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# GEOLOGY OF THE LATE CENOZOIC ALMA BASIN, NEW MEXICO AND ARIZONA

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**Abstract**—The Alma Basin is an irregularly shaped late Cenozoic basin located just south of the Colorado Plateau at the intersection of the Morenci-Reserve fault zone and the Mangas trench. The sedimentary rocks of the Alma Basin record four stages in the history of the basin: (1) a pre-Basin-and-Range-faulting stage (23 to 18.7 Ma), when the basin had a different shape than the modern basin, (2) an early Basin-and-Range stage (18.7 to about 6.0 Ma), marked by only minor deposition, during which the basin began to take on its present shape, (3) a third stage (6.0 to about 1.5 Ma), marked by significant subsidence and deposition of a relatively thick section of basin-fill fluvial sedimentary rocks, and (4) waning subsidence during the Quaternary and erosion of basin-fill deposits by the San Francisco River and its tributaries. Structurally, the Alma Basin is an asymmetric graben composed of about six non-rotated fault blocks that step progressively downward toward the Mogollon Mountains on the east. Nearly all the faults are high-angle normal faults. A depositional hiatus between about 16 and 6 Ma may have been caused by shallow emplacement of an intrusive body beneath the west side of the Mogollon Mountains. The presence of such an intrusion at this time is inferred from the age of hydrothermal alteration in the Mogollon mining district.

## INTRODUCTION

The Alma Basin lies immediately west of the Mogollon mining district (a silver district with important past production) within a remote mountainous region of great scenic beauty (Fig. 1). Although geologic studies of the region have focused chiefly on the mountains, they have also supplied significant structural data for the Alma Basin. Geologic mapping of the Alma Basin was undertaken primarily to provide a better understanding of the Morenci-Reserve fault zone.

Preliminary analysis of mapping data from the Alma Basin has given insight into the late Cenozoic history of extension of the southern Basin and Range province just southeast of the Colorado Plateau. Because of its location at the intersection of two important structural trends and because of exceptionally good exposures of basin-fill rocks, study of the Alma Basin can provide information not available in the surrounding ranges.

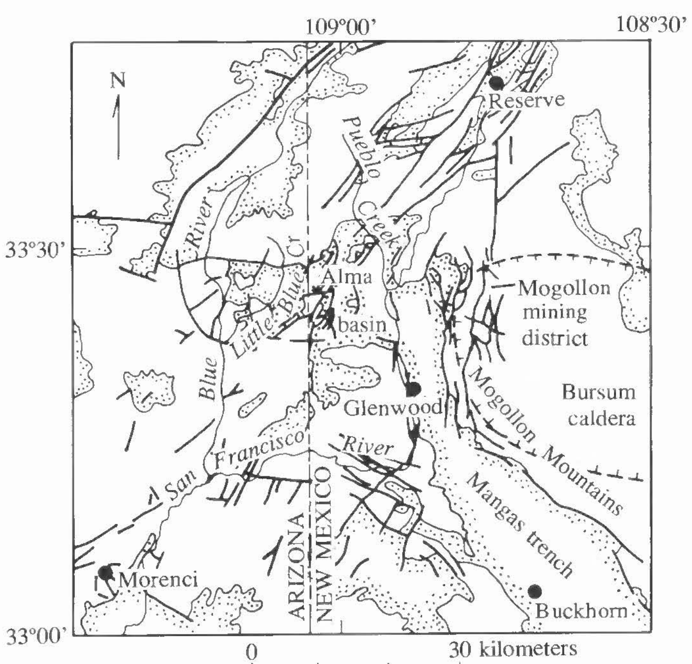


FIGURE 1. Index map showing the Alma Basin in relation to major streams and other geographic and geologic features of the region. Stippled pattern indicates late Cenozoic basins. Faults are shown by heavy lines. Modified from Dane and Bachman (1965), and Wilson et al. (1969).

## GEOLOGIC SETTING

The Alma Basin is west of the Mogollon Mountains, at the intersection of the northeast-trending Morenci-Reserve fault zone and the northwest-trending Mangas trench (Fig. 1). Ratté (1989) described the Morenci-Reserve fault zone as a complex graben with intragraben horsts that trends approximately N30°E and is 40 to 50 km wide. He interpreted the zone to be distinct from, and in part younger than, the N60°E San Agustin trend (Morenci lineament of Mayo, 1958; Chapin et al., 1978). Based on mapping in southern Arizona, Houser (1994) inferred that the Morenci-Reserve fault zone can be traced into Sonora, Mexico.

