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PALEOMAGNETISM OF THE ROSKRUGE AND GRINGO GULCH VOLCANICS, SOUTHEAST ARIZONA

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Abstract. Paleomagnetic data were obtained from nine cooling units of the Late Cretaceous (∿72 Ma) Roskruge Volcanics and from 25 flows in the lower Paleocene Gringo Gulch Volcanics, both from southeastern Arizona. Alternating field demagnetization successfully erased the infrequent secondary components of magnetization. The paleomagnetic pole position obtained from the Roskruge Volcanics is at 73.6°N, 176.0°E with dp = 6.2° and dm = 8.8°. The Gringo Gulch Volcanics pole position is at 77.0°N, 201.0°E with dp = 1.2° and dm = 1.7°. In conjunction with other recently published Paleocene and Eocene paleomagnetic poles, these data provide details of North American apparent polar wander during the Laramide orogeny (∿80 to ∿40 Ma). An episode of rapid apparent polar wander from the Cretaceous pole position in the Bering Strait to the Eocene pole position near the present rotation axis occurred during that interval of time. The initiation of this episode of apparent polar wander appears to be coincident with the major plate reorganizations which occurred at the onset of the Laramide orogeny.

Introduction

The Cretaceous paleomagnetic pole position for North America is well determined [McElhinny, 1973; Mankinen, 1978] and is located at 68°N, 186°E with A_{95} of 2.3°. The youngest rocks yielding this pole position are the Elkhorn Mountains Volcanics. Hanna [1967] studied the paleomagnetism of the Elkhorn Mountains Volcanics and indicated that the age is 'probably middle late Cretaceous' but older than the Boulder batholith from which isotopic dates ranging from 70 to 80 Ma have been obtained. Hanna's observation of reversed polarity flows indicates that the Elkhorn Mountains Volcanics are younger than the Upper Cretaceous normal polarity interval. Lowrie et al. [1980] indicate that the Upper Cretaceous normal interval ended at about 80 Ma. Thus the age of the Elkhorn Mountains Volcanics is likely between 75 and 80 Ma.

Diehl et al. [1980] have recently reviewed paleomagnetic poles for the Eocene of North America. In addition to reporting two new Eocene poles from intrusive rocks in Montana, they computed a mean of the four reliable Eocene paleomagnetic poles. The mean Eocene pole is located at 81.7°N, 171.2°E, and A_{95} of 4.4°. The Cretaceous and Eocene poles are separated by almost 20° of arc, and a significant episode of apparent polar wander must have occurred during Late Cretaceous (post 80 Ma) and Paleocene time. In order to define more clearly this episode of apparent polar wander, paleomagnetic results from latest Cretaceous and Paleocene age rocks must be examined.

Substantial progress toward determination of the Paleocene paleomagnetic pole has been made in recent years. Butler and Taylor [1978] reported a pole position from middle Paleocene continental sediments of the Nacimiento Formation. However, they speculated that the mean direction obtained may have been subject to an inclination error. Jacobson et al. [1980] reported a Paleocene paleomagnetic pole obtained from intrusive rocks in Montana, and Barnes and Butler [1980] reported a Paleocene pole from the Gringo Gulch Volcanics. These two poles are in reasonable agreement with one another but are significantly removed from the Nacimiento pole in a direction suggesting that the Nacimiento data do contain an inclination error. The two Paleocene poles of Jacobson et al. [1980] and Barnes and Butler [1980] are located at roughly 78°N, 190°E, or about 14° of arc from the mean Cretaceous pole. The available data thus indicate that rapid apparent polar wander must have occurred during the interval from latest Cretaceous through Paleocene. Latest Cretaceous through Eocene is also the time interval of the Laramide orogeny, a major compressional tectonic episode in western North America. The degree to which the timing of the Laramide orogeny is coincident with this latest Cretaceous through early Tertiary episode of North American apparent polar wander can only be revealed by acquiring additional paleomagnetic data from rocks of this age range. Reported in this paper are the details of the paleomagnetic study of the Paleocene Gringo Gulch Volcanics and the results of a paleomagnetic study of the latest Cretaceous Roskruge Volcanics.

