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CENOZOIC STRATIGRAPHY
AND GEOLOGIC HISTORY
OF
SOUTHWESTERN ARIZONA

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ABSTRACT

Recently obtained seismic data and the results of stratigraphic drilling in southwestern Arizona indicate that several alluvial-covered valleys in this area are underlain by as much as 3000 m of Cenozoic deposits. These deposits, with the exception of the marine late Miocene clastic wedge of the Yuma Basin and the Pliocene Bouse Formation of the lower Colorado River Valley, are the result of continental sedimentation. For the most part, these continental rocks consist of locally-derived clastic sediments and lesser amounts of interbedded volcanic rocks and, in some valleys, thick bodies of evaporites. On the basis of their position in the stratigraphic sequence in relation to regional or semi-regional unconformities, the Cenozoic sequence of southwestern Arizona was subdivided into an older Unit I and a younger Unit II. The boundary between these two units is a widespread unconformity surface resulting from an important period of block-faulting, uplift, and erosion which occurred in the late Miocene (13 to 12 m.y. ago). The two Cenozoic units have been dated and mapped on the basis of radiometric age determination of the interbedded volcanic rocks, on lithologic character, and with the help of seismic interpretation.

Sedimentation during the early Cenozoic (Unit I) took place in broad interior depressions under predominantly continental conditions. The late Miocene block-faulting episode changed the geography of southwestern Arizona and gave the area a typical "Basin and Range" structure of mountain-forming horsts separated by valleys underlain by grabens or half-grabens. The prevailing structural grain trends in a northwest-southeast direction, except for the Gila Trough that trends northeast-southwest. Unit II sediments were deposited in these troughs or grabens during the late Cenozoic. At least two of the five troughs located in the eastern part of the area studied contain thick sequences of evaporites that indicate interior drainage. These evaporites are assigned a late Miocene age on the basis of K-Ar ages for associated basalts and by their position in the stratigraphic sequence in relation to the late Miocene block-faulting episode. Exterior drainage systems were developed beginning sometime between 10.5 and 6 m.y. ago, and have evolved progressively to give the area its present-day geomorphology.

Key words: Cenozoic, late Miocene, fanglomerates, volcanic rocks, evaporites, block-faulting, K-Ar ages.

INTRODUCTION

An exploration program in the Basin and Range province of southwestern Arizona recently undertaken by Exxon Company, U.S.A. (Fig. 1) has provided new data concerning the area's Cenozoic stratigraphy. Seismic mapping and stratigraphic drilling revealed the presence beneath some valley floors of more than 3000 m of post-Laramide clastic sediments, volcanic extrusives and, in places, anomalously thick bodies of evaporites. Except for two marine wedges in the lower Colorado River Valley, the rocks studied are products of continental deposition. The Cenozoic section was found to be barren of marker fossils, to contain many abrupt facies changes, and to be faulted to such an extent that reliable regional lithologic correlations could not be made. Correlation was accomplished, however, by using radiometric ages determined from K-Ar ratios in extrusive volcanic intervals interbedded with the sediments. These ages were correlated with a magmatic chronology already in use in Arizona (Damon, 1964). The correlated ages were then used in combination with geologic and seismic data to subdivide the Cenozoic deposits into two unconformity-bound stratigraphic units (Fig. 2).

Although part of the study was regional, most of the seismic work and all of the drilling were done within a narrow arc extending from Yuma, through Phoenix, to the vicinity of Tucson (Fig. 3). This report summarizes the study and describes the results as related to observations made by others in surrounding regions.

STRATIGRAPHY

General

Nearly all of the Cenozoic rocks in the studied area are products of nonmarine sedimentation, deposited under oxidizing conditions in fluviatile and lacustrine environments. Included in the sedimentary sequence are some extrusive volcanic rocks. The section is almost devoid of marker fossils. Only a few of the lacustrine clays and tuff beds contain fresh-water ostracods, of which species of _Candona_ are the most abundant. _Candona_ sp. ranges throughout the Mesozoic and Cenozoic, but is most abundant in the late Cenozoic. In isolated localities mammalian fossil remains have been recorded (Bryan, 1925; Lance, 1960; McKee and Anderson, 1971). In the present study fossils were of little value in dating or correlating the continental Cenozoic rocks.

The only marine rocks occur in the Yuma Basin west of the Gila Mountains (Fig. 3), and northward along the lower Colorado River Valley. In the Yuma Basin, test holes have encountered a marine Miocene section below the Bouse Formation (Mattick and others, 1973). Marine sediments of Bouse age were deposited farther north along the lower Colorado River Valley during a Pliocene invasion of the sea (Metzger, 1968).

Cenozoic rocks of southwestern Arizona have been subdivided by previous workers using such criteria as degree of deformation, association with volcanic rocks, similarity in lithologic composition, correlation with present physiography, and presence or absence of mineralization (Heindl, 1958; Lance, 1960; Cooley and Davidson, 1963; Sell, 1968). Within the last decade, radiometric age determinations of igneous rocks have become the most reliable method to establish a time-stratigraphic framework in the continental-volcanic Cenozoic sequence of southwestern Arizona.

During the present study, all available data were utilized to establish the Cenozoic stratigraphy of southwestern Arizona. Published surface sections were compiled and 93 outcrop localities were visited. About 29,000 m of well cuttings from 56 of the oil and gas tests and deep water wells, mostly in Maricopa and Yuma Counties, were studied for lithology and stratigraphic relationships. These initial sample descriptions were supplemented by the study of the cuttings from Exxon's four stratigraphic tests (see Appendix 1). Published radiometric ages of volcanic rocks were augmented with 60 new radiometric age determinations (Table 1). In addition, an extensive net of seismic lines was utilized to complete the interpretation of the subsurface stratigraphy.

Results of integrating all the above information indicated that the lithologic composition of the Cenozoic section did not lend itself to the ready recognition of distinct lithologic units. Similarly, the lack of time-diagnostic fossils made it impossible to determine reliably the time-stratigraphy of the section. The available information indicated, however, that a major unconformity could be recognized within the Cenozoic stratigraphic section throughout southwestern Arizona, and that several, less important, unconformities could also be identified over large parts of the area. It became evident that the most effective way to subdivide the Cenozoic section of southwestern Arizona was by selecting stratigraphic units, not by means of distinctive lithologic characteristics, or chronology determined by fossil evidence, but by their position in the stratigraphic sequence in relation to the unconformity surfaces.

On this basis the Cenozoic section in southwestern Arizona has been divided into two main unconformity-bound units: an older Unit I (Eocene to late Miocene in age), and a younger Unit II (late Miocene to Holocene in age), (Fig. 2). The boundary between these two units is a widespread, easily-recognized unconformity surface resulting from a period of block-faulting, uplift, and erosion which, on the basis of K-Ar analyses, (Damon and others, 1973) dated as having taken place between 17 and 12 m.y. ago. Additional information gathered during the present study permits narrowing the date of this tectonic episode to around 13 to 12 m.y. ago. It will be referred to as the "late Miocene block-faulting

does not represent deformation event regional probably. Their unconformity producing event is later, they're imposed over this 20-15 m.y. earlier [illegible] episode".

Unit I rests directly on a major unconformity separating rocks of Eocene to Miocene age from a variety of Pre-Eocene rocks ranging in age from Precambrian to Paleocene. Unit I has been subdivided into "lower", "middle", and "upper" subunits, also on the basis of readily-recognizable unconformity surfaces (Fig. 2). The middle subunit is composed predominantly of volcanic rocks and lesser amounts of interbedded pyroclastic sediments, formed during a period of uplift and volcanism which Damon (1964) has called the "Mid-Tertiary orogeny". During this tectonic episode the Lower Unit I sediments were folded, faulted, intruded by magmas and eroded (Figs. 4, 5, and 9).

Figure 2 summarizes the stratigraphic subdivision of the Cenozoic section of southwestern Arizona, suggested as a result of the present study. It also shows the relationship of the proposed new units to the local lithologic units previously used by various authors in the area.

Unit I

Unit I rocks rest on a floor composed of rocks having a wide range of ages. In the central part of the study area this "Pre-Eocene bedrock" is a crystalline complex of Precambrian granitic and gneissic rocks overlain by Paleozoic rocks in cases of rare preservation. Toward the northwest and southeast, the Paleozoic section is more widespread, thickens, and is overlain by Mesozoic and early Cenozoic (Paleocene) rocks that were subjected to Laramide diastrophism.

Unit I includes all rocks deposited between the beginning of post-Laramide alluviation, about 53 m.y. ago (early Eocene), and the time of the first significant movements of the late Miocene block-faulting episode, about 13-12 m.y. ago. Deposition of Unit I apparently occurred in broad, shallow depressions of a low-relief land surface. Although these depocenters were undoubtedly modified at times by tectonic adjustments and volcanism, the sediments generally contain no evidence of large-scale contemporaneous vertical movements except during the Mid-Tertiary orogeny. As interpreted from preserved remnants, these beds were deposited on an uneven floor by simple alluviation and volcanism.

Rocks of Unit I can be subdivided into three subunits: (1) a lower subunit that was deposited during the magmatic quiescent period between the Laramide orogeny and the Mid-Tertiary orogeny; (2) a middle subunit of volcanic rocks and intercalated sediments deposited during the period of volcanic activity associated with the Mid-Tertiary orogeny from 31 to 17 m.y. ago; and (3) an upper sequence of beds that postdates the volcanism, but predates the beginning of late Miocene block-faulting.

Lower Unit I. Rocks of the oldest part of Unit I occur as isolated remnants of fluviatile reddish-brown arkosic sandstones and interbedded fanglomerates. In places, the thickness of these sediments ranges up to several hundred meters. The sandstones are poorly sorted, moderately to well-indurated, and composed of quartz, feldspar, biotite, and fragments of gneissic and granitic rocks. Weathered iron oxides and a reddish-brown silty matrix give a distinctive reddish cast to these sediments. The fanglomerates are composed mainly of rounded to subangular cobbles and boulders of gneiss and granite (Fig. 10). Both the sandstones and fanglomerates apparently have been derived from nearby source areas that were parts of a widespread and fairly homogeneous Precambrian gneissic and granitic terrain.

In the northwestern and southeastern parts of the study area, Lower Unit I fluviatile sandstones and conglomerates interfinger with lake beds. These lacustrine sediments locally contain thin, algal limestones similar to those found in the Flagstaff Formation of central Utah (Spieker, 1946). Best development of this type of limestone occurs in the Artillery Formation in the Rawhide and Artillery Mountains east of Parker (Fig. 3, loc. 85) where it contains snail shells, Chara fruits, and silicified palm roots of Eocene age (Lasky and Webber, 1949).

Lower Unit I ranges in age from Eocene to late Oligocene (53 to about 31 m.y.) and includes some of the earliest middle Tertiary volcanic extrusives. Two of these are the Rillito Andesite and a bed of ash flow tuff in the Pantano Formation located in the Tucson area. These volcanic rocks have been dated as being 38.5 m.y. and 36.7 m.y. old, re-

30 m.y. is beginning of our stage I

spectively (Table 1, locs. 19, 34). They are approximately contemporaneous with volcanic activity that started in the Mogollon-Datil volcanic province of New Mexico and Arizona as early as 38 m.y. ago (Elston and others, 1973), and in central Nevada about 37 m.y. ago (McKee and Silberman, 1970). Data collected elsewhere in the study area indicate that volcanism was widespread near the end of the Oligocene and the beginning of the Miocene (26 m.y. ago).

Middle Unit I (predominantly volcanic rocks). The lower boundary of the middle subunit of Unit I is marked by the beginning of widespread volcanism associated with the Mid-Tertiary orogeny. This volcanic episode modified the geometry of earlier depositional basins and produced great quantities of rhyolitic to andesitic tuffs, breccias, and flows. Sediments intercalated with the volcanic rocks consist of indurated torrential deposits of red sand, gravel, and massive beds of fanglomerate. Isolated, thin beds of algal limestone and mudstone, and associated beds of water-laid tuff indicate intermittent local development of lakes. Unconformities are common within the unit.

As indicated by the Middle Unit I rocks, volcanic activity became intense near the end of Oligocene time, spreading during the early Miocene throughout southwestern Arizona and lasting some 6 m.y. Of the 67 K-Ar derived ages in Table 1 that fall between 31 m.y. and 17 m.y., 48 are in the time interval from 26 m.y. to 20 m.y. Twenty-seven of the 67 determinations were made for the present study and represent widespread coverage in the study area. They confirm the findings of Damon (1964), who originally documented the Mid-Tertiary magmatic pulse in the Basin and Range province.

Upper Unit I. These Mid-Miocene continental deposits consist of grayish-brown, poorly consolidated sands, fanglomerates (containing abundant volcanic detritus), varicolored mudstones, and beds of water-laid tuff. Locally, these sediments are intercalated with and overlain by basaltic lava flows. The tuffs are usually cream to white, less commonly varicolored. Well-preserved, fresh-water ostracods are common in the mudstone and tuff beds. Typical of these middle Miocene sediments are the Daniels Conglomerate in the Ajo area (Gilluly, 1946) and the Chapin Wash Formation in the Rawhide and Artillery Mountains (Lasky and Webber, 1949).