The Morenci-Reserve zone is apparently a long-lived feature. Estimated ages of mid-Tertiary sedimentary deposits associated with the zone in Arizona suggest that it may be as old as 30 Ma (Houser, 1994), while fault scarps in the Alma Basin indicate that the zone was still active during the late Pleistocene.

The Mangas trench is one of about seven northwest-trending basins that are truncated along the southeastern margin of the Colorado Plateau. These basins formed during the Basin-and-Range extensional event that began shortly after 19 Ma in this part of the southern Basin and Range province, as indicated by ages of the oldest tholeiitic or alkalic basalt flows (Richter et al., 1983; Marvin et al., 1987; Houser, unpubl.)

Within this tectonic setting, late Cenozoic uplift and subsidence has been controlled by both of these structural trends; thus, the Alma Basin has an irregular shape. In spite of the complexities of its tectonic setting, the basin is a fairly simple asymmetric graben composed of about six unrotated fault blocks, stepped down on the east side adjacent to the Mogollon Mountains.

The rocks of the surrounding ranges are intermediate to silicic Oligocene and Miocene volcanic and hypabyssal intrusive rocks of the Mogollon-Datil volcanic field (Ratté et al., 1969, 1979; Ratté, 1980, 1981, 1989). The 28-Ma Bursum caldera, immediately east of the Alma Basin, and other calderas of the Mogollon Mountains were the source of distinctive and voluminous Oligocene ash-flow tuffs (Ratté et al., 1984). These tuffs (for example, the Davis Canyon, Shelley Peak and Bloodgood Canyon Tuffs) are important regional stratigraphic markers in the volcanic rocks. Additionally, the first occurrence of these tuffs as clasts in basin-fill deposits documents and provides time constraints for uplift and unroofing of the ranges during the Miocene.

Bedrock highs within the Alma Basin are composed of 27-to-23 Ma basaltic andesite to dacite lava flows of the Bearwallow Mountain Andesite (Marvin et al., 1987; Houser, 1987). The sedimentary rocks present in the basin (Fig. 2) are the lower to middle Miocene Dog Gulch Formation (Ratté, 1981), conglomerate of Little Blue Creek, and

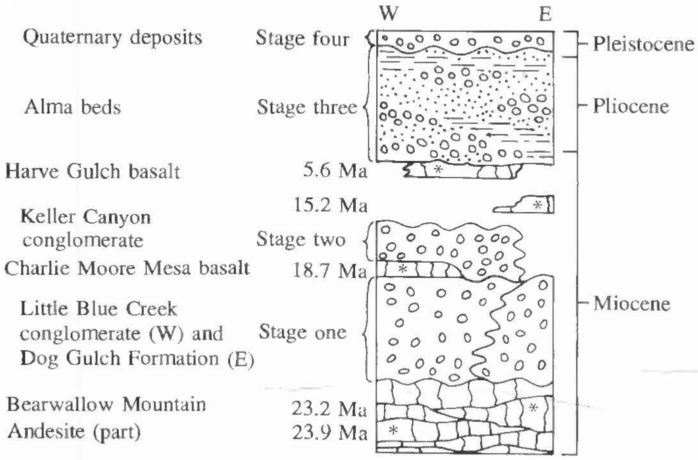


FIGURE 2. Correlation of stratigraphic units for the Alma Basin, New Mexico and Arizona.

conglomerate of Keller Canyon; the chiefly Pliocene Alma beds; and Quaternary alluvium and other surficial deposits (Houser, 1987). Miocene tholeiitic or alkalic basalt flows separate the basin-fill sedimentary units and serve as time constraints on their deposition.

## PREVIOUS WORK

The geology of the central part of the Alma Basin was mapped by Houser (1987). Quadrangle mapping of most of the rest of the basin and adjacent ranges has been completed by Houser and Ratté (unpubl.). Studies of the Mogollon mining district include Ferguson (1927), Ratté (1980), Kamilli (1994), and Senterfit et al., (1994). Reconnaissance geologic maps were prepared for mineral-resource assessments of the Gila Wilderness east of the Alma Basin (Ratté et al., 1979) and the Blue Range Primitive Area west of the basin (Ratté et al., 1969). Detailed quadrangle mapping north of the basin was done by Ratté (1980, 1989).

