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TERTIARY STRATIGRAPHY OF THE NAVAJO COUNTRY[1]

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INTRODUCTION

The Tertiary rocks of northeastern Arizona include two units of late Tertiary age that will be seen during the field conference: the Chuska sandstone of Pliocene(?) age and the Bidahochi formation of Pliocene age. Other Tertiary units border northeastern Arizona, but they are located in areas quite distant from the route of the conference and, as such, are not of particular importance to the present discussion. These units include rocks of possible early Tertiary age, southeast of St. Johns in both Arizona and New Mexico, that may be correlative with the Baca formation of Eocene(?) age; gravel deposits near Fence Lake, New Mexico, of presumed Miocene age; the Datil formation in western New Mexico and adjacent Arizona of possible Miocene age; and gravel deposits along the Mogollon Rim of late Pliocene and/or early Pleistocene age.

Of the two units discussed, the Bidahochi formation can be observed more closely along the route of the field conference; the Chuska sandstone will be seen only from a distance of several miles to the north of the route to Window Rock on the first day of the conference. Because of this, the description of the Chuska sandstone is intentionally brief.

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BASAL UNCONFORMITIES

The Chuska sandstone and the Bidahochi formation were deposited on erosion surfaces that are of distinctly different origin. The surface beneath the Chuska sandstone is essentially planar and it truncates all Laramide structures. As a result, the contact of the Chuska with underlying units is conspicuously angular. The pre-Chuska surface now lies at an elevation of about 8,000 feet.

In contrast with the pre-Chuska surface, the surface beneath the Bidahochi formation is, in part, the dip slope of resistant beds of Mesozoic and Paleozoic age. Thus the topography in the area of the Black Mesa basin at the start of the Pliocene epoch generally reflected Laramide structural relief, and the Bidahochi formation was deposited in an exhumed tectonic basin. Modern elevations on the preserved parts of the surface range from slightly below 6,000 feet to 7,200 feet (fig. 1 and fig. 2).

There are exceptions to the structural control of the pre-Bidahochi surface. Some of these resulted from local truncation of Laramide features by streams conforming to the regional gradient as they carved the pre-Bidahochi surface. Others resulted from the fact that the pre-Chuska surface completely truncated the Defiance upwarp, exposing rocks that range from the DeChelly sandstone of Permian age to the Mesaverde group of Late Cretaceous age. With Miocene uplift, erosion began downcutting from the pre-Chuska surface along these several different resistant units to form the pre-Bidahochi surface and thus the surface is regionally non-conformable.

McCann (1938, p. 171), working on the west side of the Zuni Mountains, named the erosion surface on which the Bidahochi formation was deposited the Zuni surface. Hack (1942, p. 345) called the same surface in the Hopi Buttes area the Hopi Buttes surface in belief that he was applying the name as defined by Gregory (1917, p. 121-122). However, Gregory defined the Hopi Buttes "peneplain" as the erosion surface that underlies the lava of the Hopi Buttes (the volcanic member of the Bidahochi formation) and described it as overlying beds now called the lower member of the Bidahochi, which he referred to the McElmo formation (idem, p. 89), a name since abandoned by the Geological Survey. Thus Gregory's Hopi Buttes surface is in the middle of the formation and not at its base. Because of these facts, the pre-Bidahochi surface is here referred to as the Zuni surface, as was first done by McCann; the name Hopi Buttes surface is here used for the erosion surface beneath the volcanic member of the Bidahochi in the Hopi Buttes area, as was first done by Gregory; and Hack's term "Hopi Buttes surface" is considered both synonymous to the Zuni surface and preoccupied by Gregory's term for the younger surface beneath the lava.

The Zuni surface can be seen at various points along the route of the conference between Lupton and the Petrified Forest National Monument. Over this route it is cut on the Chinle formation of Triassic age. The Zuni surface is also visible at many points between Holbrook and Keams Canyon. Along this route it is cut on units ranging from the Chinle to the Cretaceous Toreva formation. About 2 miles north of Bidahochi Trading Post, excellent exposures can be seen to the east of the road in which the lower member of the Bidahochi formation is separated from the underlying Triassic Wingate sandstone by the Zuni surface and from the overlying volcanic member of the Bidahochi by the Hopi Buttes surface of Gregory (not Hack).

CHUSKA SANDSTONE

The Chuska sandstone occurs almost exclusively in the Chuska Mountains of Arizona and New Mexico (fig. 2). Gregory (1917, p. 80) briefly described and named the unit.

