Stratigraphy of the Morrison Formation and Structure of the Ambrosia Lake District, New Mexico

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By ELMER S. SANTOS

CONTRIBUTIONS TO ECONOMIC GEOLOGY

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Ore-bearing strata and tectonic features in a major uranium-mining district in northwestern New Mexico

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By Elmer S. Santos

ABSTRACT

In the Ambrosia Lake district, McKinley and Valencia Counties, northwestern New Mexico, the Morrison Formation of Late Jurassic age is divided into three formal members; the Recapture Member at the base is overlain successively by the Westwater Canyon and Brushy Basin Members.

The Recapture Member, 125–245 feet thick, is composed of clayey sandstone, sandstone, claystone, and siltstone. The Westwater Canyon Member, 30–270 feet thick, is mainly a crossbedded fluvial arkosic sandstone interstratified with mudstone. A unit at the top of the member is locally referred to as the Poison Canyon sandstone, an informal name of economic usage. The Brushy Basin Member, 60–200 feet thick, consists of pale-grayish-green mudstone with scattered lenses of sandstone rarely more than 25 feet thick.

The Ambrosia Lake district occupies the most folded and faulted part of the homoclinal south flank of the San Juan Basin. Major structural elements in the region are believed to be related to the uplift of the Zuni Mountains, which is inferred to have taken place between early Eocene and late Pliocene time. This period of deformation was characterized by horizontal compressive forces and the development of folds and strike-slip faults. Uplift of the Colorado Plateau during middle and late Tertiary, and possibly Quaternary, time was probably accompanied by east-west-directed tension which produced north- and northwest-trending normal faults and joints.

INTRODUCTION

The Ambrosia Lake district in McKinley and Valencia Counties in northwestern New Mexico (fig. 1) contains many large uranium ore deposits and is one of the principal producers of this metal in the United States.

The stratigraphy of the ore-bearing and related sedimentary rocks, the structure of the district and adjacent areas, and the mineralogy and geochemistry of the uranium ore deposits are being studied in an attempt to determine what factors control the location of the district and of the individual ore deposits in it.

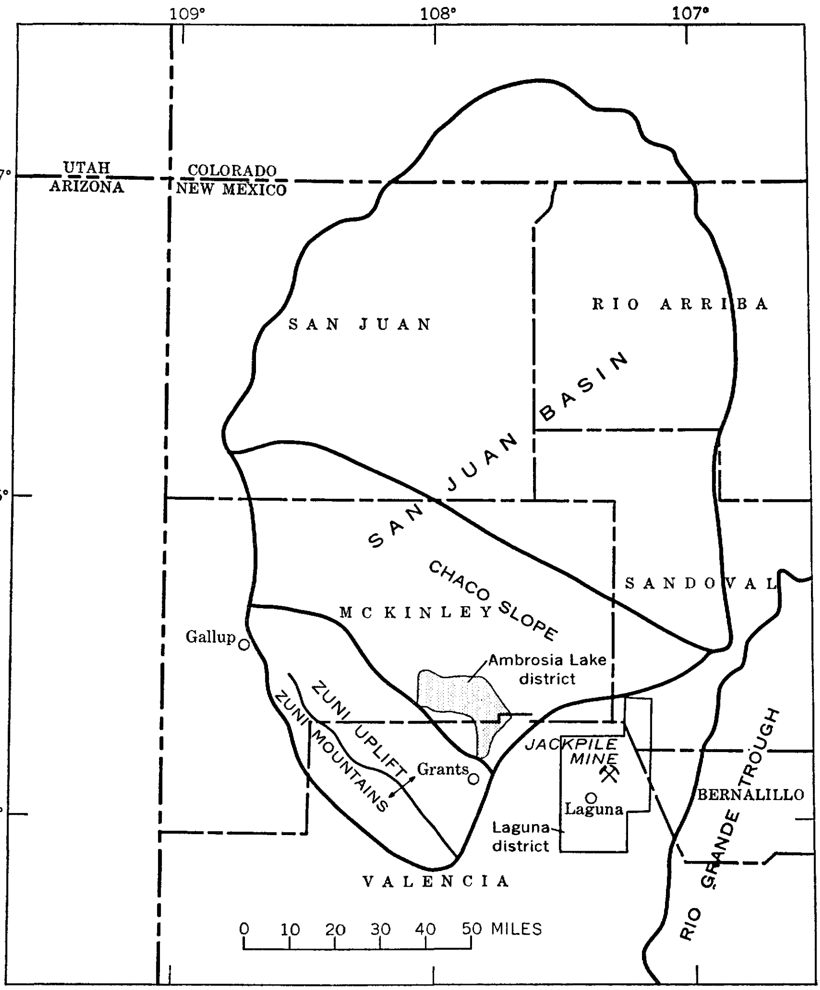


FIGURE 1.—Location of the Ambrosia Lake district, northwestern New Mexico.

This report describes the structure of the Ambrosia Lake district and the Morrison Formation, which contains most of the large uranium ore deposits. The uranium ore deposits and their relationship to structure and stratigraphy are not described.

The data presented in this report were accumulated from geologic mapping of the surface, from underground mine mapping, and from drill-hole logs furnished by the several mine operators in the district.

Data from logs of more than 6,000 drill holes were used to construct the structure-contour map (pl. 1). These include drillers' logs, lithologic logs, and geophysical logs. Data from selected logs were also used to make the isopach and lithofacies map (pl. 1) and the cross sections (pl. 1 and figs. 2, 3). The accuracy of the illustrations varies according to the type of log used, the spacing of drill holes, and the accuracy with which the location of the holes was determined.

Drillers' logs are brief descriptions, made by the drill operator, of rock type, and sometimes of color, in successive short intervals of depth, generally 5 or 10 feet. Lithologic logs are detailed descriptions of cuttings or core made by a geologist.

Geophysical logs were found to contain the most reliable information, so the data from drillers' logs and lithologic logs were used only in areas where geophysical data were lacking. Geophysical logs are of three types: (1) gamma ray, (2) combined gamma ray and electrical resistivity, and (3) combined gamma ray, electrical resistivity, and self-potential.

Gamma-ray logs are the only record made of many holes, especially those drilled in the early days of exploration in the district. The top and bottom of the Dakota Sandstone show up well on most of these logs, but the details of lithology within the Morrison Formation cannot be distinguished. Where possible, therefore, combined gamma-ray and electrical logs were used for this study because changes in lithology show clearly on them; also, the depths to formation and member contacts, and to mudstone and sandstone lenses within the several units can be measured with confidence.

In general, the data are most accurate over the ore deposits and least accurate at the margins of the district. Drill holes are 200 feet or less apart over ore bodies and as much as 1 mile apart away from ore bodies. The position and collar elevation of some drill holes that were not surveyed were picked from topographic maps at a scale of 1:24,000 and a contour interval of 20 feet. Where collar elevations were picked from maps, errors are greatest in areas of steep terrain. Drifting of holes, as much as 200 feet at a depth of 1,000 feet, also contributes to inaccuracies of some of the data.

The top of the Dakota Sandstone shows up conspicuously on virtually all the electric and gamma-ray logs. This horizon, because it probably marks a paleotopographic surface with little structural or erosional relief, was chosen as the structure-contour datum. The base of the Westwater Canyon Member of the Morrison Formation is indicated by an abrupt change in lithology on many logs. The logs of holes in some areas, however, show several subtle changes in lithology, any of which could mark the base. The thickness of the member is thus confidently determined in some areas, whereas in others the indicated thicknesses are based on the author's best guess among several possible choices.

