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Paleomagnetism of Ordovician alkalic intrusives and host rocks from the Pedernal Hills, New Mexico: positive contact test in remagnetized rocks?

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Abstract

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A set of thin dikes from central New Mexico, dated at 469 ± 7 Ma (Rb–Sr; Loring and Armstrong, 1980), have yielded a virtual geomagnetic pole which lies on the Late Paleozoic segment of the North American apparent polar wander path. The remanence of the dikes appears to be a product of Late Paleozoic hydrothermal alteration. Paradoxically, however, the magnetization of the host rocks is most simply explained in terms of a positive contact test. Samples collected between 0.2 and 0.5 dike-widths from the contact contain a component of remanence parallel to the magnetization in the dikes, with unblocking temperatures which decrease with distance from the dikes. Host rocks from a distance of more than 1 dike-width show no evidence of the characteristic dike magnetization.

There are two possible resolutions of this paradox: (1) the magnetization of the host rocks is secondary, despite the apparent positive contact test, and is a product of hydrothermal fluid migration through the dikes or along the contact zones; or (2) the magnetization of the dikes is primary, but not representative of the Ordovician paleofield for North America. Possible reasons for inaccurate representation include: (a) incomplete averaging of secular variation; (b) tectonic rotation with respect to the stable craton; or (c) erroneous age determination for the rocks. We argue that explanation (1) is the most likely.

Introduction

Parallelism of directions of magnetization in intrusive rocks and adjacent much older host rocks is conventionally considered to constitute a positive contact test, that is, evidence for acquisition of thermoremanent magnetization (TRM) during cooling immediately after intrusion (Everitt and Clegg, 1962). The test is considered particularly robust when the characteristic remanence of the intrusive is observed as an overprint on an original remanence in the host, with unblocking temperatures that decrease with distance from the contact (e.g., McElhinny, 1973). However, it is possible under certain circumstances for a similar pattern of magnetic overprinting to arise at a later time through chemical alteration related to hydrothermal activity. The mechanics of dike emplacement favor injections into pre-existing fractures, and intrusion further fractures and brecciates the contact zone (Pollard, 1985), which may then provide a path for later hydrothermal fluid migration. Chemical remanent magnetization (CRM) overprints due to hydrothermal alteration along the contact zones or more pervasively have been reported by a number of workers (e.g., Schutts et al., 1976; Buchan, 1978; Schutts and Dunlop, 1981; Lynnes and Van der Voo, 1984; Halls, 1986). In

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this paper we report an apparent positive contact test for some Paleozoic intrusives from New Mexico, which we attribute to localized remagnetization related to late Paleozoic hydrothermal fluid migration.

Geology and sampling

Alkalic intrusive rocks of Cambrian-Ordovician age occur in a number of localities in Colorado, Oklahoma, and New Mexico (Olson et al., 1977; Loring and Armstrong, 1980; Larson et al., 1985). The syenitic rocks of central New Mexico which are the subject of this study crop out about 100 km east-southeast of Albuquerque, in the Pedernal uplift (Fig. 1), and have been described by Loring and Armstrong (1980). Three thin trachytic dikes in the Pedernal Hills and a stock at Lobo Hill consist of a distinctive brick-red syenite and intrude lower greenschist facies quartz–sericite and quartz–chlorite schists of the Precambrian Torrance Metamorphic Group (Muehlberger et al., 1966; Foster et al., 1972; Grambling, 1986). The dike rocks are unfoliated and unmetamorphosed, but the host rocks exhibit a well-developed foliation, generally parallel to the dikes.

Both the intrusives and the adjacent host rocks show signs of alteration and secondary mineralization. Petrographically the syenite consists of approximately 60–70% alkali feldspar, partially replaced by very fine clay minerals; 10% quartz; and 2% opaque minerals, predominantly hematite with minor magnetite (Loring and Armstrong, 1980). The iron oxides occur both as finely disseminated grains and in a pattern resembling an amphibole crystal habit, suggesting an origin by replacement of hornblende (Loring and Armstrong, 1980). Other secondary minerals include sericite, calcite, and siderite.

Rb–Sr measurements reported by Loring and Armstrong (1980) on four whole-rock samples of the Pedernal Hills syenite indicated a maximum possible age of 496 Ma, assuming a minimal initial $^{87}Sr/^{86}Sr$ ratio of 0.703. When data for the Lobo Hill syenite stock (25 km to the northwest) were included, an isochron age of 469 ± 7 Ma was obtained (Loring and Armstrong, 1980). The Pedernall Hills dikes are thus probably of middle Ordovician (Cincinnatian) age (Van Eysinga, 1975; Harland et al., 1982). The Precambrian host rocks of the Pedernal Uplift were metamorphosed at about 1400 Ma (Grambling, 1986).

