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Stratigraphy and tectonic history of the Tucson basin, Arizona, based on re-examination of cuttings and geophysical logs of the Exxon State (32)-1 well

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ABSTRACT

Detailed study of the cuttings and geophysical logs of the Exxon State (32)-1 exploration well in the Tucson basin has led to a revised subsurface stratigraphy for the basin and provided new insight into the tectonic history of the basin. The well was drilled near the middle of the basin in 1972 to a depth of 12,556 ft. The stratigraphic section identified in the well is as follows: Pleistocene(?) to upper Miocene upper basin-fill sedimentary rocks (0-2,980 ft); upper and middle Miocene lower basin-fill sedimentary rocks (2,980-6,170); lower Miocene and upper Oligocene(?) Pantano Formation (6,170-8,256 ft); lower Miocene(?) and Oligocene middle Tertiary volcanic and sedimentary rocks (8,256-10,026 ft); Lower Cretaceous to Upper Jurassic Bisbee Group (10,026-12,001 ft); pre-Upper Jurassic granitoid crystalline rock (12,001-12,556 ft TD). This is similar to the section in Cienega Gap 15 mi east of the well site where strata of the upper and lower plates of the Catalina detachment fault are exposed, indicating that the detachment faulted terrane extends westward at least to the middle of the Tucson basin.

We obtained an $^{40}Ar/^{39}Ar$ age of 26.91 $\pm$ 0.18 Ma on biotite (8,478-8,560 ft) from an ash-flow tuff in the middle Tertiary volcanic and sedimentary rocks. Radiometric dates of selected cuttings from the Exxon well reported by Eberly and Stanley (1978) are suspect because there is a considerable amount of contamination in the sampled intervals by cuttings from higher in the well.

INTRODUCTION

In 1972 as part of an exploration program in the Basin and Range Province of southwestern Arizona, Exxon Company, U.S.A. drilled a 12,556-ft-deep test well near the center of the Tucson basin (Exxon State (32)-1, Sec. 5, T. 16 S., R. 15 E., Pima County, Arizona) (fig. 1). Granitoid rock was penetrated beneath 12,001 ft of Cenozoic and Mesozoic sedimentary and volcanic rocks, and the well bottomed in granitoid rock at the total depth of 12,556 ft. This is an important well for the Tucson basin because, in addition to being the only one to reach granitoid crystalline rock, it is the only well that has penetrated more than a few thousand feet of the 12,000-ft-thick overlying sedimentary and volcanic section. Unfortunately, only cuttings (no core) are available for study. However, a standard suite of geophysical logs was run, which provide coverage for the entire depth of the well with the exception of the upper 200 ft of surface casing and a 42-ft-thick interval (2,950 to 2,992 ft) at the base of the second casing (table 1). The combination of geophysical log data and drill cuttings analysis provides insight into sedimentologic trends, lithologic identification, and structural interpretations that would not be given by either analysis alone.

The stratigraphy and radiometric ages obtained for this well were summarized by Eberly and Stanley (1978), and were correlated by them with surface data and with data from other deep wells in the basins of southwestern Arizona. The surface and well data together with seismic data provide the basis for their interpretation of the regional Cenozoic stratigraphy of the area. Eberly and Stanley recognized that some of the K-Ar whole-rock

