Lithostratigraphy, biostratigraphy, and geochronology of the Barstow Formation, Mojave Desert, southern California

MICHAEL O. WOODBURNE *Department of Earth Sciences, University of California, Riverside, California 29521*
RICHARD H. TEDFORD *Department of Vertebrate Paleontology, American Museum of Natural History, New York, New York 10024*
CARL C. SWISHER III *Berkeley Geochronology Center, 2453 Ridge Road, Berkeley, California 94709*

ABSTRACT

The highly fossiliferous Barstow Formation, of medial Miocene age, crops out in the Mud Hills, north of Barstow, in the northwestern part of the Mojave Desert, San Bernardino County, California. The Barstow Formation is composed of a sequence of fluviatile and lacustrine sediments, and water-laid air-fall tuff beds; it is about 1,000 m thick, interfingers with the lower Miocene Pickhandle Formation, and is unconformably overlain by Pliocene basalt and Quaternary alluvium. The sediments have been folded into a syncline and broken by several faults that generally trend northwest-southeast and show right-lateral separation.

In this report, the Barstow Formation has been divided into three members. A newly expanded Owl Conglomerate Member is at least 200 m thick. It is exposed on both limbs of the syncline and is composed mainly of gray-green granitic conglomerate on the north limb and of conglomerate and conglomeratic sandstone of reddish hues on the south. Near the base of both sequences, the distinctive Red Tuff has been dated isotopically at about 19.3 Ma, and on the north limb of the syncline, the uppermost unit of the Pickhandle Formation stratigraphically overlies this tuff. Owl Conglomerate clasts in the unit indicate deposition from the north and south to southwest sides of the basin. Although the actual limits of the basin are not known, present outcrops of potential source terranes suggest that it may have been about 8 km wide from north to south. Fossil mammals, termed the "Red Division Fauna," that occur in the upper part of the Owl Conglomerate Member are of late Hemingfordian age, probably range in isotopic age from 16.5 to 16.3 m.y., and correlate to the upper part of the reversed magnetozone of magnetic chron C5C. The uppermost breccias of the Pickhandle Formation are younger than 19.3 m.y. and are likely older than 16.3 m.y., the age of the Rak Tuff that locally caps the Owl Conglomerate Member.

The middle member of the Barstow Formation lies stratigraphically above the Owl Conglomerate Member and below the Skyline Tuff. The lower contact is locally unconformable. The unit is about 570 m thick and is composed of predominantly fluviatile conglomerate and conglomeratic sandstone beds on the west and southwest that pass laterally into a sequence of predominantly lower-energy sandstone and claystone beds on the east. Facies distribution and sparse paleocurrent data suggest that the conglomeratic sequence was derived from sources to the south and southwest and that the finer-grained beds were deposited in the more distal part of the basin to the east and northeast.

The Oreodont Tuff, situated about 270 m stratigraphically above the base of the middle member, has been dated at about 15.8 Ma, and the strata that occur in the interval from the top of the Owl Conglomerate Member to a level 40 m below this tuff produce a previously unreported assemblage, herein named the "Rak Division Fauna." This fauna is biologically and stratigraphically intermediate between the Red Division and Green Hills Faunas, is assigned a latest Hemingfordian age, ranges in isotopic age from about 16.3 to 15.9 m.y., and correlates to the upper half of magnetic chron C5C and the lowermost part of Chron C5B and Chron C5AD.

Strata about 40 m below the position of the Oreodont Tuff and extending 270 m higher than the Oreodont Tuff, in the middle member of the Barstow Formation, contain fossil mammals of the Green Hills Fauna, of early Barstovian age. The *Cupidinimus lindsayi* Assemblage Zone also begins about 40 m stratigraphically below the Oreodont Tuff. Beds that contain the Green Hills Fauna range in isotopic age from about 15.9 to 15.3 m.y. and correlate to all but the lowest and uppermost parts of magnetic chron C5B.

The upper 60 m of the middle member of the Barstow Formation yields a transitional assemblage, herein named the "Second Division Fauna," that contains some elements of the Green Hills Fauna associated with other taxa typical of the succeeding Barstow Fauna. Beds that contain the Second Division Fauna range in isotopic age from about 15.3 to 14.8 m.y. and correlate to the reversed magnetozone of magnetic chron C5AC.

The upper member of the Barstow Formation begins at the base of the Skyline Tuff and extends to the top of the formation, a stratigraphic interval of about 270 m. In the eastern half of the outcrop area and on the north limb of the syncline in the western outcrop area, the deposits are largely beds of fine-grained lacustrine shale, mudstone, and claystone, with lesser amounts of interbedded sandstone and conglomeratic sandstone. To the west and southwest, the equivalent stratigraphic interval is represented by beds of sandstone and conglomeratic sandstone. The interval bearing the Lapilli Sandstone (isotopically dated at about 13.4 Ma) and 30 m of capping beds of limestone and equivalent beds of mudstone appears to be the geologically youngest part of the Barstow Formation in the Mud Hills.

This part of the Barstow Formation also seems to have been deposited in a basin that was filled from the west and southwest by fluviatile deposits, whereas lacustrine sedimentation took place mainly on the north and east. A distinctly northern source may have been responsible for an ~30-m-thick unit of hornblende-rich sandstone including the Lapilli Sandstone.

Fossil mammals from the upper member of the Barstow Formation pertain to the Barstow Fauna, of late Barstovian age, defined by the first appearance of proboscideans (just below the Dated Tuff). The Barstow Fauna thus is found in beds just below the Dated Tuff to the

Geological Society of America Bulletin, v. 102, p. 459–477, 6 figs., 1 table, April 1990.

top of the Barstow Formation in the Mud Hills, ranges in isotopic age from about 14.8 to 13.3 m.y., and correlates to most of the normal magnetozone of Chrons C5AC and C5AB. Three rodent assemblage zones (*Pseudadjidaumo stirtoni*, *Copemys longidens*, and *Copemys russelli*, from oldest to youngest) have been described from the interval that begins just below the Dated Tuff and extends upward for about 250 m.

The evidence from the Barstow Formation provides local calibration of important biochronological events: the Hemingfordian-Barstovian boundary at 15.9 Ma, and the local first appearance of proboscideans at about 14.8 Ma.

INTRODUCTION

The Barstow Formation, of medial Miocene age, crops out discontinuously in a northwardly concave belt about 83 km long in the central Mojave Desert, in central San Bernardino County, southern California. The exposures extend from the Gravel Hills on the west to the West Cronese basin on the east. Between these end points, the Barstow Formation occurs in the Mud Hills, Calico Mountains, Yermo Hills, and Alvord Mountain (Fig. 1).

The type area of the Barstow Formation is located in the Mud Hills, or Barstow syncline, 16 km north of Barstow (Fig. 1). There, the formation is about 1,000 m thick and consists of a complex network of basin-margin facies of coarse-grained fanglomeratic units that interdigitate with finer-grained epiclastic fluvial and lacustrine sediments and interbedded water-reworked air-fall tuffs. The unit in part unconformably overlies but also interfingers with the unfossiliferous, largely pyroclastic Pickhandle Formation of Dibblee (1968), of early to medial Miocene age, and is unconformably overlain by the Black Mountain Basalt dated at about 2.5 Ma (Burke and others, 1982) and Quaternary alluvium.

Prominent volcanic ash beds and other lithologic markers are used to divide the formation into at least three superposed lithic units, the upper two of these being locally highly fossiliferous. Because of the abundance of fossils, the faunas from the Barstow Formation were chosen to typify a portion of medial Miocene time termed the "Barstovian land-mammal age" in North America (Wood and others, 1941). As such, the unit is a cornerstone of the network of biochronologic correlations based on fossil mammals that is used by vertebrate paleontologists and nonmarine stratigraphers to determine the age of continental deposits in North America. Barstow Formation strata are locally fossiliferous in the other districts mentioned above, but those of the Mud Hills preserve the best biostratigraphic record.

K/Ar isotopic calibration of tuffaceous units of the Barstow Formation, correlation of its contained faunas, and consideration of accumulation rates suggest that it is at least 19 m.y. old at its base, and about 13.3 m.y. old at its stratigraphic top in the Mud Hills. Correlation of paleomagnetic data from the Mud Hills (MacFadden and others, 1990) to the Magnetic Polarity Time Scale as currently calibrated is consistent with the age estimates given above. Other parts of the regionally extended Barstow Formation are contained within those ages.

The purpose of this report is to upgrade previous information and to integrate that with our newly acquired data on the lithostratigraphy and biostratigraphy of the Barstow Formation in its type area and the new isotopic and magnetostratigraphic data reported by MacFadden and others (1990). Our aim is to place present knowledge in a framework from which further studies can be initiated, and to identify aspects of Barstow Formation sedimentation that reflect at least local tectonic events during the 19 to

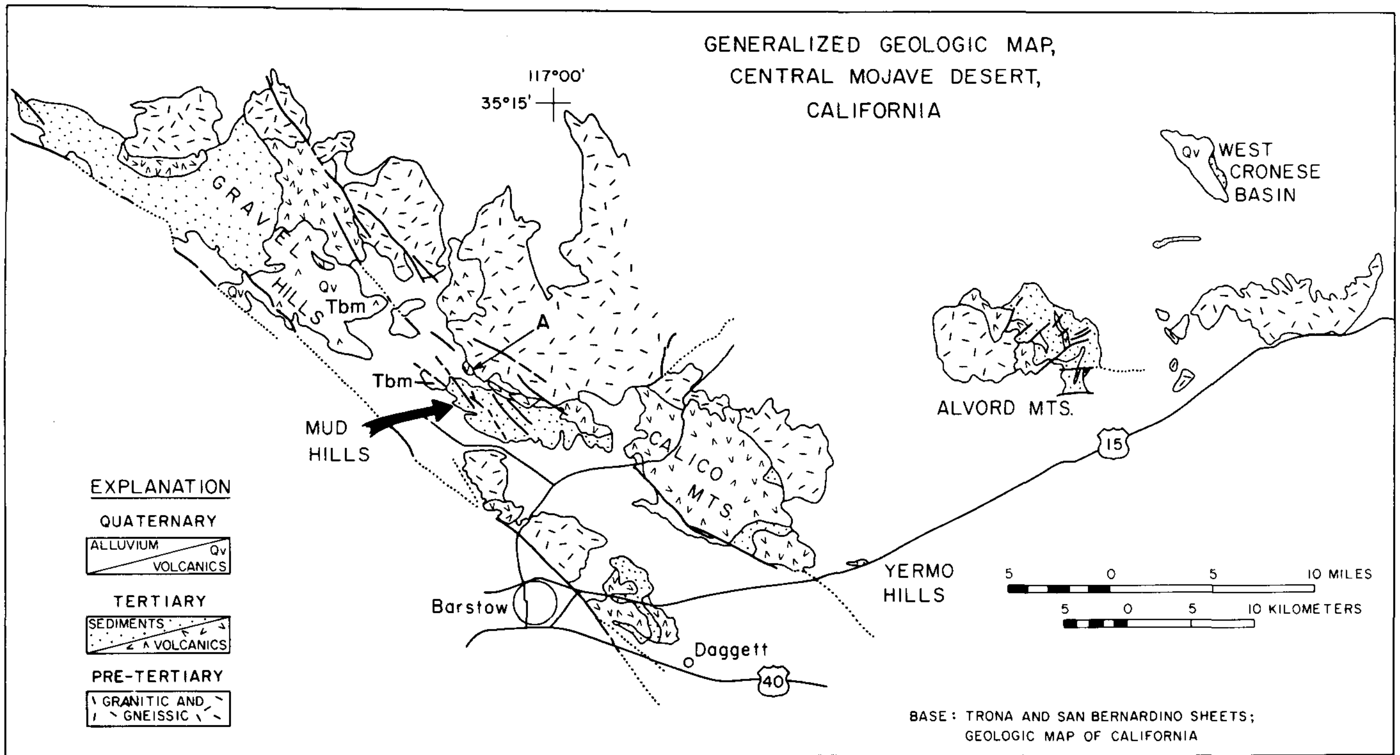

Figure 1. Index map of the central Mojave Desert, California, showing districts in which the Barstow Formation crops out. Tbm, Black Mountain Basalt of Pliocene age; A, Andesite of Murphy's Well.

13.3 Ma interval. To this end, then, we (1) summarize the past history of study of the Barstow Formation, (2) utilize new lithostratigraphic data to establish a more refined framework for stratigraphic analyses, (3) give a new and more detailed biostratigraphy of the formation than previously available, (4) integrate these with newly acquired information on the isotopic calibration and magnetostratigraphy of the formation (MacFadden and others, 1990), (5) use the above to perform regional correlations with other districts in North America, (6) bring together data on the original depositional context of the formation and the provenance of the sediments that compose the unit, and (7) show that at least local tectonic activity continued in or near the Barstow basin during the deposition of the Barstow Formation. This discussion will provide a basis of comparison in the analysis of the age, provenance, geologic setting, and distribution of other upper Cenozoic rock units in the central Mojave Desert (Fig. 1) and will stand as a reference for evaluation of rocks and faunas of Barstovian age in other parts of North America.

HISTORY OF STUDY

The term "Barstow [Series]" was first applied to deposits of Quaternary age adjacent to the Mojave River between Barstow and Daggett, California (Fig. 1) (Hershey, 1902). Hershey (1902) also coined the term "Rosamond Series" (Fig. 2) for essentially all strata of known or presumed Tertiary age on and adjacent to the western part of the Mojave Desert and included deposits on the north side of the Mojave River between Barstow and Daggett in that unit. Subsequent field work by parties from the University of California, Berkeley (Baker, 1911; Merriam, 1911, 1913, 1915a, 1915b, 1919), followed discovery of the fossiliferous strata in the Mud Hills, north of Barstow. At first, Baker (1911) utilized the name "Rosamond Series" for the deposits of the Mud Hills; he divided them into the five units shown in Figure 2 and noted that the uppermost of these (Fossiliferous Tuff Member) contained abundant fossils. Baker (1911, p. 344) also noted that fossils were present in the next lower unit (Resistant Breccia Member). Merriam (1915a, 1919) discussed the possible ways in which the Rosamond Series might be related to the deposits in the Mud Hills that contained fossils he termed the "Barstow Fauna." Merriam (1915a) initially intended the term "Barstow beds" to be restricted to the Fossiliferous Tuff Member of Baker (1911) but later (Merriam, 1919) indicated that the lithostratigraphic term could include related units, both laterally and vertically, rather than rocks restricted to that member. Thus, Merriam (1919) recorded fossil mammals from the Resistant Breccia Member of Baker (1911) and indicated that this unit could be included in the Barstow beds or formation. Although procedurally incorrect (Hedberg, 1976), use of the term "Barstow Formation" for deposits of Tertiary age in the Mud Hills was stabilized in 1924 by the U.S. Geological Survey (see Lewis, 1964). The studies of Merriam (1915a, 1919) remain the basic references for the vertebrate paleontology of the Barstow Formation in the Mud Hills.

