Cenozoic Geology in the Mammoth Area Pinal County, Arizona

By L. A. HEINDL

CONTRIBUTIONS TO GENERAL GEOLOGY

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CONTRIBUTIONS TO GENERAL GEOLOGY

CENOZOIC GEOLOGY IN THE MAMMOTH AREA, PINAL COUNTY, ARIZONA

By L. A. Heindl

ABSTRACT

The mapping and stratigraphic analysis of separate alluvial units have led to a revised interpretation of the Cenozoic history of the lower San Pedro Valley in the vicinity of Mammoth, Ariz.

Seven alluvial and two volcanic units were mapped; previously, the six oldest alluvial deposits had been mapped generally as a single formation, the Gila conglomerate. The oldest of these six deposits forms the fanglomerate unit of the Cloudburst formation as defined in the present report, and the succeeding five alluvial units are defined herein as forming the Gila group in this area. The seventh and youngest alluvial unit consists mainly of the flood-plain and channel deposits of the San Pedro River and its tributaries.

The seven alluvial and two volcanic units are predominantly Cenozoic in age. Locally the basal part of the sequence may be as old as Late Cretaceous, but in the area west of Mammoth the deposits are believed to be restricted to the Cenozoic.

Three major erosion intervals are described—Cretaceous(?) to Late Cretaceous(?) or early Tertiary, middle(?) Tertiary, and the well-known late Quaternary period of degradation.

Volcanic and fanglomeratic deposits of Late Cretaceous(?) and Tertiary age, which covered the earliest surface, were deformed and eroded to form the middle(?) Tertiary surface. These deposits and the surface cut on them extended across basins now in part occupied by fault-block ranges.

A thick tableland of middle(?) Tertiary volcanic rocks was laid down on the lower slopes of the middle(?) Tertiary surface. Remnants of these volcanic rocks form the present Galiuro Mountains. Middle(?) Tertiary alluvial deposits were laid down in an ancient valley postulated to have developed along the west side of the present San Pedro Valley trough. These deposits were subsequently displaced along the San Manuel fault, which, on the basis of stratigraphic relationships, is interpreted as a thrust rather than as a tilted normal fault.

The San Pedro structural trough was developed by subsequent block faulting accompanied by differential uplift of the Galiuro Mountains and Black Hills, which began in late Tertiary, probably no earlier than late Miocene, time. Aggradation contemporaneous with differential displacement continued episodically into early Pleistocene time, partly filling the structural trough.

Degradation of the fill began in middle(?) Pleistocene time but was not continuous. Subsequent to the development of the highest erosional bench (Tombstone pediment) within the basin, temporary through drainage was established. The resulting valley was largely refilled with alluvial material, including a well-developed basal channel fill, before a second lower erosional bench (Whetstone pediment) was developed.

Renewed degradation further incised the basin to below the base of the older channel deposits, and the new channel was partly backfilled to form the present flood plain of the San Pedro River.

INTRODUCTION

The purpose of this report is to show how mapping of discrete units of the valley fill may lead to a broadened understanding of Cenozoic history of intermontane basins in Arizona. The area described is in the vicinity of Mammoth, Ariz. (fig. 1), where deep dissection has exposed a complex sequence of terrestrial deposits and related rocks. The alluvial deposits were divided into units by application of standard stratigraphic procedures and were mapped individually wherever possible. Detailed study provided information about environments of deposition, particularly source areas, and this information in turn was used to interpret the sedimentary and structural history of the area during the Cenozoic.

The area described is about 35 miles northeast of Tucson and includes the town of Mammoth and the San Manuel copper mine near Red Hill (pl. 1). It includes the full width of the lower San Pedro Valley between the Galiuro Mountains and the north slopes of the Santa Catalina Mountains.

The geologic mapping upon which this report is based was a part of a geologic reconnaissance and investigation of the ground-water resources of the lower San Pedro Valley, made by the U.S. Geological Survey in cooperation with the Arizona State Land Department. The San Manuel Copper Co. generously permitted access to its properties around the San Manuel mine. The geology of the area immediately around the San Manuel mine has been discussed by Peterson (1938), Steele and Rubly (1947), Creasey (1950), Schwartz (1953), Wilson (1957; 1960), and Pelletier (1957). Mr. S. C. Creasey, of the Geological Survey, kindly provided a manuscript map of his recent geologic mapping in the area as a check against the reconnaissance mapping done by the writer, but the geologic map in plate 1 is the work of the writer alone.

This paper was presented at the Symposium on Cenozoic Geology of Arizona, held jointly by the Arizona Academy of Science and the Southwestern and Rocky Mountain Divisions of the American Association for the Advancement of Science held in Tucson, Ariz., in April 1957. It was prepared originally for publication by the Geo-

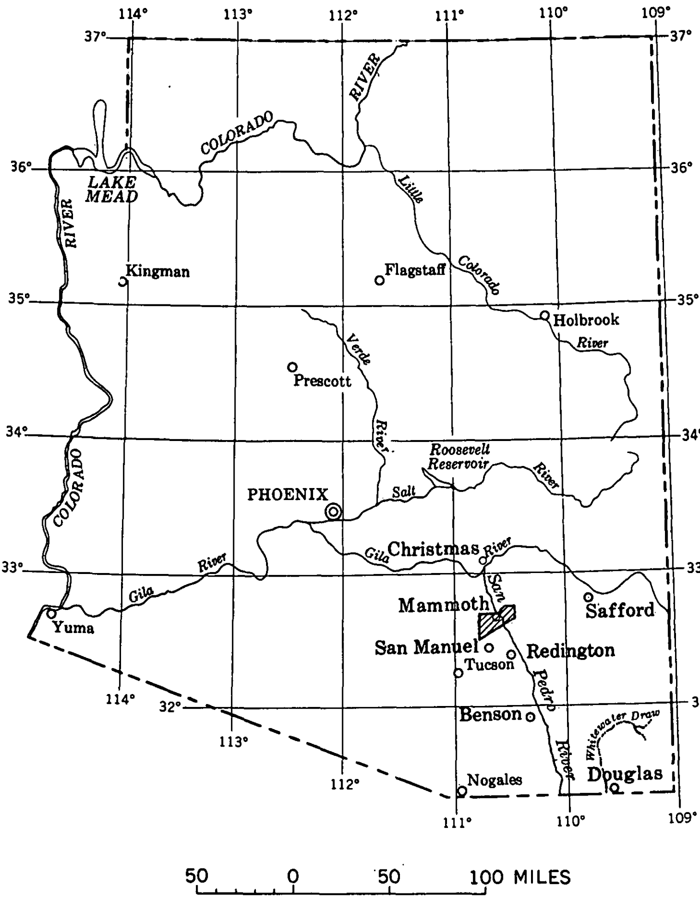

FIGURE 1.—Map of Arizona showing the Mammoth area, Pinal County. Cross-hatched area is shown in detail in plate 1.

chronology Laboratories of the University of Arizona. Subsequently the scope of the sections on stratigraphy was enlarged and Mr. T. L. Smiley, Director of the Geochronology Laboratories, agreed to its issue as a Geological Survey bulletin to facilitate its release.

GEOLOGY

The Mammoth area is within the Basin and Range province; the boundary ranges are the Santa Catalina and Galiuro Mountains, and the basin is the valley of the San Pedro River (pl. 1). Within the basin, which is largely covered by terrestrial deposits, there are small inliers of consolidated rocks, the largest of which is the Black Hills. The rocks in the Mammoth area are composed of pre-Late Cretaceous(?) igneous bodies and Cenozoic, or largely Cenozoic, sedimentary, volcanic, and intrusive units. The pre-Late Cretaceous(?) rocks include early Precambrian quartz monzonite and Mesozoic quartz monzonite porphyry. Paleozoic and Cretaceous(?) sedimentary rocks are exposed nearby in the Santa Catalina and Galiuro Mountains and in the Black Hills, but, except for blocks in the Cenozoic alluvial deposits, they are not exposed in the Mammoth area. Presumably, the Paleozoic and Cretaceous(?) rocks were stripped away in this area because the Cenozoic, or largely Cenozoic, rocks rest on an erosion surface cut on Precambrian quartz monzonite. The post-Cretaceous(?) rocks include volcanic and sedimentary units ranging in age from Late Cretaceous(?) through early(?) Tertiary to Recent (pl. 2). The area is cut by several systems of faults, most of which trend from slightly west of north to northwest.

From the last known deformation to the present time, erosion and deposition have alternated. During some intervals of Pleistocene time, the rocks were beveled to form two conspicuous benches, known in order of decreasing altitude and age as the Tombstone and Whetstone pediments (Bryan, 1926). Subsequently, the San Pedro River cut less conspicuous surfaces and formed the present narrow central flood plain.

PRE-LATE CRETACEOUS(?) ROCKS

Pre-Late Cretaceous(?) rocks exposed in the Mammoth area are composed principally of quartz monzonite. The quartz monzonite, commonly called Oracle granite, is of early Precambrian age (Schwartz, 1953; Banerjee[1]; Damon, 1959) and is exposed in several areas (pl. 1). In the southern part of the Black Hills and in the line of exposures extending southward from the Black Hills, the quartz monzonite is characterized by pink to red feldspar and has an overall reddish to red-brown color. At the north end of the Santa Catalina Mountains, the quartz monzonite contains light-colored feldspar, is comparatively fresh, and has a speckled gray appearance. The differences in the color of the quartz monzonite have aided in determining the source areas of quartz monzonite fragments in the alluvial deposits.

The quartz monzonite is intruded by aplite, diabase, andesite porphyry, and fine-grained quartz monzonite porphyry, which are not separately mapped. The fine-grained quartz monzonite porphyry is related to the San Manuel copper deposit and may be of Mesozoic age (Damon, 1959).

LATE CRETACEOUS(?) AND CENOZOIC ROCKS

Most of the rocks exposed in the Mammoth area are younger than the pre-Tertiary rocks and include sedimentary and volcanic deposits

[1] Banerjee, A. K., 1957, Structure and petrology of the Oracle granite, Pinal County, Arizona: Arizona Univ., Tucson, unpublished doctoral thesis.

of possibly Cretaceous, Tertiary, and Quaternary ages (pl. 1). Small bodies of intrusive rocks that cut some of the Tertiary rocks are not shown in plate 1 but are shown schematically on figure 2.

Previous reports on the San Manuel area west of Mammoth subdivide these rocks generally into older volcanic rocks and associated sedimentary deposits, the Gila conglomerate, and younger alluvial deposits (pl. 2). However, the stratigraphic boundaries of the units differ in the several reports, and the type of boundary is not everywhere uniformly described. As a part of this study, the volcanic and alluvial rocks were reexamined and were subdivided on the basis of local structure and stratigraphic relations (pl. 2).

LATE CRETACEOUS(?) AND TERTIARY CLOUDBURST FORMATION

Conglomerate and andesitic flows, generally red brown, crop out extensively in the northwestern part of the area and along the west front of the Galiuro Mountains. The name "Cloudburst" has been applied to these rocks by geologists of the San Manuel Copper Corp. and by Wilson (1957). The Cloudburst formation is divided locally into volcanic and fanglomerate units, and west of the San Manuel fault the volcanic unit underlies the fanglomerate.

The term "fanglomerate" is not used here to make a genetic distinction between the alluvial deposits of the Cloudburst formation and those of the younger units. It is used here only as a means to distinguish readily the conglomerate sequence in the Cloudburst from the many other conglomeratic units in this area.

