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Paleomagnetism of Late Jurassic Rocks in the Northern Canelo Hills, Southeastern Arizona

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The Canelo Hills volcanics are exposed in the Canelo Hills, a northwest trending range in Santa Cruz County, southeast Arizona. The formation is composed of silicic tuffs and flows as well as volcaniclastic conglomerates and sandstones. Strikes of the rocks are generally to the northwest with moderate dips to the southwest and northeast. Apparent age results from the sequence studied paleomagnetically include two published isotopic dates of 147 ± 6 Ma (K-Ar, biotite) and 149 ± 11 Ma (whole rock, Rb-Sr) and a Rb/Sr isochron age, reported here, which indicates an age of 151 ± 2 Ma. Paleomagnetic samples were collected from 17 cooling units in the northern Canelo Hills. Samples from most of these units responded to alternating field (af) demagnetization, and secondary components were generally erased by peak af between 10 and 50 mT. Samples from five sites showed no response to af demagnetization. Thermal demagnetization of samples from these units produced no significant changes in direction of natural remanent magnetization (NRM), although within-site clustering of NRM directions was improved. Data from two sites were rejected because of failure to isolate a well-determined characteristic NRM. Of the remaining 15 sites, 10 sites were of normal polarity, while five sites showed reversed polarity. Intensities of the characteristic NRM ranged from 4×10^{-3} to 3×10^{-1} A/m. The data from these 15 cooling units yield a formation mean direction of I = 29.9°, D = 334.9° with k = 33.4 and α_{95} = 6.7°. The resulting paleomagnetic pole is at 62.2°N, 130.3°E (dp = 4.1°, dm = 7.4°). This pole is between poles obtained from the Summerville and lower Morrison formations. The Canelo Hills pole is thus consistent both in position and age with the Late Jurassic episode of rapid apparent polar wander originally defined by paleomagnetic data from the Summerville and Morrison formations.

INTRODUCTION

As discussed by *Steiner and Helsley* [1972] and *Steiner* [1975], the Mesozoic apparent polar wander (APW) path for North America is quite well known during Triassic and Cretaceous time but lacks definition during the Jurassic. Compilations of paleomagnetic pole positions for North America indicate that the Cretaceous pole position is well determined at 68°N, 186°E with A_{95} of 2.3° [*Mankinen*, 1978]. The paleomagnetic pole position for Late Triassic time is also reasonably well determined. *McElhinny* [1973] gives an average Late Triassic pole of 68°N, 97°E with A_{95} of 6°, which agrees well with the 200-Ma pole of *Irving* [1979] at 68°N, 93°E and A_{95} = 6°. The Late Triassic and Cretaceous poles are thus separated by ~40° of arc, suggesting substantial APW during Jurassic time.

If one restricts consideration to paleomagnetic studies of Jurassic rocks which (1) possess a well-determined characteristic natural remanent magnetization (NRM), as evidenced by thorough magnetic cleaning experiments and lack of present field overprint, (2) are reasonably well dated either on biostratigraphic or isotopic evidence, and (3) are located within stable North America, then only the results from the Summerville and Morrison formations can be considered. These formations of the Colorado Plateau have been extensively studied by *Steiner and Helsley* [1972, 1975] and *Steiner* [1978]. The Summerville Formation is dated as probably middle Callovian age (late Middle Jurassic) [*Imlay*, 1980; *Pipiringos and Imlay*, 1979] and, on the Jurassic time scale of *Van Hinte* [1978], has an absolute age of approximately 150–155 Ma. However, it should be noted that no diagnostic fossils are known from the Summerville Formation, and a geologic age can only be assigned by inferences drawn from regional stratigraphic correlations relative to fossiliferous units. Also, geologic time scales for the Jurassic show significant differences in the absolute ages assigned to stages within the Jurassic. For example, *Van Hinte* [1978] gives the upper and lower boundaries of Callovian as 149 and 156 Ma, whereas *Armstrong* [1978] gives these same boundaries as 162 and 168 Ma. Although we favor the time scale of *Van Hinte* [1978], it must be remembered that the absolute age of the Summerville probably cannot be confined any better than 150–165 Ma.

The Morrison Formation is of Kimmeridgian age [*Pipiringos and O'Sullivan*, 1978], indicating an absolute age of approximately 138–143 Ma [*Van Hinte*, 1978]. The paleomagnetic pole from the Summerville Formation (68°N, 111°E) is near the Late Triassic pole, while the paleomagnetic poles from the lower and upper portions of the Morrison Formation are between the Summerville and Cretaceous poles. As concluded by *Steiner* [1975], the available Jurassic paleomagnetic poles thus suggest that APW from the Late Triassic pole to the Cretaceous pole may have taken place within a relatively short time interval between late Middle Jurassic (160 Ma) and the Jurassic-Cretaceous boundary (135 Ma).

