Cenozoic Rocks in the Barstow Basin Area of Southern California — Stratigraphic Relations, Radiometric Ages, and Paleomagnetism

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CONTRIBUTIONS TO STRATIGRAPHY

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CENOZOIC ROCKS IN THE BARSTOW BASIN AREA OF SOUTHERN CALIFORNIA— STRATIGRAPHIC RELATIONS, RADIOMETRIC AGES, AND PALEOMAGNETISM

By D. B. Burke, J. W. Hillhouse, E. H. McKee, S. T. Miller, and J. L. Morton

ABSTRACT

Potassium-argon dates on Cenozoic volcanic flows and welded ash-flow tuff in the Fremont Peak, Opal Mountain, and Lane Mountain 15-minute quadrangles of the north-central Mojave Desert, Calif., require revision of previous age assignments, stratigraphic correlations, and nomenclature for several rock units of the area. Stratigraphically isolated quartz latite welded tuff at Lane Mountain has been dated at 23.1±0.2 m.y. (early Miocene). Undated volcanic and volcaniclastic rocks of dacitic to basaltic composition in the Jackhammer Formation that are probably next in stratigraphic succession are also early Miocene. Dacitic to rhyolitic volcanic and volcaniclastic rocks of the Pickhandle Formation overlying the Jackhammer are early Miocene, as indicated by a date of 18.9±1.3 m.y. on welded tuff in the Opal Mountain Volcanic Member at the top of the Pickhandle Formation. A dacite porphyry flow overlying the Jackhammer and Pickhandle Formations in the Calico Mountains, and a nearby andesite dike intruding the Jackhammer Formation, are both 18.1±0.5 m.y. (early Miocene). A basalt flow within sedimentary strata of the basal part of the Barstow Formation is 16.5±0.4 m.y. old, a date indicating an early or middle Miocene age for the lowest member of the formation. The andesite of Murphy's Well is 13.5±0.1 m.y. old (middle Miocene); it may have been extruded while deposition of the Barstow Formation continued elsewhere in the area. The Black Mountain Basalt, the youngest Tertiary unit in the area, is 2.55±0.58 m.y. old (late Pliocene).

Paleomagnetic-field directions from Miocene volcanic rocks generally cluster to the west of where they would fall if the region had been tectonically stable, and allow for as much as 30° of counterclockwise rotation of fault-bounded structural blocks in the area since middle Miocene time. Alternatively, the westerly bias in declination could have been caused by secular variation in the Miocene geomagnetic field.

INTRODUCTION

The Barstow basin area in the north-central Mojave Desert of southern California consists of broad pediment surfaces, isolated hills, and low mountains of deeply eroded pre-Cenozoic plutonic and metamorphic rocks unconformably overlain by Cenozoic volcanic and sedimentary strata. The Cenozoic rocks include flows of basalt, andesite, and dacite, welded and unwelded quartz latite and rhyolite ash-flow tuff, tuffaceous alluvial and fluvial deposits, and lacustrine sandstone, shale, and limestone. Hilly and mountainous areas are separated by bajadas and playas containing Pleistocene and Holocene alluvial, eolian, and lacustrine deposits. Topographic relief in the area is in part generated by right-lateral and lesser vertical displacements on a northwest-trending system of active faults that extends across the Mojave Desert between the San Andreas and Garlock fault zones (pls. 1, 2).

Most of the varyingly deformed Cenozoic units of the area represent deposits within a tectonic basin that existed in the north-central Mojave Desert region during early and middle Miocene time. This basin was an irregular elongate warped and faulted trough, about 40 km wide, that may have extended as far as 160 km—from as far west as Boron and the Kramer Hills eastward to beyond the Cady Mountains (pl. 1; Byers, 1960; Dibblee, 1967; Miller, 1978). In the Fremont Peak, Opal Mountain, and Lane Mountain 15-minute quadrangles, basin-filling Cenozoic volcanic and sedimentary rocks are folded for more than 30 km in the east-west-trending Barstow syncline and are offset, largely in a right-lateral sense, by active faults of the Blackwater, Calico, Black Mountain, and Harper-Gravel Hills fault zones. Warping and faulting during trough development and irregular uplift during folding of the syncline have left incomplete sequences and isolated remains of Cenozoic rocks between zones of the present right-lateral fault system.

This report presents results of field and laboratory studies of volcanic rocks in the area of the Barstow basin and syncline that clarify the age, stratigraphy, and origins of the Cenozoic units and that place paleomagnetic constraints on models of Neogene deformation in the region.

Acknowledgment.—We thank C. W. Hedel, J. S. Hite, L. G. Masten, and Gordon Thrupp for their assistance in the field and laboratory.