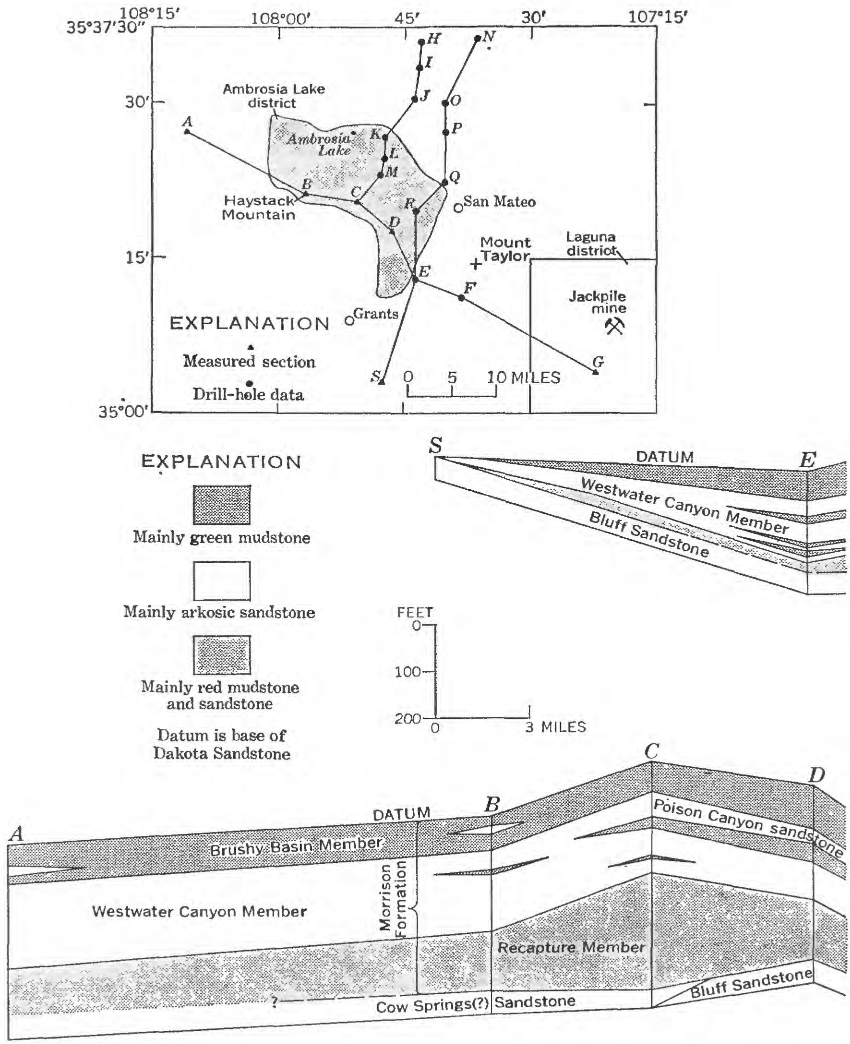
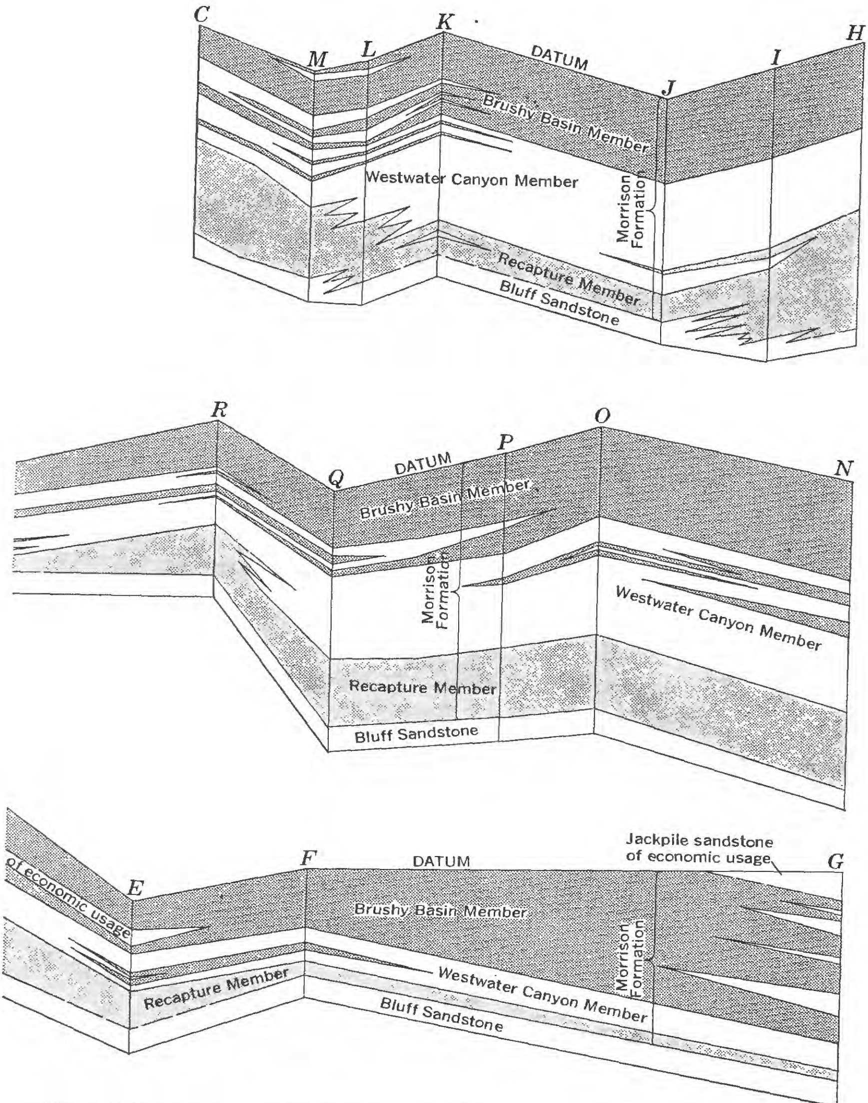


Figure 2.—Cross sections of the Morrison Formation through the Ambrosia Lake (Craig, 1959) ; *B*, *C*, *D*, and *S* measured by R. E. Thaden (unpub. data) ; *G* Hilpert, 1956, p. 320) ; *E*, *F*, and *H–R* from drill-hole data.



district and adjacent areas. *A* measured by L. C. Craig and V. L. Freeman measured by L. C. Craig, V. L. Freeman, and T. E. Mullens (Freeman and

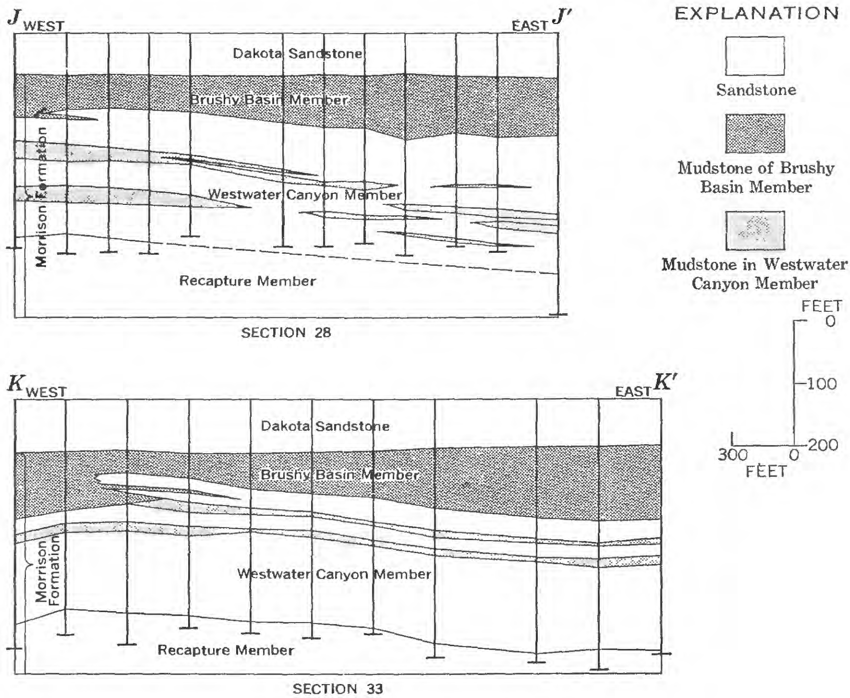


FIGURE 3.—Cross sections through parts of secs. 28 and 33, T. 14 N., R. 9 W. Lines of sections are shown on plate 1.

The extent of mineralized ground indicated on the cross sections does not conform to that shown in plan on the structure-contour map. The map shows only ore-grade material, whereas the cross sections include both ore- and subore-grade material. In addition, some of the information used to construct the cross sections is from logs of holes which are projected to the line of section. Some of these holes are barren but are projected to the line of section where it crosses ore; others contain subore-grade mineralization and are projected to the line of section where no ore is shown.

ACKNOWLEDGMENTS

The author is grateful to the officials of the companies mining in the Ambrosia Lake district for permission to examine company drill-hole logs and to map various mines. Discussions with geologists employed by the several mining companies and by the U.S. Atomic Energy Commission were particularly helpful. The author also thanks H. C. Granger, U.S. Geological Survey, who helped in the acquisition and interpretation of much of the information and who discussed many of the problems with him. The courtesies extended by E. W. Grutt, Jr., and other members of the Grants, N. Mex., Branch Office of the U.S. Atomic Energy Commission are gratefully acknowledged.