Geologic Setting

Locations and generalized geologic maps of the Roskruge Volcanics and Gringo Gulch Volcanics are shown in Figure 1. The Roskruge Volcanics are located in the Roskruge Mountains 60 km west of Tucson, Arizona, on the Papago Indian Reservation. The formation consists of 400 to 550 m of highly welded ash flows and air fall tuffs with thicknesses between several meters and several tens of meters for each unit. A high temperature of emplacement is evident from the extreme flattening of pumice shards during the welding process. This is most pronounced in the lowermost unit, the Viopuli Red Ignimbrite [Damon et al., 1964], which has been K/Ar dated as 76 Ma. The upper units of the formation have been K/Ar dated as 74-68 Ma (original ages by Bikerman [1967], recalculated using revised decay constants given by Steiger and Jäger [1977]).

Four to seven oriented core samples were taken from each of 11 cooling units on Bell Mountain. Cores were oriented using a Brunton compass. These orientations were tested for possible deflection by local magnetic anomalies by duplicating several core orientations using

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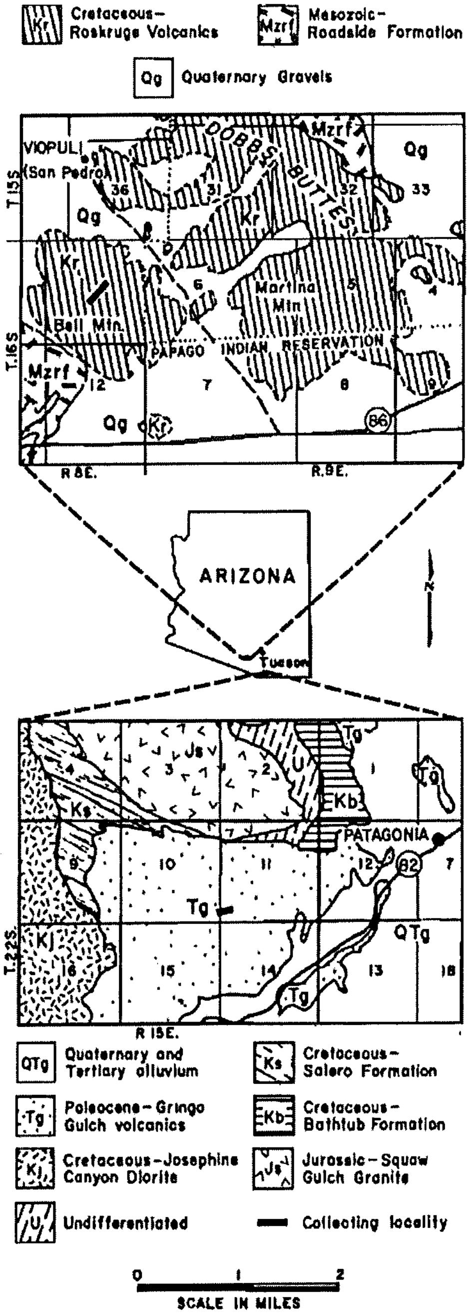

Fig. 1. Location and generalized geology of the Roskruge Volcanics of the Roskruge Mountains [after Keith, 1976] and the Gringo Gulch Volcanics of the Santa Rita Mountains [after Drewes, 1972]. Both maps at same scale.

a sun compass. However, no evidence of such deflections was found. The section in which the paleomagnetic samples were collected extended from the Viopuli Red Ignimbrite to the summit of Bell Mountain. Flows on Bell Mountain are tilted at an attitude of N76°E strike and 19°SE dip. Since this present attitude is the result of local block faulting during the Basin and Range orogeny, tectonic corrections were applied to the data to restore the beds to horizontal before the final pole position calculations were done.

With the exception of one rejected site, no units appear to have experienced even minor alteration or metamorphism. Indeed, the Roskruge Volcanics are quite unusual for their age in that many of the units contain glass shards which have not devitrified. This observation rules out the possibility of any postcooling metamorphic events having affected the Roskruge Volcanics.

The Gringo Gulch Volcanics, located in the Santa Rita Mountains near the town of Patagonia, Arizona (Figure 1), are largely a sequence of rhyolitic to dacitic tuffs with some andesitic flows. The total thickness is estimated to be between 450 and 600 m [Drewes, 1972]. Paleomagnetic collection was restricted to a sequence of well-exposed, flat-lying andesite flows approximately 40 to 50 m thick. Four to six oriented cores were collected from each of 26 flows.