Exposures in the area show only fault contacts between the lower volcanic unit of the Cloudburst formation and the Precambrian quartz monzonite, but Peterson (1938, p. 10) reported that at the 300-foot level in the abandoned Mohawk mine, volcanic flows overlie a granite arkose deposited on quartz monzonite. The upper fanglomerate unit, however, appears to be deposited directly on quartz monzonite 2 miles southwest of Red Hill. This unconformity represents a hiatus during which Cretaceous(?), Paleozoic, and younger Precambrian rocks were stripped away, exposing a surface of older Precambrian quartz monzonite. Partial sections of these older, greatly deformed rocks are exposed about 10 miles north in the Black Hills and about 10 miles south in the Santa Catalina Mountains. The significance of this highly localized depth of pre-Cloudburst erosion is beyond the scope of this paper.

Also tentatively included in the Cloudburst are the conglomeratic beds, exposed half a mile east of Red Hill in a wedge completely surrounded by faults, and the generally red-brown sequence of conglomerates and volcanic rocks, reported from bore holes east of the Cholla fault in sec. 35, T. 8 S., R. 16 E.

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The conglomerate within the faulted wedge is composed of grayish-purple, angular to subrounded, pebble- to cobble-sized volcanic fragments, chiefly of andesitic, felsitic, and rhyolitic composition, and only minor amounts of quartz monzonite. These beds dip 25° to 45° NE. Drill-hole data (Schwartz, 1953) show that the conglomerate was deposited on quartz monzonite and that the contact dips 10° to 20° NE.

Drillers' logs of several bore holes in sec. 35, T. 8 S., R. 16 E., shown as a single location in plate 1, are summarized as follows:

Drillers' logs of bore holes in secs. 35, T. 8 S., R. 16 E.

Material	*Approximate range in thickness (feet)*
Mixed conglomerate: gray; subangular to subrounded; fragments of quartz monzonite, andesite, felsite, rhyolite, quartzite, and fanglomerate of the Cloudburst formation	300–500
Volcanic conglomerate: red-brown; angular to subrounded; fragments of andesite and basalt are predominant; few rhyolitic, granitic, and porphyritic fragments	150–300
Andesitic and basaltic flows and agglomerates	0–800
Conglomerate: red-brown; angular to subrounded; fragments of volcanic and granitic debris, with granitic debris apparently increasing with depth	100–600
Quartz monzonite and other intrusive rocks	>200

The conglomerate in the faulted wedge and the buried red-brown conglomerate and volcanic sequence east of the Cholla fault are tentatively considered to be related because (1) their composition is similar, (2) both were deposited on a quartz monzonite surface, and (3) their relationships along the Cholla fault appear to be those of a single formation displaced by a normal fault (pl. 1). The presence of the andesitic and basaltic flows makes the assignment to the Cloudburst preferable to assignment to the San Manuel formation of the Gila group. Steele and Rubly (1947) and Schwartz (1953) also considered the base of the conglomerate in the faulted wedge to be the base of the Gila or Gila(?), within which they included the fanglomerate unit of the Cloudburst. Nonetheless, this assignment must be considered speculative, and the possibility that these deposits represent younger rocks cannot be eliminated.

The drillers' logs of test wells in sec. 25, T. 8 S., R. 16 E., and sec. 32, T. 8 S., R. 17 E., show red material and red beds below depths of 785 and 1,440 feet, respectively. Samples of the red material from the well in sec. 25 are composed of red-brown finely crystalline igneous rocks of dacitic or andesitic composition. The samples from 800 to 2,144 feet, total depth of the hole, show little variation and may be fragments of flows or volcanic conglomerate. The red beds at the bottom of the hole in sec. 32 appear to have been different from the overlying deposits of clay, sand, and conglomerate. Tentatively, the red material and red beds in the two holes are suggested to be parts of the Cloudburst formation, although the assignment is based on meager evidence, particularly from the hole in sec. 32.

The Cloudburst formation, particularly the massive flows of the volcanic unit and the lower parts of the fanglomerate exposed north of the Turtle fault, is extensively intruded by bodies of andesite, latite, rhyolite, and basalt. These intrusive bodies are not shown separately in plate 1, but are shown schematically in figure 2. In the vicinities of the larger of these intrusive bodies, the fanglomerate is indurated and epidotized. On the east side of the San Pedro Valley, indurated and epidotized volcanic and fanglomerate rocks also are exposed in the Galiuro Mountains.

VOLCANIC UNIT

The volcanic unit of the Cloudburst formation is best exposed in the northwest corner of the area, where it is composed predominantly of andesitic flows and some intercalated clastic beds. The flows are typically dark purple to maroon and brown and generally strike northwesterly with dips of about 45° NE. The total thickness of the volcanic unit locally may exceed 3,000 feet. The volcanic unit is missing in sec. 4, T. 9 S., R. 16 E. Apparently the volcanic unit filled local depressions in the topography and was overlapped by the fanglomerate. These relationships are shown diagrammatically in plate 3, block A.

FANGLOMERATE UNIT

The fanglomerate unit of the Cloudburst formation is developed best along the upper parts of Cloudburst and Tucson Washes west of Red Hill. Here the fanglomerate consists predominantly of cobble to boulder conglomerate but also contains beds of impure arkose, graywacke, and, more rarely, sandy mudstone. The fanglomerate may be divided into two subunits—the lower, containing predominantly volcanic rock fragments, and the upper, composed predominantly of granitic rock fragments. Near the base of the lower subunit there are a few intercalated andesitic flows; near the top of the upper subunit there are a few discontinuous lenses of rhyolitic tuff. Between the two subunits there is a transition zone that includes lenses composed of a mixture of rock types intertongued with lenses composed predominantly of either volcanic or granitic rocks. The fanglomerate is silicified in those places where it has been intruded, as well as where it is below the rhyolitic tuff lenses; elsewhere, the beds are generally moderately well cemented by calcium carbonate, and calcite veining is common along fractures.

The color of the lower part of the fanglomerate is typically gray maroon. The basal beds are made up of thin-bedded sandy mudstone and muddy sandstone and a few lenses of conglomerate as much as 2 feet thick. In addition to volcanic and granitic rocks, the basal beds contain quartzite, pink and gray limestone, and schistose and lime-silicate fragments, which are absent higher in the section. Individual lenses are moderately well sorted and well bedded. Above the basal beds, the lower part of the fanglomerate contains pebbles and cobbles and, less commonly, small boulders composed mainly of subangular to subrounded fragments of andesite and felsite. Granitic fragments, although not predominant, are conspicuous because of their light color and large size. There are occasional fragments of monzonite porphyry and diabase. The monzonite porphyry is similar in appearance to the quartz monzonite porphyry related to the San Manuel copper deposit. The matrix is composed of quartz, feldspar, and chips of volcanic rocks as large as small pebbles.

The upper part of the fanglomerate is made up largely of quartz monzonite fragments. Individual lenses range in color from gray to light reddish brown, and in many lenses the arkosic matrix is silty and greenish. Locally the beds are grayish yellow. The quartz monzonite fragments contain large phenocrysts of pink and red feldspar. The fragments are as much as 5 feet in maximum dimension but more commonly are of pebble to small boulder size. Sorting and bedding are less well developed in the upper part of the fanglomerate than in the lower part.

Because the fanglomerate has been extensively intruded, sheared, and faulted, its thickness west of Red Hill can be estimated only—about 5,000 feet.

AGE AND CORRELATION

The Cloudburst formation is considered to form a unit because its volcanic flows and fanglomerate lenses intertongue. These rocks also were considered to form a unit by Peterson (1938), Creasey (1950), and Wilson (1957). Steele and Rubly (1947) and Schwartz (1953), however, considered the fanglomerate to be a part of the Gila(?) conglomerate. This designation is rejected by the writer for three reasons: (1) the intertonguing demonstrates the stratigraphic continuity between the volcanic and fanglomerate units of the Cloudburst formation; (2) the Cloudburst formation is an integral part of the mountain block that forms the Black Hills in contrast to most sediments referred to the Gila conglomerate which characteristically fill the basins; and (3) there is a disconformity between the top of the fanglomerate and the overlying deposits, and the overlying deposits contain fragments of the fanglomerate, indicating a hiatus between the Cloudburst and subsequent deposition.

The interpretation of the age of the Cloudburst formation is complicated by a lack of datable material. Correlations to other deposits are based principally on lithologic, stratigraphic, and structural similarities and must be considered tentative. Furthermore, the Cloudburst formation exposed west of Mammoth in the Black Hills may have a different range in age than the Cloudburst in the Galiuro Mountains. The following discussion applies only to the age and correlation of the Cloudburst formation exposed in the Black Hills because only this part of the formation was examined in detail. The interpretation of the age and correlations of the Cloudburst formation in the Black Hills are shown schematically in figure 2.

Fragments of the quartz monzonite porphyry related to the San Manuel copper deposit in the Cloudburst formation, as exposed in the Black Hills, indicate that the Cloudburst here is younger than the porphyry. This quartz monzonite porphyry is dated by the alpha-lead age of its zircon separates to be about 120 million years old (Damon, 1959). Although the dating is only preliminary, the quartz monzonite porphyry seems to be late Mesozoic and probably Cretaceous in age. The Cloudburst is also, as shown on pages E27–E29, older than the oldest rocks involved only in the basin-and-range deformation, which are definitely post-early Miocene and pre-middle Pliocene. The Cloudburst formation, therefore, was deposited some time between latest Mesozoic and late Tertiary time. The lack of fossil and geochemical dates precludes precise dating at this time, and some authors have suggested Upper Cretaceous(?) (Wilson, 1957; 1960) or Late Cretaceous or early Tertiary (Creasey, 1950) ages for the Cloudburst formation west of Mammoth. Although the possibility of a very Late Cretaceous age for the basal part of the Cloudburst cannot be denied, for the reasons itemized in the following paragraphs, my contention is that the Cloudburst formation in the Mammoth area, and particularly in the Black Hills, is probably early(?) to middle(?) Tertiary.

1. The suggested Late Cretaceous age is based in part on the erroneous premise that deposits similar to the Cloudburst north of Mammoth form a continuous series with Late Cretaceous beds. Ross (1925) considered the volcanic strata, including boulder conglomerate, in the vicinity of Christmas and the Reed basin, about 25 miles north of Mammoth, to be of Late Cretaceous age because he interpreted the contact with the underlying sandstone and shale as interstratified. The Late Cretaceous age of the sandstone and shale was established on the basis of a few invertebrate fossils. Courtright (1958, p. 8), however, points out that the volcanic strata, including