POTASSIUM-ARGON AND PALEOMAGNETIC SAMPLING AND ANALYSIS

Of the seven new potassium-argon dates reported here (table 1),

TABLE 1.—*Paleomagnetic data and potassium-argon analyses of volcanic rocks in the Barstow basin area, southern California*

[*N*, number of specimens; *I*, inclination corrected for tilt of bedding; *D*, declination corrected for tilt of bedding; *k*, precision parameter (Fisher, 1953); α_{95}, half-angle of 95-percent-confidence cone; θ, latitude of virtual geomagnetic pole; ϕ, longitude of virtual geomagnetic pole]

Sample localities			Paleomagnetic data							K-Ar data				
Site	Unit	Lat N., long E.	N	I	D	k	α_{95}	θ (N.)	ϕ (E.)	Material	K_2O (mol pct)	^{40}Ar (rad×10^{-11} mol/g)	^{40}Ar (rad pct)	Apparent age (m.y.±σ)
1	Black Mountain basalt	35.14° 242.82°	10	-54.8	183.9	996	1.5	86.8°	328.0°	Whole rock	0.603	0.2219	6.2	2.55±0.58
2	Andesite of Murphy's Well.	35.17° 242.93°	8	29.2	321.3	157	4.4	50.3°	133.5°	Biotite	6.43	12.5863	44.3	13.5±0.2
3	--do----------------	35.18° 242.92°	8	48.2	327.4	334	3.0	61.9°	149.9°	---	---	---	---	---
4	--do----------------	35.14° 242.93°	9	57.8	338.9	301	3.0	72.8°	170.3°	---	---	---	---	---
5	Basalt of the Barstow Formation.	35.15° 242.80°	8	62.3	1.1	305	3.2	81.5°	248.0°	Whole rock	.622	1.4877	18.1	16.5±0.4
6	Dacite in the Calico Mountains.	35.03° 243.11°	--	--	--	--	--	--	--	Plagioclase	.508	1.3306	72	18.1±0.5
7	Andesite dike in the Calico Mountains.	35.03° 243.11°	--	--	--	--	--	--	--	Hornblende	.477	1.2540	27	18.1±0.5
8	Quartz latite of the Opal Mountain Volcanic Member of the Pickhandle Formation.	35.16° 242.81°	5	30.9	334.3	41	12.0	60.6°	120.6°	---	---	---	---	---
9	--do----------------	35.21° 242.65°	7	38.3	324.7	93	6.3	56.3°	138.3°	Whole rock	5.23	14.2924	7.6	18.9±1.3
10	Lane Mountain Quartz Latite.	35.09° 243.06°	6	22.2	41.2	130	5.9	45.9°	355.1°	Sanidine	11.33	37.8525	74.4	23.1±0.2
11	--do----------------	35.09° 243.06°	6	-6.6	53.2	528	2.9	23.2°	359.2°	---	---	---	---	---

one each was made on sanidine, plagioclase, hornblende, and biotite, and three on crushed whole rock. Potassium analyses were performed by flame photometry (Ingamells, 1970). Standard isotope-dilution procedures were used in argon analysis (Dalrymple and Lanphere, 1969). Five samples were analyzed with a Neir-type mass spectrometer (60° sector, 15.3-cm radius) operated in the static mode with six manual scans of the ^{40}Ar, ^{38}Ar, and ^{36}Ar peaks; the two other samples were analyzed on a five-collector mass spectrometer (90° sector, 22.9-cm radius) that simultaneously records peak heights in three argon-isotope collectors. Radioactive-decay and ^{40}K-abundance constants used in the age calculations are:

$$\lambda_\beta = 4.962\times10^{-10}\ \mathrm{yr}^{-1},$$
$$\lambda_\epsilon + \lambda_\epsilon' = 0.581\times10^{-10}\ \mathrm{yr}^{-1},$$
$$^{40}\mathrm{K}/^{\mathrm{total}}\mathrm{K} = 1.167\times10^{-4}\ \mathrm{mol/mol}.$$

These constants were recommended by the International Union of Geological Sciences, Subcommission on Geochronology (Steiger and Jäger, 1977), and differ from those in common use before 1976. Previously published ages cited in the text have been recalculated with the new decay constants for comparison with our ages.

Orientations of rock cores collected for paleomagnetic analysis were determined in the field with a magnetic compass. Local declination deflections due to magnetic anomalies at exposures were removed by backsighting to landmarks and applying corrections. Only unaltered and flat-lying or moderately inclined strata that were amenable to simple structural reconstructions were sampled; strongly magnetic exposures that may have been remagnetized by lightning strikes were avoided.