Samples were collected from three localities: (a) a pair of dikes separated by 20–30 m; (b) a third dike approximately 4 km to the south; and (c) the Lobo Hill stock. The dikes range in width from 1 to 5 m and crop out over a length of about 1.5 km. Surface exposures are somewhat weathered at all of the localities, but relatively fresh rock was accessible for sampling at the northern Pedernal Hills locality in a series of excavated exposures 2 to 3 m deep. It was from these excavations that

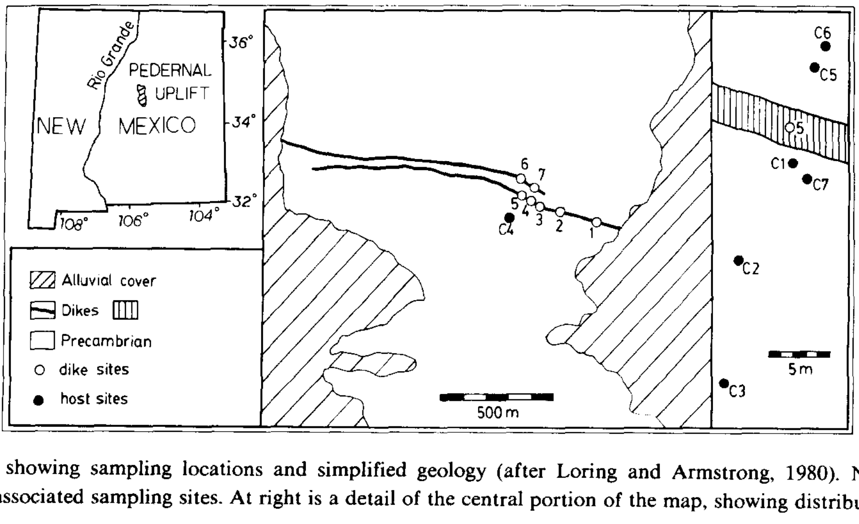

Fig. 1. Index map showing sampling locations and simplified geology (after Loring and Armstrong, 1980). Not shown are the southern dike and associated sampling sites. At right is a detail of the central portion of the map, showing distribution of sites in the host rock.

the petrographic and isotopic samples of Loring and Armstrong were obtained. Both drill cores and hand samples, oriented with a Brunton compass, were collected from seven sites in the northern dikes, five in the excavated pits (Fig. 1). In addition, oriented drill cores were collected from seven sites in the host rock near the northern dikes, at respective distances of 1, 2, 5, 6, 10, 20, and 100 m from the dike contact. Samples from the Lobo Hill intrusion and from the southern dike and its associated host rocks contained unstable magnetizations with no directional consistency; we will not consider these further.

Methods

Following measurement of the natural remanent magnetization (NRM) of the dikes and host rocks, all samples were subjected to stepwise demagnetization by alternating-field (AF) or thermal methods. Collinear and coplanar segments of the demagnetization trajectories were isolated by visual inspection of orthogonal vector projections (Zijderveld, 1967) and stereographic projections. Directions were determined by principal component analysis (Kirschvink, 1980) and means were computed using the method of Bailey and Halls (1984).

Several rock magnetic experiments were performed in order to characterize the remanence carriers. Isothermal remanent magnetization (IRM) was imparted in a stepwise manner to a number of samples of the dike and host rocks, using an electromagnet, up to a peak field of 1.4 T. Thermomagnetic analysis of magnetic separates from several dike and host samples was performed with a horizontal Curie balance. Modified Lowrie-Fuller tests (Johnson et al., 1975) were performed in order to elucidate the domain state of magnetites in the host rock.

Results

Paleomagnetism

Dike rocks

The NRM directions for the dike rocks were rather strongly dispersed, with a shallow southeasterly mode (Fig. 2). The shallow directions were obtained mostly from samples collected from excavated exposures, while for natural outcrop samples there was no consistent grouping of NRM directions. Overall, there was a rough planar structure, with the majority lying in a near-vertical NW–SE plane.

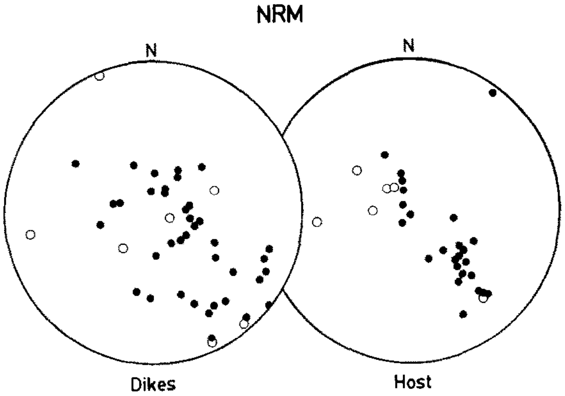

Fig. 2. Equal area projections of NRM directions from the northern Pedernal Hills dikes (left) and host rocks (right). Open symbols are projections on the upper hemisphere, closed on lower. Directions are not corrected for tilt.