The age of the Gringo Gulch Volcanics is bracketed by geologic relationships [Drewes, 1972]. The Gringo Gulch Volcanics unconformably overlie the Upper Cretaceous Salero Formation and are inferred to overlie unconformably the Upper Cretaceous Josephine Canyon Diorite, which has been dated as 65 Ma in its youngest phase. The time lapse between the emplacement of the Josephine Canyon Diorite and the extrusion of the volcanics is not thought to have been large. Furthermore, the Gringo Gulch Volcanics are intruded by the Gringo Gulch Pluton which has been K/Ar dated as 61.5 Ma [Drewes, 1976]. On the basis of these relationships, the age of the Gringo Gulch Volcanics is bracketed between 61.5 and 65 Ma and thus is assigned a lower Paleocene age.

Paleomagnetic Analysis

Oriented cores were cut into 2.5-cm-long specimens. Core diameter was also approximately 2.5 cm. Natural remanent magnetization (NRM) was measured with a ScT C-102 cryogenic magnetometer. Alternating field (AF) demagnetizations were performed using a Schonstedt GSD-1 demagnetizer. Thermal demagnetizations were performed using a noninductively wound furnace with mu-metal shields. The magnetic field in the thermal demagnetization apparatus is less than 20 gammas (1 gamma = 1 nT).

In general, the Gringo Gulch Volcanics exhibit an NRM which is notably devoid of secondary components. Following initial measurement of NRM, representative samples were subjected to detailed progressive AF and thermal demagnetizations. For most sites, the progressive demagnetizations indicated that no significant secondary components were present. Figure 2 shows a vector demagnetization diagram of a typical sample. AF demagnetization to 1000 Oe (1 Oe = 10^{-4} T) shows a basic trend toward the origin with no evidence of low coercivity secondary components. Subsequent thermal demagnetization indicates that a substantial portion of the NRM has blocking temperatures exceeding the Curie temperature of magnetite (580°C). On average, between 60 and 70% of the NRM had blocking temperatures greater than 580°C. These observations indicate that hematite must be a significant carrier of the NRM. In all cases the components of NRM with blocking temperatures greater than 580° were parallel to the components with low blocking temperatures.

A few sites with significant secondary components were encountered. When present, secondary components appeared to be simply viscous components acquired preferentially by low coercivity grains. These secondary components were almost always erased by AF demagnetization to 500 Oe peak field.

Isothermal remanence (IRM) acquisition experiments confirmed the presence of a ferromagnetic component with high coercivity. Although IRM was acquired more rapidly between 0 and 3 kOe magnetizing field, significant additional IRM was acquired up to 9 kOe. Since magnetite does not exhibit coercivities in excess of 3 kOe, the IRM acquisition experiments suggest the presence of a significant proportion of hematite.

Both magnetite (or titanomagnetite) and specular hematite were observed during microscopic examination of polished thin sections. The magnetite and specular hematite were sometimes observed in separate grains, but more commonly the specular hematite was found as very small (1 μ or smaller), wormy inclusions within much larger magnetite grains. These inclusions were neither large enough nor continuous enough to yield laths of specular hematite within the magnetite grains. The specular hematite thus appears to have been produced by deuteric oxidation which ceased before laths of specular hematite could be produced. No alteration rims on magnetite grains or other evidence of post-cooling alteration of the opaque minerals was observed. These data indicate that the primary NRM component is a thermoremanence formed during original cooling of the flows.

As with the Gringo Gulch Volcanics, many of the Roskruge Volcanics contain little or no secondary components of NRM. For some sites, the pilot samples subjected to progressive AF and thermal demagnetization showed no significant changes in direction of NRM during the demagnetization treatments. However, several units from

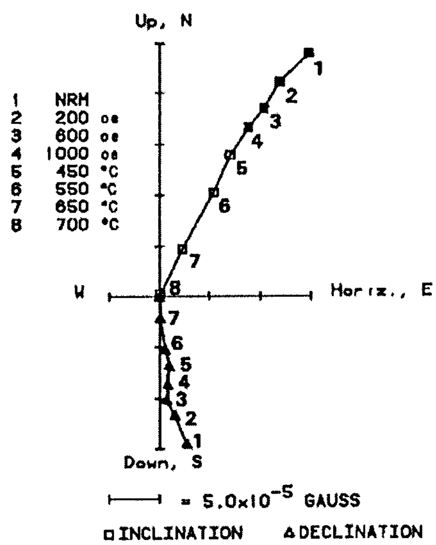

Fig. 2. Vector demagnetization diagram for a typical sample of the Gringo Gulch Volcanics. Numbers adjacent to data points refer to demagnetization treatments listed at left of diagram.

