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1983, pp. 205-210. https://doi.org/10.56577/FFC-34.205

in:

Socorro Region II, Chapin, C. E.; Callender, J. F.; [eds.], New Mexico Geological Society 34 th Annual Fall Field Conference Guidebook, 344 p. https://doi.org/10.56577/FFC-34

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PRELIMINARY RESULTS FROM A PALED- AND ROCK-MAGNETIC STUDY OF OLIGOCENE ASH-FLOW TUFFS IN SOCORRO COUNTY, NEW MEXICO

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INTRODUCTION

The Oligocene volcanic rocks of Socorro County include five extensive ash-flow tuffs, several subordinate pyroclastic units, and basaltic-andesite lavas. Within a 1400 km' area, these volcanic rocks exhibit significant potassium metasomatism. Associated with this area of metasomatism is an aeromagnetic anomaly pattern that is subdued relative to that of unaltered areas (Chapin and others, 1978, Pl. 1).

The present magnetic study was undertaken for three reasons: (1) to investigate the paleomagnetic stratigraphy and rock-magnetic properties of Socorro County ash-flow tuffs; (2) to assess the potential of paleomagnetism as a tool for stratigraphic correlation of these units; and (3) to evaluate whether metasomatic alteration of oxide minerals is responsible for the subdued nature of aeromagnetic anomalies. (Editor's note: A sample location map is not included with this paper because it was written while the author was in Antarctica and his field sheets were at home.)

GEOLOGY AND STRATIGRAPHY

The five most extensive Oligocene ash-flow tuffs in Socorro County are termed, in ascending stratigraphic order, the Hells Mesa, La Jencia, Vicks Peak, Lemitar, and South Canyon Tuffs (Osburn and Chapin, 1983). Radiometric data indicate ages of 33, >31, 31, 28, and 27 m.y., respectively (Chapin and others, 1978; Osburn and Chapin, 1983). The outflow facies of these tuffs reach maximum thicknesses of 122 to 213 m. Variable thicknesses of basaltic-andesite lavas are intercalated between these outflow sheets. Source cauldrons have been identified for the Hells Mesa, La Jencia, and Vicks Peak Tuffs, and tentatively identified for the South Canyon Tuff (Osburn and Chapin, this guidebook). Intracaldera ash-flow tuff facies as much as 915 m thick are exposed. An unnamed ash-flow tuff overlies the South Canyon Tuff in western Socorro County; the two units are lithologically similar.

The outflow facies of the Hells Mesa, Vicks Peak, Lemitar, and South Canyon Tuffs are multiple-flow, moderately to densely welded, simple cooling units. The La Jencia Tuff is also multiple-flow and moderately to densely welded, but exhibits compound cooling with a lower gray-massive member and an upper flow-banded member. The tuffs can be divided into two types: crystal-poor to moderately crystal-rich, one-feldspar rocks (Vicks Peak, La Jencia, lower Lemitar, South Canyon) and crystal-rich, two-feldspar rocks (Hells Mesa, upper Lemitar). The one-feldspar tuffs contain 1 to 20 percent phenocrysts that are dominantly anorthoclase with minor quartz and biotite. The two-feldspar tuffs contain 30 to more than 50 percent phenocrysts of sanidine, plagioclase, quartz, and biotite. See Osburn and Chapin (this guidebook) for details.

In portions of Socorro County, the entire Oligocene volcanic section shows evidence of pervasive potassium metasomatism. The K_2O content in metasomatized ash-flow tuff samples ranges from 6 to 11.5 percent, compared to 4 to 6 percent in unaltered samples (Chapin and others, 1978; D'Andrea-Dinkelman and others, this guidebook). In addition to this regional potassium metasomatism, several areas exhibit localized propyllitic alteration (Lindley, 1979) or hydrothermally induced reddening (Eggleston and others, this guidebook).

The Socorro area is broken into a series of tilted fault blocks trending north-south. These structures are the result of regional extension beginning in the Oligocene and climaxing in late Miocene-Pliocene time (Chapin and Seager, 1975). Superimposed episodes of low- and high-angle faulting have produced considerable structural complexity (Chamberlin, this guidebook). Dips typically range from 0 to 50°, but in places ash-flow tuffs are vertical to slightly overturned.