Determining the timing and path of apparent polar wander during the Jurassic is quite important. Paleomagnetic poles obtained from allochthonous terranes must be compared with equivalent age pole positions from cratonic North America in order to draw conclusions regarding amount of

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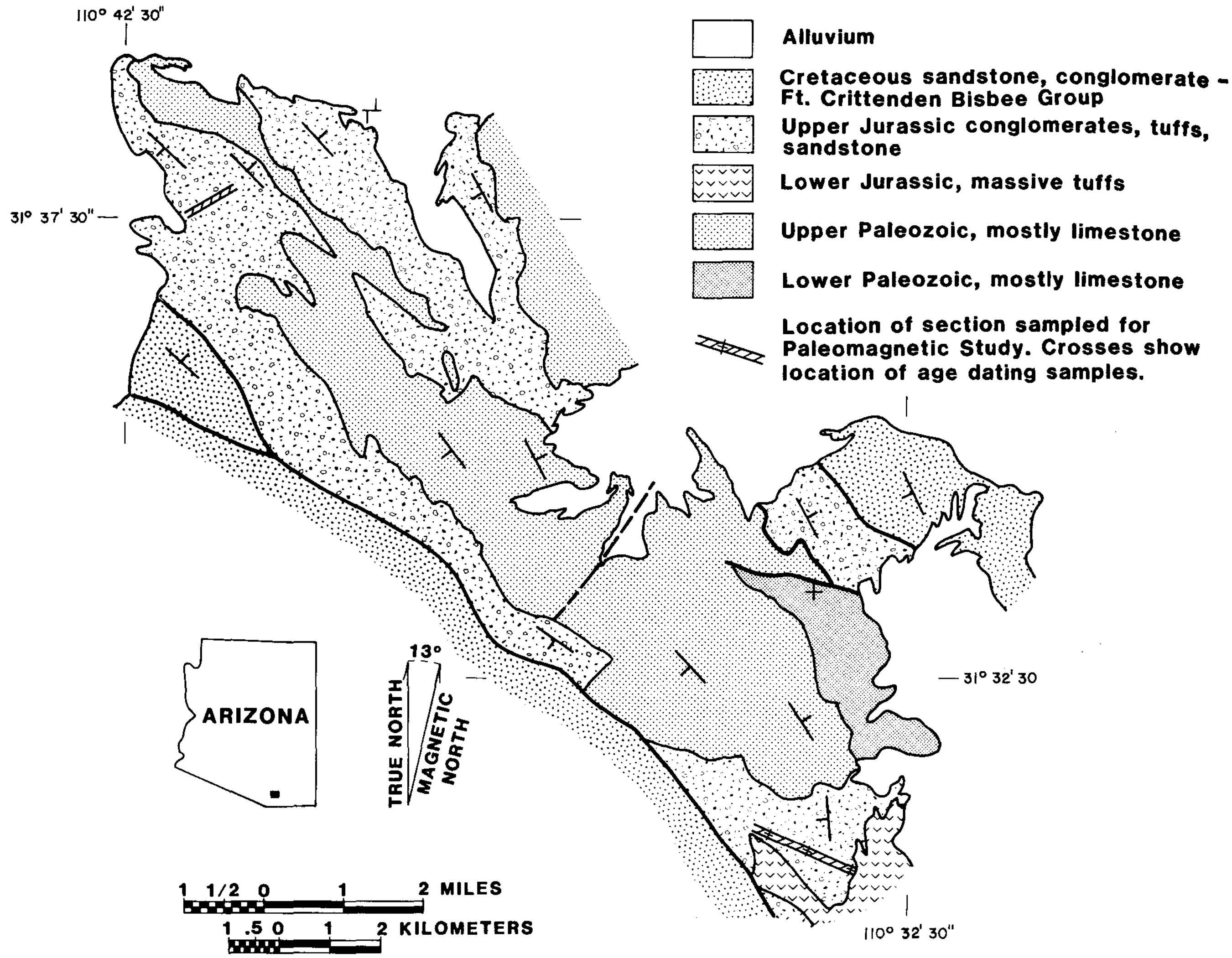

Fig. 1. Generalized geologic map of the northern Canelo Hills [after *Kluth*, 1982]. Double lines indicate sampled section. Crosses indicate Rb/Sr dating samples.

displacement. This cannot be done satisfactorily as long as portions of the APW path are not well established. Also, correspondence between episodes of APW and tectonic events such as reorganization of plate motions and initiation and rates of seafloor spreading cannot be assessed without a well-established APW path. The Late Jurassic is of particular interest, as this is the time of initial opening of the central Atlantic produced by separation of North America and Africa. In addition, episodes of rapid APW are critical in evaluating parameters such as minimum absolute velocities of continental plates [*Gordon et al.*, 1979]. Additional paleomagnetic data from North American rocks are badly needed to more clearly establish the episode of rapid APW during the Late Jurassic, which is suggested by the data from the Morrison and Summerville formations. We report here the results of a paleomagnetic and radioisotopic study of the Jurassic Canelo Hills volcanics in southeastern Arizona.

