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David W. Love

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BIDAHOCHI FORMATION: AN INTERPRETIVE SUMMARY

DAVID W. LOVE
New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico 87801

Abstract—The upper Tertiary Bidahochi Formation covers over 16,000 km^2 in eastern Arizona and western New Mexico. The depositional "basin" consisted of paleovalleys and interfluves sloping southwest and west from Black Mesa, Defiance and Zuni uplifts, and north from the White Mountains toward the ancestral Little Colorado River. Facies are generally alluvial, lacustrine, eolian, monchiquitic eruptives, travertine and other spring deposits and silicic ash. After initial erosion of valleys through tilted older Cenozoic, Mesozoic and upper Paleozoic rocks, deposition of the Bidahochi Formation began by at least 9 my. Lower parts of the Bidahochi Formation in Arizona may be lateral age equivalents of the upper Fence Lake Formation in western New Mexico. Eruptions of basaltic and monchiquitic lavas and tephra from diatremes influenced the formation of lakes in the Hopi Buttes area between 8.5 and 6 my and again between 4.5 and 4 my. Up to 240 m of Bidahochi Formation accumulated in some paleovalleys on the flanks of uplifts, possibly by longitudinal and lateral progradation of alluvial facies. Major episodes of valley-scale cuts-and-fills may occur within the formation. Aggradation of alluvial and eolian facies of the Bidahochi Formation had ceased at least locally by 4 my, and erosion beveled the upper part of the Bidahochi prior to eruptions in the Springerville volcanic field less than 4 my. Episodic incision and terrace formation have subsequently occurred along all major drainages cutting the Bidahochi. Depositional facies and age of the Bidahochi Formation are similar to the Ogallala Formation in eastern New Mexico and northwestern Texas, implying similar tectonic, geographic and climatic reasons for both accumulations. Non-migrant cyclicity in volcanic eruptions may be similar to basaltic fields to the south and east but is in contrast to the San Francisco volcanic field to the west.

INTRODUCTION

The upper Tertiary Bidahochi Formation in eastern Arizona and western New Mexico presently covers over 16,000 km^2 near the southern margin of the Colorado Plateau, west of the Defiance and Zuni uplifts (Fig. 1) and ranges up to 240 m thick. Uncertainties concerning the Bidahochi Formation include: (1) its original lateral extent, (2) the upper and lower lithologic boundaries of the formation, (3) its age, (4) its depositional environments and (5) its relation to regional tectonics and the development of the Little Colorado River drainage. All these uncertainties affect the definition and interpretation of the formation and should be considered together. Previous workers have dealt with these uncertainties at least at local scales, and have included or excluded different upper Tertiary and Quaternary units within the Bidahochi Formation. Much of the "classic" work on the Bidahochi Formation was done before radiometric dates became common. Radiometric and calibrated land-mammal ages define the units' relationships more precisely and solve several correlation problems with other Tertiary formations in the region but raise questions about previously described stratigraphic relationships. This paper summarizes current published work on the Bidahochi and attempts to synthesize its mode of deposition and tectonic and geomorphic significance.

Previous work

Tertiary sediments in the region were first noted by Newberry (1861) and briefly described by Gregory (1917). The Bidahochi Formation was named by Reagan (1924) and described by Reagan (1932) from outcrops north of Holbrook, Arizona. More comprehensive descriptions were made by Repenning and Halpenny (1951), Repenning and Irwin (1954), Repenning et al. (1958), Shoemaker et al. (1958), Howell (1959), Akers (1964), Cooley et al. (1969), Sutton (1974b) and Shafiqullah and Damon (1986a, b). Fossils in the formation were described by Reagan (1932), Stirton (1936), Lance (1954), Taylor (1957), Uyeno and Miller (1965), Breed (1973) and Sutton (1974b). The volcanic edifices in the Bidahochi Formation were studied by Williams (1936), Hack (1942), Shoemaker et al. (1962 and references therein), Lowell (1956), Scarborough et al. (1974), Sutton (1974a, b), Shafiqullah and Damon (1986) and Wenrich (1989 and references therein). Sabels (1962) did preliminary work on tephra correlations and thermoluminescent dating of the formation. Clays of the Bidahochi Formation were described by Kiersch and Keller (1955a, b), Howell (1959) and Eyde and Eyde (1987). Uranium mineralization related to the Hopi Buttes diatremes was described by Shoemaker et al. (1962 and references therein) and Wenrich and Mascarenas (1982). Ground water in the Bidahochi Formation was investigated by Harrell and Eckel (1939), Akers (1964) and Cooley et al. (1969). Geomorphology of the region was considered by Gilbert (1875), Gregory (1917), McCann (1938), Hack (1942), Cooley and Akers (1961a, b), McKee et al. (1967), Cooley et al. (1969) and Sutton (1974a, b).

