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A POSSIBLE MID-HOLOCENE AGE OF THE CARRIZOZO MALPAIS FROM PALEOMAGNETICS USING SECULAR VARIATION MAGNETOSTRATIGRAPHY

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Abstract—To place constraints on the age of the malpais northwest of Carrizozo, New Mexico, 14 samples were collected from two different sites on the eastern edge of the flow. One site is located on the surface of a small lobe of basalt on the eastern margin. The second site is located about 150 m west of the eastern limit of the flows in the interior of a filled lava tube. Both groups of samples held strong paleomagnetic signatures; however, the samples on the margin of the flow exhibited differing alternating field and thermal demagnetization behavior. Demagnetization by alternating field produced a strong single-component demagnetization path while thermal demagnetization shows multi-component behavior. Similar behavior was demonstrated by the samples from the interior of the flow, except that the multi-component behavior of the thermal samples was less pronounced. This differing behavior is indicative of magnetic overprinting. In the data analysis a least-squares line was fit to the alternating field samples while both lines and planes were fit to the thermal samples. The results showed good clustering of all lines within a group and a well-defined girdle of poles to planes. The directions of all groups are steeply inclined and significantly east of the dipole field for this site, making them unique. The archaeomagnetic secular variation reference curve for the southwestern United States contains no virtual geomagnetic pole corresponding to these directions constraining the flow to older than 580 A.D. We prefer an approximate age of approximately 5000 years b.p. based upon the Fish Lake, Oregon, secular variation record, an age corroborated by a preliminary ^{36}Cl date on the flow.

INTRODUCTION

The Carrizozo malpais, a series of basaltic lava flows that emanate from Little Black Peak and flowed 72 km southward through the Tularosa Basin, presents an interesting problem in age determination. Its relative youthfulness is apparent from its lack of significant soil development and vegetation, iridescent crust and blocky surface. However, an absolute age has not yet been placed on this feature. Allen (1951) estimated an age of 950 A.D. based upon its geomorphic appearance and degradation relative to other recent flows, including McCartys flow in northwest New Mexico (post-700 A.D.; Nichols, 1946) and the Craters of the Moon area of Idaho (most recent eruption from 3000 to 2000 years b.p.; Kuntz et al. 1986). If this age is appropriate, it places the age of the flow in the middle of the best constrained section of an archaeomagnetic secular variation master curve for the southwestern United States, SWCV588, of Eighmy and Kline (1988). This presented an opportunity to date a geologic feature using this curve and secular variation (SV) magnetostratigraphy.

SV magnetostratigraphy differs from the better known reversal magnetostratigraphy only in the accuracy of the magnetic directions being matched. In reversal magnetostratigraphy, the pattern of normal and reversed magnetic field directions is matched to a known pattern and the section of correspondence places age constraints on the stratigraphic section. In a similar manner, SV magnetostratigraphy matches a pattern of precise magnetic field directions to a known pattern to constrain the age. In both of these methods, the pattern is usually not unique and some independent evidence of the age is necessary to provide a unique match to the known pattern.

I approached this study with the preliminary age from Allen (1951) and the knowledge that over the range of the reference curve, most directions were unique with the only overlap at about 1000 A.D. and 1300 A.D. Therefore, if the estimated age is approximately correct, a match could probably be made to the reference curve with a possible ambiguity of 300 yrs.

The magnetization of the samples was more complicated than anticipated. Also, the samples' magnetic directions are unique, dip steeply to the east of north, and the mean direction of the samples falls outside the range of directions in the reference curve. This indicates strongly that the age does not fall within the range of the reference curve. To provide a weak, but possible age constraint, I look at curves that cover a greater age range, but lie farther away from the site. From these curves, a date with a reasonable match to the mean magnetic directions is at about 5000 b.p.

SAMPLES

Two groups of samples were collected from the eastern edge of the lava flow along NM Route 164. Because much of the surface of the flow shows dramatically tilted blocks and pinched-up crust, we were careful to collect two groups of samples from locations unlikely to be disrupted after the onset of cooling. Then a comparison of the two groups could be made to constrain the lack of disruption.

The first group was collected from the margin of the flow with the assumption that the lobe was extruded outward and quickly solidified, becoming stable. From this lobe, six samples were collected from the surface of the flow. All but one of the samples were large enough to be divided into two subsamples from each sample.

The second site is about 150 m westward into the flow. At this location, the highway cuts through the flow, providing good exposure into a massive portion of the basalt. Very little disruption was visible at the surface in this area and the homogeneous and massive nature of the cross section suggested that this portion of the flow probably cooled in place. From this location, eight samples were collected from both sides of the roadcut in the depth range of 1.5 to 3 m below the surface of the flow. Six of the samples were subdivided into two subsamples.