Wright (1954, p. 1831-1833) named the lower, predominantly fluvial, 250 feet of Gregory's type Chuska sandstone the Dezas formation. Although the Dezas formation can be recognized in some exposures throughout the Chuska Mountains, good exposures are not plentiful and for the most part the Deza-Chuska contact, which is gradational, is very difficult to map. Because of this the Deza formation has not been accepted as a map unit by the authors and Gregory's original definition of the Chuska is followed.

Lithology and Distribution

Composition

The Chuska sandstone consists of pinkish-gray and yellowish-gray sandstone that weathers yellowish gray (color terminology from the National Research Council Rock-Color chart). The lower part of the formation, which was called the Deza formation by Wright, contains a considerable amount of silt and clay. Clay beds are most common near the base, although they occur locally throughout the formation.

Two types of sandstone alternate throughout the Chuska. One sandstone type is composed of coarse- to fine-grained, rounded to subrounded, clear and stained quartz with prominent black, white, and red accessory grains that

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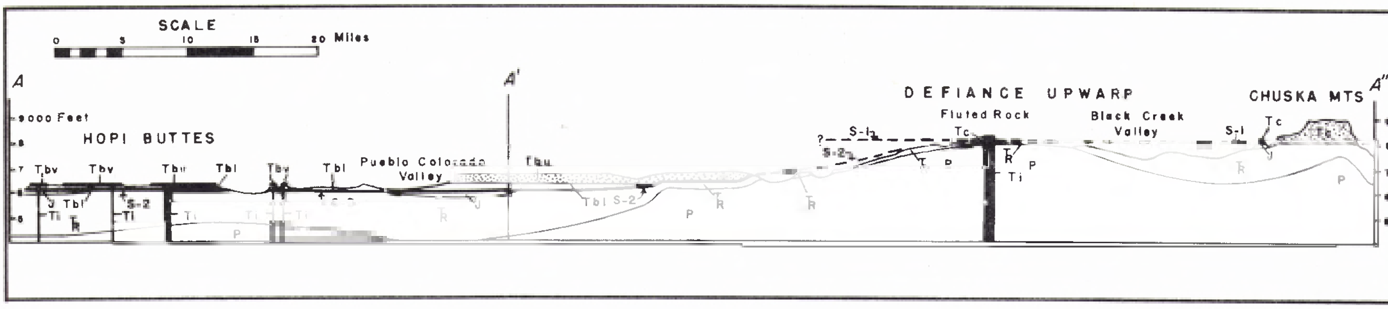

FIGURE 1. Diagrammatic cross section A-A'-A'' from the Chuska Mountains to the Hopi Buttes showing: the Chuska sandstone (Tc); the lower (Tbl), volcanic (Tbv), and upper (Tbu) members of the Bidahochi formation; Tertiary intrusive rocks (Ti); and the pre-Chuska (S-1) and Zuni (S-2) surfaces and their relation to generalized Laramide structure. Jurassic (J), Triassic (T), and Permian (P) beds are generalized. Vertical exaggeration X 10.

average, respectively, about 4, 3, and 2 percent of the total volume by megascopic estimate. This sandstone is usually firmly cemented with calcareous cement and generally forms ledges; in some places opal and chalcedony are also cementing agents (Wright, 1951).

The second sandstone type is finer grained, loosely cemented, and forms slopes which are generally covered by float from the overlying ledge-forming sandstone. Some of these units have no appreciable cement. This sandstone type contains fine- to very fine grained sand and is most abundant in the lower part of the Chuska where it is interbedded with many siltstone units and a few bentonitic clay and white ash beds. The ash beds are similar to, although less common than, those found in the Bidahochi formation. Some of the ash beds contain glass shards.

Depositional features

The Chuska sandstone is predominantly crossbedded, although the finer-grained units are parallel and very thinly bedded; the bentonitic ash beds are usually structureless. Crossbedding consists of two types, which are interpreted as being both eolian and fluvial in origin. That considered eolian is in beds 4 to 20 feet thick and is of the trough type in which each crossbedded set has a curved surface of erosion as its lower boundary. The eolian type has crossbeds, usually over 20 feet long, which were deposited on fore-set slope of 20 to 30 degrees. This type of crossbedding shows markedly greater consistency in dip direction than does the fluvial type; most of the dips observed fall within a 45-degree arc between east and northeast, indicating winds from the west and southwest. Wright (1956, fig. 2) obtained fairly similar results in his study of the crossbedding, with winds indicated from the southwest to south-southwest.