MORRISON FORMATION

The Morrison Formation of Late Jurassic age is divided into three members in the Ambrosia Lake district; the Recapture Member at the base is overlain by the Westwater Canyon Member, which in turn is overlain by the Brushy Basin Member. The formation is underlain by the Bluff Sandstone of Late Jurassic age and overlain by the Dakota Sandstone of Early(?) and Late Cretaceous age. Figure 2 shows three cross sections illustrating the character of the several units in and adjacent to the Ambrosia Lake district. The three members are described here with emphasis on the Westwater Canyon Member, in which most of the large uranium ore deposits occur.

PREVIOUS STRATIGRAPHIC WORK

The Morrison Formation was named by Eldridge (Emmons and others, 1896, p. 60) for strata at the type locality near Morrison, Colo., but the name first appeared in print in a description of the formation in the Pikes Peak quadrangle (Cross, 1894). The type section was redefined by Lee (1920, p. 183; 1927, p. 28) and by Waldschmidt and Leroy (1944, p. 1100). Gregory (1938, p. 58) recognized four members of the Morrison Formation in southeastern Utah, three of which—the Recapture, Westwater Canyon, and Brushy Basin—were found by Rapaport, Hadfield, and Olson (1952, p. 30) to extend into and beyond the Ambrosia Lake district southward.

Before the extension of members of the Morrison Formation into New Mexico, strata of Jurassic age in the Laguna district were informally subdivided (Kelley and Wood, 1946). In ascending order, the informal names used were the buff shale, the brown-buff sandstone, the white sandstone, and the variegated shale. L. C. Craig (written commun., 1956) considered the buff shale to be an equivalent of the Summerville Formation, the brown-buff and white sandstones to be equivalents of the Bluff Sandstone, and the variegated shale to be an equivalent of the Recapture, Westwater Canyon, and Brushy Basin Members of the Morrison.

A partly new set of names for members of the Morrison Formation in northwestern New Mexico was proposed by Smith (1951; 1954, p. 15). In an area near Thoreau, N. Mex., he divided the Morrison Formation into (1) the Chavez Member at the base, which he stated might be equivalent to the Recapture Member; (2) an overlying Prewitt Sandstone Member, equivalent to the Westwater Canyon Member; and (3) the Brushy Basin Member at the top. This nomenclature has not been adopted by the mining companies nor by others working in the region.

Two units within the Morrison Formation, because of their economic potential, have been given informal names that are widely used locally by the mining companies. The large uranium deposits in the Laguna area occur in a sandstone at the top of the Brushy Basin Member. This sandstone is known locally as the Jackpile sandstone, named after the Jackpile mine (fig. 1). Mention is made of this unit in a number of early reports, but the most comprehensive description is given by Schlee and Moench (1961, p. 134–150).

The first ore body to be discovered in the Morrison Formation in the Ambrosia Lake district is in a sandstone unit at the top of the Westwater Canyon Member. This sandstone unit is known locally as the Poison Canyon sandstone and was named after the Poison Canyon mine. The unit is briefly mentioned in several early reports, and a description of it is given below.

RECAPTURE MEMBER

The Recapture Member forms the lowest part of the Morrison Formation over a part of northeastern Arizona and northwestern New Mexico (Craig and others, 1955, p. 139). It attains its maximum thickness of 680 feet in northeastern Arizona. It thins, intertongues, and grades into the upper part of the Salt Wash Member to the north, and is recognized as far as Monticello, in southeastern Utah. To the southeast, the member thins and pinches out a few miles south of Gallup and about 7 miles southeast of Grants (fig. 2). In the Laguna district it is generally 50 feet thick. Locally, the Recapture is absent where the overlying Westwater Canyon Member has filled channels scoured in the underlying Bluff Sandstone (Moench and Schlee, 1967, p. 17). The eastward extent of the Recapture in north-central New Mexico is not yet known.

Craig and others (1955, p. 139) recognized three distinct lateral facies in the member. A conglomeratic sandstone facies occupies a narrow lobate area north of Gallup. A sandstone facies surrounds the conglomeratic facies on the north, west, and possibly east and is in turn surrounded on the north, west, and east by a claystone and sandstone facies, which is the most extensive of the three.

The Recapture Member in the Ambrosia Lake district represents the claystone and sandstone facies described by Craig and his colleagues. The member attains a maximum thickness of 245 feet east of Haystack Mountain (fig. 2, section *C;* R. E. Thaden, written commun., 1965) but is generally 125–145 feet thick elsewhere at the outcrop. Logs of a few holes drilled through the member indicate a thickness ranging from 125 to 170 feet in the subsurface as much as 5 miles north of the outcrop.

In the Ambrosia Lake district the member is composed predominantly of clayey sandstone, sandy claystone, sandstone, claystone, and siltstone with minor amounts of arkosic sandstone and impure limestone. The clayey sandstone and sandy claystone are pale red, grayish red, and very dusky red and are fine and very fine grained. The claystone and siltstone are dark reddish brown mottled with pale greenish gray, yellowish gray, and dark purplish gray. Clayey sandstone and sandy claystone strata range in thickness from less than 1 foot to 25 feet and, in places, compose 50 percent of the total thickness of the member.

The sandstone is quartzose, white, pale yellowish gray, and pale pinkish gray, and fine, medium, and coarse grained. Some conglomerate lenses are present and contain scattered chert pebbles as much as 1 inch in diameter. The sandstone consists of moderately to poorly sorted rounded to subrounded quartz grains and orange, black, and white accessory minerals. Some well-sorted sandstone strata are also present as layers and lenses a few feet to 60 feet thick. These layers and lenses are distributed throughout the entire vertical span of the member. In one measured section, sandstone makes up 73 percent of the member, but throughout the district it generally makes up less than this.

Medium- to coarse-grained arkosic sandstone occurs as lenses near the top of the member. This sandstone is generally light gray or grayish orange and is lithologically identical with the sandstone in the overlying Westwater Canyon Member. (See description under "Westwater Canyon Member.")

Small- to medium-scale low-angle crossbeds have been observed in the medium- to coarse-grained sandstone units, but bedding in the sandy claystone and clayey sandstone is obscure. Bedding in the claystone is poorly developed, but slight fissility has developed in places.

The contact with the underlying Bluff Sandstone is distinct and appears to be conformable in most exposures in the Ambrosia Lake district; dark-red clayey strata of the Recapture Member contrast sharply with pale-colored sandstone below. In places, however, this contact is between sandstones, and there is some question about where the contact should be drawn. Rapaport, Hadfield, and Olson (1952, p. 51) showed 95 feet of Recapture Member at Haystack Mountain. (See fig. 4.) Freeman and Hilpert (1956, p. 327) measured 133 feet, and R. E. Thaden (written commun., 1965) measured 129 feet. Sandstone which was shown by Rapaport, Hadfield, and Olson as part of the Bluff was included in the Recapture Member by Freeman and Hilpert. Some of the sandstone there was considered by Thaden to be a tongue of the

