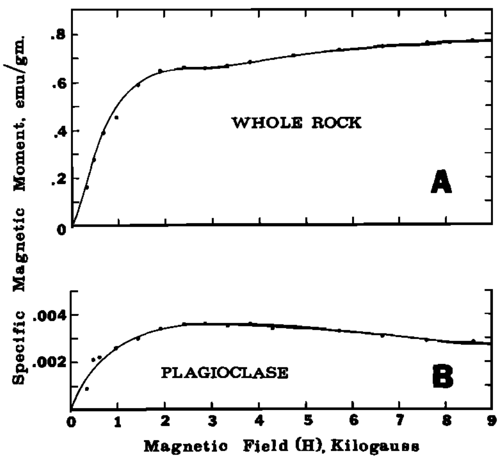


Fig. 5. Specific magnetic moment J as a function of applied field H. Curves are for (a) the whole rock and (b) the plagioclase concentrate.

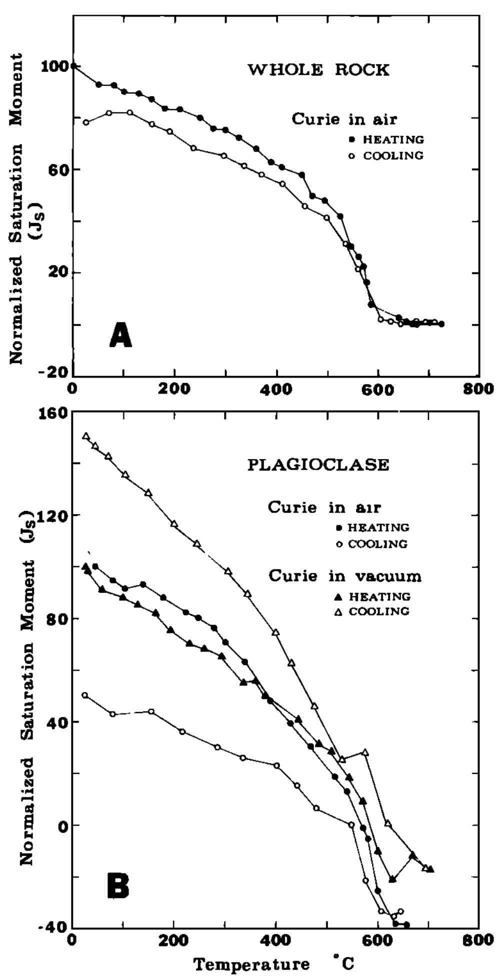


Fig. 6. Saturation magnetic moment (J_s of 8100 Oe) versus temperature for samples of (a) whole rock and (b) plagioclase concentrate. The plagioclase was heated both in air and in a vacuum of 2 x 10^{-15} torr.

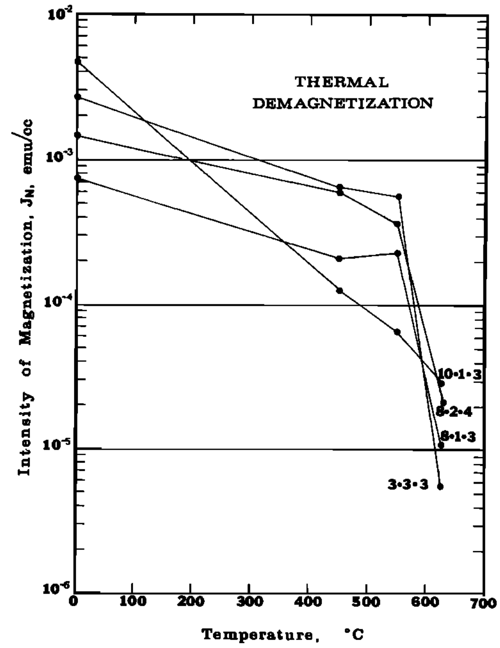


Fig. 7. Thermal demagnetization curves (in air) for primary quartz monzodiorites.

remanence of this specimen is presumed to be dominated by a secondary magnetization, perhaps due to weathering.