LATERAL EXTENT

As shown in Figure 1, the Bidahochi Formation presently extends from Springerville, Arizona, at the southern limit, northwestward to Woodruff and Montezuma's Chair, then northeast to Keams Canyon and east to Ganado Mesa. From Ganado Mesa the formation extends southeast to the New Mexico–Arizona line near Lupton, east to the Zuni Mountains, south to Zuni Salt Lake and Quemado and southwest to Springerville. The formation is preserved predominantly on slopes between the Defiance and Zuni uplifts and the Little Colorado River, except for outcrops a few km west of Saint Johns, Arizona. Although Repenning et al. (1958) interpreted outcrops farther southwest as Bidahochi (based on aerial photographic interpretations), later workers (Johnson, 1962; Condit, 1984) do not show Tertiary sediments beneath the basalt flow at Point of Mountain. Sediments possibly correlative with the Bidahochi Formation extend south of Springerville where they are named the Sheep Crossing Formation (Merrill and Péwé, 1971, 1977; Merrill, 1984).

Other Tertiary sediments in the region that were once considered coeval with the Bidahochi Formation such as the Rim Gravels (Howell, 1959; cf. Condit, 1984), sediments exposed on Escudilla Mountain (Howell, 1959; Wrucke, 1961) and the Chuska and Deza formations (Repenning and Irwin, 1954; Repenning et al., 1958; Howell, 1959; Cooley et al., 1969; cf. Wright, 1956; Armstrong, 1969) are now known by radiometric dating to be older. Much of the Fence Lake Formation (McClellan et al., 1982) apparently predates the Bidahochi Formation (see age discussion below), but the upper part of the Fence Lake Formation and lower part of the Bidahochi Formation may be coeval lateral facies of the same depositional system.

Because of poor exposures and lithologic similarities, Quaternary deposits that occupy similar landscape positions as the Bidahochi Formation have also been mistaken for Bidahochi Formation (Repenning et al., 1958; cf. Akers, 1964) or vice versa (a Quaternary terrace remnant with Rancholabrean fauna known as the Richville gravels of Brady,