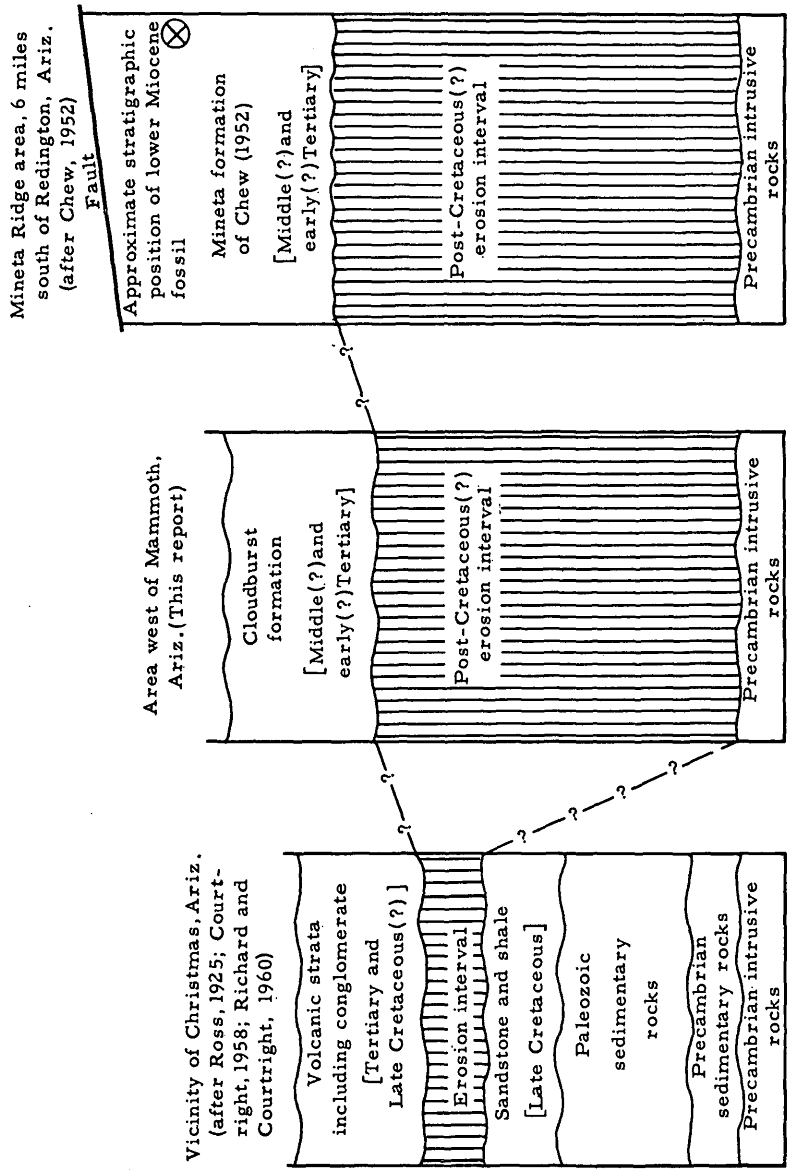

FIGURE 2.—Diagram showing the age relationships of the Cloudburst formation west of Mammoth, the volcanic strata including conglomerate in the vicinity of Christmas and the Reed basin (Ross, 1925), and the Mineta formation of Chew (1952), as interpreted in this report.

conglomerate, lie disconformably on the sandstone and shale. Courtright further states that "* * * unconformable relationships are indicated in adjacent areas by aerial photo patterns * * *" and that the volcanic strata overlie Paleozoic deposits west of Christmas. The fossil evidence for the Late Cretaceous age is confined to the sandstone and shale which lie unconformably below the volcanic conglomerate. Consequently, the Late Cretaceous age of the sandstone and shale cannot be extended without question to the overlying volcanic strata including conglomerate near Christmas and, by inference, to the Cloudburst formation.

2. The basal fanglomerate of the Cloudburst contains fragments of quartz monzonite porphyry that are related to the San Manuel copper deposit. The quartz monzonite porphyry is of probable Cretaceous age, and, therefore, the Cloudburst formation is younger than these rocks. Although the possibility that the Cloudburst may be Late Cretaceous is not eliminated, this possibility is minimized for the next three reasons.

3. The local absence of Cretaceous(?) and Paleozoic rocks suggests a long period of erosion in the Mammoth area after the intrusion of the quartz monzonite porphyry and before the deposition of the Cloudburst. In contrast, the volcanic strata including conglomerate near Christmas lie unconformably on Upper Cretaceous sediments, which in turn overlie a large part of the Paleozoic section common to southern Arizona. This relationship suggests that the period of erosion between the deposition of the Upper Cretaceous sandstone and shale, and the volcanic strata including conglomerate in the Christmas area, was short compared to the erosion interval preceding the Cloudburst formation. It is suggested that the basal part of the volcanic strata including conglomerate near Christmas may be older than the basal part of the Cloudburst formation in the Mammoth area and that these two units do not correlate throughout.

4. The Cloudburst formation is lithologically, stratigraphically, and structurally similar to the volcanic strata including conglomerate near the town of Christmas and to the lower part of the Mineta formation (Chew 1952; Chew [2]). All three are characterized by thick fanglomerate deposits that were deformed and eroded before the deposition of the rocks which were involved only in basin-and-range faulting and folding. The matrix of the Cloudburst is composed principally of quartz, feldspar, and chips of volcanic rocks; in this respect, except for the volcanic chips, it is more similar to the matrix of the conglomerate constituting the lower unit of the Mineta formation than it is to the matrix of the conglomerate in the Christmas area. The Mineta formation lacks a volcanic unit similar to that of the Cloud-

[2] Chew, R. T., 1952, Geology of the Mineta Ridge area, Pima and Cochise Counties, Arizona: Arizona Univ., unpublished master's thesis.

burst formation, but this lack does not invalidate the comparison between the two units, because volcanic units may pinch out within short distances. For example, the volcanic unit of the Cloudburst is absent 2 miles southwest of Red Hill, where the fanglomerate rests directly on the Precambrian quartz monzonite.

5. South of Red Hill, the Cloudburst and the San Manuel formation are nearly conformable and their textures are similar.

The lithologic similarity of the fanglomerate of the Cloudburst formation to the lower part of the Mineta formation, and the textural similarity of the top of the Cloudburst to the overlying San Manuel, make the correlation of the fanglomerate of the Cloudburst formation to the lower part of the Mineta formation preferable to its correlation to the complete section of the volcanic conglomerate in the Christmas area.

The period of erosion after the deposition of Cretaceous(?) rocks in the Mammoth area was probably longer than the period of erosion between the deposition of the Upper Cretaceous sandstone and shale and that of the volcanic conglomerate in the Christmas area. Therefore, the probability of the Cloudburst formation west of Mammoth in the Black Hills being in part Late Cretaceous in age is minimized and an early(?) to middle(?) Tertiary age appears to be more likely.

The age of the Cloudburst in the Black Hills does not necessarily represent the total range in age of other deposits with which the Cloudburst may correlate in part. For example, the highly indurated Cloudburst formation exposed in the Galiuro Mountains may be older than the basal part of the Cloudburst west of Mammoth. Consequently, the age of the Cloudburst formation in the Mammoth area is Late Cretaceous(?) and Tertiary.

ORIGIN

The Cloudburst formation appears to have been laid down in a continental environment characterized by high relief. The high relief is suggested by the fanglomeratic nature of the sediments. The occurrence of contemporaneous vulcanism also suggests that the Cloudburst was laid down during a period of tectonic unrest. Lance (1960, p. 157) summarizes the period that included the deposition of the Cloudburst as follows: "Orogeny in southern Arizona was largely continuous from near the end of the Cretaceous into Miocene time." Although the orogeny was widespread throughout the region, it did not occur everywhere at the same time. The extent of the basin containing the Cloudburst deposits and its relationships to other nearly contemporaneous areas of deposition, including those in the Christmas and Mineta Ridge areas, only can be conjectured at this time.

MIDDLE(?) TERTIARY VOLCANIC ROCKS

On the east side of the valley, a thick sequence of volcanic rocks constitutes a large part of the Galiuro Mountains. In the small area mapped (pl. 1), these volcanic rocks consist of about 1,800 feet of flows, agglomerates, tuffs, and welded tuffs, ranging in composition from basalt to rhyolite, all of which dip at low angles to the east and northeast.

The volcanic rocks in the Galiuro Mountains in the mapped area lie with angular unconformity on older volcanic rocks and on interbedded fanglomerate deposits that are tentatively correlated with the Cloudburst formation of Late Cretaceous(?) to middle(?) Tertiary age. Southeast of Redington, the volcanic pile forming the Galiuro Mountains rests with angular unconformity on Cretaceous(?) and Tertiary(?) sedimentary rocks (Heindl, 1952, pl. 10) which probably correlate with the Mineta formation of Chew (1952). The sequences of volcanic rocks in the Galiuro Mountains near Mammoth and southeast of Redington are similar and the Cretaceous(?) and Tertiary(?) sedimentary rocks southeast of Redington are lithologically and stratigraphically similar to the Mineta formation (Heindl, 1952, pl. 10 and unpublished notes). The upper part of the Mineta formation is at least lower Miocene, and therefore the lower age limit of the volcanic rocks in the Galiuro Mountains is probably post-early Miocene. Their upper age limit can be defined only by their debris which forms a large part of the deposits of the Gila group. Part of the Gila group is Pliocene and part may be somewhat older. Consequently, the volcanic rocks in the Galiuro Mountains are assigned tentatively to the middle(?) Tertiary, although they probably are restricted to some part of Miocene time.

Although these middle(?) Tertiary volcanic rocks are not reported on the west side of the San Pedro River in the Mammoth area, their considerable thickness in the fault-line scarp of the Galiuro Mountains suggests that at one time they must have extended farther to the west. More than 2 miles west of the Galiuro Mountains, volcanic rocks, penetrated in a bore hole in sec. 19, T. 8 S., R. 18 E., below an altitude of about 2,700 feet, are similar in composition to those exposed in the Galiuro Mountains and are tentatively assigned to this unit (pl. 1). Furthermore, fragments as large as small cobbles in the volcanic and granitic conglomerate on the west side of the valley, about 10 miles west of the Galiuro Mountains, are in part composed of andesite, felsite, and rhyolite that are similar in composition and texture to volcanic rocks of the middle(?) Tertiary volcanic sequence in the Galiuro Mountains. These admittedly tenuous lines of evidence suggest that at one time the middle(?) Tertiary volcanic rocks extended westward far enough to supply moderately coarse debris to the deposits on the west side of the valley.

TERTIARY AND QUATENARY GILA GROUP

NOMENCLATURE AND DEFINITION

The largest part of the alluvial deposits within the lower San Pedro Valley previously have been referred to the Gila, or Gila(?) conglomerate (Ransome, 1919; Bryan, 1926; Peterson, 1938; Steele and Rubly, 1947; Creasey, 1950; Schwartz, 1953; Pelletier, 1957; Wilson, 1957, 1960). The term "Gila conglomerate" was originally applied to undeformed or mildly deformed alluvial deposits in eastern Arizona and western New Mexico (Gilbert, 1875). The closest of these is about 80 miles east of the lower San Pedro Valley. Subsequently, the term was extended to other alluvial deposits in Arizona on the basis of three criteria—textural similarity, lithologic similarity, and, in some places, physical continuity.

During the past few years, I have maintained (Heindl, 1954) that the use of Gila conglomerate as a formation is unsatisfactory because "* * * it includes a substantial proportion of deposits other than conglomerates; it suggests that deposits in separate basins are identical; its use masks sequences of alluvial deposits within individual basins; and it oversimplifies a complex history." Recently it was proposed (Heindl, 1958) that the term "Gila" should be raised to group status to include "* * * those deposits that appear to have been laid down during a certain more or less contemporaneous phase of the development of large structural troughs of the basin-and-range variety * * *" in southeastern Arizona and southwestern New Mexico. In general, the Gila group was proposed to include deposits derived from uplifted ranges that partly filled the depressed areas between them as a result of the most recent major structural deformation. The Gila group includes deposits in depositional or normal-fault contact with the bedrock in adjacent mountains and represents a nearly continuous aggradational sequence. Alluvial deposits not included in the Gila group are (1) deposits clearly related to the most recent major cycle of degradation; (2) somewhat older deposits that are clearly younger than the highest erosional surface cut on the basin fill; and (3) highly deformed alluvial deposits, similar to those of the Cloudburst formation and the Mineta formation of Chew (1952), that are clearly related to rocks older than the basin fill or are in marked angular unconformity with the basin fill.

The Gila group is proposed to include all deposits younger than the middle(?) Tertiary volcanic rocks and older than the late Quaternary deposits. In ascending order, these form the San Manuel, Quiburis, and Sacaton formations.