Both sites lie in the "Upper Carrizozo Flows" of Renault (1970), although group 2 is topographically higher than group 1 and may be a younger flow. However, they are closely associated with no clear unconformity between them and may represent a relatively short interval between their emplacement.

Each sample was demagnetized by step-wise alternating-field (AF) demagnetization up to 10 mT and then by step-wise thermal demagnetization up to 600°C. Where a second subsample was available, it was demagnetized by AF up to 150 mT, the physical limit of the system. Least-squares lines, and where appropriate planes, were fit to the demagnetization paths using the method of Kirschvink (1980).

RESULTS AND INTERPRETATION

The first step in the analysis of the paleomagnetic directions was the comparison of AF and thermal mean directions for each group. Surprisingly, the mean directions differ significantly in group 1 (Fig. 1, Table 1). The mean direction for the six thermal samples is Declination (D) = 2.8°, Inclination (I) = 65.1°, whereas the AF samples have a mean direction of D = 20.5° and I = 62.5°. The directions are much closer for group 2, with D = 15.2° and I = 66.0° for the thermal samples and D = 16.6° and I = 69.0° for the AF samples.

Examination of the thermal demagnetization paths for group 1 shows

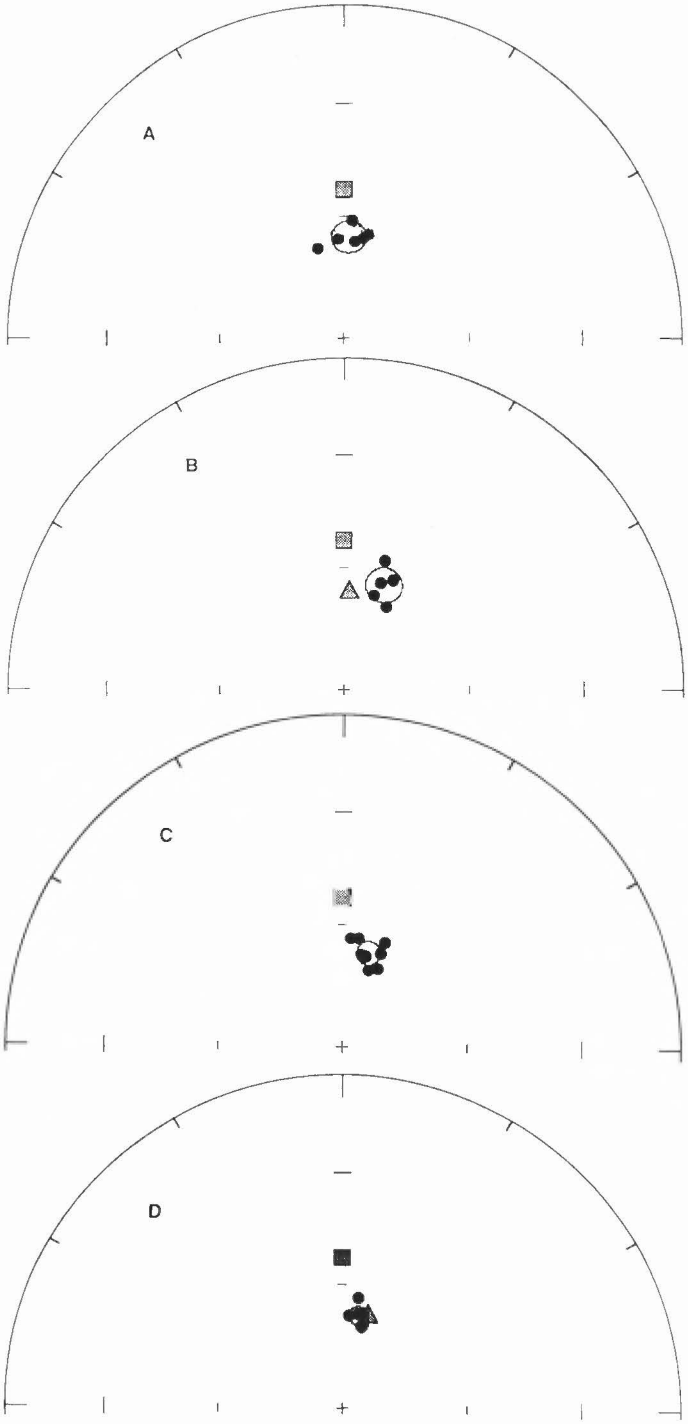

FIGURE 1. Lower hemisphere equal-area plot of sample magnetic directions from different groups and demagnetization methods. A, Group 1, thermal; B, Group 1, alternating field (AF); triangle is the mean direction of the group 1 thermal samples; C, Group 2, thermal; D, Group 2, AF; triangle is the mean direction of the group 2 thermal samples. Square is the dipole field direction, circle is the 95% confidence region of the mean.