Paleomagnetic specimens were given conventional treatment in alternating magnetic fields in a three-axis tumbler to remove unstable components of magnetization, such as those caused by lightning and viscous remanence. Remanent magnetism was measured with spinner magnetometers and a superconducting magnetometer. Two pilot specimens from each site were progressively demagnetized in alternating fields as strong as 80 mT (1 mT = 10 gauss), and vector diagrams (Zijderveld, 1967) were used to determine the optimum cleaning field for samples from each site. Each pilot specimen gave a single characteristic magnetization at field strengths above 30 mT and acquired spurious magnetic remanence due to instrumental noise at fields exceeding 60 mT; optimum fields were selected from within these limits. Field directions are well defined, and 95-percent-confidence limits are generally less than 6°.

PREVIOUS STRATIGRAPHIC INTERPRETATIONS

Description and nomenclature of the Cenozoic rocks in the Barstow basin area derive largely from the studies by McCulloh (1952, 1960) and Dibblee (1967, 1968). Figure 1 summarizes their stratigraphic interpretations.

Of the several Cenozoic rock units in the Fremont Peak, Opal Mountain, and Lane Mountain quadrangles, only the Miocene Barstow Formation was formally defined (Merriam, 1919) before McCulloh's (1952, 1960) studies. The names of McCulloh's (1952) informal Jackhammer Formation, Pickhandle Formation, and Lane Mountain Volcanics in the Lane Mountain quadrangle were formalized and adapted for use in the Fremont Peak and Opal Mountain quadrangles by Dibblee (1967, 1968), who also recognized and defined the Opal Mountain Volcanic Formation and the Black Mountain Basalt in his map area.

McCulloh (1952) based his stratigraphic interpretation in the Lane Mountain quadrangle on exposures of incomplete sequences of Cenozoic rocks in the Calico Mountains, at Lane Mountain, and in the Mud Hills (pl. 2). In the Calico Mountains, dacite tuff, tuff breccia, basalt, and conglomerate of his Jackhammer Formation unconformably overlie deeply eroded pre-Cenozoic basement rocks and are overlain with local unconformity by andesitic to dacitic volcaniclastic rocks and coarse conglomerate and breccia of his Pickhandle Formation. The Pickhandle is in turn overlain unconformably by flows of andesite and dacite, which have their shallow-intrusive equivalents in dikes, sills, and plugs that cut both the Jackhammer and Pickhandle Formations. McCulloh (1952) included the andesite and dacite flows in his Lane Mountain Volcanics because he thought the flows to be correlative with stratigraphically isolated quartz latite that lies on pre-Cenozoic granitic rocks at Lane Mountain, about 6 km northwest of the Calico Mountains. No andesite and dacite flows like those in the Calico Mountains occur in the Cenozoic section in the Mud Hills, where the Jackhammer and Pickhandle Formations are unconformably overlain by the easternmost exposures of alluvial, fluvial, and lacustrine sedimentary rocks and basalt of the Barstow Formation. The Barstow is nowhere in contact either with andesite and dacite like that in the Calico Mountains or with quartz latite like that of Lane Mountain.

Lacking fossils or radiometric dates, McCulloh (1952) considered the Jackhammer and Pickhandle Formations to be Miocene(?), both because of their position beneath the Barstow Formation, which he understood to be late Miocene, and because no

Cenozoic rocks older than Miocene were known elsewhere in the Mojave Desert region. The quartz latite at Lane Mountain and the andesite and dacite flows in the Calico Mountains he considered to be Pliocene(?) because the flows in the Calico Mountains above the