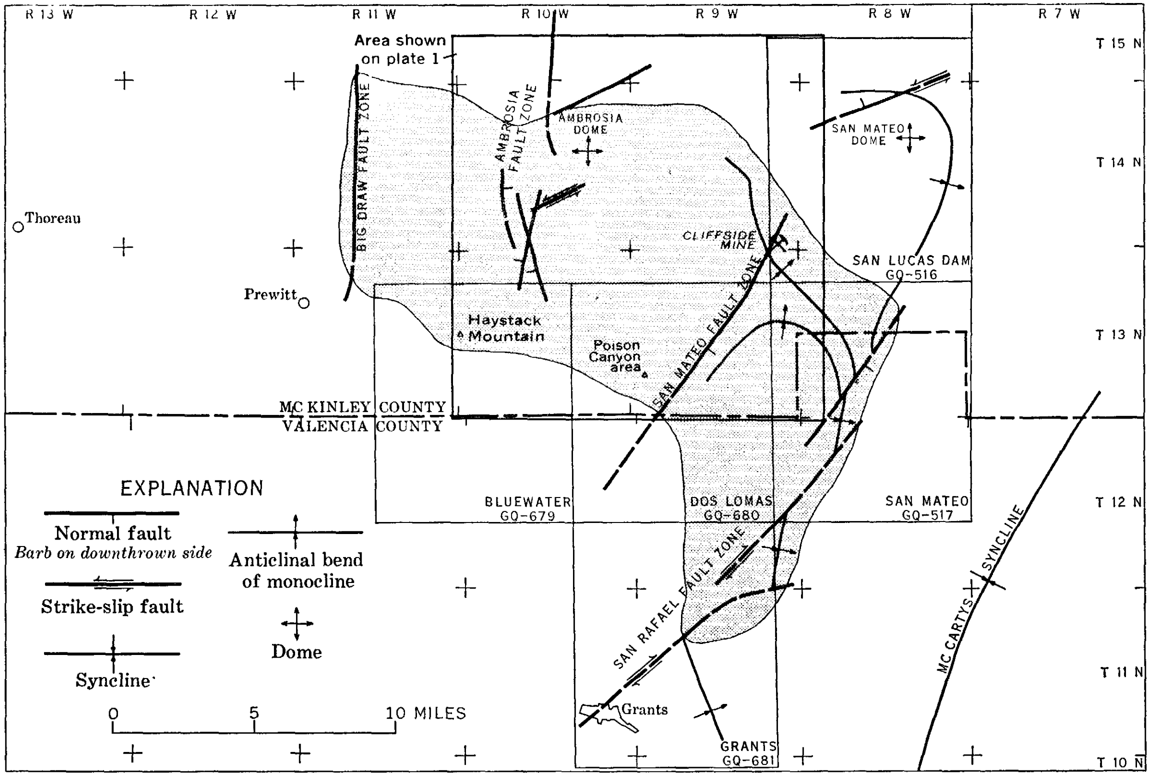


Figure 4.—Major structures in and near the Ambrosia Lake district (shaded area) and index to published geologic maps.

Cow Springs Sandstone encroaching from the west and was not included in either the Recapture Member or the Bluff Sandstone. West of the district, near Gallup, the base of the Recapture Member intertongues with the Cow Springs Sandstone (Harshbarger and others, 1957, pl. 3). To the east, in the Laguna district, the Bluff-Recapture contact is generally sharp, but in places the contact intertongues.

The character of the contact with the overlying Westwater Canyon Member varies. At the outcrop, in places, the contact is an erosional surface marked by channels of Westwater Canyon–type sandstone scoured in the dark-red clayey beds. At other places Westwater Canyon–type sandstone intertongues with red clayey strata. In some places the contact is gradational, and arkosic sandstone lenses alternate with beds of red clayey strata. Where the lithologies are gradational, the contact is arbitrarily placed at the base of the lowest Westwater Canyon–type sandstone unit which is not thinner than an overlying red mudstone stratum.

Electric logs of many holes which penetrate ore deposits in the main part of the district show a sharp change in lithology at this contact, about 400 feet below the top of the Dakota Sandstone. Cuttings and cores from a few holes verify that this is a change from medium- or coarse-grained arkosic sandstone to either fine-grained quartzose sandstone or red sandy claystone. In some areas, notably in the vicinity of Ambrosia dome (fig. 4), a sharp change in lithology occurs about 310 feet below the top of the Dakota Sandstone. Logs of cuttings indicate a change from arkosic sandstone to red mudstone. The red mudstone appears to be as much as 40 feet thick in places, and most of the holes drilled in this area were bottomed in it. A few deep holes penetrate this mudstone, and the electric logs indicate the presence of a sandstone stratum below it which appears to correlate with the lower part of the Westwater Canyon Member in areas adjacent to the dome (pl. 1, sections *A–A′* and *E–E′*). Some geologists working in the area are of the opinion that the thick mudstone there is part of the Westwater Canyon Member; others consider it to be a part of the Recapture Member.

In some places comparable changes in lithology, as interpreted from electric logs, occur 450 feet below the top of the Dakota Sandstone, and in some places no obvious change in lithology is indicated by logs of holes extending considerably below this horizon. Thus, in the subsurface, as well as at the outcrop, the contact can be definitely located in some areas and must be arbitrarily chosen in others.

WESTWATER CANYON MEMBER

The Westwater Canyon Member is present throughout part of northeastern Arizona and northwestern New Mexico (Craig and others, 1955, p. 154). The maximum thickness is 330 feet, 30 miles northwest of Gallup, N. Mex. To the north the member intertongues with, and grades into, the lower part of the Brushy Basin Member and is recognizable to within a few miles south of Monticello, in southeastern Utah. To the south it thins to extinction a few miles south of Gallup and about 7 miles southeast of Grants, N. Mex. (fig. 2). It thins to the east and is locally absent in the Laguna district (Freeman and Hilpert, 1956, p. 314).

Craig and others (1955, p. 154) recognized two facies in the member. A conglomeratic sandstone facies occupies a lobate area north of Gallup and is surrounded on the north, east, and west by a sandstone facies.

The Ambrosia Lake district is at the transition between the two facies. The thickness of the member is about 125 to 270 feet in the main part of the district and may be as little as 30 feet in adjacent areas. An isopach map of the member on plate 1 shows the variations in thickness in relation to the ore deposits in the main part of the district. Data from at least five drill holes per section were used to compile this map. Over ore deposits in the main part of the district, the holes are in the center of each quarter section and in the center of the section. At the margins of the district, holes from which data were obtained are irregularly distributed.

The member is composed mainly of crossbedded arkosic sandstone interstratified with mudstone. The mudstone strata are thicker, more numerous, and more continuous in the upper one-third of the member than in the lower two-thirds. A lithofacies map on plate 1 shows the distribution and amount of mudstone in the member in the main part of the district. Data from at least five drill holes per section were used to compile this map. Over ore bodies in the main part of the district, the holes are located, one each, in the center of the four quarter sections and one in the center of the section. At the margins of the district, the holes from which data were obtained are irregularly distributed.

Facies changes are more abrupt southward than northward from the main part of the district, and in the area to the south the member contains more mudstone than to the north. Mudstone strata from less than 1 foot to 40 feet thick compose from a little less than 10 percent to a little more than 40 percent of the total thickness of the member within the district.

The sandstone at the outcrop is pale yellowish gray, reddish brown, and yellowish orange. In the subsurface, the sandstone is light gray, pale yellowish orange, dark yellowish orange, dusky red, and moderate reddish brown. The mudstone is generally pale grayish green but locally may be mottled red, yellow, and dark gray.

Cross-stratification is mainly of the high-angle medium-scale trough type and, less commonly, of the low-angle large-scale simple type (McKee and Weir, 1953, p. 386). Cosets from a few feet to more than 100 feet thick are vertically separated from each other by mudstone strata and diastems. The disconformities are irregular erosion surfaces that truncate cross-strata. Mudstone conglomerate, tightly cemented by calcite, immediately overlies the diastems in many places. Pebble- to cobble-size rounded and angular fragments of mudstone are embedded in a matrix of poorly sorted conglomeratic sandstone containing a few chert pebbles up to 1 inch in diameter. The traceable extent of the diastems is generally only a few tens of feet but, rarely, is as much as several hundred feet. Diastems terminate by dying out into bedding planes or by being cut out by other diastems.

The sandstone consists of rounded to subrounded quartz and chert grains and angular feldspar grains in proportions which vary from one set of cross strata to another. Quartz ranges from 56 to 90 percent, feldspar from 3 to 33 percent, and chert from 1 to 28 percent. Heavy minerals, other than sulfides, constitute less than 0.5 percent (Cadigan, 1967, p. 73). Grain size ranges from very fine to very coarse and conglomeratic, but the medium-grained size predominates. Data from the cores of four holes drilled in sec. 23, T. 14 N., R. 10 W., indicate that the relative amounts of the several grain-size fractions average about 33 percent fine, 58 percent medium, and 9 percent coarse. Data from electric logs suggest that in a large area in sec. 28, T. 14 N., R. 9 W., there is as much as 75 feet of fine-grained sandstone at the base of the Westwater Canyon.

Cementing materials are calcite, iron oxide, and clay, and the rock ranges from very friable to very hard and dense depending on the type and amount of cementing material present. Very hard, very calcitic sandstone occurs as layers, lenses, concretions, and irregular-shaped masses. Much of the calcite is in the form of large crystals, from less than 1 inch to 6 inches across, which enclose many sand grains and result in luster mottling. Finely crystalline calcite cement is also abundant.