PROCEDURES

Two hundred eighty-nine ash-flow tuff samples were collected from 37 sites located in the Joyita Hills and the San Mateo, Magdalena, and Lemitar Mountains. Thirty-five of the sites represent unaltered and metasomatized examples of the Hells Mesa, La Jencia, Lemitar, and South Canyon Tuffs; the remaining two sites represent an unnamed ash-flow tuff that overlies the South Canyon Tuff. All samples consisted of field-drilled cores (2.4 cm diameter) which were oriented with sun and magnetic compasses to an accuracy of ± 3°. The paleomagnetic directions reported in this paper have been corrected for structural attitude, which was estimated at each site from the orientation of flattened pumice clasts or welding zones.

Measurements of remanent magnetism of specimens (2.4 cm long) were performed on a Schonstedt SSM-1 spinner magnetometer interfaced with a Star microcomputer. Alternating field (AF) demagnetization was accomplished on a noncommercial, single-axis unit capable of producing peak fields of 40 mT. A Schonstedt TMD-1 was used for thermal demagnetization. Rock-magnetic properties were measured at the University of Colorado at Boulder using a PAR 4001 susceptibility bridge and a Curie balance apparatus consisting of a Cahn electrobalance, a 500 mT permanent magnet, and an automatic temperature programmer. Vetical illumination and oil-immersion objectives were used to observe oxide mineralogy in standard polished thin sections.

OXIDE MINERALOGY

Preliminary observations of unaltered ash-flow tuff samples revealed a sharp distinction in oxide mineralogy between crystal-rich and crystal-poor samples. Crystal-rich samples of the Hells Mesa, Lemitar, and South Canyon Tuffs contain abundant iron-titanium oxides totaling approximately 2 to 5 percent of the volume of each sample. These oxides characteristically include martite, rutile-bearing titanohematite, specular hematite, and microcrystalline hematite. The martite grains typically range from 75 to 250 p. in diameter, reaching 600 p. in some Lemitar samples. They consist of polycrystalline specular hematite displaying a (111) arrangement of individual crystals and containing 0 to 25 percent relict magnetite. The rutile-bearing titanohematite grains range from 25 to 100 p, in diameter and display rutile and ilmenite lamellae within monocrystalline titanohematite. Specular hematite is developed as rims on martite and as a replacement product of biotite. The microcrystalline hematite consists of translucent red crystallites, typically less than 1 vt, in diameter. These are concentrated within and around oxide and biotite phenocrysts and at the margins of glass shards. In addition to the above oxides, Lemitar Tuff samples contain phenocrysts of pseudobrookite-bearing martite. These grains range from 100 to 400 11 in diameter and consist of martite with 20 to 50 percent blebby pseudobrookite lamellae and 0 to 5 percent relict magnetite.

Crystal-poor samples of the La Jencia, Lemitar, and South Canyon Tuffs were found to contain mainly disseminated microcrystalline hematite. Iron-titanium oxide microphenocrysts, typically 2 to 50 pi, in diameter, comprise less than 0.5 percent of the volume of each sample. The mineralogy of the smaller microphenocrysts is difficult to assess, but in general these grains show a range of compositions similar to that of the crystal-rich samples. Pseudobrookite-bearing martite is confined to Lemitar Tuff samples. Samples from crystal-poor portions of the Hells Mesa Tuff have not yet been examined. Moderately metasomatized ash-flow tuff samples show a range of iron-titanium oxide grains similar to that of unaltered samples. However, many of the phenocrysts show the effects of slight to advanced dissolution. In addition, grain-sized voids lined with microcrystalline hematite suggest complete dissolution of some oxide phenocrysts. Microcrystalline hematite is present in a range of concentrations similar to those observed in unaltered samples. Two additional strongly metasomatized samples were found to be devoid of oxide phenocrysts; they contain only sparse amounts of microcrystalline hematite.