Beginning in 1923, personnel of the Frick Laboratory, American Museum of Natural History, New York, began a long field campaign, first under the direction of J. Rak (1923–1930), followed by J. Wilson (1930–1937), C. Falkenbach (1930), and later T. Galusha (1950–1952). Voluminous records of the extended field work of the Frick Laboratory clearly establish that a detailed stratigraphy based on the subdivisions of

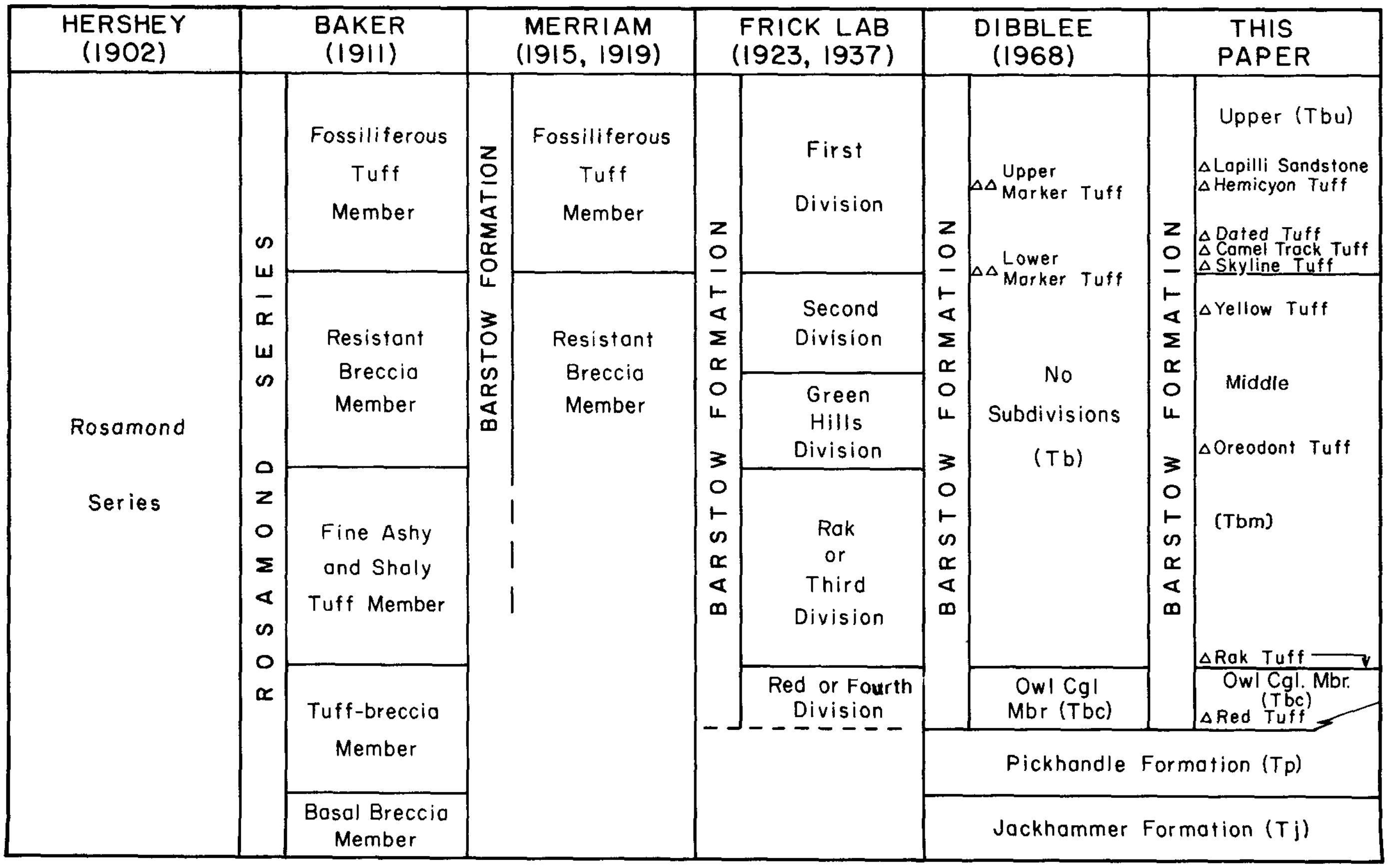

Figure 2. Chart showing present and past nomenclature of divisions of the Barstow Formation in the Mud Hills.

Baker (1911) was used in 1923–1937 during the period of their intensive collecting. Figure 2 indicates the stratigraphic terms developed from 1923 to 1937 and their relationships to Baker's (and Merriam's) units and to the terminology utilized subsequently. The Frick Laboratory nomenclature (Fig. 2) initially used a numerical system beginning with the stratigraphically highest unit, but this was gradually supplanted with more specific terms when the Green Hills Division was broken out of the base of the previously used Second Division. Lithologic markers were utilized to separate the divisions, especially the Skyline Tuff, which serves as the boundary between the First and Second Divisions. In other cases, prominent changes in texture were used. Sketch maps, sections, and summary reports were prepared by J. Rak and J. Wilson, and by T. Galusha, who mapped the Mud Hills in 1950–1952 using an aerial photographic base with results generally similar to those published by Dibblee (1968). The Frick Laboratory terminology was used in the publications by Schultz and Falkenbach, and Frick, cited below. Schultz and Falkenbach (1941, 1947) published studies on oreodonts that included specimens from the Barstow Formation. Frick (1926a, 1933, 1937) presented a study of the hemicyonine bears, mastodonts, and horned ruminant artiodactyls, respectively, that similarly included Barstow taxa but published few of the stratigraphic data accompanying the material, which was contained in collections of the American Museum of Natural History.

Lewis (1964, 1968) reported on stratigraphically important, if taxonomically limited, additions, based on collections of the U.S. Geological Survey. Other, taxonomically restricted, studies that concerned specimens from the Barstow Formation include Davidson (1923, camels), Furlong (1927, horned ruminants), Hall (1930, rodents and lagomorphs), Stirton (1930, an insectivore), Wood (1936, rodents), Stock (1937, a peccary), Tedford and Alf (1962, an anchitheriine horse), Woodburne (1969, peccaries), and Lindsay (1972, rodents). An informal preliminary summary of the biostratigraphy of the Barstow Formation was made by personnel of the American Museum of Natural History to accompany a field trip of the Society of Vertebrate Paleontology in 1966. Lindsay (1972) introduced a zonation of the upper part of the Barstow Formation based on rodents. Despite these contributions, very little work that is both a general taxonomic as well as biostratigraphic synthesis has been published on the vertebrate fossils of the Barstow Formation since Merriam (1919). A brief, but stratigraphically and taxonomically modern, discussion of the biostratigraphy has been prepared by R. H. Tedford and others (1987), and pertinent aspects of that work are included herein.

The most recent studies of the geology of the Barstow Formation in the Mud Hills are Steinen (1966), Dibblee (1968), and through Dibblee (1968), McCulloh (1954). Durrell (1953), however, published a discussion of the general geology of the Tertiary deposits and the mineralogy of strontianite-bearing beds in the vicinity of Solomon Canyon, east of Owl Canyon, in the Mud Hills (Fig. 3). As noted by Dibblee (1968), this discussion pertains to a reasonably undeformed sequence of deposits, and the cross sections and measured section offered by Durrell (1953) include not only the stratotype of the Barstow Formation as redefined by Dibblee (1968), but also show its relationships to the Pickhandle Formation. Sheppard and Gude (1969) discussed the diagenesis of tuff beds in the Barstow Formation in the Mud Hills and presented a modern version of the nomenclature of units and beds that enables subdivision of the upper third of the Barstow Formation in that area.

A sedimentological and biostratigraphic study of the Barstow Formation in the Mud Hills was initiated in 1964 by R. H. Tedford and R. P. Steinen, while both were at the Department of Geological Sciences, University of California, Riverside. Steinen mapped the Mud Hills in 1964–1965 (Steinen, 1966). One aim of this project was to locate and integrate into a stratigraphic framework the fossil localities developed by various institutions during the past decades so as to develop a detailed biostratigraphy for the Barstow Formation in the Mud Hills. This study is still in progress, but certain aspects of the biostratigraphy of the Barstow Formation have been cited in recent years in studies on rock units in adjacent districts (for example, Woodburne and Golz, 1972; Woodburne, 1969; Miller, 1980; Woodburne and others, 1982) as well as on the Barstow Formation itself (Lindsay, 1972; Woodburne and Tedford, 1982; Tedford and others, 1987).

A more regional perspective, which includes comments on the Barstow Formation, is given by S. T. Miller (1980) in an open-file report for the U.S. Geological Survey, and by Woodburne, Tedford, and Miller (1982). An earlier version of the present report (now strongly revised) was published by Woodburne and Tedford (1982). Personnel of the Department of Earth Sciences, University of California, Riverside, have maintained a steady, if intermittent, study of the stratigraphy and vertebrate paleontology of the Barstow Formation (as well as of the Mojave Desert in general) since 1959.

Historically, the Mud Hills sequence has played a central role in the calibration of the Barstovian mammal age (Lindsay, 1972; Woodburne and Tedford, 1982; Woodburne and others, 1982). The dating of these faunas was addressed as early as 1964 by Evernden, Savage, Curtis, and James in their pioneering work on the age calibration of North American mammalian faunas. These authors published ^{40}K-^{40}Ar dates from two tuffaceous horizons in the Barstow Formation, the "Dated Tuff" of Rainbow basin in the Mud Hills area and a tuff from the Cronese basin, located some 60 km to the northeast (Fig. 1). These ages were the first numerical calibration points for Barstovian fossils from the Barstow Formation.

Additional ^{40}K-^{40}Ar calibration points were later added, as discussed in MacFadden and others (1990), including ages obtained by the $^{40}Ar/^{39}Ar$ laser-fusion method, and we utilize these in our discussion of the isotopic age of the Barstow Formation.

LITHOSTRATIGRAPHY OF THE TYPE BARSTOW FORMATION

The lithostratigraphy of the Barstow is depicted in Figures 3 and 4, which reflect new mapping by us and the development of new stratigraphic sections during our work (see also MacFadden and others, 1990). These stratigraphic sections (Fig. 4) were originally obtained during our paleomagnetic sampling program and hence were chosen to be representative of units on both north and south limbs of the Barstow syncline. Whereas many of the sections are in tectonically isolated blocks, their correlation has been accomplished by use of the various marker tuff beds shown in Figures 3 and 4. The general facies relationships shown in Figure 4 have been interpolated between the measured sections based on Figure 3 and on our other observations. Figure 4 is somewhat diagrammatic in that the disposition of the various sections is only approximately scaled to the dimensions of Figure 3 and roughly restores the effects of postdepositional folding and faulting. Nevertheless, sections 2, 3a, and 6 occur along a southeast-trending line in the northwestern Mud Hills on the north limb of the syncline and are clearly separated from sections 3b, 5, 7, 4, and 1 that occur in a somewhat irregular southeastward alignment on the south side of the syncline. The Carnivore Canyon section (2) is the farthest northwest, the Rainbow Loop section (1) farthest southeast. We also add a composite northeastern section on the north limb of the syncline taken from Dibblee (1968, p. 21, Pickhandle Formation in Owl Canyon; p. 29, the type section of the Barstow Formation exposed between Owl and Solomon Canyons).

Based on our work (Figs. 3 and 4) and that of Steinen (1966) and Dibblee (1968), the following stratigraphic summary is given in order to orient the reader to the data discussed below. The Barstow deposits are epiclastic fluviatile and lacustrine sediments that reach a thickness of about 1,000 m. The deposits vary widely in color, with hues of brown, green, orange, and red being common. Interbedded ash units commonly are vitreous white in color but may be yellow or brown, particularly where zeolitized (Sheppard and Gude, 1969). We utilize some of these tuff beds, along with textural considerations, to establish a threefold division of the Barstow Formation. This tripartite division breaks down where distinctive criteria are masked by coarse-grained deposits that reflect vigorous erosion of tectonically active basin margins. On the basis of our data along with

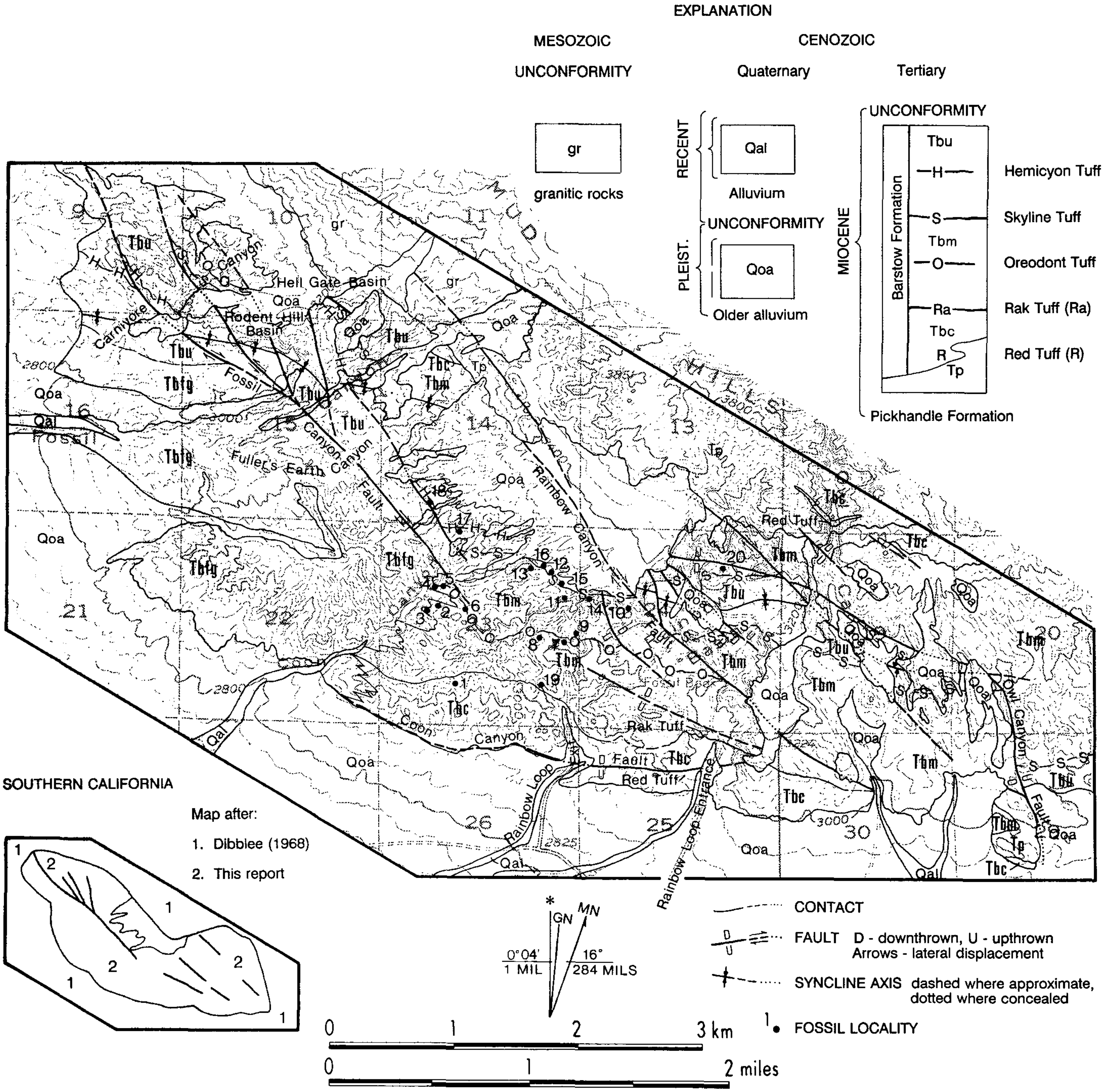

Figure 3. Generalized geologic map of the Mud Hills, showing the overall outcrop pattern of the Barstow Formation, the threefold subdivision of the formation used in this report, locations of major faults, locations of important quarries of the Frick Laboratory, and stratigraphic position of important marker beds. Simplified and modified from Dibblee (1968, Pl. 3) and our mapping. Fossil mammal quarries of the Frick Laboratory are numbered: 1, Red Division; 2, Steepside; 3, Sunset; 4, Oreodont; 5, Turbin; 6, Rak; 7, Raven; 8, Deep; 9, Camp; 10, Valley View; 11, Sandstone; 12, May Day; 13, Hailstone; 14, Skyline; 15, Starlight; 16, New Year; 17, Easter; 18, Hemicyon; 19, Camel; 20, Saucer Butte. See Figure 5 for stratigraphic disposition.