Geologic Setting

The Canelo Hills are low, northwest trending linear hills in Santa Cruz County, Arizona (Figure 1). The hills are underlain by Paleozoic sedimentary rocks typical of southeastern Arizona [*Bryant*, 1968] and Mesozoic volcanic and sedimentary rocks of the Canelo Hills volcanics [*Hayes et al.*, 1965].

The Canelo Hills volcanics are a thick sequence of silicic tuffs and flows and volcaniclastic conglomerates and sandstones deposited unconformably on the Paleozoic rocks. As originally described, the sequence was divided into three informal members [*Hayes et al.*, 1965]. The lowest unit is made up of interbedded red sandstones, conglomerates, and silicic tuffs exposed mainly in the northern Canelo Hills. Large exotic blocks of Paleozoic sedimentary rocks are incorporated into the red sandstones of this unit [*Hayes et al.*, 1965; *Simons et al.*, 1966; *Hayes and Raup*, 1968; *Denney*, 1971; *Davis et al.*, 1979]. According to *Hayes et al.* [1965], the volcaniclastic unit is overlain by a middle member of rhyolite lavas and a thick upper unit of massive, welded tuffs. Recent mapping in the northern Canelo Hills [*Kluth*, 1981, 1982] (Figure 1) has shown that the red sandstones, conglomerates, and tuffs of the 'lower' member actually rest depositionally on top of the 'upper' massive welded tuffs.

The sites sampled for this study were from two sections within the 'lower' red sandstones, conglomerates, and welded tuff unit. One of the sections is a welded tuff sequence within the middle of this unit, located at the northwestern end of the study area (Figure 1). The other section consists of interbedded sandstones, conglomerates, and welded tuff from the upper part of this 'lower' unit. It is located just northwest of Canelo Pass at the southeastern end of the study area (Figure 1).

The northwestern part of the study area is a highly faulted anticlinal flexure. The southeastern part of the study area consists of highly faulted generally homoclinally southwest to westerly dipping rocks. All of the field data indicate that deformation was brittle in nature. All exposed folds have concentric form. Detailed mapping [*Kluth*, 1982] shows that rocks on the opposing limbs of this anticline have the same strike direction. This indicates that the fold axis has almost no plunge in this area. This suggests that rotation of rocks back to original horizontality is possible around the strike of bedding or foliation. In general, original horizontality can be determined from eutaxitic foliation in the welded tuffs. In many cases, the orientations determined for the tuff units was confirmed by strike and dip of intercalated sedimentary units.

The age of the 'lower' volcaniclastic unit studied here was reported by *Hayes* [1970] as 144 ± 4 Ma and recalculated by *Marvin et al.* [1978] to 147 ± 6 Ma (K-Ar on biotite). *Hayes et al.* [1965] had reported an age of 173 ± 7 Ma (K-Ar on biotite) for the 'upper' massive welded tuffs. To solve this obvious dilemma, *Hayes* [1970] interpreted the biotite from the 'lower' member to be altered and to have lost argon. He suggested that since both ages are probably minimum ages due to possible argon loss, the age of the 'lower' unit was greater than approximately 177 Ma. *Marvin et al.* [1978] reported a Rb-Sr age (Rb-Sr, whole rock) of 149 ± 11 Ma for the volcaniclastic unit that *Hayes* (1970) had dated. The age of approximately 150 Ma for this 'lower' unit is considered to be compatible with the field data discussed above [*Kluth*, 1981, 1982], and this unit is approximately 25–30 Ma younger than the 'upper' massive welded tuff unit. The two previously published isotopic age dates on the volcaniclastic rocks and the concordant age date presented here are the best documented ages yet published for any mid-Mesozoic rocks in southeastern Arizona.

Rb-Sr Dating

Sampling and Analytical Technique

Five samples from three localities (Figure 1) were analyzed for Rb and for Sr isotopes to determine an isochron. Strontium was separated by conventional ion exchange techniques and analyzed using a computer controlled 6-inch, 60° sector single focusing mass spectrometer having a triple filament thermionic source. Total strontium was determined by isotope dilution and rubidium by atomic absorption techniques. Analyses of the Eimer and Amend interlaboratory standard $SrCo_3$ gave a mean of 0.70799. All isotopic analyses were normalized to an $^{86}Sr/^{88}Sr$ ratio of 0.1194. The mean experimental uncertainties were taken as ±2% for $^{87}Rb/^{86}Sr$ for the data listed in Table 1.