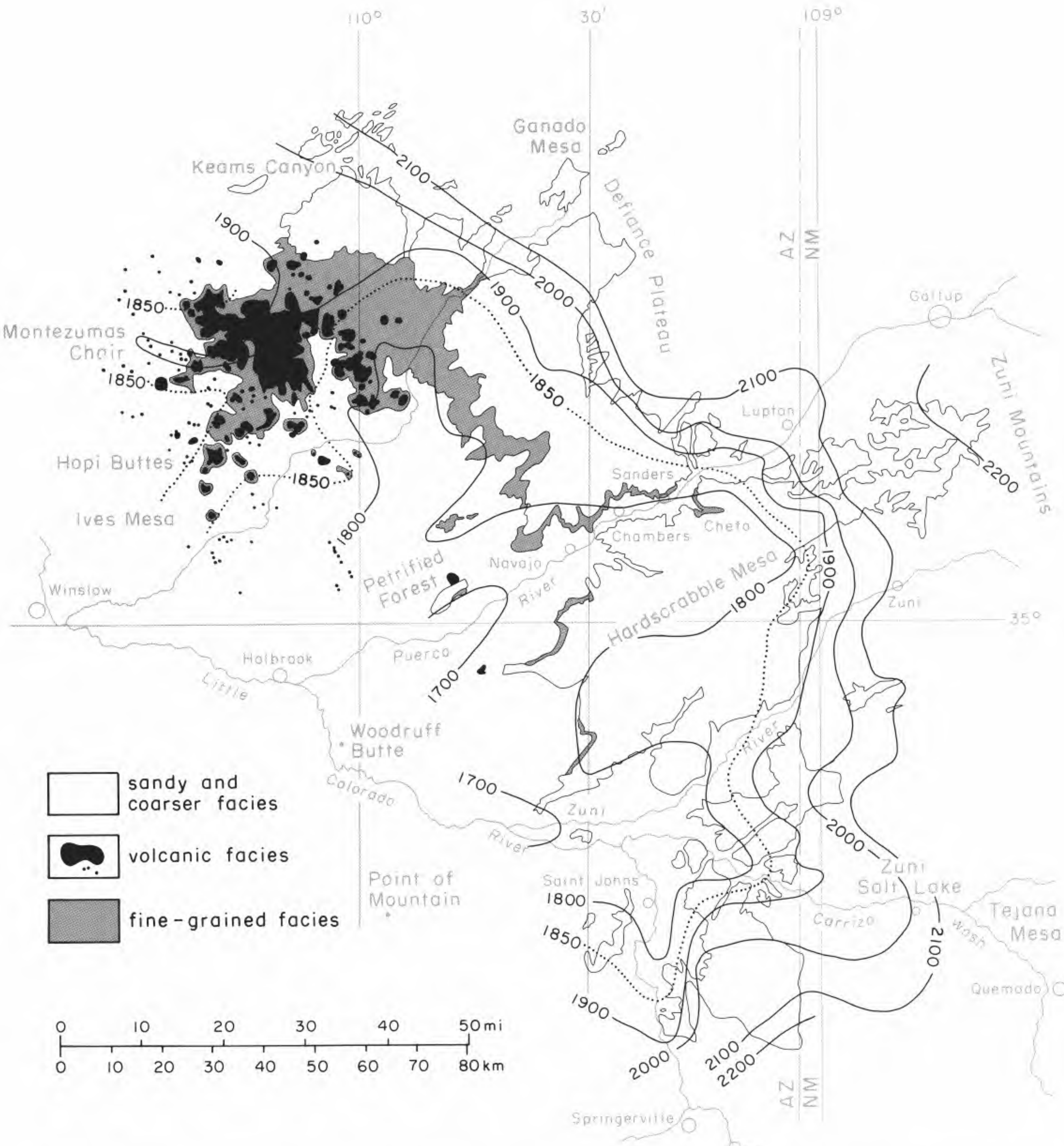

FIGURE 1. Map of extent of Bidahochi Formation showing fine-grained, volcanic and predominantly sandy facies and elevation contours (meters) at the base of the formation (compiled from Akers, 1964; Hackman and Olson, 1977; Ulrich et al., 1984; O. Anderson and D. Daude, unpublished maps).

1933, was misapplied to Bidahochi Formation by Sirrine, 1958; cf. Akers, 1964).

LOWER AND UPPER BOUNDARIES

The lower and upper contacts of the formation have been placed at different stratigraphic positions by previous workers; most workers have designated other contacts within the formation. The internal contacts are also boundaries between facies and are considered below.

Older upper Tertiary deposits may exist locally beneath the Bidahochi near the Arizona–New Mexico line west of Fence Lake, Quemado and Gallup. In this article, however, the contact between upper Tertiary deposits and underlying Mesozoic bedrock in the area described above is considered the base of the Bidahochi Formation (following Akers, 1964). Relief on the lower surface locally exceeds 60 m. The elevation of the contact is contoured in Figure 1 and ranges from 2275 m near the Zuni uplift to 1730 m near the Petrified Forest. Shafiqullah and Damon (1986b) suggested that the base of the Bidahochi Formation graded to a level only 82 m above the present Little Colorado River. The lower bounding surface of the Bidahochi Formation was described and named in local areas by McCann (1938), Hack (1942), Repenning and Irwin (1954), Repenning et al. (1958), Howell (1959), Cooley and Akers (1961a, b) and Akers (1964).

The upper contact is more difficult to define because exposures are generally poor. In most places, except for very thin eolian and alluvial-colluvial veneers, the Bidahochi Formation is the uppermost stratigraphic unit in the area and is partially eroded at the top. In other places, Quaternary sediments overlie the Bidahochi Formation but are commonly thin, reworked colluvial, eolian or alluvial sediments derived from the underlying formation. These Quaternary units may or may not be graded to terraces along major streams, particularly to the Little Colorado River. Local, unambiguous upper surfaces are capped by basalt flows and/or well-developed calcic soils.

Various names have been applied to boundary surfaces above, within and below the Bidahochi Formation, and have been correlated to other geomorphic surfaces and erosion cycles proposed for the Colorado Plateau (cf. Cooley and Akers, 1961a). Many of these names, correlations and cycles were proposed before radiometric age controls were established. Therefore, much revision of such terms and concepts is warranted but is beyond the scope of this summary.

AGE

Neither the upper nor lower boundaries of the Bidahochi Formation are well constrained by radiometric or fossil dates. Vertebrate fossils of Clarendonian (to possibly Barstovian) age have been found in the lowermost stratigraphic unit only 3 m above the basal contact at the Cheto Mine [also called Graywater Wash site, UALP-11] near Sanders, Arizona (Lance, 1954; Howell, 1959; Breed, 1973; Lindsay and Tessman, 1974). Howell (1959) considered these beds to be older than the Bidahochi Formation, but other workers have included them in the lower member (see stratigraphy and facies discussion below). The fossiliferous lowest unit is at an elevation of 1830 m, whereas the lowest part of the formation is preserved to the west at an elevation of less than 1730 m (Fig. 1). E. H. Lindsay (personal commun., 1988) indicates possible curatorial problems and incompatible species found within collections from the Cheto site. Berggren et al. (1985) consider the Clarendonian land-mammal age to range from 9 to 12 my.