Fluvial crossbedding occurs in beds from 2 to 4 feet thick that are made up of more poorly sorted sandstone which contains a higher percentage of silt-sized particles. These units are usually interbedded with parallel-bedded siltstone or claystone. The crossbedding is either trough or planar-tabular type (having planar and essentially parallel erosional surfaces directly above and below the sets of crossbeds) with crossbeds as much as 20 feet long, but usually from 2 to 5 feet long. This type was deposited on foreset slopes of up to 20 degrees, but averaging about 10 degrees. Although the fluvial crossbedding shows much less consistency in dip direction than the eolian crossbedding the most significant difference is that most crossbeds are oriented in a 90-degree arc between southwest and southeast, indicating southerly flowing streams.

Sandstone units of the fluvial type, as well as silt and clay units, are concentrated in the lower part of the Chuska sandstone; the upper part of the Chuska is interpreted as being predominantly eolian.

Thickness and distribution

The Chuska sandstone caps the Chuska Mountains and forms the bulk of the mountains above the 8,000-foot topographic contour. Except for local lava flows, the Chuska is the youngest unit in the Chuska Mountains and its thickness is variable because of recent erosion. Gregory (1917, p. 80) reported 700 feet of Chuska in the type area at the south end of the range. The thickness is greater northward—1,277 feet was measured in the central part of the range and a maximum thickness of about 1,800 feet is indicated near the northern end. Throughout the area the lower predominantly fluvial part of the formation is approximately 250 feet thick and the northward increase in thickness occurs only in the upper, predominantly eolian part of the formation.

A few erosional remnants west of the Chuska Mountains indicate that the Chuska sandstone was once deposited across the northern part of the Defiance upwarp and to the west as far as the central part of the Chinle Valley near the northern end of the Defiance upwarp.

Age of the Chuska Sandstone

Hack (1942, p. 350) tentatively correlated the Chuska with the Bidahochi formation and Williams (1936, p. 148) correlated the volcanic member of the Bidahochi with the volcanic rocks that intrude and overlie the Chuska sandstone. Repenning and Irwin (1954) accepted and elaborated these correlations to the extent of tentatively correlating the Chuska sandstone with the lower member of the Bidahochi. Although this correlation seems within reason in the light of present information, the reasoning used to defend it is, in some respects, in error. Some of these errors have been pointed out by Wright (1956, p. 429). The formation is currently assigned a Pliocene(?) age by the U. S. Geological Survey and this age is accepted by the authors as being reasonable until more convincing evidence becomes available.

BIDAHOCHI FORMATION

The Pliocene Bidahochi formation lies in the upper part of the valley of the Little Colorado River, mainly in northeastern Arizona but extending into New Mexico a short distance west and southwest of the Zuni Mountains. The formation was named by A. B. Reagan (1924 and 1932).

The Bidahochi formation comprises fluvial and lacustrine sedimentary rocks and basaltic volcanic rocks. It has been subdivided into three members (Repenning and Irwin, 1954): a predominantly lacustrine lower member, a medial volcanic member, and a chiefly fluvial upper member. The lower and upper members are present throughout most of the area occupied by the formation, but the volcanic member is considerably less widespread (fig. 2).

Lower Member

Lithology and depositional features

The lower member is composed almost entirely of banded gray, brown, and pink mudstones and argillaceous fine-grained sandstone. The member contain a few beds of white rhyolitic shards which have been altered to high-grade bleaching clay along the southwestern flank and southern nose of the Defiance upwarp. The lithology is uniform except in the valley of Rio Puerco, where the beds become increasingly sandy and interfinger eastward with deltaic and fluvial sands. Easternmost exposures of the lower member, near Sanders, app to be entirely fluvial. In this same area a basal conglomerate locally overlies the Zuni surface and contains quartzite pebbles with diameters up to 2 inches and boulders of scoriaceous basalt with diameters up to one foot. These basalt boulders would appear to have come from the northeast. Basalt is not present in the basal conglomerate farther west.

Mudstone and sandstone beds alternate throughout the lower member. Although the shaly slopes of the member would suggest otherwise, sandstone is the predominant lithology. The sandstone is of fairly uniform color, ranging from a predominant grayish orange-pink to grayish brown. It is composed of fine- to very fine-grained subrounded to subangular moderately well sorted clear and encrusted quartz grains with prominent red and black accessory grains similar to those in the Chuska sandstone. Although sandstone units predominate, argillaceous material is abundant in most of these beds so that the overall grain size of the lower member is in the silt-size range, averaging 0.049 mm. The lower member is better sorted than the upper member or the Chuska sandstone. Argillaceous material combines with calcareous minerals to cement the sandstone units so that the average content of soluble minerals is considerably less than that of the upper member and slightly less than in the Chuska. The sandstone units weather into smooth shaly slopes, in most places topographically indistinguishable from the mudstone units.