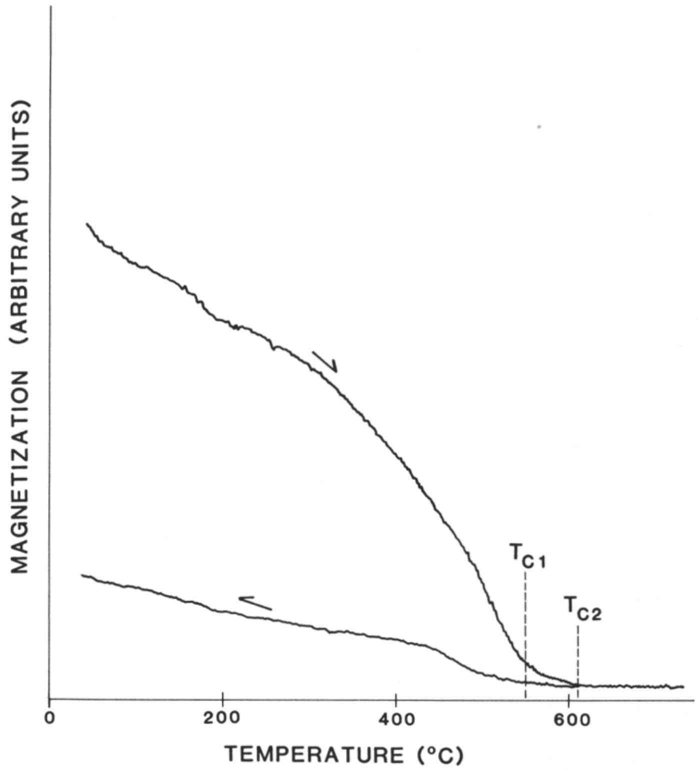

Figure 1. Strong-field induced magnetization versus temperature curve for a whole-rock sample of the La Jencia Tuff, heated in air. The presence of magnetite and hematite is indicated by the primary and secondary Curie temperatures (T_{C1}=545°C, T_{C2}=615°C). The reduced magnetization of the cooling curve probably reflects oxidation of magnetite during measurement.

ROCK MAGNETISM

The rock-magnetic properties measured from ash-flow tuff samples include strong-field induced magnetization (J,), J, versus temperature behavior (J,T curves), and initial susceptibility.

J,T curves were determined for eleven samples from unaltered and metasomatized examples of the studied ash-flow sheets. Each of the J,T curves can be divided into two segments: (1) a convex-downward, lower-temperature segment displaying an indistinct primary Curie temperature between 540 and 590°C; and (2) an approximately linear higher temperature segment showing a secondary Curie temperature between 610 and 700°C (fig. 1). These segments respectively indicate the presence of Ti-poor magnetite and hematite, but cannot be used to estimate the relative proportions of the two minerals because the applied field in the Curie balance (500 mT) was insufficient to saturate hematite.

Values of J, and susceptibility varied systematically among samples (Table 1). The highest J, and susceptibility values were observed in unaltered samples from the densely welded interiors of crystal-rich ash-flow tuffs. Both values were found to be somewhat lower in crystal-poor samples and much lower in flow-top and metasomatized samples (Table 1).

DEMAGNETIZATION BEHAVIOR

Measurements of natural remanent magnetism (NRM) of the ash-flow tuff samples showed a distribution of intensities resembling the distribution of J, values: highest in samples of densely welded flow interiors, and lower in flow-top and metasomatized samples (Table 1). The NRM directions of samples from each of 27 sites (15 unaltered and 12 metasomatized) were well-grouped = 1.9 to 12.5°). Each of the remaining 10 sites (five unaltered and five metasomatized) showed poor grouping of NRM directions ((x„ = 20.5 to 70.4°).

AF demagnetization of samples from the sites with well-grouped NRM directions resulted in slightly lower within-site scatter and significantly lower remanence intensities. Minimum scatter (a„ = 1.9 to 5.5°) was achieved at peak fields of 20 to 40 mT (fig. 2a). Demagnetization to 40 mT reduced remanence intensities to between 9 and 90 percent of their NRM values. Stepwise thermal demagnetization of 21 samples from these sites did not affect remanence directions significantly but produced steadily declining intensities. Following demagnetization at 590°C, the remanence intensity of the samples ranged from 17 to 64 percent of their NRM values.

Samples from the five unaltered sites with poorly grouped NRM directions (sites 14 to 18) showed a dramatic response to AF demagnetization. Peak fields of 40 mT significantly lowered scatter (a., = 3.2 to 25.5°; fig. 2b) and reduced remanence intensities to between 2 and 17 percent of their NRM values. This demagnetization behavior suggests the removal of large isothermal remanence (IRM) components related to lightning strikes. All five sites are located on the flanks of a topographic high in an area that is frequented by thunderstorms. Peak fields of 40 mT were sufficient to completely remove the IRM components of samples from three sites (sites 14, 15, and 16; a, less than 5°); higher peak fields will be applied to samples from the remaining two sites.

Very little demagnetization work has been performed on samples from the five metasomatized sites showing poorly grouped NRM directions. Samples from three of these sites (31, 32, and 33) are strongly metasomatized. Their NRM intensities were low but their remanence was quite stable to thermal demagnetization. Between 45 and 91 percent of their NRM intensity remained after demagnetization of 590°C. Samples from the remaining two sites (29 and 30) exhibit reddening as-

Table 1. Rock-magnetic properties.