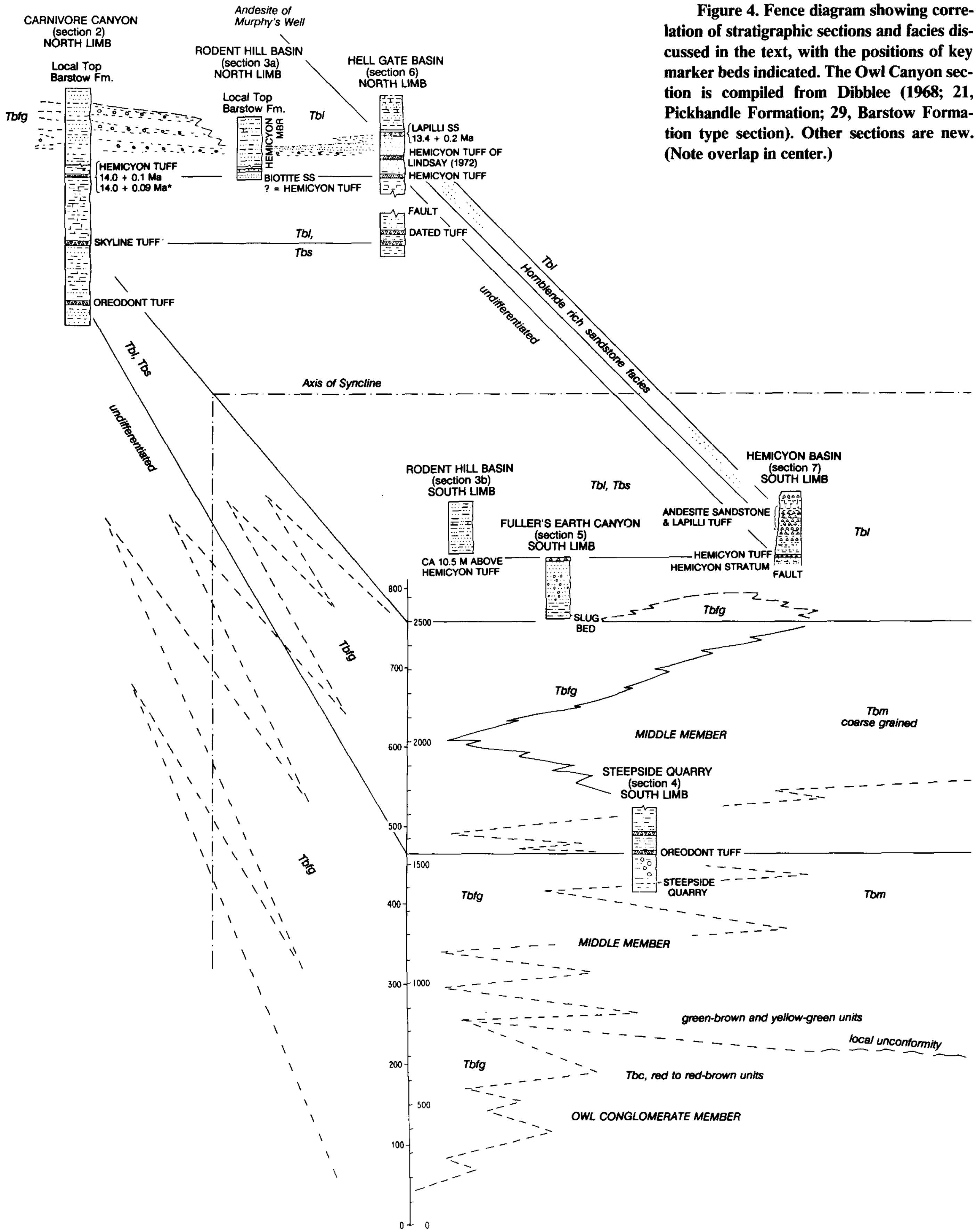

Figure 4. Fence diagram showing correlation of stratigraphic sections and facies discussed in the text, with the positions of key marker beds indicated. The Owl Canyon section is compiled from Dibblee (1968; 21, Pickhandle Formation; 29, Barstow Formation type section). Other sections are new. (Note overlap in center.)

those of Steinen (1966) and Dibblee (1968), it is clear that coarse-grained facies were shed into the Barstow basin from the north, northwest, west, and southwest during much of the 6-m.y. interval of its deposition. These data and the presence of local breccias and intraformational unconformities discussed below, indicate syn-depositional tectonism during this time. We begin our discussion with Dibblee's (1968) concept of the Barstow Formation and its stratotype, followed by our modification of its lower boundary and discussion of the tripartite division of the unit employed by us.

Barstow Formation of Dibblee (1968)

Dibblee (1968, p. 26, 27) redefined the Barstow Formation to be essentially equivalent to the upper two members of Baker (1911): "that sequence of deformed, stream-laid conglomerates, sandstones, lacustrine clays, and several thick tuffs, which lies unconformably above granitic

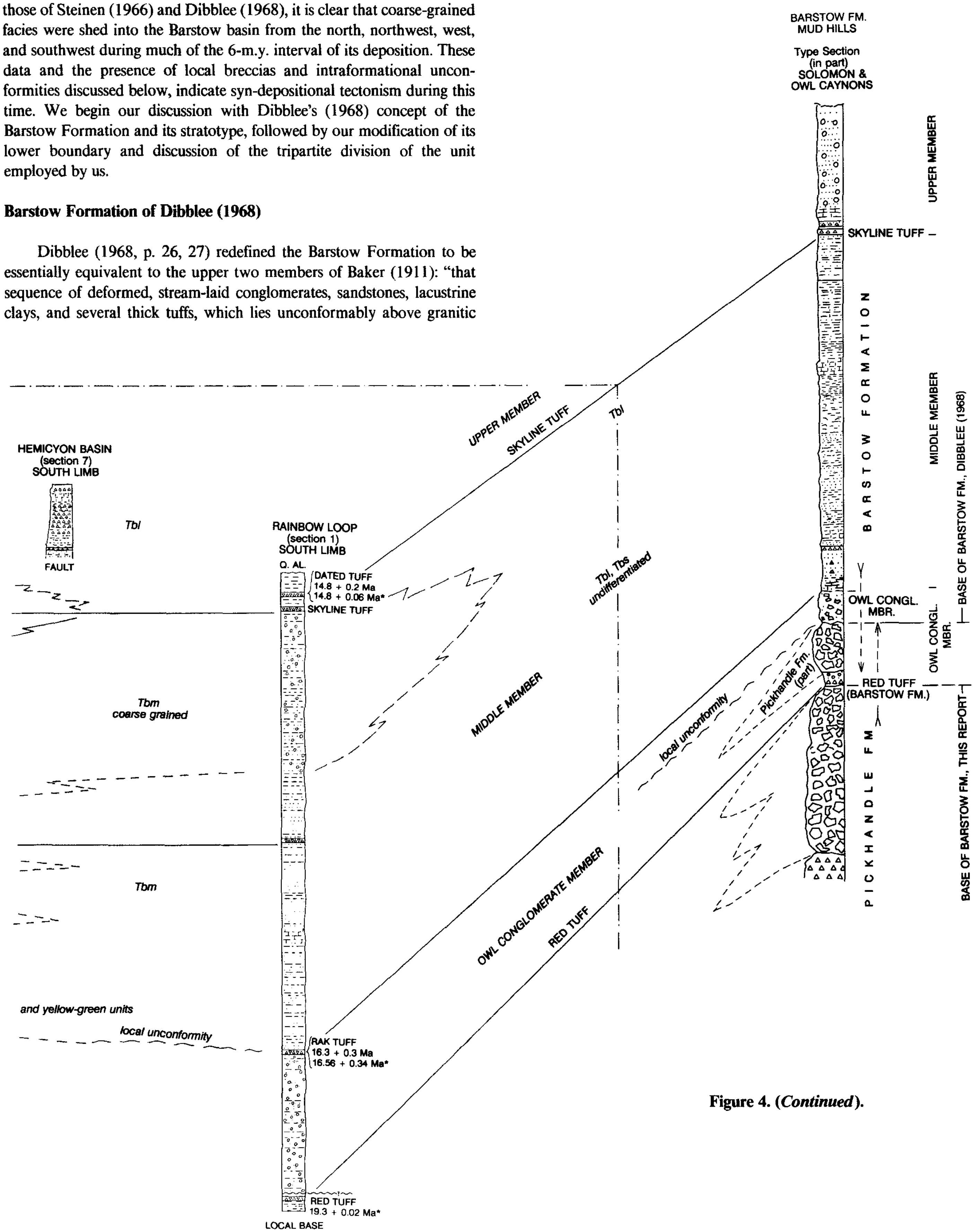

Figure 4. (*Continued*).

breccia and tuff of the Pickhandle Formation, unconformably below flat-lying older alluvium of Pleistocene age, and which contains a mammalian fauna of late-middle and upper Miocene age" (Dibblee, 1968, p. 27). Although clearly of secondary importance, Dibblee's correlation of Baker's units is incorrect. Dibblee's angular unconformity separating the predominantly epiclastic Barstow Formation from older pyroclastic rocks (Pickhandle Formation of McCulloh, 1954; extended to the Mud Hills by Dibblee, 1968) is clearly contained within the Tuff-breccia member of Baker (1911), as depicted in Figure 2. Our work shows that the Barstow Formation is virtually equivalent to four of the five members of the Rosamond Series of Baker (1911).

Although Dibblee (1968) indicated that the Barstow Formation unconformably overlies the lower to middle Miocene Pickhandle Formation, information recently developed by us shows that the base of the Barstow in part interfingers with the top of the Pickhandle on the north limb of the syncline, in Owl Canyon (Figs. 3 and 4). Regionally, in the Mud Hills and Gravel Hills to the west, the Barstow Formation is unconformably overlain by the Black Mountain Basalt (Fig. 1) of late Pliocene age (2.5 m.y., Burke and others, 1982) and Quaternary alluvium.

Stratotype of the Barstow Formation

Dibblee (1968, p. 29) designated the type section as the "most complete and unbroken sequence of the Barstow Formation [in]. . . the south-dipping section at the east end of the Mud Hills, just west of Solomon Canyon." This section was measured by Durrell (1953). An abridged version of this measured section is given in Table 1, and it is displayed in Figure 4. Although not containing all of the lowest or highest intervals of the formation as exposed farther south and west in the Mud Hills, the stratotype section effectively corroborates the threefold subdivision of the Barstow Formation employed herein.

As indicated in Figures 2 and 4, Dibblee (1968) considered the Owl Conglomerate Member to be the basal unit of the Barstow Formation, which unconformably overlies granitic breccias attributed by him to the Pickhandle Formation on the north limb of the syncline, between Solomon and Owl Canyons (Figs. 3 and 4). As discussed below, we utilize a lower base of the Barstow Formation on the north limb, composed of epiclastic coarse-grained deposits containing a distinctive unit named herein the "Red Tuff," and interpret the base of the Barstow Formation to interfinger with the top of the Pickhandle Formation of Dibblee (1968).

Subdivisions of the Barstow Formation

Figure 2 shows the subdivisions of the Barstow Formation utilized by previous workers, as discussed above. Although facies relationships are rather complex (for example, Fig. 4), we employ a basic threefold subdivision of the Barstow Formation (Figs. 3 and 4), generally comparable to that of the Frick Laboratory but incorporating the names of the tuffaceous units utilized by Sheppard and Gude (1969; Fig. 5) and Lindsay (1972) and the Owl Conglomerate of Dibblee (1968).

We also recognize a conglomeratic unit of granitic debris in the western Mud Hills (Tbfg; Figs. 3 and 4) that interfingers eastward with all other units. Dibblee (1968, Pl. 1) employed a similarly designated unit for strata of the same general lithology but of somewhat lesser areal and stratigraphic extent (interfingered only with units above the Owl Conglomerate Member of the Barstow Formation). Where different from that in Dibblee (1968), subsequent reference to the unit labeled as Tbfg follows our interpretation of its extent and boundaries with other units of the Barstow Formation. Except for his Owl Conglomerate Member, and pointing out the presence of several layers of white tuff, Dibblee (1968, p. 29) recognized no lithic subdivisions other than facies of the Barstow Formation in the Mud Hills: Tbfg, fanglomerate of granitic detritus; Tbl, lacustrine clay shale; Tbs, terrestrial sandstones (Dibblee, 1968, Pl. 1).

TABLE 1. STRATOTYPE OF THE BARSTOW FORMATION

Quaternary alluvium

—Unconformity—

Barstow Formation

Upper Member of the Barstow Formation (subdivision employed for this paper, not found in Dibblee, 1968).
Light gray-brown to rusty yellow, poorly consolidated and sorted conglomerate and sandstone, composed mostly of granitic and volcanic detritus (134 m), preceded successively by gray, algal limestone (8 m); light gray, fine- to medium-grained arkosic sandstone, minor limestone, and tuff (15 m); and a basal unit of white, massive, fine-grained rhyolitic tuff (1 m). Although queried by Dibblee (1968), this is, in fact, the "lower marker tuff" of Dibblee (1968) and the Skyline Tuff of Sheppard and Gude (1969). It forms the base of the upper member of the Barstow Formation as used herein. The total thickness of this unit in the stratotype section is about 159 m, increasing to about 200 m in the western part of the Mud Hills (for example, Carnivore Canyon; Fig. 4).

Middle Member of the Barstow Formation (subdivison employed for this paper, not found in Dibblee, 1968).
Sandstone; light gray and green-gray clay (59 m) overlies green claystone, with white limestone beds and nodules (80 m); brown, tuffaceous bentonite (26 m); brown arenaceous limestone and green claystone (20 m); green claystone with white calcareous nodules (14 m); brown bentonite (9 m); green claystone and white nodular limestone (44 m); gray and green sandstone and green and buff claystone (101 m); yellow and greenish-gray claystone, minor sandstone, limestone, and strontianite nodules, and tuff beds (36 m); green and gray arkosic sandstone, with minor nodular green and red clay (8 m); white and gray calcareous, rhyolitic tuff (0–1 m); light gray pebbly, pumiceous sandstone (42 m); and a basal algal limestone (9 m). This interval, between the Owl Conglomerate Member and the Skyline Tuff, is about 449 m thick.

Owl Conglomerate Member of Dibblee (1968). Conglomerate, gray to green-gray, crudely and locally cross-bedded, moderately to poorly consolidated, composed of subrounded cobbles and boulders of quartz monzonite, some of aplite, pegmatite, and rarely of brown andesitic porphyry. This is effectively Dibblee's (1968) lower unit of the Barstow Formation in its stratotype on the north limb of the Barstow syncline. The Owl Conglomerate Member is about 41 m thick and unconformably overlies the Pickhandle Formation.

—Unconformity—

Pickhandle Formation

The Owl Conglomerate Member of the Barstow Formation

The Owl Conglomerate Member is the stratigraphically lowest part of the Barstow Formation as redefined by Dibblee (1968), and he mapped the unit (Tbc, Dibblee, 1968, and Fig. 3 of this report) as cropping out on both limbs of the Barstow syncline in the Mud Hills. We follow this herein. The Owl Conglomerate Member is about 41 m thick in the stratotype, near Owl Canyon on the north limb of the syncline (Table 1; Fig. 3) but is more than 200 m thick in the vicinity of the Rainbow Loop Road on the south limb as mapped by him and measured by us (Figs. 3 and 4). Our only departure from Dibblee (1968) in this regard is including an interval of epiclastic sediments on the north limb of the syncline that occurs about 80 m below the type Owl Conglomerate beds in Owl Canyon as part of that member. This results in the Owl Conglomerate Member, and thus the Barstow Formation, interfingering with, rather than unconformably overlying, granitic breccias mapped by Dibblee (1968) as the Pickhandle Formation. This is discussed below.