Grain size, sorting, depositional structures, and penecontemporaneous deformation of the lacustrine sediments of the lower member indicate that at least three distinct environments existed in the lake. These were in the marginal zone of wave-working, on the sloping sides of the lake floor below wave base, and on the bottom of the lake floor where undisturbed deposition took place. Sandstone units that are attributed to deposition on the sloping lake floor are thin bedded and in many places individual beds within the units were crinkled prior to consolidation. Near the eastern margins of deposition this deformation is greater and involves entire units so that contorted beds sweep from the base to the top of units and are repeatedly overturned. These contortions are not reflected in underlying mudstone units and contacts between individual sandstone and underlying mudstone units within the lower member are always sharp and even. However, in places where mudstone units overlie contorted sandstone the contact, although sharp, is uneven and reflects the disturbed nature of the underlying sandstone. Where the contorted sandstone is overlain by another sandstone unit, the underlying slumped beds are beveled and the contact is even as well

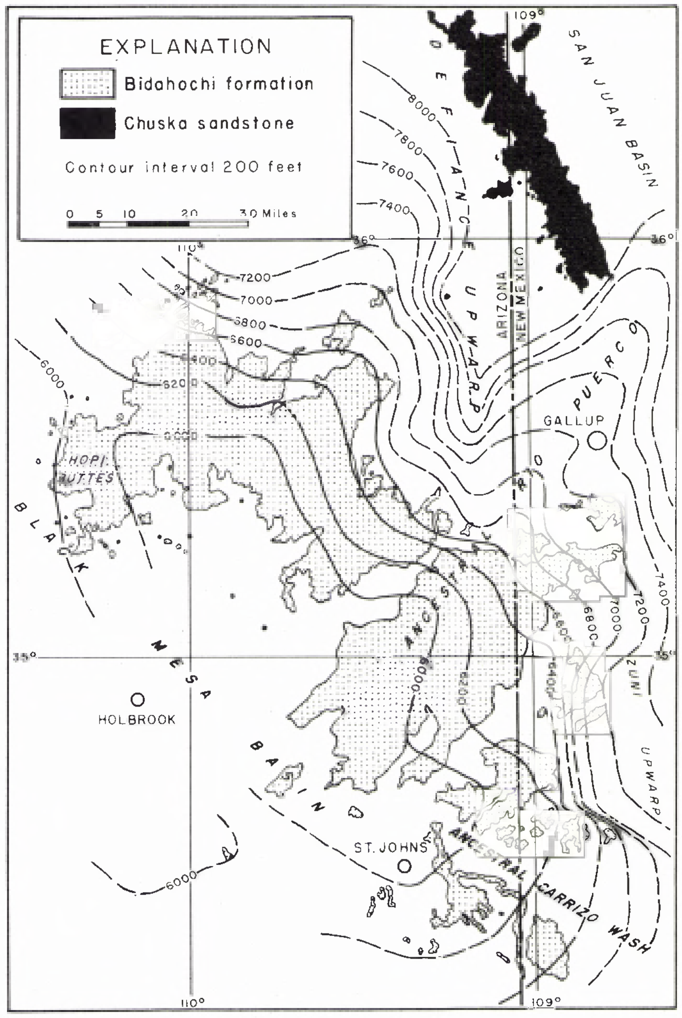

FIGURE 2. Present configuration of the Zuni surface in the Black Mesa basin-Defiance upwarp area and the distribution of the Bidahochi and Chuska formations. Contours show modern altitude above sea level and only relative Pliocene altitude. Not corrected for post-Bidahochi deformation and also showing the effect of middle Pliocene uplift in the Hopi Buttes area. Modified in part from McCann (1938) and Hack (1942).

as sharp. Deformation of the bedding is attributed to down-slope sliding of sediments near the margin of the lake floor.

The mudstone units in the lower member of the Bidahochi range from silty claystone to sandy mudstone and are of various colors including dark reddish brown, light greenish gray, yellowish gray, and pale yellowish brown. Some mudstone units contain small nodules and nodular stringers of limestone. Most are extremely flat and thinly laminated. These features all suggest bottom deposition, a facies more central and deeper in the lacustrine basin than the contorted sandstone units.

In much of the area, rocks deposited in the zone of wave working are not recognized in the lower member of the Bidahochi but are present in the lower part of the upper member, the zone of transition from lacustrine deposition to fluvial deposition. However, some wave-worked sandstone deposits are recognized within the lower member in small areas along the eastern margins of deposition. They are characterized by better sorting, due to the partial winnowing out of finer grained materials by wave churning, and by ubiquitous crossbedding. These sandstone units are not contorted by sliding. This marginal lake facies is not present in westernmost exposures of the lower member where contorted slope-deposited sandstone units are few.