The inclusion of the San Manuel formation in the Gila group may be open to question because it appears to have been deposited in a valley antedating the structural trough that now forms the San Pedro Valley. However, the San Manuel formation meets the other criteria for the Gila group—it is composed of fragments derived from the adjacent mountains and is in part in depositional contact with the bedrock of these mountains. In addition, it appears locally to grade into the Quiburis formation, which fulfills all criteria for a unit in the Gila group. Furthermore, the sedimentary characteristics of the San Manuel formation are those commonly associated with Gila group deposits. For these reasons, and because for many years these rocks have been considered by geologists working in the Southwest to be part of the Gila conglomerate, the San Manuel formation is included here in the Gila group.

The relationship between the San Manuel and Quiburis formations is not shown clearly in any one exposure. The topographic and structural positions of the two formations, however, and the greater degree of deformation of the San Manuel, make their general age relationship obvious. The two formations are separated along the San Manuel and Cholla faults. On the south side of Mammoth Wash and east of the Cholla fault, a large block of the San Manuel formation, several feet in maximum dimension, lies within the Quiburis. At the south end of the San Manuel fault, in the NW¼ sec. 18, T. 9 S., R. 17 E., where exposures are poor, the San Manuel formation apparently grades upward into the Quiburis formation. The proximity of faulted and probable gradational contacts between the upper two formations emphasizes the contemporaneity of deformation and deposition in the accumulation of alluvial deposits in intermontane troughs.

Drillers' logs from bore holes between the Cholla fault and the San Pedro River suggest that the Quiburis overlies conglomerate characterized by a red or red-brown color and by red beds. The meager available data suggest that the composition of these deposits is similar in part either to that of the fanglomerate of the Cloudburst formation or to that of the San Manuel formation, but because of the prevailing red-brown or red colors reported, they are tentatively considered to be equivalent to the Cloudburst formation.

The Sacaton formation is deposited within a valley that was entrenched into the Quiburis formation and is nearly conformable with it. The period of erosion between the deposition of the Quiburis and Sacaton formations represents a major cycle of degradation. However, the Sacaton formation is included in the Gila group because it was derived from the adjacent mountains and because it was laid down before the last general period of degradation that resulted in the present topography. It may be that the Sacaton formation and the period of erosion preceding it represent a transitional phase between predominantly aggradational cycle represented by the San Manuel and Quiburis formations and the predominantly degradational cycle that followed the deposition of the Sacaton.

In summary, the Gila group in the Mammoth area includes three units, all of which are similar in many respects but only one of which—the Quiburis formation—satisfies the classical concept of basin-filling deposits. These formations, which heretofore have been considered to represent a single nearly continuous cycle of aggradation are actually composed of several units that reflect several distinct events in the geologic history of the area.

SAN MANUEL FORMATION

The San Manuel formation of the Gila group is named for the San Manuel mine near Red Hill, in whose vicinity the formation is well exposed. (See pl. 1.) The San Manuel formation is restricted in this area to the west side of the San Pedro Valley and includes most of the exposures between the San Manuel fault and the Precambrian quartz monzonite at the northwest end of the Santa Catalina Mountains.

The San Manuel formation is undifferentiated southeast of a line between the quartz monzonite in sec. 28, T. 9 S., R. 16 E., and the San Manuel fault in sec. 1, T. 9 S., R. 16 E. North of this line, the San Manuel formation is divided, in ascending order, into a local conglomerate member at the base, the Kannally member, and Tuscon Wash member. The Kannally member includes two areas of breccia deposits which are shown separately on plate 1.

The San Manuel formation of the Gila group is composed principally of conglomerate whose fragments range in size from boulders several feet in maximum dimension to pebbles. Most of the fragments, including the boulders, are composed of gray quartz monzonite. The degree of rounding differs with the type of material—the quartz monzonite is well rounded; most of the mafic igneous rocks are subangular to subrounded; and the felsite and rhyolite are subangular to angular. The degree of sorting and uniformity of bedding differ considerably. Near the flanks of the Santa Catalina Mountains, the fragments are predominantly large, the sorting is poor, and the lensing may be either stubby or attenuated; away from the mountains, the average fragment size becomes progressively smaller, individual lenses are well developed, and the sorting within lenses is fair. The unit as a whole is moderately well consolidated, and the lime content, although generally low, appears to increase upward in the section. The lower member erodes into rounded slopes where it is not undercut and stands up in steep ledgy cliffs where dissection has been rapid.

There is no well-defined type section of the San Manuel formation, although it is well exposed along the major washes south and west of Red Hill and highway and railroad cuts. Detailed descriptions of some exposures are presented in the sections describing the Kannally and Tuscon Wash members. In addition, the formation is excellently exposed in Cottonwood and Smelter Washes, although the top and bottom of the formation are truncated by faults.

The basal contact of the San Manuel formation is exposed in three areas: (1) in the vicinity of the SW¼ sec. 32, T. 8 S., R. 16 E., where the local conglomerate member is exposed; (2) along a generally north-south line between the SE¼ sec. 28, T. 8 S., R. 16 E., and the NW¼ sec. 10, T. 9 S., R. 16 E., where the Kannally member rests upon the Cloudburst formation and the quartz monzonite; and (3) along the northwest flanks of the Santa Catalina Mountains, where the Kannally member rests unconformably on the quartz monzonite. In two of these areas, on opposite sides of a large body of Cloudburst rocks centering in secs. 32 and 33, T. 8 S., R. 16 E., the relationships of the San Manuel to the underlying Cloudburst are different. On the west side (see item 1), the local conglomerate member at the base of the San Manuel formation is in sharp angular unconformity with the Cloudburst formation. In contrast, on the east side (see item 2), the Kannally member of the San Manuel rests nearly conformably upon the Cloudburst formation. The Kannally member of the San Manuel is so nearly conformable to the Cloudburst in this area that it is difficult to distinguish the contact in the absence of the topmost rhyolitic tuff beds of the Cloudburst formation. Although this contact appears to be nearly conformable, the Kannally member overlaps the Cloudburst formation to rest also on the quart monzonite. The significance of the differences between the basal contacts of the San Manuel formation in the two areas is discussed in the section "Deposition of San Manuel formation."

UNDIFFERENTIATED SAN MANUEL FORMATION

Where the San Manuel formation is undifferentiated, the quartz monzonite fragments are abundant near the Santa Catalina Mountains, and volcanic fragments, particularly a grayish-lavender felsite, are common to the north and east of the probable fault in sec. 9, T. 9 S., R. 16 E. The volcanic part of the San Manuel also contains fragments of andesite, flow-banded rhyolite, biotite rhyolite, welded tuff, and dacite(?). Quartz monzonite is common, invariably forming the larger fragments. The beds are comparatively thin, ranging from sandy mudstone layers less than an inch thick to conglomerate beds about 18 inches thick. Large boulders are locally surrounded by thin fine-grained beds. In Cottonwood and Smelter Washes immediately southwest of the San Manuel fault, the proportion of volcanic material, particularly the gray felsite, increases upward in the section, and the average size of the fragments in the conglomerate also increases as the fault is approached.

In the northeastern half of the exposures of the undifferentiated San Manuel, small faults and fractures are abundant but are too small to show on plate 1. Many of these dip steeply to the southwest as well as to the northeast, but the amount of throw is not known because marker beds are lacking. In some exposures, particuarly in sec. 11, T. 9 S., R. 16 E., the deformation is intense. The San Manuel formation is estimated to be about 5,000 feet thick; faulting prevents more accurate determination of the thickness.

LOCAL CONGLOMERATE MEMBER

A local basal conglomerate unit of the San Manuel formation crops out along upper Tucson Wash, centering in sec. 5, T. 9 S., R. 16 E. This unit was deposited on the Cloudburst formation, and it is separated from the rest of the San Manuel formation by faults.

The local basal conglomerate member consists mainly of red quartz monzonite fragments, but in its basal part it contains volcanic fragments of the Cloudburst formation and felsite and rhyolite. This unit is generally thickly bedded and poorly sorted, and the fragments, except those composed of rounded quartz monzonite, are angular to subrounded. The unit is cut by small faults, and the maximum thickness of the beds exposed is estimated to be not more than 1,000 feet.

The local basal conglomerate overlies the Cloudburst formation with a distinct angular unconformity. It is tentatively considered to be a locally distinctive unit probably equivalent to the basal part of the Kannally member elsewhere.

KANNALLY MEMBER

Alluvial deposits, characterized by the widespread distribution of large boulders of gray quartz monzonite, overlie the fanglomerate of the Cloudburst formation and the Precambrian quartz monzonite and constitute the Kannally member of the San Manuel formation. Although alluvial deposits are not sufficiently well exposed along Kannally Wash (pl. 1) to justify the use of the name for the unit, the lack of other unpreempted names in the area necessitates its adoption. The Kannally member constitutes the main part of the tilted alluvial deposits, younger than Cloudburst, generally south and west of Red Hill.

West of Red Hill, the Kannally member rests on an erosion surface of moderate relief cut on the fanglomerate of the Cloudburst formation, with which it is nearly conformable, and in turn the Kannally member is overlain disconformably by the Tucson Wash member. Southward the Kannally member merges with the undifferentiated sequences of the San Manuel formation.

Where the Kannally member lies on Precambrian quartz monzonite, its fragments are composed predominantly of the underlying rock. The basal part of the Kannally member is well exposed along the new highway in the center of sec. 20, T. 9 S., R. 16 E. The boulders of gray quartz monzonite are rounded to well rounded and are as much as 10 feet in maximum dimension. The second most abundant constituent is a gray-green quartz monzonite porphyry whose fragments are as large as cobbles. There are a few fragments of diabase and other basic intrusive rocks, aplite, deeply weathered volcanic rocks, olive-green phyllite, and, rarely, quartzite. The matrix is a weakly consolidated pebbly arkose. Bedding is distinct only locally and the sorting generally is poor.

About 400 feet stratigraphically above the base of the Kannally member, as exposed along a highway in the NE¼ sec. 20, the proportion of rocks other than quartz monzonite increases, and the average size of the fragments is smaller, ranging in size from pebble to cobble. The matrix commonly contains large amounts of silt. About 2,000 feet above the base, along the highway in the S½ sec. 16, T. 9 S., R. 16 E., most of the material ranges in size from silty coarse sand to small pebble conglomerate derived principally from quartz monzonite and monzonite porphyry, and the unit is thinly and neatly bedded.

East of these fine-grained deposits in the NW¼ sec. 15, T. 9 S., R. 16 E., the Kannally member again is composed of thick lenses, containing many large boulders as much as 5 feet in maximum dimension. This zone of boulder conglomerate is at least several hundred feet thick and is separated from the coarse deposits along the Santa Catalina Mountains by a zone of fine-grained deposits. This separation, combined with the large size of the boulders, suggests that the source of these deposits is formerly high quartz monzonite areas to the north and east rather than the Santa Catalina Mountains.

The Kannally member strikes generally northwest and dips to the northeast. Where it overlies the gray quartz monzonite of the Santa Catalina Mountains, the unit dips from 15° to 20° NE., and these dips steepen to 45° near the San Manuel fault. The apparent thickness is excessive because of faulting, and the true thickness is estimated to be between 3,000 and 5,000 feet.

The Kannally member includes two areas of breccia deposits, centering in the NE¼ sec. 7 and the NW¼ sec. 9, T. 9 S., R. 16 E. The breccia deposits crop out along a broad, poorly defined zone of intense crushing. The breccias are of two types. The first is composed of dark-green diabasic fragments set in a matrix of smaller fragments of the same composition and red-brown sandy silt. The breccia appears to be interbedded with beds of the Kannally member. The second type is composed of indurated graywacke, banded cherty limestone, and large, almost mappable, blocks of Paleozoic quartzite and limestone and Cretaceous(?) phyllite. These blocks have a general northwest alinement and small to moderate southwest dips. The material within these blocks has been comminuted and recemented. Between the larger blocks there are areas of conglomerate that are in part similar to beds of the Kannally member.