Owl Conglomerate Member: North Limb of the Barstow Syncline

In its type area on the north limb of the Barstow syncline near Owl and Solomon Canyons, the Owl Conglomerate Member is about 41 m thick. It consists of gray to green-gray arkosic sandstone that contains gray subrounded to rounded clasts of quartz monzonite, aplite, pegmatite, quartz, and brown andesitic porphyry, in a matrix of arkosic sandstone; local finer-grained, in some cases tuffaceous, units are interbedded in the upper part of the unit. According to Dibblee (1968, Pl. 3), the main outcrops of the Owl Conglomerate Member (as used herein) occur on the north limb of the syncline between Solomon and Owl Canyons (Fig. 3). To the west, the Owl Conglomerate Member pinches out against the subjacent Pickhandle deposits, with minor outcrops being found in sec. 14, T. 11 N., R. 2 W., in the vicinity of the Rainbow Canyon fault (Dibblee,

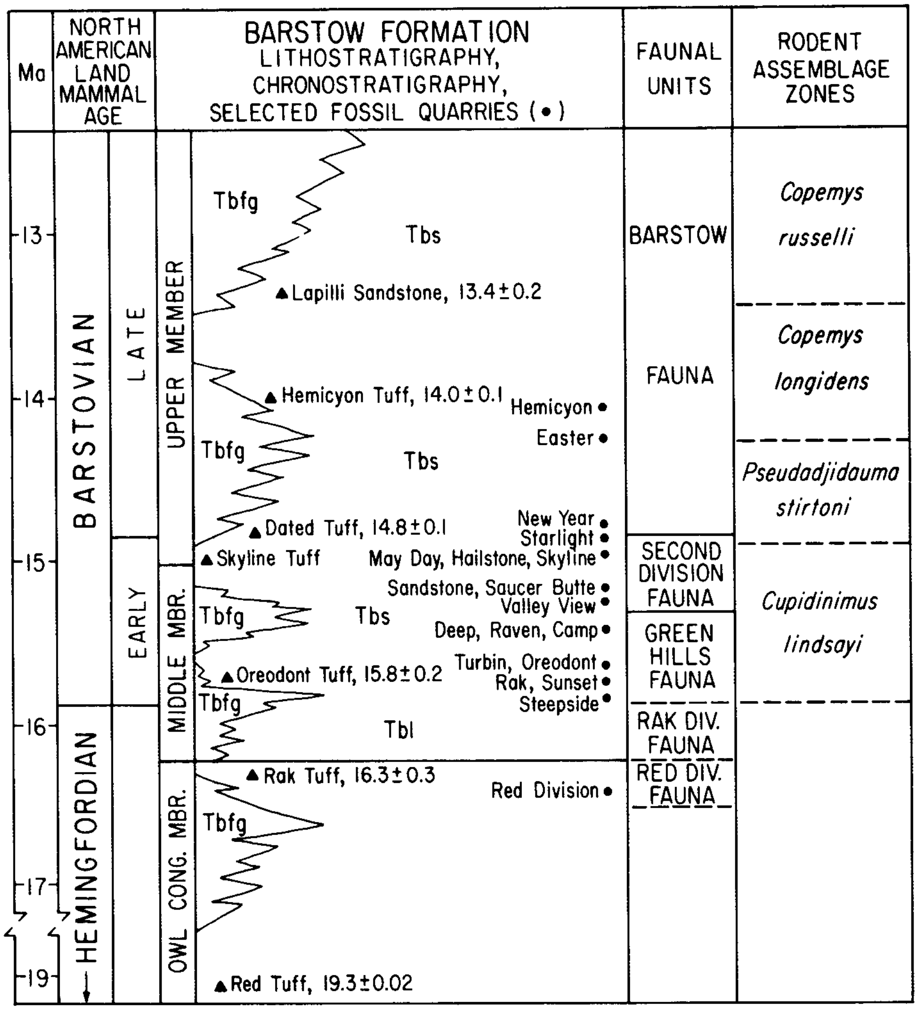

Figure 5. Geochronology of the Barstow Formation in the Mud Hills, showing the interrelationships of the lithic subdivisions of the formation, marker tuff beds and their isotopic ages (as known), the faunal units used herein, selected Frick Laboratory quarries, the rodent assemblage zones of Lindsay (1972), the North American land-mammal ages, and the isotopic time scale (Ma). See Figure 3 for location of Frick quarries.

1968, Pl. 3; Fig. 3 of this report). Dibblee (1968, p. 32) suggested that the Owl Conglomerate Member was derived from sources to the north of the syncline.

The Owl Conglomerate Member of Dibblee (1968) unconformably overlies the subjacent beds of granitic and rhyolitic breccias of the Pickhandle Formation (Dibblee, 1968), with about 5 m of relief. The Pickhandle beds also lie at attitudes that are about 15° steeper (~40° versus ~25°) than those of the overlying units. The Pickhandle breccia unit thus apparently was disturbed tectonically and eroded prior to the deposition of the following Owl Conglomerate beds. If one takes into account the variations in attitude (from 45° to 22°) displayed by units of the upper part of the Pickhandle Formation (Dibblee, 1968, Pl. 3), the erosional unconformity between the Owl Conglomerate and the underlying uppermost granitic breccia (Dibblee, 1968) is perhaps the most striking difference between the two rock bodies.

A distinctive bed of red tuff, ~10 cm thick, that we believe correlates with a similar unit exposed in the Rainbow Loop entrance section on the south limb of the Barstow syncline is found on the north limb in Owl Canyon (Figs. 3 and 4), about 80 m below the top of the Pickhandle Formation. The red tuff bed occurs in an interval composed of red-colored epiclastic conglomerate, conglomeratic sandstone, sandstone, and siltstone about 15 m thick and is virtually identical in texture, color, and composition to the beds mapped by Dibblee (1968) and by us as the Owl Conglomerate Member of the Barstow Formation on the south limb of the syncline, as discussed below. On the basis of the overall similarities in color, texture, composition, and the presence in both locations of the Red Tuff, we assign these northern-limb beds to the Owl Conglomerate Member of the Barstow Formation.

On this basis, we believe that the base of the Barstow and top of the Pickhandle Formations interfinger on the north limb of the Barstow syncline. Note that the Pickhandle breccias do not occur on the south limb of the Barstow Formation, where they would be expected to be present above and below the Red Tuff there. In that it affects only strata above the Red Tuff, this difference cannot be attributed to action of the Coon Canyon fault (Fig. 3). It appears that at least the Pickhandle breccias above the Red Tuff are restricted to a northern distribution and likely had a northern source (also Dibblee, 1968, p. 32). In fact, Dibblee (1968, p. 3) mapped a distinctly different Pickhandle unit (hornblende andesite) as lying unconformably below red-hued basal Barstow units west of the mouth of Solomon Canyon (for example, Fig. 3).

Owl Conglomerate Member: South Limb of the Barstow Syncline

On the south limb of the syncline, the Owl Conglomerate Member of the Barstow Formation is at least 200 m thick. The actual base of the formation is unexposed in the vicinity of the Rainbow Loop Road, but farther eastward, west of the mouth of Solomon Canyon (Fig. 3), correlative strata unconformably overlie the Pickhandle Formation of Dibblee

(1968; hornblende andesite). Elsewhere, faults or alluvial cover obscure the base of the Barstow Formation on the south limb of the syncline. The Owl Conglomerate Member is stratigraphically below the top of the Rak Tuff or, if absent, the overlying fine-grained green-hued sediments. The unit crops out from the Rainbow Loop exit road, where it interfingers westward with Tbfg (Fig. 3), and extends eastward to the vicinity of Solomon Canyon (Fig. 3, Tbc; Fig. 4). Except for interfingering with Tbfg, this is effectively similar to the mapping of Dibblee (1968).

These southern Owl Conglomerate outcrops consist of beds of dull to vivid red-brown and maroon to pale brown and yellow coarse-grained sandstone, breccia, and sparse beds of tuff (see also Steinen,1966; Dibblee, 1968). Color and bedding are variable laterally. The predominant clasts are mainly of granitic and volcanic rocks, but metamorphic clasts apparently derived from the Waterman Hills to the south occur in strata below the Rak Tuff.

As mentioned above, a distinctive, red-colored tuff bed (Red Tuff, Figs. 2–4), ~5 cm thick, crops out near the base of the Owl Conglomerate deposits on the south limb of the syncline in the vicinity of the Rainbow Loop entrance road, where it has been isotopically dated (below). This unit is considered equivalent to the Red Tuff found on the north limb of the syncline in Owl Canyon.

Figure 3 shows a diagrammatic separation of Tbfg (marginal coarse-grained beds; orange- to yellowish-brown deposits of granitic debris) from Tbc (and from Tbm, middle member of the Barstow Formation), with the main differences being the generally yellow- to orange-brown color of Tbfg in contrast to the distinctly redder hues of Tbc and the yellowish-green color of coarse-grained equivalent deposits in Tbm. Steinen (1966) and Dibblee (1968) suggested that the deposits here labeled "Tbfg" and "Tbc" were derived from the south and southwest. Potential source terranes to the south (Fig. 1) include Mesozoic granitic rocks, Tertiary volcanic rock, and pre-Tertiary Waterman Gneiss (Dibblee, 1968).

The Middle Member of the Barstow Formation

The middle member is taken as that part of the Barstow Formation that conformably overlies the Owl Conglomerate Member on the north limb of the syncline and beds just above the Rak Tuff or equivalent level on the south limb. The unit extends stratigraphically upward to the base of the "lower marker tuff" of Dibblee (1968), or the Skyline Tuff of Sheppard and Gude (1969). The middle member of the Barstow Formation, as used herein, is nominally equivalent to the Resistant Breccia and Fine Ashy and Shaly Tuff Members of Baker (1911) and the Second through Third Divisions of the Frick Laboratory. The middle member of the Barstow Formation reaches a thickness of as much as 570 m on the south limb of the syncline (section 1, Fig. 4) and is about 470 m thick on the north limb, at the type section of the Barstow Formation (Fig. 4). The best exposures of the middle member of the Barstow Formation are found on the south limb of the syncline between Owl and Coon Canyons and on the north limb between Owl and Solomon Canyons.

The middle member of the Barstow Formation on the north limb of the syncline between Owl and Solomon Canyons (Fig. 4) consists of a variety of epiclastic fluviatile and lacustrine deposits, with some beds of tuff, and is capped by the Skyline Tuff. As indicated by Dibblee (1968, p. 29) the sequence begins (Table 1) with dark gray algal limestone beds and ends with layers of gray sandstone, green-gray claystone, and minor calcareous and bentonitic beds. This sequence is shown as Tbs (sandstone) and Tbl (lacustrine deposits) in Figure 4 and is generally similar in overall fine grain size and predominantly drab (green and gray) colors to strata of the middle member seen on the south limb in Owl Canyon and in the vicinity of the Rainbow Loop entrance and exit roads (Figs. 3 and 4). Overall, however, the Owl Canyon exposures are finer grained than those found in the Rainbow Loop area on the south limb, especially above the Oreodont Tuff.

In the Rainbow Loop area, the middle member of the Barstow Formation is in part separated from the Owl Conglomerate Member by an unconformity on the south limb of the syncline (Fig. 4). This is seen by the discontinuous outcrop of the Rak Tuff on the south limb (Fig. 3) and the fact that the contact between the drab-hued and underlying red-hued Barstow sediments is an unconformity, having local relief of as much as 5 m. Magnetic polarity stratigraphy discussed by MacFadden and others (1990) and its correlation to the Magnetic Polarity Time Scale suggest that if this unconformity represents tectonic adjustments of the Barstow basin during accumulation, they were of short duration and did not significantly interrupt Barstow Formation deposition (that is, Chron C5C of the MPTS appears to be fully represented).

The Oreodont Tuff (no. 5, Fig. 3; named from its occurrence just above Frick Laboratory Oreodont Quarry) is a prominent marker unit along the southern limb of the syncline and can be traced from the Rainbow Loop exit road to Coon Canyon (sections 1 and 4, Fig. 4). It is shown at the Steepside Quarry section in Figure 4, near its westernmost occurrence on the south limb of the syncline. The Oreodont Tuff also is exposed on the north limb of the syncline in the Carnivore Canyon section (section 2, Fig. 4) and has been dated isotopically (see below).

The interval between the Oreodont and Skyline Tuffs is 274 m thick in the Rainbow Loop area and contains deposits that are coarser grained than those below (Steinen, 1966; our observations, Tbm, coarse grained; Fig. 4). As shown in section 1 (Fig. 4), this interval of largely alluvial sandstone, conglomeratic sandstone, and breccia is about 200 m thick and is capped by the Skyline Tuff. These drab green-gray, greenish-brown, yellow-brown, and locally brownish-gray deposits rival the textures and grain sizes seen in the Owl Conglomerate Member on the north but pertain to a much higher part of the section. Both eastward (Owl to Ross Canyons) and northeastward (north limb, Owl Canyon area; Fig. 4), the comparable interval is occupied by finer-grained, distal, and (limestones) basinal facies.

An even sharper contrast is seen in the northwestern part of the north limb of the syncline (Carnivore Canyon section; Fig. 4). There, the interval between the Oreodont and Skyline Tuffs is only 75 m thick (versus 274 m in the Rainbow Loop area), with the sediments (sandstone, claystone, and minor limestone) being conspicuously finer grained than in the comparable part of the section to the southeast.

In general, the middle member of the Barstow Formation becomes finer grained eastward, northward, and northeastward, being composed mainly of Tbs (continental sandstone) and Tbl (lacustrine deposits) in the terminology of Dibblee (1968) and as shown in Figure 4. On the west and southwest, the middle member interfingers with the granitic fanglomerate unit (Tbfg), as previously noted. This unit is extensively developed on the southern limb of the Barstow syncline (Figs. 3 and 4). Steinen (1966) indicated (and our studies corroborate) that the fanglomeratic deposits consist of pale brown to yellowish-brown coarse- to fine-grained deposits with many conglomeratic channel fills. Although these are composed of generally angular fragments of granitic rock, volcanic rock clasts also are conspicuous. Metamorphic clasts are rare. Scour-and-fill features coupled with pebble imbrications indicate that the sediments were deposited in a generally northward direction (in fact, the fanglomeratic units are generally not known on the north limb of the syncline) and eastward as well, where they pass into and are superseded by finer-grained deposits (Tbs, Tbl of Dibblee, 1968, Pl. 1; Fig. 4).

The Upper Member of the Barstow Formation

The upper member, which crops out over much of the Mud Hills but is thicker and more extensive in the west, is defined as those strata that conformably include, and continue upward from, the base of the "lower marker tuff" of Dibblee (1968), or the Skyline Tuff of Sheppard and Gude (1969). As such, these deposits are essentially equivalent to the Fossiliferous Tuff Member of Baker (1911) and the First Division of the Frick Laboratory (Fig. 2). Steinen (1966) utilized another tuff bed, the Hemicyon Tuff of Sheppard and Gude (1969) (not the "*Hemicyon* Stratum" of Frick, 1926a, and Lewis, 1968) to further subdivide this interval (see also Lindsay, 1972). For the present, we do not propose formal lithic subdivisions of the upper part of the Barstow Formation but will make use of marker beds within it to discuss relevant aspects of the biostratigraphy.

As shown in the type section (Fig. 4; Table 1; Dibblee, 1968), the upper member of the Barstow Formation is at least 159 m thick, with the Skyline Tuff at its base occurring about 490 m above the local top of the Pickhandle Formation. In the vicinity of Rainbow Loop Road (Figs. 3 and 4), the Skyline Tuff occurs about 572 m above the Rak Tuff.

Above the "lower marker tuff" or Skyline Tuff, the unit stratotype is composed, in ascending order, of light gray fine- to medium-bedded arkosic sandstone; minor limestone and tuff (15 m); gray, crudely laminated algal limestone (8 m); and light gray-brown to rusty-yellow beds of conglomerate and sandstone, with subrounded clasts of granitic rock, andesite, and minor hornfels and quartzite (134 m) (Dibblee, 1968, p. 29; Table 1).

In most areas to the west of the type section, the basal unit of the upper member of the Barstow Formation can be recognized as containing the commonly thick (0.3–1 m or more) Skyline Tuff at its lower boundary, with overlying strata generally comparable to those seen in the stratotype but differing in details of thickness and sequence. In Carnivore Canyon (Fig. 4) and other sites in the far west (Figs. 3 and 4), beds of orange to orange-red coarse-grained arkosic sandstone and conglomeratic sandstone (Tbfg; Fig. 4) make a major contribution to the sedimentary sequence, masking many of the tuff beds and other finer-grained basinal deposits more typically found to the east. Nevertheless, the Skyline Tuff and the Hemicyon Tuff (see below) have been recognized in these western outcrops on the north limb of the syncline. The upper member of the Barstow Formation is about 200 m thick in its westernmost outcrops.

