Paleomagnetic studies in the Jemez Mountains, New Mexico: A progress report on Quaternary volcanic rocks from Valles Caldera VC-2A, Sulphur Springs, and Lower Permian strata in San Diego Canyon and from VC-2B

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PALEOMAGNETIC STUDIES IN THE JEMEZ MOUNTAINS, NEW MEXICO: A PROGRESS REPORT ON QUATERNARY VOLCANIC ROCKS FROM VALLES CALDERA VC-2A, SULFUR SPRINGS, AND LOWER PERMIAN STRATA IN SAN DIEGO CANYON AND FROM VC-2B

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Abstract—Paleomagnetic data from Quaternary volcanic rocks intersected in the VC-2A drilling experiment are interpreted to indicate that, despite considerable alteration in an elevated geothermal gradient, the initial, reverse polarity thermoremanent magnetization of intracaldera and pre-caldera ignimbrites is preserved over much of the 1731 ft sampled interval. In all volcanic materials, magnetite is the principal remanence carrier. Overall, the data are consistent with the interpreted stratigraphy, but many rocks below about 800 ft are partially to completely overprinted, due to hydrothermal alteration, by a positive inclination (normal polarity) remanence interpreted to be less than 780 ka (Brunhes normal polarity chron). Below about 1400 ft, NRM intensities decrease by about an order of magnitude, to between 2 and 7 mA/m. Lower Permian Abo and Yeso Formation strata from the VC-2B experiment yield steep, positive inclination magnetizations as the single or dominant component, suggesting that these rocks have been remagnetized during the Brunhes. The mechanism of remagnetization may involve a combination of heating to no greater than 300°C and changes to the population of hematite grains. The same Permian strata exposed in San Diego Canyon, however, do not show evidence of partial remagnetization related to Quaternary magmatism. Of 16 sites fully demagnetized, 12 yield high-precision results providing a grand mean, corrected for gentle tilt of the strata (Declination= 148°, Inclination= -1.4°, α_{95} = 4.6°, k= 88.7; paleomagnetic pole at 44N, 120E, dp = 2.3°, dm = 4.6°), that is displaced in a small, and statistically indistinguishable clockwise sense (R = 2.6°, ΔR = 3.7°) from an expected Early Permian direction. The San Diego Canyon data are interpreted to indicate that this part of the westernmost margin of the Rio Grande rift did not experience appreciable cumulative vertical axis rotation since the Early Permian.

INTRODUCTION

The Jemez Mountains and its Miocene to Quaternary volcanism have been the focus of considerable paleomagnetic research. In the early 1960s, fundamental paleomagnetic and geochronologic information was obtained from Valles caldera rocks (Doell et al., 1968) that served as the basis for the initial geomagnetic polarity time scale and defined some of the fine structure of that scale (e.g., identification of the Jaramillo "event" or subchron by Doell and Dalrymple, 1966). Three drilling experiments in the Valles Caldera, as part of the Continental Scientific Drilling Program, have provided new opportunities for investigation.

Experiment VC-1 (Fig. 1) was drilled in the southwest moat of the Valles caldera and penetrated post-Bandelier volcanic rocks and upper Paleozoic strata. Paleomagnetic and rock magnetic work on VC-1 (Geissman, 1988) demonstrated that upper Paleozoic strata had been uniformly partially remagnetized during Quaternary volcanism. The thermal demagnetization characteristics of these secondary magnetizations were used to better understand the thermal potency of viscous partial thermoremanent magnetization acquisition. Paleomagnetic data from the Quaternary volcanic part of the core stratigraphy aided in the identification of the volcanic materials intersected. Experiment VC-2A (Figs. 1, 2) was drilled into the Sulfur Springs hydrothermal system, near the intersection of the ring fracture zone and the western margin of the resurgent dome and principally intersected intercaldera and pre-caldera ignimbrites. VC-2B, cored 0.5 km northeast of VC-2A (Fig. 1) was located with the intent of penetrating well into the floor of the caldera, and intersected Quaternary volcanic rocks and over 3000 ft of upper Paleozoic strata and Proterozoic rocks.

This contribution is a progress report on Quaternary volcanic rocks from the VC-2A and Permian strata from the VC-2B experiments. Study of VC-2A aids in defining the volcanic stratigraphy and in evaluating the degree to which the rocks may have been remagnetized during hydrothermal alteration at moderate temperatures. Interest in the Permian section of VC-2B centers around the ability of these rocks to retain a "primary" Early Permian magnetization. Here we also present the results of preliminary work on a well-exposed section of Permian strata in San Diego Canyon which became important because initial data from Permian strata from VC-2B indicated that these rocks were pervasively remagnetized, probably in the late Quaternary. To test the hypothesis that remagnetization was in direct response to Quaternary magmatism, information on the intensity and laboratory unblocking temperature spectra of Permian strata, as unaltered and thermally unaffected as possible, was required. Research on all three components of this study is still in progress.