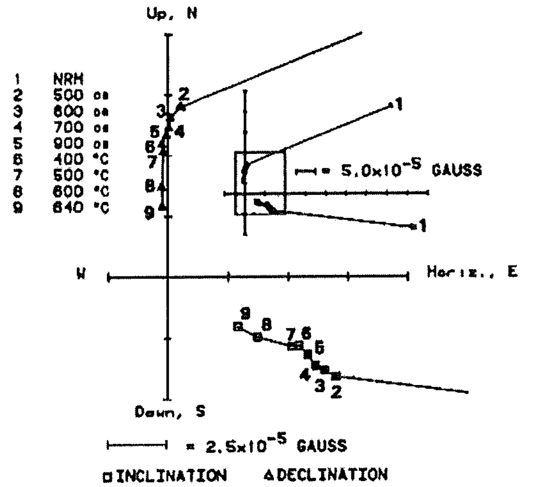

Fig. 3. Vector demagnetization diagram for the Viopuli Red Ignimbrite of the Roskruge Volcanics.

the Roskruge Volcanics did contain significant secondary components. An example of progressive demagnetization results for a sample with an unusually large secondary component is illustrated in Figure 3. This sample is from the Viopuli Red Ignimbrite at the base of the section. Initial AF demagnetization up to 500 Oe peak field produced a large directional change. From 500 to 700 Oe peak field, little directional change was observed, and a trend toward the origin in the vector demagnetization diagram was established. Subsequent thermal demagnetization of this sample produced continued motion toward the origin, indicating that no additional high coercivity secondary components are present. The demagnetization diagram of Figure 3 does show some segments above 500 Oe with slightly different trends. However, we do not interpret these as evidence for multiple components of NRM. The site mean NRM showed only a linear trend to the origin following erasure of the low coercivity secondary component at 500 Oe peak field. None of the small changes in trend observed during demagnetization of individual samples were evident in the site mean directions. Also, no difference in site mean direction was observed between the AF and thermal demagnetizations.

Thermal demagnetization experiments revealed the presence of NRM components of blocking temperatures greater than 580°C. Thus hematite must be an important carrier of the NRM, as evidenced both by the resistance to AF demagnetization and by the presence of NRM components with blocking temperature greater than 580°C. These progressive demagnetization studies indicate that the NRM of most sites contain little or no secondary components, while other sites contain secondary components of NRM which can be cleaned by AF demagnetization to between 400 and 600 Oe peak field.

IRM acquisition for representative samples of the Roskruge Volcanics exhibited a positive slope up to the maximum field of 9 kOe. As with the AF and thermal demagnetization data, these IRM acquisition experiments indicate the presence of significant hematite.

Microscopic examination of polished thin sections revealed the presence of specular hematite in all samples studied, and magnetite (or titanomagnetite) was observed in some samples. The oxidation state of the opaque minerals was quite variable even within a single sample. Volcanic rock fragments with apparently unoxidized euhedral grains of magnetite (or titanomagnetite) were observed in close proximity to rock fragments where only specular hematite is present. There is no evidence of alteration of the opaque minerals subsequent to incorporation of these rock fragments in the welded tuffs and ignimbrite units composing the Roskruge Volcanics. One anticipated observation which was confirmed by the polished section study was that volcanic units exhibiting the largest low coercivity secondary components were found to contain the highest concentrations of magnetite (or titanomagnetite). The rock magnetic and microscopic data thus indicate that the primary NRM is a thermoremanence formed during the original cooling of the sampled units.

Results

The progressive demagnetization studies were used as a guide to determining the demagnetization treatment for the remaining samples from each site. All samples from all sites were subjected to AF demagnetization, the progressive demagnetization studies having indicated that secondary components were successfully removed by AF demagnetization. In most cases, all samples were demagnetized at several peak fields. The site mean direction following the demagnetization treatment yielding the highest k value (estimate of Fisher's [1953] precision parameter) was taken as the best determination of the stable component of NRM.

