Paleomagnetic Analysis of Miocene Basalt Flows in the Tehachapi Mountains, California

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By J.B. Plescia, Gary J. Calderone, *and* Lawrence W. Snee

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New paleomagnetic directions and $^{40}Ar/^{39}Ar$ extrusion ages from Miocene basalt flows on the north flank of the Tehachapi Mountains, Southern California

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PALEOMAGNETIC ANALYSIS OF MIOCENE BASALT FLOWS IN THE TEHACHAPI MOUNTAINS, CALIFORNIA

By J. B. Plescia[1], Gary J. Calderone[2], and Lawrence W. Snee[3]

ABSTRACT

In an attempt to constrain the timing and extent of clockwise vertical-axis tectonic rotation of the Tehachapi Mountains, we have determined paleomagnetic directions and isotopic dates from Miocene basalt flows exposed along the northern flank of the range. $^{40}Ar/^{39}Ar$ spectrum-analyses yield an average extrusion age of 22.6±0.6 Ma. The paleomagnetic data set of 22 flow-mean directions and virtual geomagnetic poles (VGPs) probably does not adequately average the secular variation of the Miocene geomagnetic field. Consequently, no tectonic significance may be attached to the mean pole (in-situ: long 350.6°E., lat 54.9°N., Fisher (1953) semi-angle of 95% confidence, A95=5.4°, Fisher (1953) best estimate of the precision parameter, K=34.2; after tilt correction: long 9.6°E., lat 59.3°N., A95=5.7°, K=30.6) of the 22 site mean VGPs. Although the result would permit post-Miocene clockwise vertical-axis rotation of the Tehachapi Mountains, it neither supports nor requires such rotation. Although not tectonically significant, it is interesting to note that the rotational discordance (27.2°±5.5° after tilt correction) is consistent with rotation of the underlying Cretaceous granitic rocks.

INTRODUCTION

The Tehachapi Mountains of southern California are the southernmost part of the Sierra Nevada batholithic terrane and may represent the upended, structurally deepest level of the batholith (Ross, 1985). Several geologic patterns in the Tehachapi Mountains trend northeast, apparently deflected in a clockwise sense relative to the Sierra Nevada where the trends are north-northwest (Ross, 1980; Burchfiel and Davis, 1981). Paleomagnetic data (Kanter and McWilliams, 1982; McWilliams and Li, 1983, 1985) suggest that these directional changes are the result of a tectonic rotation of the Tehachapi Mountains.

Paleomagnetic analysis of the crystalline basement rocks (Kanter and McWilliams, 1982; McWilliams and Li, 1983, 1985) suggests increasing clockwise rotation southwestward across the range. Virtually no rotation is indicated north of Tehachapi Valley, whereas rotation of more than 90° may have occurred to the southwest near Grapevine Canyon (McWilliams and Li, 1983).

The timing of the rotation has been only broadly constrained to postdate the rotated 80–120 Ma plutonic rocks. These ages are based on U/Pb, K/Ar, and Rb/Sr analyses (Sams and others 1983; D. B. Sams, oral commun., 1985; Ross, 1983, 1989). Near Tehachapi Valley, the rotation must have occurred prior to emplacement of the unrotated 16–18 Ma Kinnick Formation and associated volcanic rocks (Evernden and others, 1964; corrected for new decay constants, Dalrymple, 1979; Kanter and McWilliams, 1982; McWilliams and Li, 1985). It is uncertain to what extent this minimum age also constrains the timing of rotation farther to the southwest. In an attempt to constrain the timing and extent of the rotation, a section of Miocene basalt flows which crop out along the northern flank of the Tehachapi Mountains was sampled for paleomagnetic analysis and for isotopic dating (figs. 1 and 2).

GEOLOGIC SETTING

The study area is along the northern flank of the Tehachapi Mountains, Calif., between Pastoria Canyon to the southwest and Tunis Canyon to the northeast (figs. 1 and 2). Within this area the volcanic rocks are