a significant component of magnetization being removed in the low AF steps and the first few thermal steps, up to about 275°C (Fig. 2a). The AF samples in each group show no significant multi-component behavior (Fig. 2b). The thermal samples in group 2 show multi-component behavior like group 1 samples but with a much less pronounced low-demagnetization component.

To investigate this multi-component behavior, I fitted planes to the

TABLE 1. Mean paleomagnetic directions for different demagnetization methods. Statistics are Fisher distribution. N, number of samples; κ, precision parameter; α_{95}, radius of cone of 95% on the mean direction.

Site	Demag.	Dec.	Inc.	N	κ	α_{95}
1	Thermal	2.8°	65.1°	6	234.5	4.0°
1	AF	20.5°	62.5°	5	258.7	4.3°
2	Thermal	15.2°	66.0°	8	344.0	2.8°
2	AF	16.6°	69.0°	6	353.8	3.3°

demagnetization paths. The use of planes is based upon the geometric relationship that any two lines define a plane. Therefore two linear demagnetization components, even paths with overlapping coercivity ranges, will define a plane. If one of these components is coherent and the same from one sample to another, and one is incoherent, or "random," when the poles to the fit planes are plotted they will define a great circle on a stereonet plot (Kirschvink, 1980). The pole to the plane of this great circle will be the direction of the coherent component in the multi-component paths.

The poles to the fitted planes from group 1 define a great circle which is supplemented well by the poles from group 2 (Fig. 3). The two groups have a better agreement of their poles than their mean thermal demagnetization directions. For group 1 the pole to the great circle is D = 18.1°, I = 61.8°, and for group 2, D = 11.2°, I = 66.4° (Table 2). The pole to the great circle defined by the combined group 1 and group 2 samples is D = 13.9°, I = 63.6°.

These pole directions show good agreement with the AF demagnetization mean directions in each group, suggesting that the AF com-

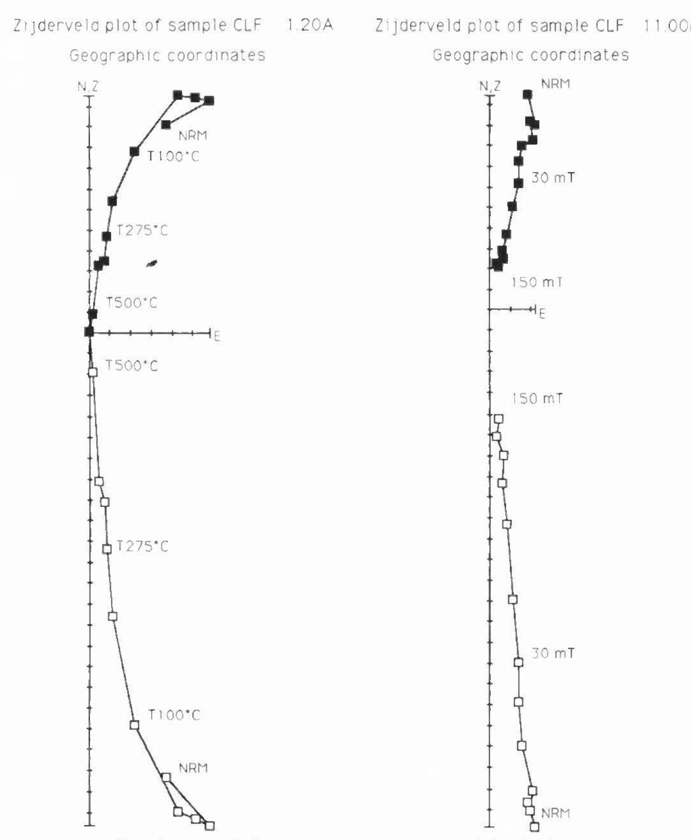

FIGURE 2. Orthogonal demagnetization diagrams for a thermal demagnetization from group 1 (left) and an AF demagnetization from group 2 (right).