Upper Unit I deposition began as the Mid-Tertiary orogeny started to wane about 20 m.y. ago. Available evidence suggests a decrease and cessation of orogenic and magmatic activity with the establishment of new interior drainage patterns. Topographic lows and areas of local subsidence became new sites of alluvial-fan and playa deposition.

Beginning about 15 m.y. ago, volcanic activity was renewed with a rather widespread outpouring of basaltic lava. This volcanic episode continued for about 5 m.y. with large-scale block-faulting starting about midway through its duration. Volcanic activity appears to have been more intense during the pre-fault period, judging from a preponderance of K-Ar ages ranging from 15 to 13 m.y. (Table 1).

Unit II

Late Miocene block-faulting destroyed previous drainage and depositional patterns and created a new horst-and-graben terrain. Rocks of Unit I were faulted and eroded and have a distinct angular relationship with the overlying beds of Unit II. The fault troughs, or grabens, became depocenters for clastics eroded from adjacent, rising highlands and, to a lesser extent, for the products of declining volcanism. Unit II includes the rocks deposited in these grabens.

What is [illegible]
the angularity?
[illegible] implied [illegible]

Unit II can best be described by treating separately three geographic areas in which the sediments of this unit have distinct and differing characters: (1) an eastern area, where thick, late Miocene fluvio-lacustrine sediments, containing locally thick bodies of evaporites, accumulated in rapidly subsiding trough-like basins; (2) a central area, where a much thinner fluvio-lacustrine sequence, without evaporites, was deposited; and (3) a western area, the Yuma Basin and the lower Colorado River Valley, where marine sedimentation dominated.

Unit II in the Eastern Area. In two of the five trough-like basins that occur between Phoenix and Tucson (Fig. 4), Unit II contains thick evaporite sequences.

A well drilled near Phoenix in 1969 by the Arizona Salt Company penetrated 1219 m of massive halite without reaching its base. This occurrence was described and named the Luke Salt by Eaton and others (1972). Subsequent seismic mapping by Exxon showed that the well drilled into a shallow, large, dome-like salt mass possibly more than 3000 m thick (Fig. 7). The material underlying this salt mass has not been penetrated by wells, but its age and lithology can be postulated from widespread well data and seismic correlations.

The Exxon State (74)-1 (Appendix 1), located 115 km to the southeast of Phoenix in the Picacho Basin, penetrated slightly more than 1800 m of massive anhydrite containing only minor interbeds of shale, tuff, halite and limestone nodules. The anhydrite was encountered in a stratigraphic position comparable to that of the Luke Salt, suggesting that at least the upper part of the two evaporite sequences may be time correlative. The State (74)-1 encountered a basalt flow at a depth of 2765 m that yielded a K-Ar age of 17 m.y. (middle Miocene, Table 1, loc. 5). Overlying the basalt flow are fanglomerates that grade upward into the Picacho Basin evaporites. This evaporite section grades upward into an undated section of red-brown claystone containing some sand, anhydrite, and gypsum. In the Phoenix Basin, however, some thin

? flows [illegible]

basalt flows are locally intercalated in an equivalent clastic section that lies stratigraphically above the Luke Salt. One of these flows, penetrated by the Goodyear Farms water well (Table 1, loc. 59), yielded a K-Ar age of 10.5 m.y. (late Miocene). This is approximately the age of younger basalts of the Hickey Formation of central Arizona (McKee and Anderson, 1971). If it is assumed that the Luke Salt and the Picacho Basin anhydrite are approximate time equivalents, the occurrence of basalt of late Miocene age in beds above the former and basalt of middle Miocene age below the latter dates both evaporites.

[illegible] 17 - 10.5 m.y. [illegible] evaporites ?

Anhydrite and gypsum have been encountered in the Chandler, Red Rock, and Tucson basins but no thick evaporite sections have been penetrated by wells. These are areas of very sparse deep subsurface control, however, and contain large volumes of unexplored sediments.

Over 1200 m of relatively pure halite was penetrated in a well north of Kingman in the Hualapai Valley (Peirce, 1972). Peirce believes this deposit, which he named the Red Lake Salt, is tabular in shape and was formed in a closed basin.

The Muddy Creek Formation in the Lake Mead area also contains thick salt deposits (Longwell, 1963). This salt has not been dated, but late Miocene ages have been determined for the overlying Fortification Basalt Member of the Muddy Creek Formation (Anderson and others, 1972).

A sample of a thin basalt flow in the Muddy Creek Formation collected on the west shore of the Overton arm of Lake Mead (Fig. 1) yielded a late Miocene K-Ar age of 8 m.y. (Table 1, loc. 124). Locally, this basalt has been domed by upward movement of the underlying salt. Other basalts and dikes that have been assigned to the Fortification Member have yielded K-Ar ages as young as 4.5 m.y. (Anderson and others, 1972).

Unit II in the Central Area. The central part of the report area lacks the deep Tertiary troughs that characterize the eastern part, and it is probably barren of evaporites. Information from wells drilled by others and from Exxon's seismic data indicates that Unit II in this area is thin and composed of fanglomerates, red-brown clays, and basalt flows. Ross (1923) noted a persistent occurrence of red-brown clay in the subsurface of the lower Gila River area and correlated it with similar deposits in the Mesa area, 20 km east of Phoenix (Lee, 1905). Red-brown clays were also described in the Gila Bend area by Heindl and Armstrong (1963). In the Exxon State (74)-1, red-brown clay was encountered between 198 and 707 m directly above the Picacho anhydrite. In the Tucson Basin, the same kind of clay was encountered by Exxon's State (32)-1 (Appendix 1) between 350 and 813 m. In the latter well the interval from 564 to 686 m contained an abundance of gypsum crystals.

Ross concluded that the red-brown clays found in the subsurface of the lower Gila River area were probably lake deposits, and data gathered in this study support that conclusion. Also, these data suggest that the clays were products of the same period of interior drainage that produced the evaporites in the eastern troughs making them contemporaneous.

These red-brown clays grade upwards into river gravel deposits indicating termination of lacustrine conditions and the development of exterior-drainage systems. A K-Ar age of 6.0 m.y. was obtained for a basalt flow overlying minor amounts of river gravels near Gillespie Dam, about 70 km west-southwest of Phoenix (Fig. 3, loc. 97). Based on this age and the 10.5 m.y. age of the basalt flow intercalated with lacustrine sediments overlying the Luke Salt in the Phoenix Basin, exterior-drainage systems began developing sometime between 10.5 and 6.0 m.y. ago.

Along the lower Colorado River Valley, in the Cibola-Parker area, a poorly consolidated sand and gravel fanglomerate (Metzger, 1968) may be the time equivalent of the late Miocene interior basin deposits. Some 10 km east of Parker in Osborne Wash this fanglomerate rests unconformably on steeply tilted red beds of Unit I (Fig. 11).

Unit II in the Western Area. Unit II in the western area consists of a marine wedge of clastic sediments of probable late Miocene age confined to the Yuma Basin and the overlying more widespread Pliocene Bouse Formation. Overlying the Bouse Formation are Colorado River gravel deposits.

Marine Late Miocene of Yuma Basin. In the subsurface of the Yuma Basin, a few of the drilled wells have encountered a marine sequence (Mattick and others, 1973). Exxon's Yuma Federal No. 1 well (Appendix 1), located 25 km southwest of Yuma (Fig. 3, loc. 115), penetrated, from 1627 to 2115 m, 488 m of light gray, greenish-gray, and salmon colored mudstones and fine-grained tuffaceous sandstones. In the basal 40 m, the fine-grained sediments grade downward into a medium-to coarse-grained conglomeratic sandstone that rests unconformably on volcanic rocks and intercalated continental-type sediments. A similar appearing clastic section was noted between 1136 and 1962 m in the Colorado Basin Associates, Inc. Federal No. 1 well, located 10 km northeast of the Exxon well.

Sample cuttings from the Exxon well contain abundant specimens of minute shallow water foraminifera, scattered pelecypod fragments, and echinoid spines. This fauna, however, was not recognized in the Colorado Basin Associates, Inc. well. Foraminifera observed in cuttings from the Exxon well include abundant benthonic forms of Bolivina sp., Cibicides sp. and Nonion sp. Species of Discorbis, Spiroplectammina, Gyroidina and Planulina are also present. Poorly preserved specimens of Globigerina and Sphaeroidinella are present in the basal 10 m of the clastic sequence. No specific determination of these forms was possible and, consequently, they could not be used for age determinations.

A late Miocene age is assigned to this marine clastic sequence based on the following relationships: (1) the beds are overlain unconformably by the Pliocene Bouse Formation; (2) dipmeter data from the Exxon well indicate the sequence dips gently and overlies with distinct angular discordance the underlying steeply dipping volcanic rocks and intercalated sediments which have been dated on the basis of K-Ar analyses as being 20 m.y. old (Mid-Miocene) (Table 1, loc. 115); and (3) seismic data indicate the clastic section to be younger than the late Miocene block-faulting episode (13-12 m.y.).

Equivalents to this marine sequence may be the late Miocene continental sediments found in the Gila Valley and the fanglomerate cropping out along the lower Colorado River Valley in the Parker-Cibola area. They may also be correlative to the redefined marine Split Mountain Formation (Woodward, 1974) present on the west side of Imperial Valley.

Marine Pliocene Bouse Formation. The Pliocene Bouse Formation in the Yuma Basin (Metzger, 1968; Smith, 1970) unconformably overlies the previously described late Miocene marine sediments. The Bouse Formation also overlies unconformably the late Miocene fanglomerate in the Cibola-Parker area (Figs. 11, 12). In the lower Colorado River Valley, this relatively flat-lying formation crops out at several localities north of Yuma and was penetrated in the subsurface near the International border by the Exxon Yuma Federal No. 1 between 963 and 1627 m.

In outcrops, the formation is composed of a basal, white, tuffaceous limestone overlain by an olive-gray claystone. Minor amounts of silt, sand, and gravel occur generally throughout the unit and the silt and sand percentage increases upward. The basal limestone was not encountered by the Exxon well or by the Colorado Basin Associates, Inc. Federal No. 1, located 10 km northeastward. At both locations, Bouse claystone rests directly on the older marine clastics already described. At the Exxon location the Bouse Formation is composed of fossiliferous, light-gray claystone containing occasional thin beds of fine-grained, light-gray sandstone with varying amounts of tuff. Occasional foraminifers, ostracods, charophytes, barnacles, and mollusks are contained in the formation, the mollusks being more common in the sandy upper portion.

A tuff layer in the basal limestone of the Bouse Formation has been dated as 5.4 m.y. old (Damon, 1972, oral commun., Table 1, loc. 122). This Pliocene date confirms that the Bouse is probably younger than the red-brown clays of the lower Gila River Valley.

Possible Bouse Equivalents. Beds equivalent to the Bouse Formation have been recognized in several localities within the general area of this study. Noble (1931) described sediments similar to the Bouse along the Colorado River Valley near Needles, California, and in the Chemehuevi Valley west of Lake Havasu (Fig. 1). Similar sediments have also been observed as far north as Lake Mohave (Fig. 1), where Bouse-like white, limy tuff and olive-green clays unconformably overlie a fanglomerate of local derivation in the washes east of the lake. Overlying the clays are Colorado River gravel deposits.

It has been suggested (Lucchitta, 1972) that the thick marine Imperial Formation cropping out in the mountains west of the Imperial Valley may correlate with the Bouse Formation. The only information collected during the present study that may have a bearing on this problem was a stratigraphic relationship observed in the Coyote Mountains (Fig. 1, loc. 123) where the Imperial Formation seems to rest unconformably on the 16 m.y. old Alverson Volcanics (Table 1, loc. 123).

STRUCTURAL DEVELOPMENT

General

Southwestern Arizona has a typical "Basin and Range" structure of mountain-forming horsts separated by valleys underlain by grabens or half-grabens. The prevailing structural grain trends in a northwest-southeast direction. A notable exception is the Gila Trough that closely corresponds with the northeast-southwest-trending lower valley of the Gila River.

The following brief description of the structure of the area is almost exclusively restricted to the beds of Unit II, deposited after the late Miocene block-faulting episode and the resulting subsequent regional unconformity. Good seismic data allow interpretation with reasonable certainty of the attitude of these younger beds beneath the alluvium-covered valleys. Evidence to interpret the structure of the pre-late Miocene-unconformity section (Unit I) is, on the other hand, restricted to the exposed remnants of this unit in the mountain ranges, since the quality of seismic data below the unconformity is very poor.

The geologic structure of southwestern Arizona is illustrated by means of five cross sections (Figs. 4 to 8). Their location is shown on a generalized geologic map of the area (Fig. 3). On the cross sections A-A' and B-B' (Figs. 4, 5) an attempt has been made to restore the structure of the area to the time just previous to the beginning of the deposition of Unit II. The cross sections are based on subsurface information, on seismic data recorded in the valleys, and on surface observations in the surrounding mountains.

Late Tertiary Northwest-Southeast-Trending Troughs

Section A-A' (Fig. 4) crosses five depositional basins that border the central Arizona mountainous region. They are referred to on the cross section as the Phoenix, Chandler, Picacho, Redrock, and Tucson basins. They are the deepest fault trenches encountered in the study east of the Salton Trough. As interpreted from seismic data and the lithology of the deposits that fill them, these fault troughs resulted from late Miocene block-faulting. Previous to this tectonic episode, during early Cenozoic time, the area appears to have been stable and relatively free of subsidence. At shallow depths, all five troughs are simple structural basins, but with increasing depth they grade into narrow, complex grabens bounded by parallel to sharply-converging normal faults. The grabens are irregular in shape but tend to be rectangular, having lengths about three to six times their widths. In a general way, they parallel the bordering mountain ranges.