For the three stable samples, although the remanent magnetism (RM) after thermal demagnetization to 625°C is much weaker, it is still very close in orientation to the stable 550°C NRM. This suggests that part of the primary stable NRM resides in phases with blocking temperatures above 625°C, presumably purer hematite.

In summary, the data indicate that the stable and presumably primary remanence resides in both magnetite and titanohematite mineral

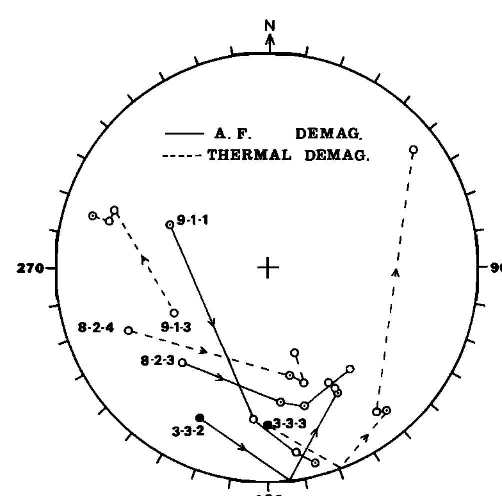


Fig. 8. Equal-area diagram showing migration of remanent vectors for primary quartz monzodiorites during progressive thermal (dashed lines, NRM , 450°, 550°, and then 625°C) and af (solid lines, NRM , 100, 200, and then 300 Oe) demagnetization. Circles with dots are on upper hemisphere, and filled circles are on lower hemisphere. Companion specimens from individual sites are compared.

grains. These minerals are microscopically observable and appear to be products of primary crystallization of the quartz monzodiorite magma under conditions of high f_{O_2} [Ashwal, 1974; Ashwal et al., 1974]. Upon cooling, titanohematite underwent subsolidus exsolution. The remanence of the magnetite is a pure thermoremanent magnetization (TRM) acquired upon cooling, and that of the titanohematite is either a pure TRM or a thermochemical RM acquired as ilmenite exsolved and the blocking temperature of the residual hematite rose. The similarity in the orientations of RM in both phases is related to their original cooling. Although the interval during which the remanent magnetization of these rocks was acquired is uncertain, we assume that the pluton is sufficiently large (surface area of 120 km^2 and minimum thickness of 0.5 km) and cooled slowly enough theoretically to average out secular variation [Morgan, 1976].

Comparison of Results With Other Paleomagnetic Data

The paleomagnetic record for Paleozoic rocks of North America is relatively sparse but shows comparatively little directional variation [McElhinny, 1973]. The interpretation of the paleomagnetism of lower Paleozoic rocks from Europe, however, has been subject to some controversy for a number of years [McElhinny and Opdyke, 1973]. Creer [1968], for example, has argued that the true Devonian pole position was quite different from that commonly accepted and that many lower Paleozoic red beds, including those in North America, have been remagnetized in Permian times. The acquisition of paleomagnetic data from well-dated Devonian igneous rocks such as the Belchertown pluton is therefore particularly valuable.

However, as is often the case with massive plutonic intrusions, there is no unambiguous method of ascertaining whether any tectonic rotation has occurred since the acquisition of magnetization. At best there may be slightly younger unconformably overlying sedimentary rocks, the present attitude of which may be inferred to indicate that of the pluton [Proko and Hargraves, 1973]. Unfortunately, no such younger sedimentary outliers are present within the Belchertown pluton.

Alternatively, a consistently oriented NRM vector in the pluton throughout a geographically large area may be considered to indicate that no significant internal differential tectonic rotation has occurred since its magnetization was acquired. Furthermore, if this measured vector is oriented in a direction parallel to the mean NRM vector for rocks of similar age, then no gross tectonic rotation would be implied.

The maximum separation of sample sites within the Belchertown pluton is approximately 4 km (Figure 1a). Whether the variation in orientation of remanent vectors between individual sites (Table 1 and Figure 3) is due to secular variation or to differential tectonic rotation of blocks within the pluton is not clear. There is no direct evidence for major faulting or folding within the pluton itself, although it is bounded on its western margin by a Triassic border fault (Figure 1a).