GENERAL GEOLOGY AND SAMPLING

Volcanic and volcaniclastic rocks, and alteration features, intersected in the VC-2A experiment (total depth of 1731 ft) at Sulfur Springs (Figs.

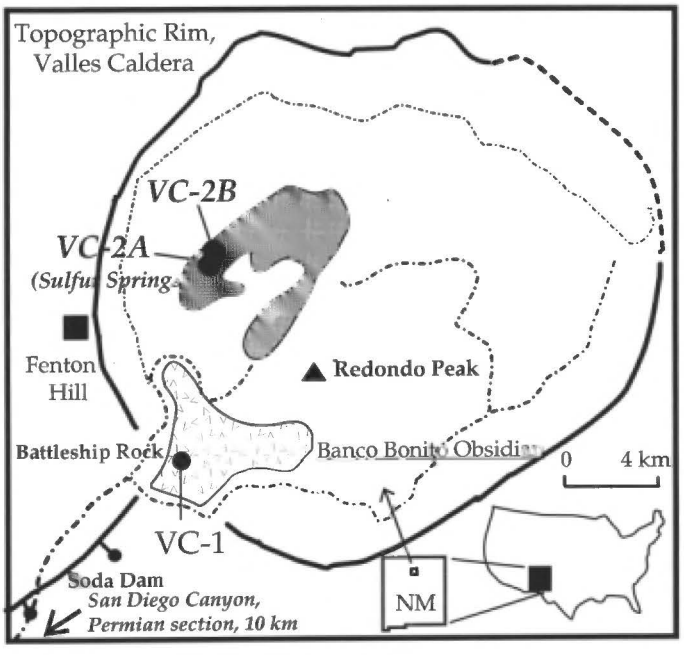

FIGURE 1. Location map of the Valles caldera and VC-2A, VC-1 and VC-2B core holes. Stippled pattern shows area of intense near-surface leaching. Modified from Goff et al. (1987).

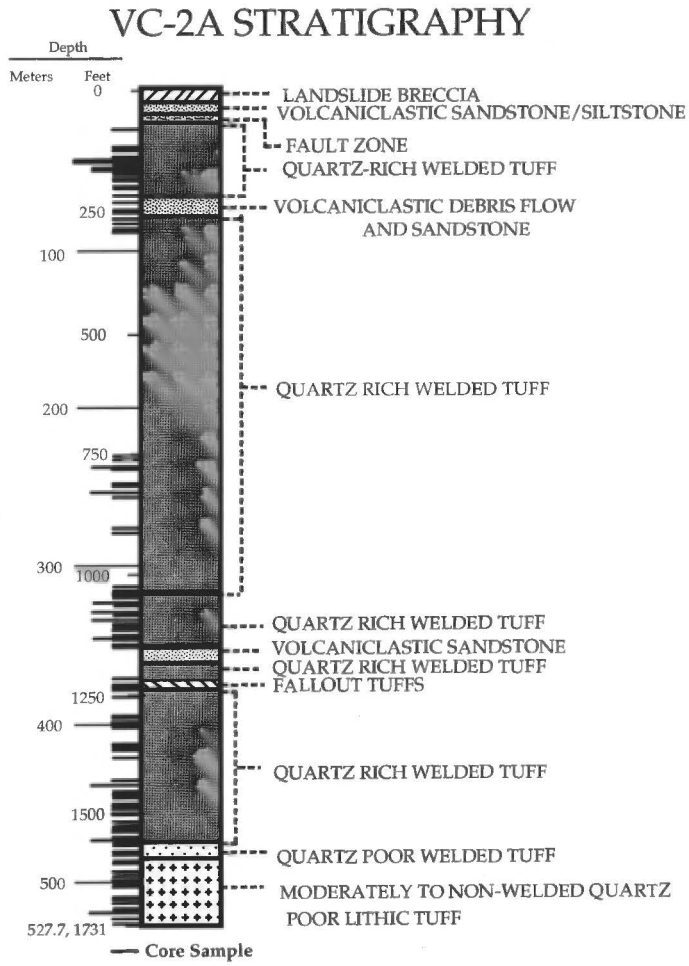

FIGURE 2. Generalized stratigraphy of VC-2A, Valles caldera, New Mexico, modified from Goff et al. (1987), showing locations of core segments (samples) collected.