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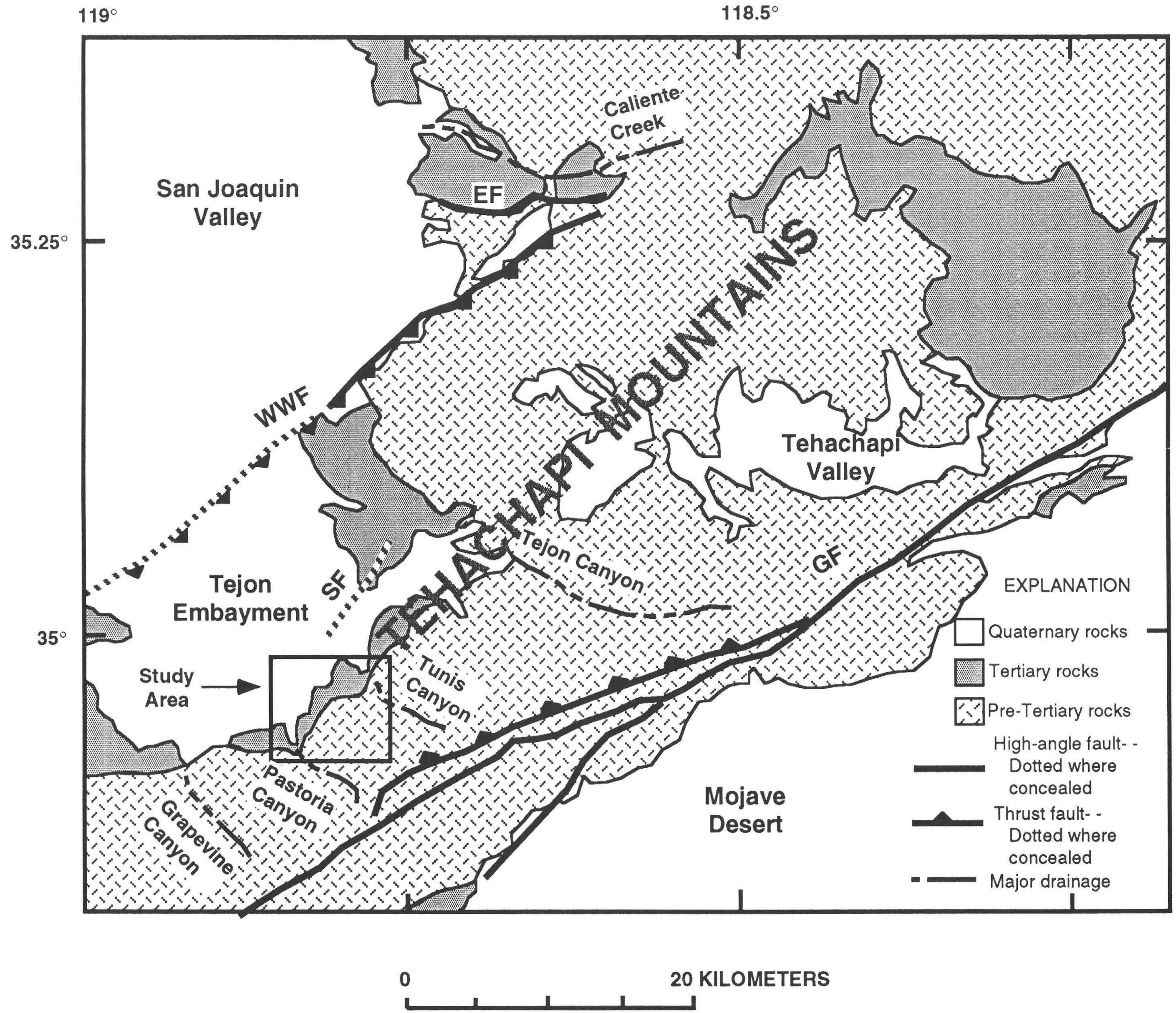

Figure 1. Generalized geologic map of the Tehachapi Mountain region showing pre-Tertiary, Tertiary, and Quaternary rock units. Also shown are geographic features mentioned in the text. The box outlines the study area shown in detail in figure 2. WWF, White Wolf fault; GF, Garlock fault; EF, Edison fault; SF, Springs fault.