Stepwise demagnetization of the samples with shallow southeasterly NRM's showed univectorial magnetizations (Fig. 3a). AF treatments up to 80 mT had virtually no effect on these samples. Thermal cleaning showed a distributed unblocking temperature spectrum, with about 40% of the magnetization remaining above 600 ° C.

Samples from the natural outcrop sites all exhibited either non-linear demagnetization trajectories, or linear trajectories bypassing the origin, indicating incomplete determination of two or more components of magnetization (Fig. 3b). This was true for both thermal and AF demagnetization methods. In contrast to the excavated sites, samples from the natural outcrop sites often had a substantial component removable by AF cleaning to 80 mT. Unblocking temperatures for these samples also extended up to 675 ° C, but even then the characteristic shallow southeasterly direction could not be cleanly recovered. In stereographic projection the demagnetization trajectories for these samples defined great circle paths, mostly with Maximum Angular Deviation (MAD) values (Kirschvink, 1980) of less than 15 °, or Q values

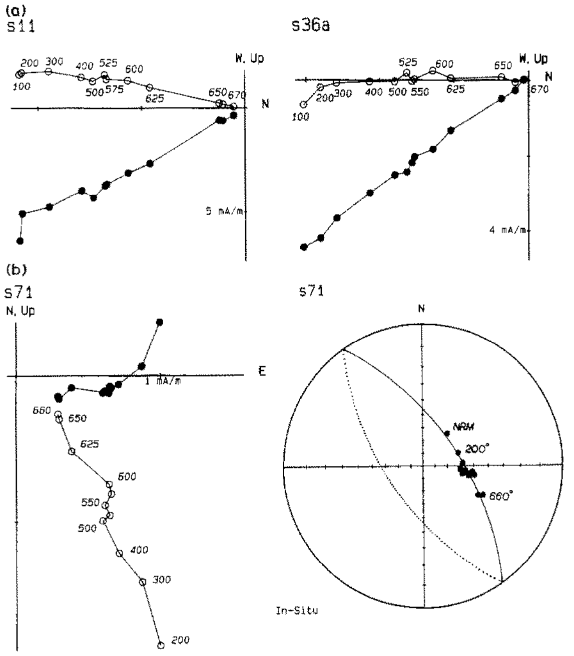

Fig. 3. Orthogonal vector diagrams (Zijderveld, 1967) showing results of stepwise thermal demagnetization of dike samples. Solid circles represent successive positions of the magnetization vector endpoint, projected onto the horizontal plane; open circles are projections on the vertical plane. a. Univectorial decay of remanence in samples from excavated exposures. b. Remanence does not decay toward the origin but follows a great circle trajectory due to unresolved dual-component remanence.

(Halls, 1976, 1978) of less than 10^{-5} (Fig. 3b).

The directions of the univectorial magnetizations cluster well in a shallow southeasterly direction, and the poles to the individual great circles fall along the plane normal to the characteristic direction (Fig. 4). Most of the great circle poles lie about 90° from the present-day field (PDF) direction. These samples contain the characteristic magnetization as well as a PDF component, with strongly overlapping stability spectra for thermal and AF cleaning methods. Site mean directions (Fig. 4C, Table 1) were computed using both great-circle and stable endpoint data by the method of Bailey and Halls (1984). For site 7 we calculated a site-mean great circle pole, since the individual sample poles all clustered together. The mean of the seven site means is $D/I = 147°/4°$, $k = 310$, $\alpha_{95} = 3.6°$, without tilt correction.

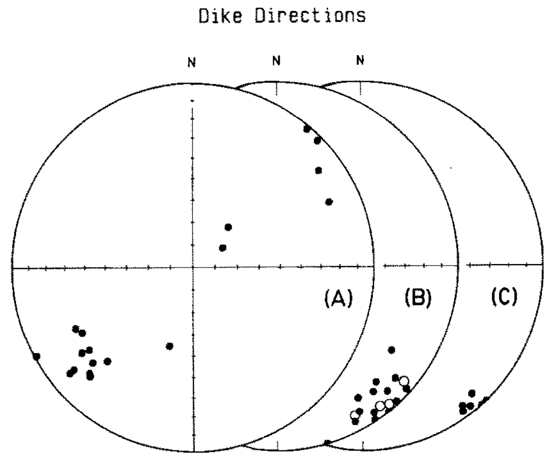

Fig. 4. Summary of magnetic directions isolated in dike samples. A. Poles to great-circle paths of individual samples define a clear girdle distribution around a southeasterly horizontal axis. B. Univectorial sample directions. C. Site means, computed by the method of Bailey and Halls (see text). For site 7, a site mean great-circle pole was computed (not shown).