Iron oxide cements are limonite and, presumably, hematite, which also form stain and coat the sand grains. The color of the sandstone is attributable to the absence or presence of iron oxide cement. Light-gray to white sandstone contains no iron oxides. The several shades of yellow and yellowish orange reflect varying amounts of limonite, and pale red to dusky red, varying amounts of hematite (Granger and others, 1961, p. 1193).

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Clay minerals in the sandstone are montmorillonite and kaolinite with minor amounts of chlorite and illite (Granger, 1962, p. D16; Keller, 1962, p. 35). Where the Brushy Basin Member is present, the dominant clay mineral in the Westwater Canyon Member is montmorillonite, both in the cement and in the mudstone fragments and layers. Where the Brushy Basin Member is absent, kaolinite is the dominant clay mineral in the interstitial cementing material. Kaolinite also is present throughout most of the Westwater Canyon Member sandstone in the form of scattered nests (Gruner and Knox, 1957) or aggregates as much as one-half inch across that completely fill the interstices and cause the rock to have a white-spotted appearance. These white spots occur even where the Brushy Basin is present.

Coalified and silicified tree trunks and branches as well as dinosaur bone fragments are common, though not abundant, throughout the member in the Ambrosia Lake district. Part of the Marquez ore deposit in sec. 23, T. 13 N., R. 9 W., is overlain along an erosional disconformity by a sandstone unit containing abundant macerated and coalified plant fragments. This is an unusual occurrence; very little carbonaceous trash was observed in the workings of other mines.

POISON CANYON SANDSTONE OF ECONOMIC USAGE

The Poison Canyon sandstone is an informal name widely used in the district to designate a sandstone unit at the top of the Westwater Canyon Member. The name has been mentioned in a number of earlier reports, but the unit has never been completely defined or described. Hilpert and Corey (1957, p. 371) considered this sandstone to be a basal unit of the Brushy Basin Member, but in this report it is included in the Westwater Canyon Member.

The unit was named after the Poison Canyon mine (pl. 1) in sec. 19, T. 13 N., R. 9 W. At the time the ore body was discovered in 1951, no minable ore was known to occur in the lower part of the Westwater Canyon Member. Over much of the outcrop near the mine the limonitic-yellow colors of this sandstone unit contrast with the hematitic-red colors in the sandstone of the lower part of the Westwater Canyon Member. The unit was thought, therefore, to be a distinctive, favorable part of the Morrison Formation, and much of the early exploration in the district was confined to it.

At the Poison Canyon mine, the sandstone unit is 55 feet thick; it lies just below 65 feet of pale-greenish-gray Brushy Basin mudstone. The sandstone unit is separated from the main body of the Westwater Canyon Member by a mudstone stratum, which in places attains a thickness of 40 feet. At the outcrop, this mudstone can be traced westward 2.6 miles to sec. 14, T. 13 N., R. 10 W., where it pinches out

(Thaden, Santos, and Ostling, 1967). To the east and south, along the outcrop, it has been traced 4.9 miles to sec. 10, T. 12 N., R. 9 W., where the entire Morrison Formation disappears under cover. In a few outcrops through this cover, a thin mudstone stratum is present at approximately the same horizon, but it is not known if this mudstone is continuous with that at the Poison Canyon mine. Thus, along the outcrop, the sandstone can be traced as a unit for 7.5 miles and may extend even farther (fig. 2).

Where one mudstone stratum is present in the subsurface near the top of the Westwater Canyon Member, it is considered to be the base of the Poison Canyon sandstone. Where several are present, the thickest is generally considered to be the base. Where several strata of about equal thickness are present, any one of the several is considered to be the base, depending upon which one correlates best with adjacent areas where only one mudstone stratum is present. Thus, the mudstone which marks the base in one area may not be the same as that which marks the base in another area.

The thickness of the Poison Canyon sandstone ranges from slightly less than 20 to at least 90 feet. This range in thickness is, for the most part, not due to channeling or convergence of the upper and lower boundaries, but results from choosing different mudstone strata as the base.

Despite the fact that the Poison Canyon sandstone cannot be defined precisely in the subsurface, mining personnel find the term convenient and consider the unit to extend throughout much of the district. It is realized that the mudstone chosen as the base is not everywhere the same and, in a strict sense, does not necessarily correlate with the basal mudstone at the Poison Canyon mine. The presence of any prominent mudstone stratum near the top of the Westwater Canyon Member serves to delimit a Poison Canyon sandstone. The unit, so defined, is present throughout the Ambrosia Lake district and extends far beyond, covering a total area of at least 220 square miles.

The Poison Canyon sandstone is identical with the sandstone in the lower part of the Westwater Canyon Member with respect to mineralogy and sedimentary structures, and the description of the member applies to this unit as well. Some minor differences were noted, however. There appears to be less fine-grained sandstone in the Poison Canyon than in the lower part of the member. The difference is not conspicuous; most of the sandstone in both is predominantly medium grained. As mentioned previously, this unit contains more mudstone strata and probably more mudstone fragments than does the lower part of the member. Although the color of this unit at the outcrop contrasts with that of the main body of the member, in the subsurface the colors are identical. All the shades of yellow, red, and gray seen in the lower part have also been observed in the Poison Canyon sandstone. Current lineations in the tongue generally trend northeast and east-southeast, whereas those in the lower part trend east-southeast.

BRUSHY BASIN MEMBER

The Brushy Basin Member is recognizable as a distinct unit of the Morrison Formation in western Colorado, eastern Utah, northern New Mexico, and part of northeastern Arizona (Craig and others, 1955, p. 155). Near Laguna, N. Mex., it attains its maximum thickness of 372 feet (Freeman and Hilpert, 1956, p. 320). Pre-Dakota erosion has removed much of the upper part of the member throughout the region near the southern edge of the San Juan Basin.

The wedge edge can be seen in the outcrops about 8 miles northeast of Gallup and about 7 miles southeast of Grants. Southward from these points, the Dakota Sandstone rests on successively older formations of the Jurassic System (fig. 2).

In the Ambrosia Lake district the member is 60–200 feet thick and crops out as steep slopes. It consists predominantly of a clay facies in which bedding is obscure and which ranges from claystone to very fine grained clayey sandstone. Over broad areas of outcrop these grade into one another through slightly sandy to very sandy claystone. Rocks of the clay facies are mostly shades of pale grayish green, but some display various shades of red and yellow. Clay minerals are montmorillonite and mixed-layer chlorite-montmorillonite derived from the alteration of volcanic ash (Waters and Granger, 1953, p. 6; Keller, 1962, p. 5, 35).

Sandstone, occurring as scattered lenses rarely over 25 feet thick, constitutes as much as 50 percent, but generally less than 10 percent, of the member. Pale-yellowish-gray crossbedded arkosic sandstone identical with that in the Westwater Canyon Member is common near the base of the Brushy Basin Member but also occurs at various horizons throughout. Less common are lenses of fine-grained very light gray quartzose sandstone and quartzite pebble conglomerate.

At its base the Brushy Basin Member intertongues with the underlying Westwater Canyon Member (pl. 1), and, therefore, the selection of the contact is arbitrary. The contact with the overlying Dakota Sandstone is an erosion surface having small local relief, generally less than a few feet. Typically, black shale and coal at the base of the Dakota Sandstone rests on pale-grayish-green claystone along an irregular surface. In places sandstone strata directly underlie the coal and shale units. These sandstone strata appear in some places to be Dakota-type sandstone filling shallow scours in the green claystone, whereas in others they appear to be lenticular strata of Brushy Basin-type sandstone which were partly removed by pre-Dakota erosion. In the subsurface the two are not readily distinguishable.

ORIGIN

The source of the Recapture and Westwater Canyon Members and of the coarser clastics in the Brushy Basin Member appears to have been south of Gallup in west-central New Mexico (Craig and others, 1955, p. 150, 156; Moench and Schlee, 1967, p. 21). Composition of the clastic materials in these units indicates that they were derived from sedimentary, igneous, and metamorphic terranes. The Recapture Member is regarded as a fan-shaped alluvial plain constructed by aggrading streams carrying clastic materials to the north and east. Rejuvenation of the source area resulted in the deposition of a blanket of coarser sand—the Westwater Canyon Member—over northwestern New Mexico and adjacent States. The trend of current lineations in the Ambrosia Lake district indicates that in this area the streams that deposited the sand flowed east-southeastward in early Westwater Canyon time and northeastward in late Westwater Canyon time. Distribution of the Jackpile sandstone in the Laguna area suggests that the northeast direction of streamflow persisted into latest Morrison time (Moench and Schlee, 1967, p. 19).