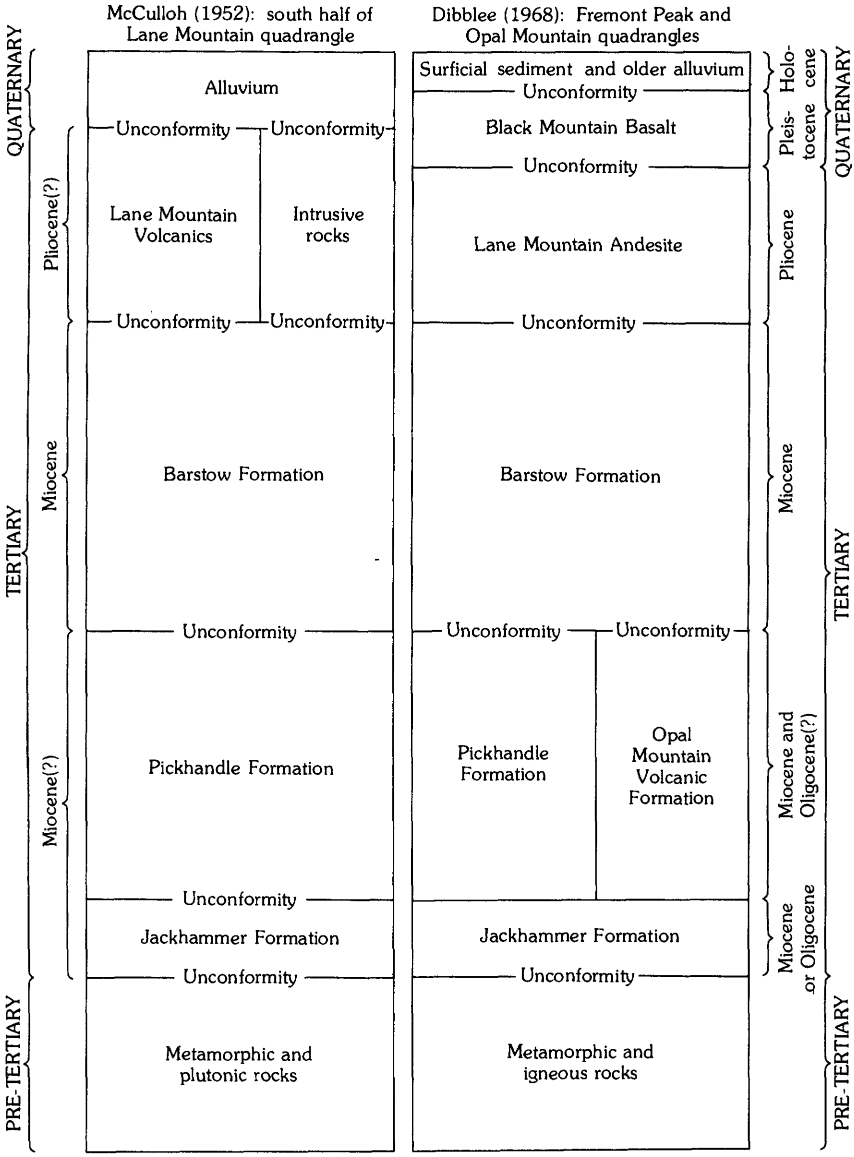

FIGURE 1.—Stratigraphic nomenclature, interpretation of stratigraphic succession, and age assignments of Cenozoic units in Barstow basin area, as reported by McCulloh (1952) and Dibblee (1968).

Pickhandle Formation appeared to be less deformed and, therefore, younger than strata of the Barstow Formation above the Pickhandle in the Mud Hills.

Like McCulloh, Dibblee (1967, 1968) believed the Jackhammer Formation to be the oldest unit in the Cenozoic sequence, and he thought it to be Oligocene or early Miocene; he considered the overlying Pickhandle Formation to be Oligocene(?) to middle Miocene. He assigned the quartz latite flows and shallow-intrusive bodies near Opal Mountain and the Gravel Hills to the newly named Opal Mountain Volcanic Formation. This formation was assigned the same age as the Pickhandle Formation because the quartz latite was seemingly intercalated with volcaniclastic rocks of the Pickhandle. He correlated isolated andesite flows in the mesas near Murphy's Well between Opal and Lane Mountains with the Lane Mountain Volcanics of McCulloh (1952), and, being in error about the composition of the rocks in the type area (which is quartz latite), he formalized this unit as the Lane Mountain Andesite of Pliocene(?) age (Dibblee, 1968, p. 38). He recognized basalt flows around Black Mountain as the Black Mountain Basalt and believed them to be Pleistocene because of their slight weathering and absence of erosion.

POTASSIUM-ARGON DATES AND STRATIGRAPHIC REVISIONS

Figure 2 shows the stratigraphic position of potassium-argon-dated samples reported here and the revisions of ages that these dates require.

LANE MOUNTAIN QUARTZ LATITE

Quartz latite welded tuff in the type area of McCulloh's (1952) Lane Mountain Volcanics and Dibblee's (1968) Lane Mountain Andesite is early Miocene, not Pliocene, according to a date of 23.1±0.2 m.y. from near the base of the tuff at Lane Mountain (site 10, pl. 2). The rocks at Lane Mountain are apparently the oldest Cenozoic unit in the area; they are not correlative with the flows and intrusions of andesite and dacite that McCulloh (1952) mapped as overlying the Jackhammer and Pickhandle Formations in the Calico Mountains, nor are they correlative with the isolated andesite flows that Dibblee (1968) mapped near Murphy's Well. The rocks at Lane Mountain are an eroded remnant of several welded quartz latite ash-flow sheets that contain unwelded tuff and vitrophyre locally at the base. These rocks were derived from an unknown vent and appear to be the remains of composite ash flows