Felsic volcanic ashes within the Bidahochi Formation were correlated with Thirteen Mile Rock eruptions of north-central Arizona by Sabels (1962) on the basis of similar chemistry and thermoluminescence. Thirteen Mile Rock itself was erupted only 3 to 5 my ago (McKee and Elston, 1980). However, the Thirteen Mile Rock section of volcanics from Hackberry Mountain record eruptions between 7.9 and 11.5 my (Elston et al., 1974; McKee and Elston, 1980; Elston, 1984).

The Bidahochi Formation west of Fence Lake, New Mexico, is inset and in erosional contact with the Miocene Fence Lake Formation (Anderson, 1981; McLellan et al., 1982). The Fence Lake Formation northeast of Quemado is cut by a dike dated 9.07 ± 0.22 my (M. J. Aldrich and M. Shafiqullah, written commun., 1984; sample UAKA 84-157), and Bidahochi Formation is inset below the dike (Guilinger, 1982). At Veteado Mountain, the Fence Lake Formation is capped by a basalt flow dated 12.6 ± 0.8 my (Baldridge et al., 1989, table 1). On Tejana Mesa near Quemado, the Fence Lake Formation is capped by an extremely well developed petrocalcic soil which in turn is overlain by basaltic surge deposits and a basalt flow dated 6.73 ± 0.18 my (Dethier et al., 1986). The soil took more than one million years to develop (J. W. Hawley, personal commun., 1984; also in Dethier et al., 1986). The Bidahochi Formation inset northeast and northwest of Tejana Mesa should be younger than the capping flow.

To the southwest, south of Springerville, Arizona, the Sheep Crossing Formation is thought to have been deposited while Mount Baldy volcano was active from 8.5 to 12 my (Merrill and Péwé, 1977; Merrill, 1984). The Sheep Crossing Formation underlies a basalt dated 8.9 ± 0.9 my (Merrill and Péwé, 1977).

Monchiquitic diatremes and lava flows of the Hopi Buttes in the "middle" part of the Bidahochi Formation (see below) in the northwestern part of its extent are dated by K/Ar from about 4 to 8.5 my (Scarborough et al., 1974; Shafiqullah and Damon, 1986a). A date of 4.1 my reported by Evernden et al. (1964) was considered a minimum age; Scarborough et al. (1974) reported a 6.69 my age for the middle volcanic member near White Cone. Naeser (1971) reported fission-track ages on apatite of 2.1 ± 0.2 my for Colliseum and 5.5 ± 1.1 my for Hoskietso diatremes, but Shafiqullah and Damon (1986a) report ages of 8.2 my and 4.22 my respectively for the two diatremes.

Fossils overlying the monchiquitic ash in the Bidahochi section at White Cone, Arizona, are Hemphillian in age (Stirton, 1936; Lance, 1954; Breed, 1973; Lindsay and Tessman, 1974). The Hemphillian land-mammal age is estimated to range from 5 to 9 my (Berggren et al., 1985).

Basalt flows overlying sediments capping the Bidahochi Formation near Springerville, Arizona, have K/Ar dates of 3.67 ± 0.12 and 2.94 ± 0.14 my (Laughlin et al., 1979, 1980). Basalt flows in stream valleys cut into the Bidahochi Formation have been dated 1.98 ± 0.6 my (Aubele et al., 1986), 1.67 ± 0.09 and 1.41 ± 0.29 my (Laughlin et al., 1979).

Several terraces are inset below the top of the Bidahochi Formation in the Hopi Buttes area (Sutton, 1974a, b). The second terrace from the top, the Dilkon terrace, is inset 170 m below the base of the Bidahochi Formation and has Blancan-Irvingtonian vertebrate remains preserved in the middle part of the section (R. Sutton, personal commun., 1980). The Blancan-Irvingtonian land-mammal age boundary is considered to be about 1.5 my (Berggren et al., 1985).

All these dates suggest that deposition of the Bidahochi Formation began by 9 my (possibly by 12 my) and ceased after 4 my.

STRATIGRAPHY AND FACIES

One major source of confusion in understanding the Bidahochi Formation stems from interpreting facies as layer-cake stratigraphic members. Facies within the Bidahochi Formation are generally alluvial, lacustrine, eolian, monchiquitic eruptives, spring deposits (both travertine and cienega) and silicic windborne ash. Early workers in the Hopi Buttes area noted fine-grained deposits in the lower part of the Bidahochi Formation, volcanic debris and flows in the middle part of the sections and coarser, sandy alluvial deposits in the uppermost part. Repenning and Irwin (1954; from Repenning and Halpenny, 1951) formalized these observations by dividing the Bidahochi Formation into three members—a lower, mostly fine-grained, predominantly lacustrine member, a middle volcanic member and an upper alluvial member. Repenning and Irwin (1954) indicated that the alluvial member on the flanks of the uplifts may be laterally equivalent to the lower member, but other workers have correlated all coarse alluvium with the upper member. Shoemaker et al. (1957, 1958) further divided the formation into six members: four lower fine-grained members, a volcanic member and an upper alluvial member. However, the members of Shoemaker et al. (1958) are clearly interpreted as depositional facies and show complex interfingering relations. For example, locally the alluvial member (six) is at the base of the formation and interfingers with fine-grained siltstone (unit one). Basaltic volcanic debris (considered part of member five) is locally at the base of the Bidahochi Formation (Howell, 1959; Akers, 1964), but in other areas interfingers with the upper alluvial member (six). Members three and four are interpreted as deltas on the margins of a large lake because of their fan shapes and fine-grained nature (Shoemaker et al., 1958). As mentioned above, Howell (1959) interpreted the lowest fine-grained unit in the Sanders area as older than Bidahochi Formation and called it the Cheto Formation.