The source area of the clayey material in the Brushy Basin Member is not clear. Much of this material is derived from the alteration of volcanic ash. The condition of the relict shards indicates that much of the clay was derived from ash falls which were not transported and reworked (Keller, 1962, p. 6). Craig and others (1955, p. 157) suggested that the source area may have been southwest of south-central Utah, the same as for the Salt Wash Member.

STRUCTURE

The Ambrosia Lake district is on the homoclinal south flank of the San Juan Basin, a part of the basin that has been called the Chaco slope or platform (Kelley, 1951, p. 124). (See also fig. 1.) The regional dip to the northeast is modified at many places by folds and faults, and the Ambrosia Lake district occupies probably the most folded and faulted part of the Chaco slope. The crest of the northwestward-trending Zuni uplift, which forms the southern boundary of the San Juan Basin, is 20 miles south of the district.

The major structural elements in the region are believed to be related to the uplift of the Zuni Mountains. The uplift has been recurrently active since Paleozoic time. Strata of Pennsylvanian age are absent in the uplift but are present and increase in thickness to the north, south, and east (Kelley and Clinton, 1960, p. 47). Uplift during Late Jurassic or Early Cretaceous time is indicated by depositional thinning and by truncation of successively older formations of the Jurassic System by the Dakota Sandstone southward from the district. Tectonic activity at this time is further indicated by the development of pre-Dakota folds in the Laguna district, as described by Moench and Schlee (1967, p. 36).

The most recent uplift of the Zuni Moutains cannot be directly or closely dated. The age of this uplift is inferred from the attitude of Eocene strata exposed 65 miles to the north near the center of the San Juan Basin. The northward tilt of the San Jose Formation there is attributed to the uplift which, therefore, must have occurred after early Eocene time (Hunt, 1934, p. 188–189). The basalt flows north of Grants (Thaden, Santos, and Raup, 1967) are younger than 3.3 million years (Bassett and others, 1963, p. 214) and are not involved in the deformation. They are virtually horizontal and truncate the tilted strata in the McCartys syncline on mesas about 1,400 feet above local base level of erosion. The age of the uplift is, therefore, post-early Eocene and pre-late Pliocene or Pleistocene, and the McCartys syncline (fig. 4), as well as the other folds in and near the district, apparently developed during this time.

During middle and late Tertiary and probably Quaternary time, the Colorado Plateaus province was uplifted regionally, and the Rio Grande trough subsided. Hilpert and Moench (1960, p. 429) noted that in the Laguna district this was the period of most intense fracturing. Undoubtedly, some of the faults and joints in the Ambrosia Lake district also developed during this episode.

Folds in strata of Jurassic age which are not reflected in the overlying Dakota Sandstone are called pre-Dakota folds. These are well developed in the Laguna district and presumably formed as the Morrison Formation was being deposited. Folds that involve the Dakota Sandstone and that probably developed during the most recent uplift of the Zuni Mountains are called post-Dakota folds.

POST-DAKOTA FOLDS

The McCartys syncline is the largest fold in the region and is present along the eastern edge of the Ambrosia Lake district (fig. 4). The fold is asymmetrical, and the monocline that forms the steep west limb has a maximum structural relief of about 1,600 feet (Hunt, 1938, p. 74). The anticlinal bend of the monocline trends northward and is offset at three places by the San Rafael fault zone. It branches to the north into three sinuous folds, two of which swing to a westward trend and die out abruptly. One branch trends northwestward then swings sharply to the southwest, where the strata plunge into the San Mateo fault zone; the result is a northward-plunging anticline whose axis trends northward.

Ambrosia dome (fig. 4) is the next largest fold in the district. In plan, the dome is an asymmetrical triangular fold with steep flanks on the south and west and a gentle flank on the northeast. The steep west flank plunges into the Ambrosia fault zone, producing a maximum structural relief of 1,150 feet. Closure on the dome is about 400 feet (pl. 1).

PRE-DAKOTA FOLDS

Pre-Dakota folds in the nearby Laguna district were described by Hilpert and Moench (1960, p. 429) and by Moench and Schlee (1967, p. 36). Two sets of folds occur in the Laguna district; a major set trends eastward and northeastward, and a minor set trends northward. Folds of the major set are sinuous and have an amplitude of several hundred feet. Folds of the minor set have a maximum amplitude of 100 feet. The folding is believed to have begun during or shortly after Todilto time and to have continued through to very latest Jurassic and possibly Early Cretaceous time.

Hilpert and Corey (1957, p. 378) and Hilpert and Moench (1960, p. 443) proposed the existence of similar pre-Dakota folds in the Ambrosia Lake district. They suggested that deposition of the easterly trending zone of thick Westwater Canyon Member (pl. 1) here may have been controlled by a fold.

The thickness of the interval between the top of the Dakota Sandstone and the top of the Todilto Limestone should vary within the Ambrosia Lake district if a fold had developed during deposition of the Westwater Canyon Member. The maximum difference in thickness should be normal to the trend of the thick zone. Data from holes drilled through the Todilto Limestone indicate that the span between the Dakota and Todilto Formations ranges from 1,020 to 1,050 feet. The maximum variation in the thickness of this span occurs parallel to and within the trend of thick Westwater Canyon Member. Most likely, therefore, no pre-Dakota fold is present which may have controlled the deposition of the Westwater Canyon Member.

To corroborate the existence of such folds, many cross sections were drawn at various places across the main part of the district. Plate 1 shows several cross sections which are typical of the many others drawn across the trend and along the trend of the thickest zone of ore-bearing sandstone. The top of the Dakota Sandstone is adjusted to a common datum to exclude the effects of post-Dakota deformation. No indication of folds is displayed by the attitudes of the Brushy Basin Member or of mudstone strata within the Westwater Canyon Member.

The apparent thinning of the Westwater Canyon Member in the vicinity of Ambrosia dome (pl. 1) was cited by Young and Ealy 1956, p. 9) and by Hilpert and Corey (1957, p. 366) as evidence for the existence of a pre-Dakota fold in this area.

Plate 1 shows two cross sections (*A–A′* and *E–E′*) through the dome that are based on recent drill-hole data not available at the time the earlier reports were written. The thinning of the Westwater Canyon Member is seen to be the result of extensive intertonguing with red mudstone strata near its base in the vicinity of the dome. Individual mudstone and sandsone strata are not warped.

No pre-Dakota folds of the magnitude of those in the Laguna district occur in the Ambrosia Lake district. None were observed at the outcrop; and if any exist in the subsurface, they are too subtle to be indicated by the drill-hole data available. Thinning of the Brushy Basin Member in the western part of sec. 28, T. 14 N., R. 9 W., was mentioned by Hazlett and Kreek (1963, p. 86) as possibly indicating the presence of a northward-trending pre-Dakota fold in that area. Figure 3 shows two west to east cross sections through the west half of secs. 28 and 33. This is the only area in which the Brushy Basin Member thins along a fairly well defined trend. A fold with a structural relief of about 85 feet in a half mile is indicated. The intertonguing shown on the west side of the southern (lower) cross section (*K–K′*), however, complicates the picture of mudstone thinning over the crest of a pre-Dakota fold. If this is indeed a pre-Dakota fold, it is the only one of its kind detected in a distance of 9 miles explored by close-spaced drilling.

The thinning and truncation of the Morrison Formation southward from the district indicate an uplift of the area to the south during and after Morrison time. The deformation which produced the pre-Dakota folds in the Laguna district may be related to the uplift to the south. Apparently this subsidiary deformation diminished westward, and, as a result, folds of the number and magnitude observed in the Laguna district did not develop in the Ambrosia Lake district.

Innumerable intraformational folds occur in the Todilto Limestone. These range in size from minute, nearly microscopic crenulations to features 50 feet wide and 250 feet long that deform the entire thickness of the formation and several feet of overlying and underlying strata. The axes of many of these folds are very sinuous; some diverge as much as 90° from their dominant direction or even double back on themselves. Many split into several branching folds before dying out. The results of deformation range from broad open warps to very tight folds, some of which are recumbent and broken by small thrust faults.