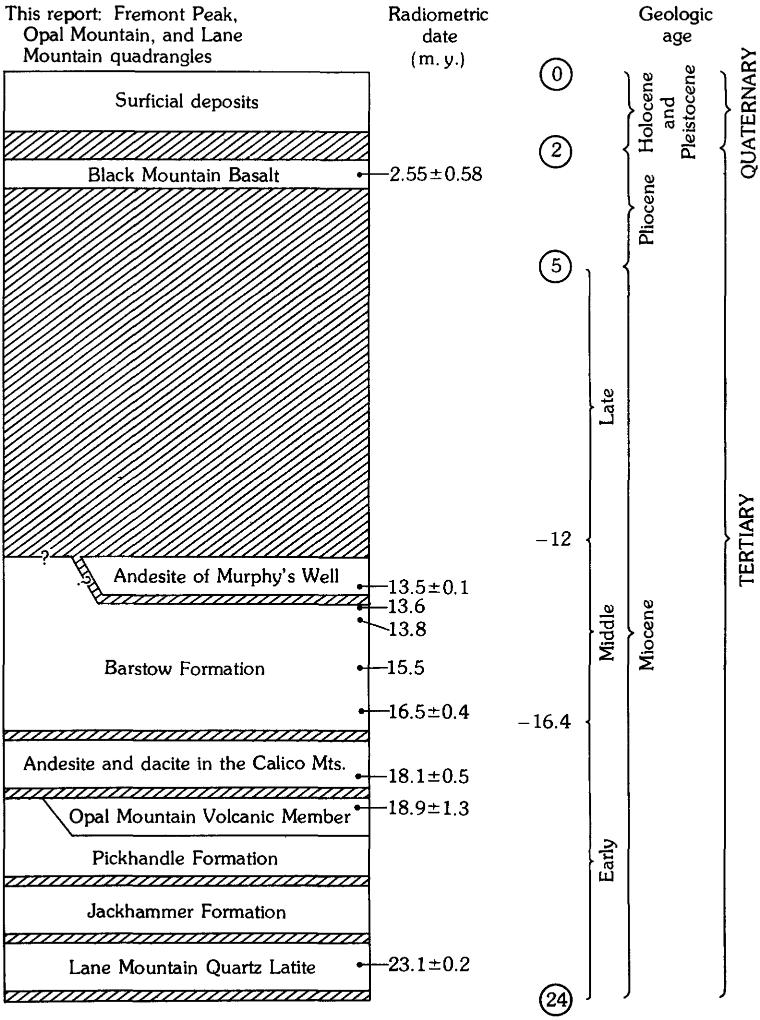

FIGURE 2.—Revisions to stratigraphic nomenclature, interpretation of stratigraphic succession, and age assignments of Cenozoic units in Barstow basin area. Diagonal lines indicate missing intervals. Circled ages of epoch boundaries are estimates presently adopted by the U.S. Geological Survey (Sohl and Wright, 1980). Ages of subdivisions of the Miocene (Ryan and others, 1974) are approximate. Potassium-argon dates without analytical uncertainties are recalculated from Evernden and others (1964) and Lindsay (1972).

that may once have been widespread in the area. Absence of the Lane Mountain Quartz Latite in the Cenozoic section elsewhere suggests that this unit was largely removed by erosion before younger units were deposited in the tectonic depression of the Barstow basin.

JACKHAMMER AND PICKHANDLE FORMATIONS

Undated basin-filling rocks of the Jackhammer Formation that crop out with only local angular unconformity beneath the early Miocene Pickhandle Formation in the Calico Mountains and Mud Hills are apparently not much older than the Pickhandle. If it is only slightly older than the early Miocene Pickhandle, then the Jackhammer is younger than the early Miocene Lane Mountain Quartz Latite and thus must also be early Miocene.

A date of 18.9 ± 1.3 m.y. on quartz latite welded tuff at the top of the Pickhandle Formation at Opal Mountain (site 8, pl. 2) indicates an early Miocene age for the Opal Mountain Volcanic Formation of Dibblee (1967) and for the underlying Pickhandle Formation as well. The volcanic rocks of Opal Mountain, which consist of welded quartz latite tuff and shallow-intrusive bodies, derive from the final explosive phase of volcanism in the Barstow basin that initially generated large volumes of lithic tuff and tuff breccia for the Pickhandle Formation. Where exposed around Opal Mountain and in the Gravel Hills, extrusive parts of the Opal Mountain volcanic rocks represent the remains of a single cooling unit of densely welded vitrophyre and eutaxitic aphanitic tuff that grades upward from loose tuff containing lithic fragments in the underlying Pickhandle Formation. Flow structure and brecciation observed by Dibblee (1968) derive from collapse and local flow during compaction and welding of the tuff sheet, and not, as he suggested, from viscous quartz latite lava flow.