Deep central parts of the troughs apparently are not interconnected. Depositional continuity seems to occur only at shallow depths in younger beds that extend laterally without interruption over buried horst blocks and around fault ridges. As described in the section on stratigraphy, some basins contain thick sequences of evaporites. These evaporites are strong evidence that the northwest-southeast-trending troughs interrupted the regional drainage for a prolonged period of time, creating widespread lakes.

Section B-B' (Fig. 5) crosses three depositional areas of special interest: the Yuma Basin, the Gila Trough, and the Phoenix Basin. The Yuma Basin is a segment of the eastern flank of the Salton Trough and may be more closely related to Salton Trough tectonics than to those of the Basin and Range province to the east. Presence in the Yuma Basin of a thin Unit I is interpreted as evidence that this was a fairly stable area before the beginning of late Miocene block-faulting and that most deposition occurred after this event. The basin is in trend with the San Andreas and Algodones fault zones and may have been modified by their movements.

Section C-C' (Fig. 6) is a cross section of the Tucson Basin, roughly at right angles to cross section A-A', showing the structural relationship of this trough to the adjacent mountain ranges. The Tucson Basin is one of five anomalously deep troughs and has structural characteristics typical of other troughs in the study area. Structure beneath the wide valley floor is composed of a narrow central graben between broad, sloping mountain pediments. The profile suggests that a once-narrow valley between broad ranges has grown in width at the expense of the eroding surrounding highlands. The Tucson Basin is interpreted as a product of late Miocene block-faulting. Locally thick Unit I rocks in the graben are not necessarily evidence of pre-fault subsidence. Rocks of this unit are composed mostly of fanglomerates and volcanic extrusives, and these deposits can vary in thickness for reasons other than local subsidence.

Section D-D' (Fig. 7) is a seismic profile across the Phoenix Basin showing its block-fault structure and an interpretation of the shape and distribution of the Luke Salt mass. As described in the section on stratigraphy, subsurface well and seismic data show that upward movement of salt has domed the overlying sediments at the location of the Arizona Salt Company well.

The Gila Trough

In contrast to the northwest-southeast structural grain of other basins in southwestern Arizona, the Gila Trough is a northeast-southwest-trending, sediment-filled trench underlying the lower Gila River Valley east of Ligurta (Fig. 3). It is 140-150 km long and 15 to 25 km wide. Section B-B' (Fig. 5) follows roughly the axis of this trough for about 100 km between Ligurta and a point near Hyder where the line of section leaves the trough. Near Horn, the only place where Exxon seismic lines cross it at right angles, the Gila Trough is a true graben bound by two (or more) faults (Section E-E', Fig. 8). The trough was crossed by seismic lines at three other widely separated places, but the lines intersected its axis at low angles, making the interpretation of the geometry of the trough difficult. Seismic data indicate zones of abrupt stratigraphic thickening and faulting within the trough, but the orientation of these faults could not be determined with certainty. It seems probable, however, that the trough throughout its length is a graben or half-graben.

Sufficient data are not available to adequately explain the anomalous northeastern trend of the Gila Trough. It may represent a reactivated Precambrian structural element which controls the course of the lower Gila

River and possibly even parts of the course of the Salt River upstream from Tempe. In any case, the presence in the Gila Trough of thick deposits of Unit I indicates that it predated late Miocene block-faulting. Younger block-faulting overprinted the older northeast-southwest structural trend, forming horsts and grabens within the Gila Trough that are aligned with the northwest-southeast trend of other present-day valleys and ranges.

GEOLOGIC HISTORY

Based principally on K-Ar age determinations of volcanic rocks and their stratigraphic relationships to associated sediments, the following is an attempt to reconstruct the chronology of geologic events in southwestern Arizona:

1. Beginning with the decline of the Laramide orogeny, about 53 m.y. ago and lasting until about 31 m.y. ago, southwestern Arizona was an area of general magmatic quiescence (Damon, 1966). This was a time when subaerial fanglomerates and associated lake beds were deposited in interior-drainage basins developed on older bedrock surfaces. The predominant red to reddish-brown color of the sediment indicates deposition in an oxidizing environment.

2. Widespread tectonism began approximately 31 m.y. ago, in late Oligocene, and continued until around 18-17 m.y. ago. This episode, known as the Mid-Tertiary orogeny, was accompanied by regional

heating of the crust, plutonism, minor mineralization, and extrusion of great quantities of rhyolitic to andesitic tuffs, breccias, and flows which modified earlier drainage patterns and the location of depositional sites. Isolated lacustrine sediments were deposited in newly formed interior-drainage basins. Locally, torrential deposits of fluviatile red sandstone and boulder beds were intercalated with the volcanic rocks. Rocks deposited during and preceding this event were faulted, steeply tilted, and locally folded.

Damon (1966) states that large sections of the crust in the Basin and Range province were heated to high temperatures during the Mid-Tertiary orogeny and that recrystallization of the Precambrian Catalina Gneiss north of Tucson occurred 28 to 26 m.y. ago. A quartz-diorite gneiss apparently having a similar history was encountered at 3101 m in Exxon's State (74)-1 near Picacho (Table 1, loc. 5). A K-Ar age determination of biotite separated from a core of this material yielded an Oligocene-Miocene age of 26 m.y., while a Rb-Sr whole rock determination on the same sample indicated a Precambrian age of from 1275 to 1540 m.y. These discordant ages lend additional support for Damon's conclusions.

Thrusting associated with the Mid-Tertiary orogeny has been described near Parker and Tucson (Lasky and Webber, 1949; Wilson and Moore, 1959; Cooper, 1960). Lasky and Webber interpreted the presence of large, exotic rock masses, brecciated blocks, and breccia beds of Precambrian and Paleozoic rocks in the Rawhide and Artillery Mountain areas as evidence of a thrust sheet within the Artillery Formation. Field observations in this area, and others to the west in the vicinity of Parker, lead us to believe that this chaotic material does not represent remnants of thrust sheets, but is gravity-induced landslide blocks and debris associated with wrench-faulting in the early Miocene.

Similar gravity-induced rock masses have been interpreted in the Tucson area. Cooper (1960) describes mudflow-landslide breccia and large individual block landslides in the Pantano Formation. Davidson (1970) believes some of the large outcrops of Precambrian and Mesozoic rocks in the western foothills of the Rincon and Santa Catalina mountains east of Tucson may be large landslide masses emplaced during the deposition of the Pantano Formation. Davis (1975), however, believes that these large outcrops of Precambrian and Mesozoic rocks represent gravity-induced folded remnants off of the Catalina-Rincon complex during domal uplift by ascent of gneissic domes and arches 28 to 24 m.y. ago. His data indicate that the gravity-induced folding during low-angle displacement took place under substantial cover, possibly 3 to 4 km. Davis does not present any evidence that wrench-faulting was associated with the domal uplift.

3. From 18 to 15 m.y. ago, a relatively quiet period occurred during which fluviatile and lacustrine sediments were deposited.

4. From 15 to 10 m.y. ago, volcanic activity resumed with widespread outpourings of basaltic lava.

5. Regional block-faulting began in the late Miocene, approximately 13-12 m.y. ago, and modified all earlier landforms. The preceding surface was converted into a horst-and-graben terrain with the subsiding fault troughs forming new interior-drainage basins. These basins were depositional sites for locally derived detritus, and at least two basins in the study area contain thick bodies of evaporites. Peirce (1973) has postulated that the thick evaporite sections found in the subsurface of some valleys between Lake Mead and the Picacho Basin were formed in deep troughs adjacent to the Colorado Plateau; he further suggested that these evaporites may all have had similar geologic histories. About 10 m.y. ago, faulting began to wane and sedimentation in previously separate interior basins began to coalesce.

As stated previously, Damon and others (1973) dated the late Miocene episode of block-faulting between 17 and 12 m.y. old. In some places basalts as young as 13 m.y. (Table 1, loc. 86) have been significantly displaced by faulting. It is of interest that Anderson and others (1972) concluded that large-scale fault displacements in the Lake Mead area (Fig. 1) ceased before deposition of the Fortification Basalt.

This member of the Muddy Creek Formation has K-Ar ages as old as 11.3 m.y.

6. Exterior-drainage systems began developing sometime between 10.5 and 6 m.y. ago. In the Phoenix Basin a thin basalt flow occurring within lacustrine sediments and overlying the Luke Salt mass indicates that a closed basin environment was still present approximately 10.5 million years ago (Fig. 3, loc. 59). Presence of minor amounts of river gravels below a 6.0 m.y. old basalt near Gillespie Dam, about 70 km west-southwest of Phoenix, (Fig. 3, loc. 97) indicates that exterior-drainage began to form in early Pliocene. Thick deposits of Gila River gravels below the 3.0 m.y. old Sentinel basalt (Fig. 3, loc. 106) are evidence that through-going drainage was well established by late Pliocene and probably reached the Yuma area. According to Lucchitta (1972), the lower Colorado River drainage was developed between 10 and 3.3 m.y. ago, but probably after 5.4 m.y. ago. High, flat-lying terrace deposits of the Colorado River, from the Grand Canyon to the Gulf of California, first noted by Lee (1908), are believed to be older than 3.0 m.y. Ross (1923) recognized old Gila River terraces some 20 to 25 m above the present lower Gila River flood plain. Horse bones found in these terrace deposits near Ligurta suggest an early Pleistocene age (Bryan, 1925). Lee (1905) described similar terraces, 7 to 8 m above the Salt River at Mesa.

Available evidence suggests volcanic activity increased during the period from 6 to 3 m.y. ago.

7. By 3.0 m.y. ago, the lower Gila River had reached its base level of deposition when the basalt flows around Sentinel were extruded on the surface. Increase of gradients since 3 m.y. ago along the Colorado and Gila rivers has allowed these systems to remove great quantities of material from their lower valleys, thus exposing older valley fill material in the adjacent bluffs.

Geophoto analysis of the study area shows only one minor remaining closed drainage basin. It is located southeast of the town of Sentinel, contiguous to the Sentinel basalt flows, and was probably formed when these flows disrupted local drainage.

ACKNOWLEDGMENTS

We gratefully acknowledge the help of many earth scientists in Arizona who willingly shared their knowledge of the area. We are indebted to members of the Laboratory of Isotope Geochemistry, Department of Geoscience, University of Arizona, for many radiometric ages and for prompt dating of samples from two of Exxon's wells. We thank, also, the Arizona Bureau of Mines, the Arizona Oil and Gas Conservation Commission, the U. S. Geological Survey, and the Bureau of Reclamation for many favors. Finally, we acknowledge many other Exxon geologists and geophysicists who contributed to the interpretations presented here. H. W. Peirce read an earlier version of this manuscript and suggested changes for its improvement.