1, 2) have been described in detail (e.g., Goff et al., 1987; Starquist, 1988; Goff and Gardner, 1994). The section is comprised principally of the intracaldera Tshirege and Otowi Members and, possibly pre-caldera ignimbrites. Intracaldera ignimbrites would have formed at about 1.13 and 1.50 Ma, during the Matuyama reversed polarity chron. The age of pre-caldera ignimbrites intersected at about 1550 ft in VC-2A is unknown, but they may correlate with San Diego Canyon ignimbrites dated at about 1.78 Ma (Hulen et al., 1992). The VC-2A experiment revealed that the active hydrothermal system at Sulfur Springs consists of a thin (about 6 ft) acid condensation zone above a vapor-dominated zone (much of the section) and a liquid-dominated zone at the bottom. The unequilibrated bottom hole temperature was 212°C. All of the rocks in VC-2A have been moderately to intensely altered. The presence of illite throughout the section was interpreted by Goff et al. (1987) and WoldeGabriel and Goff (1989) to indicate that the modern acid sulfate environment is superimposed on an older, higher temperature alteration. Below about 450 ft, most materials contain abundant illite, chlorite, calcite, quartz, pyrite and fluorite. A total of 115 azimuthally unoriented sections (Fig. 2) of core from VC-2A were obtained from Los Alamos National Laboratory in 1987. Because core material between about 360 and 780 ft is uniform in character, we deferred sampling this interval for our initial efforts. The core sections, here referred to as independent samples, range from about 2 in. to over 2 ft in length. The inclination of the VC-2A borehole is within a few degrees of vertical throughout the experiment (Goff et al., 1987). The hole was spudded vertically and the requirement of extremely high core recovery mandated that drilling was carried out slowly to maintain a constant borehole orientation.

The VC-2B (Fig. 1) experiment was continuously cored to a total depth of 5780 ft and penetrated about 2500 ft of Permian and Pennsylvanian carbonate and detrital strata between a depth of about 2600 ft and 5100 ft (Hulen and Gardner, 1989). This section is overlain by intracaldera and pre-caldera volcanic rocks and volcaniclastic strata. Of the more than 300 azimuthally unoriented sections of core collected from VC-2B for paleomagnetic study, 79 are from Lower Permian Abo and Yeso strata between 2620 ft and 4250 ft. The core sections (independent samples) range from about 2 in. to over 2 ft in length. Orientation surveys through about 4600 ft of the section indicate that the VC-2B borehole is less than one degree from vertical (Hulen and Gardner, personal commun., 1989). Cross-beds and laminar beds have dips up to about 30° (Hulen and Gardner, 1989). Yeso and Abo rocks are largely unaltered, except adjacent to structures or in high permeability, coarse-grained sandstones.

Lower Permian strata, principally of the Abo and Yeso Formations, are exceptionally well-exposed in San Diego Canyon (Smith et al., 1970). Romer (1960) reported the age of the Abo Formation as Wolfcampian based on vertebrate paleontology, and Needham and Bates (1943) placed the overlying Yeso strata into the lower two thirds of the Leonardian Series. We sampled 53 discrete beds (paleomagnetic sampling sites, with site number increasing stratigraphically upward) and the lowermost, moderately welded part of the Otowi Member of the Bandelier Tuff along a section about 2.5 mi south of Jemez Springs below Virgin Mesa. At each bed, between 7 and 15 independent samples, as drilled cores, were obtained and, where possible, the orientation of bed contacts was also measured.

LABORATORY METHODS

Procedures used for the preparation of individual specimens from drill core segments for remanence and rock magnetic measurements, progressive demagnetization, and statistical evaluation of demagnetization data follow standard practices, as detailed in Geissman (1988). The nature of the natural remanent magnetization (NRM) in the rocks discussed was evaluated using progressive alternating field or thermal demagnetization, and in some cases a combination of both methods. Directions of individual magnetization "components" contributing to the NRM were determined following the method of Kirschvink (1980); unanchored line segments, defined by at least four demagnetization steps, with MAD values less than 10° were accepted for further analysis. For azimuthally unoriented core, only the inclination of a magnetization component, generally relative to the present horizontal, can be confidently determined. In examples of demagnetization results (Figs. 3, 6, 7), the demagnetization results are plotted according to the method of Roy and Park (1974), where the vertical component of the magnetization is plotted against the (full) horizontal component, facilitating measurement of the inclination of the magnetization isolated over a range of demagnetization steps.

PALEOMAGNETIC DATA

Quaternary rocks, VC-2A

Most Quaternary volcanic and volcaniclastic rocks intersected in VC-2A yield interpretable results in either progressive alternating field or thermal demagnetization (Fig. 3). One common demagnetization behavior involves the removal of essentially a single component of magnetization over a wide range of high peak alternating fields and laboratory unblocking temperatures exceeding 350°C (e.g., core sample 223-6, Fig. 3). In these cases, inclinations of the magnetization isolated are usually of moderate negative values. Another behavior encountered involves the removal of a substantial steep to moderate positive inclination magnetization at low peak fields or laboratory unblocking temperatures and the isolation of, again, a moderate negative inclination magnetization above peak fields of about 30 mT and laboratory unblocking temperatures of about 350 to 400°C (core samples 52-5 and 45-3, Fig. 3). Finally, many core samples from depths greater than about 800 ft exhibit more complex behavior, such as (1) alternating field and thermal demagnetization do not yield the same results (core sample 355-4, Fig. 3); (2) the magnetization isolated is of unexpectedly shallow inclination; or (3) a magnetization of positive inclination is the principal magnetization and is isolated over relatively low alternating fields and/or laboratory unblocking temperatures. In all thermal demagnetization experiments, over 99% of