Pole position

The Permian strata which crop out in a belt around the Pedernal Hills are nearly horizontal, but there is evidence from subsurface data for tilting of older units. Foster et al. (1972) analyzed abundant well-log data from east-central New Mexico, and concluded that the regional basement consists of fault-bounded blocks which were tilted in late Paleozoic time. They mapped a fault 30 km east of the Pedernal Hills, trending north-northwest. Structural contours on the Precambrian surface parallel the fault and the surface has an average dip of 7° to the east. The oldest sediments on the Pedernal block are Mississippian and Pennsylvanian; the top of the Pennsylvanian dips about 5° to the east. With no tilt correction, the Pedernal Hills pole falls at 42°N, 121°E, with $dp = 1.8°$, $dm = 3.6°$. A 7° tilt correction is required if the magnetization is older than Pennsylvanian, and yields a D/I of 147°/0° and a pole position of 43°N, 123°E (Fig. 5). This is not significantly different from the pole from the trachyte dikes of the McClure Mountain Complex (Lynnes and Van der Voo, 1984).

Host rocks

NRM directions of samples collected near the

TABLE 1

Site mean directions for the syenite dikes

Site	Mean D/I	N	k	α_{95}
1	151/4	6	40	12
2	150/7	6	41	12
3	148/4	5	100	8
4	145/9	4	11	40
5	143/0	5	22	24
6	145/0	5	713	6
7 *	239/25	4	65	16
Mean	147/4	7	310	3.6

Directions not corrected for tilt. D/I: declination (°)/inclination (°); k: precision parameter; α_{95}: radius of 95% confidence.

* Site-mean great-circle pole.

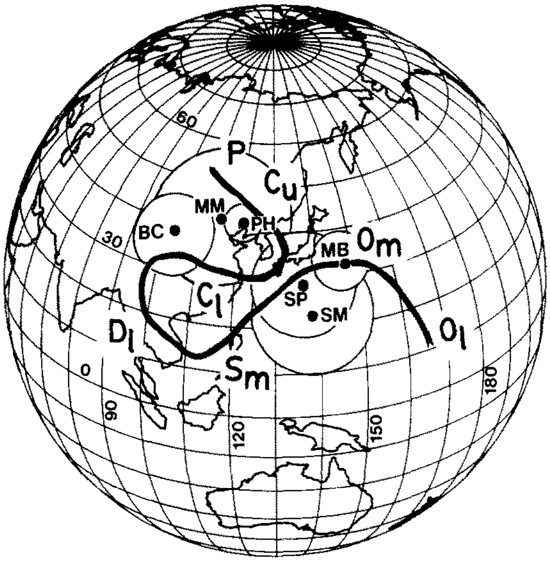

Fig. 5. Orthographic projection of pole positions discussed in text: *BC*—Black Canyon dikes, Colorado; *MM*—McClure Mountain dikes, Colorado; *MB*—Moccasin-Bays formation, Tennessee; *PH*—Pedernal Hills dikes (this study); *SM*—Steel Mountain anorthosite, western Newfoundland; *SP*—St. Peter sandstone, Wisconsin. Circles of 95% confidence are shown for each pole. Apparent polar wander path from Van der Voo (1987).

northern dikes show a well-defined great-circle distribution (Fig. 2), suggesting that the remanence is dominated by the same two components that we observed in the dike rocks: a PDF overprint and a shallow southeasterly component. The distribution of directions within the plane is strongly related to distance from the dike margin, y. Samples from site C1 ($y = 1$ m) clustered very close to the dike characteristic direction, though somewhat steeper. NRM directions become progressively steeper, and intensities generally higher, with distance from the contact.

Stability of the remanence against thermal and alternating-field (AF) demagnetization also varied strongly with distance. For the two sites closest to the dike, C1 ($y = 1$ m) and C7 ($y = 2$ m), AF demagnetization to peak fields of 100 mT caused a slight shallowing of the remanence direction but left 90% of the intensity remaining. Figure 6 shows the typical behavior of samples from sites C1 and C7 during thermal demagnetization. We can identify four components of remanence. A northerly downward component (A), which we interpret as a Brunhes age viscous overprint, is removed by 270° to 300°C in each case. A shallow southeasterly component (B), parallel to the characteristic direction from the dikes, is removed next, with maximum T_{ub}'s of approximately 450° to 500°. The contact test for the dike magnetization depends upon the origin of this component, which we discuss below.