Although the origin of these breccia deposits is uncertain, they probably are sedimentary deposits associated with tectonic movement contemporaneous with the deposition of the Kannally member of the San Manuel formation. Similar breccia deposits are reported in the Tortilla Mountains, about 30 miles north of Mammoth (Benedict and Hargraves [3]).

TUCSON WASH MEMBER

The Tucson Wash member of the San Manuel formation is best exposed along the southwest side of the San Manuel fault near Red Hill. It is well exposed along Tucson Wash, after which the member is named, and in road cuts along the new highway and railroad connecting the town of San Manuel and the San Manuel mine near Red Hill. The Tucson Wash member lies disconformably on an erosional surface cut on the Kannally member.

The Tucson Wash member is dark gray to purplish gray, and it characteristically contains boulder-size fragments of volcanic and fanglomerate rocks derived from the Cloudburst formation as well as granitic rocks derived from the quartz monzonite. South of Mammouth Wash, most of the fragments are of gray felsite, and flow-banded rhyolite fragments are not uncommon. Fragments derived from the Cloudburst formation in the Tucson Wash member distinguish it from the Kannally member. The Tucson Wash member becomes noticeably finer grained to the south, as it merges into the undifferentiated part of the San Manuel formation.

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[3] Benedict, P. C., and Hargraves, R. B., 1953, A folded overthrust fault and sediments derived from the scarps of overthrust and normal faults in the Tortilla Mountains, Arizona: unpublished paper, presented at a meeting of Geol. Div., Ariz. Sec., Am. Inst. Mining Metall. Engineers, Tucson, Ariz., December 1953.

The Tucson Wash member is more than 1,000 feet thick, but the unit is intensely faulted, precluding an accurate measurement of its thickness.

QUIBURIS FORMATION

The name Quiburis formation is here proposed for the valley-wide alluvial deposits that now underlie most of the San Pedro Valley. The Quiburis formation is named for Lake Quiburis. The name was proposed by Blake (1902) for the ancient lake in the San Pedro trough in which the fine-grained deposits in the center of the valley were laid down. The term "Quiburis" is derived from an early Spanish name for the San Pedro River, the Rio de San Joseph de Quiburi, and also from the name of a long-abandoned Indian settlement a few miles south of Benson (Granger, 1960).

The Quiburis formation of the Gila group crops out extensively in the San Pedro Valley between the Black Hills on the west and the Galiuro Mountains on the east and includes two units which are not mapped separately. The lower unit includes the fine-grained deposits exposed in the center of the valley and the coarser deposits into which they grade laterally. The upper unit of the Quiburis formation is recognizable only on the east side of the valley and is composed of conglomerate that disconformably overlies the lower unit.

The relationships of the Quiburis and San Manuel formations already have been discussed (p. E15). Between the Cholla fault and the San Pedro River, the Quiburis formation is assumed to overlie Cloudburst deposits. On the east side of the valley, cuttings from a drilled hole in sec. 19, T. 8 S., R. 18 E., show that the Quiburis formation lies on a sequence of volcanic, tuffaceous, and alluvial rocks similar in composition to the middle(?) Tertiary volcanic rocks in the Galiuro Mountains, about 3 miles to the east. The Quiburis formation is overlain disconformably by the Sacaton formation in the central part of the valley and by younger alluvial deposits along the river and major tributaries. Elsewhere the Quiburis has been extensively eroded and underlies the Tombstone and Whetstone pediments in addition to younger surfaces.

No single type section for the Quiburis formation is adduced at this time, because rapid vertical and lateral changes preclude any single area of exposure being considered as typical. Also, a large part of the formation is known only from bore holes. The following paragraphs, however, describe some of the variations in the formation and present a sort of "three-dimensional view" which could not be encompassed in a single vertical stratigraphic section.

In the center of the valley, the lower unit of the Quiburis formation consists of lake beds of finely laminated very light brown to pinkish mudstone, sandy mudstone with stringers of small pebbles, interbedded tuff, and some pumiceous and diatomaceous deposits. Gypsum occurs in these fine-grained deposits as irregular thin beds, in disseminated particles, and along seams and fractures.

The fine-grained deposits on both sides of the valley grade outward rapidly into grayish-brown pebbly sandstone and sandy pebble conglomerate. On the west side, the conglomerate is composed of a mixture of volcanic and quartz monzonite fragments and minor amounts of light-colored quartzite, gray-green graywacke, and phyllitic rocks. The predominant volcanic rock is gray felsite. The matrix is a light-brown silty sandstone to sandy siltstone, either weakly cemented with lime or bonded by fine clastic particles. The conglomerate beds are seldom composed of fragments larger than small cobbles.

On the east side of the San Pedro River, the lake beds grade eastward into pebbly conglomerate along a general north-northwest line, passing through the center of sec. 36, T. 8 S., R. 17 E. Half a mile east of this line, the beds that can be traced into the fine-grained deposits pass below the surface. The lower 300 feet of deposits in the hole in sec. 19, T. 8 S., R. 17 E. contain a high proportion of clay and may be a subsurface extension of the lower unit of the Quiburis formation.

At an altitude of about 3,100 feet in the center of sec. 36, T. 8 S., R. 17 E., the lower unit of the Quiburis formation is overlain by pebbly to bouldery conglomerate of the upper unit. The upper unit extends eastward to the Copper Creek fault, along which it has an exposed thickness of about 700 feet. The upper unit contains channel-type crossbedding and is poorly sorted, bedded, and consolidated.

The fragment composition in both the lower and upper units of the Quiburis formation on the east side of the San Pedro River is nearly the same and includes basalt, andesite, and a variety of felsite and rhyolite flow rocks, welded tuff, and intrusive rocks. Boulders of diorite, andesite, and spherulitic rhyolite are common. Minor rock types include an andesite porphyry, epidotized volcanic conglomerate, and schist.

On the west side of the river near the Cholla fault, the Quiburis formation, where it overlies the red-brown deposits assigned to the Cloudburst formation, ranges in thickness from about 300 to 700 feet. Fine-grained gypsiferous deposits, containing some gravel and sand similar to exposed parts of the Quiburis along the San Pedro River, are reported to depths of about 1,400 feet below the level of the river in the well in sec. 32, T. 8 S., R. 17 E. The exposures of the formation along the river are locally as much as 300 feet thick, indicating a total local thickness of about 1,700 feet for the Quiburis formation in the central part of the valley. On the east side of the valley, in the drilled hole in sec. 19, T. 8 S., R. 18 E., the Quiburis formation is about 500 feet thick and about 500 feet of the unit is exposed above the site of the drilled hole; these figures indicate that the total thickness of the Quiburis at this point is about 1,000 feet.

Except near the boundary faults along the Galiuro Mountains and the Black Hills, the Quiburis formation dips at low angles, ranging from about 50° to horizontal, into a central north-northwest-trending shallow syncline; the axis lies roughly parallel to and about 2 miles east of the San Pedro River.

SACATON FORMATION

Alluvial deposits consisting predominantly of poorly consolidated sand and gravel are exposed extensively along the steep bluffs rising above the flood plain of the San Pedro River and its tributaries. These deposits are here named the Sacaton formation for their exposures in the vicinity of the Sacaton Ranch, about 12 miles southeast of Mammoth. The Sacaton formation is separated from the Quiburis formation because it lies disconformably on an erosion surface cut into the Quiburis. The base of the Sacaton formation in the central part of the San Pedro Valley is marked by a conspicuous bouldery channel fill.

On the west side of the valley, the Sacaton formation above its basal bed is composed of unconsolidated granule to pebble conglomerate made up mainly of feldspar and quartz fragments. Fragments of felsite, andesite, and quartzite are common and there are minor quantities of diabase, olive-green graywacke, and phyllite. The matrix is composed of sand and a small amount of silt. Cement either is lacking or is weak and consists of lime. On the east side of the valley, the Sacaton formation is much less well developed than on the west side and consists for the most part of gravel deposits composed of volcanic materials. The Sacaton formation attains a maximum thickness of about 250 feet along the axis of the valley and thins progressively outward toward the mountains.

In the cliffs along the San Pedro River and some of its tributary washes, the basal unit of the Sacaton formation is a boulder to pebble gravel as much as 20 feet thick. The deposits consist predominantly of subrounded to well-rounded fragments of quartz monzonite and volcanic rocks characteristic of the Santa Catalina and Galiuro Mountains in the immediate vicinity. In addition, they contain fragments of Paleozoic limestone, red calcareous mudstone, marble, and gneiss that are exposed south of and upstream from the area. The Sacaton formation lies on a scoured surface cut into the underlying fine-grained deposits of the upper member of the valley fill.

The basal channel fill is generally parallel to the course of the San Pedro River and 30 to 50 feet above its flood plain. The Sacaton and the Quiburis formations are essentially conformable along the river, but along the tributary washes away from the center of the valley, their contact is marked by a small angular discordance.

AGE AND CORRELATION

The age of the deposits constituting the Gila group in the Mammoth area in the lower San Pedro Valley cannot be given with certainty, but tentatively it appears to range from middle(?) Tertiary to early Pleistocene. The age of the San Manuel and Sacaton formations is surmised from their stratigraphic positions; the age of the exposed parts of the Quiburis is obtained by correlating them, on the basis of lithologic similarity, topographic position, and apparent continuity, with fossiliferous beds to the south.

The age of the Gila group in the lower San Pedro Valley is given here as Tertiary and Quaternary. This is a broader age span than the Pliocene and Pleistocene span usually ascribed to deposits heretofore assigned to the Gila congolomerate. A Tertiary and Quaternary age is assigned to the Gila group in this area because: (1) The Gila group includes 1,400 feet of buried sediments assigned to the Quiburis formation whose exposed beds, ranging in thickness from about 300 to 700 feet, range in age from about middle Pliocene to probable early Pleistocene; and (2) the San Manuel formation, which antedates probable middle Pliocene beds, is estimated to be about 5,000 feet thick and may represent deposition during middle(?) Tertiary, probably including parts of Pliocene and Miocene, time. The age span suggested for the Gila group in this valley may not coincide with the age span of probably partly equivalent alluvial deposits exposed in nearby valleys.

In the lower San Pedro Valley, middle(?) Pliocene fossils have been collected from the lower fine-grained unit of the Quiburis formation south of Mammoth at an altitude of about 2,500 feet, and middle Pliocene fossils have been collected from fine-grained deposits near Redington at an altitude of about 3,200 feet (J. F. Lance, oral communication, 1953 and 1959). Fine-grained deposits near Benson (fig. 1), about 50 miles south of and about 1,200 feet higher than Mammoth, are considered to be late Pliocene to early Pleistocene in age (Gazin, 1942). The highest beds of the Quiburis formation are at about the same elevation as the fine-grained deposits near Benson. The age of the exposed part of the upper member is therefore tentatively considered to be Pliocene and Pleistocene; the age of the base of the nearly 1,400 feet of unexposed beds of the Quiburis formation below the elevation of the San Pedro River south of Mammoth must be early Pliocene in part and may be older.

The age of the San Manuel formation cannot be stated with certainty. It is younger than the Cloudburst formation of Late Cretaceous(?) and Tertiary age. The upper part of the undifferentiated San Manuel formation and the Tucson Wash member are younger than the middle(?) Tertiary volcanic rocks, but the relationships of the lower strata of the San Manuel formation to these volcanic rocks are not known. Locally the San Manuel formation apparently grades upward into the Quiburis, whose base is probably no younger than early Pliocene age. Consequently, the San Manuel formation is tentatively considered to be of middle(?) Tertiary age.