In Table 2 and Figure 9 the mean remanent vector for the Belchertown pluton is compared with the vectors appropriate to other Phanerozoic pole positions determined from rocks in North America. The Belchertown vector is far removed from those for Mesozoic and Cenozoic rocks, and in contrast to the Belchertown vector, all vectors for Paleozoic rocks have positive (north-seeking pole down) inclinations and somewhat more southerly declinations

TABLE 2. Mean Pole Positions for Phanerozoic Rocks of North America and Their Remanent Vectors Calculated for Belchertown, Massachusetts

Period	N	Pole Position Latitude	Pole Position Longitude	α_{95},deg	Remanent Vector* D,deg	Remanent Vector* I,deg
Plio-Pleistocene (P-p)	9	87.4°N	162.3°E	12.7	177.2	-59.9
Upper Tertiary (u-T)	13	86.9°N	192.9°E	2.6	175.8	-60.9
Lower Tertiary (l-T)	5	73.8°N	154.3°W	11.5	158.0	-61.4
Cretaceous (K)	11	65.9°N	174.7°W	5.8	151.5	-52.8
Jurassic (J)	4	86.8°N	96.4°E	12.4	180.0	-58.5
Triassic (Tr)	12	63.2°N	100.0°E	5.6	183.6	-29.3
Permian (P)	9	42.7°N	115.9°E	6.3	173.9	+9.3
Carboniferous (C)	14	35.6°N	126.8°E	4.6	164.2	+19.7
Devonian (Perry formation) (D)	4	29.4°N	119.0°E	9.6	169.6	+32.2
Silurian (Bloomsburg formation) (S)	1	32.0°N	102.2°E	...	184.9	+29.1
Cambrian (Є)	5	7.4°S	160.4°E	27.6	111.3	+51.4

Mean pole positions are taken from Irving and Park [1972]

*Vector calculated for Belchertown, Massachusetts (latitude, 42.3°N; longitude, 72.4°W). The remanent vectors are those plotted in Figure 9.

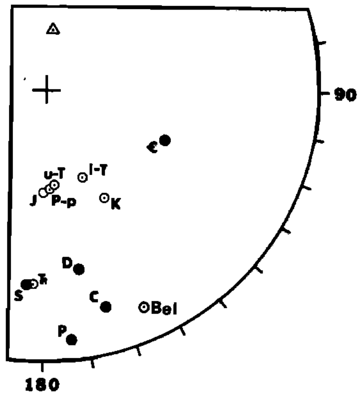


Fig. 9. Equal-area diagram comparing mean Belchertown remanent vector (Bel) with mean remanent vectors for Phanerozoic rocks from North America recalculated for the latitude and longitude of Belchertown, Massachusetts. Symbols are the same as in Table 2. Triangle is Creer's [1969] proposed Devonian pole equivalent to Belchertown, Massachusetts. Circles with dots are on upper hemisphere, and filled circles are on lower hemisphere.

(Figure 9). From this consistent difference a gross tectonic rotation of the pluton subsequent to its acquisition of magnetization is inferred. A northwestward rotation of the pluton by some 30°-60° about a horizontal N30°E axis would minimize the discrepancy between the measured Belchertown vector and the mean of the vectors from other Devonian rocks in North America. Further evidence for such rotation will be given in the next section.

In Figure 10 the pole corresponding to the mean remanent vector of the Belchertown pluton is compared with the Phanerozoic path of apparent polar wandering relative to North America [Irving and Park, 1972]. The Belchertown pole is distinctly removed from the mean Devonian pole and is also anomalous in relation to the postemplacement segment of the polar wandering path. This suggests that the pluton was not remagnetized subsequent to its emplacement.

The Belchertown vector is also far removed from the Devonian direction favored by proponents of the Permian remagnetization hypothesis (Figure 9). To bring these vectors into coincidence requires a northerly tectonic rotation of the pluton of greater than 90° about a roughly E-W axis, for which there is no supporting evidence.

Thus while the Belchertown paleomagnetic vector weighs against the remagnetization hypothesis, it does indicate that the pluton may have undergone up to 60° of northwestward rotation since its formation and is therefore not straightforwardly reliable as a Devonian paleomagnetic pole.