Subsequent behavior of these samples is rather unusual. A northwesterly component (C), often nearly antiparallel to the characteristic dike remanence, is removed up to temperatures of about 560° to 590°. Such behavior might be ascribed to chemical/mineralogical changes produced during laboratory heating, but a number of factors argue against such an origin in this case. First, there is no significant difference observed in anhysteretic susceptibility or IRM acquisition between heated and unheated samples. Second, the orientation of the C component is not systematic in sample coordinates, as would be expected if it were a spurious TRM acquired due to a residual magnetic field in the demagnetizing furnace. It is reasonably inconsistent in geographic coordinates (northwesterly and up). Third, several AF-demagnetized samples also show evidence of the C component, and therefore it cannot be attributed to "self-reversal" on cooling during thermal treatment.

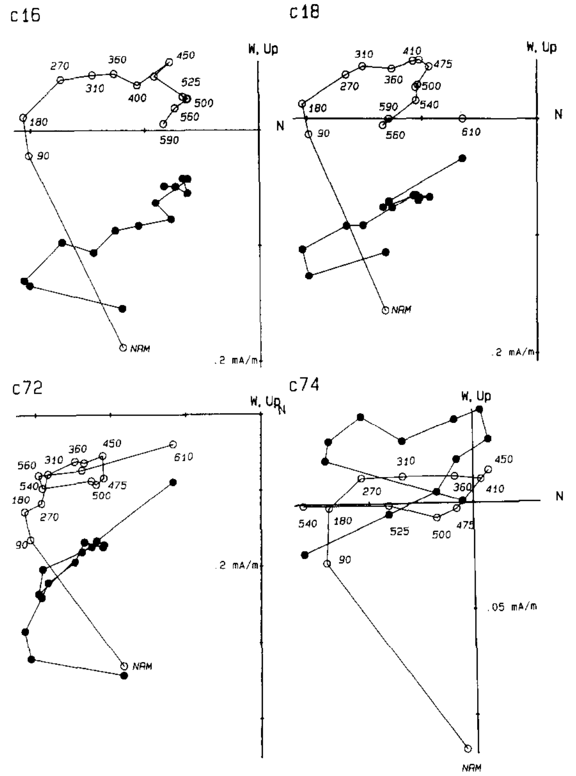

Fig. 6. Thermal demagnetization of samples from sites C1 (top) and C7 (bottom), showing multivectorial remanence decay. A component parallel to the dike characteristic remanence is unblocked by 475° to 500°C in C1 samples, and by about 450° in C7 samples. This component was probably acquired by thermal processes related to dike intrusion. A parallel component of probable thermochemical origin is unblocked above 560° to 590°.

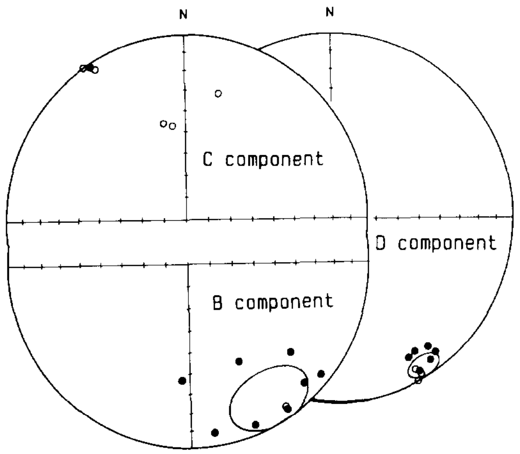

Fig. 7. Characteristic components of magnetization from sites C1 and C7 in the host rock. The B and D components closely parallel the dike characteristic direction, while the C component is often nearly antiparallel. The B component unblocks at temperatures up to 450° to 500°C, the C component up to about 580°, and the D component above 580°.

TABLE 2

Host mean directions

Component	Mean D/I	N	k	α_{95}
B	149/15	9	12	15
D	148/6	9	81	6

Data from thermal demagnetization of sites C1 and C7 (combined).

The final component (D) is parallel to the B component and to the dike characteristic direction. It is typically unblocked at temperatures above 590°, and clearly resides in hematite. Mean directions for the B and D components are virtually identical to the dike characteristic remanence (Fig. 7, Table 2). We attribute the higher dispersion of the B component to its lower intensity and in some cases to partial contamination by the A component. The distribution of C component directions is distinctly elongate, so it is inappropriate to compute a mean. We note, however, that the C directions tend to be antiparallel to those of the B and D components. We discuss this further below.