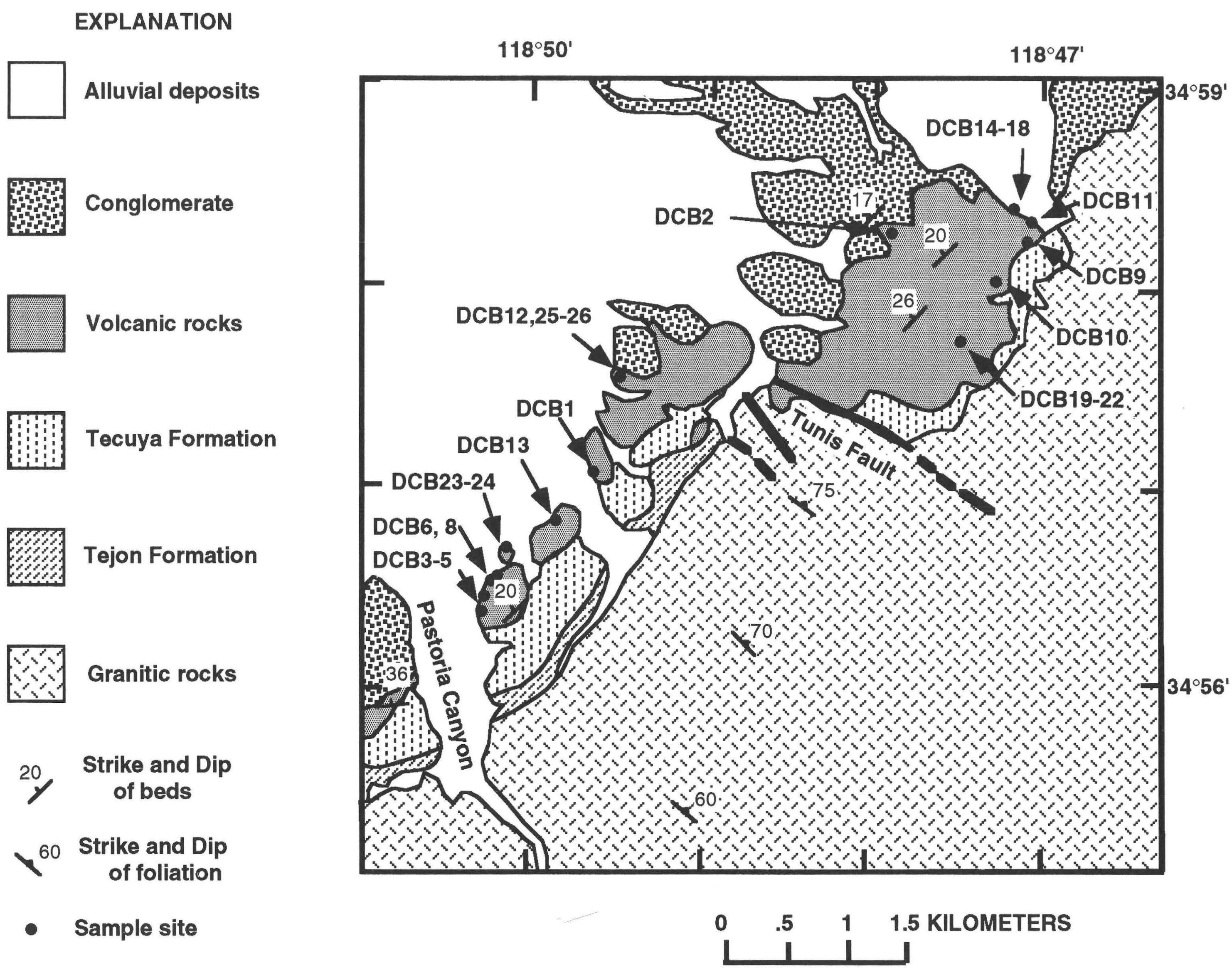

Figure 2. Generalized geologic map of the study area (modified from Dibblee, 1973) showing structure and sample sites. Flow (site) numbers correspond to those listed in table 2.

Table 1. $^{40}Ar/^{39}Ar$ **age-spectrum data for Miocene basalt flows from Tehachapi Mountains, Calif.**

[T °C = degassing temperature. The total of $^{39}Ar_t$ and $^{40}Ar_r$ expressed in percent. ^{39}Ar expressed in moles X 10^{-13}. K/Ca expressed as apparent K/Ca in mole/mole. Date expressed as apparent date X 10^6 years and error as one standard deviation from the mean. J = irradiation dosage]

T °C	$Ar^{40/39}$	$Ar^{37/39}$	$Ar^{36/39}$	$^{39}Ar_t$	$^{40}Ar_r$	^{39}Ar	K/Ca	Date
DCB 4	Whole-rock basalt; sample weight = 0.9960 g; J = 0.005795							
300	25.900	0.6773	0.0839	0.6	4.4	0.39	0.77	11.9±0.3
450	4.087	0.7524	0.0075	6.5	47.3	4.17	0.69	20.1±0.1
600	3.082	0.8840	0.0029	10.6	74.2	6.78	0.59	23.8±0.1
750	2.359	1.1870	0.0009	18.9	92.8	12.00	0.44	22.7±0.1
1000	2.245	0.8874	0.0005	41.8	95.6	26.60	0.59	22.3±0.1
1450	2.635	3.2900	0.0018	21.5	89.3	13.70	0.16	24.4±0.1
					TOTAL GAS DATE			22.8
				PREFERRED DATE (600 °C - 1450 °C):				23.0±1.0
DCB 5	Whole-rock basalt; sample weight = 0.9709 g; J = 0.005780							
300	11.730	0.1845	0.0336	11.9	15.4	7.79	2.80	18.8±0.1
450	5.462	0.4776	0.0112	11.6	40.1	7.59	1.10	22.7±0.2
600	4.197	0.8088	0.0068	21.5	53.5	14.00	0.64	23.3±0.2
750	3.308	0.9989	0.0042	16.3	64.3	10.70	0.52	22.1±0.1
1000	2.864	1.5780	0.0029	19.5	73.9	12.70	0.33	21.9±0.1
1450	3.360	4.1600	0.0054	19.2	62.0	12.50	0.13	21.6±0.1
					TOTAL GAS DATE			21.8
				PREFERRED DATE (600 °C - 1450 °C):				22.3±0.7
DCB 13	Whole-rock basalt; sample weight = 0.9971 g; J = 0.005750							
300	14.990	1.195	0.0442	1.5	13.4	1.09	0.44	20.6±0.3
450	2.949	0.8718	0.0034	8.9	68.4	6.35	0.60	20.8±0.1
600	2.930	0.9573	0.0022	9.5	79.7	6.77	0.54	24.1±0.1
750	2.445	1.2350	0.0008	16.5	93.7	11.80	0.42	23.6±0.1
1000	2.291	1.1920	0.0005	38.7	97.0	27.70	0.44	22.9±0.1
1450	2.371	2.8280	0.0015	25.0	90.6	17.90	0.18	22.1±0.1
					TOTAL GAS DATE			22.7
				PREFERRED DATE (750 °C - 1450 °C):				22.9±0.9

well exposed, the geology is well mapped, and the structure is relatively simple. The structure becomes increasingly complex to the southwest. The volcanic rocks of the southern San Joaquin Valley are within the upper part of the Tecuya Formation east of Pleito Creek and within the upper part of the Temblor Formation west of Pleito Creek (Nilsen, 1973; Nilsen and others, 1973; Nilsen and Clarke, 1975). The Tecuya and Temblor Formations interfinger and are coeval marine and continental deposits, respectively.

Northeast of Pastoria Canyon (fig. 2) the volcanic rocks are unconformably overlain by an unnamed conglomerate (Dibblee, 1973) which may be correlative with the Bena Gravels to the north and northeast (Bartow and Dibblee, 1981; Bartow, 1984; Bartow and McDougall, 1984). In the study area the Tecuya Formation unconformably overlies marine rocks of the Eocene Tejon Formation, and they in turn overlie compositionally heterogeneous basement rocks (Dibblee, 1973; Ross, 1980, 1983, 1989).