The lack of marginal facies in western outcrops of the lower member appears contradictory to the westward thinning of the lower member, which suggests that the western edge of deposition was near the west side of the Hopi Buttes. However, this thinning was due not to proximity to the western shore, but to uplift and erosion of the lower member in the Hopi Buttes area near the end of lake deposition and immediately prior to the eruption of the volcanic member of the Bidahochi in middle Pliocene time. This erosion of the lower member produced the Hopi Buttes surface of Gregory (not Hack) upon which the volcanic member lies. Because uplift was restricted to the area of eruption, the erosion that formed the Hopi Buttes surface did not take place in areas to the east, and lacustrine deposition continued there without interruption into late middle Pliocene time, after volcanic activity in the Hopi Buttes had come to an end. The effect of this uplift on the Zuni surface beneath the Bidahochi in the Hopi Buttes area can be seen in the configuration of the 6,000-foot contour in figure 2.

Thus, the westward thinning of the lower member of the Bidahochi formation in the Hopi Buttes area is due to middle Pliocene erosion and the western limit of deposition was an unknown distance farther west. Because the Bidahochi depositional basin is an exhumed structural basin and is outlined by Laramide structural highs, the lower member may have extended to the Kaibab upwarp 80 miles farther west than present outcrops.

Eastern fluvial facies

Along its eastern and northeastern margins, the lower member of the Bidahochi is covered by the upper member. However, the Rio Puerco cuts through the formation and excellent exposures in its valley show a gradation of the lacustrine facies of the lower member eastward into crossbedded tan sandstone. This crossbedded sandstone seems to represent both the marginal lacustrine wave-worked deposits and fluvial sands of deltaic origin, but the two types are difficult to distinguish where interbedded. In gross aspect the fluvial sandstone units appear to be more lenticular and more intimately associated with differing lithologies, such as flat-bedded silty sandstones presumably of flood plain origin; the near-shore wave-worked sandstone units occur in more extensive blanket-like deposits.

The transition of the entire lower member from the lacustrine facies into the tan sandstone facies takes place within about 10 miles, suggesting a relatively stable shoreline during the deposition of the lower member. At Chambers only a few feet of presumably lacustrine green claystone and brown mudstone are present in the upper part of the lower member. The remainder of the unit here consists of tan, in part silty, flatbedded and crossbedded sandstone, believed to be entirely fluvial except for a prominent crossbedded sandstone in the middle which may represent a nearshore wave-worked deposit. The lower member also thins eastward and is only about 50 feet thick north of Chambers, near the old clay mine which will be visited during the conference. The clay mined at Chambers is believed to be very near the top of the lower member, but the boundary is questionable because the volcanic member is absent and the upper and lower members are very similar. In this area the distinction between the fluvial sandstones of the upper member and lower members is based upon the common occurrence of gravel lenses in the upper member.

The fluvial sandstone deposits in the lower member of the Bidahochi in the valley of Rio Puerco are not known from other areas of marginal deposition, although crossbedded lacustrine sandstone units are more extensive along the eastern margins of deposition. It appears, therefore, that a major river flowed from the northeast across the structural saddle between the Defiance and Zuni upwarps and around the southern nose of the Defiance upwarp into the Bidahochi lake basin (fig. 2). This river is further indicated by compositional facies of the upper member. Another major stream southwest of the Zuni Mountains is also indicated in these younger beds, although its presence has not been detected in the lower member perhaps because of incomplete field work. These streams are discussed further in considering the facies of the upper member.

Tuff and bentonite beds

The beds of white tuff interbedded with the sediments of the lower member of the Bidahochi are composed of very fine-grained glass shards. Where deposited in quiet water, they are almost devoid of foreign material. Similar tuff beds occur in the fluvial sands of the upper member, but these are mixed with sand in many places and the shards are somewhat abraded so that they cannot be seen with a hand lens. In general, tuff beds in the upper member are relatively thicker and more lenticular. Where tuff beds are intercalated with contorted sandstone beds of the lower member, they show very thin laminations. Where disturbed, no bedding is observable in the tuff. These tuff beds are similar to the less abundant tuffs in the lower part of the Chuska sandstone.