## STRATIGRAPHY

The correlation of the stratigraphic units in the Alma Basin is shown in Figure 2. The sedimentary deposits of the Alma Basin (mostly Gila Group) are interpreted to record four stages in the history of the basin: (1) a pre-Basin-and-Range-faulting stage (23 to 18.7 Ma), when the basin had a different shape than the modern basin, (2) an early Basin-and- Range stage (18.7 to about 6.0 Ma), during which the basin began to take on its present shape, (3) a third stage (6.0 to about 1.5 Ma), which was marked by significant subsidence and deposition of a relatively thick section of basin-fill fluvial sedimentary rocks, and (4) waning basin subsidence during the Quaternary, accompanied by erosion of basin-fill deposits by the San Francisco River and its tributaries.

### Stage one

The earliest stage of deposition in the Alma Basin is represented by the conglomerate of Little Blue Creek on the west side of the basin and by the Dog Gulch Formation (Ratté, 1981) on the east side. The ages of volcanic rocks below and above these units indicate that they were deposited between about 23 and 19 Ma. Both units are chiefly conglomeratic and both overlie an erosional surface cut on the 27-to-23-Ma Bearwallow Mountain Andesite, a compositionally variable volcanic unit 100 to more than 300 m thick (Ratté et al., 1979; Ratté, 1981; Marvin et al., 1987). The conglomerate of Little Blue Creek overlies a rhyolite ash-flow tuff that, in turn, overlies a silicic dome complex dated at 23.9 Ma (Ratté et al., 1969; Marvin et al., 1987). The Dog Gulch Formation overlies the 23.2-Ma Last Chance Andesite (Ratté, 1981). The minimum age of the Little Blue Creek conglomerate is 18.7 + 2.0 Ma based on a whole-rock K-Ar date on the overlying basalt of Charlie Moore Mesa (R. F. Marvin, written commun., 1986). The minimum age of the Dog Gulch Formation is 15.2 Ma based on the age of an overlying basalt flow near Bearwallow Mountain (Ratté, 1981).

The thicknesses of the Little Blue Creek conglomerate and Dog Gulch Formation are more than 300 m and as much as 200 m, respectively; both are fairly well indurated and consist chiefly of poorly-sorted fluvial and debris-flow conglomerate facies, although minor mudstone and sandstone facies occur in both. The facies changes in the Little Blue Creek and Dog Gulch units (particularly the distribution of basin center facies) bear no relationship to the modern topography, suggesting that the shape of this early basin was probably different than that of the modern basin. Also, although the clasts in the conglomerates consist entirely of volcanic rocks having a wide range of compositions, there are no clasts of the Davis Canyon, Shelly Peak and Bloodgood Canyon Tuffs, indicating that these regional ash-flow tuff sheets were not yet exposed to erosion in the vicinity of the basin during stage-one deposition.

### Stage two

During the second stage of the Alma Basin (about 18.7 to 6.0 Ma), the conglomerate of Keller Canyon (Houser, 1987) was deposited. This conglomerate unit is as much as 85 m thick and becomes coarser grained adjacent to the modern bedrock boundaries of the basin. This indicates that the basin configuration at the time of deposition was similar to the modern basin.

As with the Little Blue Creek conglomerate and Dog Gulch Formation, there are no clasts of the regional ash-flow tuff sheets in the Keller Canyon conglomerate. These tuffs are present along the northern edge of the basin and, if they had been exposed at that time, presumably would have been carried into the basin and deposited along with the rest of the varied volcanic clasts of the Keller Canyon conglomerate. Their absence in the Keller Canyon conglomerate is evidence that the ash-flow tuffs were still covered by the younger volcanic pile of the 100-to-300-m thick Bearwallow Mountain Andesite.

The conglomerate of Keller Canyon is similar in appearance to the conglomerate of Little Blue Creek, but is slightly less indurated. Poorly-sorted, pebbly to bouldery, volcanic conglomerate is the dominant facies, much of it matrix supported, indicating deposition by debris flows. Other facies are very poorly sorted mudstone, and poorly sorted to well-sorted sandstone and conglomerate.