Discussion of Age

The Canelo Hills volcanics define a Rb-Sr isochron for an age of 151 ± 2 Ma (Figure 2). The computed initial ratio is 0.7092 ± 0.0009 (σ), within the range of 0.7069 to 0.7096 typical of mid-Tertiary volcanic rocks in southeastern Arizona [*Damon and Shafiqullah*, 1976; *Shafiqullah et al.*, 1978, 1980]. *Lafferty* [1981] also noted high initial ratios around 0.7095 for Late Jurassic rocks in the Big and Little Maria Mountains of eastern California. The mid-Tertiary volcanic rocks are interpreted to have initial ratios higher than mantle values for this area because of a significant crustal component in the magmas generated by the regressing magmatic arc. We believe we are justified in a similar interpretation for the scattered data from the transgressing Jurassic magmatic arc [*Damon et al.*, 1981].

TABLE 1. Rb-Sr Analytical Data for Canelo Hills Volcanics, Southeastern Arizona

Sample	Rb, ppm	Sr, ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm \sigma$
UAKA-80-44a	365.0	23.55	45.272	0.80555 ± 0.00022
UAKA-80-44b	420.0	26.08	47.064	0.81082 ± 0.00025
UAKA-80-45	100.0	71.10	4.074	0.71797 ± 0.00017
UAKA-80-46a	170.0	60.74	8.110	0.72387 ± 0.00016
UAKA-80-46b	205.0	84.05	7.069	0.72503 ± 0.00030

Paleomagnetic Analysis

Oriented core samples were collected at 17 sites, each in a separate flow or tuff unit. Locations of these sites are illustrated in Figure 1. Coring techniques were similar to those described by *Doell and Cox* [1967], and core orientation was accomplished using a Brunton compass. Seven to nine cores were collected at each site. In addition, seven cores were collected from cobbles and small boulders in a conglomerate layer interbedded within the volcanics. Structural attitude of each flow unit was determined, and all directions of magnetization were corrected by restoring the units to horizontal. As several sandstone units are interbedded with the volcanics, the original attitude of the volcanics can be well established. Measurements of natural remanent magnetization (NRM) were done using a cryogenic magnetometer (ScT C-102) while a single-axis (Schonstedt GSD-1) demagnetizer was used for alternating field (af) demagnetization. A furnace with mu-metal shielding was used for thermal demagnetization. Magnetic field in this thermal demagnetization apparatus is less than 10 gamma (1 gamma = 10^{-9} T).

Progressive Demagnetization

Following initial measurement of NRM, a representative sample from each site and all samples from the conglomerate were subjected to progressive af demagnetization to peak fields of at least 40 mT (1 mT = 10 Oe). Samples showing

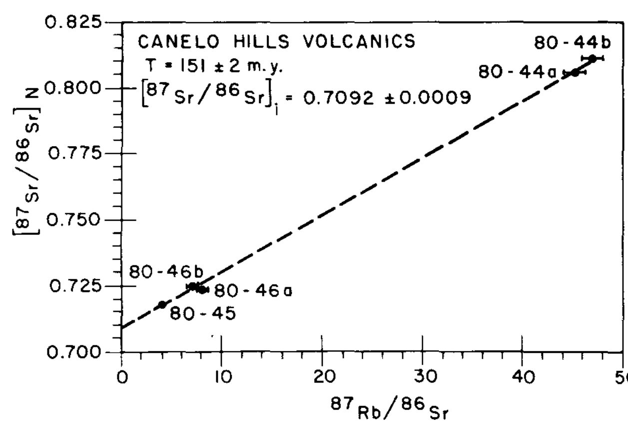

Fig. 2. Rb/Sr isochron $^{87}Sr/^{86}Sr$ ratios are plotted against $^{87}Rb/^{86}Sr$ ratios. The resulting isochron indicates an age of 151 ± 2 Ma.

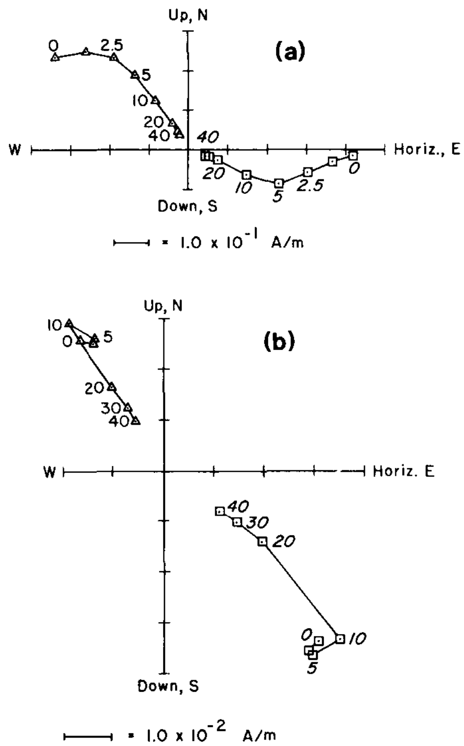

Fig. 3. Vector demagnetization diagrams. Response of samples CH029E and CH028B to progressive af demagnetization is illustrated in Figures 3*a* and 3*b*, respectively. This vector demagnetization diagram plots the horizontal projection of the NRM vector with triangles, while the vertical versus horizontal components are plotted by squares. Numbers adjacent to data points indicate the peak af in mT.

little or no response to af demagnetization were subsequently thermally demagnetized. Two contrasting responses to the progressive demagnetizations were observed.