Bentonite beds (altered tuff) are found near the edge of the basin of deposition of the lower member along the southwestern flank and southern nose of the Defiance upwarp. Restriction of the bentonite beds to the fluvial facies of the lower member and to a structural bench (fig. 1, center) exhumed by the erosion that formed the Zuni surface, suggest that alteration of tuff to bentonite occurred only in a limited environment. The bench bordered the lake in which the lower member was deposited, and was transgressed by the lake only a few times. Thus tuff, deposited simultaneously in the lake and on the bench, was relatively rapidly and deeply buried in the lake but was either exposed or covered by the thick fluvial sequence of the upper member. This prolonged exposure, or shallow burial, may have brought about the alteration to bentonite. The tuff beds in the overlying upper member are unaltered. The relation of the clay beds to the lower member and to the structure of the Defiance upwarp has been discussed by Repenning (in Kiersch and Keller, 1955, p. 477-478 and fig. 3).

Thickness and distribution

The greatest known thickness of the lower member of the Bidahochi formation is 214 feet. This thickness was measured in the southern part of Pueblo Colorado Wash, an area about central to outcrops of the lower member. The member thins westward because of deeper erosion at the base of the volcanic member and is absent beneath its westernmost exposures. North, east, and southeast of Pueblo Colorado Wash the lower member thins against the

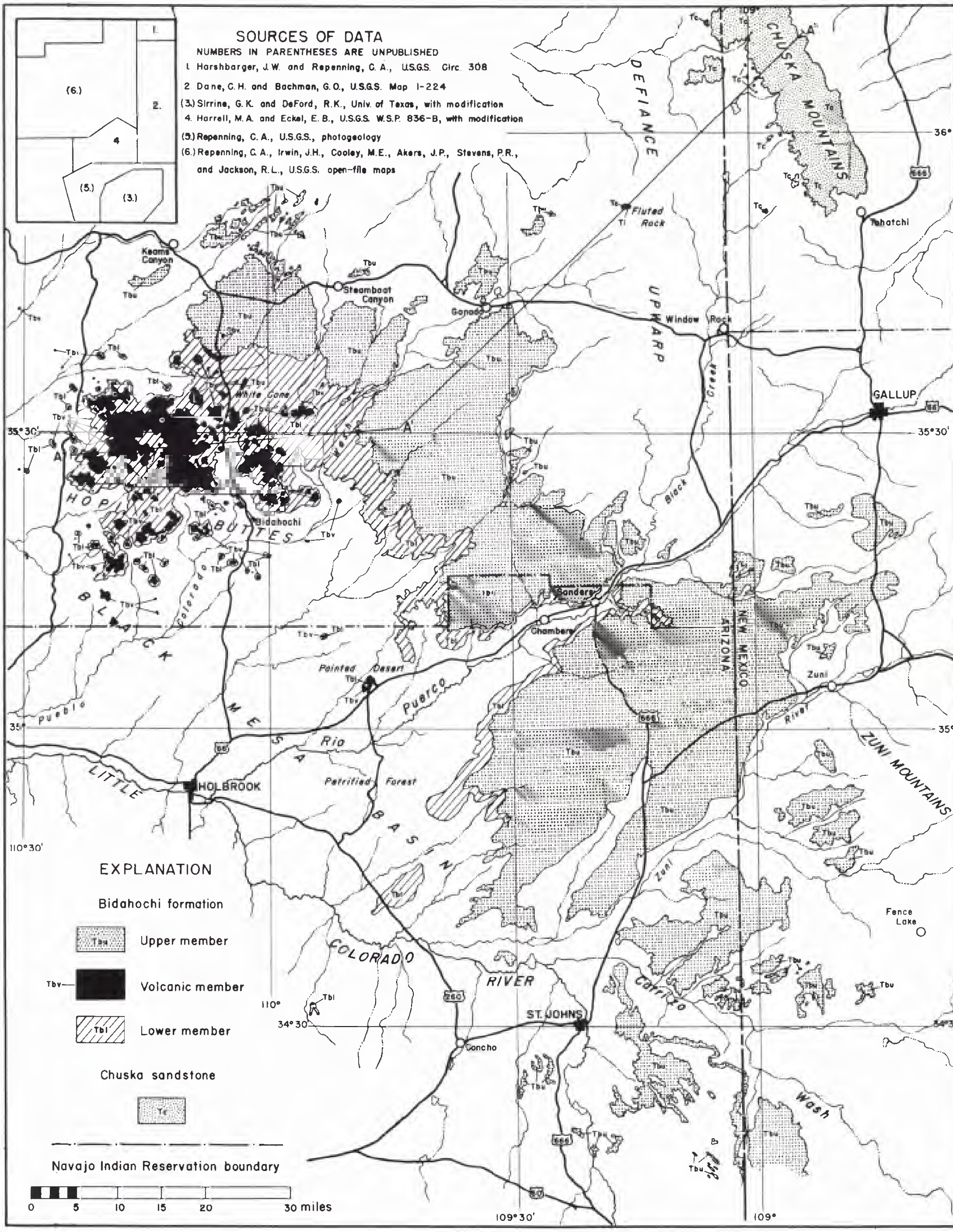

FIGURE 3. Distribution of the Chuska sandstone and the Bidahochi formation.

eastern margin of the basin.