Site mean directions from the Roskruge Volcanics are summarized in Table 1 and illustrated in Figure 4. Results from two sites were rejected because the scatter within each of those sites was excessive and the demagnetization treatment did not convincingly reveal the existence of a well-defined primary NRM. Both of these sites were collected from cooling units which did not appear to have been highly welded and were more porous than the other units. These units either did not acquire a significant thermoremanence when extruded or the remanence has been disturbed by weathering.

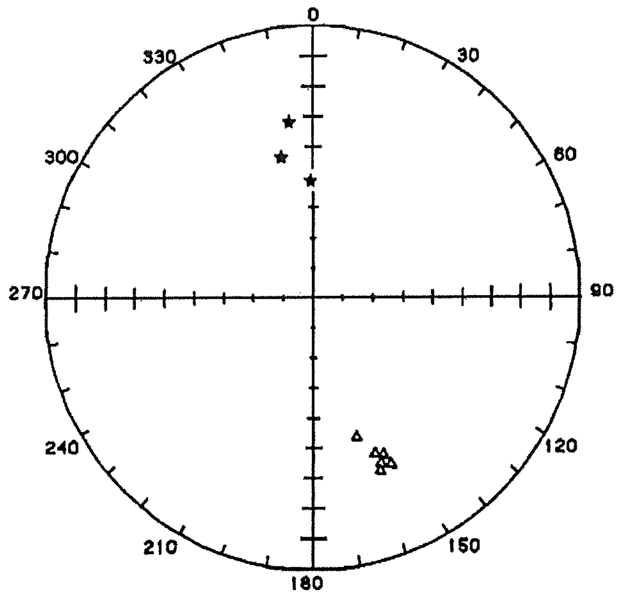

Fig. 4. Equal area stereographic projection of site mean directions from the Roskruge Volcanics.

Both normal and reversed polarities were observed in the Roskruge Volcanics. As seen by the results listed in stratigraphic succession in Table 1, at least three polarity intervals have been sampled in this section. The lack of antiparallel relationship between the normal and reversed polarity units is attributed to inade-

TABLE 1. Roskruge Volcanics Data

Site	HAF Oe	Inclination, deg	Declination, deg	Jr	N	R	k	α95 deg
RV4	800	31.29	352.06	46.5	7	6.98	271	3.7
RV5	500	-41.43	162.46	1.9	5	4.90	41	12.0
RV6	500	-34.29	158.14	2.8	4	3.98	175	7.0
RV7	500	-32.92	155.51	5.1	5	5.00	1163	2.2
RV8	500	-30.73	157.65	7.6	5	4.97	142	6.4
RV9	500	-28.94	154.82	1.2	4	3.99	231	6.1
RV10	500	-28.29	158.68	1.2	4	3.99	503	4.1
RV11	500	50.49	356.95	1.0	4	3.88	25	18.6
RV12	500	42.36	347.15	2.4	5	4.98	192	5.5

Site location is 32.06°N, 248.51°E; mean inclination is 35.8°; mean declination is 342.1°; structural attitude is N75°E strike, 19°SE dip; after structural correction the mean inclination is 54.74° and the mean declination is 340.52°; pole is 73.6°N; 176.0°E; α95, dp, and dm are 6.2°, 6.2°, and 8.8°, respectively. HAF is the peak alternating demagnetization field, Jr is the remanent magnetization in 10^{-5} G, N is the number of samples, and α95, R, and k are the statistical parameters of Fisher [1953]. Directions are listed before structural correction.

quate sampling of the secular variation by these nine cooling units. Unfortunately, no more units were available. The formation mean direction and resultant paleomagnetic pole from the Roskruge Volcanics are the only available data from ~72 Ma from North America. However, this result should be regarded as preliminary until more data are available from rocks of this age.

Site mean results from the Gringo Gulch Volcanics are summarized in Table 2 and illustrated in Figure 5. Data from one of the 26 sites collected were rejected. This site exhibited anomalously high NRM intensities, large secondary components which were not successfully removed, and excessive scatter of NRM directions. Because of these characteristics and the fact that this site occupies a promontory, it is likely that this site has been struck by lightning. All of the remaining 25 sites are of reversed polarity.