The Sacaton formation was laid down in a broad, but not basinwide, valley cut into the Quiburis formation about 30 feet above the present flood plain. The Sacaton formation is beveled by the Whetstone but apparently not by the Tombstone surface. In the vicinity of Benson, the lake-bed and other playa deposits upon whose lateral extensions the Tombstone surface has been cut have been dated as Blancan, or Pliocene and Pleistocene, and also as early Pleistocene (Gazin, 1942). In the same area, the basal beds of the pediment gravels underlying the Whetstone surface contain a late Pleistocene fauna (J. F. Lance, oral communication, 1954). The age of the Sacaton formation is therefore tentatively considered to be Pleistocene.

The problem of correlating alluvial deposits is intricate. The earlier workers in the Mammoth area correlated the alluvial deposits with the Gila conglomerate on the basis of general lithologic and textural similarity and the similar structural relationships The relationships of the several units of the Gila group described in this report to the alluvial units previously designated in the area are shown on plate 2. The Gila group conforms to the Gila conglomerate designation of Peterson (1938) and forms part of the deposits included in the Gila or Gila(?) conglomerate by Bryan (1926), Steele and Rubly (1947), Creasey (1950), and Schwartz (1953). Schwartz' descriptions of alluvial deposits are not altogether clear as to whether the lake beds along the San Pedro River should be included within his Gila(?) conglomerate or within his alluvial-slope-deposits unit. The confusion resulting from differences in the definition of the Gila conglomerate in the Mammoth area demonstrates the advisability of designating local units of alluvial deposits for mapping and for stratigraphic and structural analysis.

Detailed correlations between the Gila group in the Mammoth area and the Gila conglomerate of previous workers in other parts of the San Pedro Valley and in nearby valleys in southern Arizona cannot be made at this time. Nonetheless, the descriptions of the lithology, texture, and structural relationships of these deposits suggest that many may be included in the Gila group.

Within the San Pedro Valley, the recent fossil collections indicate that the fine-grained deposits near Benson are not synchronous with those near Mammoth, as suggested by Bryan (1926). The differences in the ages and altitudes of the exposed beds and the complexity of structural deformation between the two areas (Heindl, *in* Halpenny, 1952) preclude a definite correlation between the fine-grained deposits of the two areas at this time, although a correlation between the deposits as a whole appears to be justified by their lithologic and structural similarities.

Knechtel (1936) correlated all the basin-filling deposits of the San Pedro and Safford Valleys on the basis of general lithologic, textural, and structural similarity and the ages of fossils near Safford and Benson, calling them both Gila conglomerate of Pliocene and Pleistocene ages. Van Horn[4] demonstrated the presence of at least three units in the Safford area. This report documents the complexity of deposits in the Mammoth area. As a result, Knechtel's correlation must be considered to be limited to a correlation of the ages of the stratigraphic intervals from which the fossils came, extended judiciously to strata in stratigraphic continuity with those intervals.

PLEISTOCENE AND RECENT ALLUVIAL DEPOSITS

Pleistocene and Recent alluvial deposits, consisting of flood-plain, channel-fill, and terrace deposits, occur along the inner valley of the San Pedro River and its principal tributaries.

Along the San Pedro River and its tributaries, particularly near their mouths, poorly developed terraces are from 10 to 30 feet above the surface of the adjoining channels. The terrace deposits are composed of silty pebble sandstone to silty cobble and boulder conglomerate and contain a wide variety of materials. These deposits are discontinuous and may represent ephemeral stages in the late Quaternary degradational cycle.

The surface of the San Pedro River flood plain in this area is from less than 5 to about 10 feet above the floor of the river channel. Exposed parts of the flood plain consist of sand and gravel, sandy silt, and sandy mudstone. The upper few feet commonly are composed of finer materials, mostly sandy silt and mudstone, in beds 1 to 3 feet thick. Old soil surfaces or planes or erosion occur between individual beds. Well logs indicate that the finer deposits are underlain by sand and gravel to depths of 60 to 80 feet, below which lie

[4] Van Horn, W. L., 1957, Late Cenozoic beds in the upper Safford Valley, Graham County, Arizona: Arizona Univ., Tucson, unpublished master's thesis.

fine-grained gypsiferous deposits of the Quiburis formation. The channel is floored with unconsolidated sand and gravel and occasional small areas of mudstone.

In a discussion of similar rocks along Whitewater Draw in southeastern Arizona, Hunt (1953) placed the Pleistocene-Recent boundary along an unconformity between an unbedded 3-foot thick clay bed containing stone artifacts of the San Pedro and Chiricahua stages and a thinly laminated clay containing elephant, camel, and horse fragments. The similarity of the upper flood-plain deposits along the San Pedro River to those along Whitewater Draw and the similarity of their stratigraphic position in relation to the latest period of degradation suggest that the flood-plain deposits along the San Pedro River also are Pleistocene and Recent in age. The Recent channel deposits along the San Pedro River have been dated by Bryan (1926) as being post-1883.

In addition, unmapped slump and talus deposits are common along the steep slopes of hills, mesas, and arroyos. This rubble is derived from and masks these deposits, except where rapid erosion has swept the rubble away.

STRUCTURE

The lower San Pedro Valley lies in a large northwest-trending structural depression. It is bounded on the east by tilted fault blocks that form the Galiuro Mountains and on the west by irregularly spaced ranges which include the Santa Catalina Mountains and Black Hills. Schwartz (1953) suggested that the Black Hills are a northward extension of the Santa Catalina Mountains. The almost continuous exposures indicate that the Black Hills form a complex block that is separate from but related to the Santa Catalina Mountains.

Structure in the mapped area is dominated by faults, which have offset all units except the Quaternary deposits (pl. 1). Slickensided fracture planes in older alluvial deposits and crushed zones in the granite are common, but, because of the nature of the materials, the amount of throw is seldom decipherable. Only the two principal sets of faults are discussed in this report—the San Manuel and probable related faults that are exposed in and south of the Black Hills, and the Cholla, Copper Creek, and related faults, that define the downdropped basin between the Black Hills and the Galiuro Mountains.

SAN MANUEL AND RELATED FAULTS

The most prominent structural feature in the southern part of the Black Hills is the San Manuel fault (Steele and Rubly, 1947). This fault crops out in a broad, northwestward-trending arc that has been traced into the quartz monzonite block northwest of the San Manuel mine at Red Hill and southeastward to about the center of sec. 18, T. 9 S., R. 17 E., where it passes under the Sacaton formation. The strike of the fault swings from about N. 30° W. to N. 70° W.; the dip of the fault is about 20° to 30° SW. The hanging wall contains rocks of the Cloudburst formation and the Tucson Wash member and undifferentiated beds of the San Manuel formation; the footwall includes quartz monzonite and Cloudburst volcanic rocks. Alluvial deposits in the hanging wall dip about 30° NE. into the fault plane; deposits of the fanglomerate member of the Cloudburst formation in the footwall between the San Manuel and Cholla faults dip at angles ranging from about 20° to 40° NE.

A nearly parallel second line of faulting is suggested by a disturbed zone, less well defined, that trends about N. 70° W. from the SE¼ sec. 6 to the SW¼ sec. 10, T. 9 S., R. 16 E. This disturbed zone is poorly exposed and is postulated on the basis of the alinement of discontinuous breccia outcrops, comminuted zones, and zones of erratic attitudes.

The San Manuel fault is definitely older than the Sacaton formation, and it is younger than parts of the Quiburis formation, but it cannot be accurately dated because its relationships to datable beds in the Quiburis are not known. Sedimentary and structural relationships of the San Manuel fault are discussed in the section "Sedimentation and the San Manuel Fault."

CHOLLA AND RELATED FAULTS

The Cholla fault (Schwartz, 1953) lies east of the San Manuel fault. It trends about N. 40° W., and dips at high angles to the northeast. It is the largest of a system of north-northwestward-trending normal faults which cut the San Manuel fault; the downthrown side is to the northeast. In the vicinity of Red Hill, the Cholla fault brings older rocks in contact with the Quiburis formation, but this displacement dies out to the southeast.

Three miles southwest of Red Hill, a zone of normal faults between sec. 31, T. 8 S., R. 16 E., and sec. 9, T. 9 S., R. 16 E., brings the Kannally member of the San Manuel formation in contact with quartz monzonite, the Cloudburst formation, and the local conglomeratic member of the San Manuel formation. The western part of the zone trends northwest, nearly parallel to the Cholla fault, and the relationships of the rocks in the hanging and footwalls are clearly those of a normal fault. The eastern part of the zone, however, trends east-west, and the relationships of the rocks in the hanging and footwalls are those of a reverse high-angle fault. The detailed relations of the eastern and western parts of the fault zone are not known, but the net effect is that the rocks north and east of the zone are upthrown relative to the rocks south and west of the zone. Thus, the Black Hills form a horst bounded by this fault zone on the west and the Cholla and nearly parallel faults on the east. Although the fault zone on the west side of the Black Hills horst is only in part parallel to the Cholla fault and in part has reverse-fault characteristics, the general stratigraphic and structural relationships suggest the two fault zones are related.

The Cholla and the faults parallel to it are younger than the San Manuel fault, and the Quiburis formation and they are older than the Sacaton formation.

The differences in altitudes of the tops of the red-brown conglomerate or red beds in the drilled holes between Red Hill and the San Pedro River suggest either an unusually steep gradient toward the river or additional buried normal faults.

COPPER CREEK FAULT

The Copper Creek fault (Davis and Brooks, 1930) forms the contact between the Quiburis formation and the middle(?) Tertiary volcanic and older rocks of the Galiuro Mountains. It is a generally north- to northwestward-trending high-angle normal fault that dips to the west. The fault is well exposed in Copper Creek, and it has been traced for several miles in both directions beyond the limits of the mapped area. The Copper Creek fault has a maximum exposed throw of about 700 feet.

Differences in the thickness of the Quiburis formation penetrated by bore holes along the San Pedro River and differences between the river and the Galiuro Mountains suggest normal faulting and considerable total displacement. Many inconspicuous faults parallel to the Copper Creek fault are exposed along the main washes, but no single fault appeared sufficiently distinctive to warrant being mapped.

GEOLOGIC SYNTHESIS

Earlier work in the Mammoth area was concerned largely with hard-rock geology, and the alluvial deposits received comparatively little attention. Alluvial units were described and correlated in broad general terms, and the Cenozoic history, except for late Pliocene and Quaternary time, was correspondingly generalized. In the following discussion, a new interpretation of the Cenozoic history of the area is offered, in which the events are related to evidence derived from study of the alluvial deposits.

Generalized block diagrams show postulated relationships across the San Pedro Valley at different stages after the deposition of the Cloudburst formation (pl. 3).

LATE CRETACEOUS(?) TO MIDDLE(?) TERTIARY TIME

The oldest rocks exposed in the Mammoth area are the early Precambrian quartz monzonite and the unmapped blocks of Paleozoic rocks in sedimentary or tectonic breccias. Quartz monzonite porphyry of Mesozoic age is reported to be in the subsurface. Before the deposition of Cloudburst rocks, erosion had reduced the Mammoth area to a moderately rugged surface, over much of which only the Precambrian quartz monzonite was exposed.