In sites between Carnivore Canyon (west) and Rainbow Loop (east; sections 1, 2, 3a; Fig. 4), the Skyline Tuff commonly is overlain by about 10 to 30 m of beds composed of dark brown mudstone, but including fine-grained sandstone, siltstone, and minor conglomerate and limestone, capped by a thinner (3 to 6 cm) brown, biotite-crystal tuff (Dated Tuff of Sheppard and Gude, 1969). Westward, the Dated Tuff grades locally into a biotite sandstone (Steinen, 1966). This persistent pair of tuffs provides a useful stratigraphic marker for mapping and biostratigraphic purposes.

In Rainbow basin (area of the Rainbow Loop Road; Fig. 3), and in Owl Canyon to the east, about 100 m of deposits overlies the Dated Tuff (Fig. 4). These deposits are mostly red-brown to brown, but locally green to greenish-gray, beds of siltstone, claystone, and minor sandstone mapped by Dibblee (1968, Pl. 1) as Tbl. Westward, in Coon Canyon (Fig. 3), some stratigraphically equivalent rocks are coarser-grained beds of conglomerate and sandstone, but green-gray and brown claystone beds dominate. Beds in this area also grade into and interfinger with granitic conglomerate units as mapped by Steinen (1966), by Dibblee (1968, Pl. 1), and by us as Tbfg (between sections 5 and 7, Fig. 4).

The Hemicyon Tuff occurs about 75–82 m stratigraphically above the Skyline Tuff in sections measured by us (sections 2, 5, 7; Fig. 4) and can be recognized on both limbs of the syncline in the vicinity of Hemicyon basin (south) and Hell Gate basin (north; Figs. 3 and 4). In general, calculations for biostratigraphic purposes (below), we use a figure of 80 m between the Hemicyon and Skyline Tuffs. The Hemicyon Tuff is the "upper marker tuff" of Dibblee (1968). The unit occurs stratigraphically about 3–30 m above a unit known as the "*Hemicyon* Stratum" of Frick (1926a, p. 34; section 7, Fig. 4, of the present report), contrary to the suggestion of Lewis (1968, p. 34). The "*Hemicyon* Stratum" consists of beds of limestone and marly mudstone in section 7. On the north limb of the syncline in Carnivore Canyon (section 2, Fig. 4), a thick sequence of limestone and interbedded fine-grained mudstone beds extends from the Skyline Tuff to just below the Hemicyon Tuff. The "*Hemicyon* Stratum" cannot be identified, however.

Another important unit, known as the "Lapilli Sandstone" (Lindsay, 1972, p. 4; Fig. 2), occurs about 63 m stratigraphically above the Hemicyon Tuff, as mapped by us, on the northern limb of the Barstow syncline, and about 33 m above the Hemicyon Tuff of Lindsay (1972; Hell Gate basin, section 6, Fig. 4). Our work indicates that the Hemicyon Tuff actually occurs about 3 m stratigraphically above the "*Hemicyon* Stratum" (limestone) at Hell Gate basin; this is followed by an interval of 30 m of limestone and cherty limestone beds capped by a thick rhyolitic tuff (Hemicyon Tuff in Hell Gate basin section of Lindsay, 1972, Fig. 2; see Fig. 4 herein). Stratigraphically above this tuff is an interval about 33 m thick composed mostly of hornblende-bearing sandstone beds and minor beds of tuff (section 5, Fig. 4). The prominent Lapilli Sandstone occurs in the upper few meters of this sequence and is capped by about 30 m of limestone beds, with minor sandstone, claystone, and tuff. We have identified an equivalent sequence above the "*Hemicyon* Stratum" on the south limb as well (Hemicyon basin, section 7, Fig. 4), associated, as in the Hell Gate basin section, with a distinctive interval of hornblende-rich sandstone. The Lapilli Sandstone and the Hemicyon Tuff have been dated isotopically, as discussed below.

In the northwestern part of the mapped area (Carnivore Canyon; section 2, Fig. 4), the generally fine-grained units that include the "*Hemicyon* Stratum" are overlain by, and interfinger with, a sequence of orange-brown to reddish-brown arkosic coarse-grained sandstone and conglomeratic sandstone that can be distinguished from the generally greenish-gray beds below (Tbfg, section 2, Fig. 4). Both units contain interbedded green tuffaceous siltstone and fine-grained sandstone beds. The interval with the coarser-grained unit is about 114 m thick in that area and represents the locally stratigraphically highest sequence of the Barstow Formation in the Mud Hills. As such, it is important from a biostratigraphic standpoint.

On the basis of lithostratigraphic evidence, however, we have been able to demonstrate that the sedimentary package that contains the coarse-grained arkosic units pinches out eastward on the north limb of the syncline (vicinity of Hell Gate basin; Fig. 4). Distal tongues of arkosic sandstone are overlain stratigraphically by the ~30-m-thick interval, described above, that contains abundant and conspicuous beds of hornblende-rich sandstone, tuffaceous sandstone, and the Lapilli Sandstone and that is capped by about 30 m of limestone, calcareous siltstone, and minor beds of tuff. This sequence (hornblende-bearing sandstone and capping limestone), also found at Hemicyon basin (section 7, Fig. 4) on the south limb, comprises the stratigraphically highest interval of the Barstow Formation in the Mud Hills, and we suggest that there is either a depositional hiatus or a marked decrease in accumulation in the Hell Gate basin and Hemicyon basin sections below the stratigraphically lowest hornblende-bearing sandstone bed. Either of these alternatives could account for the conspicuously thinner interval between the Hemicyon Tuff and the Lapilli Sandstone at Hell Gate basin versus the thicker but apparently equivalent interval exposed in Carnivore Canyon. The massive rhyolitic tuff seen in Hell Gate basin (section 6, Fig. 4) apparently has been masked in the Carnivore Canyon section by the coarse-grained deposits that dominate there. If not masked by those coarser-grained units, this rhyolitic tuff would be expected to occur at or near the upper third of the Carnivore Canyon section depicted in Figure 4.

Evidence seen by us indicates that effectively all of the hornblende-rich interval (with the Lapilli Sandstone and overlying sequence of limestones and sparse beds of sandstone and tuff) stratigraphically overlies all or most of the interval in Carnivore Canyon occupied by the sequence of coarse-grained arkosic sandstone and conglomeratic sandstone. Thus, although the linear stratigraphic separation of the Lapilli Sandstone and the Hemicyon Tuff in Hell Gate basin is on the order of 63 m, its equivalent position in Carnivore Canyon would be at least 100 m above that tuff (Fig. 4).

We note that the interval containing the Lapilli Sandstone in Hell Gate and Hemicyon basins records the first stratigraphic occurrence of hornblende-rich sediments in the Barstow Formation. We point out the similarity in age between this part of the section (about 13.4 m.y.) and the Andesite of Murphy's Well (dated at 13.5 ± 0.2 Ma by Burke and others, 1982), located about 10 km due north of the relevant part of the Mud Hills (Figs. 1 and 4), and suggest that this similarity is not coincidental.

The above description of the deposits from the upper member of the Barstow Formation is taken mostly from sediments on the north limb of the Barstow syncline, a major exception being the sequence exposed in Hemicyon basin, and in the Rainbow Loop Road area (Figs. 3 and 4). On the south, especially in the districts northwest of Coon Canyon (Fig. 3), rocks that pertain to the same interval are mostly coarser-grained fluviatile, rather than basinal lacustrine, materials, and consequently, both the lithic characteristics and distinctive tuff beds are absent, the latter probably having been washed from topographically higher areas into the lacustrine basin. For these reasons, it is difficult to identify the boundary between the middle and upper members of the Barstow Formation in this area. The dashed line shown between Tbfg and Tbu near the mouth of Fossil Canyon (west part; Fig. 3) reflects the gradational contact between these units there. Figure 4 also shows diagrammatically the interfingering relationships between Tbfg and other parts of the Barstow Formation.

On the basis of the generally fine-grained lithology and the presence of numerous beds of tuff, some of which preserve mud cracks and tracks of mammals and birds on their lower surfaces, a lacustrine origin is suggested for a majority of the deposits above the Skyline Tuff. The presence in areas to the west of increasing amounts of interbedded coarser-grained units suggests that the local basin margin lay in that direction (see also Dibblee, 1968, p. 32).

In summary, the Owl Conglomerate Member of the Barstow Formation is at least 200 m thick and apparently was derived from sources on the north and northeast, as well as from the south and southwest. The unit unconformably overlies the Pickhandle Formation on the south limb of the syncline and interfingers westwardly with the coarse-grained unit, Tbfg. It is capped locally by the Rak Tuff and also is locally unconformably overlain by the middle member of the formation. To the north, a sequence containing the Red Tuff (also found on the south) interfingers with granitic breccias of the Pickhandle Formation of Dibblee (1968).

The middle member of the Barstow Formation apparently was derived mostly from the southern side of the basin where it is coarsest grained. Overall, the northwestern (Carnivore Canyon) representatives of the middle part of the formation appear to be somewhat thinner than the southern counterparts, at least for those parts of the section that can be compared. A major influx of very coarse grained units (Tbfg) between the Oreodont and Skyline Tuffs, and the equally coarse-grained equivalent strata northwest of Coon Canyon, indicates the presence of a very active basin margin in this vicinity. The central part of the basin apparently was located farther to the north or northeast, partly exemplified by the section in Carnivore Canyon and equally fine-grained sediments in Hell Gate basin.

The upper member of the Barstow Formation is composed almost exclusively of lacustrine sediments and minor coarser-grained clastic beds. Conglomeratic beds at the top of the sequence east of Owl Canyon (Dibblee, 1968, p. 29; Fig. 4), in Carnivore Canyon on the north limb of the syncline, and above the Hemicyon Tuff in Hemicyon basin on the south limb of the syncline record more marginal settings.

At times (Owl Conglomerate Member), it appears that coarse-grained facies were contributed from both northern and southern or southwestern (Tbfg) sources, but distal basin facies are most commonly found in northern, eastern, and northeastern sections of the Barstow Formation outcrops. The Carnivore Canyon deposits appear to be a late example of the coarse-grained package derived from the west and southwest. On the basis of data summarized herein, it appears that a final episode of clastic input is recorded by the hornblende-bearing sandstones in Hell Gate basin and at Hemicyon basin with a probable northern source. Terminal beds of limestone in these areas record the final, basinal, sedimentation of the Barstow Formation in the Mud Hills.

BIOSTRATIGRAPHY OF THE BARSTOW FORMATION

Baker (1911) and Merriam (1919) noted the presence of locally abundant fossil mammals in the Resistant Breccia and Fossiliferous Tuff Members of the Barstow Formation. These units are essentially equivalent to part of the middle and all of the upper members of the formation as used herein (see Fig. 2). Description of the fauna of the Barstow Formation began with an announcement of the discovery of fossil mammals (Merriam, 1911) and preliminary description of some new forms (Merriam, 1913, 1915a, 1915b) and finally, a review of the fauna as a whole (Merriam, 1919). Thereafter, descriptions centered on specific taxa as cited above and in Woodburne and Tedford (1982).

In addition to reconsideration of all previously published biostratigraphic information, the present contribution presents new evidence on the nature of the fauna from the lowest and uppermost strata of the middle member of the Barstow Formation (the Fine Ashy and Shaly Tuff Member of Baker, 1911). This new information, from the Frick Laboratory collection and records at the American Museum of Natural History, fills gaps in the biostratigraphy as previously reported. Taxonomic names that appear in quotation marks indicate use of a generic name that probably should be restricted to other species. We begin with the stratigraphically lowest units.

Red Division Fauna

As can be seen in Figure 5, fossil mammal remains have been recovered from all four lithological intervals we recognize in the Barstow Formation in the Mud Hills. The oldest mammals occur in the southwestern part of the Mud Hills in the upper part of the Owl Conglomerate Member of the Barstow Formation, about 602 m below the Skyline Tuff and 30 m below the Rak Tuff. The collections were obtained mostly from two or three sites (including the Red Division Quarry of the Frick Laboratory) covering a 30-m interval and contain only a few taxa. These include the horse *"Merychippus" carrizoensis*; the oreodont *Merychyus relictus fletcheri* Schultz and Falkenbach, 1947 (holotype); the miolabine camel *"Miolabis"* cf. *"M." tenuis*, another form within the genus *Miolabis*; and a pronghorn, *Meryceros* sp., referred to *M. joraki*, but not represented by horncores. These taxa belong to the Red Division Fauna of this report (Fig. 5).

Rak Division Fauna

The lower 235 m of the middle member of the Barstow Formation comprises the Rak or Third Division of the Frick Laboratory and contains scattered ungulate skeletons. These are mostly those of camels, but a number pertain to horses as well. The specimens occur as articulated remains in green mudstone beds and in channel-form sandstone bodies. The fauna is of limited diversity but includes the canid *Tomarctus* cf. *T. rurestris*; the amphicyonid *Amphicyon* cf. *A. sinapius*; the pliohippine horse *"Merychippus"* cf. *"M." isonesus*; a large rhino, *Aphelops*; the miolabine camel *"Miolabis"* cf. *"M." tenuis* (the range zone of which continues upward from the Owl Conglomerate Member), associated with *"M."* cf. *"M." singularis*, a larger form of the same unnamed genus. Protolabine camels make their first appearance in the local section with both *Protolabis* and *Michenia* present, and a large and small species of *Aepycamelus* also appear, along with the continued presence of pronghorns referred to *Meryceros joraki* (no horn cores are known from this level, however). We group these taxa under the name "Rak Division Fauna," which extends from the level of the Rak Tuff to just below Steepside Quarry, an interval of about 235 m. In addition, Alf (1970) has described leaf impressions of oaks and palms from the Rak Division shale beds, indicating the nature of the riparian vegetation in the areas in which the mammals flourished.

Green Hills Fauna

Fossils are more abundant in the upper part of the middle member of the Barstow Formation. These taxa were grouped together under the name "Green Hills Fauna" (Woodburne and Tedford, 1982). As revised herein, the Green Hills Fauna occurs in rocks that extend upward from Steepside Quarry to just below Valley View Quarry, 60 m below the Skyline Tuff, an interval of about 280 m. The Oreodont Tuff (with an isotopic age of 15.8 ± 0.09 m.y.) occurs stratigraphically about 40 m above Steepside Quarry (Fig. 4), which contains taxa [*Copemys*, *Hemicyon* (*Plithocyon*)] that define the base of the Green Hills unit (Tedford and others, 1987). Taxa of the Green Hills Fauna include the rodents *Peridiomys* and *Copemys*; the bear *Hemicyon* (*Plithocyon*); the canids *Euoplocyon*, *Cynarctoides*, *"Tomarctus" kelloggae*, *T. confertus*, and *T. rurestris*; the amphicyonid carnivore *Amphicyon* cf. *A. ingens*; the pliohippine horse *"Merychippus" stylodontus* and *Merycchippus* cf. *M. insignis*; the peccaries *Hesperhys*, *Dyseohyus fricki*, and *Cynorca occidentale*; the oreodont *Brachycrus buwaldi*; the cervoid *Rakomeryx*; the pronghorns *Merriamoceros* and *Meryceros* cf. *M. joraki* (also not represented by horncores); and miolabine camels, one closely related to *Miolabis fissidens* and the other species related to *"Miolabis" tenuis*. Protolabine camels are represented by *Protolabis* cf. *P. barstowensis* and a *Michenia*, both of which are members of lineages continuing upward from the Rak Division; large and small *Aepycamelus* species also continue upward from the underlying deposits.