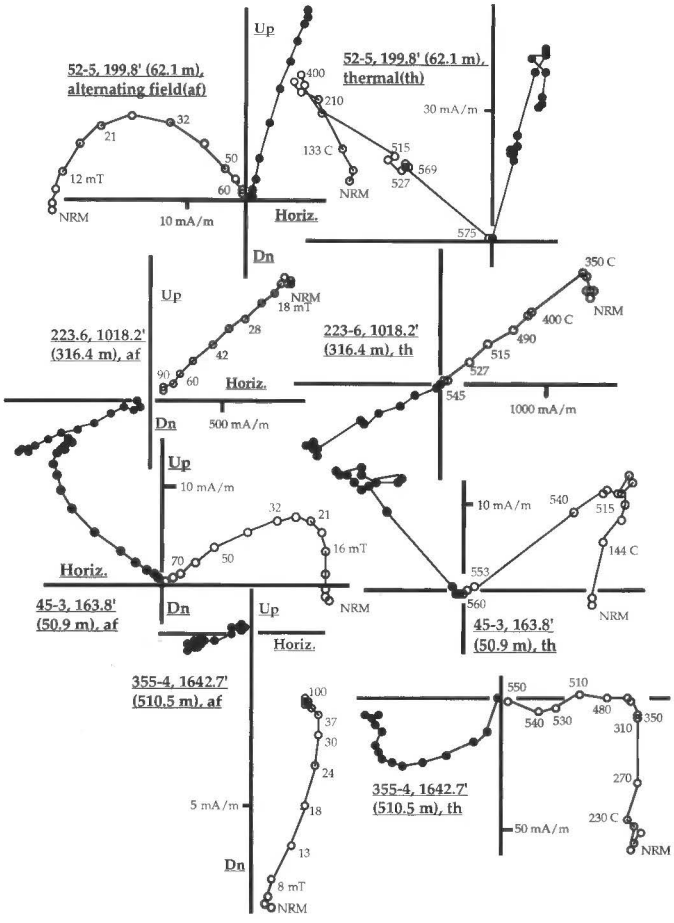

FIGURE 3. Representative modified orthogonal demagnetization diagrams (Zijderveld, 1967; Roy and Park, 1974) for specimens from samples from VC-2A, arranged in stratigraphic order. In each diagram, the endpoint of the magnetization vector measured after each step of demagnetization is simultaneously projected onto the (artificial with unoriented core) horizontal plane (solid symbols) and the true vertical plane (open symbols) assuming the axis of the core segment is vertical. Peak demagnetization inductions or temperatures are given along the vertical projections. Magnetization intensity (in milliamperes/meter, mA/m) is indicated by a tic along one axis. Modified orthogonal demagnetization diagrams give the true inclination of a single magnetization vector isolated over a series of several demagnetization steps.

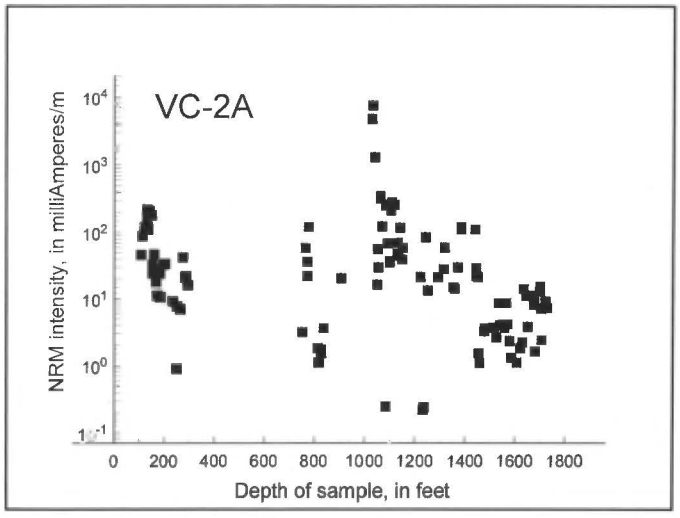

FIGURE 4. NRM intensity vs. core sample depth for Quaternary rocks from the VC-2A experiment.

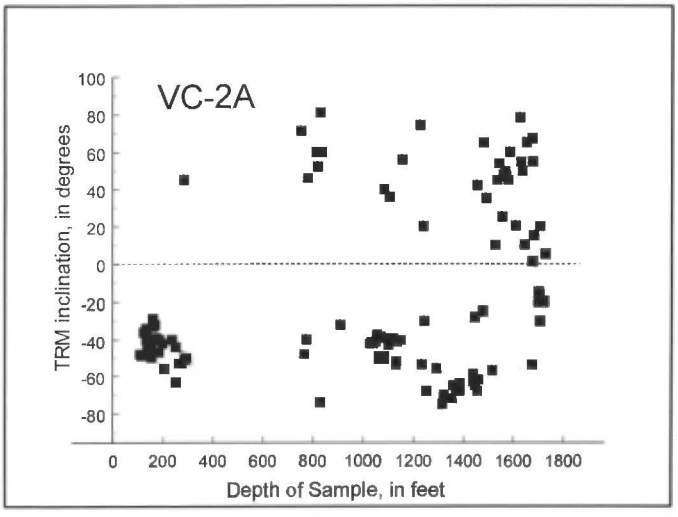

FIGURE 5. Inclination of the magnetization isolated, toward the origin, over the highest peak fields or laboratory unblocking temperatures vs. core sample depth for Quaternary rocks from the VC-2A experiment.