The basalt flows dip 10°– 25° to the northwest and crop out along the range front in a series of northeast-striking hogbacks. Because of the patchy nature of outcrops in the hogbacks, however, we could not discern an unambiguous flow-by-flow stratigraphy within the basalt flows. This lack of known internal stratigraphy limits our ability to rigorously analyze the paleomagnetic data in this report.

GEOCHRONOLOGY

Samples from three flows (DCB4, DCB5, and DCB13; fig. 2) were analyzed for $^{40}Ar/^{39}Ar$ dating. These relatively unaltered samples were ground and sieved and the 180–250 µm whole-rock size fraction was treated with 10 percent HCl to remove secondary calcium carbonate. Standard procedures were used in this experiment as described in Dalrymple and others (1981) and Snee and others (1988). The samples were irradiated to produce ^{39}Ar from ^{39}K. After irradiation, each sample was progressively heated under vacuum in six temperature steps from 300 °C to 1,450 °C. For each temperature step, the released argon was analyzed by mass spectrometer and an apparent age was calculated. Decay constants used are those of Steiger and Jäger (1977). The geochronologic standard used was MMhb–1 hornblende with an age of 519.4 Ma (Alexander and others, 1978). The argon age-spectrum data are presented in table 1 and figure 3.

In general, all three age spectra show minor internal discordance, and no "plateaus" are present; therefore, a preferred date was calculated for each sample. The preferred date is an average of all contiguous temperature steps that contain more than 10 percent of the total ^{39}Ar released from the sample and that have greater than 50 percent radiogenic argon ($^{40}Ar_R$). The preferred dates for flows DCB4, DCB5, and DCB13 are 23.0±1.0, 22.3±0.7, and 22.9±0.9 Ma, respectively. Since these dates are statistically indistinguishable from each other, the average date of 22.6±0.6 Ma is the best estimate for the extrusion age of these basalt flows. This age is statistically identical to that determined by Turner (1970), about 22.5 Ma, for samples from the same stratigraphic unit in the San Emigdio Mountains to the west. The volcanic rocks in the San Emigdio Mountains have K-Ar dates of 22.1–25.2 Ma and an average of 22.5 Ma (Turner, 1970; corrected for new decay constants, Dalrymple, 1979).

FIELD AND LABORATORY METHODS

Twenty-five basalt flows between Pastoria Canyon and Tunis Canyon were sampled for paleomagnetic analyses (figs. 1 and 2). Seven to fifteen oriented cores were collected from each site (flow) using a portable rock drill. Both sun and magnetic compasses were used to orient all cores. Because solar and magnetic azimuths had local discrepancies of as much as 20°, solar azimuths were used in all orientation calculations.

Natural remanent magnetizations (NRM) of the samples were measured on a two-axis superconducting magnetometer. Sample NRM intensities average about 5.7 amperes per meter (Am^{-1}). Progressive stepwise alternating field (AF) demagnetizations were performed on two or three pilot specimens from each site. Median destructive fields ranged from about 15 to >100 milliTesla (mT), averaging about 37 mT. Many specimens contained both low- and high-coercivity components of magnetization (fig. 4). The low- to moderate-coercivity components have steep inclinations (about 60°) and northerly declinations (about 350°), and they are removable by AF demagnetization at a peak field of 20 mT. These components are most likely viscous remanent magnetizations (VRM) acquired during the present-day geomagnetic field. The stable high-coercivity components, isolated by AF demagnetization to peak fields of >20 mT, are almost certainly high-temperature thermal remanent magnetizations (TRM) acquired at the time of extrusion.

Stepwise progressive thermal demagnetizations, at temperatures as high as 600 °C, were also run on pilot specimens for comparison with the AF demagnetization behavior. The directions determined by principal component analysis (Kirschvink, 1980) of the thermal trajectories are indistinguishable (at the 95 percent confidence level) from trajectories determined by AF analysis. The similarity of the AF and thermal demagnetization data supports the interpretation that the high-coercivity components of magnetization are indeed TRM. The thermal demagnetization analysis indicates unblocking temperatures of 400–580 °C, suggesting that magnetite is the principal carrier of remanence.

On the basis of the demagnetization behavior of the pilot specimens, all samples were AF demagnetized in peak fields of 20–40 mT, a level sufficient to completely remove the secondary VRM. The few specimens for which a meaningful direction could not be isolated were deleted from the data set. Samples from three sites in this same section were independently collected and analyzed by M.O. McWilliams (written commun., 1985) and exhibit directions similar to those reported here.