The Cloudburst formation filled in the irregularities of the terrain. Locally, as in the area underlying the Galiuro Mountains, the deposition of the Cloudburst may have begun in Late Cretaceous(?) time. West of Mammoth, however, the earliest Cloudburst deposits probably are no older than early Tertiary. Arkosic debris from the predominantly granitic terrain filled local depressions and in turn was covered by andesitic and basaltic flows. Erosion of these flows began before their period of extrusion ended, and later flows are interbedded with clastic rocks derived from earlier flows. The volcanic activity decreased, and erosion of the volcanic terrain resulted in the volcanic part of the fanglomerate unit of the Cloudburst formation. Dikelike masses of rhyolite, latite, and andesite were intruded, and some degree of deformation may have occurred contemporaneously. Some of the intrusions in the Galiuro Mountains may be of Late Cretaceous(?) age but those west of Mammoth are younger. The type and trend of the deformation are not known, but the coarse quartz monzonite boulder beds of the upper part of the fanglomerate unit of the Cloudburst formation suggest a rejuvenated terrain of considerable relief and broad exposures of quartz monzonite. The comparatively finer deposits of the Cloudburst underlying the Galiuro Mountains suggest that the rugged terrain had been considerably reduced by the end of Cloudburst time.

Although some ancient highlands existed in the vicinity of the Black Hills and the north end of the Santa Catalina Mountains at the end of Cloudburst time, deposition extended into other areas now marked by mountain ranges, such as the Galiuro Mountains. The inference seems clear that the present mountain ranges, although locally including remnants of older highlands, were developed largely subsequent to the deposition of the Cloudburst formation.

Plate 3*A* presents schematically conditions during the final stages of the deposition of the Cloudburst formation.

After the deposition of the Cloudburst rocks, the area was subjected to folding, faulting, and intrusion. The deformation is clearly marked by the angular discordance between the Cloudburst and younger rocks in the Black Hills and Galiuro Mountains. Probably related deformation has been reported in the Santa Catalina Mountains (DuBois, 1959) on the west side of the San Pedro Valley south of Mammoth (R. T. Chew [5]; and Heindl, *in* Halpenny, 1952), on the southwest side of the Santa Catalina Mountains (Moore and others, 1941), and between Tucson and Benson (D. J. Brennan [6]). Some movement probably occurred along the San Manuel fault zone during this interval, thus providing a zone of weakness along which the valley was subsequently eroded. The mountain terrain that unquestionably developed as a result of this deformation was generally reduced; over broad areas, as in the Galiuro Mountains, the eroded surface was beveled to a low relief. The degree of planation suggests that this erosion interval was of considerable duration and may have regional significance. Locally, this surface is referred to informally as the "Galiuro surface."

However, all the area was not equally reduced, and the available evidence suggests that the rejuvenated Santa Catalina Mountains remained a notable topographic feature.

The middle(?) Tertiary volcanic rocks, now exposed in the Galiuro Mountains, were deposited upon the lower levels of the broad Galiuro erosion surface that truncated the Cloudburst formation. The westward extent of the middle(?) Tertiary volcanic rocks is not known, but the large angular pebbles of flow-banded rhyolite contained in the Kannally member of the San Manuel formation are not unlike rhyolite in the middle(?) Tertiary volcanic sequence, and the size of these pebbles suggests a moderately nearby source. The flow-rhyolite pebbles are found low in the sequence of the San Manuel formation, suggesting also that these volcanic rocks antedated the San Manuel fault. Consequently, the middle(?) Tertiary volcanic rocks are postulated to have extended to the east side of the Black Hills, forming a tableland that continued to the east of the present Galiuro Mountains. During this time there was no San Pedro Valley. These relationships are shown diagrammatically in plate 2*B* and are presumed to have occurred some time during the early(?) Miocene to Miocene(?) time.

DEPOSITION OF THE SAN MANUEL FORMATION

The extent and size distribution of fragments in the San Manuel formation suggest that the debris was derived from nearby source areas to the west, north, and east. The southward diminution of fragment sizes suggests a south-trending drainage with the heads of the valleys at about the present south front of the Black Hills. The preexisting valley was one of considerable and possibly intricate relief, developed in part on bedded rocks that had been considerably

[5] Chew, R. T., 1952, Geology of the Mineta Ridge area, Pima and Cochise Counties, Arizona: Arizona Univ., Tucson, unpublished master's thesis.

[6] Brennan, D. J., 1957, Geological reconnaissance of Cienega Valley, Pima County, Arizona: Arizona Univ., Tucson, unpublished doctoral thesis.

deformed. As a result, the San Manuel formation was deposited locally against the frontal faces of exposed beds and elsewhere on their dipslopes. The small areal extent of the local conglomerate member and its depositional contact on the east side with a ridge of the Cloudburst formation suggest that it was deposited locally in a small tributary valley. In contrast, the Kannally member has coarse phases along the northeast flanks of the Santa Catalina Mountains and the west side of the southern Black Hills and fine-grained phases between them.

The valley in which the San Manuel was deposited was structurally active, as attested to by the breccias within the Kannally member and the erosional unconformity and change in composition between the Kannally and Tucson Wash members.

The number of large fragments of middle(?) Tertiary volcanic rocks in the upper part of the San Manuel formation suggests that part of the ancient middle(?) Tertiary volcanic tableland was drained westward to where the San Manuel was being accumulated.

Therefore, it is postulated that, contemporaneously with or shortly after the deposition of middle(?) Tertiary volcanic rocks across the present San Pedro Valley, erosion scooped out valleys along lines of structural weakness between the ancient Black Hills and Santa Catalina Mountains, and that the San Manuel was deposited in these valleys (pl. 3*C*). Collectively, these valleys form the west-side valley, as the term is used in this text, and indicate that the San Manuel formation was deposited in a structural trough separate from the subsequent trough developed between the Black Hills and the Galiuro Mountains.

Upstream, deposits such as the local conglomerate member were laid down in small valleys and closely reflected their source areas; downstream, the deposits in small valleys merged to fill the broader valley between the ancient Santa Catalina Mountains and the Black Hills. The deposits from the small valleys, as they moved downstream, mixed with and lost their identity in the surge of deposition of the Kannally member from the flanking mountains. The large boulders in the northern deposits of the Tucson Wash member suggest renewed uplift nearby and exposure of previously buried rocks, including the Cloudburst formation. Where the deformation was greatest, the Tucson Wash member contains huge boulders, and, as the amount of deformation along the same structural trend diminished, the resulting deposits lost their distinctiveness and merged upward with the Quiburis formation around the south end of the ancient Black Hills.

SEDIMENTATION AND THE SAN MANUEL FAULT

The San Manuel fault arcs along the south and east sides of the Black Hills and dips at angles of about 20° to 30° SW. Near Red Hill and to the south, the hanging wall is composed of the San Manuel formation; the footwall includes quartz monzonite and Cloudburst rocks. The San Manuel fault has been interpreted to be a normal fault that originally dipped 60° SW. and subsequently was tilted 30° NE. to bring it approximately to its present position (Steele, *in* Wilson, Wilson, and Steele, 1948, p. 7; Schwartz, 1953, p. 17). The sedimentary features of the San Manuel formation, however, are compatible with a thrust interpretation of this fault (fig. 3).

The tilted normal-fault interpretation of the San Manuel fault implies that the base of the deposits on the east side of the San Manuel fault is a part of the surface upon which the complete section of the terrestrial deposits was laid down. A simplified version of the structural relationships across the San Manuel fault from the vicinity of Red Hill to the north end of the Santa Catalina Mountains is shown in figure 3*A*.

If the San Manuel fault is tilted back to its suggested original position as a normal fault dipping 60° SW., and if the displacement along the San Manuel fault is restored, the structural and stratigraphic relationships will be those shown in figure 3*B*. The suggested vertical displacement along the San Manuel fault is in the magnitude of more than 10,000 feet, which is not impossible. However, the large number of blocks and boulders in the San Manuel formation in this vicinity strongly suggest they were derived from nearby source areas, to the west, north, and east, having extensive exposures of quartz monzonite and Cloudburst rocks. Such source areas are difficult to visualize under conditions which must have existed before movement occurred along a normal San Manuel fault. The nearly horizontal attitude of the Cloudburst formation at the time the Kannally member was being deposited, as implied by the normal-fault hypothesis, suggests a lack of nearby pre-San Manuel deformation. Consequently, the apparently unbroken succession of flat-lying beds of the Cloudburst does not appear to allow for a nearby source of quartz monzonite to provide the large quartz monzonite boulders at the base of the Kannally member. If deposition of the San Manuel formation was contemporaneous with movement along a normal San Manuel fault and the San Manuel was derived from a rising scrap, why is the Kannally member composed predominantly of quartz monzonite instead of Cloudburst fragments, and why do Cloudburst fragments begin to appear only above an erosional surface cut on the Kannally member? In short, if the San

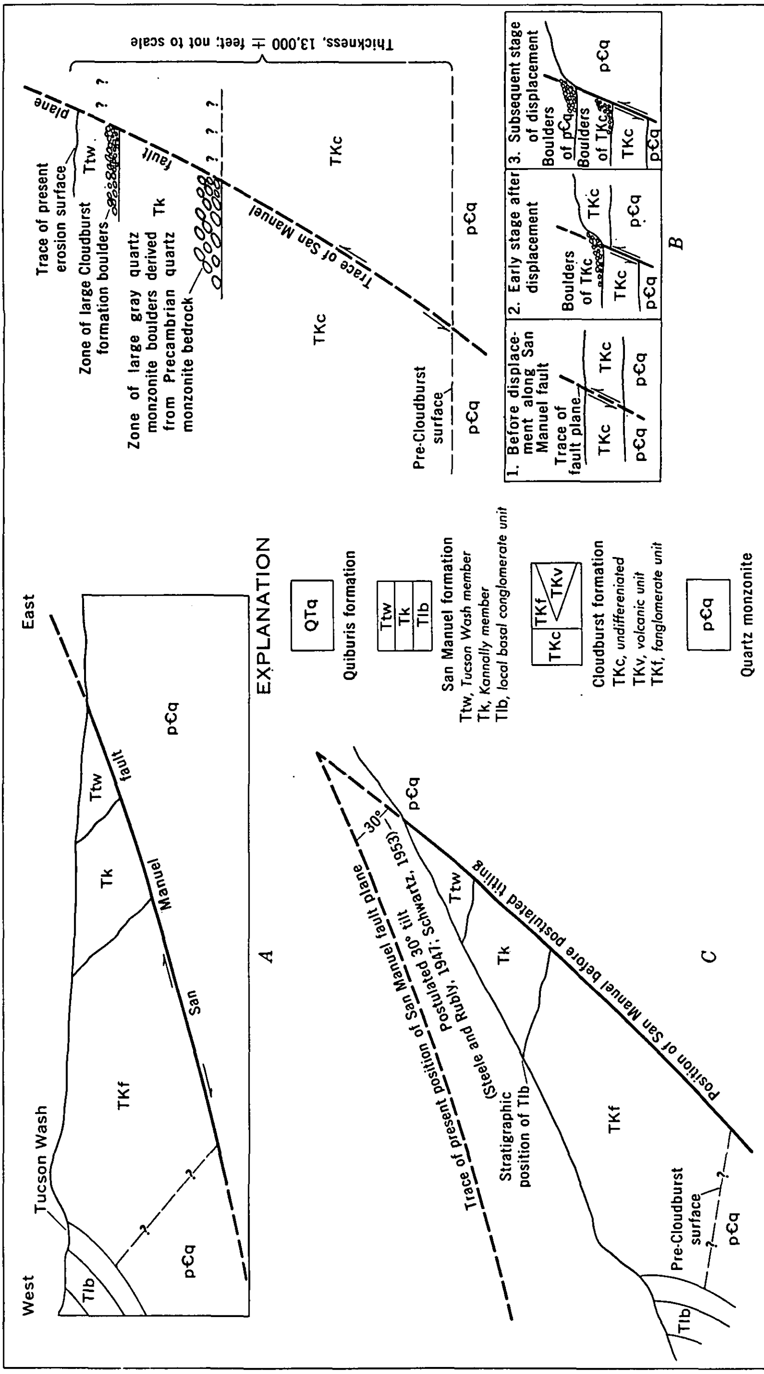
West
East
Tucson Wash
San Manuel fault
Tlb
TKf
Tk
Ttw
p€q
A
EXPLANATION
QTq
Quiburis formation
Ttw
Tk
Tlb
San Manuel formation
Ttw, Tucson Wash member
Tk, Kannally member
Tlb, local basal conglomerate unit
TKc
TKf
TKv
Cloudburst formation
TKc, undifferentiated
TKv, volcanic unit
TKf, fanglomerate unit
p€q
Quartz monzonite
Trace of present position of San Manuel fault plane
Postulated 30° tilt
(Steele and Rubly, 1947; Schwartz, 1953)
30°
Stratigraphic position of Tlb
Position of San Manuel before postulated tilting
Pre-Cloudburst surface
C
Thickness, 13,000 ± feet; not to scale
Trace of present erosion surface
Zone of large Cloudburst formation boulders
Zone of large gray quartz monzonite boulders derived from Precambrian quartz monzonite bedrock
Trace of San Manuel fault plane
1. Before displacement along San Manuel fault
Trace of fault plane
2. Early stage after displacement
Boulders of TKc
3. Subsequent stage of displacement
Boulders of p€q
Boulders of TKc
B

Figure 3.