Rock type	n	Js (Am^2/kg)	X (A/m/mT)	JNRM (A/m)	Q
Crystal-rich samples					
flow interior	4	.63 (.45-.77)	5.Ø (4.1-6.Ø)	1.8 (1.Ø-3.5)	7
flow top	2	.11 (.Ø6-.15)	.55 (.47-.62)	.85 (.74-.96)	31
metasomatized	7	.Ø4 (.ØØ4-.14)	.3Ø (.ØØ5-1.4)	.67 (.ØØ1-1.5)	44
Crystal-poor samples					
flow interior	11	.44 (.32-.55)	3.3 (.14-6.3)	2.Ø (.11-6.9)	12
metasomatized	11	.1Ø (.ØØ6-.29)	.72 (.ØØ6-3.1)	.15 (Ø.35-.5)	4
hydrothermally reddened	2	.19 (.Ø6-.31)	4.3 (3.2-5.4)	2.2 (.51-3.9)	1Ø

Explanation: Values are reported as mean and range (in parentheses); n = number of sites; Js = strong-field induced magnetization; x = initial susceptibility; Jnrm = intensity of natural remanence intensity; Q = Konigsberger ratio (ratio of remanent to induced components in a field of .Ø5 mT).

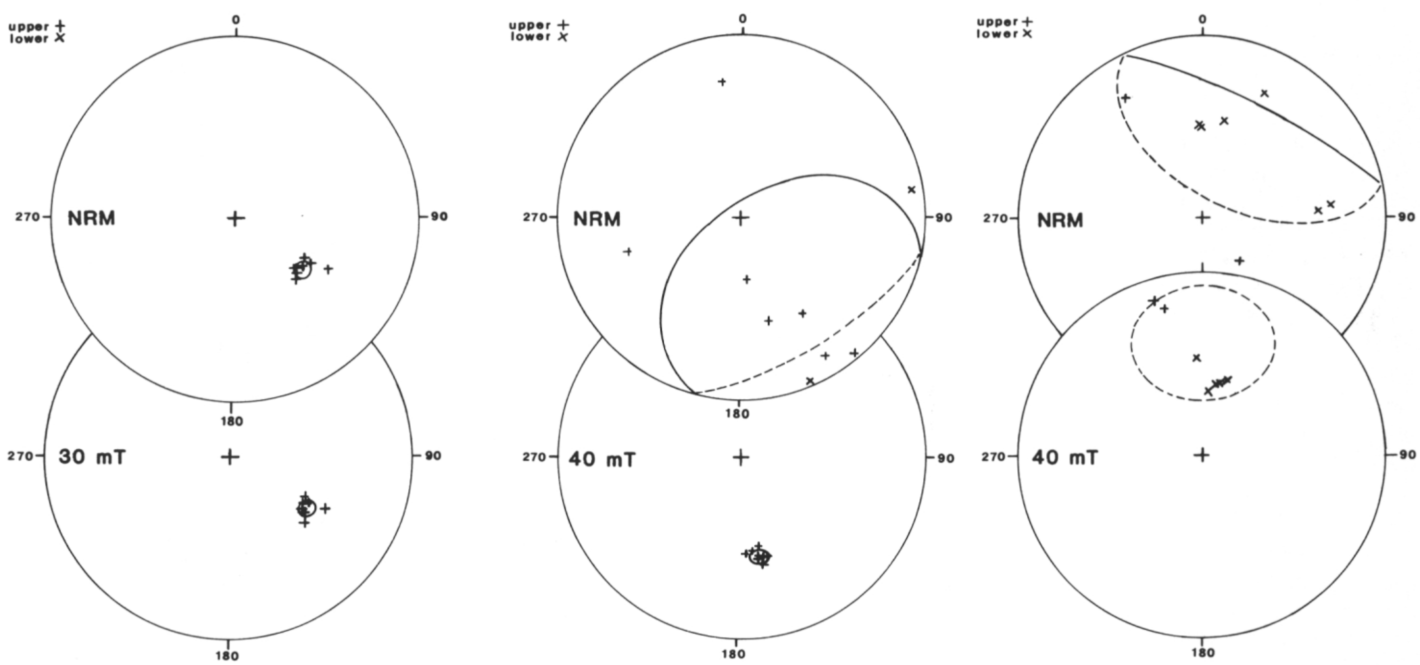

Figure 2. Demagnetization behavior of samples from representative sites. The equal-area stereoplots show sample directions and cones of 95 percent confidence (dashed in lower hemisphere). (a) One of the 27 sites showing tightly grouped NRM directions. (b) One of the five sites showing scattered NRM directions due to lightning effects. (c) One of two hydrothermally reddened sites showing NRM directions.

sociated with local hydrothermal veining. These samples showed relatively high NRM intensities. Significant scatter of remanence direction remained after AF demagnetization to 40 mT (fig. 2c).