Farther south (on the south side of Surprise Creek between the Puerco and Zuni rivers), fine-grained members pinch out and only the uppermost alluvial member (unit six) remains (Akers, 1964). In New Mexico and Arizona south and east of Hardscrabble Mesa, the Bidahochi Formation has been interpreted to consist solely of the uppermost alluvial member (Akers, 1964; Dane and Bachman, 1965). Based on local crosscutting relationships, local Pleistocene fossil content and differences in petrography between the Bidahochi Formation north of the Puerco River and bluffs to the south, Howell (1959) interpreted the southern sections to be all post-Bidahochi Formation, a unit he called "High Mesa fill."

Lacustrine facies

The lower member of Repenning and Irwin (1954) is generally described as banded gray, brown, pink and green mudstone, argillaceous siltstone and sandstone with thin continuous beds of white volcanic ash. The unit is nearly 150 m thick at the reference section along Pueblo Colorado Wash east of Bidahochi.

Interpretations of lacustrine facies in the lower part of the Bidahochi Formation fall into three categories: (1) an extensive, long-lasting lake (Hopi Lake of Williams, 1936), (2) more localized, ephemeral lakes and (3) lakes associated with volcanic events. Early workers (Gregory, 1917; Hack, 1942) recognized local lacustrine facies and attributed them to ponds along streams and damming of drainages by volcanic eruptions. Williams (1936), Repenning and Irwin (1954), and Repenning et al. (1958), Shoemaker et al. (1957, 1958), McKee et al. (1967) and Sutton (1974a, b) interpreted much more extensive lacustrine deposits, based primarily on fine-grained deposits, subaqueous slump structures and laterally continuous silicic ash beds. Fresh-water fossils, with the exception of some ostracods and mollusks, are found only in member five (volcanic or White Cone Member of Shoemaker et al., 1962; Breed, 1973).

Three problems arise from interpretations of extensive lacustrine deposits. First, no large natural dam has been found. Second, a lake with shores at 1830 m or more would have had to extend across the Little Colorado drainage. Third, the lake would have had to exist for millions of years in order for the "middle" volcanic member to have erupted into it.

McKee et al. (1967) suggested a lake could have formed during drainage reversal along the Little Colorado River as it shifted from flowing southeast into New Mexico to flowing northwestward into the Colorado River. However, no evidence has been presented for a southeast drainage into New Mexico during Miocene time, for drainage reversal or for an extensive lake extending west of the Little Colorado River. In fact, the Miocene Fence Lake Formation in New Mexico was shed northwestward from highlands to the southeast, and the ancestral Little Colorado River probably joined the ancestral Colorado River and crossed the Kaibab-Coconino uplift prior to Bidahochi time (Lucchitta, 1984; Beus and Lucchitta, 1987).

Sutton (1974b) suggested that Hopi Lake could have been dammed behind a cuesta of Triassic rock similar to present Ives Mesa and that the lake developed independent of the Little Colorado River. Sutton suggested that a pre-existing drainage was blocked catastrophically by volcanism or flooding, or that tectonism had made the area subside. He noted, however, that contours at the base of the Bidahochi Formation were not closed in the Hopi Buttes area (see Fig. 1).

Shafiqullah and Damon (1986b) suggested that two separate lakes formed: one perched behind a Triassic cuesta at an elevation of 1800 m as Sutton suggested, and a separate one 100 to 200 m lower within the Little Colorado–Puerco River valleys. Shafiqullah and Damon (1986b) did not describe what dammed either of the lakes.

It is conceivable that lava flows from Mormon Mesa or Sunset Mountains could have dammed the ancestral Little Colorado River to form a lake and subsequently were eroded. However, the dam would have had to have been at least 110 m high in the vicinity of Winslow and persisted for millions of years. More recent lava flows from the San Francisco field have reached the Little Colorado River, but none is thick enough to have formed a major dam and extensive lake. The Black Point flow, dated 2.39 ± 0.32 my (Damon et al., 1974), has retained its form despite topographic reversals along its flanks and snout. A lava dam thick enough to create a lake for millions of years should be expected to persist in a landform similar to the Hopi Buttes.