Along the northern and northeastern margins of the basin little of the lower member is covered by the upper member (fig. 2). However, along the southern nose of the Defiance upwarp relatively extensive outcrops of the member are underlain by the lower member, which extends up the Rio Puerco valley as far as Sanders. To the southeast of the Pueblo Colorado Wash area, the lower member crops out along the south side of the Rio Puerco valley and southward into the Little Colorado River valley. The lower member is not known to extend eastward up the Little Colorado and its tributaries, but the authors have not tried to map this area and quite possibly a sandy facies, like that near Sanders, is present. An isolated outcrop about 30 miles west of St. Johns and another at Painted Desert Lookout northeast of Holbrook show part of the former distribution across the southeast-trending axis of the Black Mesa basin.

Age of the lower member

Six and a half miles east of Sanders, on the south side of the Rio Puerco, a vertebrate fauna was found beneath a clay bed of the lower member. The fauna consisted of many pronghorn "antelope," a large and a small camel, a mastodontid, and a fox. The indicated age is early Pliocene, or possibly late Miocene (Lance, 1954). The faunal horizon is a few feet above the base of the lower member so presumably earliest Bidahochi deposition is represented. However, these deposits on the topographic bench most distant from normal lake beds cannot be correlated with any specific part of them so that the basal beds of the lower member farther west may be older than the vertebrate fauna.

A late middle Pliocene vertebrate fauna from the lower part of the upper member on White Cone (fig. 4) is a composite collection from several beds within a 130-foot sequence. The lowest fossil-bearing zone of this sequence is 35 feet stratigraphically above the top of the lower member and 138 feet below the top of the fossiliferous sequence. The Hopi Buttes surface separates the lower and volcanic members at White Cone, but is not prominent and does not appear to require many missing strata because it seems to be absent a short distance farther east. Thus, the lower member of the Bidahochi may include middle Pliocene beds as well as some definitely early Pliocene, and possibly some late Miocene beds.

Volcanic Member

Basaltic rocks were extruded in the Hopi Buttes area shortly before lake deposition came to an end. Lava flows, and detritus from them constituting the volcanic member of the Bidahochi formation, covered a considerable area centered around the Hopi Buttes. Lavas are largely confined to the Hopi Buttes area and the volcanic member is represented nearby by volcanic conglomerate. Williams (1936) describes the volcanic rocks and Hack (1942) describes the various structural features related to them.

Basalt and basaltic lapilli-tuff both intrusive and extrusive make up most of the member. Reworked lapilli-tuff, volcanic conglomerate, and interbedded travertine are also included in the member. Although variable, the detrital part of the volcanic member consists of a poorly sorted mixture of basaltic rocks. It is a moderate olive-brown conglomerate with a matrix of coarse- to fine-grained sandstone that holds subangular to angular fragments 2 to 10 mm in diameter of tuff, basalt, and abraded augite crystals. The bedding is usually thin and parallel but locally cross-

FIGURE 4. White Cone, on the northeast side of the Hopi Buttes. Lower member of the Bidahochi formation in the foreground, volcanic member forming the thin dark ledge in the center, and the upper member forming White Cone. Late middle Pliocene fossils have been found between horizons A and B.

bedded. The member forms a blocky ledge. Within the Hopi Buttes area the flows are locally as much as 50 feet thick but are extremely variable; elsewhere the member is from 2 to 5 feet thick. Several interesting extrusive, intrusive, and collapse features of the volcanic member can be seen along the route of the conference through the Hopi Buttes.

Upper Member

Lithology and depositional features

The predominantly fluvial upper member of the Bidahochi formation is composed almost entirely of sandstone and a few beds of white rhyolitic ash. This member weathers into ledges alternating with steep, very light gray slopes. It is the most extensive member of the formation and is present also outside the Navajo Indian Reservation along the west and southwest sides of the Zuni Mountains in Arizona and New Mexico (fig. 2). There are no measurable exposures of the entire thickness of the upper member in the Navajo Reservation; however, water wells along the southwest flank of the Defiance upwarp have penetrated as much as 450 feet of the unit.