EXPLANATION FOR FIGURE 3

Manuel fault was normal, where were the source areas for the boulders in the eastern exposures of the Kannally member, and why are the stratigraphic positions of the boulders of different compositions the reverse of what a normal-fault hypothesis implies? (See fig. 3*B*.)

Furthermore, a tilted block such as that suggested would have either to include or to come short of the area of the local conglomerate member of the San Manuel formation which is in depositional contact with northeast-dipping deposits of the fanglomerate of the Cloudburst formation (fig. 3*A*). However, the stratigraphically continuous exposures of the fanglomerate between the local conglomerate member and the San Manuel fault preclude the possibility of a major break in this zone, although there was much small-scale movement. If, then, the basal conglomerate is within the tilted block, the tilting would imply that this conglomerate had been deposited at nearly vertical angles of repose (fig. 3*C*). This is patently impossible. The above evidence indicates that the field relationships do not support the tilted normal-fault hypothesis as an explanation for the San Manuel fault.

E. D. Wilson questioned the possibility of tilting on the basis of the depth of oxidation of the ore below the San Manuel fault, and L. K. Wilson suggested thrusting along the San Manuel fault (Wilson, Wilson, and Steele, 1948). Since the original draft of this paper was prepared, E. D. Wilson (1957) has demonstrated the probable thrust nature of the San Manuel fault on the basis of secondary fault-plane attitudes. Although the sedimentary characteristics of the San Manuel formation do not themselves prove thrust relationships along the San Manuel fault, they do not contradict this hypothesis as they do that of the tilted normal-fault plane.

Consequently, it is postulated that compressional forces broke along the San Manuel fault and related zones and resulted in the thrusting of the San Manuel formation over the rocks from which it was derived. The zones of structural weakness may be related to

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Diagrams showing stratigraphic and structural relationships in the vicinity of Red Hill implied by a tilted normal-fault interpretation of the San Manuel fault. *A*, Generalized section of San Manuel fault through vicinity of Red Hill. (See pl. 1.); *B*, Section showing reconstruetion of the San Manuel fault, based on tilted fault-block hypothesis, and the actual sequence of deposits. Three small inset diagrams show normal sequence of deposits expected during deposition contemporaneous with movement along a normal fault; *C*, Diagrammatic section showing deposition relationships between the local basal conglomerate unit of the San Manuel formation and the fanglomerate unit of the Cloudburst formation implied by the tilted normal-fault hypothesis if the tilted block were hinged east of the contact between the units.

zones developed during the post-Cloudburst deformation. Large blocks, several feet in maximum dimension in the San Manuel formation along the hanging wall of the San Manuel fault suggest that the plane of thrusting may have been at or close to the surface along which the eastern part of the Tucson Wash member was deposited.

DEPOSITION OF THE QUIBURIS FORMATION

The deposition of the Quiburis formation may have begun with the destruction of the west-side valley by deformation along the San Manuel fault, and shortly later by differential displacement along the Copper Creek, Cholla, and related fault systems. The Galiuro and Santa Catalina Mountains were elevated episodically to about their present positions, and the blocks between the ranges were depressed to form the trough of the present San Pedro Valley. These movements and attendant erosion and deposition began some time in the early part of late Tertiary time. The apparent absence of middle(?) Tertiary volcanic rocks in the western and central parts of the San Pedro Valley suggest that the materials were removed by through drainage during an early stage of erosion. Subsequently through drainage was blocked and the Quiburis formation was laid in the previously eroded valley.

The Quiburis formation, more closely than any other deposit in the Mammoth area, resembles the classical concept of sedimentation in an intermontane structural basin (pl. 3*D*, *E*). Coarse deposits were laid down along the margins of the valley, and, for reasons not now known, through or well-integrated drainage was not established and lakes and playas were formed. Pumiceous deposits indicate some contemporary vulcanism. The central axis of these deposits was located generally 2 miles east of the course of the San Pedro River.

Renewal of movement along the normal faults on the east side of the valley resulted in the outpouring of huge fans of coarse material from the Galiuro Mountains. Later, local movement broke through these fans and still younger fans were formed. The deposition of the Quiburis formation continued into early Pleistocene time in this area.

Bryan (1926) stated that the differential faulting between the San Pedro basin and the bordering mountains occurred after the deposition of the valley fill, presumably the Quiburis formation of this report, and implied that faulting and deposition were not contemporaneous. The apparent displacement of middle(?) Tertiary volcanic and older rocks below the Quiburis and changes in the sedimentary characteristics of the lower and upper units of the Quiburis formation suggest that faulting and deposition did occur contemporaneously. However, the faulting was episodic, and contemporaneity here does not imply incessant deformation during the course of deposition.

DEPOSITION OF THE SACATON FORMATION

The erosional surface underlying the Sacaton formation represents a through drainage, the main stem and tributaries of which were subparallel to the present San Pedro River system. This middle Pleistocene period of downcutting may have been contemporaneous with or younger than the development of the Tombstone surface. After the through drainage developed a valley at least 250 feet deep, the base-level control was changed through some unknown effect, and the valley was in part refilled with the fluvial and alluvial deposits of the Sacaton formation (pl. 3*E*).

The Sacaton deposits are considered to be a distinct unit of the Gila group because they were deposited on an erosion surface cut into the Quiburis formation and because they do not extend the full width of the basin—rather, they filled a central valley and its tributaries and then, as aggradation continued, coalesced across the ancient interfluves. The distribution of Sacaton deposits can best be visualized by imagining the present flood-plain deposits aggraded to an elevation of about 200 feet above their present level, partly burying the intricate topography along the San Pedro River.

LATE QUATERNARY HISTORY

The latest sequence of downcutting began with the development of a through drainage on the Whetstone surface, which was developed across the preexisting Sacaton formation (pl. 3*E*). The course of this drainage, like that of the previous through stream, was offset to the west of the central axis of the Quiburis deposits. This similarity in the position of the two drainage systems suggests that little, if any, structural deformation occurred in this area subsequent to the period of erosion which preceded deposition of the Sacaton beds.

The San Pedro River cut down through the Sacaton and older deposits to incise a channel about 60 to 80 feet below its present level. Subsequently, this inner valley was partly refilled with flood-plain deposits, and the present channel began to cut into the flood-plain deposits in the late 1880's (Bryan, 1926, p. 170).

CONCLUSIONS

The following conclusions regarding the geologic history of the Mammoth area are based largely on the mapping and stratigraphic analysis of discrete alluvial units.

1. The Cenozoic rocks, including some possibly Late Cretaceous beds, were deposited on Precambrian quartz monzonite from which younger Precambrian to Cretaceous(?) rocks had been stripped during an erosional interval that apparently extended across the Cretaceous-Tertiary boundary.

2. The Cloudburst formation, the oldest post-Cretaceous(?) unit in the area, may be Late Cretaceous(?) and Tertiary in age at many places, but west of Mammoth it is probably of early(?) to middle(?) Tertiary age. The Cloudburst formation was deposited within a basin or a region which included the area occupied by the present Galiuro Mountains and, therefore, was not limited by the present topographic and structural features.

3. After the Cloudburst formation was deformed, intruded, and uplifted, it was beveled to a terrain of low relief at the site of the Galiuro Mountains, whereas in the Black Hills the post-Cloudburst topography was rugged.

4. Parts of the Santa Catalina Mountains and Black Hills have been topographic highs since before Cloudburst time; the Galiuro Mountains did not come into existence until after the Cloudburst formation was deformed and eroded and the middle(?) Tertiary volcanic rocks were deposited.

5. The San Pedro Valley did not exist as a major structural and topographic feature in the post-Cloudburst landscape. Instead, much of the area probably was a middle(?) Tertiary volcanic tableland that extended from about the Black Hills eastward to beyond the site of the Galiuro Mountains. The Galiuro Mountains are an erosional remnant of deformed segments of this tableland.

6. Contemporaneously with or shortly after the deposition of the middle(?) Tertiary volcanic rocks, deformation including folding and faulting occurred between the ancient Santa Catalina Mountains and the Black Hills, and a deep southward-draining valley was incised west of the axis of the present San Pedro Valley. This west-side valley was filled with alluvial deposits whose debris was obtained from nearby source areas to the west, north, and east. These deposits, totaling about 4,000 to 6,000 feet in thickness, form the San Manuel formation of middle(?) Tertiary age.

7. The sedimentary features of the San Manuel formation, which forms the hanging wall of the San Manuel fault, are compatible with a thrust interpretation of that fault. They are not compatible with the hypothesis of normal faulting and tilting.

8. The Black Hills, or their south end and southeastern extension, stood as part of an ancient highland supplying debris to the San Manuel formation; the Black Hills were not formed subsequent to the deposition of the San Manuel, although later differential movement did occur.

9. Block faulting of the classic basin-and-range type did not occur extensively in this area until after the last major movement along the San Manuel fault. This movement occurred after the deposition of the San Manuel formation of middle(?) Tertiary age and before the

deposition of the Quiburis formation of late Tertiary and Pleistocene age. Tentatively, block faulting did not begin in the Mammoth area until about the beginning of Pliocene time, and the concept of basin-and-range structure and sedimentation cannot be applied to post-Cretaceous(?) and pre-Pliocene features in this area.

10. The deposits in the central trough of the San Pedro Valley are not a record of continuous aggradation but show, even within the approximately 300 feet of deposits exposed along the San Pedro River, two periods of aggradation represented by the Quiburis and Sacaton formations. These two periods are separated by a significant interval of erosion and entrenchment, represented by the unconformity at the base of the Sacaton. A similar relationship is shown by the Kannally and Tucson Wash members of the San Manuel formation and the erosional unconformity between them. Furthermore, the deposits on both sides of the San Pedro Valley between the Black Hills and the Galiuro Mountains are not symmetrical and probably reflect uplift on the two sides of the valley that was neither simultaneous nor necessarily of the same magnitude.

11. The classical concept of degradation of alluvial deposits in the region as one of nearly continuous erosion marked principally by the periods of more or less rapid incisement (Bryan, 1926) must be modified on the basis of evidence in the San Pedro Valley. The degradation of the valleys was interrupted by periods of considerable aggradation, as shown by the deposition of the Sacaton formation between two successive intervals of incisement which are marked by unconformities at levels of about 30 to 50 feet above and about 60 to 80 feet below the San Pedro River.

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