Most of the site mean directions are statistically different from other sites. This scatter of directions is attributed to sampling of geomagnetic secular variation. The site mean directions are very tightly grouped. This low dispersion suggests that the secular variation of the Paleocene geomagnetic field was not adequately sampled by this sequence of flows. Development of soil profiles on the tops of several flows prior to extrusion of the subsequent flow does indicate the presence of some time breaks during the extrusion of the sequence. However, the magnitude of these time breaks is difficult to assess and it is probable that the sampled flows were extruded within a time span less than the longest periodicities of secular variation. The degree to which the mean direction of magne-

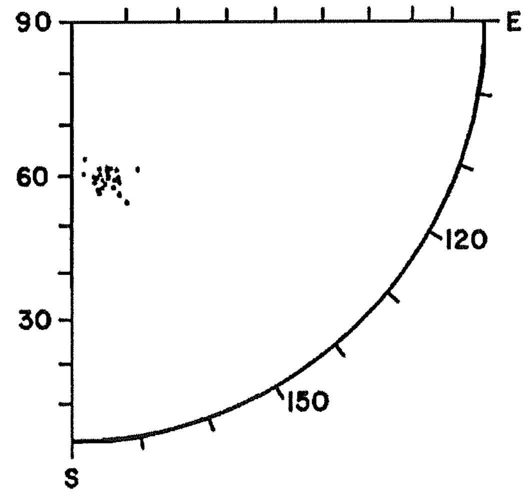

Fig. 5. Equal area stereographic projection of site mean directions from the Gringo Gulch Volcanics.

TABLE 2. Gringo Gulch Volcanics Data

Site	HAF Oe	Inclination, deg	Declination, deg	Jr	N	R	k	α95 deg
GG10	400	-58.8	169.3	3.3	4	4.00	2145	2.0
GG11	600	-60.5	175.7	2.6	5	5.00	1723	1.8
GG12	600	-57.4	169.5	7.6	5	4.99	563	3.2
GG13	400	-55.3	164.1	2.9	6	6.00	3323	1.2
GG21	600	-58.4	162.9	2.2	5	5.00	1380	2.1
GG22	600	-60.6	169.5	3.5	5	5.00	1164	2.2
GG23	400	-56.5	165.9	2.4	6	5.98	325	3.2
GG24	400	-56.2	170.7	2.2	5	4.99	626	3.1
GG25	600	-58.1	168.7	3.7	5	5.00	848	2.6
GG26	600	-53.1	162.7	1.4	4	3.95	60	11.9
GG27	600	-58.3	164.5	5.1	6	5.98	213	4.6
GG28	400	-61.0	165.8	6.9	5	5.00	1141	2.3
GG29	600	-60.6	165.2	6.9	5	5.00	8570	0.8
GG30	600	-58.7	172.2	3.4	5	5.00	1194	2.2
GG31	400	-59.5	172.2	4.5	5	4.99	567	3.2
GG32	600	-60.4	167.1	5.4	5	5.00	2570	1.5
GG33	600	-59.8	169.4	8.0	5	5.00	1518	2.0
GG34	600	-59.5	171.2	3.4	5	5.00	2160	1.6
GG35	600	-58.7	155.8	8.3	5	4.89	36	12.9
GG36	600	-60.0	163.3	0.8	5	4.98	261	4.7
GG37	600	-63.7	174.5	2.7	5	5.00	2051	1.7
GG38	400	-59.8	166.8	4.6	5	5.00	2375	1.6
GG39	600	-59.2	167.4	4.2	5	5.00	1565	1.9
GG40	600	-57.2	171.3	1.3	5	5.00	3898	1.2
GG41	600	-57.8	162.9	4.7	5	5.00	1544	1.9

Site location is 31.53°N, 249.51°E; mean inclination is -58.8°; mean declination is 167.5°; antipole is 77.0°N, 201.0°E; α95, dp, and dm are 1.1°, 1.2° and 1.7°, respectively. Jr is the remanent magnetization in 10^{-5} G (other headings as in Table 1).

tization obtained from the Gringo Gulch Volcanics is reflective of the mean direction of the Paleocene geomagnetic field can only be assessed by comparison of the Gringo Gulch pole with Paleocene poles determined from other studies. As discussed below, this comparison is favorable and indicates that the pole from the Gringo Gulch Volcanics is in reasonable accord with other available Paleocene poles from North America. We do wish to caution, however, that the small oval of confidence of the Gringo Gulch pole is probably an artifact of the incomplete sampling of secular variation and should not be taken to indicate that this pole is more 'accurate' than other Paleocene poles.