the magnetization is unblocked by about 580°C. NRM intensities of the core samples over most of the sampled section range from 3 to 10 mA/m (Fig. 4). At depths greater than about 1450 ft, NRM intensities decrease by about an order of magnitude.

The distribution of values of inclination of the magnetization isolated over the highest peak fields and laboratory unblocking temperatures (Fig. 5) is complicated. With the exception of the section above 360 ft, where the inclinations are consistently negative (presumably reversed polarity magnetizations), there no strong correlation with rock type.

Lower Permian strata, VC-2B

Paleomagnetic work on samples from Lower Permian strata in VC-2B is in preliminary stages. All rocks analyzed to date have a moderate positive inclination NRM, and the principal magnetization, isolated beginning at less than 100°C up to maximum unblocking temperatures of hematite (about 680°C), is of steep to moderate positive inclination. Assuming this magnetization is north-seeking, it can be interpreted as of normal polarity (Fig. 6). Less than 20% of the 35 core samples fully demagnetized to date contain a sub-horizontal inclination magnetization (e.g., sample 453B, Fig. 6) isolated at temperatures above 600°C or exhibit a progressive shallowing of inclination at unblocking temperatures above about 500°C. The average NRM intensity for 66 specimens from 52 core segments is 25.8 mA/m (std. dev. = 17.9 mA/m).

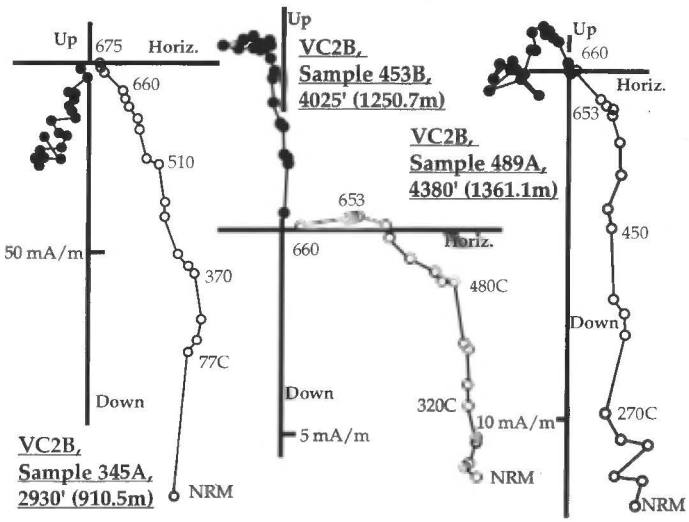

FIGURE 6. Representative modified orthogonal demagnetization diagrams (Zijderveld, 1967; Roy and Park, 1974) for specimens from Permian strata intersected in VC-2B. Conventions follow those in Figure 3.

TABLE 1. Paleomagnetic data from Lower Permian Abo and Yeso strata, San Diego Canyon, Jemez Mountains, New Mexico.

Site	N/No	Decl.,Incl.	α_{95}	k	$\alpha_{952\text{-}1}$,$\alpha_{952\text{-}3}$	J_o,SD
3	5/8	124.1,-4.8	24.3	10.9		
5*	8/8	149.8, 9.5 11.8	22.9	6.4,12.5		4.91, 1.16
7*	5/7	147.2,-10.0	9.7	63.4	3.4, 9.4	16.16, 9.91
9*	9/11	154.1,1.3 17.3	9.7	—		4.25, 5.76
11*	8/8	142.3,-3.6	5.5	102.7	2.5, 5.9	5.49, 1.119
15	5/8	138.0,-14.5	36.2	5.4	—	
18*	10/10	139.7,-3.5	17.4	8.7	—	3.12, 1.85
20*	9/9	140.1,0.1 3.0	285.9	2.2,2.9		7.50, 1.79
22	4/8	123.9,28.7	24.1	15.5	—	
28*	8/8	148.4,1.3 4.7	136.8	1.6,5.5		22.3, 7.53
31*	6/7	152.9,-13.5	14.3	22.8	6.1, 14.5	5.38, 2.93
32*	6/9	154.6,14.1	12.4	30.1	6.0, 12.2	4.47, 2.09
41*	8/8	146.9,-3.0	6.8	67.5	5.1, 6.2	4.33, 0.84
43*	6/8	151.8,-0.8	6.4	109.9	2.3, 6.6	6.86, 5.28
48*	9/11	155.3,-0.8	9.9	27.9	5.7, 10.5	4.52, 2.35
50	4/9	143.7,3.0 18.5	25.7	—		