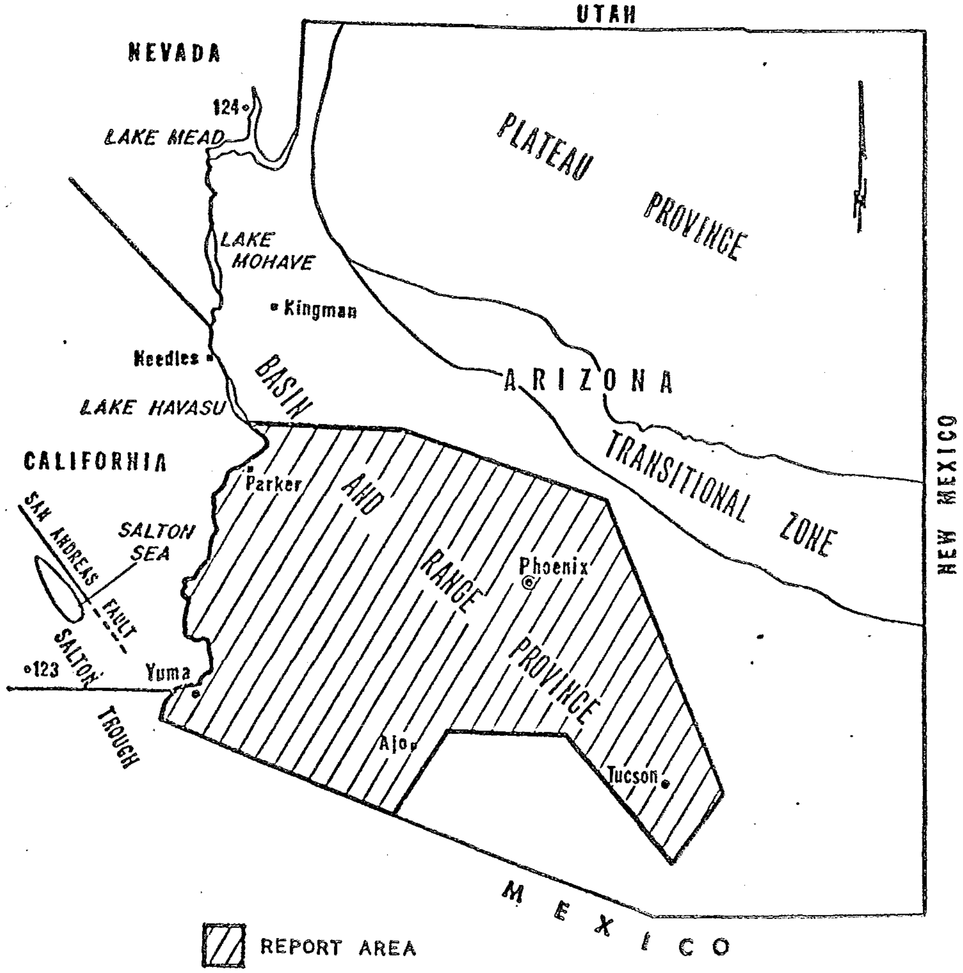
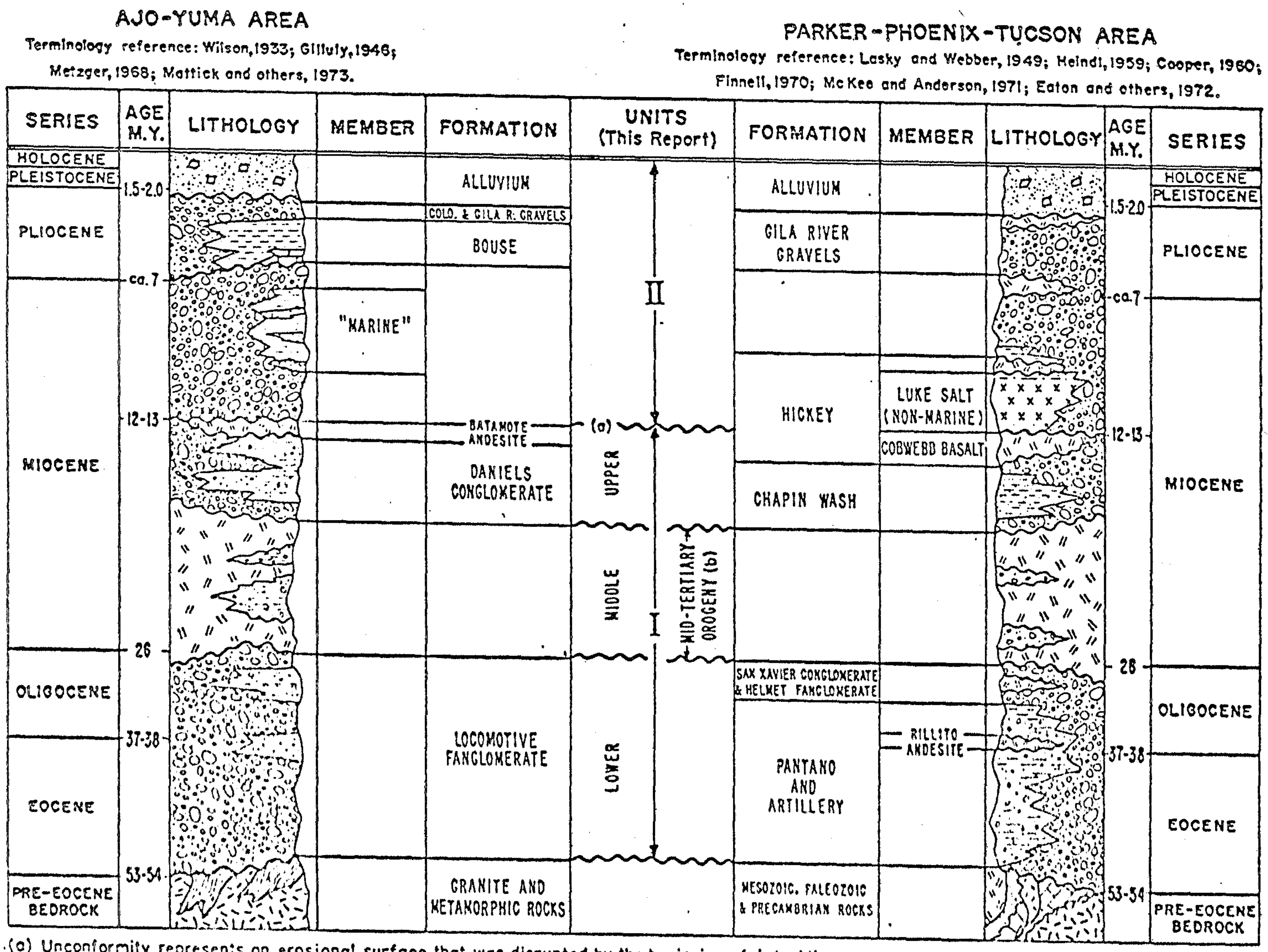


Figure: I Map showing report area (Modified after Wilson and Moore 1959)



basalts
Gila cgl.

Superstition
Apache Leap

Galiuro

whitetail

(a) Unconformity represents an erosional surface that was disrupted by the beginning of late Miocene block faulting.
(b) Modified from Damon, 1964, P 13-15

Figure: 2 Composite stratigraphic column of Southwestern Arizona. (Ages of series bounderies from Geological Society of London, 1964, P. 260-262).

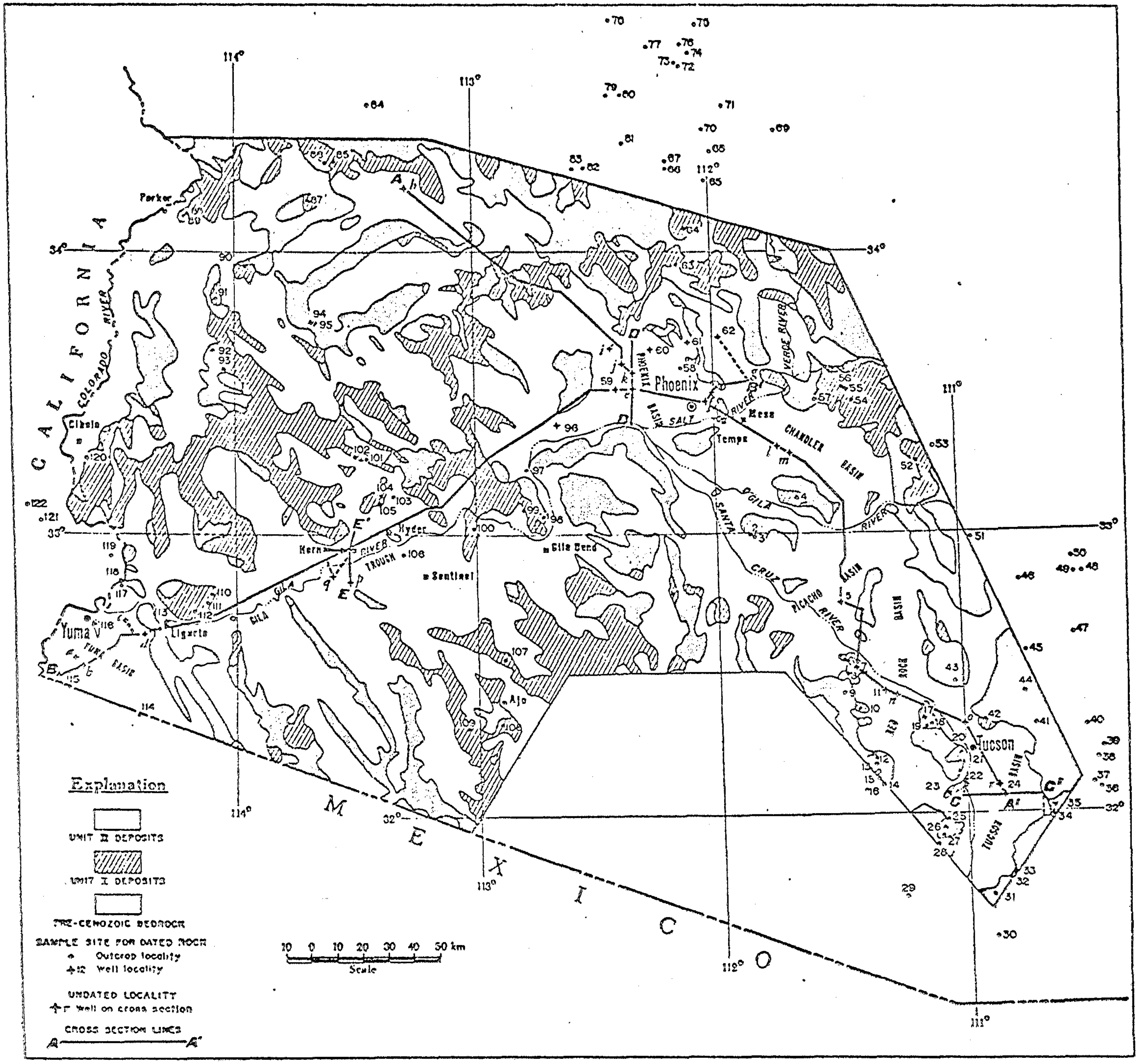


Figure: 3 Geologic map of report area (Modified from Wilson and others, 1969).

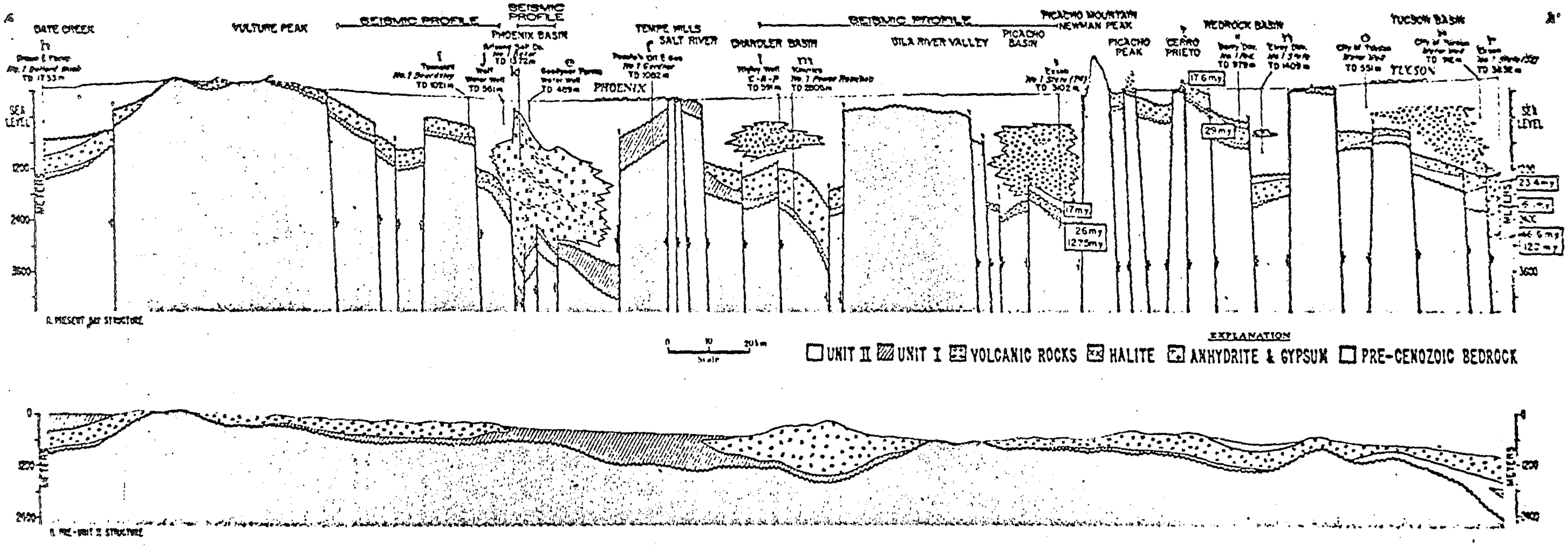


Figure 4 Cross Section A-A' (letters and numerals refer to localities on figure 3. Seismic control shown above cross section.)