Geophysical Modeling

The magnetic anomaly observed over any isolated homogeneous body is a function of its three-dimensional shape and the vector sum of its induced (parallel to the earth's present field being equal to χH) and remanent magnetizations. Koenigsberger ratios ($Q = J_N/\chi H$) for the analyzed primary igneous rocks of the Belchertown pluton average 7.0 (Table 1). Given that the earth's field is approximately 0.5 G, the implication is that any magnetic anomaly observed over the pluton must be primarily due to the natural remanent magnetism of the rocks, with a negligible induced component (< 10%).

As we have determined the mean remanent vector, we can use the total field aeromagnetic anomaly recorded over the pluton (Figure 1b) [Gilbert et al., 1968a, b] to model a three-dimensional shape for its unaltered core. This is possible only because this central core of highly remanent material is completely surrounded by an outer zone of nonmagnetic metamorphic equivalents of the primary rocks and interference from magnetic country rocks is unlikely.

We have utilized a computer program written originally by Vine [1965] and modified somewhat by Campbell [1971a, b] which calculates a best fit magnetization vector, given the characteristics of the earth's present field at the location in question, digitized aeromagnetic data and a postulated three-dimensional shape for the body under consideration. Numerous models were attempted; however, the closest fit to the measured remanent vector is produced by a shallow (0.5 km) slab with a deeper (5 km) root under the broad aeromagnetic low southeast of the present surface exposure of primary igneous rocks (Figure 1b). Although this model applies only to the volume of unaltered igneous rocks, we assume that the regions of metamorphically altered rocks are more or less symmetrically disposed about the central core. A geologic cross section through the pluton

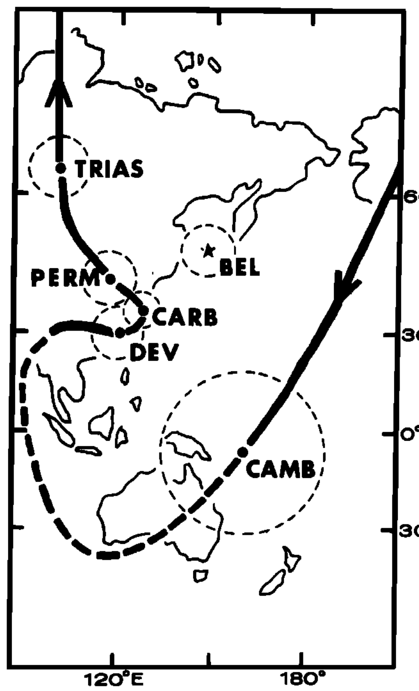


Fig. 10. Mercator projection comparing pole calculated for Belchertown pluton (BEL) with Phanerozoic apparent polar wandering curve relative to North America (taken from Irving and Park [1972]. Dashed circles are circles of 95% confidence (α_{95}).

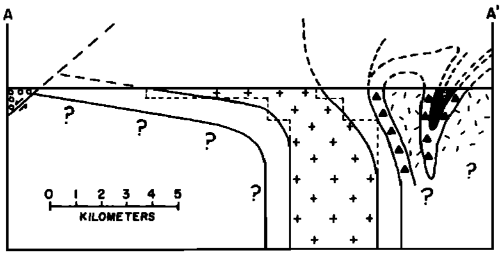


Fig. 11. Geologic cross section which is consistent with computer-derived three-dimensional model of the pluton (dashed lines). Symbols are the same as in Figure 1 except that outer and transition zones of the pluton are combined.

which is consistent with our modeling is shown in Figure 11. This model could be considered to indicate that the Belchertown pluton was once roughly a vertically symmetrical funnel-shaped intrusion and that it has been tectonically rotated between 30° and 60° to the northwest about a NE-SW axis.