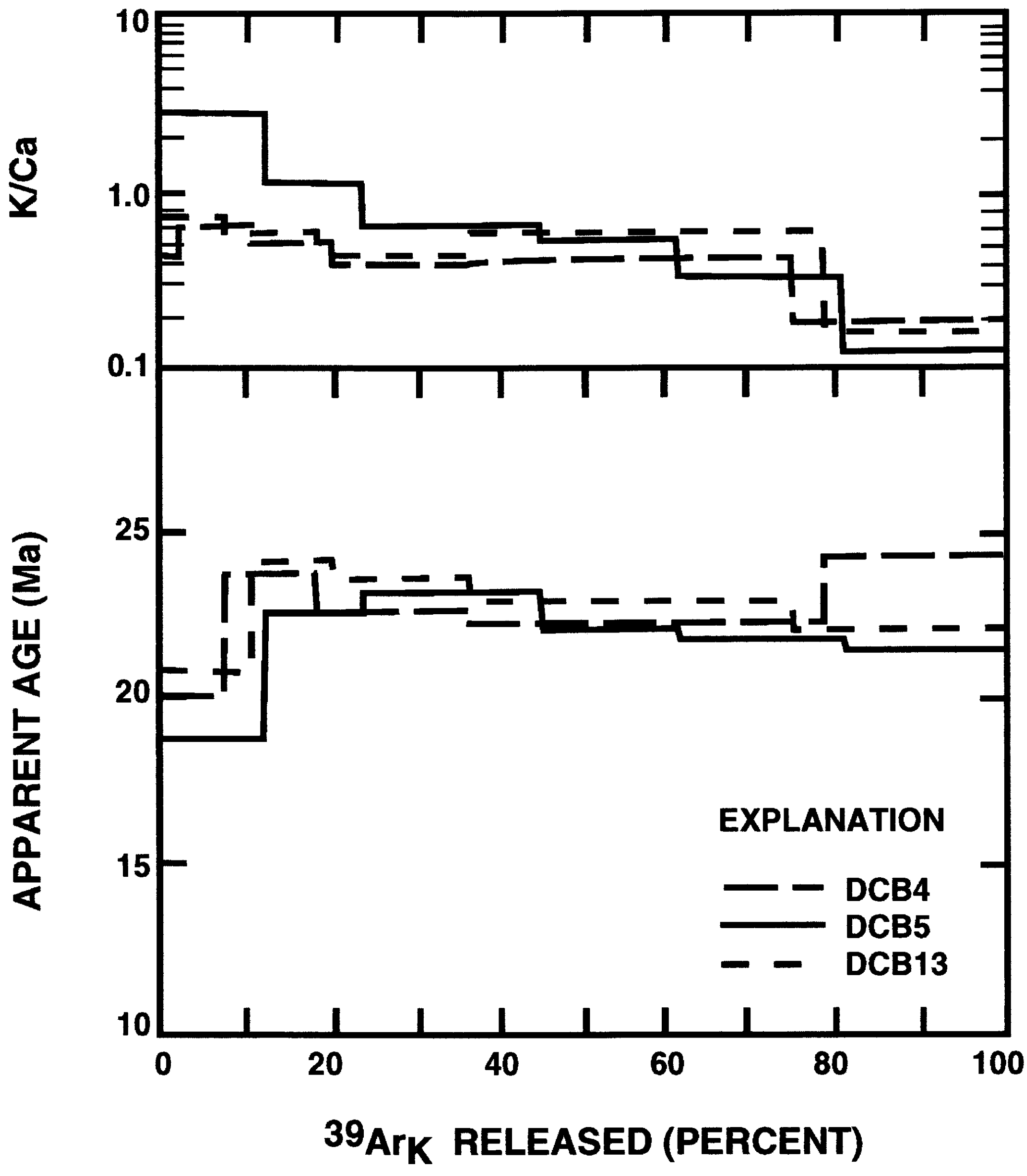

Figure 3. Argon age-spectrum diagram for Miocene basalt flows DCB4, DCB5, and DCB13. The upper panel shows the K/Ca ratio as a function of percent total Ar released for each temperature step. The lower panel shows the apparent age for each temperature step. $^{39}Ar_K$ is the reactor-produced ^{39}Ar from ^{39}K (see text for details).

After magnetic cleaning, a mean direction and Fisher (1953) statistics were calculated for each flow (see table 2 and figure 5A) in both tilt corrected and in-situ coordinates. Using the mean directions and the standard dipole formula, a mean virtual geomagnetic pole (VGP) was calculated for each flow (table 2 and figure 5B).

PALEOMAGNETIC ANALYSIS

Critical examination of the data in figure 5 and table 2 reveals several problems with the data set of site mean paleomagnetic directions and VGPs both before and after tilt correction.

(1) There are several groups of flows within which individual flow directions are statistically indistinguishable at 0.99 probability using the test of McFadden and Lowes (1981). This coincidence of directions within groups of flows may be the result of (a) rapid extrusion of multiple flows recording the same geomagnetic field direction; (b) multiple flows recording similar but independent directions of the geomagnetic field as would be common near the mean of Fisher-distributed vectors; or (c) both causes. Lacking firm control of the internal stratigraphy we cannot