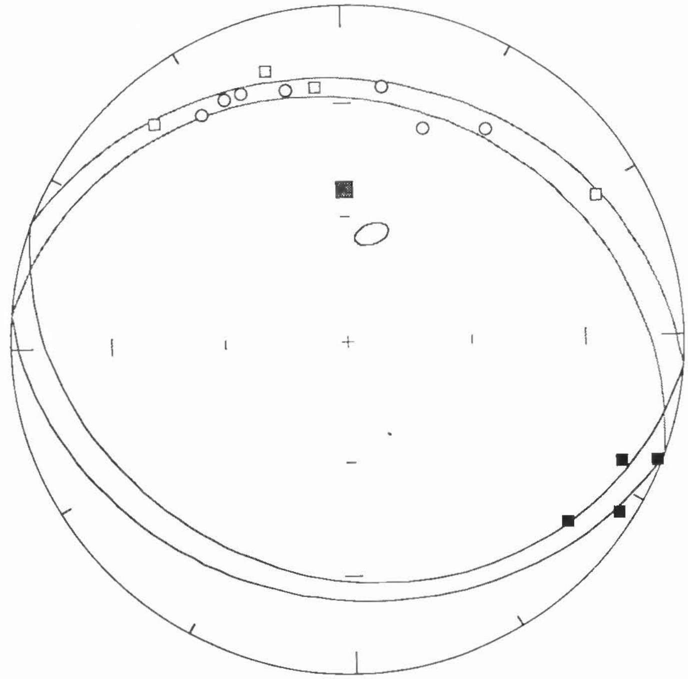

FIGURE 3. Equal-area plot of poles to planes and 95% confidence limits on mean direction and great circle. Solid symbols are lower hemisphere, open symbols upper hemisphere. Circles are group 1 and squares are group 2.

ponents are the same components of the coherent directions in the planes. Combining the AF lines and thermal planes by the method of Kirschvink (1980), with weighting as implemented by Jones in the PaleoMag software, 1991 gives preferred group directions (Fig. 4). Combining all AF components and all planes gives a mean direction for all samples (Fig. 4).

Many of the group 1 samples show a slight, reversed-appearing magnetic component between the natural remanent magnetization (NRM) direction and the first AF step at 3 mT (Fig. 2). Viewed in core coordinates, these directions are quite consistent and point slightly upward from the core axis. Since these are a relatively weak magnetization and the core orientations cover a wide range of directions, I interpret this component to represent a weak overprint from the drilling.

The difference in magnetic behavior between the thermal and AF demagnetized samples in group 1 is more difficult to explain. First, because the coherent direction of the planes and the AF directions coincide, this direction is interpreted as the primary magnetization. The more variable direction of the overprint is suggestive of chemical overprinting with time, a consequence of conversion of magnetite to hematite and secondary iron oxides. This interpretation is supported by the petrographic work of Smith (1964) who identified magnetite in the slightly altered basalt. Hematite is reported as the only identifiable alteration product. One further observation relevant to this problem is the slight tendency for the high-AF demagnetization steps to be slightly north of the low-field steps.

Based upon these observations, I conclude that for group 1 the AF demagnetization path is dominated by magnetite magnetization and represents the primary magnetization of the samples. I suggest that further AF demagnetization, above the physical limits of the system, would have shown the demagnetization of the alteration products, which have magnetic coercivities generally above those of magnetite (O'Reilly, 1984). The thermal demagnetization paths show overlapping coercivity ranges as the magnetite is demagnetized and the secondary iron oxides dehydrate to produce hematite.

AGE CONSTRAINTS ON THE FLOW

Group 1 and group 2 produce extreme virtual geomagnetic poles (VGP) of 71.8°N, 53.6°W and 70.4°N, 80.7°W, respectively. With the

TABLE 2. Mean paleomagnetic directions for planes and combined planes and lines. Statistics are Bingham distribution after the method of Jones (implemented in the PaleoMag software, 1991). N, number of samples; κ_1 and κ_2, first two eigenvalues of the Bingham distribution; α_1 and α_2, minor and major axes of the cone of 95% confidence on the mean.

Site	Demag.	Plane or line	Dec.	Inc.	N	κ_1	κ_2	α_1	α_2
1	Thermal	Plane	18.1°	61.8°	7	-274.4	-4.7	2.4°	6.4°
2	Thermal	Plane	11.2°	66.4°	8	-142.4	-2.5	3.4°	6.1°
1&2	Thermal	Plane	13.9°	63.6°	15	-150.3	-2.2	2.4°	4.1°
1	AF & Thermal	Line Plane	19.8°	62.0°	12	-220.9	-1.3	2.0°	2.8°
2	AF & Thermal	Line Plane	13.1°	67.8°	14	-154.3	-0.85	2.3°	2.9°
1&2	AF & Thermal	Line Plane	15.7°	65.2°	25	-134.5	-0.79	1.8°	2.1°

estimated age of 950 A.D. I had hoped to find an acceptable fit to the archaeomagnetic curve for the southwestern United States, SWCV588, of Eighmy and Klein (1988). This curve covers 1650 A.D. to 580 A.D. No VGP from any of the mean directions falls on this curve. The directions are all steeply inclined, producing a VGP latitude between 70° and 73°, latitudes lower than any in SWCV588. Acceptance of the directions and SWCV588 as accurate eliminates any time between 580 A.D. and 1650 A.D. as possible ages of eruption.