Discussion and Conclusions

Atwater [1970] has suggested that the San Andreas transform system and crustal extension within the Basin and Range Province are related. Beck [1976] proposed that clockwise rotations caused by this right lateral shear system are responsible for discordant paleomagnetic directions observed in rocks from the western Cordillera. Paleomagnetic data obtained from Oligocene rocks in Nevada and western Utah indicate that no significant rotations about vertical axes have occurred in the northern portion of the Basin and Range Province [Grommé et al., 1972; Gose, 1970]. However, no similar data are presently available from the southern Basin and Range. Therefore, the question of possible rotations about vertical axes in southeastern Arizona must be confronted.

There are two lines of evidence suggesting that no significant rotations about vertical axes have taken place. First, Coney [1978a] discussed the crustal extension within southeast Arizona and indicates that reassemblage of this area can be done simply by reversing the ∿20% crustal extension in this area. Rotations about vertical axes are not indicated although this technique certainly cannot rule out rotations of 10°-15°.

Stronger evidence against rotations can be obtained simply from the internal consistency of the presently available Paleocene paleomagnetic poles. As pointed out by Barnes and Butler [1980] and illustrated in Figure 6, the paleomagnetic pole from the Gringo Gulch Volcanics falls very close to a great circle path between the paleomagnetic pole from the Nacimiento Formation and its collection site in the San Juan Basin. Although the Nacimiento sediments may not provide an accurate pole because of an inclination error, the declination is reliable. The observation that the paleomagnetic pole from the Gringo Gulch Volcanics falls so close to this great circle argues strongly against any significant rotation of this volcanic series with respect to the Colorado Plateau. Also, as illustrated in Figure 7, the pole from the Gringo Gulch Volcanics is contained within the 95% confidence limits surrounding the pole obtained by Jacobson et al. [1980] from Paleocene intrusives in Montana. Furthermore, the Paleocene poles from the Montana intrusives and Gringo Gulch Volcanics can be compared with Paleocene poles from the British Isles. A Paleocene paleomagnetic pole for North America can be determined from the British data by rotating the European plate and its paleomagnetic poles back toward a fixed North American plate by using the finite-rotation pole of Pitman and Talwani [1972]. Both Mankinen [1978] and Butler and Taylor [1978] have used this technique to predict a Paleocene paleomagnetic pole for North America and both obtained poles at about 78°N, 170°E, in reasonable agreement with the poles from the Montana intrusives and the Gringo Gulch Volcanics. This internal consistency of North American Paleocene paleomagnetic poles, both directly and indirectly determined, indicates that the Gringo Gulch Volcanics have not been subjected to tectonic rotation with respect to stable North America.

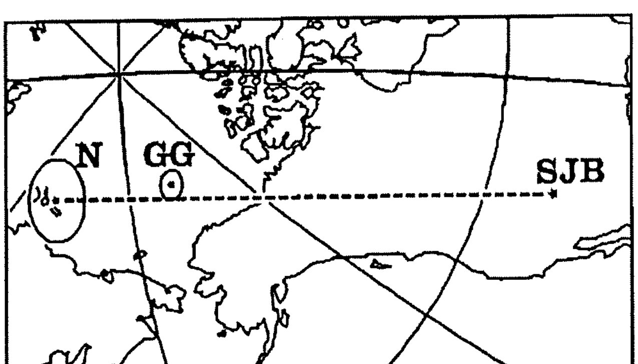

Fig. 6. Great circle connecting the Nacimiento Formation pole (N) and its collection site in the San Juan Basin (SJB) [after Barnes and Butler, 1980]. The Gringo Gulch Volcanics pole (GG) falls very close to this line.

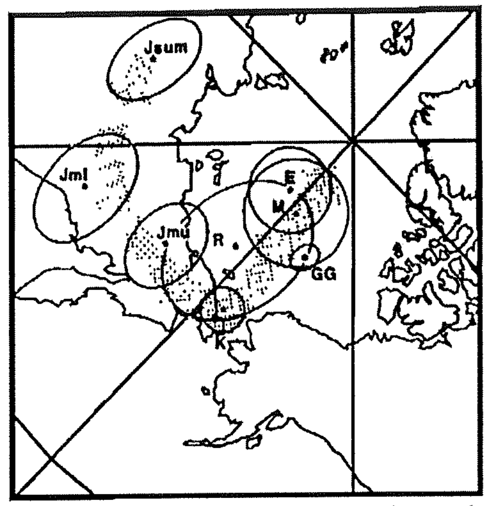

Fig. 7. Revised apparent polar wander path for North America. Pole data are listed in Table 3.