Dibblee (1968) mapped strata of the Pickhandle Formation above quartz latite of his Opal Mountain Volcanic Formation in exposures near Opal Mountain and thus interpreted the latite to have been emplaced during deposition of tuffaceous Pickhandle strata. However, the quartz latite welded ash-flow sheet is everywhere at the top of the Pickhandle section. Tuffaceous sandstone, basalt, and lacustrine limestone overlying the quartz latite in the critical exposures about 1.5 km southwest of Opal Mountain are better assigned to the Barstow Formation on the basis of both their lithology and age.

Given the genetic relation between the unwelded tuff of the Pickhandle Formation and the overlying quartz latite welded ash-flow sheet and its shallow-intrusive feeder bodies, Dibblee's (1967) unit of Opal Mountain volcanic rock is here reconsidered as the uppermost member of the Pickhandle Formation, rather than as a separate formation.

ANDESITE AND DACITE OF THE CALICO MOUNTAINS

A dacite porphyry flow that uncomformably overlies both the Jackhammer and Pickhandle Formations and a calcic, quartz-bearing porphyritic hornblende-biotite andesite dike that intrudes the Jackhammer Formation near Jackhammer Gap in the Calico Mountains (sites 6, 7, pl. 2) are both 18.1±0.5 m.y. old and thus early Miocene. Although McCulloh (1952) included the dacite flow in his Lane Mountain Volcanics, it is certainly younger than and unrelated to the quartz latite tuff in the type area; he mapped the andesite dike as Tertiary intrusive andesite. These dates indicate that the flows and intrusive bodies of this local episode of volcanism in the Barstow basin followed the eruption of the rocks of the Pickhandle Formation and preceded basin-filling tuffaceous sediment and basalt of the Barstow Formation.

BARSTOW FORMATION

Trough-filling sedimentary deposits, rhyolite ash, and basalt flows of the Barstow Formation have long been assigned a Miocene age on the basis of abundant vertebrate fossils in the unit: the formation includes latest Hemingfordian fossils and the typical fauna for the Barstovian land-mammal stage (Merriam, 1911, 1915, 1919; Frick, 1937, p. 349-372; Lewis, 1968; Lindsay, 1972). Evernden and others (1964) reported a potassium-argon date of 15.5 m.y. on biotite from rhyolite tuff near the base of the highest, Barstovian member of the formation in the Mud Hills; Lindsay (1972) reported dates of 13.8 and 13.6 m.y., respectively, on plagioclase and biotite from a tuff bed about 150 m higher in the upper member. Another 100 m or so of strata of the Barstow Formation above the younger dated bed suggests that sediment belonging to the formation was still being deposited in the area of the Mud Hills while flows of the andesite of Murphy's Well were extruded onto pre-Cenozoic basement a few kilometers to the north (see below).

A basalt flow in the unfossiliferous basal part of the Barstow Formation (the Owl Conglomerate Member of Dibblee, 1968) is 16.5±0.4 m.y. old (site 5, pl. 2; included in the Pickhandle Formation of Dibblee, 1968, pl. 1). This date indicates that this lower part of the formation could be either early or middle Miocene.

ANDESITE OF MURPHY'S WELL

The lowest of several blocky andesite flows in the mesas near Murphy's Well between Opal and Lane Mountains (site 2, pl. 2) is 13.5±0.1 m.y. old, that is, middle Miocene. Dibblee (1968) assigned these flows, which lie in stratigraphic isolation on eroded pre-Cenozoic basement, to his Lane Mountain Andesite, but like the post-Pickhandle volcanic rocks in the Calico Mountains that McCulloh (1952) included in his Lane Mountain Volcanics, the andesite flows of Murphy's Well are unrelated in age and lithology to lower Miocene rocks of the Lane Mountain Quartz Latite.

The slight age difference between the andesite and a dated stratum within the upper member of the Barstow Formation (Lindsay, 1972) indicates that the two units may be in part coeval.