In order to cover a wider age range I turned to a second source of paleomagnetic directions, lake sediments. Although lake sediments have the advantage of providing a continuous record of the magnetic field, they are not as well constrained in age as archaeomagnetic data. This is due to uncertainties in both the exact age of the sediments, due to a lack of organic carbon in the sediments, and the time of acquisition of the magnetic direction. The magnetic direction is not necessarily acquired at the time of deposition but may be acquired later during dewatering of the sediments. This study is hindered by a third disadvantage of lake sediment records, the lack of a good record for the southwestern United States. While the archaeomagnetic curve has been developed for this region, good lake sediment curves are not available. This latter problem necessitates considering any ages from lake sediment correlation only approximate.

The closest published curve is from Fish Lake, Oregon, a significant distance away (Verosub et al., 1986). Because the earth's magnetic field is not a true dipole, a simple comparison of my direction with this curve is much less precise than comparison with the closer archaeomagnetic curve. To account for this lack of precision, Salyards (1989) developed curves for 95% confidence limits on extending local SV curves over regional distances. Comparing the Carrizozo malpais with Fish Lake, Oregon, this uncertainty would be $\pm 3.0°$ in the declination and $\pm 2.5°$ in the inclination. This uncertainty includes the "westward drift" component of the magnetic field. The lack of constraint on the age does not make this component worth considering separately.

The magnetic direction at Fish Lake from the group VGPs, and the combined group VGP is plotted in Fig. 5 with the corresponding uncertainty. There are three regions where either the declination, the inclination, or both are within our preferred range: 400 yrs b.p. (1580 A.D.) to present, about 2700 yrs b.p., and 4800 to 5000 yrs b.p.

The most recent age range is within the historical period for New Mexico. Although there are no reports of volcanic activity, the historical period for this local area probably began about in 1850, with significant development following the discovery of gold near Nogal in 1865. Eruption of the flows could have occurred between 1645 and 1850, but two arguments show this as unlikely. The first is the appearance of the flow. Although youthful, some vegetation growth has taken place and some soil development has occurred. I consider it unlikely that this would have occurred within the requisite 300 years in this arid environment. Second, the sketchy magnetic data for this area do not favor this inter-