The Keller Canyon conglomerate overlies the 18.7-Ma basalt of Charlie Moore Mesa and the conglomerate of Little Blue Creek; it is capped by the 5.6-Ma basalt of Harve Gulch (Ratté and Finnell, 1978) and the Alma beds of stage three (Houser, 1987). The ages of the lower and upper basalts indicate that deposition of the Keller Canyon conglomerate could have spanned a time interval of about 13 Ma. This is unlikely, however, because it is a relatively thin unit (85 m) and its conglomeratic character implies a high rate of deposition. It was probably deposited in only a few million years. The similarity of its lithologic character to that of the underlying Little Blue Creek conglomerate suggests that it is probably closer in age to that unit than to the Alma beds.

The Keller Canyon is exposed in the central and western part of the Alma Basin and around all the margins except for the eastern side next to the Mogollon Mountains, where it is probably present at depth, but has been covered by the mostly Pliocene Alma beds.

### Stage three

The Alma beds (Houser, 1987) were deposited during the third stage in the development of the Alma Basin (about 6.0 to 1.5(?) Ma) and are the youngest basin-fill unit. They are more than 300 m thick in exposures throughout the basin. They overlie the basalt of Harve Gulch and the conglomerate of Keller Canyon, and underlie gravel deposits of the San Francisco River and other Quaternary surficial deposits. The minimum age of the Alma beds is not well constrained. The age of 1.5 Ma (early Pleistocene) was chosen because skeletal remains of *Paenemarmota*, a Pliocene giant ground squirrel, have been found in the Alma beds at several locations in the basin (Houser, 1987 and unpubl.). Pleistocene faunal remains, however, have been found at only one locality in the southern part of the basin east of Pleasanton (Ratté and Finnell, 1978). The paucity of Pleistocene faunal localities may indicate that deposition in the Alma Basin did not continue very long into the Pleistocene. The stratigraphic context of a Pleistocene mammoth occurrence near San Francisco hot springs at the southern end of the basin (Ratté, personal commun., 1983) has not been investigated.

In the Alma quadrangle (Houser, 1987), the Alma beds were separated into three units overlain by a fourth unit, the Whitewater Mesa beds. For the present purposes, these four units are combined as the Alma beds. They document a transition from deposition dominated by conglomeratic mudflows, through distal alluvial fan and braid plain deposits, to proximal and medial fan deposits of streams having seasonal(?) sustained flow. Stream flow was to the south and southeast through the Mangas trench toward the lacustrine depocenter of this trench in the vicinity of the village of Buckhorn.

The Alma beds are well indurated at the base and semi-indurated at the top of the section. Clasts of the regional ash-flow tuffs are prominant in all the units indicating that a significant interval of erosion had occurred between deposition of the Keller Canyon conglomerate and the Alma beds. The beginning of integration of the headwaters of the San Francisco River is shown by the rare occurrence in the upper Alma beds of red granite clasts reworked from Tertiary conglomerate to the west and north (Ratté et al., 1969).

### Stage four

The fourth stage in the history of the Alma Basin probably was confined to the Quaternary. Subsidence waned, basin-fill deposition ceased, and erosion of the basin fill began during this stage. Although fault scarps as high as 15 m provide clear evidence for continued fault movement into Quaternary time, the rate of subsidence apparently has not been rapid enough to cause ponding of the San Francisco River and result in deposition of basin fill.

Integration of the headwaters of the San Francisco River continued, as indicated by the common occurrence in river gravel deposits of red granite and other exotic clasts derived from Tertiary conglomerate sources to the north and west. Two deposits of San Francisco River gravel in the northeastern part of the basin show that the ancestral San Francisco flowed 3-5 km east of its present course when it was about 150 m higher than it is now. The general elevations of pediment surfaces in this area are consistent with the slope of the surfaces being at grade with the course of the ancestral San Francisco River between the two gravel deposits. The pediments were probably abandoned soon after the course of the river was diverted westward, presumably by stream capture, although the evolution of the course of the San Francisco River has not been studied.

## STRUCTURE

Three main sets of faults exist in the Alma Basin (Fig. 1). The northwestern part of the basin is dominated by N30°E-trending faults of the Morenci-Reserve fault zone. Faults in the central and eastern part of the basin trend generally north-south and are probably part of the fault system of the Mangas trench. Discontinuous, generally east-west-trending faults are present throughout the basin and along the northern and southern basin margins.