Samples from the other host rock sites ($y > 2$ m) behaved in a generally erratic and inconsistent manner during cleaning. As previously mentioned, these sites had substantially higher NRM intensities than the sites close to the dikes. The stability of the NRM to AF and thermal cleaning was also much lower. The large, soft, steeply-inclined component dominating the NRM of these sites generally made it impossible to recognize any higher-stability components. One sample each from site C2 ($y = 10$ m), C3 ($y = 20$ m) and C4 ($y = 100$ m) followed great-circle trajectories toward the dike characteristic direction. The latter two samples nearly reach an endpoint near the dike characteristic direction at temperatures above 600°C. However, other samples from these sites followed divergent great-circle trajectories, and we conclude that the dike characteristic remanence is not present at distances of about 1 dike-width or more.

Rock magnetism

Dike rocks

IRM acquisition curves (Dunlop, 1972) for samples of the dikes show a smooth increase in IRM in applied fields up to 1.4 T. Samples remain unsaturated at the maximum available field. This behavior, in conjunction with the thermal demagnetization characteristics, indicates that the remanence of these samples resides dominantly in hematite. Thermomagnetic curves consistently show an inflection at about 575 ° C, indicating the presence of minor magnetite as well.

Host rocks

The host rocks appear to contain both magnetite and hematite in variable amounts. IRM acquisition curves exhibit two types of behavior (Fig. 8a). Several samples approached saturation remanence at 0.2 to 0.3 T, indicating that the remanence resides dominantly in magnetite. Other samples show evidence of both magnetite and hematite, as the curves rise rapidly up to 0.2 T and then continue to rise at a much lower rate up to the maximum applied field. Thermomagnetic analysis confirms the presence of magnetite and hematite, and indicates that the magnetite is titanium-poor, with Curie temperatures between 565 ° and 580 ° C. IRM acquisition characteristics varied considerably within each site, and are not systematically related to distance from the dikes. The relative proportions of magnetite and hematite thus do not correlate with distance. IRM decay patterns, on the other hand, show the same relation to distance as NRM decay, namely a general decrease in stability with distance (Fig. 8b). This is probably related to increasing grain sizes away from the dikes (Dunlop, 1981, 1986; Dankers, 1981). However, decay of anhysteretic remanent magnetization (ARM) followed IRM decay precisely in almost all cases; the Lowrie-Fuller test (Johnson et al., 1975) thus shows no evidence of any systematic variation in domain state with distance.

In view of the strong foliation of the host rocks, anisotropy of anhysteretic susceptibility (AAS; McCabe et al., 1985) was measured for several host samples. The magnetic fabric is strongly planar and coincides with the macroscopic foliation, roughly parallel to the dikes (striking E–W, dipping 45 ° to 60 ° S). There is a tendency for the host NRM directions to lie in or near the plane of foliation (Fig. 2), suggesting partial control of the remanence directions by the fabric. However the behavior during stepwise demagnetization (Fig. 6) shows little evidence of this; instead the NRM directions are seen to result from superposition of the PDF component on the shallow southeasterly characteristic remanence components.

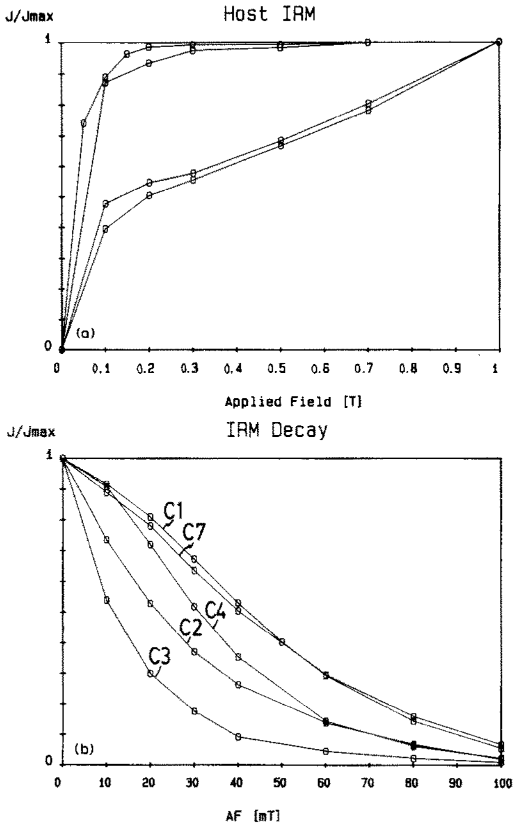

Fig. 8. a. Acquisition of isothermal remanent magnetization by host rock samples shows two patterns. Some approach saturation by 0.2 T, indicating magnetite as the sole important remanence carrier. Others continue to acquire IRM in fields up to 1 T, indicating an additional, higher-coercivity carrier, in this case hematite. The occurrence of hematite was not spatially related to the dikes. b. AF demagnetization of IRM acquired in 0.1 T, showing much higher stability in sites near the dikes.