REMANENCE DIRECTIONS

The major features of the remanence data from the 37 sites are summarized in the following points. Most of the site-mean directions referred to below were calculated from samples demagnetized at 20 to 40 mT; NRM data were used for the samples not yet demagnetized.

1. Data from the Lemitar Tuff indicate normal polarity. Data from the other units show reversed polarity.

2. The site-mean directions are in moderately good agreement within each of the single-cooling-unit formations (figs. 3a, d, e, and g). In many cases, however, the differences between site-mean directions are statistically significant; in other words, the cones of 95 percent confidence do not overlap.

3. The site-mean directions from the crystal-poor and lithologically similar La Jencia and Vicks Peak Tuffs vary between units. The two sites in the Vicks Peak Tuff show considerably lower average inclination than the seven sites in the underlying gray-massive and flow-banded members of the La Jencia Tuff (figs. 3b and c).

4. Within each unit, sites that are located close to each other typically show small differences in their mean directions (for example, fig. 3a, sites 38 and 39; fig. 3g, sites 24 and 25). Larger differences are observed between the mean directions of sites from widely separated localities, particularly in cases involving sites from structurally complex areas (for example, fig. 3a, sites 15 and 38; fig. 3c, sites 6 and 37).

5. No systematic differences are apparent between the mean directions of unaltered and metasomatized sites in most of the units (figs. 3b, d, and e). Such differences are observed in the data from two units (figs. 3b and c), but both cases involve sites from few locations. One of the two hydrothermally reddened sites shows a mean direction which is considerably different from the mean directions of the unaltered and metasomatized sites from the same unit (fig. 3e).

6. Significant stratigraphic variation in remanence direction is suggested by data from two sites (40 and 41) in the Lemitar Tuff. The 20 samples from these sites provide a stratigraphic sequence throughout the entire thickness of the formation. The NRM directions of these samples reveal a systematic variation in declination and inclination between the interior of the unit and the upper and lower margins (fig. 4).

7. The sites in the outflow-facies of the South Canyon Tuff (fig. 3e) show very closely grouped mean directions (excluding the hydrothermally reddened site). The mean directions of sites in the intracaldera facies are more poorly grouped (fig. 3f).

8. Average remanence directions for each ash-flow tuff unit were calculated from the site-mean data (table 2; fig 3h). The average directions of the Lemitar, Vicks Peak, and South Canyon Tuffs are statistically unique among the studied units (each cone of 95 percent confidence does not overlap with those of other units). The average directions of the remaining units are not statistically distinguishable from each other.

DISCUSSION

Genesis of Oxide Minerals

Petrographic and rock-magnetic observations of Socorro County ash-flow tuffs suggest the following sequence of events.

(1) Oxide phenocrysts originally crystallized as magnetite and ilmenohematite. In Lemitar magma, formation of these phases was preceded by titanomagnetite crystallization.