Nearly all the faults are high-angle normal faults (70° to 85°) that dip to the southeast or east. The lowest dip measured is 43° and only a few are in the range of 45° to 60°. Striations indicating oblique-slip and essentially strike-slip movement on faults were noted at five locations along the margins of the Alma Basin in the course of geologic mapping. Three of the locations are in late Oligocene and early Miocene volcanic rocks at the west, north and southeast sides of the basin. The remaining two locations are in sedimentary rocks at the east side of the basin near Mineral Creek. At one of these, a north-trending vertical fault showing striae at a rake angle of 13°S displaces conglomerate of the Miocene Dog Gulch Formation, and at the other, the Pliocene Alma beds are displaced by a north-trending normal fault dipping at 60°E with striae at a rake angle of 30°S.

Except for a complex horst block that cuts diagonally across the basin and apparently bounds the southeast side of the Morenci-Reserve fault zone in this area, the sense of displacement on the majority of both the northeast-trending faults of the Morenci-Reserve fault zone and the north-trending faults of the Mangas trench is down to the southeast—toward the deepest part of the Alma Basin next to the Mogollon Mountains. The total structural displacement of the basin (which may be only moderate) is distributed across about six nonrotated fault blocks.

Models of extensional deformation predict domino-style rotation of fault blocks back toward the master fault. This is the deformation style observed by Crews (1990) in his study of the Reserve graben about 20 km northeast of the Alma Basin. In the Alma Basin, however, most fault blocks are either unrotated or are rotated less than 10° (away from the faults), opposite from the direction predicted in domino-style rotation. In two areas mapped by Ratté (1980, 1989) between the Alma Basin and Crews' study area, Ratté showed strata within fault blocks tilted toward the normal faults, away from the normal faults, or unrotated. The lack of correspondence of the tilt direction of the Alma Basin fault blocks to those of extensional models (and the partial correspondence in the areas mapped by Ratté) may be a result of the tectonic interaction of the Morenci-Reserve trend with the Basin-and-Range trend, or it may indicate that there has not been very much extension in the area.

## DISCUSSION

### Sedimentation and the Mogollon mining district

The characteristics of the four stages of basin-fill sedimentary rocks of the Alma Basin indicate that there was a significant hiatus between deposition of the conglomerate of Keller Canyon and the Alma beds. The Keller Canyon conglomerate is inferred to be closer in age to the underlying 18.7-Ma Charlie Moore Mesa basalt and Little Blue Creek conglomerate than to the overlying 5.6-Ma Harve Gulch basalt and Alma beds. The reasons for this inference are, first, that the contacts of the Keller Canyon conglomerate with the Charlie Moore Mesa basalt and the Little Blue Creek conglomerate are for the most part conformable or only slightly unconformable. Second, in general appearance and sedimentologic character, the Keller Canyon is much more similar to the Little Blue Creek conglomerate than to the overlying Alma beds. Finally, the Keller Canyon is only about 85 m thick, implying that it was deposited in a relatively short time period, perhaps only 1 or 2 Ma.

Thus, there may have been a hiatus spanning about 10 Ma (16 Ma to 6 Ma) between deposition of the Keller Canyon conglomerate and the Alma beds. There must have been significant erosion during this time interval, because the cover of the 100- to 300-m thick Bearwallow Mountain volcanic rocks over the ranges surrounding the Alma Basin was breached and the regional Oligocene ash-flow tuffs were exposed to erosion. Presumably, this detritus was carried by an axial stream southward out of the Alma Basin to the Mangas trench where it was deposited.

It is tempting to speculate that the apparent lack of deposition in the Alma Basin during the latter half of the Miocene may have been associated with the hydrothermal event that resulted in mineralization of the nearby Mogollon mining district (Ratté, 1981). The timing of the two events is appropriate. An $^{40}Ar/^{39}Ar$ date on vein adularia from the district indicates that hydrothermal alteration occurred in the Mogollon Mountains at about 16.7 Ma (W.C. McIntosh, personal comm., 1993). A possible source of the hydrothermal fluids may have been a shallow intrusion beneath the western side of the Mogollon Mountains. Emplacement of the intrusion is likely to have caused uplift of the surrounding area or at least to have minimized subsidence.

Renewed deposition and subsidence at about 6 Ma in the Alma Basin may have occurred after the intrusive body cooled, or may have been associated with tectonic events related to the eruption of the the basalt of Harve Gulch.

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