Explanation: *, site mean accepted for inclusion in determination of grand mean. N/No, ratio of number of independent samples accepted for determination of the site mean to the total number or samples demagnetized. Decl., Incl., declination of the site mean direction, in degrees east of north and inclination of the site mean direction, in degrees downward (+) or upward (-). α_{95}, semi-angle of the cone of confidence about the estimated mean direction, within which, at a 95 percent probability level, the true mean lies. k, best estimate of the precision parameter of the dispersion of sample directions about the estimated site mean. $\alpha_{952\text{-}1}$,$\alpha_{952\text{-}3}$, estimated semi-angles of the elliptical cone of confidence about the estimated mean direction (Onstott, 1980) (for α_{95} values greater than about 15°, these estimates cannot be determined). J_o, NRM intensity, in milliamperes/meter. SD, standard deviation.

Lower Permian strata, San Diego Canyon

To date, samples from 16 sites (beds) in the Abo/Yeso sequence have been completely demagnetized. At the site level, the NRM intensity is somewhat variable (Table 1) but most materials have intensities of a few mA/m. Of the samples demagnetized, over 95% yield interpretable demagnetization results. For all of these samples at least 50% of the magnetization is unblocked at temperatures exceeding 590°C (Fig. 7), consistent with hematite as the principal magnetization carrier, and the direction of the magnetization isolated is of SSE declination and variable, but generally shallow, in inclination. A total of 12 sites (Table 1) yield acceptable (a_{95} values for 5 or more samples less than 18°) site means and, in general, these are from beds of siltstone to silty mudstone. For beds of medium- to coarse-grained sandstone yielding interpretable demagnetization results, the dispersion of within-site directions is unacceptably high, a common phenomenon in paleomagnetic studies of red beds (e.g., Butler, 1992). The directions of all site means lie in the southeast quadrant and are of relatively shallow inclination (Fig. 8). The in situ "grand" mean direction from the 12 accepted sites is D = 149°, I = -3°, α_{95} = 4.6°, k = 89. Applying a correction for 5° of WSW side down tilt of the section, the mean is D = 148°, I = -1.4° and this direction translates into a paleomagnetic pole at 44N, 120E (dp = 2.3°, dm = 4.6°).

INTERPRETATION AND DISCUSSION

Although the paleomagnetic data from the Quaternary volcanic section intersected in VC-2A are complicated, the overall results are consistent with the complete to partial retention of a primary, thermoremanent magnetization, acquired during formation of intracaldera ignimbrites in the reverse polarity Matuyama chron. The dispersion of the negative inclination magnetization isolated in many core samples (Fig. 5), in particular at depths below about 1100 ft, may reflect such factors as post-remanence acquisition deformation (layering in some volcaniclastic deposits have dips up to 30°, Starquist, 1988); geomagnetic field directional variations; and, for shallow inclinations, inability to fully remove a normal polarity secondary magnetization. The positive inclination magnetization removed at relatively low peak fields and laboratory unblocking temperatures up to about 400°C is possibly a young, viscous, partial thermoremanent magnetization acquired under ambient thermal conditions. The single, positive inclination magnetizations in many core samples below about 760 ft, and particularly prevalent at depths greater than 1500 ft, may be the consequence of extreme hydrothermal alteration and partial destruction of primary, magmatic magnetite (WoldeGabriel and Goff, 1989) and, in turn, acquisition of a normal polarity thermoviscous remanence. This possibility is consistent with the general decrease in NRM intensities in material below about 1400' (Fig. 4), where propylitic alteration dominates (Goff and Gardner, 1994). Alternatively, the prevalence of positive inclinations in the deepest part of the core may indicate that the pre-Bandelier ignimbrites are of normal polarity. Surface exposures of these rocks have never been studied for paleomagnetism. Based on demagnetization characteristics alone, and specifically the fact that maximum laboratory unblocking temperatures are below 580°C, magnetite is interpreted to be the dominant magnetic phase, regardless of the nature of alteration of the rock and the direction of the magnetization isolated.