Foliations $(F=[\frac{1}{2}(k_{\max}+k_{\mathrm{int}})-k_{\min}]/k_{\mathrm{mean}})$ range from approximately 30% to 50%, with lineation/foliation ratios much less than 1. From this we can calculate a maximum expected deviation of remanence from the ambient field direction of about 15°, rotated toward the foliation. This may account in part for the steeper inclinations of the B and C components in some samples. However the AAS results may not be representative of the fabric of the remanence-carrying grains, because the maximum AF available for the AAS experiments was 30 mT. As previously mentioned, the AF stability spectrum of the natural remanence was largely above 100 mT. Further, the A component exhibits little or no deviation due to the foliation. Therefore we believe that in general the foliation probably does not significantly affect the remanence.

Discussion

Origin and age of magnetizations

Dikes

Where present (mostly in surface samples), the PDF overprint has a T_{ub} spectrum extending all the way up to 675°C. We conclude that it is dominantly a chemical remanent magnetization (CRM) residing in hematite of recent origin. The strong overlap of coercivity and blocking temperature spectra for the characteristic magnetization and the PDF overprint suggests that the dike characteristic remanence is also carried by secondary hematite. This is consistent with the observation of Loring and Armstrong (1980) that the hematite is of secondary origin. However, it is not clear whether the alteration is deuteric or due to a later hydrothermal event. The pole position we have obtained is quite close to the one for the trachyte dikes of the McClure Mountain Complex, Colorado (43° N, 114° E), which was attributed by Lynnes and Van der Voo (1984) to late Paleozoic remagnetization, based on: (1) K–Ar dates as young as 300 Ma, (2) hematite as the sole remanence carrier and (3) the proximity to the late Paleozoic portion of the APWP. The similarity in direction of magnetization to the rocks studied by Lynnes and Van der Voo (1984) suggests that the remanence of the Pedernal Hills dikes may be a record of the same late Paleozoic remagnetization event.

Host rocks

On the other hand, the observed T_{ub} ranges of the B component are broadly compatible with a thermal-pulse origin, related to dike intrusion. Standard thermal conduction calculations (Jaeger, 1964; Turcotte and Schubert, 1982) indicate peak temperatures for site C1 of about 400°C. According to McClelland-Brown (1982) the corresponding T_{ub}'s for magnetite and hematite extend up to about 450° and 475° respectively, in reasonable agreement with our observed T_{ub}'s. The substantial southeasterly D component which is unblocked above 560° to 590°, however, cannot be accounted for by thermal overprinting by the dikes, although a thermochemical origin is clearly possible.

The age and origin of the C component are difficult to constrain. If the B and C components are both carried dominantly by magnetite, the C magnetization most likely predates the B, because activation of a discrete high T_{ub} window without resetting of the B magnetization seems improbable. The C component does not appear to date from the time of metamorphism; expected directions from the APWP of Van der Voo (1981) are northeasterly to easterly from 1450 to 1200 Ma. If the D component is of thermochemical origin and coeval with B, as suggested, its T_{ub} range probably overlaps with the C range. The true direction of the C component is therefore more nearly antiparallel to B and D than it appears in Figs. 3 and 7, and it may therefore be of approximately the same age. This would imply that all three components record the same event, which would have to be of sufficient duration to include a field reversal.

The steeply-inclined remanence of the sites at $y > 2$ m is actually rather close to an expected direction for several time periods in the 1450–1200 Ma interval. However, in view of the low stability of the remanence in these sites it is more reasonable to conclude that the remanence of these more distant sites is geologically young.

Implications

The pole position we have obtained from the Pedernal Hills dikes falls in an area occupied by late Paleozoic as well as late Ordovician–Silurian poles (Van der Voo, 1987). However, if the age determination of Loring and Armstrong (1980) is correct, it is appropriate to compare our results with middle Ordovician paleopoles. The middle Ordovician Moccasin-Bays pole of Watts and Van der Voo (1979) lies at 33° N, 147° E, approximately 22° away from the Pedernal pole (Fig. 5). The Moccasin-Bays pole is supported by a result from the St. Peter sandstone (Eckert, 1984) and by an overprint from the Steel Mountain anorthosite, from which a K–Ar age of 451 Ma has been obtained (Murthy and Rao, 1976). We can offer several possible explanations for the discrepancy between the Pedernal pole and middle Ordovician paleomagnetic poles. These involve (1) errors in the pole position, due to (a) incomplete averaging of secular variation or (b) block rotations; or (2) an age for the remanence younger than Ordovician, because of (a) erroneous age assignment to the rocks, or (b) remagnetization caused by a hydrothermal event.