The majority of the pilot samples did respond to af demagnetization. Vector demagnetization diagrams for two representative samples are illustrated in Figure 3. Low coercivity, secondary components of NRM are present but are erased by af demagnetization to peak fields of between 10 and 60 mT. Most samples exhibited a linear trend toward the origin in the vector demagnetization diagram at peak af $\geq$ 20 mT. The vector demagnetization diagrams were used to determine the peak alternating field required for removal of the secondary components.

Subsequent thermal demagnetization of samples responding to af demagnetization revealed a blocking temperature spectrum distributed below 580°C. No change in direction of NRM was observed during thermal demagnetization. Acquisition of isothermal remanent magnetization (IRM) by samples responding to af demagnetization revealed a positive slope up to a magnetizing field of 300 mT but no significant increase in IRM at higher magnetizing fields. The af and thermal demagnetization behavior and IRM acquisition properties of these samples indicate that magnetite is the dominant carrier of the remanent magnetization.

Pilot samples from five sites showed no response to af demagnetization up to 40-mT peak field. These samples were then thermally demagnetized at progressively increasing temperatures up to 680°C. No significant changes in direction of NRM were observed during this process, indicating the absence of secondary components. Most of the NRM had blocking temperatures >580°C. IRM acquisition experiments on these samples were performed in magnetizing fields up to 900 mT. IRM increased with increasing magnetizing field throughout the experiment. These observations indicate that hematite is the dominant carrier of remanent magnetization in samples from these five sites.

Conglomerate Test

Because of the variety of lithologies represented in the seven samples from the conglomerate, each sample was subjected to the progressive demagnetization experiments described above. The lithologies sampled in the conglomerate were representative of the lithologies of the cooling units in the sampled sequence. Four samples responded to af demagnetization, while three did not. Modest secondary, low coercivity components of NRM were erased from these samples at peak alternating fields $\leq$40 mT. Vector demagnetization diagrams were used to determine the peak af treatment required for each sample. The demagnetization behaviors were similar to those observed for the samples from cooling units which did respond to af demagnetization. The remaining three samples were thermally demagnetized, but no secondary components of NRM were observed.

Directions of characteristic NRM of the samples from the conglomerate are plotted in Figure 4. A mean direction was calculated using *Fisher*'s [1953] technique. The statistical parameters for the computed mean direction are $N = 7$, $R = 1.52$. With N of 7, R must exceed 4.18 for the clustering to be significant from random at the 95% confidence level [*Watson,* 1956]. The grouping of directions from this conglomerate falls far below the critical R value and is not significant from random at the 95% confidence level. This is, of course, the desired result. The conglomerate test thus indicates that no secondary components are present which are resistant to the demagnetization treatments. The characteristic NRM of the conglomerate samples was acquired prior to incorporation of the sampled cobbles and boulders in the conglomerate. This characteristic NRM is almost certainly a thermoremanent magnetization (TRM) acquired at the time of cooling of each flow or tuff. As outlined above, the demagne-

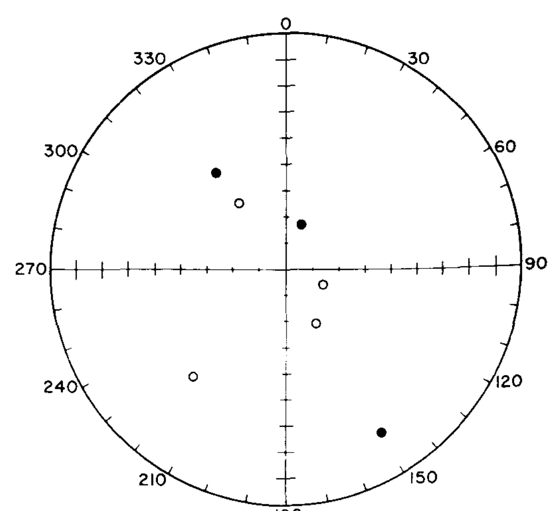

Fig. 4. Characteristic NRM directions for conglomerate samples. Projection is an equal-area stereographic projection. Solid circles are directions on the lower hemisphere, while open circles are on the upper hemisphere.