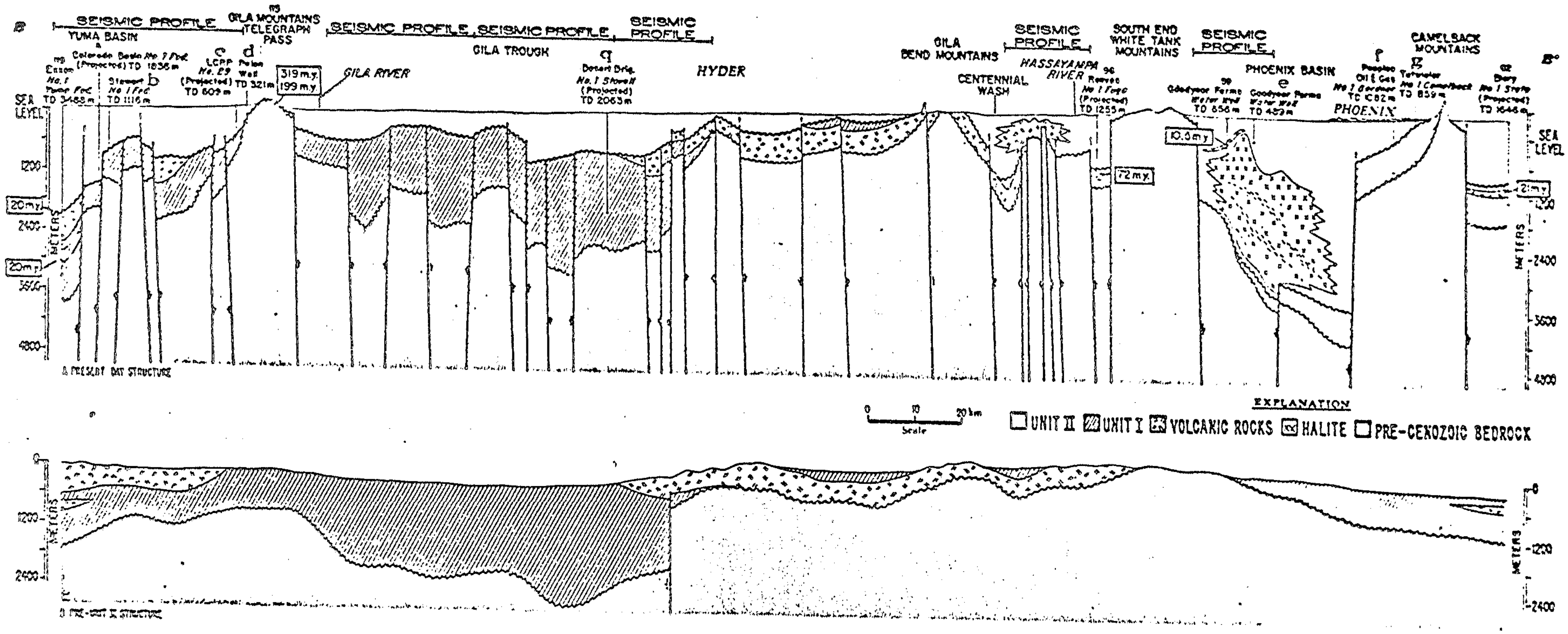


Figure: 5 Cross Section B-B' (letters and numbers refer to localities on figure 3. Seismic control shown above cross section)

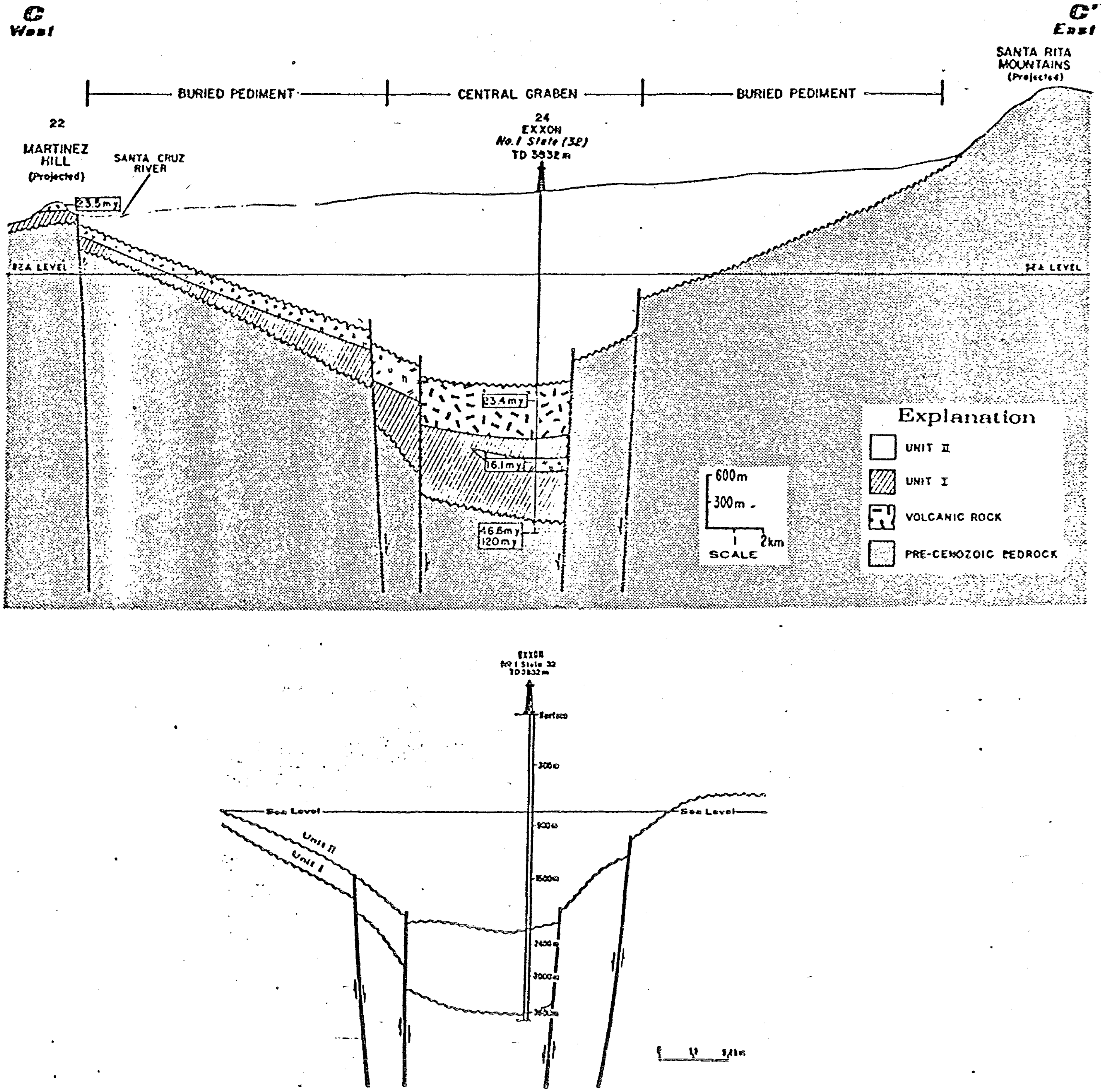


Figure: 6 Structural Cross Section of Tucson Basin. (Numbers refer to localities on figure 3).

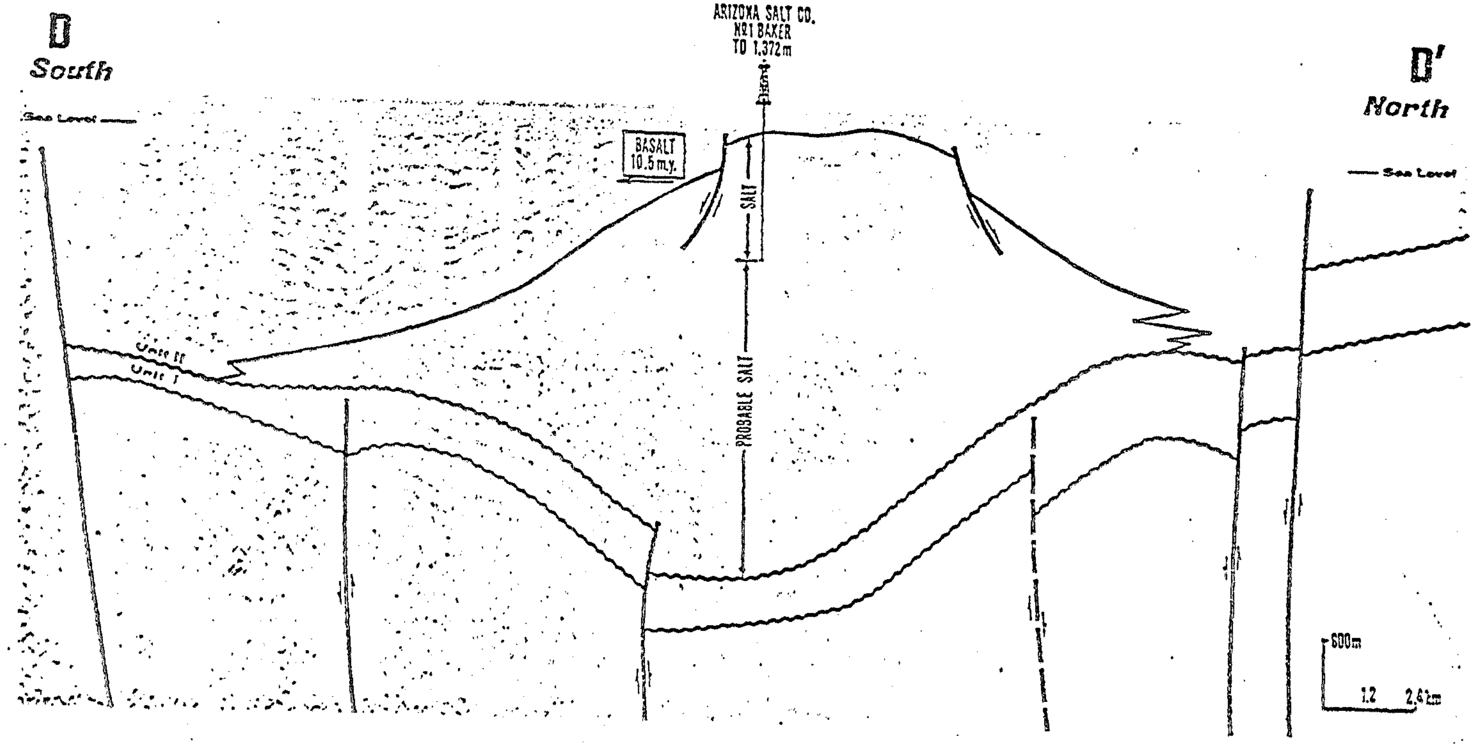


Figure: 7 Seismic Cross Section of the Phoenix Basin showing the Luke Salt mass.

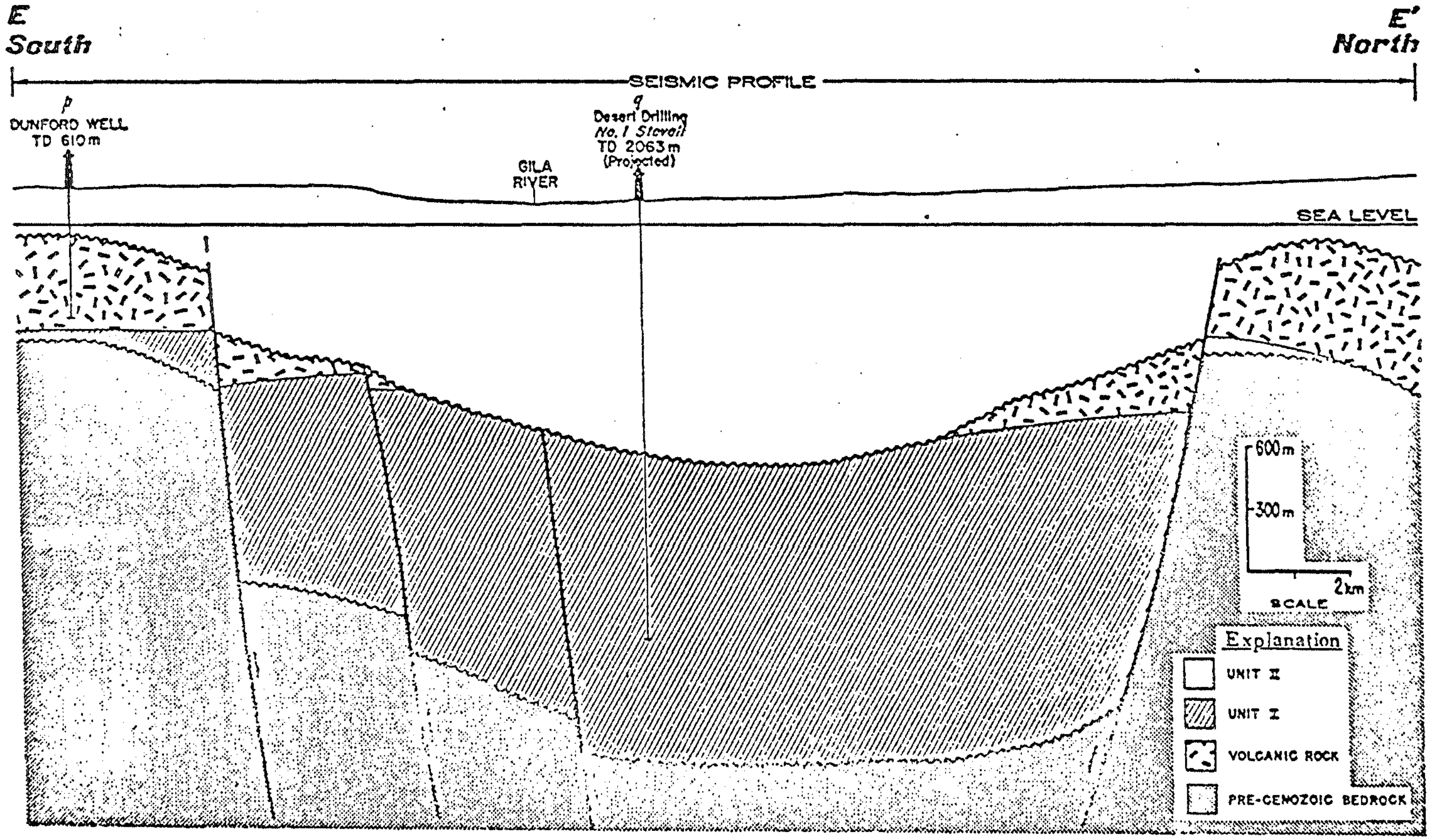


Figure: 8 Structural Cross Section across Gila Trough. (letters refer to localities on figure 3. Seismic control is shown above cross section.)