Until further work reinforce the interpretation of a widespread, long-lasting lake in the Hopi Buttes area, at least three alternative explanations are possible. First, some of the earlier workers may be right in interpreting the lakes as small and ephemeral. The "lakes" may have included a more extensive cienega environment along drainageways (J. W. Hawley, personal commun., 1989; Quade and Pratt, 1989). Extensive cienegas could trap fine-grained sediments and silicic ashes in alluviating valleys as parts of broader alluvial systems. This explanation of small ephemeral lakes and cienegas would make sense if there has been little post-Bidahochi deformation, and the contours of the base of the Bidahochi Formation correctly show that the landscape in the Hopi Buttes area was actually a low-relief upland alluvial plain. After initial erosion to form low-relief stream valleys to the Little Colorado River, the alluvial plain(s) could have prograded westward over distal, fine-grained toe-slope and cienega deposits. Parts of the fine-grained alluvial plain near Sanders have travertine-spring and eolian deposits as well as overbank silts and clays.

Second, local volcanic eruptions undoubtedly caused temporary lakes upstream from the flows and tuff-rings. All of the freshwater vertebrate fossils are found in beds directly above a major local volcanic ash or in craters of maars. Drainages are disrupted by volcanic eruptions—Pueblo Colorado Wash makes several right-angle turns around volcanic edifices, suggesting local ponding and diversion in the past. Local ponding by volcanic eruptions would have been episodic rather than persistent through millions of years.

A third possible explanation for lacustrine deposits includes some damming of local southwest-flowing streams from the Hopi Buttes and Defiance Plateau as major streams from the Zuni uplift aggraded large alluvial plains westward toward the vicinity of Holbrook. The large alluvial plains (envisioned as low-relief braid plains) may have decreased the gradients of the northeastern tributaries and caused deposition of the fine-grained lower members after the initial cutting of the drainages. Eolian deposits derived from the larger alluvial plains may also have caused some damming of small drainages locally.

Volcanic member

The "middle" volcanic member of the Bidahochi Formation crops out mainly in the Hopi Buttes, where several hundred eruptive centers and flow remnants are concentrated in 2000 km^2 near the northwestern margin of the Bidahochi Formation. A few isolated eruptive centers occur south, east and northwest of the main concentration. Many of the vents are nearly circular, funnel-shaped diatremes with surface expressions as maars and tuff rings up to 2.3 km in diameter (Williams, 1936; Hack, 1942; Lowell, 1956; Shoemaker et al., 1962; Sutton, 1974b; Wenrich, 1989). Most of the volcanic rocks are dark-gray to greenish-gray alkalic lamprophyres, limburgites or monchiquites (Williams, 1936; Hack, 1942). They are undersaturated in silica and have modal analcime or nepheline. They have small phenocrysts of olivine and titaniferous augite (Sutton, 1974b). They have higher amounts of titanium, phosphorous, zirconium, barium, niobium and cerium REE and water than normal olivine basalts (Shoemaker, 1956). These volcanics have more sodium and less potassium than the Oligocene minettes to the northeast (Shoemaker, 1956). Potassium apparently decreases and chromium and nickel increase north to south (Howell, 1959). Normal olivine basalt occurs as a flow at the Painted Desert overlook

(Williams, 1936; Howell, 1959). Away from the eruptive centers the original tephra has been altered to palagonitic tuff.

The stratigraphic distribution of tephra and ash of the "middle" volcanic member shows that the volcanics erupted at many different places and times and are not confined to one stratigraphic level. According to Shafiqullah and Damon (1986a, b), eruptions were frequent between 8.5 and 6 my. Then there was a gap from 6 to 4.5 my and a few eruptions between 4.4 and 4.2 my. No age trend in any direction has been noted.

Alluvial and other facies

Alluvial deposits make up the thickest part of the Bidahochi Formation with exposed thicknesses to 180 m and subsurface thicknesses of over 240 m. According to Repenning and Irwin (1954) and Kiersch and Keller (1955a), the alluvial unit generally is white to yellow to pale brown, crossbedded, poorly cemented, medium- to fine-grained sandstone with some gravelly beds. Silty and clayey units occur adjacent to channels, and eolian units interfinger with the alluvium. Channels are oriented generally from the major uplifts (Defiance, Zuni) toward the Little Colorado River. No detailed description of the types of channels and facies within the alluvial units has been undertaken. Although alluvial channels are found within the "lower" clayey member locally, much of the alluvial member truncates and overlies the "lower" clayey member. The nature of the contact on a regional scale and the possibility of westward or southward progradation of the coarser alluvial member remains to be investigated.

Casual observations north of Chambers and descriptions by Howell (1959) suggest incision and backfilling of large paleovalleys within the alluvial-eolian upper member. Whether these totally refilled valleys are within the Bidahochi or are post-Bidahochi remains to be determined. Inset, backfilled paleovalleys or terraces containing Pleistocene fauna are found in similar landscape positions (Howell, 1959; Akers et al., 1962).