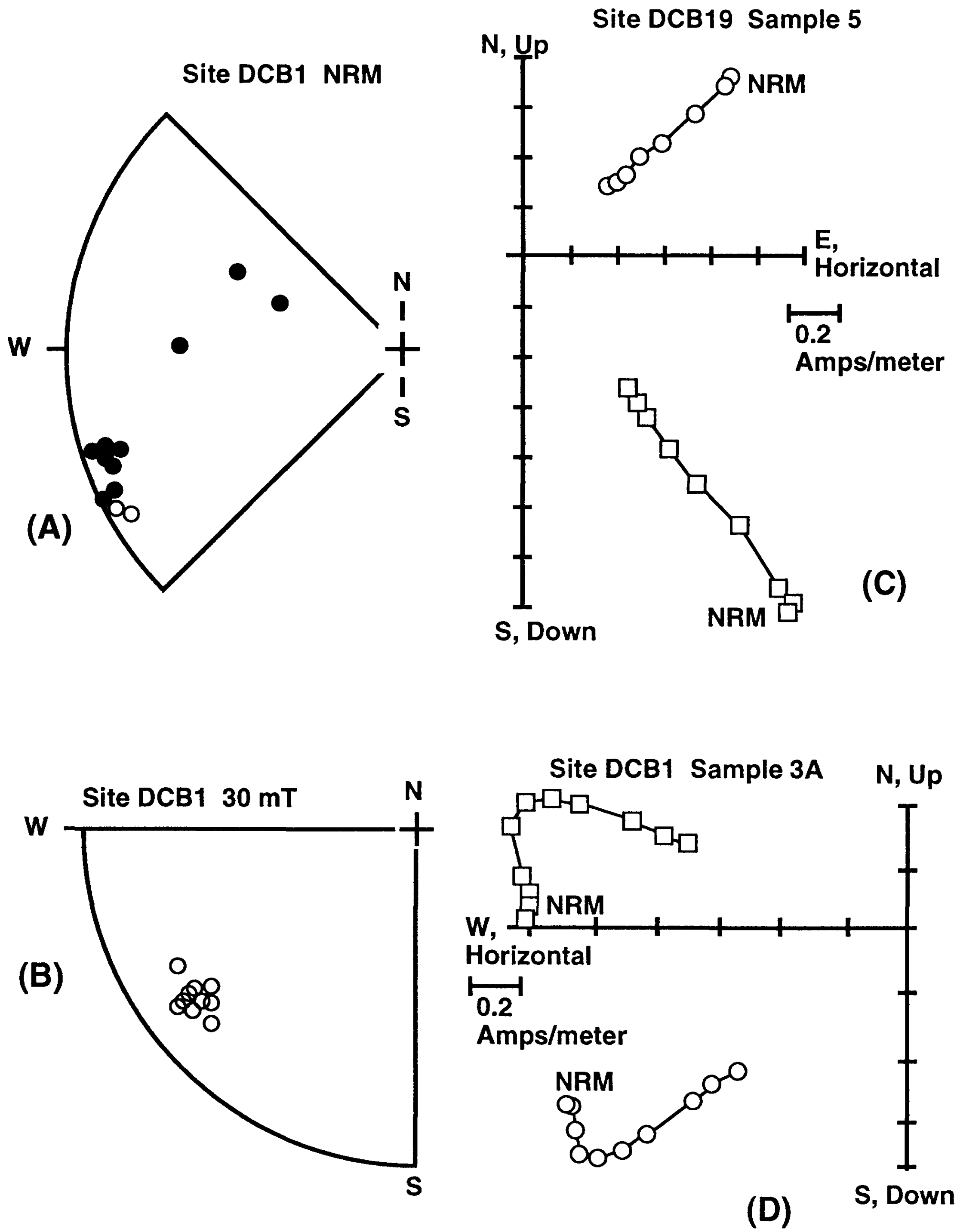

Figure 4. Alternating field (AF) demagnetization results. Equal-area projection of (A) in-situ initial and (B) post-AF demagnetization (at peak fields of 30 mT) directions from flow DCB1 (solid circle = lower hemisphere projection; open circle = upper hemisphere projection). Note scatter of initial natural remanent magnetization (NRM) directions along great circle containing present field directions. (C) Vector demagnetization diagram showing univectorial decay of remanence toward origin during progressive AF demagnetization; squares represent the projection of the magnetic declination into the horizontal plane, circles are the projection of the magnetic inclination into a vertical plane passing through the declination. (D) Vector demagnetization diagram showing removal of a northerly component of magnetization having steep inclination probably caused by a present field viscous remanent magnetization (VRM); squares and circles are as represented in part C.

Table 2. Mean remanence directions, virtual geomagnetic poles (VGPs), and Fisher (1953) statistics of Miocene basalt flows from the Tehachapi Mountains, Calif.

[Lat and Lon are the north latitude and east longitude of the site. D-Level is the alternating field demagnetization treatment in milliTesla. Dec and Inc are the components of the site mean direction. a95, and k are the parameters of Fisher (1953). Plon and Plat are the coordinates of the VGP calculated from Dec and Inc using the standard pole transformation. Dm and dp are the axes of the the 95% confidence ellipse around the VGP. cDec and cInc are the components of the mean direction after tilt correction . cPlon and cPlat are the coordinates of the tilt corrected VGP calculated from cDec and cInc using the standard pole transformation. N is the number of specimens used to calculate the mean. GN is the cooling unit group to which each flow belongs]