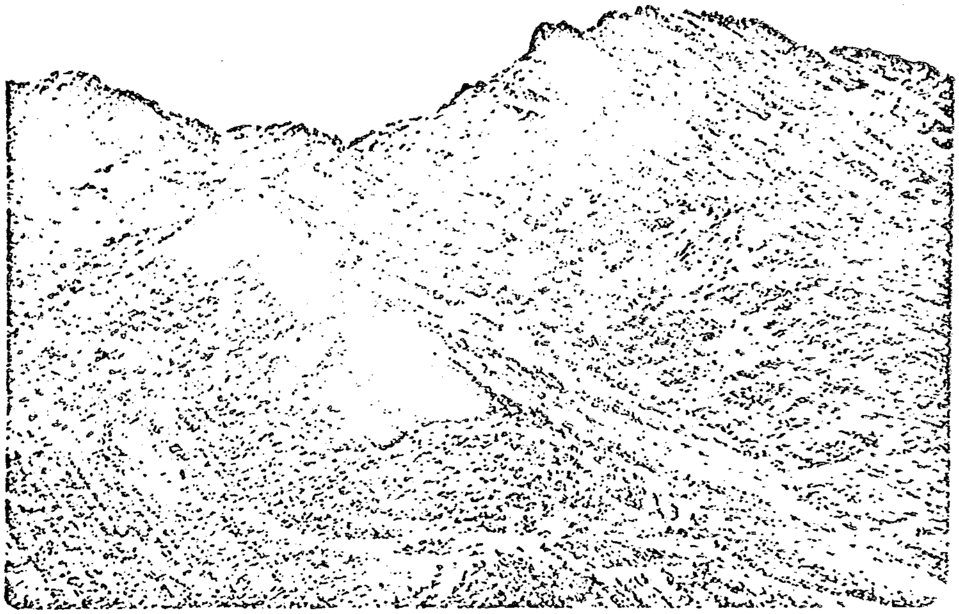


Figure 9. Steep westerly dipping beds of Unit I at the northern end of the Mohawk Mountains, east of Yuma.

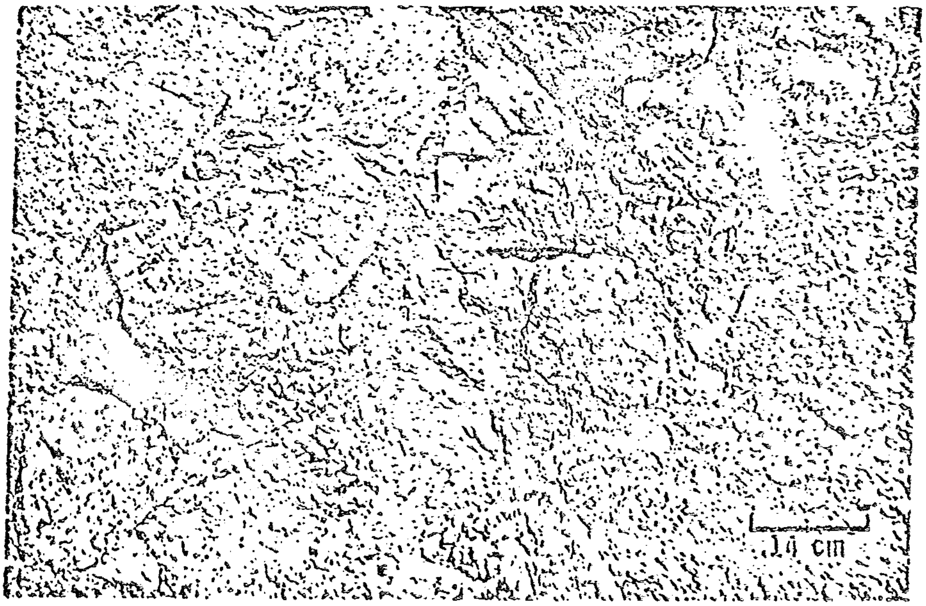


Figure 10. Typical boulder fanglomerate of Unit I.

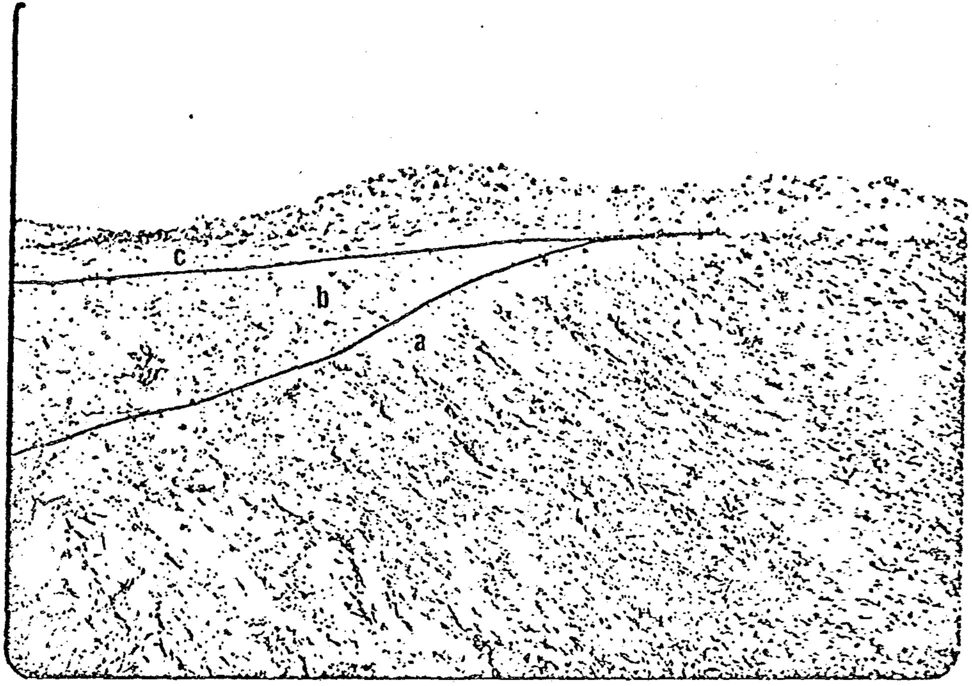


Figure 11. Gentle westerly dipping late Miocene fanglomerate (b) and white Bouse limestone (c) of Unit II unconformably overlying tilted beds of Unit I (a), Osborne Wash east of Parker.

Figure 12. White Bouse limestone resting on late Miocene fanglomerate near Cibola. Contact represents an erosional surface.

TABLE 1. RADIOMETRIC AGES OF ROCK SAMPLES IN SOUTHWESTERN ARIZONA AND ADJACENT AREAS

Sample Locality	Rock Type, Igneous Body or Stratigraphic Formation	Location	Apparent Age m.y.	Radiometric Age Method and Mineral Dated	Reference, Sample Number and Comments
Shown on Fig. 1					
1	Basalt (Antelope Peak)	Lat 32° 47'51"N, Long 112° 10'30"W	25 ± 5.2	K-Ar, whole rock	This report
2	Granite	32° 59'30"N 111° 51'00"W	861 ± 26 853 ± 26	K-Ar, muscovite	J. C. Balla, 1972, Unpublished Univ. of Ariz. Ph.D. thesis, KA-71-70
3	Monzonite	32° 59'00"N 111° 49'00"W	71.7 ± 2 70.9 ± 2	K-Ar, biotite	do. KA-71-69
4	Welded tuff	33° 07'32"N 111° 39'14"W	155 ± 7.9	K-Ar, biotite	This report. Age is spurious. Tuff is probably Miocene.
5	Exxon State (74) No. 1	NW/4, NW/4 Sec. 2, T8S, R8E, Pinal Co.			This report
	2,792m-2,807m (basalt)		17	K-Ar, whole rock	K-Ar date of 26 m.y. for the gneiss is a reduced age. Rb-Sr date indicates a Precambrian age for the gneiss.
	3,101m-3,102m (quartz diorite gneiss)		26	K-Ar, biotite	
	3,101m-3,102m (quartz diorite gneiss)		1,275 1,540	Rb-Sr, whole rock	
6	Sasco Andesite	Samaniego Hills, Pinal and Pima Cos.	15.2 ± 4.8	K-Ar, whole rock	Eastwood, 1970, RLE-20-68
7	Cerro Prieta Basalt	do.	17.6 ± 1.3	K-Ar, whole rock	do. RLE-27-67
			26.6 ± 0.8	K-Ar, whole rock	do. RLE-31-68
8	Samaniego Andesite	do.	19.8 ± 1.2	K-Ar, whole rock	do. RLE-27-68
9	Quartz latite	Lat 32° 26'36"N, Long 111° 29'30"W	25.0 ± 2.0	K-Ar, biotite	Mauger and others, 1965, RM-4-63
10	Petroglyph Hill Andesite	32° 23'07"N 111° 24'42"W	27.9 ± 1.4	K-Ar, biotite	Damon and Bikerman, 1964; Mauger and others, 1965, PED-1-63
11	Berry No. 1 Federal	NE/4, SE/4 Sec. 27, T11S, R10E, Pima Co.			This report
	1,057m-1,072m (welded tuff)		29 ± 2.5	K-Ar, whole rock	
12	Basalt dike	Lat 32° 12'34"N, Long 111° 22'14"W	9.7 ± 1.7	K-Ar, whole rock	Bikerman, 1967, MB-17-64
13	Rhyodacite (Recortado ash flow)	32° 10'44"N 111° 21'24"W	12.6 ± 0.6	K-Ar, sanidine	do. MB-3-64
14	Basalt	32° 05'50"N 111° 19'17"W	10.4 ± 1.3	K-Ar, whole rock	do. MB-7-64
15	Basaltic andesite	32° 07'29"N 111° 19'50"W	23.5 ± 1.4	K-Ar, whole rock	do. MB-12-64
16	Basaltic andesite	32° 04'03"N 111° 24'23"W	23.3 ± 0.7	K-Ar, whole rock	do. MB-6-64
17	Safford Peak Dacite	32° 20'44"N 111° 08'55"W	24.5 ± 0.9	K-Ar, biotite	Bikerman and Damon, 1966, PED-1-64
18	Safford Tuff	32° 19'43"N 111° 08'21"W	25.2 ± 1.4	K-Ar, biotite	do. PED-10-63
19	Hillito Andesite	32° 19'34"N 111° 08'22"W	38.5 ± 1.3	K-Ar, biotite	do. PED-9-63
20	Uppermost basaltic andesite (Tumamoc Hill)	32° 12'47"N 111° 00'20"W	19.8 ± 3.0	K-Ar, whole rock	do. PED-8-63
21	"A" Mountain gray tuff	32° 12'32"N 110° 59'22"W	25.8 ± 0.9	K-Ar, sanidine	do. PED-76-63
			29.7 ± 0.9	K-Ar, sanidine	do. PED-17-62
22	Basaltic andesite (Martinez Hill)	SW/4, Sec. 23, T15S, R13E, Pima Co.	23.5 ± 0.7	K-Ar, whole rock	Percious, 1968, JKP-10-67
23	Basaltic andesite (Black Mountain). Overlies San Xavier Conglomerate	Sec. 6, T16S, R12E, Pima Co.	24.8 ± 0.7	K-Ar, whole rock	do. JKP-49-66
24	Exxon State (32) No. 1	NE/4, NE/4, SW/4 Sec. 5, T16S, R15E, Pima Co.			This report
	2,420m-2,426m (andesitic basalt)		23.4 ± 0.6	K-Ar, whole rock	VAKA-72-66
	2,895m-2,898m (andesitic basalt		16.1 ± 0.6	K-Ar, whole rock	VAKA-72-70. Interpreted to be an intrusive body, possibly sill or dike.
	2,572m-3,002m (andesitic basalt)		18.0 ± 1.5	K-Ar, whole rock	do.
	3,753m (quartz monzonite)		46.6 ± 0.6	K-Ar, whole rock	K-Ar date is a reduced date. VAKA-72-78.
			120 ± 60	Rb-Sr, whole rock	See localities 28 and 31
25	Andesite	Lat 31° 56'45"N, Long 111° 04'15"W	24	K-Ar, biotite	Marvin and others, 1973; Creasey and Kistler, 1962, 7.
26	Turkey track porphyry (pillow lava in the Helmet Fanglomerate)	31° 57'06"N 111° 04'30"W	30.7 ± 1.2	K-Ar, plagioclase	Damon, 1968, RM-2-64a
27	Fine tuff in the Helmet Fanglomerate	31° 55'49"N 111° 06'49"W	27.9 ± 2.6	K-Ar, biotite	Damon and Bikerman, 1964, RM-1-64
28	Alkali Granite	31° 54' N 111° 11'30"W	55 ± 3	K-Ar, biotite	Marvin and others, 1973; Cooper, 1971, T169.
			150 ± 20	Pb-a, zircon	K-Ar date is a reduced age. See locality 31.
29	Basaltic andesite	31° 43' N 111° 15' W	23.4 ± 0.9	K-Ar, whole rock	Damon, 1969, JKP-2-68
30	Rhyodacite vitrophyre (Grosvenor Hills Volcanics)	31° 34'05"N 110° 53'10"W	26.2 ± 1.9	K-Ar, plagioclase	Marvin and others, 1973; Drewes, 1971a, 710
31	Elephant Quartz Monzonite	31° 43'35"N 110° 53'50"W	69.0 ± 2.9	K-Ar, biotite	do. Drewes, 1968, 1971a, 876.
			190 ± 30	Pb-a, zircon	Drewes, 1968, p C13-14 suggests that the quartz monzonite is completely recrystallized Squaw Gulch Granite of Jurassic age.
32	Rhyolite vitrophyre (Box Canyon dike swarm)	31° 45'30"N 110° 48'05"W	25.9 ± 1.3	K-Ar, sanidine	Marvin and others, 1973; Drewes, 1971c, 899.
33	Continental Granodiorite	31° 47'55"N 110° 48'30"W	55.5 ± 2.4	K-Ar, biotite	Marvin and others, 1973; Drewes, 1971c, 1046.
			1,360 ± 200	Pb-a, zircon	K-Ar date is a reduced age. Biotite shows recrystallization fabric.
34	Rhyolite ash flow (Pantano Formation)	31° 59'48"N 110° 38'36"W	36.7 ± 1.7	K-Ar, sanidine	Damon and Bikerman, 1964; PED-13-62
			32.8 ± 2.6	K-Ar, biotite	
35	Pantano tuff	32° 01'24"N 110° 38'06"W	29.2 ± 0.9	K-Ar, biotite	Damon, 1966, PED-7-65
	Turkey-track porphyry (upper part of Pantano Formation)	Location unknown	24.4 ± 2.6	K-Ar, biotite	Finnell, 1970
36	Quartz monzonite	Lat 32° 06' N, Long 110° 26' W	1,540 ± 60	K-Ar, biotite	Marvin and others, 1973.
37	Quartz monzonite	32° 07' N 110° 28' W	23.5 ± 0.9	K-Ar, biotite	Marvin and others, 1973.
			24.8 ± 0.9	K-Ar, muscovite	