The orientations of folds in many places appear random, but, in some places, vague to strong preferred orientations can be discerned. Moench and Schlee (1967, p. 39) found that, in the Laguna district, the folds trend chiefly east to northeast and slightly north-northwest. Rapaport, Hadfield, and Olson (1952, p. 41) described a right-angle conjugate pattern, the trend of which changes systematically with changes in the strike of strata on the flanks of the Zuni uplift. Figure 5 is a plot of the orientation of 53 folds in sec. 9, T. 12 N., R. 9 W., each of which has an amplitude of more than 4 feet. A strong northerly trend and a somewhat weaker east-northeasterly trend, much like those in the Laguna district, are indicated. When the trend of folds whose amplitudes are less than 4 feet is plotted, the pattern remains virtually the same, except that a prominent northwest trend is added.

The age and origin of all the intraformational folds in the Todilto Limestone have not definitely been established. Moench and Schlee (1967) noted that in trend these folds in the Laguna district parallel the larger pre-Dakota folds there. They proposed that the folds are also of pre-Dakota age and that they were developed by sliding of semiconsolidated limestone down the flanks of pre-Dakota synclines shortly after the deposition of the Todilto Limestone. The occurrence of many Todilto folds remote from any pre-Dakota fold indicates that their origin is not necessarily related to the pre-Dakota folds. The Todilto folds may be related to gravity sliding in Jurassic time on the north slope of a positive area to the south (the Mogollon Highland of Harshbarger and others, 1957) or, as suggested by Rapaport, Hadfield, and Olson (1952, p. 41), in Late Cretaceous or Tertiary time when the Zuni Mountains were uplifted.

McLaughlin (1963, p. 143) noted that some minor folds showed flowage but no pronounced fracturing, whereas others were extremely fractured and brecciated. He concluded that folds of two different origins are present—those that developed as a result of flowage and those that developed in response to tectonic stresses during uplift of the Zuni Mountains.

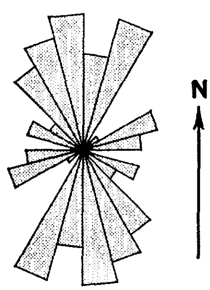

FIGURE 5.—Orientation of folds in the Todilto Limestone.

The widespread distribution of Todilto folds indicates that their origin was related to processes operating on a regional rather than local scale. The absence of pre-Dakota folds in the Ambrosia Lake district and elsewhere where Todilto folds are numerous indicates that there need not have been pre-Dakota folds present for Todilto folds to form.

FAULTS AND JOINTS

The Ambrosia Lake district occupies the most faulted part of the Chaco slope. West of Thoreau, N. Mex. (fig. 4), Rapaport, Hadfield, and Olson (1952, p. 42) found only four minor en echelon eastward-striking faults of not more than 20 feet vertical displacement, whereas east of Thoreau they mapped 32 faults varying in vertical displacement from 5 to 570 feet. Although detailed mapping west of Thoreau may eventually disclose more faults in that region, the Ambrosia Lake district will still be seen as the most faulted part of the northeast flank of the Zuni uplift.

The distribution of faults is shown on plate 1 and in figure 4. Most appear to be normal, dip-slip faults, but several show evidence of strike-slip movement. Vertical displacement along most normal faults is less than 40 feet, but for all normal faults it ranges from less than 1 foot to 450 feet.

Structurally, the district is bounded on the west by the Big Draw fault zone and on the east by the San Rafael fault zone (fig. 4). More than 90 percent of the large ore deposits in the Morrison Formation between Grants and Gallup occur within the span between the Ambrosia fault zone on the west and the San Mateo fault zone on the east.

The San Rafael fault zone, striking northeastward through Grants, N. Mex., is the largest in the region (fig. 4). The zone comprises several faults which fracture the monoclinal west flank of McCartys syncline. Although equivalent strata are displaced 1,000 feet vertically along the fault zone 3 miles northeast of Grants, movement along the fault zone is mainly, if not entirely, horizontal. The Dakota Sandstone–capped hogbacks on opposite sides of the fault are at approximately the same elevation but are displaced 20,000 feet horizontally by right-lateral movement (Thaden, Santos, and Raup, 1967).

The Big Draw fault zone, called the Bluewater fault by Rapaport, Hadfield, and Olson (1952, p. 43), strikes northeastward in the Zuni Mountains, curves, and strikes due north where it transects the Jurassic outcrop north of U.S. Highway 66 (fig. 4). According to Smith (1954, p. 21), the maximum stratigraphic throw is 600 feet, and Rapaport, Hadfield, and Olson (1952, p. 43) indicated a displacement of 570 feet, 3½ miles northeast of Prewitt, N. Mex. The displacement decreases to 250 feet northward in a distance of 3 miles. The fault is downthrown on the east, but locally a parallel fault that is downthrown on the west forms a graben in conjunction with the fault.

The San Mateo fault zone, downthrown on the east, strikes northeastward through sec. 21, T. 13 N., R. 9 W., where it has a maximum displacement of 450 feet (pl. 1 and fig. 4). The displacement diminishes northward to 50 feet in a distance of 7.5 miles. The fault plane dips about 45° to the east near the Cliffside mine. Strata on the downthrown east side dip about 12° toward the fault plane. Strata on the upthrown west side appear to abut the fault plane with little or no drag.

The Ambrosia fault zone, downthrown on the east, strikes due north along the west side of sec. 3, T. 14 N., R. 10 W., where it has a maximum displacement of about 350 feet. As in the San Mateo fault zone, strata on the downthrown east side dip toward the fault plane, and strata on the upthrown side abut the fault plane with little or no drag.

The apparent "reverse drag" exhibited by strata long these faults was explained by Hamblin (1965, p. 1145–1161). A horizontal shift of the downthrown side normal to the fault plane would result in a void adjacent to the fault plane. The void is then filled by draping of the strata near the fault plane. Apparent "reverse drag" is therefore indicative of elongation in response to horizontally directed tension.

In addition to the San Rafael fault zone, three unnamed faults were observed which display evidence of horizontal movement.

About 5 miles northeast of the district, in the northern part of the San Lucas Dam quadrangle (Santos, 1966a), near San Mateo dome, an east-northeast-striking fault displaces strata of Late Cretaceous age (fig. 4). In this area the Satan Tongue of the Mancos Shale, which splits the Point Lookout Sandstone into two units, pinches out. At one place along the fault in sec. 7, T. 14 N., R. 8 W., 90 feet of shale of the Satan Tongue is present on the north side of the fault directly across from an uninterrupted section of Point Lookout Sandstone on the south side. The pinchout of the Satan Tongue on the north side of the fault is 1.5 miles east of the uninterrupted section of Point Lookout Sandstone, and the interpretation is that the south side of the fault is displaced eastward by at least this distance.

Near the north edge of secs. 22 and 23, T. 14 N., R. 10 W., a fault, striking east-northeast, displays horizontal slickensides on the fault plane (H. C. Granger, written commun., 1967). A northwest-striking fault with as much as 30 feet vertical displacement abuts this fault on the north, and a series of northwesterly trending fault traces with much smaller vertical displacements continues southward from the easterly trending fault. The southward extensions of the northwesterly trending fault are offset to the east, and the interpretation is that the northwest-trending fault was repeatedly offset by left-lateral movement along the easterly trending fault. The presence of the strike-slip fault was not revealed by the drill-hole data, and the details of the faulting are too small in scale and too intricate to be shown on plate 1.

In the course of the author's mapping the Kermac Sec. 10 mine (sec. 10, T. 14 N., R. 10 W., pl. 1), the only observed reverse movement was found along an easterly trending fault. The mine geologist, Robert Lott (written commun., 1959), however, found horizontal slickensides along the fault plane of this and several other easterly and west-northwesterly trending faults there, and he interpreted the apparent reverse offset to be the result of horizontal movement, rather than reverse throw.

The abrupt change in thickness of the Brushy Basin Member on opposite sides of the San Mateo fault zone west of the Cliffside mine (pl. 1, section A–A′) may be attributable to horizontal movement that caused a relatively thick section of Brushy Basin mudstone to be displaced to a position opposite a relatively thin section. The thin section is on the west side of the fault, and because the Brushy Basin Member thins southward, a right-lateral shift is inferred.

The strike-slip faults probably developed in response to horizontally directed compression. The close association of these faults with the San Mateo dome and with the monoclinal west flank of McCartys syncline suggests that horizontal stress, strike-slip faulting, and folding are interrelated phenomena of a distinct period of deformation. The prevalence of normal displacement along the northerly and northeasterly trending faults, and the apparent "reverse drag" along the San Mateo and Ambrosia fault zones, may, however, indicate faulting during a period of deformation that was characterized by east-west-directed tension. That these are distinct, temporally separate periods is indicated by the relationship of several faults to the upper Pliocene lava flows in the region. A segment of the San Rafael fault zone has displaced strata of Mesozoic age but not the flows in the southwest corner of the San Mateo quadrangle (Santos, 1966b). Other nearby faults in the Grants quadrangle (Thaden, Santos, and Raup, 1967) do displace the same flows.