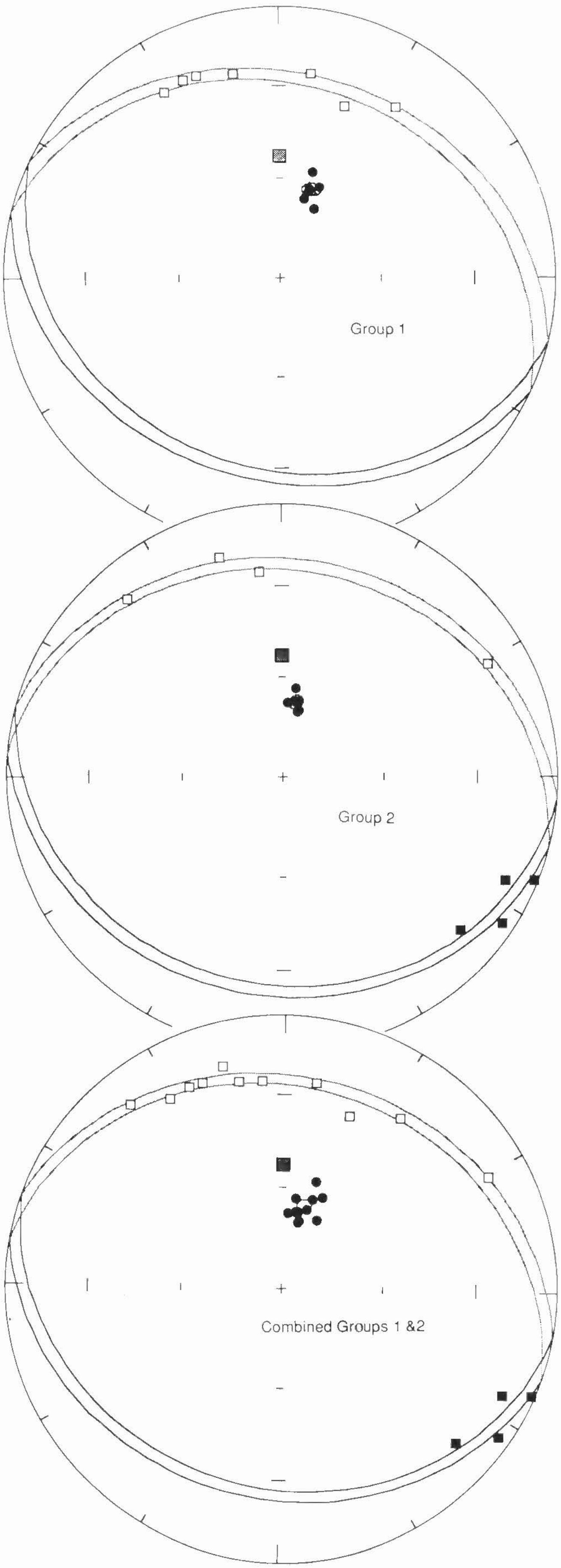

FIGURE 4. Equal-area plot of poles to planes and lines fit to AF demagnetization paths. Circles and ovals show the 95% confidence limits on mean combined direction and great circle to the mean direction. Squares are the dipole field direction; triangles, where present, are the mean directions of the planes alone.

pretation. In 1645 the magnetic pole was a significant distance from our preferred VGP and time would be necessary to travel to that position, at least several decades, making the flow younger and placing it closer to the historical period. Spherical harmonic analysis of the earth's magnetic field for epochs between 1600 A.D. and 1910 A.D. by Barraclough (1974) show the magnetic declination at about 0° in 1600, in exact agreement with SWCV588, and slowly increasing to the historical value of 10° in 1910. The magnetic declination does not exceed this value, precluding a match to either of our group mean directions.

It must be noted, however, that for an SV-dating study a direction from a spherical harmonic analysis does not provide a particularly well constrained direction. The fit to the magnetic field is smoothed and the detail is limited by location of data points, most of which were from nautical observations. Although suggestive, it is not definitive and so an age in this range cannot be dismissed.

I have no conclusive way to choose between the remaining two age ranges. For neither age range is there agreement for both the declination and the inclination. The younger age of about 2750 yrs b.p. would be preferable if the youthfulness of the flow, particularly its similarity to the most recent flows in the Craters of the Moon field, is considered.

Alternatively, the preferred VGP is closer to the direction between 4800 and 5000 yrs b.p. At 2750 b.p. the VGPs have an angular separation of 13° with the combined group direction, while at 5000 b.p. the angular separation is 5°. In addition, at 2750 b.p. the maximum declination and the inclination lag slightly in phase with the maximum declination almost 200 yrs before the high inclination is reached. Based upon these considerations I favor an age of approximately 5000 yrs b.p. for the age of the Carrizozo malpais.

An important independent constraint on this preferred age is a preliminary ^{36}Cl age on these lava flows. Leavy (1987) reported isotopic information on two samples from the Carrizozo malpais collected about 1 km northwest of group 2. Although no age was reported by Leavy, all of the necessary information is reported to calculate one. The first sample, CZ-1, was found to have a very low chlorine content (<25 ppm) and so the age represents a maximum age on the sample. The sample has a normalized ^{36}Cl/Cl ratio of $<1108 \times 10^{-15}$. This represents a maximum age of 0.042 Ma based upon the production rate of ^{36}Cl predicted by the rock chemistry, or a maximum age of 0.160 Ma based upon the reference curve. Sample CZ-2 had a higher chlorine content, providing a better age estimate. Its normalized ^{36}Cl/Cl ratio was 41×10^{-15} for age ranges of 4533-5911 b.p. (rock chemistry) and 4300–5607 b.p. (reference curve). Although these two samples are widely different in estimated age, the better sample (CZ-2) certainly provides support for my proposed age of about 5000 b.p.

CONCLUSIONS

There are three possible responses to the constraints on the age of the Carrizozo malpais. The first is the acceptance of the age of about 5000 yrs. The direction is unique, generally stable and in good agreement between the two sites. Therefore, this is our preferred hypothesis.

I could reject this age for one of two reasons. First, the rocks may not accurately preserve the magnetic field direction, a possibility I discuss below. Second, and more important, this magnetic field direction may have also occurred more recently but is not recorded in the master curves. Two processes remove detail from both SWCV588 and the Fish Lake curve. The first is finite sampling. The SWCV588 curve is dependent upon identified archaeological sites and so a time interval with few or no sites will be poorly represented in the curve. The Fish Lake curve is more complete, but still has a finite sampling interval making it possible, although unlikely, to miss a magnetic field direction this far away from the axial dipole field.