TABLE 1. (continued)

Sample Locality	Rock Type, Igneous Body or Stratigraphic Formation	Location		Apparent Age m.y.	Radiometric Age Method and Mineral Dated	Reference, Sample Number and Comments
38	Granodiorite	32° 12' N	110° 27' W	27.3 ± 1.1	K-Ar, biotite	do.
				36.8 ± 1.6	K-Ar, muscovite	
39	Mica schist (Pinal Schist)	32° 13'30"N	110° 25'30"W	33.8 ± 1.2	K-Ar, biotite	do. Recrystallized Precambrian. Pinal Schist
				29.0 ± 0.9	K-Ar, muscovite	
40	Turkey-track porphyry (overlies Mineta Formation)	32° 20'15"N	110° 29'50"W	26.3 ± 2.4	K-Ar, plagioclase	Damon, 1970, PED-3-69.
41	Banded gneiss	32° 20'03"N	110° 41'04"W			Livingston and others, 1967, Mauger and others, 1968. PED-18-62L
	(light band)			25.4 ± 1.0	K-Ar, muscovite	
				25.1 ± 1.0	K-Ar, biotite	
				26.8 ± 0.8	K-Ar, orthoclase	
	(dark band)			27.5 ± 0.9	K-Ar, biotite	PED-18-62d.
42	Banded gneiss	32° 20'06"N	110° 55'04"W	31.2 ± 0.9	K-Ar, muscovite	Mauger and others, 1968, PED-56-66
43	Quartz monzonite gneiss	32° 28' N	111° 05' W	27.3 ± 0.9	K-Ar, biotite	do. PED-20-62
44	Leatherwood Quartz Diorite	32° 26' N	110° 45' W	29.6 ± 0.6	K-Ar, biotite	Damon, 1969, PED-1-68
45	Quartz monzonite	32° 35' N	110° 45' W	1,420	K-Ar, plagioclase	Livingston and others, 1967, DEL-13-62
				1,370	K-Ar, biotite	
46	Rhyolite dike	32° 50'00"N	110° 45'30"W	22.3 ± 0.7	K-Ar, biotite	Krieger, 1973c
47	Vitric tuff in the Quiburis Formation	32° 39'10"N	110° 32'52"W	4.6 ± 0.4	K-Ar, glass	Damon, 1969, LDA-1-66.
48	Tuff	32° 51'30"N	111° 29'54"W	24.4 ± 1	K-Ar, biotite	Krieger, 1968b
49	Quartz latite	32° 51'34"N	110° 32'06"W	25.6	K-Ar, biotite	do.
				25.4	K-Ar, sanidine	do.
50	Rhyolite tuff	32° 54'52"N	110° 32'48"W	24.6 ± 1	K-Ar, biotite	Krieger, 1968a
				22.4 ± 1	K-Ar, sanidine	
51	Rhyolite tuff	32° 58'45"N	110° 56'45"W	24.1 ± 0.7	K-Ar, sanidine	Krieger, 1973b
52	Quartz latite (uppermost formation on Picketpost Mountain)	33° 15'20"N	111° 09'21"W	18.0 ± 0.5	K-Ar, biotite	Damon, 1966, PED-11-65
				18.2 ± 2.5	K-Ar, plagioclase	
53	Superior Dacite (ash flow overlying the Whitetail Conglomerate)	33° 18'36"N	111° 05'00"W	19.9 ± 0.9	K-Ar, biotite	Damon, 1966, PED-4-62
54	Welded tuff	33° 28'36"N	111° 25'41"W	22.6 ± 1.0	K-Ar, biotite	Damon, 1969, PED-18-68
55	Dacite dome	33° 31'11"N	111° 27'25"W	20.1 ± 1.2	K-Ar, biotite	do. PED-16-68
56	Basalt	33° 31'26"N	111° 28'02"W	17.8 ± 3.1	K-Ar, whole rock	do. PED-14-68
57	Quartz latite lava	33° 28'21"N	111° 34'45"W	21.3 ± 0.8	K-Ar, biotite	do. PED-17-68
58	John Jacobs Probe No. 2	NW/4, SW/4, SW/4, Sec. 23, T3N, R2E, Maricopa Co.				This report
	380m- 382m (basalt)			21 ± 3	K-Ar, whole rock	
59	Goodyear Farms water well	NE/4, SW/4, SE/4, Sec. 14, T2N, R1W, Maricopa Co.				This report. Basalt overlies thick halite found in the Arizona Salt Co. and El Paso Natural Gas Co. well in Sec. 2, T2N, R1W.
	469m- 487m (basalt)			10.5 ± 4.5	K-Ar, whole rock	
60	G. D. Isabel No. 1, Maricopa Co.	NW/4, SW/4, SW/4 Sec. 27, T4N, R1E, Maricopa Co.				This report. K-Ar date of 51 m.y. appears spurious. Lower basalt is probably late Oligocene or early Miocene.
	288m- 325m (basalt)			23 ± 5		
	588m- 610m (basalt)			51 ± 2		
61	Sperry Gyroscope No. 1	NW/4, NW/4, NW/4 Sec. 19, T4N, R3E, Maricopa Co.				This report. K-Ar date of 44 m.y. appears spurious. The basaltic andesite is probably late Oligocene or early Miocene.
	222m- 271m (basalt)			22 ± 2	K-Ar, biotite	
	466m- 472m (basaltic andesite)			44 ± 5	K-Ar, biotite	
62	Biery #1 Federal	SE/4, SE/4, SW/4 Sec. 8, T4N, R4E Maricopa Co.				This report
	1,430m-1,442m (basaltic andesite)			21.6 ± 0.9	K-Ar, whole rock	
63	Basalt (underlies white tuff and clastics)	Lat 33° 58'10"N, Long 112° 07'36"W		20 ± 1.3	K-Ar, whole rock	This report
64	Basalt (overlies white tuff and clastics)	34° 04'20"N	112° 06'30"W	15 ± 2.1	K-Ar, whole rock	This report, probably the Hickey Formation.
65	Basalt (Hickey Formation)	34° 16'42"N	112° 02'22"W	10.4 ± 0.4	K-Ar, whole rock	McKee and Anderson, 1971, MY6
66	do.	34° 18'21"N	112° 11'09"W	13.1 ± 0.5	K-Ar, whole rock	do. MY5
67	Latite protusive dome	34° 21'00"N	112° 11'30"W	18.5 ± 0.6	K-Ar, hornblende	do. MY1
68	Basalt (Hickey Formation)	34° 22'51"N	112° 00'18"W	11.0 ± 0.5	K-Ar, whole rock	do. MY7
69	Hackberry Mountain Tuff (Hickey Formation)	27 km. east of locality 70		14 ± 7	K-Ar, biotite	Damon, 1964, BES-58-282
70	Basalt (Hickey Formation)	Lat 34° 27'27"N, Long 112° 02'51"W		10.1 ± 0.4	K-Ar, whole rock	McKee and Anderson, 1971, MY8
71	Black Hills Basalt	34° 32'07"N	111° 56'14"W	12.8 ± 2.2	K-Ar, whole rock	Damon, 1968, PED-28-66
72	Basalt (Hickey Formation)	34° 41'57"N	112° 07'15"W	11.6 ± 0.5	K-Ar, whole rock	McKee and Anderson, 1971, MM2
73	Mingus Mountain Basalt	34° 42'10"N	112° 08'21"W	12.9 ± 0.8	K-Ar, whole rock	Damon, 1968, PED-9-67
74	Trachyandesite flow (Hickey Formation)	34° 44'29"N	112° 06'25"W	14.6 ± 1.1	K-Ar, biotite	Krieger and others, 1971, MM4
75	Basalt (Verde Formation)	34° 49'42"N	112° 02'45"W	4.5 ± 0.2	K-Ar, whole rock	McKee and Anderson, 1971, CD2
76	Basalt (Hickey Formation)	34° 45'20"N	112° 07'03"W	14.0 ± 0.6	K-Ar, whole rock	do. CD1
77	Sullivan Buttes Latite	34° 45'23"N	112° 15'28"W	23.4 ± 1.0	K-Ar, biotite	Krieger and others, 1971, PA5
78	do.	34° 51'08"N	112° 25'19"W	26.7 ± 1.1	K-Ar, hornblende	do. PA4
79	Basalt (Hickey Formation)	34° 34'44"N	112° 26'21"W	13.1 ± 0.5	K-Ar, whole rock	McKee and Anderson, 1971, PR3
80	do.	34° 34'45"N	112° 22'30"W	13.4 ± 0.5	K-Ar, whole rock	do. PR2
81	do.	34° 23'36"N	112° 21'45"W	13.5 ± 0.5	K-Ar, whole rock	do. MU2
82	Latite flow (Milk Creek Formation)	34° 18'57"N	112° 31'48"W	14.0 ± 0.5	K-Ar, biotite	do. K2
83	Latite flow (Milk Creek Formation)	34° 18'24"N	112° 34'45"W	14.6 ± 0.5	K-Ar, biotite	do. K3
84	Basalt	Along Hwy. 93, NW/4, Sec. 20, T14N, R11W, Mohave Co.		22	K-Ar, whole rock	This report
85	Basalt (upper part of Artillery Formation)	Lat 34° 19'55"N, Long 113° 35'34"W		21 ± 3.6	K-Ar, whole rock	This report; Lasky and Webber, 1949

TABLE 1. (continued)