TABLE 2. Summary of Final Site Mean Results

Site	Demagnetization Treatment	I, deg	D, deg	J, A/m	N	R	k	α_{95}, deg
CH010	H40	29.6	339.1	8.9×10^{-3}	8	7.25	9.4	19.1
CH011	H60	34.1	342.8	1.3×10^{-2}	8	7.95	130.8	4.9
CH021	H40	−39.5	157.8	2.6×10^{-2}	8	7.99	487.5	2.5
CH022	T600	−24.7	125.7	5.6×10^{-2}	8	7.95	131.3	4.9
CH023	T600	−39.7	174.5	2.9×10^{-1}	9	8.97	259.4	3.2
CH026	H40	22.0	348.0	8.8×10^{-3}	9	8.84	48.7	7.4
CH027	H30	8.8	352.2	1.1×10^{-1}	7	6.99	1136.3	1.8
CH028	H30	32.7	331.6	2.8×10^{-2}	7	6.81	32.2	10.8
CH029	H20	25.3	330.8	7.8×10^{-2}	8	7.96	185.6	4.1
CH030	T600	−39.2	157.8	6.0×10^{-1}	7	6.99	436.0	2.9
CH031	T600	−36.6	161.9	4.0×10^{-2}	7	6.99	615.3	2.4
CH032	T600	17.4	323.8	1.1×10^{-1}	7	6.98	396.4	3.0
CH033	H40	29.8	324.9	5.4×10^{-2}	7	6.98	325.7	3.4
CH034	H30	30.6	323.8	1.0×10^{-2}	8	7.89	62.4	7.1
CH035	H40	29.2	331.4	4.0×10^{-3}	9	8.98	365.2	2.7

Demagnetization treatments labeled H are af demagnetizations where the number indicates the peak field in mT. Demagnetization treatments labeled T are thermal demagnetizations where the number indicates the temperature in °C. I is inclination, D is declination, J is intensity of remanence. R, k, and α_{95} are standard statistical quantities [*Fisher*, 1953].

tization behaviors and IRM acquisition behaviors of the sampled cooling units indicate that the NRM of some units is carried by magnetite, while the NRM of other units is carried by hematite. We believe that the characteristic NRM is a TRM and that the contrasting mineralogies are the result of different deuteric oxidation conditions.

Paleomagnetic Results

Samples from one site exhibited anomalously weak magnetization ($<10^{-3}$ A/m, 1 A/m = 10^{-3} G) and directions of NRM were highly scattered. Demagnetization did not improve the clustering, and consequently, the results from this site were rejected. Samples from an additional site showed large secondary components. During af demagnetization, directions of NRM for samples from this site moved toward but did not reach a stable end point. A vector demagnetization diagram showed that a linear trend to the origin was not achieved before the NRM intensities dropped to $<10^{-3}$ A/m from initial intensities of 10^{-1} A/m. Since a characteristic NRM could not be convincingly isolated, results from this site were rejected. One sample from site CH027 was rejected because (1) the NRM intensity of this sample was more than 10 times the intensity of any other sample from that site, (2) the direction of NRM of this sample was far removed from the site mean, and (3) af demagnetization failed to bring the NRM direction of this sample into the cluster of directions exhibited by the other samples at this site. We suspect that this sample had been struck by lightning.

Progressive demagnetization results were used to estimate the demagnetization treatment required to remove secondary components successfully. For sites on which af demagnetization was employed, all samples were exposed to af treatment at several peak field values surrounding the value indicated by the progressive demagnetizations as sufficient for removal of secondary components. From the resulting set of mean directions at each site, the treatment yielding the highest k value was chosen as providing the best determination of the characteristic NRM for that site. Sites for which af demagnetization was not effective were thermally demagnetized at 600°C. As indicated by the progressive demagnetizations, no significant change of the site mean direction of NRM resulted from this treatment. However, some increase in k value (decrease in α_{95}) was observed. Site mean directions, demagnetization treatments, and *Fisher* [1953] statistical parameters are listed in Table 2.

Stereographic projections of directions of magnetization following magnetic cleaning are illustrated in Figure 5 for two representative sites. Site CH027 (Figure 5*a*) is illustrative of sites with very tight within-site grouping of characteristic NRM directions. Results from site CH022 (Figure 5*b*) are more typical of the majority of sites. Only two sites show $\alpha_{95} > 10°$, so that all site mean directions are very well determined.

The site mean directions are plotted in Figure 6. Ten cooling units are of normal polarity, while five cooling units have reversed polarity. The mean directions of the normal and reversed polarity groups are not statistically significant from antipodal. The intersite scatter of directions is attributed to sampling of geomagnetic secular variation. The presence of both polarities, along with the observed intersite scatter of directions, suggests that the formation mean direction provides an accurate measure of the time-averaged geomagnetic field at the collecting locality during the interval of geologic time represented by this volcanic sequence.

A formation mean direction was calculated by averaging the antipodes of the site means from the reversed polarity sites with the site means of the normal polarity sites. The resulting formation mean direction is inclination = 29.9° and declination = 334.9° with α_{95} = 6.7°. A summary of the formation mean results and statistical parameters is provided in Table 3. The paleomagnetic pole calculated from this mean direction is λ_p = 62.2°N, ϕ_p = 130.3°E, with dp = 4.1° and dm = 7.4°.