Flow	Lon(°)	Lat(°)	D-Level	Dec(°)	Inc(°)	α95(°)	k	Plon(°)	Plat(°)	dm(°)	dp(°)	cDec(°)	cInc(°)	cPlon(°)	cPlat(°)	N/GN
DCB1	241.17	34.95	30	232.1	-17.1	2.4	330.5	167.1	-35.8	2.3	1.4	225.8	-14.6	173.4	-39.8	12/1
DCB2	241.20	34.96	20	205.3	-24.1	2.2	497.4	189.3	-58.0	2.3	1.1	199.2	-14.1	204.3	-57.1	10/2
DCB3	241.16	34.94	30	204.7	-41.1	1.2	375.1	172.4	-65.7	1.7	1.1	192.4	-24.3	211.3	-65.1	7/3
DCB4	241.16	34.94	40	211.5	-39.3	2.8	340.9	167.5	-59.7	3.4	1.7	198.4	-24.7	199.5	-62.4	9/4
DCB5	241.16	34.94	20	201.8	-44.4	1.8	587.4	170.5	-69.3	2.3	1.1	188.9	-26.6	217.9	-67.6	12/5
DCB6	241.16	34.94	40	196.4	-41.7	6.1	51.5	184.3	-72.1	7.4	4.5	185.8	-22.6	227.0	-66.2	10/5
DCB8	241.16	34.94	20	200.6	-46.0	2.3	290.4	168.8	-70.9	2.9	1.7	187.4	-27.7	221.1	-68.7	15/5
DCB9	241.22	34.97	30	204.3	-27.2	3.0	343.9	188.4	-60.0	3.4	1.7	199.0	-18.9	202.2	-59.4	8/2
DCB10	241.21	34.97	30	211.8	-26.2	4.4	99.4	179.7	-54.4	4.6	2.3	207.5	- 7.7	195.7	-49.8	12/6
DCB11	241.21	34.97	30	200.1	-31.4	3.1	198.2	191.2	-64.6	3.4	1.7	191.2	-21.8	215.2	-64.2	12/7
DCB12	241.18	34.96	20	346.8	- 3.3	4.3	167.6	82.6	51.4	4.8	2.4	349.5	-20.1	75.5	43.6	8/15
DCB13	241.17	34.95	30	233.0	-18.1	2.9	519.7	165.9	-35.4	2.9	1.7	223.6	-23.1	170.4	-44.4	6/1
DCB14	241.21	34.97	30	202.0	-22.8	2.7	438.0	195.0	-59.5	2.9	1.7	197.4	-12.1	208.1	-57.0	8/2
DCB15	241.21	34.97	30	226.0	-27.3	3.3	333.8	165.8	-44.0	3.4	1.7	217.7	-22.9	175.8	-48.8	7/8
DCB16	241.21	34.97	20	223.5	-21.9	3.1	313.2	171.5	-44.1	3.4	1.7	217.3	-17.0	179.8	-47.0	8/8
DCB17	241.21	34.97	40	222.6	-22.5	1.4	1151.8	171.6	-45.0	2.3	1.1	216.3	-17.3	180.6	-47.8	9/8
DCB18	241.21	34.97	30	222.5	-21.9	3.6	236.1	172.1	-44.9	4.0	2.3	216.4	-16.7	180.9	-47.5	8/8
DCB19	241.21	34.96	40	39.6	44.7	3.3	245.4	334.4	55.1	4.0	2.8	20.5	42.2	356.5	69.4	9/9
DCB20	241.21	34.96	20	32.9	43.2	2.5	604.5	341.3	60.0	2.8	1.7	15.7	38.7	10.7	71.0	7/10
DCB21	241.21	34.96	40	28.1	35.9	2.4	621.5	355.1	61.0	2.8	1.7	15.3	30.5	20.9	67.0	7/11
DCB22	241.21	34.96	30	30.5	42.2	2.6	534.8	344.7	61.6	3.4	1.7	14.2	37.1	16.2	71.1	7/12
DCB23	241.16	34.94	30	231.2	-42.4	3.3	341.3	150.0	-44.8	4.0	2.3	211.8	-45.8	158.2	-61.8	7/13
DCB24	241.17	34.94	30	242.1	-20.1	3.5	302.1	158.8	-28.7	3.4	1.7	233.8	-28.9	159.1	-38.2	7/14
DCB25	241.18	34.96	20	340.3	-5.6	4.8	114.7	91.4	47.9	4.8	2.4	343.1	-22.1	83.3	40.9	9/15
DCB26	241.18	34.96	30	341.2	-0.2	3.5	250.2	91.8	50.8	3.5	1.8	342.9	-16.6	84.9	43.7	8/15