Second Division Fauna

Some taxa that are characteristic of the succeeding Barstow Fauna actually have their first local appearance in the Frick Laboratory Valley View Quarry, 60 m stratigraphically below the Skyline Tuff (Fig. 5), and continue upward for about 80 m, 20 m above the Skyline Tuff to just below New Year Quarry. The most important of these are the canids, *Aelurodon*, *Cynarctus*, and *Tomarctus paulus*. These same levels record the appearance of a small pliohippine horse similar to *"Merychippus" stylodontus* but smaller and possessing higher-crowned cheek teeth. This taxon persists to the Skyline Quarry level, just below the Skyline Tuff, where it coexists with the lowest stratigraphic occurrence of *"M." intermontanus*. This occurrence represents the last local appearance of pliohippine equids that are so characteristic of the Barstow Formation below the Skyline Tuff. The tiny anchitheriine horse *Archaeohippus mourningi* is virtually restricted to the top of this interval (locally being present to about 10 m above the Skyline Tuff). The span 20 m above to 60 m below the Skyline Tuff also contains the last local occurrences of *Michenia* and the *"Miolabis"* cf. *"M." singularis* clade. *Miolabis* and *Protolabis* cf. *P. barstowensis* continue through this interval, but *Aepycamelus* is locally absent. Significantly, the Green Hills Fauna taxa *Brachycrus*, *Rakomeryx*, and *Merriamoceros* are lacking here. Merycodont horn cores are present for the first time in this interval and represent *Ramoceros*, *Meryceros joraki*, and *Paracosoryx*. We use the term "Second Division Fauna" for this assemblage, taking the name from the Frick Laboratory designation of the stratal interval that encompasses it. Alf (1970) attributes fossil wood from the Skyline Tuff as representing a chapparal flora with juniper, poison oak, and buckbrush.

Barstow Fauna

The youngest assemblage of the Barstow Formation, the Barstow Fauna, begins with the lowest stratigraphic occurrence of proboscideans, at or but a short stratigraphic distance below the Dated Tuff, about at the level of the Frick Laboratory New Year Quarry (Fig. 5), and extends to the top of the Barstow Formation, an interval of about 225 m. The Dated Tuff (noted below) occurs 10–17 m stratigraphically above the Skyline Tuff. This recognizes most of the interval utilized by Merriam (1919) in naming the Barstow Fauna (but would exclude the Second Division faunal sites equivalent to the Frick Laboratory Skyline Quarry, about 7 m stratigraphically below the Skyline Tuff, which Merriam included in his concept of the Barstow Fauna). If one uses the principle that the boundary of a unit is defined by its base, the upper limit of the Second Division Fauna is defined as the base of the Barstow Fauna in the sense utilized herein.

Taxa of the Barstow Fauna include the first local appearance of the rodent *Pliosaccomys*; the horses *Megahippus mckennai* and *"Merychippus" sumani* (belonging to the same unnamed generic taxon as *"M." intermontanus*); the mastodonts, *Miomastodon* and *Gomphotherium*; and the canids *Epicyon* and *"Tomarctus" temerarius*, and the extended range of *Aelurodon*, *Cynarctus*, and *Tomarctus paulus*; the ursid *Hemicyon barstowensis* (high in the unit only); the upper part of the range of the peccary *Dyseohyus fricki*; the restricted occurrence of the oreodont *Medi-ochoerus mohavensis* (Skinner and Johnson, 1984, footnote 11, p. 259); and the pronghorns *Ramoceros* and *Cosoryx*, with *Meryceros joraki* continuing from lower levels (type specimen from the upper unit, however). The miolabine camels, represented by a large form, *Miolabis* cf. *M. fissidens*, occur in the lower part of the unit and represent the last local occurrence of the group. The protolabine camels are represented by *Protolabis* cf. *P. barstowensis* and a larger form, *"Protolabis"* cf. *"P." inaequidens*. *Michenia* is not present in this unit; giraffe-camels are represented only by *Aepycamelus alexandrae*, and metapodials suggest the appearance of *Procamelus* at these levels.

Figure 5 also shows the distribution of the rodent assemblage zones nominated by Lindsay (1972) from the Barstow Formation. These were described from strata of the western part of the formation, so that thicknesses reported by Lindsay (1972) are unlikely to be strictly applicable throughout the lateral extent of the formation. Note also that neither the name-bearer of a particular zone nor the taxa that characterize it are necessarily restricted to the zone; that the taxa characteristic of one zone may not persist to its top, with boundaries being recognized on the stratigraphic lowest occurrence of the characterizing taxa of the next highest zone (thus all zonal boundaries are represented by dashed lines; Fig. 5); and that identification of a given zone is based largely on abundance criteria (for example, Lindsay, 1972, Tables 1 and 2). At present, the rodent assemblage zones of Lindsay (1972) are largely descriptive, comparative studies in other sections of the Barstow Formation or its correlatives have yet to be accomplished, and the chronological significance of the rodent assemblage zones of the Barstow Formation is yet to be determined. *Cupidinimus lindsayi* (Barnosky, 1976) was originally identified as *C. nebraskensis* (Lindsay, 1972), hence our use of the *C. lindsayi* assemblage zone in Figure 5.

ISOTOPIC CALIBRATION OF THE BARSTOW FORMATION

The major emphasis of this section is threefold: (1) to review the data on previously reported isotopic dates, (2) to present new isotopic ages, and (3) to discuss the quality and basis of proposed calibration points of the Barstow sequence. The isotopic data utilized herein are discussed further in MacFadden and others (1990). All isotopic ages cited have been recalculated when necessary to conform to the current IUGS (International Union of Geological Sciences) decay constants (Steiger and Jaeger, 1977). The Skyline Tuff is an important stratigraphic marker unit but, because of being fine grained and altered (for example, Sheppard and Gude, 1969), is not datable.

Isotopic ages determined for some of the volcanic units interbedded with strata of the Mud Hills provide important calibration points for the Barstow Formation and outline the general age parameters of the unit (below). The following comments on the nature of these tuff beds is summarized from Sheppard and Gude (1969, p. 8). According to these authors, most of the tuffs in the Barstow Formation were deposited in alkaline lakes; most occur in the upper half of the formation; and they range in thickness from about 0.6 cm to 2.3 m, but most are less than 0.3 m thick. The thicker tuffs generally are more continuous laterally. Most contain vitric shards and are even-bedded (beds commonly fining upward). The base of some tuffs (that is, the Dated Tuff and Camel-Track Tuff) shows casts of mudcracks or animal tracks. A number of the thicker units show reworking of their upper portions and may grade laterally into tuffaceous sandstone. Rock fragments in the tuffs are chiefly volcanic and granitic materials but may include quartzite, chert, and schistose and metamorphic constituents. Accretionary lapilli, signifying that they were formed by accretion of moist ash in eruptive clouds and then fell as mud-pellet rains (Moore and Peck, 1962), are common in the bases of the Skyline and Hemicyon Tuffs.

Inasmuch as most of the tuff beds of the Barstow Formation appear to have been water laid, and many have been zeolitized and some show evidence of reworking in their upper portions, the question of origin of dated materials must be considered when evaluating the accuracy of the isotopic ages. These problems are addressed in this report by (1) dating individual mineral grains, (2) dating the same unit at laterally different sites, and (3) dating mineral pairs from the same unit. Also, some of the ages originally reported for Barstow Formation and other tuffs in western North America (Evernden and others, 1964) were based on analyses that were heterogeneous, containing biotite, glass, and hornblende, which resulted in lower potassium values and lower amounts of radiogenic argon. Improved methods of potassium analyses for iron-bearing minerals such as biotite indicate that some potassium analyses included in the Evernden and others (1964) study were on the order of 1% too low (Jochim Hampel, 1989, personal commun.). These low potassium values yielded artificially old ages. Although this problem with the early potassium measurements was known since 1966, the important calibration points listed in Evernden and others (1964) have never been corrected, and these potentially old ages are currently in widespread use. It is apparent that other biotite dates included in Evernden and others (1964) need examination (see also the discussion in MacFadden and others, 1990, on the "Dated Tuff" of the Barstow Formation). We begin our discussion with the geologically oldest unit.

The Red Tuff

The stratigraphically lowest tuff to be dated is the Red Tuff, found about 17 m stratigraphically above the local base of the Barstow Formation near Rainbow Loop entrance road (Figs. 3 and 4; section 1) on the south limb of the Barstow syncline and about 80 m below the base of the middle member (that is, the base of the Owl Conglomerate Member) on the north limb, as discussed above. MacFadden and others (1990) reported a $^{40}Ar/^{39}Ar$ laser-fusion date (average of 3 determinations) of 19.3 ± 0.02 Ma for the Red Tuff on the south limb of the syncline. As reported above, the eastward extension of the Coon Canyon fault separates beds about 3 m stratigraphically above the Red Tuff from the remainder of the Owl Conglomerate Member of the Barstow Formation on the south limb of the syncline.

The Rak Tuff

The Rak Tuff as named herein crops out locally just below the contact between the lower and middle members of the Barstow Formation on the south limb of the syncline (Fig. 4, section 1) and about 572 m below the Skyline Tuff. The Rak Tuff is located on the south limb of the Barstow syncline west of the Rainbow Loop entrance road (Fig. 3). ^{40}K-^{40}Ar analyses yielded an average age of 16.3 ± 0.2 m.y. for the Rak Tuff, as discussed below. Fossil mammals of late Hemingfordian age occur stratigraphically above and below this tuff (see Biostratigraphy section, above), and MacFadden and others (1990) suggested that this part of the Barstow Formation correlates best with the upper half of Chron C5C of the Magnetic Polarity Time Scale, or to an age of about 16–17 m.y. Calibration of sequences that bear fossil mammals similar to those of the Red Division Fauna that occurs stratigraphically below the equivalent level of the Rak Tuff to the west of Rainbow Loop exit road (Fig. 3) is consistent with an age of about 16.3 m.y. for the Rak Tuff.

That the following discussion concerning the age of the Rak Tuff is rather extensive is due to the fact that the age of this sample is somewhat ambiguous but also important.

Three ^{40}K-^{40}Ar analyses on biotite separates obtained from the Rak Tuff yielded ages of 16.4 ± 0.24 (KA 5336R), 16.5 ± 1.1 (KA 5336R2), and 15.9 ± 0.23 m.y. (KA 5336; see MacFadden and others, 1990). The average age for the three determinations is 16.3 ± 0.2 m.y. The biotite is somewhat altered and has a slightly oxidized appearance. This alteration is reflected by the low K value of 5.3% (the K value of unaltered biotite is in most cases between 6% and 7%). See MacFadden and others (1990) for additional comments on the age of the Rak Tuff.

Burke and others (1982) reported a whole-rock date of 16.5 ± 0.4 Ma on a basalt from lower beds of the Barstow Formation (correlated by them with the Owl Conglomerate Member) at Opal Mountain, about 16 km west of the Mud Hills. Although not associated with fossil mammals, the early Barstow Formation date at Opal Mountain is similar to that obtained from the Rak Tuff and carries a similarly normal magnetic polarity signature (Burke and others, 1982; MacFadden and others, 1990). We now know, however, that based on the Red Tuff, the basal age of the Barstow Formation is on the order of 19 m.y. in the Mud Hills.

To evaluate further the validity of the analytical ages of the Rak Tuff, which provide an upper age limit for the Red Division Fauna (Fig. 5), we examined the isotopic data associated with faunas in the Coast Ranges that are similar to those of the Red Division Fauna, as well as ages associated with a correlative succession in the Great Plains.

The age of the Rak Tuff is consistent with an age of 16.5 ± 1.3 m.y. obtained from the Lower Triple Basalt of the Caliente Formation, southern Coast Ranges, of California (Turner, 1970; see also Tedford and others, 1987). Repenning and Vedder (1961) reported that faunas of late Hemingfordian age (including CIT 315, the type locality of *Merychippus carrizoensis*) occur to within 10 m below the base of the basalt.

Also of interest is that the ages discussed herein are similar to $^{40}Ar/^{39}Ar$ ages and fission-track ages on the Sheep Creek Tuff of western Nebraska that overlies the Sheep Creek Fauna of late Hemingfordian age. Naeser and others (1980) dated zircon by fission-track methods at 16.5 ± 0.6 Ma, and Boellstorf in Skinner and others (1977) obtained an age of 16.3 ± 3.7 m.y. on glass. C. C. Swisher (unpub. data) has reported a mean $^{40}Ar/^{39}Ar$ age of 16.3 ± 0.13 m.y., based on four separate analyses.

In conclusion, combined data from the Barstow Formation indicate an overall age of 16.3 to 16.5 m.y. for the Red Division Fauna. The date on the Rak Tuff that overlies the Red Division Fauna is concordant with the 16.3 ± 0.13–m.y. age on the Sheep Creek Tuff that overlies the Sheep Creek Fauna of late Hemingfordian age in Nebraska.

Oreodont Tuff

The Oreodont Tuff crops out near the middle of the middle member of the Barstow Formation, about 274 m below the Skyline Tuff. An isotopic age of 15.8 ± 0.09 m.y. was obtained as an average of many determinations from this unit (MacFadden and others, 1990). Its age was virtually identical at all sections noted in Figure 4. See MacFadden and others (1990) for further discussion of the age analysis of this tuff. The Oreodont Tuff occurs about 40 m above the boundary between the Rak and Green Hills Fauna and thus provides an important calibration point for the Hemingfordian-Barstovian boundary.

The Dated Tuff

The Dated Tuff of Sheppard and Gude (1969; KA 449 of Evernden and others, 1964) occurs about 18 m stratigraphically above the Skyline Tuff in Rainbow basin (Fig. 4) and yielded a K-Ar age of 15.5 m.y. (Evernden and others, 1964, p. 176); it is an important marker bed for the upper member of the Barstow Formation, and MacFadden and others (1990) reported a number of new age analyses of it. On the basis of those analyses, the Dated Tuff has an average age of 14.8 ± 0.09 m.y.

Hemicyon Tuff

The Hemicyon Tuff of Sheppard and Gude (1969) occurs about 80 m stratigraphically above the Skyline Tuff and is an important marker bed for the upper member of the Barstow Formation. This is the "upper marker tuff" of Dibblee (1968). As discussed by MacFadden and others (1990), the Hemicyon Tuff has an average age of 14.0 ± 0.04 m.y.

The Lapilli Sandstone

The Lapilli Sandstone occurs approximately 150 m stratigraphically above the Skyline Tuff and about 63 m above the Hemicyon Tuff in Hell Gate basin. As indicated above, the equivalent stratigraphic position for this tuff would be at least 100 m above the Hemicyon Tuff in Carnivore Canyon. MacFadden and others (1990) indicated that the mean age for the Lapilli Sandstone is 13.4 ± 0.03 m.y. The Lapilli Sandstone occurs about 30 m below the stratigraphic top of the Barstow Formation in the Mud Hills.

The dated range of the Barstow Formation in the Mud Hills appears on present evidence to extend from about 19.3 to about 13.4 Ma. Inasmuch as at least 10 m of section is present below the lowest age determination and about 30 m remains above the highest, the actual age range of the formation is somewhat greater than its isotopic calibration.

ACCUMULATION OF THE BARSTOW FORMATION IN THE MUD HILLS

Here, we assess the apparent accumulation rate of the Barstow Formation, using data primarily from the well-calibrated main section (1), in the Rainbow Loop entrance and exit area, and the Carnivore Canyon section (2) (Figs. 4 and 6). Our aim is to demonstrate the sharp drop in accumulation rate of the Barstow Formation beginning with the Skyline Tuff and to assess the approximate age of events important for an understanding of the faunal changes and other data pertinent to reconstructing the history of deposition of the Barstow Formation that are not directly supplied with isotopic ages.

Overall, we interpret the sediments of the Barstow Formation to comprise a fining-upward sequence of basin-fill deposits. The lower and middle members of the Barstow Formation show predominantly coarser-grained sediments and rapid initial basin filling and tectonic adjustments between the Owl Conglomerate and middle members of the formation (both limbs). Beginning with the Skyline Tuff, finer-grained deposits of predominantly lacustrine origin indicate a much slower rate of accumulation for the upper member of the Barstow Formation, possibly indicating increased tectonic stability (Fig. 6).