Sample Locality	Rock Type, Igneous Body or Stratigraphic Formation	Location		Apparent Age m.y.		Radiometric Age Method and Mineral Dated	Reference, Sample Number and Comments
86	Cobwebb Basalt	34° 19'17"N	113° 36'12"W	13	2.1	K-Ar, whole rock	do.
87	Crystal tuff (intercalated with lake beds)	34° 11'28"N	113° 41'16"W	48	2.8	K-Ar, biotite	This report. Age appears spurious. Tuff is probably late Oligocene or early Miocene.
88	Basalt	34° 07'12"N	114° 13'17"W	16.4	0.7	K-Ar, whole rock	Damon, 1970, PED-7-68
				15.1	4.4	K-Ar, whole rock	
89	Basalt	34° 07'18"N	114° 13'05"W	21	± 3.1	K-Ar, whole rock	This report
90	Andesite	33° 56'37"N	113° 55'31"W	20	± 1.1	K-Ar, biotite	do.
91	Welded rhyolitic tuff	33° 49'52"N	114° 05'38"W	24	± 1.6	K-Ar, biotite	do.
92	Quartz monzonite	Plomosa Mountains		1,730		Pb-a, zircon	Miller and McKee, 1971
				1,750			
93	Rhyodacite	Lat 33° 35'10"N, Long 114° 02'35"W		19.1	± 0.6	K-Ar, hornblende	do.
				20.2	± 0.2	K-Ar, biotite	
94	Granodiorite	33° 44'46"N	113° 40'27"W	69		K-Ar, biotite	This report
95	do.	(?)33° 45'00"N	113° 40'31"W	55.0	± 5.5	K-Ar, biotite	Damon, 1968, PED-3-68
96	Reeves No. 1 Fuqua	NE/4, NW/4 Sec. 34, T1N, R4W, Maricopa Co.					This report. Age appears spurious. Basalt probably Miocene.
	1,050m-1,062m (basalt)			72	± 12.9	K-Ar, biotite	
97	Basalt	Lat 33° 13'50"N, Long 112° 46'28"W		6	± 2.0	K-Ar, whole rock	This report
98	Gneissic granite	33° 03'10"N	112° 42'50"W	936	± 39.0	K-Ar, biotite	do.
99	Welded rhyolite tuff (upper part of Sil Murk Formation)	33° 04'52"N	112° 47'48"W	27	± 3.8	K-Ar, whole rock	do.
100	Basalt	33° 01'03"N	112° 59'58"W	17	± 5	K-Ar, whole rock	do.
101	Rhyolitic tuff (intercalated with sediments underlying lacustrine limestone)	33° 16'23"N	113° 26'51"W	23	± 1.6	K-Ar, biotite	do.
102	Basaltic andesite	33° 16'43"N	113° 29'41"W	28	± 4.2	K-Ar, biotite	do.
103	Exxon State (14)-1	NW/4, SE/4 Sec. 25, T3S, R11W, Yuma Co.					do.
	229m- 238m (andesite)			20.5	± 1.0	K-Ar, whole rock	VAKA-72-54
	771m- 777m (gneissic granite)			163.7	± 4.0	K-Ar, whole rock	VAKA-72-57. K-Ar date of 163.7 m.y. is a reduced age. Gneissic granite recrystallized in the Jurassic.
				1,080		Rb-Sr, whole rock	
	799m (aphanitic volcanic rock)			21.3	± 0.9	K-Ar, whole rock	VAKA-72-58. Highly brecciated and veined with calcite. Interpreted to be a fissure dike.
104	Leucocratic rhyolite	Lat 33° 08'11"N, Long 113° 23'52"W		18.5	± 1.5	K-Ar, whole rock	This report; VAKA-72-48
105	Basalt	33° 06'59"N	113° 33'51"W	29.3	± 3.1	K-Ar, whole rock	do. VAKA-72-47
106	Basalt	32° 56'06"N	113° 18'05"W	3.0	± 0.1	K-Ar, whole rock	do.
107	Basalt	32° 33'03"N	112° 52'43"W	21	± 2.0	K-Ar, whole rock	do.
108	Basalt (Ajo Volcanics). Overlies Locomotive Fanglomerate	32° 19'37"N	112° 52'13"W	25	± 2.7	K-Ar, whole rock	do.
109	Basalt (Batamote Andesite). Overlies Daniels Conglomerate	32° 18'20"N	113° 00'26"W	15	± 2.2	K-Ar, whole rock	do.
110	Rhyolitic tuff intercalated with red clastics	32° 47'17"N	114° 06'19"W	23	± 2.7	K-Ar, whole rock	do.
111	Muggins Mountain Tuff	32° 45'17"N	114° 07'54"W	21.9	± 0.9	K-Ar, biotite	Damon, 1968, PED-23-67
112	White crystal tuff intercalated with poorly consolidated clastics	32° 42'41"N	114° 11'36"W	78	± 4.3	K-Ar, biotite	This report. Age is spurious. Some biotite is metamorphic and actual age is probably Miocene.
113	Gneiss	32° 39'46"N	114° 18'58"W	319	± 15.7	K-Ar, biotite	This report. Gneiss is interpreted as Precambrian. Reduced age represents Mesozoic recrystallization, probably during Jurassic time.
		32° 39'33"N	114° 19'17"W	199	± 9.5	K-Ar, biotite	
114	Los Cerritos Gneiss	38 km southeast of San Luis, Sonora, Mexico		59	± 3.2		This report. Gneiss is probable Precambrian. Reduced age probably represents Laramide recrystallization.
				57	± 3.1		
115	Exxon Yuma-Federal No. 1	SW/4, NE/4 Sec. 8, T11S, R24W, Yuma Co.					This report
	2,194m-2,224m (andesitic tuff)			20		K-Ar, whole rock	
	3,078m-3,108m (andesitic basalt)			20	± 10	K-Ar, whole rock	Interpreted to be intrusive, possibly sill or dike.
116	Granitic gneiss	Lat 32° 40'16"N, Long 114° 35'52"W					This report. See comments for locality 114.
	(Fine grained)			39	± 2.1		
	(Coarse grained)			59	± 3.3		
117	Crystal vitric tuff, top of 61m section of volcanic rocks overlying basement complex. Tuff is overlain by fanglomerate.	32° 48'53"N	114° 31'40"W	26.3	± 1.6	K-Ar, biotite	Damon, 1966, PED-4-65
118	Basaltic andesite	32° 49'58"N	114° 31'39"W	25.1	± 1.6	K-Ar, whole rock	Damon, 1970, PED-9-68
119	Hornblende andesite	32° 56'56"N	114° 33'12"W	24.7	± 2.1	K-Ar, hornblende	Damon, 1968, PED-1-67
120	Welded rhyolitic tuff	33° 15'05"N	114° 37'38"W	25	± 1.7	K-Ar, whole rock	This report
121	Basalt	33° 03'32"N	114° 49'55"W	10	± 1.9	K-Ar, whole rock	do.
122	Vitric tuff in basal limestone of the Bouse Formation	33° 06'29"N	114° 52'22"W	5.4		K-Ar, glass	Damon, oral commun., 1972, PED-4-69
Shown on Fig. 1							
123	Alverson Volcanics (overlain by basal conglomerate of the Imperial Formation)	32° 47'54"N (Fossil Canyon, Imperial Co., Calif.)	116° 01'34"W	16	± 1.0	K-Ar, whole rock	This report
124	Basalt in upper Muddy Creek Formation (locally domed by underlying salt movement)	36° 24'53"N (Clark Co., Nev.)	114° 24'25"W	8		K-Ar, whole rock	This report

APPENDIX 1. SAMPLE DESCRIPTIONS OF EXXON'S STRATIGRAPHIC TESTS

Exxon State (74)-1: Section 2, T8S, R8E; Pinal County, Arizona

depth	description
	Unit II
0 - 110m	Gravel, coarse, unconsolidated.
110 - 198m	Sand, unconsolidated; occasional gravel lense; few clay stringers, red-brown.
198 - 707m	Clay, red-brown; occasional silty lense; gypsum and anhydrite nodules and stringers in basal 230m; sandy and silty from 595m to 655m.
707 - 2,522m	Mostly anhydrite; occasional claystone stringer, green and greenish-gray; few thin tuff beds, green, bentonitic; scattered limestone nodules; few thin salt beds in upper part.
2,522 - 2,560m	Sand, reddish-brown, conglomeratic; claystone stringers, varicolored.
2,560 - 2,765m	Conglomerate, reddish-stained, poorly consolidated; chiefly composed of volcanic fragments, purplish-red.
	Middle Unit I (predominantly volcanic rocks)
2,765 - 2,946m	Basalt, purplish-red. Selected cuttings from 2,792m to 2,807m yielded middle Miocene age of 17 m.y. (Table 1, loc. 5).
	Lower Unit I
2,946 - 3,001m	Conglomerate, reddish-stained, consolidated, chiefly composed of quartz-diorite gneiss fragments in a matrix of sandstone and siltstone, dark red-brown, clayey.
	"Pre-Eocene bedrock"
3,001 - 3,102m	(total depth) Quartz-diorite gneiss, greenish-gray, highly fractured. Biotite separate of core sample from 3,101m to 3,102m yielded a K-Ar age of 26 m.y. whereas a Rb-Sr whole rock determination indicated a Precambrian age of from 1,275 to 1,540 m.y. (Table 1, loc. 5). Reduced K-Ar age probably

represents recrystallization of the gneiss during the Mid-Tertiary orogeny (See page 20 of text).

Exxon State (14)-1: Section 25, T3S, R11W; Yuma County, Arizona

depth	description
	Unit II
0 - 155m	Gravel, unconsolidated.
	Middle Unit I (predominantly volcanic rocks)
155 - 707m	Andesite, red and reddish-brown, basaltic; numerous zones of crystalline tuff. Selected cuttings of andesite from 229m to 238m yielded a K-Ar age of 20.5± 1.0 m.y. (Table 1, loc. 103).
	"Pre-Eocene bedrock"
707 - 777m	Granite, light colored, gneissic. Selected cuttings from 771m to 777m yielded a K-Ar age of 163.7± 4.0 m.y., whereas a Rb-Sr whole rock determination indicated a Precambrian age of 1,080 m.y. (Table 1, loc. 103). Reduced K-Ar age probably represents recrystallization of the granite during the Jurassic.
	Volcanic intrusive?
777 - 808m	(total depth) volcanic rock, greenish-gray, aphanitic; becomes reddish-brown and purplish-gray downward; highly brecciated and veined with calcite. Core sample at 799m yielded a K-Ar age of 21.3± 0.9 m.y. (Table 1, loc. 103). Interpreted to be a fissure dike.

Exxon State (32)-1: Section 5, T16S, R15E; Pima County, Arizona

depth	description
	Unit II
0 - 259m	Sand and gravel, unconsolidated; some clay and

	siltstone in basal 60m, red-brown.
259 - 350m	Sand, unconsolidated; clay stringers, red-brown.
350 - 813m	Clay, red-brown; abundant gypsum crystals between 564m and 686m.
813 - 914m	Sand; some gravel lenses; numerous clay interbeds, red-brown.
914 - 1,170m	Sand, conglomeratic in basal 20m.
1,170 - 2,218m	Sand, silt, and clay interbeds, red-brown; occasional conglomerate zone; anhydrite bed from 2,164m to 2,167m.

Middle Unit I (predominantly volcanic rocks)

2,218 - 2,588m	Tuff, varicolored, basaltic andesite; numerous intercalated beds of sandstone and shale, red-brown and gray; shale contains anhydrite and gypsum blebs. Selected cuttings of tuff from 2,420m to 2,426m yielded a K-Ar age of 23.4± 0.6 m.y. (Table 1, loc. 24).
2,588 - 2,745m	Tuff, purplish-gray, rhyolite

Lower Unit I

2,745 - 2,895m	Conglomerate, reddish-brown, consolidated; chiefly composed of volcanic, limestone, and chert fragments; occasional shale stringer. Volcanic material probably derived from the Pre-Eocene volcanic surface in the Tucson area.

Volcanic intrusive?

2,895 - 3,050m	Andesite, varicolored, basaltic, porphyritic. Selected cuttings from 2,895m to 2,898m and 2,972m to 3,002m yielded K-Ar ages of 16.1± 0.6 m.y. and 18.0 ± 1.5 m.y. respectively (Table 1, loc. 24). Interpreted to be an intrusive dike or sill.

Lower Unit I

3,050 - 3,525m	Conglomerate, reddish-brown, somewhat silicified; similar to conglomerate from 2,745m to 2,895m; lower part sandy and contains beds of shale, reddish-brown and gray, silty.

3,525 - 3,660m	Shale, gray, silty, waxy.
	"Pre-Eocene bedrock"
3,660 - 3,837m	(total depth) Quartz monzonite. Selected cuttings at 3,753m yielded a K-Ar age of 46.6± 0.6 m.y., whereas a Rb-Sr whole rock determination indicated an earlier age of 120± 60 m.y. (Table 1, loc. 24). K-Ar date is a reduced age (See Table 1, loc's 28 and 31).

Exxon Yuma-Federal No. 1: Section 8, T11S, R24W; Yuma County, Arizona

depth	description
	Unit II
0 - 964m	Colorado River gravels
	Bouse Formation
964 - 1,247m	Gravel, sand, silt, and clay transition zone; contains large fragments of mollusks.
1,247 - 1,627m	Claystone, light gray; occasional foraminifer and ostracod.
	Marine late Miocene sequence
1,627 - 2,115m	Mudstones, light gray, greenish-gray, salmon colored; numerous foraminifer, scattered pelecypod fragments and echinoid spines; lower part contains beds of sandstone, light gray, fine-grained, tuffaceous; in basal 40m, the sediment grades downward into a sandstone, medium-to-coarse-grained, conglomeratic.
	Middle Unit I (predominantly volcanic rocks)
2,115 - 2,570m	Tuff, gray and reddish-brown, andesite; intercalated beds of sandstone and claystone, gray and reddish-brown, tuffaceous and clay, pale greenish-gray, bentonitic. Selected cuttings of tuff from 2,194m to 2,224m yielded a K-Ar age of 20 m.y. (Table 1, loc. 115).

2,570 - 2,743m	Andesite, varicolored, basaltic; intercalated beds of clastics ranging from shale to conglomerate, dark red to reddish-brown, indurated, poorly sorted, dirty appearance.

Lower Unit I

2,743 - 3,286m	Granite wash; consists of subangular to subrounded gneissic and granitic rock fragments in a reddish-brown silty matrix. Intervals from 2,767m to 2,804m, 2,938m to 2,974m, and 3,040m to 3,152m consist of basalt, purplish-gray andesitic, somewhat porphyritic. Selected cuttings of basalt from 3,078m to 3,108m yielded a K-Ar age of 20 m.y. (Table 1, loc. 115). These basalts are interpreted to represent an intrusive dike and sill system into the pre-volcanic section of Lower Unit I. Volcanic fragments are absent in the intervening clastic beds.
3,286 - 3,488m	(total depth) Shale, dark red-to reddish-brown, silty, sandy and sandstone, red, arkosic. Two basalts similar to those within the interval 2,743m to 3,286m occur from 3,310m to 3,342m and 3,467m to 3,488m.

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