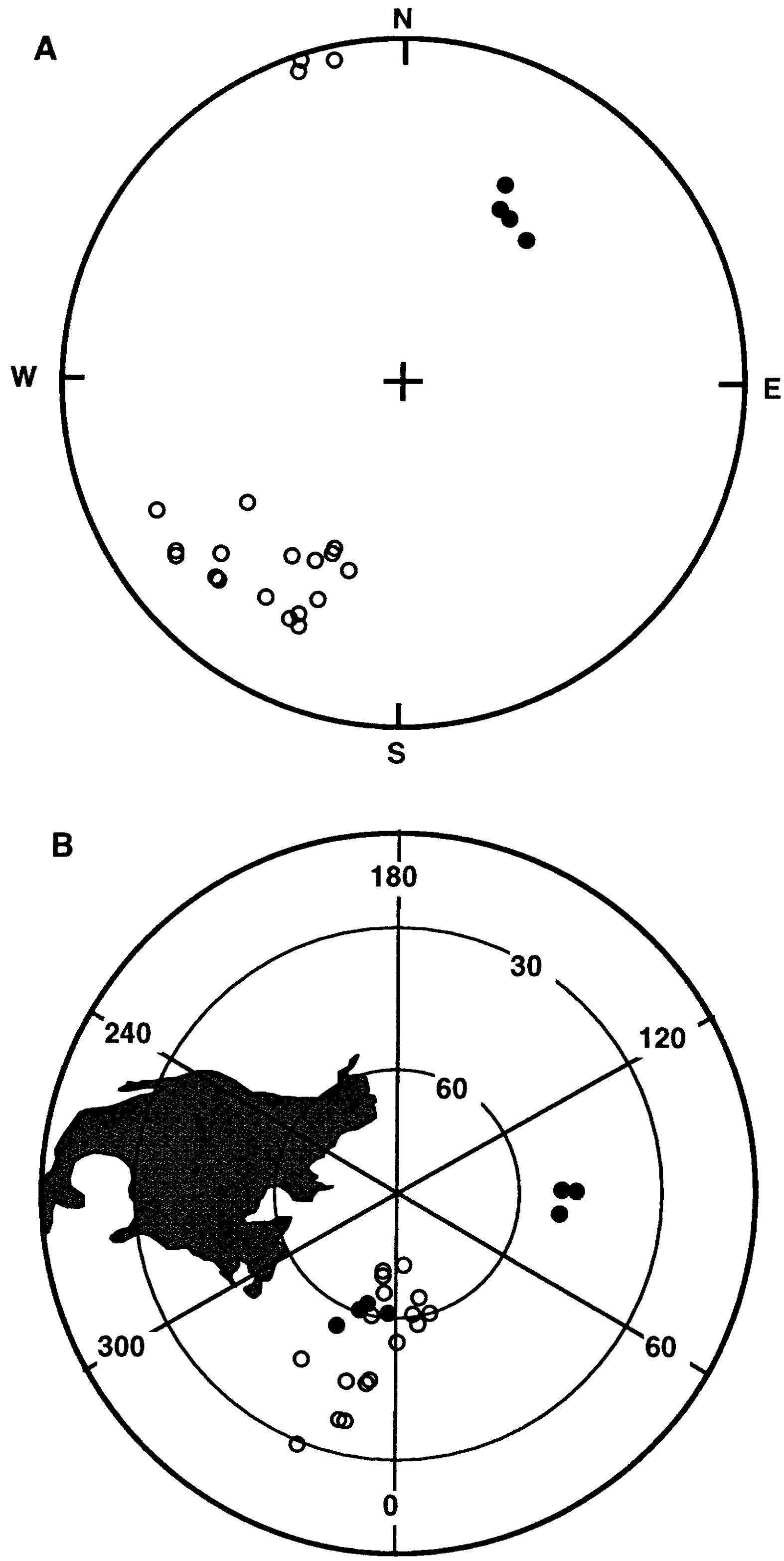

Figure 5. Mean directions and virtual geomagnetic poles (VGPs) from Miocene basalt flows from the Tehachapi Mountains, Calif. (A) Equal-area projection of in-situ site mean directions (solid circle = lower hemisphere projection; open circle = upper hemisphere projection). (B) Northern hemisphere polar projection of all site mean VGPs from this study. Solid circles are northern hemisphere VGPs. Open circles are the antipodes of southern hemisphere VGPs.

distinguish among these possibilities. Rapid extrusion has probably produced at least three of the groups (groups 5, 8, and 15, table 2). Other groups (group 2), however, cannot be interpreted because of inadequate stratigraphic control. Consequently, we cannot objectively establish the number of independent cooling units represented by the 25 site mean directions. This in turn, hampers our ability to establish meaningful estimates of both the mean direction and its confidence limits.

(2) Using the graphical methods of Lewis and Fisher (1982), flows DCB12, DCB25, and DCB26 (group 15, table 2) represent statistical outliers to the rest of the paleomagnetic directions. These flows may record a short-term excursion of the geomagnetic field.

(3) After removal of the outlying directions, the distribution of remaining directions (corrected for tilt) is roughly Fisherian, using the tests of Lewis and Fisher (1982) and McFadden (1980a). The resulting distribution of site mean VGPs, however, is streaked perpendicular to the meridian connecting the locality and the mean pole position (figure 5B). This streaking may be the result of (a) inadequate averaging of paleosecular variation; (b) tilt correction errors; or (c) both causes. In this case, however, we can attempt to distinguish between possibilities. The methods of McFadden (1980b; see Calderone, 1988, and Calderone and others, 1990, for details) using the McFadden and McElhinny (1984) model of paleosecular variation at 95 percent confidence predicts an angular dispersion between 10° and 20° for VGPs from the latitude of the Tehachapi Mountains. The total angular dispersion (14°– 18°) of site mean VGPs (insitu or tilt corrected) is well within this predicted range. Only about 6° of the observed dispersion, however, is parallel to the paleomeridian connecting the Tehachapi Mountains to their mean pole. Consequently, it is unlikely that the data average the secular variation of the Miocene geomagnetic field. Improper structural corrections may also contribute to the overall dispersion of VGPs.

DISCUSSION AND CONCLUSIONS

Paleomagnetic results from 22.6±0.6 Ma basalt flows in the Tehachapi Mountains are inconclusive. The data set of directions and VGPs, tilt corrected or not, probably does not adequately average the secular variation of the Miocene geomagnetic field. Consequently, tectonic significance may not be attached to the mean pole (long 350.6°E., lat 54.9°N., A95=5.4°, K=34.2; after tilt correction, long 9.6°E., lat 59.3°N., A95=5.7°, K=30.6) of the 22 site mean VGPs (outliers from flows 12, 25, and 26 removed). Thus, although these results would permit post-Miocene clockwise rotation of the Tehachapi Mountains, they would neither support nor require such rotation. The rotational discordance (Beck and others, 1986; Demarest, 1983) of 37.7°±5.4° before tilt correction and 27.2°±5.5° after tilt correction (using the North American reference pole calculated by Hagstrum and others, 1987) is consistent with that of the underlying Cretaceous granitic rocks (Kanter and McWilliams, 1982; McWilliams and Li, 1985). If the rotational discordance could be shown to be tectonically significant, then the age of these basalt flows and the age of the unrotated Kinnick Formation (Kanter and McWilliams, 1982) may constrain the timing of rotation to be between 23 and 16–18 Ma. Further investigation, however, will be required to constrain the timing and extent of rotation in the Tehachapi Mountains.

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