Strike-slip and dip-slip movements appear to have been contemporaneous along some faults near the Ambrosia dome. The horizontal displacement there is on a much smaller scale than that observed along the west flank of McCartys syncline. The strike-slip faults near the Ambrosia dome probably represent minor adjustments in the blocks between normal faults and are not temporally related to the larger strike-slip faults elsewhere.

If the assumption is correct that the folding in the area accompanied the uplift of the Zuni Mountains in pre-late Pliocene time, it is likely that the strike-slip faulting also occurred at the same time. Horizontally directed tension probably accompanied the stretching of the crust during epeirogenic uplift of the Colorado Plateau during Tertiary and possibly Quaternary time and postdates the period of compression. It would appear, therefore, that the northerly trending normal faults were superimposed on preexisting strike-slip faults. The absence of rocks younger than Late Cretaceous throughout most of the district precludes a direct definition of the extent to which the faults and joints that cut the ore deposits are related to the separate periods of deformation.

Figure 6 shows the orientation of joints and faults measured in the underground workings of eight mines. Sets of joints are parallel and subparallel to faults and occur in swarms near the faults. Joints striking N. 15° E. to N. 15° W. are strongly developed throughout the eastern and southern parts of the district. Along the steep west and south flanks of the Ambrosia dome, northwest- to west-northwest-trending joints are the most prominent. A weakly developed conjugate set of joints occurs approximately normal to the northwest-trending joints, whereas no conjugate set of joints is associated with the north-trending joints, except perhaps at the Marquez mine (pl. 1).

Peculiar collapse structures are common in the Morrison, Bluff, and Summerville Formations in the Ambrosia Lake district and also in the nearby Laguna district (Schlee, 1963; Thaden and Ostling, 1967; Thaden, Santos, and Ostling, 1968). They are circular in plan and vertical to near vertical in orientation; typically, they are bounded by one or several concentric ring faults. The material within the structures is displaced downward and may consist of brecciated fragments of mudstone and sandstone, a disaggregated mixture of mudstone and sandstone, or bedded material in which the beds sag toward the center of the collapse. The structures are as much as 200 feet in diameter and more than 300 feet in depth (Hilpert and Moench, 1960, p. 441). None is known whose base penetrates the Todilto Limestone or whose top penetrates the Dakota Sandstone.

In the Ambrosia Lake district the collapse structures are not associated with folds as they are in the Laguna district. The greatest concentration of these structures, near Haystack Mountain, roughly coincides with an area in which the Recapture Member is unusually thick—240 feet, compared with 125–145 feet elsewhere. Three structures are proximate to the San Mateo fault zone, and their formation may be in some way related to faulting there (Clark and Havenstrite, 1963, p. 108; Granger and Santos, 1963, p. C156). Elsewhere in the district there is no obvious relationship between the faults and collapse structures.

Most of these structures occur where the Dakota Sandstone has been removed by erosion, but at the Cliffside mine, drill-hole data indicate that the two collapses do not penetrate the Dakota Sandstone (Clark and Havenstrite, 1963, p. 110). These two structures are thus pre-Dakota in age, and it is likely that all the others in the district are also of this age.

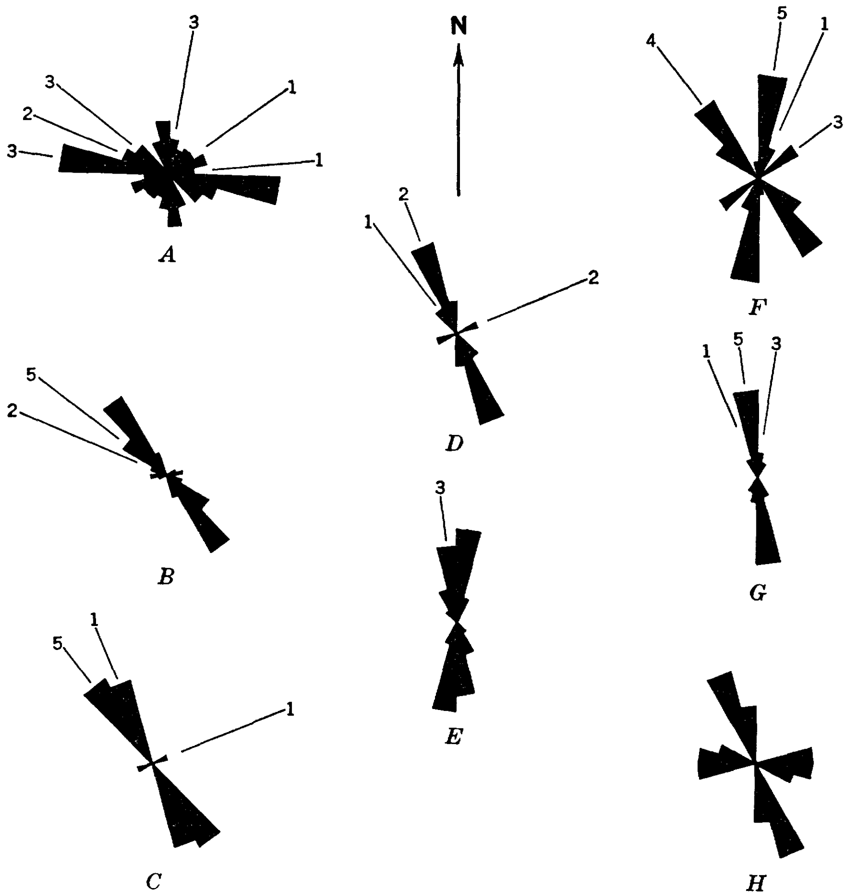

FIGURE 6.—Orientation of joints and faults in the Morrison Formation, measured in underground mine workings. Numbers indicate the number of faults whose orientation falls within the 15° segment. *A*, Kermac Sec. 10 mine (sec. 10, T. 14 N., R. 10 W.); *B*, Homestake-Sapin Sec. 15 mine (sec. 15, T. 14 N., R. 10 W.); *C*, Kermac Sec. 22 mine (sec. 22, T. 14 N., R. 10 W.); *D*, Homestake-Sapin Sec. 23 mine (sec. 23, T. 14 N., R. 10 W.); *E*, Ann Lee mine (sec. 28, T. 14 N., R. 9 W.); *F*, Dysart No. 1 mine (sec. 11, T. 14 N., R. 10 W.); *G*, Isabella mine (sec. 7, T. 13 N., R. 9 W.); *H*, Marquez mine (sec. 23, T. 13 N., R. 9 W.).

SUMMARY OF TECTONIC HISTORY

The coarsening of grain size and the thinning of Jurassic strata, as well as the inferred northward drainage during Morrison time, indicate that a highland existed south of the district in Jurassic time. During the deposition of the Morrison Formation, folds developed locally in the Laguna district, but the deformation that produced these folds did not extend westward into the Ambrosia Lake district. Truncation of successively older strata of the Jurassic System southward from the district indicates that northward tilting and uplift to the south occurred during post-Morrison and pre-Dakota time. The Dakota Sandstone was then deposited on the erosion surface during Early(?) and Late Cretaceous time.

Folds in the Todilto Limestone may have developed in Jurassic time shortly after deposition of the Todilto Limestone and prior to its complete consolidation. They may have developed during the post-Morrison tilting, or during the tilting that accompanied the uplift of the Zuni Mountains in Tertiary time. Or, the Todilto Limestone may have undergone deformation during all three periods.

In early to possibly middle Tertiary time, the Zuni Mountains were uplifted, and McCartys syncline, as well as numerous minor folds, formed on the Chaco slope. Horizontally directed compressive forces accompanying this deformation produced strike-slip faults. During middle and late Tertiary and possibly Quaternary time, the Colorado Plateaus province was uplifted. Erosion during this period stripped away the early Tertiary and Late Cretaceous cover and exposed the tilted strata of Jurassic and Triassic age. The uplift was accompanied by east-west tension which produced north-trending normal faults and joints.

During late Pliocene or possibly early Quaternary time, basalt flows covered the tilted edges of strata truncated by the erosion in Tertiary time. Faults of post-Pliocene age displace the basalt flows in a few places, but the flows have not been tilted since they were formed.

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