Howell (1959) and Trevena and Nash (1981) noted mixed provenance in sandstone petrology of the Bidahochi Formation. Both volcanic and metamorphic-plutonic feldspars are present, some of which are reworked from sand grains in adjacent older sedimentary rocks. Trevena and Nash (1981) noted that some sandstone is merely reworked ash from an alkalic rhyolitic source. Howell noted a major change in petrology to the southeast, with sources there being dominantly from reworked older Tertiary volcaniclastic rocks. However, he interpreted these derived deposits to be post-Bidahochi in age.

Travertine deposits within the Bidahochi Formation are extensive in the Saint Johns–Carrizo Wash area and are locally prominent near Sanders, Arizona. In some areas, spring mounds are entirely travertine. Clastic facies also may be well cemented with calcite, and locally, early diagenetic sulfate minerals have been replaced with calcite and silica.

Eolian facies are prominent in many eastern and southern exposures of the Bidahochi Formation (Howell, 1959; Akers, 1964). Howell (1959) indicates that some of the thicker accumulations (up to 30 m thick) consist of dunes 7–10 m high trapped against bedrock highlands and cliffs to the east.

Shoemaker et al. (1957) labeled and traced 12 silicic ash beds across 80 km^2 in the vicinity of Bidahochi Trading Post. Howell (in Kiersch and Keller, 1955a) and Kiersch and Haff (1955) mapped at least three silicic ash beds near Sanders, Arizona, and O. Anderson (personal commun., 1988) noted at least three ashes in the Bidahochi Formation near Vanderwagen, New Mexico.

Calcic soils (Machette, 1985) occur in the Bidahochi Formation, but none has been described in detail. Numerous levels of soil development occur in the alluvial-eolian sections southeast of Sanders, Arizona. Because the upper surface of the Bidahochi Formation has been eroded in most places, well-developed soils are generally not preserved at the top of the formation. Stage III to IV calcic horizons occur locally, however.

DEFORMATION

The region encompassing the Bidahochi Formation has undergone only slight deformation since Laramide formation of the Defiance and Zuni uplifts and the San Juan, Gallup-Zuni and the Tusayan–Black Mesa basins. Kiersch and Keller (1955a, b) interpreted a structural shelf or monoclinal flexure along the southwest side of the Defiance uplift, which influenced erosion and deposition in Bidahochi time and influenced the alteration of rhyolitic tuffs to montmorillonitic clay. Howell (1959), however, disputed the existence of a structural shelf. Repenning et al. (1958) and Howell (1959) indicate soft-sediment deformation in the Bidahochi Formation, particularly in the lower part. Howell (1959) also describes three small east-west, down-to-the-south normal faults north of Navajo, Arizona, a small south-facing monocline just south of Navajo and a south-facing monocline with 30 m of structural relief and dips up to 13° in the Tertiary beds exposed in Hardscrabble Mesa. Deformation associated with the emplacement of diatremes is documented by Hack (1942), Shoemaker et al. (1962) and Sutton (1974b).

Previous workers suspected uplift of the source regions of the Bidahochi Formation in post-Bidahochi time. McCann (1938) proposed over 200 m of uplift of the Zuni Mountains, tilting eastern exposures of the Bidahochi Formation to the west. Hack (1942) suggested tilting of the northern part of the Bidahochi to the south. Howell (1959) suggested a combination of the two tilts to the southwest but with much less uplift. All these interpretations of tilt are based on the fact that the unconformity beneath the Bidahochi is steeper than present streams.

LARGER SPATIAL AND TEMPORAL CONSIDERATIONS

The Bidahochi Formation should be examined with respect to regional geology, late Cenozoic tectonics, climate, analogous epicontinental clastic wedges, development of the Colorado and Little Colorado drainages and the cyclic nature of sedimentation and volcanism.

The southern margin of the Colorado Plateau has risen substantially in late Cenozoic time, particularly with respect to the Basin and Range Province to the southwest (Peirce, 1985). Gable and Hatton (1983) interpret 2000–3000 m of uplift of the Colorado Plateau in this region in the last 10 my. Eaton (1986, 1987) also suggests 2500–3000 m of uplift prior to 4 my, with uplift centered around the Rio Grande rift to the east. Uplift has renewed erosion and downstream deposition. It also caused changes in air circulation and climate in the region (Wells et al., 1982; Smiley, 1984).