Unfortunately, no comparable internal consistency test can be applied to the pole obtained from the Roskruge Volcanics, since no paleomagnetic data from other ∿70 Ma North American rocks are available. However, as illustrated in Figure 7, the pole from the Roskruge Volcanics does fall roughly midway between the well established Cretaceous pole and the Paleocene poles. The age of the youngest rocks yielding the Cretaceous pole position is ∿80 Ma. Paleocene paleomagnetic poles from the Gringo Gulch

TABLE 3. Data for Figure 7

Symbol	Name	Pole Latitude, °N	Pole Longitude, °E	A95, deg	dp, dm, deg	Reference
E	Eocene	81.7	171.2	4.4		Diehl et al. [1980]
M	Montana	80.5	185.1	5.6		Jacobson et al. [1980]
GG	Gringo Gulch	77.0	201.0		1.2, 1.7	this study
RV	Roskruge Volcanics	73.6	176.0		6.2, 8.8	this study
K	Cretaceous	67.9	185.9	2.3		Mankinen [1978]
Jmu	Upper Morrison	67.5	161.7		3.5, 5.0	Steiner and Helsley [1975]
Jml	Lower Morrison	61.4	142.2		4.0, 6.5	Steiner and Helsley [1975]
Jsum	Summerville	67.6	110.8		3.2, 5.4	Steiner [1978]

Volcanics and the Montana intrusives are concordant at about 78°N, 190°E and are close to the mean Eocene pole calculated by Diehl et al. [1980] at 81.7°N, 171.2°E. The Paleocene data thus indicate that a major portion of the apparent polar wander from the Cretaceous pole toward the Eocene pole had already occurred by Paleocene (∿60 Ma). Indeed, the location of the pole from the Roskruge Volcanics approximately midway between the Cretaceous pole and the Paleocene poles seems quite reasonable. Thus, until additional data from rocks of this age become available, we feel that the pole position from the Roskruge Volcanics must be considered the best estimate of the North American paleomagnetic pole at ∿70 Ma.

Figure 7 illustrates the poles from the Gringo Gulch and Roskruge volcanics along with the most reliable paleomagnetic poles available for definition of the North American apparent polar wander path from middle Jurassic to Eocene. Details of the paleomagnetic poles and references are listed in Table 3. As shown in Figure 7, a period of rapid apparent polar wander took place during the late Jurassic. As discussed by Steiner [1978], this episode of apparent polar wander reflects motion of the North American plate in response to opening of the South Atlantic. The Cretaceous prior to 80 Ma appears to have a time of little or no apparent polar wander. A subsequent episode of apparent polar wander from the Cretaceous pole to the Eocene pole position must have been largely completed by ∿60 Ma, as evidenced by the proximity of the Paleocene and Eocene poles. These observations, along with the observation of the pole from the ∿72 Ma Roskruge Volcanics approximately midway along this track, suggest that apparent polar wander from the Cretaceous pole toward the Eocene pole must have commenced at approximately 80 Ma.

Irving and Park [1972] suggested that the timing of changes in the direction of apparent polar wander paths would correlate with orogenic episodes and coined the term 'hairpins' for corners in the apparent polar wander path. They further suggested that the latest major hairpin in the North American apparent polar wander path occurred in the Cretaceous and is a reflection of the Laramide orogeny. Coney [1978b] has analyzed the motion of North America in the hot spot framework by analysis of relative plate motions as recorded by marine magnetic anomalies and of absolute plate motions as recorded by hot spot seamount tracks. This analysis indicates that a major reorganization of plate motions occurred at ∿80 Ma. This reorganization resulted in a major change in the motion of North America in the absolute framework at that time. The Laramide orogeny which commenced at ∿80 Ma is thought to be the consequence of accelerated convergence between the North American and Farallon plates. The apparent polar wander path illustrated in Figure 7 does suggest coincidence of the onset of a period of rapid apparent polar wander during latest Cretaceous with the initiation of the Laramide orogeny at ∿80 Ma.

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