DISCUSSION AND CONCLUSIONS

The southern Basin and Range Province, within which the Canelo Hills volcanics are located, has been subjected to three orogenic-tectonic episodes since the Late Jurassic. The Laramide orogeny in the Late Cretaceous through early Tertiary was an interval of compressive tectonics. The mid-Tertiary orogeny is characterized by extension of a warm and ductile crust, while the Basin and Range disturbance

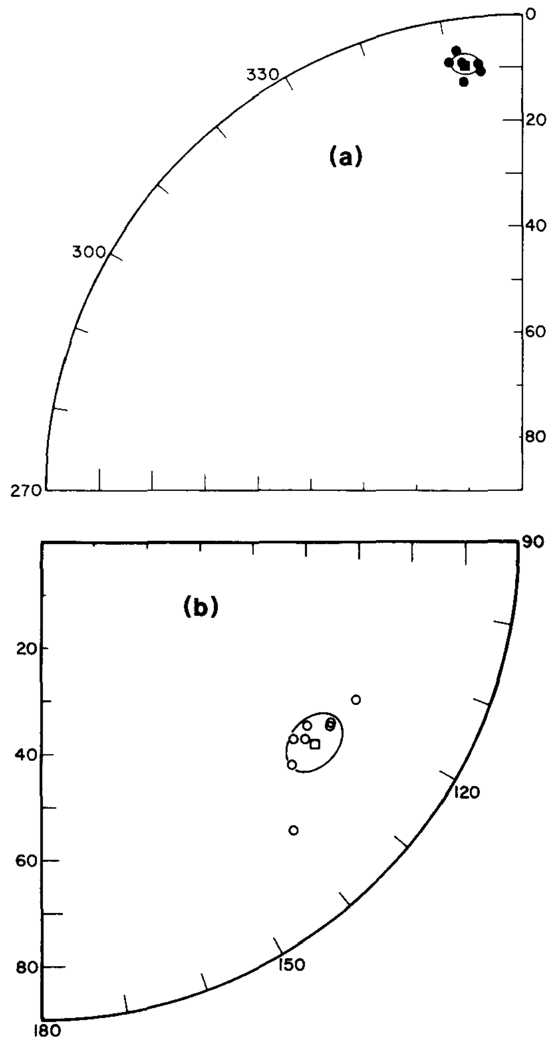

Fig. 5. Primary NRM directions and site means for sites CH027 (Figure 5*a*) and CH022 (Figure 5*b*). Projections are quadrants of equal-area stereographic projections. Solid circles are on lower hemisphere, while open circles are on upper hemisphere. The squares indicate the site mean directions and the circle of 95% confidence is plotted surrounding the mean direction.

TABLE 3. Summary of Formation Mean Results

	Value
Site Location: 31.5°N, 249.5°E	
Im	29.9°
Dm	334.9°
N	15
R	14.58
k	33.4
α_{95}	6.7°
Pole Location: 62.2°N, 130.3°E	
dp	4.1°
dm	7.4°

N, *R*, *k*, and α_{95} are standard statistical parameters [*Fisher*, 1953], while *dp* and *dm* are the semiminor and semimajor axes of the error oval surrounding the pole position. *Im* and *Dm* are mean inclination and mean declination.

involved continued extension of progressively cooler and more brittle crust. Therefore, the applicability of the paleomagnetic pole from the Canelo Hills Volcanics to construction of an APW path for 'stable' North America is at least initially open to some doubt. There are several lines of evidence which we think justify use of the Canelo Hills pole as a reference pole for stable North America.

Geologic evidence indicates that deformation in southeastern Arizona during Basin and Range tectonism is the result of simple crustal extension of approximately 20% [*Coney*, 1978]. No rotations about vertical axes are required in order to reconstruct the pre-Basin and Range configuration of the present ranges in southeastern Arizona. As discussed by *Vugteveen et al.* [1981], paleomagnetic poles from Laramide igneous rocks in southeastern Arizona are consistent with poles of similar age from other areas within the western interior of North America. It thus appears that tectonic disturbance sufficient to produce disparity of paleomagnetic results from southeastern Arizona with results from stable North America did not occur during either the Laramide or subsequent tectonic events. However, in the final analysis, the best argument for use of the Canelo Hills paleomagnetic data for stable North America is the resulting internal consistency of the presently available Jurassic paleomagnetic poles.

Figure 7 illustrates the paleomagnetic pole from the Canelo Hills volcanics along with the poles from the Summerville and Morrison formations. Also illustrated are *Irving*'s [1979] averaged poles for 200 and 190 Ma and the Cretaceous average given by *Mankinen* [1978]. Details for these paleomagnetic poles and references are given in Table 4.

The paleomagnetic pole obtained from the Canelo Hills volcanics falls on the path defined by the Summerville and lower and upper Morrison poles. The progression of the poles is also consistent with the relative ages of the formations, the Canelo Hills volcanics being younger than the Summerville Formation but older than the Morrison Formation. This internal consistency of age and paleomagnetic pole progression provides support for the Late Jurassic episode of rapid APW initially defined by the Summerville and Morrison data [*Steiner and Helsley*, 1975; *Steiner*, 1978].