BLACK MOUNTAIN BASALT

The oldest of several flows of the Black Mountain Basalt on the east flank of Black Mountain (site 1, pl. 2) is 2.55±0.58 m.y. old, that is, late Pliocene, rather than Pleistocene. Reversed geomagnetic polarity in the rocks suggests that the time of cooling, within the uncertainties of the date, was during a period of reversed earth field either before about 2.9 m.y. or after about 2.5 m.y. B.P. (Mankinen and Dalrymple, 1979). Offsets of some of these flows in the Harper and Blackwater fault zones indicate that activity on the system of Mojave Desert faults is younger than the late Pliocene (Dibblee, 1968).

PALEOMAGNETIC ANALYSIS

Paleomagnetic determinations were made on a total of 67 samples from the Lane Mountain Quartz Latite, quartz latite in the Opal Mountain Volcanic Member of the Pickhandle Formation, basalt in the basal part of the Barstow Formation, the andesite of Murphy's Well, and the Black Mountain Basalt (fig. 3; table 1). Northeasterly declinations and anomalously shallow inclinations in the lowest two ash-flow cooling units at Lane Mountain apparently record an excursion of the Earth's field during the early Miocene; magnetic directions for other early and middle Miocene units have positive inclinations and a cluster of northwesterly declinations. The magnetic direction in basal breccia of the andesite of Murphy's Well (site 4, pl. 2) differs significantly from directions in less brecciated higher flows of the unit (sites 2, 3) and reflects either slight postcooling rotation of breccia blocks or secular variation of the field during extrusion of the several flows.

Virtual geomagnetic poles from Miocene volcanic rocks of the area fall west of Irving's (1979) Miocene reference pole for a tectonically stable North America (fig. 4). The westerly distribution of these poles may be due to natural variations in the Miocene magnetic field that are accentuated by the small number of units that could be sampled. Larger data sets that more fully reflect secular variation should yield a mean paleomagnetic pole within a few degrees of the stable Miocene reference pole, which does not significantly differ from the present geographic pole.

If additional paleomagnetic sampling of Cenozoic rocks on the fault blocks in the Mojave Desert substantiates westerly pole positions, then post-middle Miocene counterclockwise rotation of the

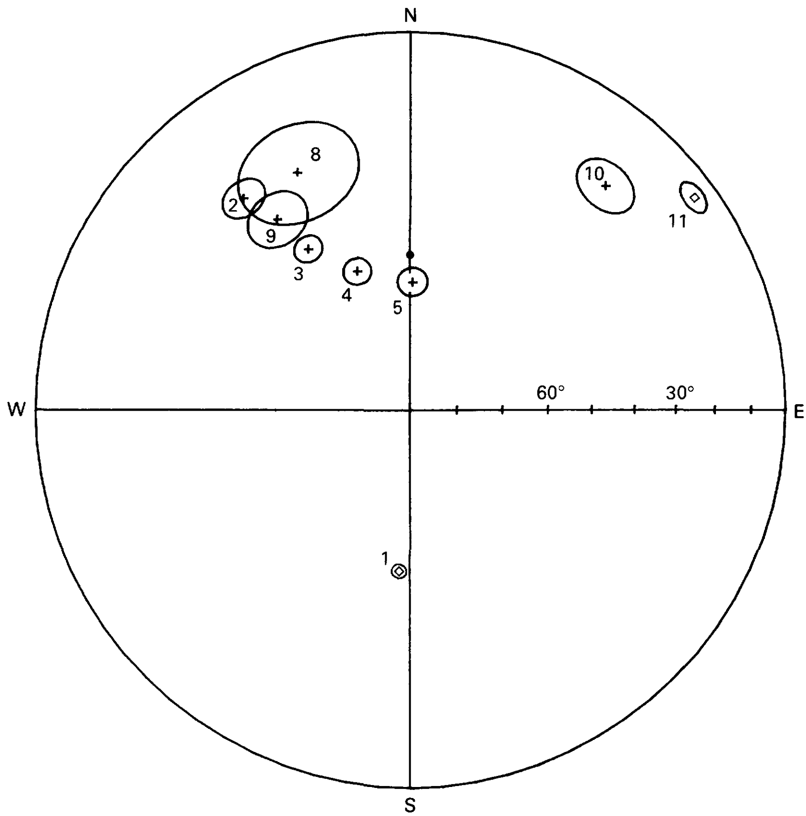

FIGURE 3.—Equal-area projection of mean paleomagnetic directions corresponding to sample sites on plate 2 and in table 1, including 95-percent-confidence limits. Downward inclinations shown as pluses; upward inclinations shown as diamonds. Dot indicates direction of present axial dipole field.