In general the upper member consists of an alternation of two types of sandstone. One is medium to fine grained and argillaceous, and forms slopes; the other is coarse to fine grained, free of clay, and forms ledges. The sandstone is yellowish gray, varying to light greenish gray with an increase in clay. Both types are composed of poorly sorted, subangular, clear and colored quartz grains with black accessory minerals. Mud pellets are locally common, concentrated in the lower part of individual strata. Cementation by calcite varies from firm to almost none, as reflected in the ledge and slope topography of outcrops.

Carbonate content of the upper member averages about 10 times greater than in the lower member. The average median diameter is in the fine sand size range. The upper member is more poorly sorted than the lower, and in sorting resembles the Chuska sandstone. Crossbedding is of the trough type, with crossbeds between one and ten feet long deposited on 5- to 15-degree slopes. Ripple marks, invertebrate tracks, and root encrustations are common in the more firmly cemented units, but are not recognizable in the loosely cemented units. Parallel-bedded units are present throughout and are prominent in the basal part. Most of the parallel-bedded units are lenticular, suggesting small ponds or floor plains, and are very thinly bedded to laminated.

In the area of predominantly lacustrine deposits of the lower member, the upper member also contains lake beds at the base, interbedded with fluvial and perhaps lagoonal deposits. This zone of transition from lacustrine to fluvial deposition is as much as 130 feet thick at White Cone (fig. 3), and is separated from the lower member by the volcanic member. The White Cone fauna of the upper member occurs throughout this transition zone and thus closely dates the culmination of lacustrine deposition as late middle Pliocene.

Facies of the upper member

Three distinct lateral facies of the upper member are evident in different areas. These were separated by two major stream courses which prevented intermixing of materials on opposite sides of the drainage basins. The most prominent stream course was near that of the Rio Puerco, and is indicated by the eastern fluvial facies of the lower member in the Sanders area and in the topography of the Zuni surface (fig. 3). This stream originated northeast of the Black Mesa basin and flowed to the basin around the southern nose of the Defiance upwarp.

The other main-stream course that formed a sediment barrier in the upper member of the Bidahochi is now approximately occupied by Carrizo Wash and originated southeast of the Black Mesa basin, entering the basin approximately down its axis. It is not known if streams followed this course during deposition of the lower member, but its position is also in evidence in the topography of the Zuni surface (fig. 3).

North and northwest of the ancestral Rio Puerco the upper member of the Bidahochi is characterized by detritus from two main sources. The most prominent was probably the Chuska sandstone to the northeast but may have been the source from which the Chuska itself was derived. The second source was the Cretaceous sandstone to the north, in what is now Black Mesa, and to the east. The upper member of the Bidahochi in this area has a whitish cast, like the Chuska sandstone, because of its source.

South of the ancestral Rio Puerco and north of Carrizo Wash the upper member was derived mainly from Cretaceous rocks of the Zuni upwarp. It also contains granitic debris distinctive to this facies and attesting the exposure of the basement core of the Zuni upwarp in middle to late Pliocene time. Most striking in this facies is the absence of Chuska-type material. Thus the brown cast of the Cretaceous source rock is the prominent color of this facies of the upper member.

South of the ancestral Carrizo Wash the third facies of the upper member of the Bidahochi contains considerably less material from Cretaceous sandstone and so is white, like the facies north of the ancestral Rio Puerco. However, in this southeastern area the member contains considerable rhyolitic debris derived from the Datil formation farther to the south and southeast in west-central New Mexico and adjacent Arizona.

Age of the upper member

The vertebrate fauna on White Cone (Stirton, 1936, and Lance, 1954) indicates a late middle Pliocene age for this part of the section and consists of beaver, horned beaver, rabbit, wolverine, camel, large cat, and a marten-like animal. Reptiles, amphibians, birds, and fish are also represented. Associated with the vertebrates are invertebrates (Taylor, 1957), plants, and pollen.

A few other fossil localities are known in the upper member, one of which contains a few fragments of camel which suggest a late Pliocene age for parts of the upper member. Along the west flank of the Defiance and Zuni upwarps and north of White Cone the upper member of the Bidahochi is overlain by middle Pleistocene and later sandy soil and dunes. In places the contact between the Bidahochi and these younger units is not recognizable and possibly deposition was more or less continuous from Bidahochi time into the middle Pleistocene. This is particularly possible in the areas west of the Zuni Mountains and south of St. Johns where as much as 100 feet of sediment overlies strata that appear to be correlative to the youngest Bidahochi north of Rio Puerco.

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