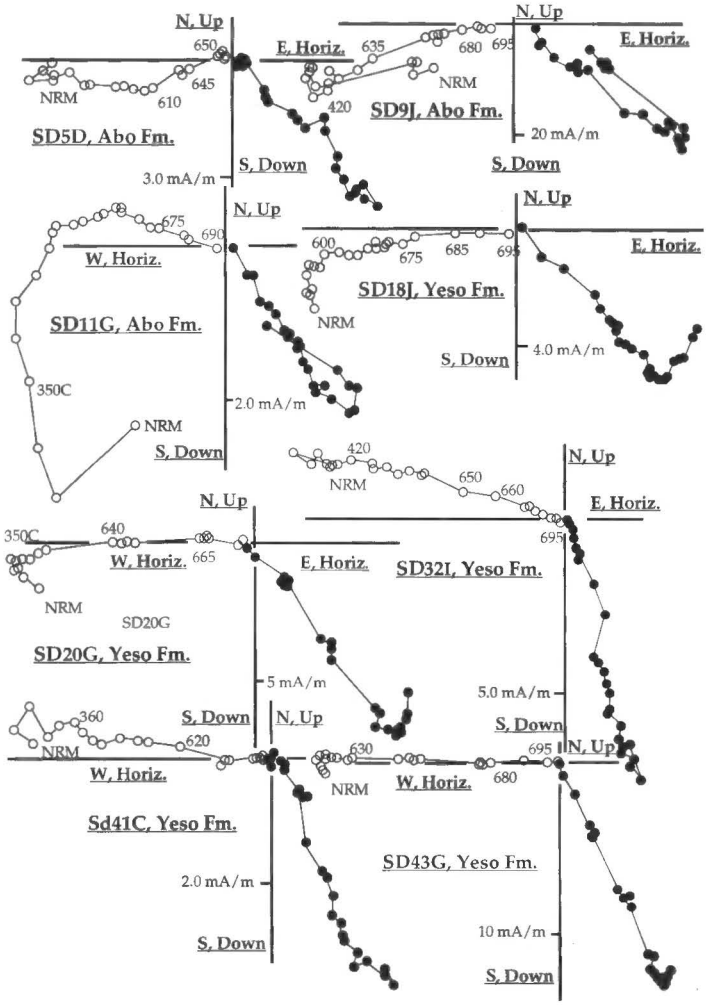

FIGURE 7. Representative modified orthogonal demagnetization diagrams (Zijderveld, 1967; Roy and Park, 1974) for specimens from Permian strata in San Diego Canyon, south of Jemez Springs. Conventions follow those in Figure 3.

The moderate to steep positive inclination NRM and principal component of magnetization isolated in Lower Permian strata intersected in VC-2B demonstrates that these rocks have been remagnetized, possibly pervasively, based on alteration studies by WoldeGabriel and Goff (1992). A primary, shallow inclination, Early Permian remanence in these materials , as present in the San Diego Canyon section, has been either completely destroyed or strongly overprinted by a younger magnetization. Also, the complete absence of a moderate inclination reverse polarity magnetization, as identified in Permian strata in VC-1A (Geissman, 1988) indicates that, if these rocks were partially remagnetized during caldera-forming processes and eruption of the Bandelier ignimbrites (time of reverse polarity of the field), then that secondary magnetization has been subsequently destroyed. The mechanism responsible for partial to complete remagnetization of hematite-dominated Permian strata is not understood and must take into consideration the fact that the NRM intensities of the Permian strata from VC-2B are about an order of magnitude higher than those for surface exposures. According to thermoviscous

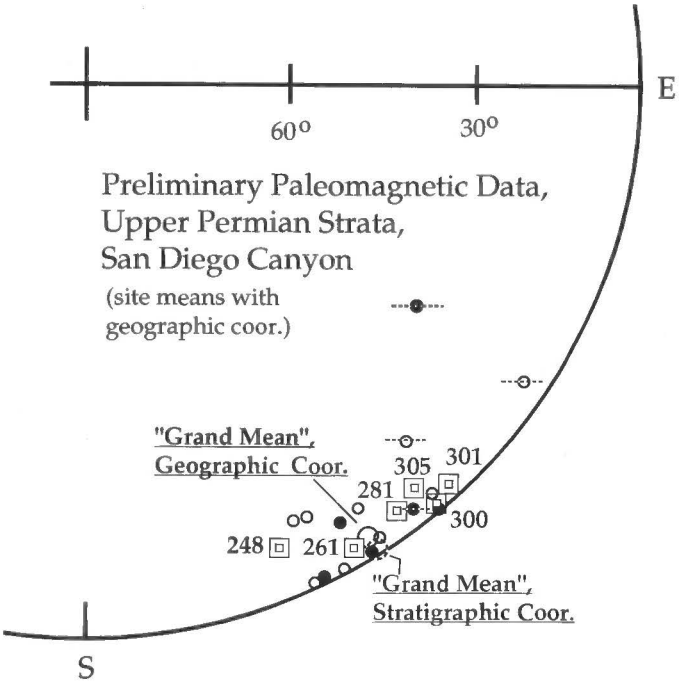

FIGURE 8. Partial equal area projection of directions of site means (small circles) in geographic coordinates, from 16 of the 53 sites sampled (the other 37 have not been demagnetized) in the Permian section in San Diego Canyon. Four of the site means (circles cut by dashed lines) have been rejected because of unacceptably high within-site dispersion. The grand mean of the 12 accepted means is given by the large circle (full for geographic coordinates and broken for stratigraphic coordinates). "Expected", time-averaged Early to Late Permian (/earliest Triassic) field directions, all of shallow negative inclination, are shown as squares. Expected directions are derived from paleomagnetic poles in Van der Voo (1989) (305 Ma), Irving and Irving (1982) (300Ma), and Miller and Kent (1988) (301, 281, 261 and 248 Ma).