region is indicated. The sense and magnitude (as much as 30°) of possible tectonic rotation are consistent with the kinematic model for Neogene deformation proposed by Garfunkel (1974), in which elongate northwest-trending blocks of the Mojave Desert are rotated counterclockwise. According to the model, the rotation occurred during north-south compression that accompanied development of the San Andreas fault system as a transform between the North American and Pacific lithospheric plates. The compressive strain in this model is taken up by right-lateral movements along the central Mojave Desert system of faults that bound the rotated crustal blocks. In contrast, major clockwise Neogene rotations of fault-bounded terranes on the southwest side of the San

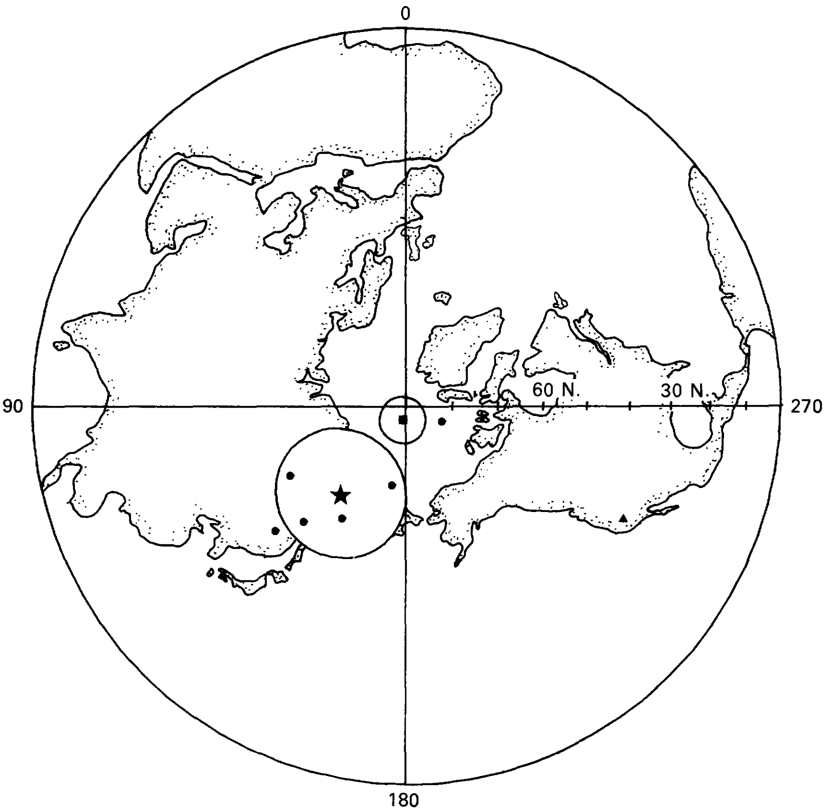

FIGURE 4.—Equal-area polar projection of paleomagnetic results. Study area indicated by triangle. Virtual geomagnetic poles of Miocene volcanic rocks in Barstow basin area shown by dots. Mean virtual geomagnetic pole shown by star (circle is 95-percent—confidence limit). Miocene reference pole for tectonically stable North America shown by square (with 95-percent-confidence limit).

Andreas fault have been substantiated by paleomagnetic data from Miocene volcanic rocks along the southern California coast (Kamerling and Luyendyk, 1979).

CONCLUSIONS

New potassium-argon ages determined from Cenozoic volcanic-rock units in the Barstow basin area fix the chronology of geologic events established by McCulloh (1952) and Dibblee (1967, 1968). Welded quartz latite ash-flow sheets that are preserved only at Lane Mountain were deposited on a deeply eroded pre-Cenozoic basement surface of low relief during early Miocene time. Deposition and much erosion of the Lane Mountain Quartz Latite apparently preceded creation of the east-west-elongate Barstow basin, within which were deposited: (1) dacitic tuff, tuff breccia, and basalt of the Jackhammer Formation, (2) copious dacitic to rhyolitic tuff and tuff breccia of the Pickhandle Formation, (3) andesitic to dacitic flows of the Calico Mountains, (4) tuffaceous nonmarine sediment and basalt of the Barstow Formation, and (5) flows of the andesite of Murphy's Well. North-south compression of basin-filling units into the Barstow syncline and development of a system of northwest-trending right-lateral faults in the central Mojave Desert region followed deposition of these units; right-lateral faulting began at least by the time of eruption of the Pliocene Black Mountain Basalt.

Neogene displacements across the Harper-Gravel Hills, Black Mountain, Blackwater, and Calico fault zones in the area may have caused as much as 30° of counterclockwise rotation of the structural blocks between the fault zones, in conjunction with north-south shortening of the crustal wedge between the San Andreas and Garlock faults, although well-controlled estimates of the extent of rotation will not be possible until the Miocene paleomagnetic pole is better defined from tectonic blocks in the Mojave Desert.

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