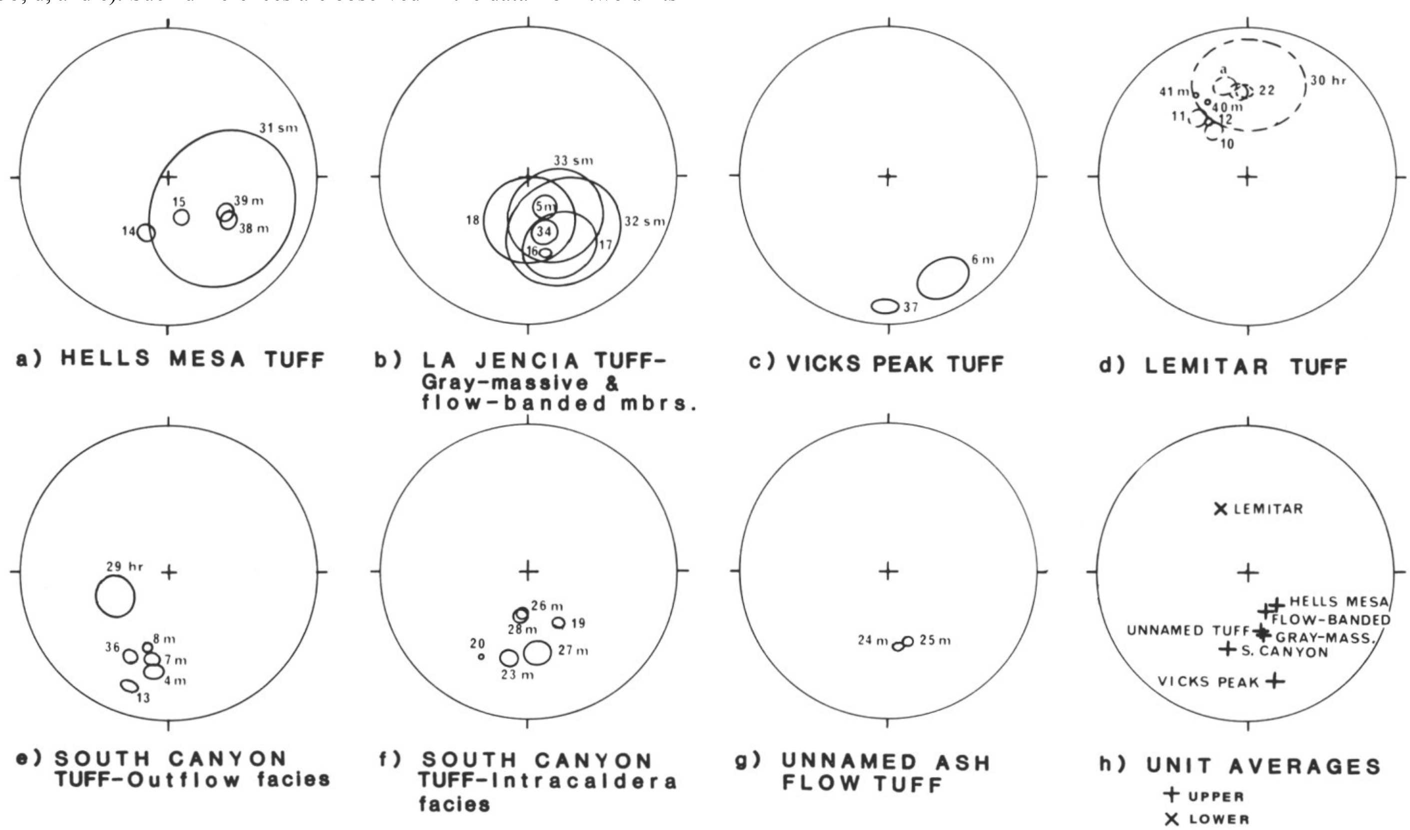

Figure 3. Site mean directions shown on equal-area stereoplots a to g. Cones of 95 percent confidence (dashed in lower hemisphere) for data from sites in each ash-flow tuff unit. Most of the data reflect demagnetization of 20 to 40 mT. Cones are numbered as to site, m = metasomatized, sm = strongly metasomatized, hr = hydrothermally reddened. h) average directions for each outflow unit.

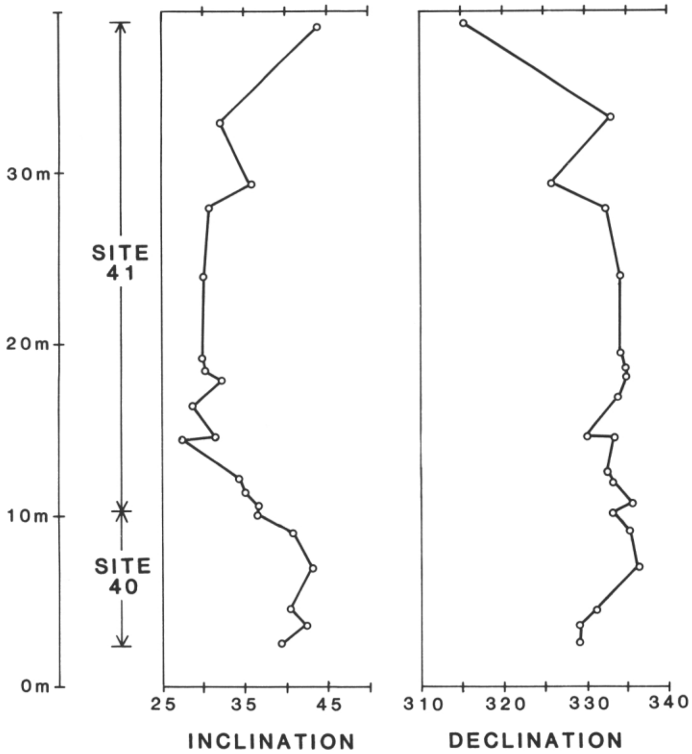

Figure 4. Stratigraphic variation in NRM directions shown by samples from two sites in the Lemitar Tuff.