activation theory for single domain grains (e.g., Pullaiah et al., 1975; Walton, 1980) full thermal remagnetization of hematite over the last 780 ka of normal field polarity requires temperatures exceeding about 600°C, and there is no evidence that the Permian strata were subjected to such high temperatures, at even a localized (e.g., vein or brecciated zone) scale. Homogenization temperatures for primary fluid inclusions in minerals from deep veins cutting Permian and older strata are similar to equilibration temperatures measured following the experiment (Hulen and Gardner, 1989), and the highest fluid inclusion temperatures measured in VC-2B material are about 310°C (Goff and Gardner, 1994). Ito and Tanaka (1995) reported zircon fission-track dates for Permian strata between 450 and 600 Ma, which they interpreted to indicate that the detrital zircons originated from Precambrian rocks and were partially annealed. These dates are inconsistent with pervasive thermal annealing at high temperatures at any time after the Permian. Finally, clay fractions extracted from the Permian strata contain mixed-layer illite/smectite, with up to 45% expandable interlayers (Hulen and Gardner, 1989). Such a high concentration of expandable interlayers, Hulen and Gardner (1989) argued, would not survive present thermal conditions and must reflect the relatively impermeable nature of the Permian beds and their isolation from K-bearing fluids. If current thermoviscous activation theories for hematite-dominated assemblages are realistic approximations to natural conditions, then a tentative explanation for remagnetization must involve some form of reconstitution of extant hematite and moderate temperatures or the growth of abundant authigenic hematite in these rocks over the past 780 ka.

For Lower Permian strata in San Diego Canyon, assessing the antiquity of a well-grouped and well-defined magnetization in essentially flat-lying redbeds is not straightforward. The uniform SSE declination and generally shallow inclination (reverse polarity) of the magnetization in all interpretable demagnetization results is consistent with a primary, Early Permian age of magnetization acquisition. The preliminary grand mean for 12 sites (Declination = 148°, Inclination = -1°) is similar to the result (Declination = 152°, Inclination = -6°, N = 74 samples, α_{95}= 1.6°) reported by Steiner (1988) for the Abo Formation exposed at Abo Pass, along the eastern margin of the Rio Grand Rift. It is difficult to evaluate the significance of the difference in directions because the mean direction determined by Steiner (1988) was based on independent sample directions, not "site" (bed) mean directions. For the San Diego Canyon strata, none of the beds, including those within 20 m of the unconformity with the overlying Bandelier Tuff, show evidence of partial remagnetization during emplacement of the reverse polarity Bandelier ignimbrites. They do not contain a well-defined reverse polarity magnetization unblocked up to moderate (e.g., 300 to 500°C) temperatures, as was seen in Permian rocks from the VC-1 experiment (Geissman, 1988). Assuming that the magnetization characteristic of the Lower Permian strata is primary, comparison with expected Early Permian field directions (Fig. 8) reveals that the San Diego Canyon result is statistically indistinguishable from expected directions. This preliminary compilation may imply a small (R = 2.6°, Δ R = 3.7°; using the estimated 281 Ma paleomagnetic pole of Miller and Kent, 1988), yet statistically indistinguishable clockwise, cumulative vertical axis rotation of this part of the easternmost margin of the Colorado Plateau since the Permian.

CONCLUSIONS AND FUTURE WORK

Preliminary paleomagnetic data from the VC-2A and VC-2B experiments and a well-exposed section of Permian strata in San Diego Canyon contribute to an improved understanding of the thermochemical history of rocks within the eastern margin of the Valles caldera. The retention of a reverse polarity magnetization in the Quaternary volcanic section in VC-2A supports the interpretation that the rocks intersected are largely intracaldera deposits. Many materials appear to have been relatively immune to intense hydrothermal alteration and despite the complexities of the data from VC-2A, we conclude that the primary thermoremanent magnetizations carried in the appropriate assemblages of magnetite grains can persist in extreme vapor- and hot water-dominated hydrothermal systems. Until more data are obtained from critical depth intervals, we cannot evaluate the timing of remanence acquisition in parts of the section relative to possible localized tilting or slumping.

Permian strata in San Diego Canyon yield, for the most part, high-quality paleomagnetic data, consistent with an Early Permian age of acquisition. Future work on these rocks will involve completion of the additional 37 sites collected and attempts to involve field-based tests, at least evaluating along-strike integrity of the magnetization of selected beds, to better define the age of the well-grouped magnetization in these rocks. Similar Permian strata intersected in VC-2B are partially to seemingly completely remagnetized and exactly how remagnetization occurred is not clear. One possibility is that hydrothermal alteration led to changes in the hematite mineralogy in these rocks and modification of the blocking temperature spectra for these materials. Thermoviscous processes, as conventionally understood for single-domain hematite, are insufficient to result in complete remagnetization. Further paleomagnetic work will focus on determining the level of remagnetization through the Permian section and inspecting, in greater detail, the unblocking characteristics of these rocks between about 630 and 690°C.

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