As outlined by *Steiner and Helsley* [1972], the proximity of the pole from the Summerville Formation to the Late Triassic and Early Jurassic poles [*Irving*, 1979] indicates that

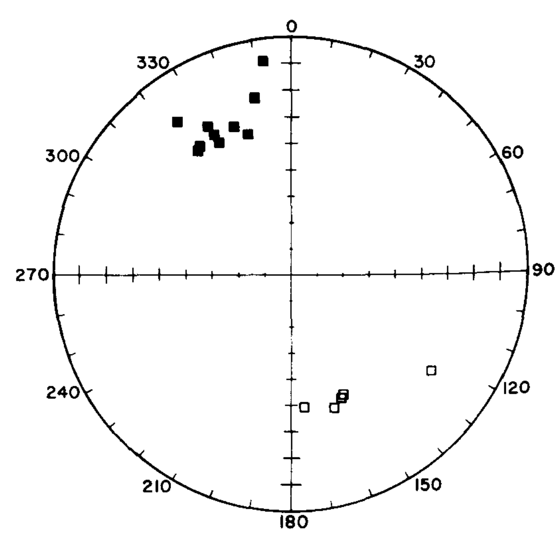

Fig. 6. Site mean directions plotted on equal-area stereographic projection. Details of site mean directions are listed in Table 2. Solid squares are site mean directions on the lower hemisphere, while open squares are site mean directions on the upper hemisphere.

TABLE 4. Paleomagnetic Poles of Figure 7

			Pole				
Symbol	Name	Age, Ma	Latitude °N	Longitude °E	A_{95}, deg	*dp*, *dm*, deg	Reference
200	200-Ma average	200	68.0	93.0	6.0		*Irving* [1979]
190	190-Ma average	190	72.0	95.0	6.0		*Irving* [1979]
S	Summerville	150–155	67.6	110.8		3.2, 5.4	*Steiner* [1978]
CH	Canelo Hills	150	62.2	130.3		4.1, 7.4	this study
lM	lower Morrison	138–143	61.4	142.2		4.0, 6.5	*Steiner and Helsley* [1975]
uM	upper Morrison		67.5	161.7		3.5, 5.0	*Steiner and Helsley* [1975]
K	Cretaceous average	135–80	67.9	185.9	2.3		*Mankinen* [1978]

APW between the Late Triassic and Cretaceous poles took place largely during the Late Jurassic. Only a small amount of APW occurred during Early and Middle Jurassic time. The APW path from the Summerville pole through the poles from the Canelo Hills volcanics and Morrison Formation to the Cretaceous pole is approximately along a line of latitude in present-day geographic coordinates. As was noted by *Steiner and Helsley* [1975], the Jurassic APW path does not include the present rotation axis.

The Jurassic APW path for North America also has important implications for the opening of the Atlantic. Having noted that Triassic and Early Cretaceous paleomagnetic data from Africa show little or no apparent polar wander, *Steiner* [1975] suggested that the entire North America–Africa separation was the result of motion of the North American plate away from a stationary African plate. In addition, *Steiner* [1975] suggested that rates of North American plate motion of the order of 15 cm/yr would be required to account for the observed Late Jurassic APW. No velocities greater than 6 cm/yr were found by *Gordon et al.* [1979], but this may be accounted for by the use of time-averaged apparent pole wander paths in their calculations of minimum absolute velocities. The available evidence on Late Jurassic APW for North America strongly supports the conclusion of *Gordon et al.* [1979] that large continental plates have, in the geologic past, attained velocities comparable to present velocities of oceanic plates.

Paleomagnetic data from the Summerville and Morrison formations [*Steiner and Helsley,* 1975; *Steiner,* 1978] indicate that approximately 40° of APW on a latitudinal path took place during the Late Jurassic. Support for this episode of rapid APW is provided by the paleomagnetic and isotopic data from the Canelo Hills volcanics.

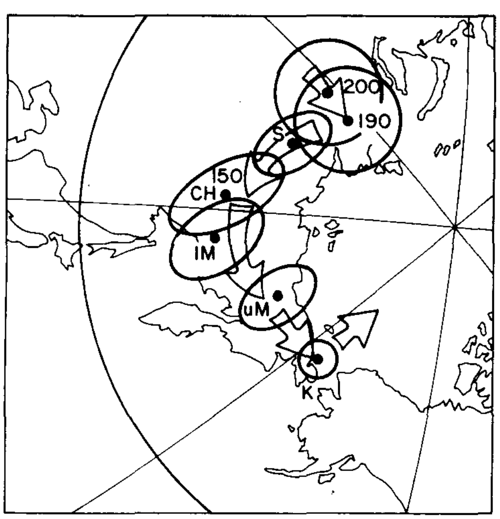

Fig. 7. Apparent polar wander path for North America from Late Triassic to Cretaceous. Pole data are listed in Table 4.

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