The modeling of the shape of the Belchertown pluton is thus consistent with the amount and direction of tectonic rotation implied by comparing the measured remanent vector with other lower Paleozoic paleomagnetic data. Also possibly compatible with the proposed model is the outcrop pattern of primary rocks and their metamorphic equivalents (Figure 1a); contacts are closely spaced near the southern portion, where the pluton is nearly vertical, and are more widely separated in the northern and western portions, where the pluton is inferred to be more gently inclined (Figure 11). The proposed rotation may also explain certain structural features of the surrounding country rocks; for example, the northern tip of the Glastonbury dome and its mantling Paleozoic metasedimentary rocks form an anticlinal structure which plunges toward the northwest (Figure 1a) [Hall, 1973]. This represents a rather abrupt change in trend from north to northwest, which may be interpreted as a result of the proposed northwesterly rotation of the pluton. The Great Hill syncline, which is overturned toward the east along the entire eastern flank of the Glastonbury done, changes in orientation and is overturned toward the west along the eastern margin of the Belchertown pluton (Figure 1a) [Peper, 1967]. This may also be a result of northwesterly tectonic rotation.

Summary

A paleomagnetic study of primary quartz monzodiorites from the Belchertown pluton indicates the presence of a strong, stable, and consistently oriented remanent vector with a high Q value. From microscopic observations and magnetic measurements it appears that the remanence resides in accessory titano-hematite and magnetite mineral grains and in submicroscopic dustlike inclusions of magnetite and titanohematite within plagioclase grains. The remanence of these phases is a thermal and/or thermochemical RM acquired upon initial cooling of the pluton. In contrast, recrystallized equivalents of the primary rocks, metamorphosed during the Acadian orogeny, yield weak and inconsistent results due to the absence of opaque minerals.

Comparison of the mean remanent vector of primary quartz monzodiorites with other Devonian paleomagnetic poles from North America shows the measured vector to be discordant in such a direction as to suggest that the entire pluton has undergone considerable tectonic rotation to the northwest. The measured NRM vector is thus not reliable as a Devonian paleomagnetic pole.

Because of the high Q value of the primary rocks and their isolation from magnetic country rocks by surrounding recrystallized equivalents, the measured NRM vector can be used with the known total field aeromagnetic anomaly to model their three-dimensional shape by using standard computer techniques. The resulting model is also consistent with tectonic rotation of a once roughly vertically symmetrical funnel-shaped intrusion by some 30°-60° to the northwest about a NE-SW axis.

Supporting geologic evidence for the rotation hypothesis comes from the outcrop pattern of primary igneous rocks and their metamorphic equivalents and also from structural features within the pluton and in surrounding country rocks.

Acknowledgments. This study was supported by NSF grant GA 41699 to R. B. Hargraves. The samples were obtained under the guidance and assistance of Peter Robinson and C. A. Lawson. All magnetic measurements were made at the Rock Magnetism Laboratory at Princeton University by Naoma Dorety. W. E. Bonini provided advice and assistance with the computer modeling aspects.

References

Ashwal, L. D., Metamorphic hydration of augite-orthopyroxene monzodiorite to hornblende granodiorite gneiss, Belchertown batholith, west-central Massachusetts, M.S. thesis, 117 pp., Univ. of Mass., Amherst, 1974.

Ashwal, L. D., P. Robinson, and R. J. Tracy, Metamorphic hydration of two-pyroxene monzodiorite to hornblende granodiorite gneiss, Belchertown batholith, Massachusetts (abstract), Eos Trans. AGU, 55, 450, 1974.

Balsley, J. R., and A. F. Buddington, Iron-titanium oxide minerals, rocks, and aeromagnetic anomalies of the Adirondack area, New York, Econ. Geol., 53, 777-805, 1958.

Campbell, B. S., A manual for Prism 111: A program to compute magnetic anomalies and vectors for three dimensional bodies, Geol. Eng. Rep. 71-2, 44 pp., Princeton Univ., Princeton, N. J., 1971a.

Campbell, B. S., Analysis of a computer program for the computation of paleomagnetic vectors from aeromagnetic data in three-dimensional rock bodies, Geol. Eng. Rep. 71-3, 43 pp., Princeton Univ., Princeton, N. J., 1971b.

Creer, K. M., The use of the sun compass, in Methods in Paleomagnetism, edited by

D. W. Collinson, K. M. Creer, and S. K. Runcorn, pp. 11-15, Elsevier, New York, 1967.

Creer, K. M., Paleozoic palaeomagnetism, Nature, 219, 246-250, 1968.