(2) Following eruption, an advanced degree of high-temperature oxidation occurred. Ilmenohematite, titanomagnetite, and magnetite, respectively, oxidized to rutile-bearing titanohematite, pseudobrookitebearing martite, and martite. Iron-rich silicates and glass oxidized to form specular and microcrystalline hematite.

Rutile-bearing titanohematite and pseudobrookite-bearing martite are both characteristic of advanced deuteric oxidation at high oxygen fugacities and temperatures of 700 to 750°C (stages R5 and C7 of Haggerty, 1976). Martite, specular hematite, and microcrystalline hematite are known to form over a wide range of temperatures (Walker and others, 1981), but their association with high-temperature oxidation products suggests that they too formed deuterically.

Oxidation of magnetite and titanomagnetite proceeded furthest near the tops of ash-flow tuff units, as shown by the low J, values and NRM intensities of flow-top samples.

(3) Potassium metasomatism affected the ash-flow tuffs in some areas, causing partial to complete dissolution of oxide phenocrysts. This dissolution was observed petrographically and is further shown by the low J, values and NRM intensities of metasomatized samples. The dissolution of hematite suggests that metasomatic fluids were acidic.

Acquisition of Remanence

Remanence in the Socorro County ash-flow tuffs is carried by both magnetite and hematite. The presence of both minerals was demonstrated by petrographic observations and by J,T curves. The presence of two components of remanence was shown by demagnetization behavior. Samples lost 10 to 98 percent of their remanence following AF demagnetization to 40 mT, indicating significant low-coercivity components of remanence carried by magnetite. Conversely, between 17 and 91 percent of NRM intensity was retained by samples thermally

Table 2. Paleomagnetic results.

	n	$\bar{D}$,deg	$\bar{I}$, deg	k	α_{95},deg
Hells Mesa Tuff	5	138.6	-59.2	16.2	19.6
La Jencia Tuff					
gray-massive member	1	167.0	-45.6	—	—
flow-banded member	6	156.2	-59.4	57.4	8.9
Vicks Peak Tuff	2	166.4	-18.9	—	—
Lemitar Tuff	8	337.0	41.2	36.4	9.3
South Canyon Tuff					
outflow facies	6	195.5	-36.5	60.5	5.9
intracaldera facies	5	182.5	-54.8	17.9	18.6
Unnamed ash-flow tuff	2	168.2	-48.3	—	—
average of all units		167.8	-46.6	21.1	12.3

Explanation: n = number of sites (two hydrothermally reddened sites excluded); D = mean declination, I = mean inclination; k = Fisher's precision parameter; α_{95} = semi-angle of cone of 95% confidence (statistical parameters not calculated for n, less than two); the average of all units was calculated using the reversed equivalent of the Lemitar direction.

demagnetized to 590°C, indicating significant high-blocking-temperature components of remanence carried by hematite. Excluding samples affected by lightning, remanence directions did not change significantly during either AF or thermal demagnetization, indicating that the remanence components carried by magnetite and hematite were parallel. This parallelism suggests that both components were acquired during cooling of the ash-flow tuffs, and supports the petrographic interpretation that the hematite in these rocks is a product of high-temperature deuteric oxidation. The remanence components of the magnetite and hematite in the Socorro County ash-flow tuffs together provide a strong, stable, and accurate record of the geomagnetic field at the time of emplacement and cooling.

Metasomatized ash-flow tuff samples showed lower NRM intensities than unaltered samples, but their demagnetization behavior was similar. No components of chemical remanence (CRM) were identified. These characteristics are consistent with the interpretation that iron-titanium oxides were dissolved and not precipitated during metasomatism.

Paleomagnetism as a Correlation Tool

Paleomagnetism is a proven tool for correlation of volcanic rocks. A nearly instantaneous record of the geomagnetic field is provided by rapidly cooled volcanic units. Because of short-term changes in the geomagnetic field (paleosecular variation), there is a high probability that any sequence of extrusive units will have acquired a series of statistically distinct remanence directions (Bogue and Coe, 1981).

Several studies of ash-flow tuffs have indicated remanence which is suitable for paleomagnetic correlation (Grommé and others, 1972; Best and others, 1973; Reynolds, 1977). Other ash-flow tuffs have been found unsuitable because of unstable or inconsistent remanence directions (Reynolds, 1977; Gose, 1970). The Socorro County ash-flow tuffs exhibit strong stable remanence. Lightning-induced IRM components are present in a few samples but are removable by AF demagnetization. Most sites show very low scatter. The site-mean directions from each individual cooling unit are in moderately good agreement. However, in many cases the cones of 95 percent confidence of the sites do not overlap. This imperfect grouping poses a major problem for paleomagnetic correlation of the units.