A second process that removes detail from both of the secular variation curves is the application of a filter. Used to smooth the curves,

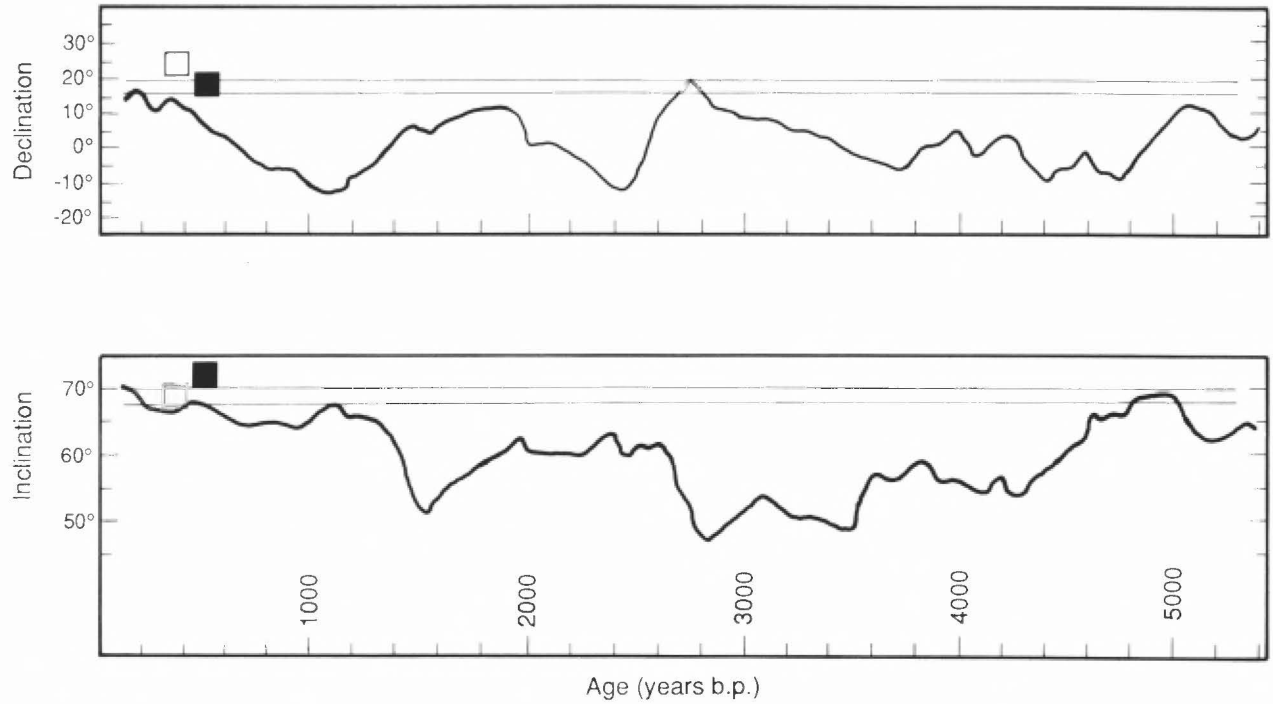

FIGURE 5. Declination and inclination from sediments from Fish Lake, Oregon, from Verosub et al. (1986). Magnetic declination and inclination at Fish Lake from the Carrizozo malpais group VGPs are shown by the open (group 1) and filled (group 2) squares. Width of the squares shows the total projected error on this direction estimate, including the error on the position of the VGP and the lack of precision induced by the translation. The lines parallel to the age axis show the magnetic field direction at Fish Lake from the combined group VGP. The higher value line is the magnetic field direction, the lower value line shows the total projected error on this direction estimate.

the filters would average out magnetic directions, removing extreme directions such as the observed direction. However, in the raw data for both SWCV588 and the recent portion of the Fish Lake curve this direction is not observed, indicating that it was not present to be averaged out. In summary, neither sampling nor averaging present compelling evidence that this direction occurred at a time more recent than 5000 yrs b.p. and was missed in the secular variation curve.

A final consideration is the quality of the magnetization of the samples. Since the samples, particularly those in group 2, have a strong and stiff magnetization and smooth demagnetization paths, the magnetization appears to be primary. Significantly, within each group there is good agreement in directions, and between groups there is enough continuity to eliminate the possibility of significant disruption of either site. No evidence suggests that we are not seeing the primary magnetization.