Cycles in Tertiary sedimentation on the southeastern Colorado Plateau include: (1) the development of the Baca drainage basin with east-northeast flow from central Arizona to central New Mexico and deposition of Baca Formation in Eocene time (Cather and Johnson, 1984; Potochnik, this guidebook), (2) the inundation and total disruption of the Baca drainage by Oligocene volcaniclastic and pyroclastic debris from volcanic eruptions in the Mogollon-Datil volcanic field to the southeast (Cather, 1986), concommittant with the destruction of the northwestern drainage divide of the Baca streams, (3) the development of the ancestral Colorado River drainage, including the ancestral Little Colorado River, (4) the deposition of the Fence Lake Formation, shed north and northwest from the Mogollon-Datil volcanic field after 28 my and prior to 8 my, (5) widespread erosion on the flanks of older uplifts and subsequent deposition of the Bidahochi Formation and (6) net incision with episodic erosion and deposition of late Pliocene and Quaternary sediments along present drainages. The earlier, longer-period cycles of drainage development, sources of sediment and depositional basins were influenced primarily by regional tectonics and volcanism. The shorter cycles of erosion and deposition noted in the late Pliocene and Quaternary record are influenced primarily by climate. The intervening interval (more than one "cycle"?) represented by the Bidahochi Formation appears to have been slightly influenced by tectonics, but to a larger extent it was influenced by episodic shifts in climate and development of the Colorado River system (all of which remain poorly documented).

The Ogallala Formation in eastern New Mexico and northwestern Texas is analogous to the Bidahochi Formation in many respects. It spans a similar time range (from 4 to 12 my), has similar alluvial and eolian facies, occurs as an epicontinental clastic wedge situated downslope from basin-and-range uplifts and rejuvenated Laramide uplifts and upslope from more permanent lowland drainages, developed in a similar climatic regime, and has been dissected by streams in late Pliocene and Quaternary time (Hawley, 1984; Eaton, 1986; Gustavson and Winkler, 1988). Uplift of the headwaters appears to have been the tectonic impetus for renewed erosion and the ultimate source for sediment. The storage of sediment in valleys, development of widespread eolian sand sheets and development of calcic soils were controlled to a large extent by climatic factors. The Bidahochi Formation differs from the Ogallala Formation in having lacustrine facies and in having crescentically arranged adjacent highlands rather than a more planar slope from uniaxial highlands.

The development of the Colorado drainage system has been a controversial subject for more than a century. Apparently drainages in northern Arizona and southern Utah flowed northward to the remnants of Lake Uinta in late Eocene time (Grande, 1984). Lucchitta (1984) and Beus and Lucchitta (1987) suggested that by at least middle Miocene time the ancestral Colorado River flowed south-southwest from Utah, swung west in a strike valley across the Kaibab-Coconino uplift, and northwestward into Nevada. The opening of the Gulf of California roughly 5.5 my led to the integration of drainages west of the Colorado Plateau and the development of a drainage incising the western edge of the Plateau in the area of Grand Wash Cliffs. According to Lucchitta (1984), the Colorado River was captured by that drainage and incised the Grand Canyon to near present levels by 1.8 my. Although Lucchitta interprets temporary lakes developing along the Colorado drainage in response to tectonic uplifts and volcanic eruptions, their influence on the development of the Little Colorado River and the Bidahochi Formation is not clearly demonstrated.

The cyclic nature of volcanic eruptions (8.6–6, 4.5–4 my) during deposition of the Bidahochi Formation is not unique. In the Lucero area near the southeastern edge of the Colorado Plateau, basaltic eruptions occurred from 8 to 6 my, a similar gap in eruptive cycles occurred from 6.2 to 4.3 my and a renewed cycle (longer in duration than the Hopi Buttes area) has occurred since 4.3 my (Baldridge et al., 1987, 1989). Lucero eruptions also do not have a spatial progression through time. The White Mountains and Springerville volcanic fields to the south have an extended gap, with only one date on basalt between about 8 and 4 my (6.03 ± 0.43 my; Laughlin et al., 1980; cf. Merrill and Péwé, 1977; Laughlin et al., 1979; Condit and Shafiqullah, 1985; Aubele et al., 1986). Springerville basalts continued to erupt well into mid-Quaternary time with no trend in location. In contrast, to the west, the "rim basalts" south of Flagstaff erupted between 8 and 5 my, and the San Francisco volcanic field erupted copiously for the past 5 my (Tanaka et al., 1986; Holm and Ulrich, 1987). The eruptive centers of the San Francisco field have migrated northeast and east more than 50 km during this time. Volume of eruptions has decreased during the past 0.25 my. Each of these volcanic fields has disrupted drainages, produced maars and preserved pond deposits containing aquatic fossils.

This review attempts to shed light on uncertainties in the definition of the Bidahochi Formation: its age, extent, upper and lower boundaries, facies interpretations and depositional cycles. Despite the need for more definitive work on each of these aspects, the context of the Bidahochi Formation in a regional framework has become better understood with the aid of modern chronologic methods and enhanced understanding of Tertiary evolution of the southeastern Colorado Plateau and adjacent areas.

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