The inconsistencies in site-mean directions are probably related mainly to problems with corrections for structural attitude. First, errors in measurement of attitude may have occurred; some outcrops exhibit irregular welding zone boundaries or variable orientations of flattened pumice clasts. Second, the assumption that the flattened pumice clasts and welding zones were originally horizontal may be false. Third, corrections were applied using rotations about horizontal axes; actual deformation may have involved net rotations about non-horizontal axes.

Paleosecular variation during cooling of some units may have also contributed to the imperfect grouping of site-mean directions. Evidence for such variation is found in the stratigraphic trend of remanence directions observed in the Lemitar Tuff. This trend was observed at two sites where the Lemitar Tuff is only 38 m thick and must have cooled quickly. The magnitude of the trend (15° inclination, 20° declination) suggests relatively rapid paleosecular variation. This process may explain some of the inconsistencies between the mean directions of other sites in the Lemitar Tuff (fig. 3d). The poor grouping of site-mean directions in the intracaldera facies of the South Canyon Tuff (fig. 3f) is almost certainly related to paleosecular variation during cooling. This unit is quite thick (>800 m) and probably cooled over a long period of time.

The effect of metasomatism on site-mean directions is apparently small. The mean directions of metasomatized and unaltered sites in some cases do not agree, but it is unlikely that metasomatism is the cause. The metasomatized sites in question show low scatter and no CRM components were indicated during demagnetization of their samples. Furthermore, those sites are located in structurally complex areas. More strongly metasomatized sites from other areas exhibit high scatter but do not differ significantly in mean direction from unaltered sites.

The remanence directions of three ash-flow tuff units are statistically unique, in spite of the imperfect grouping of site-mean directions. The Lemitar Tuff is the only unit with normal polarity and the South Canyon Tuff is the only unit showing southwesterly declination. The inclination of the Vicks Peak Tuff is distinctly low and differs from the inclinations of the underlying gray-massive and flow-banded members of the La Jencia Tuff. This difference in inclination indicates a significant age difference between the Vicks Peak and flow-banded members, as also indicated by the presence of lavas between these units.

Given the imperfectly grouped site-mean directions, it is not presently possible to paleomagnetically distinguish between the Hells Mesa Tuff, the gray-massive and flow-banded members of the La Jencia Tuff, and the unnamed tuff overlying the South Canyon Tuff. Improvements in structural corrections may eventually alleviate this problem.

Paleomagnetism should prove helpful for resolving stratigraphic problems involving the Socorro County ash-flow tuffs, particularly for identification of distal portions of outflow sheets. Paleomagnetism alone is sufficient to identify some units; in other cases it can be used to verify correlations based on lithology. Paleomagnetism does not appear to be sufficient for identification of slowly cooled intracaldera facies. Future work on susceptibility anisotropy of outflow facies may assist in caldera identification (Ellwood, 1982).

Aeromagnetic Anomalies

The low susceptibilities and NRM intensities measured in ash-flow tuff samples from metasomatized areas of Socorro County appear to be sufficient to account for the subdued nature of associated aeromagnetic anomalies. The mean KOnisberger ratios of unaltered and metasomatized samples range from 4 to 44 (Table 2), indicating that remanence components will predominate over induced components in aeromagnetic anomalies. Because all but one of the ash-flow tuffs is of reversed polarity, a complete suite of the units should produce a negative aeromagnetic anomaly with an amplitude approximately proportional to the average NRM intensity. NRM intensities of metasomatized samples range from 10 to 40 percent of the intensities of the equivalent unaltered samples. It follows that metasomatized sections should exhibit negative anomalies as much as an order of magnitude less intense than unaltered equivalents.

The aeromagnetic anomaly map of the Socorro area (Chapin and others, 1978, Pl. 1) shows that metasomatized areas are actually associated with weak negative or positive anomalies. The positive anomalies may reflect the presence of normally magnetized lavas intercalated with the metasomatized ash-flow tuffs. Detailed modeling of anomalies will be performed in the future.

ACKNOWLEDGMENTS

I wish to thank the New Mexico Bureau of Mines and Mineral Resources for supporting this work. C. E. Chapin helped in all phases of the project and G. R. Osburn and R. M. Chamberlin provided advice and assistance in field work. I also wish to thank Nina Triffleman for her critical review of the manuscript.

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