Because the lower and middle members of the Barstow Formation are coarser grained overall, the accumulation rate interpolated between the Rak and Oreodont Tuffs in the middle member of the Barstow sequence (approximately 540 m/m.y. = 270 m in 0.5 m.y.; Fig. 6) has been extrapolated stratigraphically downward to the Coon Canyon fault and upward to just above Valley View Quarry (about 60 m stratigraphically below the Skyline Tuff) in section 1 (Fig. 4). If these extrapolations are reasonable, and recognizing the above-cited analytical imprecision of the age of the Rak Tuff but also the biostratigraphic/isotopic correlations that support the age used herein, the Coon Canyon fault appears to have cut out about 2 m.y. worth of section between the Red and Rak Tuffs. Rocks containing Steepside Quarry, about 40 m below the Oreodont Tuff (ca. 15.8 Ma), project to an age of about 15.9 m.y. The base of the Green Hills Fauna and of the Barstovian mammal age appears to be about that old. The strata of the Valley View Quarry appear to be about 15.3 m.y. old, as does the base of the Second Division Fauna.

The upper member of the Barstow Formation is predominantly lacustrine in origin. Accumulation rates of 75 m/m.y. are calculated between the "Dated Tuff" and the Hemicyon Tuff (Fig. 6), and the slope of the line representing that rate of accumulation intersects the stratigraphic position of the Skyline Tuff very near its presumed age (about 15 m.y.) on isotopic grounds (older than the Dated Tuff at 14.8 m.y.). The base of the Barstow Fauna thus appears to be about 15 m.y. old.

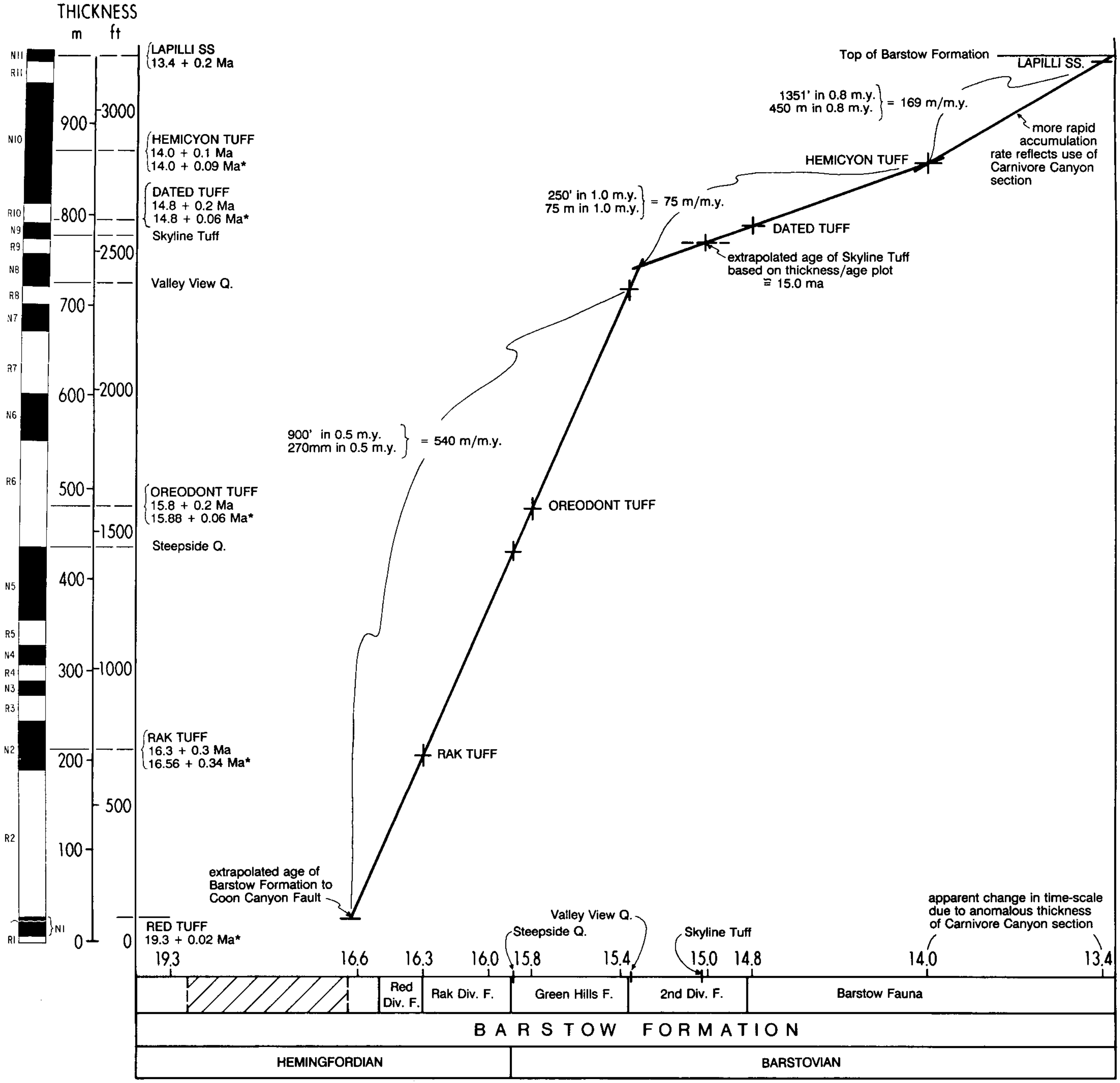

Figure 6. Plot of accumulation rates for the Barstow Formation, based on data reported herein. Note that the approximate age of the Skyline Tuff (15 m.y.) is borne out by the extrapolation of accumulation rates extended upward from the Rak and Oreodont Tuffs as well as downward from the Hemicyon and Dated Tuffs. The increase in accumulation rate shown from the Hemicyon Tuff to the Lapilli Sandstone reflects the use of the Carnivore Canyon section (Fig. 4) in this compilation, with an increase of coarse-grained sandstone units over other sections of this age. Were the section in Hell Gate basin used for this compilation, the interval from the Hemicyon Tuff to the Lapilli Sandstone would record a much slower accumulation rate (70 m/m.y.). Also, the accumulation rate calculated in the Rainbow Loop section between the Oreodont Tuff and Skyline Tuff (438 m/m.y.) is about five times greater than the accumulation rate for the same interval in Carnivore Canyon (90 m/m.y.), indicating, along with the coarser-grained facies of the Rainbow Loop section, that the basin margin lay to the southeast of Carnivore Canyon.

The somewhat steeper accumulation rate shown in Figure 6 above the Hemicyon Tuff is based on the Carnivore Canyon section (2), which is thicker than comparable parts of the section (for example, Hell Gate basin, 6; Fig. 4). The upper limit of the Barstow Formation appears to be somewhat younger than the age of the Lapilli Sandstone (for example, 13.4 m.y.), or about 13.3 m.y.

The Hell Gate basin section (Fig. 4) shows an accumulation rate of 70 m/m.y. calculated for the same interval (55 m between the Hemicyon Tuff and the Lapilli Sandstone). This is consistent with the overall lacustrine (fine-grained deposits and limestone) depositional regime recorded in the Hell Gate basin section versus the more prominently fluviatile (coarse-grained arkosic sandstone and conglomeratic sandstone) of the corresponding portion of the Carnivore Canyon sequence. Both computations show, however, the dramatic decrease in accumulation rate above the Skyline Tuff versus the section below it. Finally, the sequence below the Skyline Tuff in Carnivore Canyon includes the Oreodont Tuff, which occurs 72 m below it. The temporal interval of 0.8 m.y. indicates an accumulation rate of 90 m/m.y., a nearly five-fold decrease in accumulation rate in Carnivore Canyon, located about 5 km northwest relative to the Rainbow Loop area (Figs. 3 and 4). During the time in question, the basin center apparently lay in the vicinity of Carnivore Canyon, whereas the more marginal sites were to be found in the Rainbow Loop area on the south as well as in areas to the west (Tbfg; Figs. 3 and 4). This is in distinct contrast to the marginal setting recorded in Carnivore Canyon above the Skyline Tuff versus areas to the east (Hell Gate basin; Rodent Hill basin; Fuller's Earth Canyon; Hemicyon basin; Fig. 4). The depocenter for the upper member of the Barstow Formation apparently lay eastward of Carnivore Canyon.

BIOCHRONOLOGY OF THE BARSTOW FAUNAL SUCCESSION

In this section, we discuss the position of the Hemingfordian-Barstovian boundary as it relates to the Barstow Formation and biochronologically significant strata in the midcontinent.

Wood and others (1941, p. 12) proposed the Barstovian land-mammal age, "based on the Barstow Formation . . . and specifically on the fossiliferous tuff member and its fauna." Index fossils noted by Wood and others (1941) were *Amblycastor*, *Dyseohyus fricki*, *Hemicyon*, *Monosaulax*, and *Peridiomys*. Taxa first appearing in this age were *Aelurodon*, *Calippus*, *Hypolagus*, Proboscidea, *Prosthennops*, and *Teleoceras*. Taxa making their last appearance in this age were *Archaeohippus* and *Parahippus*. Characteristic forms include *Alticamelus*, *Amphicyon*, *Blastomeryx*, *Cynodesmus*, *Hypohippus*, *Merychippus*, *Merycochoerus*, *Merycodus*, *Mylagaulus*, *Procamelus*, and *Ticholeptus*. Taxonomic revisions in the intervening years have changed some of these generic names, and new forms have been added. Some of the taxa cited in 1941 (or their revised equivalents), however, are not restricted to the Fossiliferous Tuff Member of Baker (1911; approximately equivalent to the upper member of the Barstow Formation of this report).

Recently, the Barstovian mammal age has been defined and characterized by Tedford and others (1987), based on the biostratigraphy summarized by Woodburne and Tedford (1982). We continue to contend that virtually all North American Land Mammal Ages (including the Barstovian) are biochronologic units. In only two cases (Wasatchian; Savage, 1977; Clarkforkian; Rose, 1981) have the necessary procedural requirements been met to justify proposing formal chronostratigraphic stages for these units. This has not yet been accomplished for the Barstovian, as pointed out by Schoch (1988). We therefore reject Evander's (1986) arguments for recognition of a boundary stratotype for the Barstovian, as well as its proposed location at the base of New Year Quarry (Fig. 5). Part of his objection to our definition of the Barstovian (extended stratigraphically much lower to Steepside Quarry; Fig. 5) has been met by the details presented in this paper on the nature of the faunal change across the Hemingfordian-Barstovian boundary. We note that Wood and others (1941) limited the Hemingfordian to faunal equivalents of the "Lower Sheep Creek Fauna of Cook and Cook (1933, p. 38–40) and not on formation limits as extended upward," an admonition that clearly excludes the Lower Snake Creek Fauna (correlative with the Green Hills Fauna) from the Hemingfordian. Also, in the present instance, correlations with faunas elsewhere in North America were used to effect as broad a basis for recognition of the unit as possible. Tedford and others (1987) defined the beginning of Barstovian time using the first occurrence of two immigrant genera: the cricetid rodent *Copemys* and the ursid *Hemicyon* (*Plithocyon*). These taxa occur together in the Steepside Quarry of the Frick Laboratory (Fig. 5) in strata of the Barstow Formation that contain the Green Hills Fauna. The associated elements in that fauna include the following forms that characterize the earlier part of the Barstovian mammal age: the oreodont *Brachycrus*, the cervoid *Rakomeryx*, the peccary *Dyseohyus*, and the pronghorn *Merriamoceros*. The base of the Green Hills faunal interval, and thus the base of the Barstovian mammal age, appears to be about 15.9 m.y. old (for example, Figs. 5 and 6, and relevant discussion in the text).

The presence of the mastodont *Gomphotherium* in the stratal span of the Barstow Fauna has assumed particular significance, as Tedford and others (1987) have used the first appearance of immigrant gomphotheriid mastodonts as a useful datum for correlation. Recent review of the sparse occurrence of Proboscidea in the Barstow Formation indicates that the lowest stratigraphic occurrence of gomphotheriid mastodont remains lies about 20 m above the Dated Tuff (approximately 14.8 m.y. in age). The stratigraphically lowest determinable proboscidean is a skull of *Miomastodon* (Raymond M. Alf Museum) from just beneath the Dated Tuff. Frick Laboratory records also indicate proboscidean remains from sites 10 m above the Skyline Tuff, about coeval with the *Miomastodon* skull. The relatively close stratigraphic association of rare proboscideans in the lower part of the First Division bracketing the Dated Tuff provides an approximate datum and its calibration. At this time, the stratigraphic first occurrence of gomphotheriid proboscideans at or slightly younger than 14.8 m.y. appears to be a useful datum for correlation within North America (see also Tedford and Hunter, 1984), as the approximate beginning of the Barstow Fauna, and of late Barstovian time.

The Rak Division Fauna and Red Division Fauna are excluded from the Barstovian mammal age and are attributed to the latest part of the Hemingfordian. The Red Division Fauna contains the pliohippine horse *"Merychippus" carrizoensis*, which although unknown east of the Mojave Desert, is a common taxon in faunas from California (CIT locality 315 in the Caliente Range; Phillips Ranch Local Fauna in the Tehachapi Mountains; Upper Cady Mountains Fauna in the Mojave Desert, see Tedford and others, 1987). See the above discussion of the age of the Rak Tuff where this species occurs in strata about 16.5 m.y. old and thus is coeval with taxa of late Hemingfordian age in Nebraska. The upper part of the range zone of *"M." carrizoensis* falls within the range zone of *"M." stylodontus* and other taxa typical of the Green Hills Fauna at a site in the

Barstow Formation near Yermo (Yermo Hills; Fig. 1), 30 km southeast of the Mud Hills, indicating that the younger part of the range zone of *"M." carrizoensis* extends into early Barstovian time, that is, ca. 15.9 Ma.

The fauna of the Rak Division shows phyletic relationships to both the Red Division and Green Hills faunas. The miolabine camels represent upward extensions of the range of *"Miolabis"* cf. *"M." tenuis* with the addition of a larger form, *"M."* cf. *"M." singularis*, both of which continue into the Green Hills levels. The protolabine camels are represented by the first local appearances of *Protolabis* and *Michenia* species that increase in size into the Green Hills; *Protolabis* cf. *P. barstowensis* continues into the Barstow Fauna, but *Michenia* locally disappears from the record below the Skyline Tuff. *Aepycamelus* appears locally in the Rak Division, represented by two species, the smaller of which is restricted to the Rak Division and the lower Green Hills. The large species of *Aepycamelus* is not represented in the Second Division Fauna but reappears in the Barstow Fauna as *A. alexandrae*. Other taxa, such as *Tomarctus* cf. *T. rurestris* and the pliohippine *"Merychippus"* cf. *"M." isonesus*, range throughout the Rak Division and into the Green Hills. Their phyletic relationships lie with early Barstovian taxa (Lower Snake Creek) elsewhere. At the moment, the best evidence for assigning the Rak Division Fauna to the late Hemingfordian is the presence of *"Miolabis"* cf. *"M." tenuis* and *"M." singularis* and the absence of taxa that define the beginning of the Barstovian.

Our review of the biostratigraphy of the Barstow Formation in the Mud Hills supports the previous view (Woodburne and Tedford, 1982; Tedford and others, 1987) that both the Green Hills and Barstow Faunas should be included in the Barstovian mammal age, with the newly named Second Division Fauna forming a part of the Green Hills Fauna, *s.l.* Even though the taxa of the Barstow Fauna were specifically cited by Wood and others (1941) as typical of the age, the genera listed by them also include forms found in, and characteristic of, the Green Hills and Second Division faunas. We exclude the Rak Division and Red Division faunas from the Barstovian, based on the principle that the lowest occurrence of taxa definitive of the Barstovian limits the age, and thus place the boundary at the base of the strata span containing the Green Hills Fauna, just beneath the Frick Laboratory Steepside Quarry, which contains all the elements definitive of the Barstovian biochron. The base of the Barstovian mammal age is thus about 15.9 m.y. old. The older assemblages contain some taxa typical of late Hemingfordian faunas elsewhere, and these faunas are assigned to the latest part of the Hemingfordian mammal age, calibrated in California and Nebraska at about 16.3 Ma.