Accepting the direction as accurate, the obvious test is to date the flow using another method, possibly collecting more samples for a definitive ^{36}Cl date. If the flow is significantly younger than 5000 yrs b.p., it will provide a well constrained magnetic field direction with good age control and a direction not presently reflected by our SV master curves.

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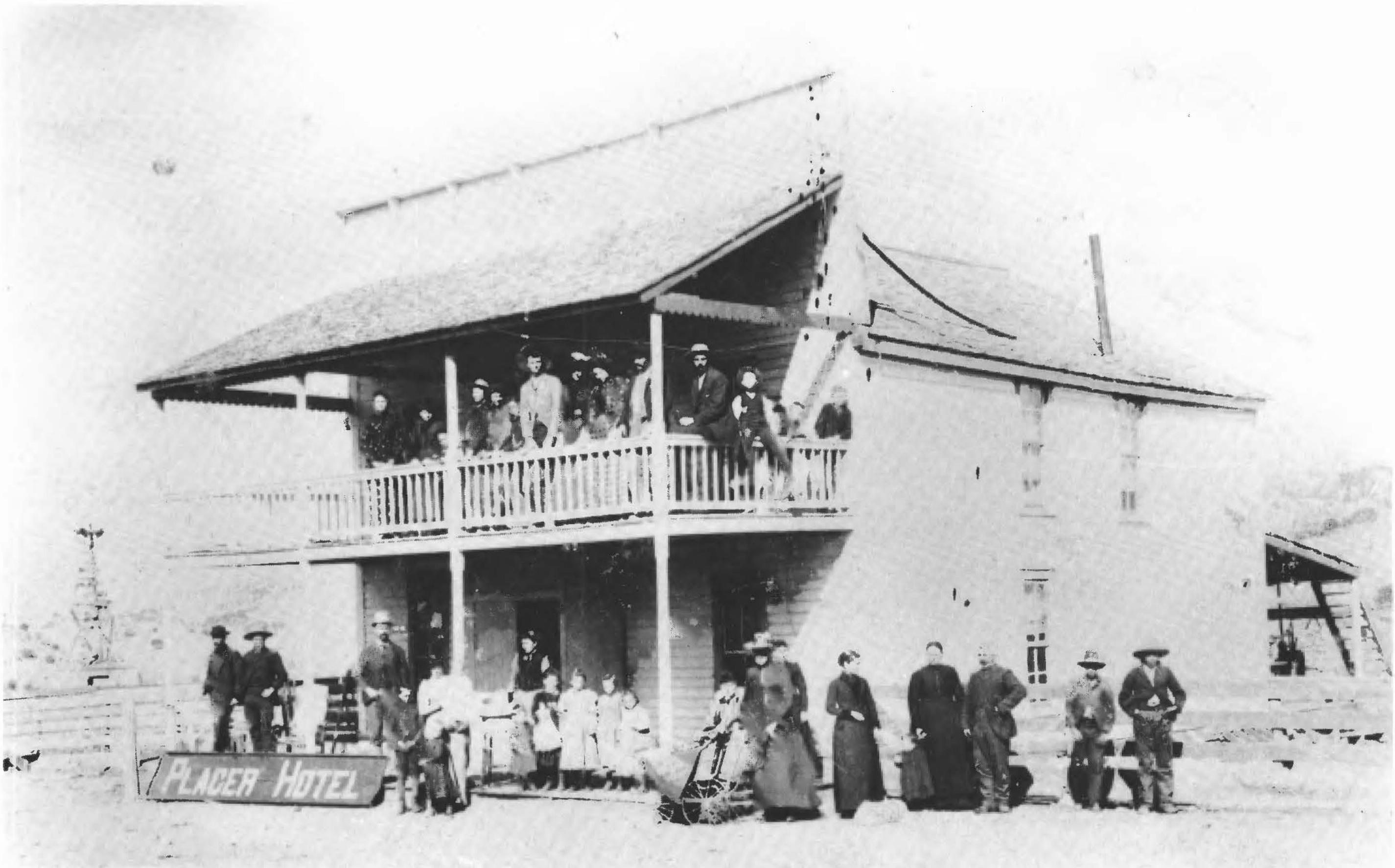

The Placer Hotel at Nogal was the place to stay when mines such as the American, Helen Rae and Parsons were in full production circa 1890. Many of the locals have turned out in their Sunday best for the above photo, possibly marking the grand opening of the structure. Photo courtesy of Rio Grande Historical Collections, Ms 98, RG78-17/7, New Mexico State University, Las Cruces.