Early Paleozoic paleomagnetic data for North America (Van der Voo, 1987) indicate equatorial paleolatitudes during Cambrian and Ordovician time; tectonic motion of the plate was dominantly a counterclockwise rotation with respect to the paleomeridian. However, there remains a good deal of uncertainty in the history of rotation over this interval. Larson et al. (1985) proposed that the early Paleozoic counterclockwise rotation of North America was essentially complete by the end of the Cambrian, and that APW for the rest of the Paleozoic was quite minor. The Pedernal result is consistent with this; however we disagree with this hypothesis because of the occurrence of reliable late Cambrian through middle Ordovician poles farther southeast (Van der Voo, 1987).

Thermal conduction models of dike cooling (Jaeger, 1964) indicate that a dike less than 5 m wide will solidify and cool in a time which is much too short to average out secular variation (McElhinny and Merrill, 1975). Therefore, if the magnetization of the dikes was acquired during initial cooling by either thermal or chemical mechanisms, the mean direction does not represent a time-averaged estimate of the paleomagnetic field. A 22° difference between observed and expected declinations could be accounted for in this way, but we regard the probability of this as rather low. For the 1980 IGRF, only about 10% of the area between latitudes ±20° has declinations of ±15° or more. If the Ordovician paleofield resembled the modern field, we can estimate that the probability of random sample encountering a declination greater than +15° at low latitudes is only about 5%. The close proximity of the Pedernal Hills pole to the Late Paleozoic segment of the APW path is more likely an indication that the remanence is younger than Ordovician. We return to this point below.

Steiner (1986) has noted a systematic clockwise rotation of as much as 10° to 15° in pre-Jurassic rocks of the Colorado plateau, when compared with coeval rocks from the rest of the craton. Although this must be treated cautiously (Bryan and Gordon, 1986), it may account for some of the difference. Rotations on a smaller scale are difficult to rule out entirely as well.

We also note the possibility of error in the age determinations for both the rocks and the remanence. The isochron determined by Loring and Armstrong (1980) relies heavily on data added from the Lobo Hill stock, 25 km northwest of the Pedernal Hills. Although it seems likely that these intrusives are indeed co-magmatic, it is possible that they are not. When the Lobo Hill measurement is excluded, the possibility of younger ages is admitted. Isotopic data from the Pedernal Hills alone are somewhat discordant (Loring and Armstrong, 1980).

Finally, if the northern Pedernal Hills dikes or their contact zones provided a conduit for late Paleozoic hydrothermal fluid migration, similar to that postulated for the McClure Mountain dikes by Lynnes and Van der Voo (1984), it is likely that this affected the magnetization at sites C1 and C7. Magnetic mineralogy is known to be quite sensitive to hydrothermal alteration (Ade-Hall et al., 1971; Merrill, 1975; Studemeister, 1983; Criss and Champion, 1984; Lapointe et al., 1986), and CRM in magnetite as an alteration product has been reported by Schutts et al. (1976), Hagstrum and Johnson (1986), and Halls (1986). That the Pedernal Hills dikes have not remained an isotopically closed system is suggested by the discordance in the Rb–Sr data of Loring and Armstrong

(1980). The variation in magnetic behavior with distance which we observe can be attributed to diminishing chemical, rather than thermal, effects farther from the dikes. Thus although the contact test appears convincingly positive, a selective remagnetization of the dikes and adjacent host rocks appears to be the most likely explanation for the Pedernal Hills magnetizations.

Summary and conclusions

The characteristic stable remanence in the Pedernal Hills dikes resides in hematite, and yields a virtual pole position of 42° N, 121° E, on the late Paleozoic segment of the North American APW path. The hematite carrying this characteristic remanence is probably of chemical origin, since its thermal and AF stability spectra overlap strongly with those of a recent weathering overprint, and petrographic observations (Loring and Armstrong, 1980) indicate a secondary origin for the hematite.

The prominence of an intermediate T_{ub} component parallel to the dike characteristic direction in sites C1 and C7, with slightly lower T_{ub}'s in the latter site, and the general lack of evidence for this component at distances greater than about one dike-width, would at face value argue for a thermal overprinting of the host rocks due to intrusion of the dikes. This in turn would require a deuteric origin for the dike hematite and early acquisition of the characteristic CRM in the dikes.

However, due to the possibility of rotation or selective remagnetization, and uncertainty in the age of the dikes, we believe that the characteristic remanence of the Pedernal Hills dikes is not representative of the middle Ordovician paleomagnetic field for North America. Our preferred explanation for the origin of the Pedernal Hills magnetizations is that they resulted from late Paleozoic hydrothermal fluid migration through the dikes and along the contact zones.

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