ACKNOWLEDGMENTS

We are deeply grateful to the late T. Galusha, American Museum of Natural History, New York, and to S. T. Miller, U.S. Geological Survey, Menlo Park, California, for their help, consultation, and discussion during the present and past years on the general topic of Mojave Desert paleontology and stratigraphy, and with regard to the Barstow Formation in particular. Morris F. Skinner and Beryl E. Taylor, American Museum of Natural History, generously shared unpublished results of their studies of Barstow horses, camels, carnivores, and horned ruminants, and participated in discussions of the biochronological significance of these mammals. Most of the Frick Collection from the study area was brought together by the late Joseph Rak and Jack Wilson, who, with many field assistants, provided many of the field data utilized in this summary. The work on the stratigraphy of the Barstow Formation in the Mud Hills by R. P. Steinen, Department of Geology, University of Connecticut, was of particular value in preparing this summary. We also wish to thank D. E. Savage, University of California Museum of Paleontology; D. P. Whistler, Natural History Museum, Los Angeles County; and E. H. Lindsay, Department of Geosciences, University of Arizona, who introduced Woodburne to the Mojave Desert in the rainy winter of 1966, and who have continued their interest in, and contributions to, the study of this region in subsequent years. The paleontological work of R. M. Alf and students from Webb School, Claremont, California, and of R. E. Reynolds, San Bernardino County Museum, California, is also recognized and appreciated. We also cite the many students of the Department of Earth Sciences, University of California, Riverside, who participated in class field trips during the past 27 yr and whose efforts contributed to our understanding of the stratigraphy of the Barstow Formation. We also wish to acknowledge grants from the University of California, Riverside, Academic Senate Committee on Research that defrayed some of the expenses associated with these studies, as well as National Science Foundation (NSF) Grant EAR86-18701 to B. E. Drake and G. H. Curtis, which supported isotopic analyses reported herein, and NSF Grant EAR82-06529 to B. J. MacFadden, which supported some of the activities undertaken in this study. Comments by S. D. Webb and an anonymous reviewer improved the manuscript.

REFERENCES

Alf, R. M., 1970, A preliminary report on a Miocene flora from the Barstow Formation, Barstow, California: Southern California Academy of Science Bulletin, v. 69, p. 183–188.

Baker, C. L., 1911, Notes on the later Cenozoic history of the Mohave Desert region in southeastern California: California University Publications in Geological Sciences, v. 6, p. 333–383.

Barghoorn, S. F., 1981, Magnetic-polarity stratigraphy of the Miocene type Tesuque Formation, Santa Fe Group, in the Española Valley, New Mexico: Geological Society of America Bulletin, v. 92, p. 1027–1041.

——— 1985, Magnetic polarity stratigraphy of the Tesuque Formation, Santa Fe Group, in the Española Valley, New Mexico, with a taxonomic review of the fossil camels [Ph.D. dissert.]: New York, Columbia University, 489 p.

Barnosky, A. D., 1986, Arikareean, Hemingfordian, and Barstovian mammals from the Miocene Colter Formation, Jackson Hole, Teton County, Wyoming: Carnegie Museum of Natural History Bulletin 26, 69 p.

Berggren, W. A., Kent, D. V., Flynn, J. J., and VanCouvering, J. A., 1985, Cenozoic geochronology: Geological Society of America Bulletin, v. 96, p. 1407–1418.

Burke, D. B., Hillhouse, J. W., McKee, E. H., Miller, S. T., and Morton, J. L., 1982, Cenozoic rocks in the Barstow basin area of southern California—Stratigraphic relations, radiometric ages, and paleomagnetism: U.S. Geological Survey Bulletin 1529-E, p. E1–E16.

Carter, J. N., Luyendyk, B. P., and Terres, R., 1987, Neogene clockwise rotation of the eastern Transverse Ranges, California, as suggested by paleomagnetic vectors: Geological Society of America Bulletin, v. 98, p. 199–206.

Cook, H. J., and Cook, M. C., 1933, Faunal lists of the Tertiary Vertebrata of Nebraska and adjacent areas: Nebraska Geological Survey Paper, no. 5, p. 1–58.

Davidson, P., 1923, *Alticamelus alexandrae*, a new camel from the Barstow upper Miocene: California University Publications in Geological Sciences, v. 14, p. 397–408.

Dibblee, T. W., Jr., 1968, Geology of the Opal Mountain and Fremont Peak quadrangles, California: California Division of Mines and Geology Bulletin, v. 188, 64 p.

Dokka, R. K., 1986, Patterns and modes of early Miocene crustal extension, central Mojave Desert, California, *in* Mayer, L., ed., Extensional tectonics of the southwestern United States: A perspective on processes and kinematics: Geological Society of America Special Paper 208, p. 75–95.

Dokka, R. K., McCurry, M., Woodburne, M. O., Frost, E. G., and Okaya, D. A., 1988, A field guide to the Cenozoic crustal structure of the Mojave Desert, *in* Weide, D. L., and Faber, M. L., eds., This extended land: Geological journeys in the southern Basin and Range: Geological Society of America Cordilleran Section Guidebook, p. 21–44.

Durrell, C., 1953, Geological investigations of strontium deposits in southern California: California Division of Mines and Geology Special Report, v. 32, p. 23–36.

Evander, R. L., 1986, Formal redefinition of the Hemingfordian-Barstovian Land Mammal Age boundary: Journal of Vertebrate Paleontology, v. 6, p. 374–381.

Evernden, J. F., Savage, D. E., Curtis, G. H., and James, G. T., 1964, Potassium-argon dates and the Cenozoic mammalian geochronology of North America: American Journal of Science, v. 262, p. 145–198.

Frick, C., 1926a, The Hemicyoninae and an American Tertiary bear: American Museum of Natural History Bulletin, v. 56, p. 1–119.

——— 1926b, Tooth sequence in certain Trilophodont-Tetrabelodont mastodons: American Museum of Natural History Bulletin, v. 56, p. 122–176.

——— 1933, New remains of Trilophodont-Tetrabelodont mastodons: American Museum of Natural History Bulletin, v. 59, p. 505–562.

——— 1937, The horned ruminants of North America: American Museum of Natural History Bulletin, v. 69, 669 p.

Furlong, E. L., 1927, The occurrence and phylogenetic status of Merycodus from the Mojave Desert Tertiary: California University Publications in Geological Sciences, v. 17, p. 145–186.

Galusha, T., and Blick, J. C., 1971, Stratigraphy of the Santa Fe Group, New Mexico: American Museum of Natural History Bulletin, v. 144, p. 1–128.

Hall, E. R., 1930, Rodents and lagomorphs from the Barstow beds of southern California: California University Publications in Geological Sciences, v. 19, p. 313–318.

Hedberg, H. D., ed., 1976, International stratigraphic guide: New York, John Wiley and Sons, 200 p.

Hershey, O. H., 1902, Some Tertiary formations of southern California: American Geologist, v. 29, p. 349–372.

Lewis, G. E., 1964, Miocene vertebrates of the Barstow Formation in southern California: U.S. Geological Survey Professional Paper 475-D, p. D18–D23.

——— 1968, Stratigraphic paleontology of the Barstow Formation in the Mud Hills area, San Bernardino County, California, *in* Dibblee, T. W., Jr., Geology of the Opal Mountain and Fremont Peak quadrangles, California: California Division of Mines and Geology Bulletin, v. 188, 64 p.

Lindsay, E. H., 1972, Small mammal fossils from the Barstow Formation, California: California University Publications in Geological Sciences, v. 93, 104 p.

Loomis, D. B., and Burbank, D. W., 1988, The stratigraphic evolution of the El Paso basin, southern California: Implications for the Miocene development of the Garlock fault and uplift of the Sierra Nevada: Geological Society of America Bulletin, v. 100, p. 12–28.

Luyendyk, B. P., Kamerling, M. J., and Terres, R., 1980, Geometric model for Neogene crustal rotations in southern California: Geological Society of America Bulletin, v. 91, p. 211–217.

MacFadden, B. J., Swisher, C. C., III, Opdyke, N. D., and Woodburne, M. O., 1990, Paleomagnetism, geochronology, and possible tectonic rotation of the middle Miocene Barstow Formation, Mojave Desert, California: Geological Society of America Bulletin (in press).

Matthew, W. D., 1924, Third contribution to the Snake Creek fauna: American Museum of Natural History Bulletin, v. 50, p. 59–210.

McCulloh, T. H., 1954, Geology of the southern half of the Lane Mountain quadrangle, California [Ph.D. thesis]: Los Angeles, California, University of California.

Merriam, J. C., 1911, A collection of mammalian remains from Tertiary beds on the Mohave Desert: California University Publications in Geological Sciences, v. 6, p. 167–169.

——— 1913, New Anchitheriine horses from the Tertiary of the Great Basin area: California University Publications in Geological Sciences, v. 7, p. 419–434.

——— 1915a, Extinct faunas of the Mohave Desert, their significance in a study of the origin and evolution of life in America: Popular Science Monthly, v. 86, p. 245–264.

——— 1915b, New horses from the Miocene and Pliocene of California: California University Publications in Geological Sciences, v. 9, p. 49–58.

——— 1919, Tertiary mammalian faunas of the Mohave Desert: California University Publications in Geological Sciences, v. 11, p. 437a–437e, 438–585.

Miller, S. T., 1980, Geology and mammalian biostratigraphy of a part of the northern Cady Mountains, California: U.S. Geological Survey Open-File report 80-978, 121 p.

Moore, J. G., and Peck, D. L., 1962, Accretionary lapilli in volcanic rocks of the western continental United States: Journal of Geology, v. 70, p. 182–193.

Naeser, C. W., Izett, G. A., and Obradovich, J. D., 1980, Fission-track and K-Ar ages of natural glasses: U.S. Geological Survey Bulletin 1489, p. 1–31.

Patton, T. H., 1969, Miocene and Pliocene artiodactyls, Texas Gulf Coastal Plain: Florida State Museum Bulletin of Biological Sciences 14, p. 115–226.

Quinn, J. P., 1987, Geology and biostratigraphy of the Bopesta Formation, southern Sierra Nevada mountains, Kern County, California: Natural History Museum of Los Angeles County Contributions in Science, v. 393, p. 1–31.

Real, C. R., Toppozader, T. R., and Parke, D. L., 1978, Earthquake epicenter map of California, 1900–1974: California Division of Mines and Geology Map Sheet 39.

Repenning, C. A., and Vedder, J. G., 1961, Continental vertebrates and their stratigraphic correlation with marine mollusks, eastern Caliente Range, California: U.S. Geological Survey Professional Paper 424C, p. C235–C239.

Rose, K. D., 1981, The Clarkforkian land-mammal age and mammalian faunal composition across the Paleocene-Eocene boundary: University of Michigan Papers in Paleontology, v. 26, p. 1–197.

Savage, D. E., 1977, Aspects of vertebrate paleontological stratigraphy and geochronology, *in* Kaufmann, E. G., and Hazel, J. E., eds., Concepts and methods of biostratigraphy: Stroudsburg, Pennsylvania, Dowden, Hutchinson, and Ross, p. 427–442.

Schoch, R. M., 1988, Comment on the formal redefinition of the Hemingfordian-Barstovian Land Mammal Age boundary: Journal of Vertebrate Paleontology, v. 7, p. 472–473.

Schultz, C. B., and Falkenbach, C. H., 1940, Merycochoerinae, a new subfamily of oreodonts: American Museum of Natural History Bulletin, v. 77, p. 213–306.

——— 1941, Ticholeptinae, a new subfamily of oreodonts: American Museum of Natural History Bulletin, v. 79, p. 1–105.

——— 1947, Merychyinae, a new subfamily of oreodonts: American Museum of Natural History Bulletin, v. 88, p. 157–256.

Sheppard, R. A., and Gude, A. J., 3rd, 1969, Diagenesis of tuffs in the Barstow Formation, Mud Hills, San Bernardino County, California: U.S. Geological Survey Professional Paper 634, p. 1–34.

Skinner, M. F., and Johnson, W. F., 1984, Tertiary stratigraphy and the Frick collection of fossil vertebrates from north-central Nebraska: American Museum of Natural History Bulletin, v. 178, p. 215–368.

Skinner, M. F., Skinner, S. M., and Gooris, R. J., 1977, Stratigraphy and biostratigraphy of late Cenozoic deposits in central Sioux County, western Nebraska: American Museum of Natural History Bulletin, v. 158, p. 263–370.

Steiger, R. H., and Jaeger, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359–362.

Steinen, R. P., 1966, Stratigraphy of the middle and upper Miocene Barstow Formation, San Bernardino County, California [M.S. thesis]: Riverside, California, University of California, 150 p.

Stirton, R. A., 1930, a new genus of Soricidae from the Barstow Miocene of California: University of California Publications in Geological Sciences, v. 19, p. 217–228.

Stock, C., 1937, A peccary skull from the Barstow Miocene, California: National Academy of Sciences Proceedings, v. 23, p. 398–404.

Tedford, R. H., 1981, Mammalian biochronology of the late Cenozoic basins of New Mexico: Geological Society of America Bulletin, v. 92, p. 1008–1022.

Tedford, R. H., and Alf, R. M., 1962, A new *Megahippus* from the Barstow Formation, San Bernardino County, California: Southern California Academy of Sciences Bulletin, v. 61, p. 113–122.

Tedford, R. H., and Hunter, M. E., 1984, Miocene marine-nonmarine correlations, Atlantic and Gulf coastal plains, North America: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 47, p. 129–151.

Tedford, R. H., Galusha, T., Skinner, M. F., Taylor, B. E., Fields, R. W., Macdonald, J. R., Rensberger, J. M., Webb, S. D., and Whistler, D. P., 1987, Faunal succession and biochronology of the Arikareean through Hemphillian interval (late Oligocene through earliest Pliocene epoch), North America, *in* Woodburne, M. O., ed., Cenozoic mammals: Geochronology and biostratigraphy: Berkeley, California, University of California Press, p. 153–210.

Turner, D. L., 1970, Potassium-argon dating of Pacific Coast Miocene foraminiferal stages: Geological Society of America Special Paper 124, p. 91–129.

Wood, A. E., 1936, Fossil heteromyid rodents in the collections of the University of California: American Journal of Science, v. 32, p. 112–119.

Wood, H. E., 2nd, Chaney, R. W., Clark, J., Colbert, E. H., Jepsen, G. L., Reeside, J. B., Jr., and Stock, C., 1941, Nomenclature and correlation of the North American continental Tertiary: Geological Society of America Bulletin, v. 52, p. 1–48.

Woodburne, M. O., 1969, Systematics, biogeography and evolution of *Cynorca* and *Dyseohyus* (Tayassuidae): American Museum of Natural History Bulletin, v. 141, p. 272–355.

Woodburne, M. O., and Golz, D. J., 1972, Stratigraphy of the Punchbowl Formation, Cajon Valley, southern California: California University Publications in Geological Sciences, v. 97, 45 p.

Woodburne, M. O., and Tedford, R. H., 1982, Litho- and biostratigraphy of the Barstow Formation, Mojave Desert, California, *in* Geologic excursions in the California desert: Geological Society of America, Cordilleran Section, Annual Meeting, 78th, Anaheim, California, Volume and Guidebook, p. 65–76.

Woodburne, M. O., Tedford, R. H., and Miller, S. T., 1982, Stratigraphy and geochronology of Miocene strata in the central Mojave Desert, California, *in* Geologic excursions in the California desert: Geological Society of America, Cordilleran Section, Annual Meeting, 78th, Anaheim, California, Volume and Guidebook, p. 47–54.

Manuscript Received by the Society September 6, 1988
Revised Manuscript Received July 7, 1989
Manuscript Accepted July 18, 1989