Creer, K. M., Comments on paper by J. L. Roy, N. D. Opdyke, and E. Irving, 'Further paleomagnetic results from the Bloomsburg formation,' J. Geophys. Res., 74, 3299-3302, 1969.

Doell, R. R., and A. Cox, Paleomagnetic sampling with a portable coring drill, in Methods in Paleomagnetism, edited by D. W. Collinson, K. M. Creer, and S. K. Runcorn, pp. 21-25, Elsevier, New York, 1967.

Gilbert, F. P., P. Popenoe, and P. W. Philbin, Aeromagnetic map of the Ludlow quadrangle, Hampden and Hampshire counties, Massachusetts, Geophys. Invest. Map GP-619, U. S. Geol. Surv., Reston, Va., 1968a.

Gilbert, F. P., P. Popenoe, and P. W. Philbin, Aeromagnetic map of the Palmer quadrangle, Hampden, Hampshire, and Worcester counties, Massachusetts, Geophys. Invest. Map GP-617, U. S. Geol. Surv., Reston, Va., 1968b.

Guthrie, J. O., Geology of the northern portion of the Belchertown intrusive complex, Contrib. 8, 109 pp., Dep. of Geol., Univ. of Mass., Amherst, 1972.

Hall, D. J., Geology and geophysics of the Belchertown batholith, west-central Massachusetts, Ph.D. thesis, 110 pp., Univ. of Mass., Amherst, 1973.

Hall, D. J., Integrated geophysical analysis of the Belchertown batholith, western Massachusetts and the meaning of vertical contacts (abstract), Geol. Soc. Amer. Abstr. Programs, 7(7), 1095, 1975.

International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks, Plutonic rocks: Classification and nomenclature recommended by the IUGS Subcommission on the Systematics of Igneous Rocks, Geotimes, 18(10), 26-30, 1973.

Irving, E., and N. D. Opdyke, The paleomagnetism of the Bloomsburg red beds and its possible application to the tectonic history of the Appalachians, Geophys. J. Roy. Astron. Soc., 9, 153-167, 1965.

Irving, E., and J. K. Park, Hairpin and superintervals, Can. J. Earth Sci., 9, 1318-1324, 1972.

LaRochelle, A., Adaptation of an astrocompass for collection of oriented rock specimens, Top. Rep. 32, 4 pp., Geol. Surv. Can., Ottawa, Ont., 1961.

McElhinny, M. W., Theory and operating procedures; Rock magnetism instruments at Princeton University, Geol. Eng. Rep. 63-1, 24 pp., Princeton Univ., Princeton, N. J., 1963.

McElhinny, M. W., Paleomagnetism and Plate Tectonics, 358 pp., Cambridge University Press, New York, 1973.

McElhinny, M. W., and N. D. Opdyke, Remagnetization hypothesis discounted: A paleomagnetic study of the Trenton limestone, New York State, Geol. Soc. Amer., Bull., 84, 3697-3708, 1973.

Morgan, G. E., Paleomagnetism of a slowly cooled plutonic terrain in western Greenland, Nature, 259, 382-385, 1976.

Nagata, T., Rock Magnetism, 350 pp., Maruzen, Tokyo, 1961.

Peper, J. D., Stratigraphy and structure of the Monson area, Massachusetts and Connecticut, Guidebook for Field Trips in the Connecticut Valley of Massachusetts, pp. 105-113, New England Intercollegiate Geological Conference, Amherst, Mass., 1967.

Phillips, J. D., A thermal demagnetization device, Geol. Eng. Rep. 64-3, 35 pp., Princeton Univ., Princeton, N. J., 1964.

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

Thompson, J. B., Jr., P. Robinson, T. N. Clifford, and N. J. Trask, Jr., Nappes and gneiss domes in west-central New England, in Studies of Appalachian Geology-Northern and Maritime, edited by E. Zen, W. S. White, J. B. Hadley, and J. B. Thompson, Jr., pp. 203-218, John Wiley, New York, 1968.

Vine, F. J., Interpretation of magnetic anomalies observed at sea, Ph.D. thesis, Cambridge Univ., Cambridge, England, 1965.

(Received May 18, 1976;
revised August 23, 1976;
accepted September 28, 1976.)