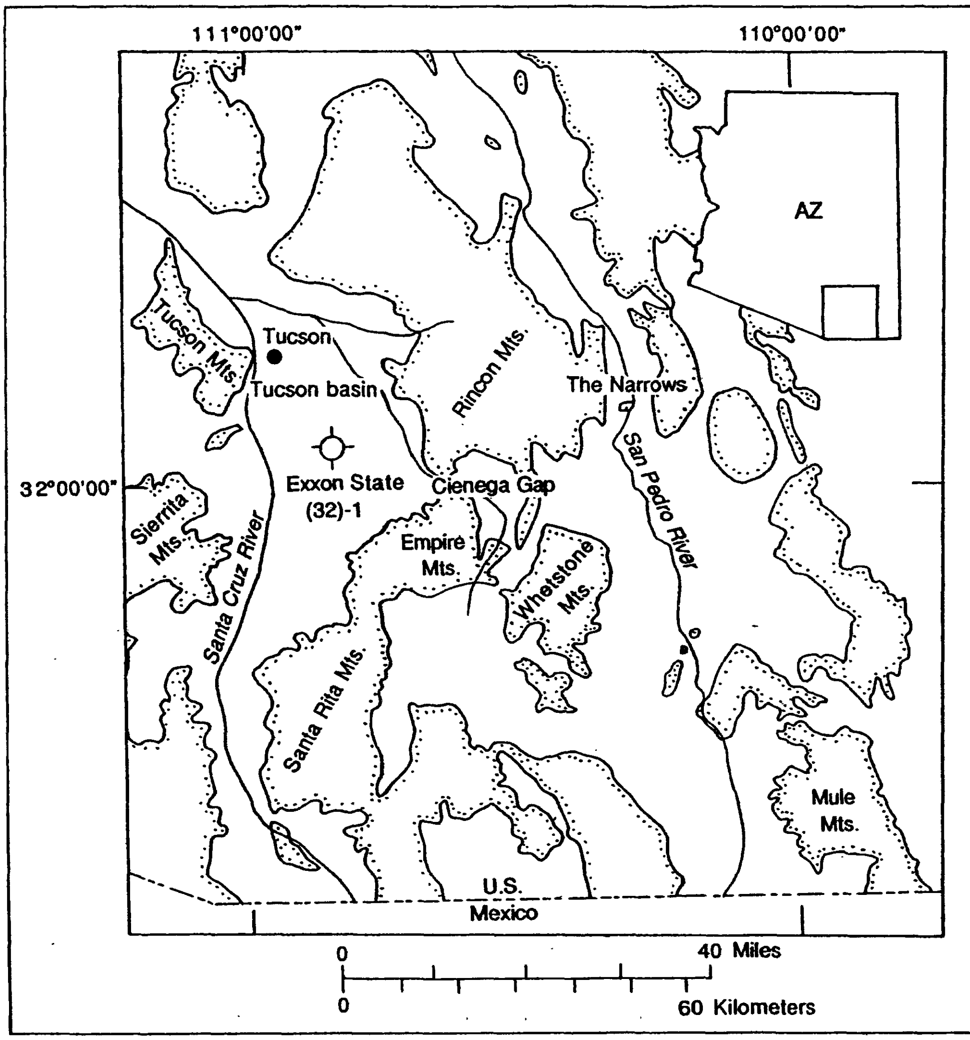

Figure 1. Map of part of southeastern Arizona showing location of the Exxon State (32)-1 well in the Tucson basin and locations of other features mentioned in the text. Inset map shows location of study area.

Table 1. Summary of geophysical logs, dates, and depth intervals over which the logs were run in the Exxon State (32)-1 well; and summary of borehole and casing diameters and intervals. Bit size indicates minimum borehole diameter.

Log type	Date logged	Depth interval (ft)	Borehole diameter
Compensated gamma-gamma (density), Natural gamma, Caliper, Induction, Spontaneous potential, Compensated sonic (transit time)	9-21-72	199 – 2,950	Bit = 13.75 in.
Compensated neutron formation density, Natural gamma, Caliper, Dual induction laterolog, Spontaneous potential, Compensated sonic (travel time)	12-14-72	2,992 – 12,556	Bit = 9.63 in. (2,992 – 9,598) Bit = 7.63 in. (9,598 – 12,556)

Casing

Surface to 199 ft	16 in. dia.
Surface to 2,992 ft	10.75 in. dia.

Location data

Sec. 5, T. 16 S., R. 15 E., NE 1/4, NE 1/4, SW 1/4
Surface elevation: 2,873 ft
Total depth: 12,556 ft

age dates obtained on selected cuttings of volcanic rocks from Exxon State (32)-1 were out of chronologic order. To resolve this discrepancy, they inferred that rocks lower in the well (giving younger dates than rocks higher in the well) were intrusive volcanic rocks.

The present study has three objectives: (1) to resolve some of the uncertainties associated with radiometric dates obtained previously from the well cuttings, (2) to develop a stratigraphy for the Tucson basin, and (3) to interpret as much of the tectonic history of the basin as possible from the sedimentary and volcanic stratigraphy of the well. To this end, we obtained a new $^{40}Ar/^{39}Ar$ age date for a 554-ft-thick silicic tuff underlying the Pantano Formation; and we present a detailed stratigraphy that includes recognition of Late Jurassic and Early Cretaceous Bisbee Group sedimentary rocks overlying crystalline granitoid rock at the bottom of the well. We also discuss the correlation of the geophysical logs with the physical properties of various rocks penetrated by the Exxon State (32)-1 well. This analysis will be useful to other researchers working with geophysical logs in lithologically varied terrane.

ACKNOWLEDGMENTS

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STRATIGRAPHY OF THE EXXON (32)-1 WELL

Methods and Data Used

This study involved a detailed microscopic examination of the drill cuttings of the Exxon State (32)-1 well[1]. The sampled interval begins at 230 ft and runs through the total depth of the well at 12,556 ft. We examined and described the composition of lithic fragments and mineral grains, and other characteristics of the cuttings at 10- to 50-ft spacings, depending on proximity to lithologic contacts. In some cases, minerals were identified using oils and a petrographic microscope.

Cuttings are available for every 10 ft of depth, except for a few intervals where cuttings had been removed for analysis by various researchers over the years. There is a note in the mud log that the samples from 5,990 to 6,030 ft were lost in the hole. However, samples are present for this interval, so the sample containers were probably filled with material from adjacent intervals either at the drill site or later. This is not a critical interval and it is adequately characterized by the geophysical logs. These intervals of missing

[[1] Cuttings are stored in the Arizona Geological Survey core and cuttings repository at 416 W. Congress St., Tucson, Arizona.]

or substituted cuttings did not affect the present study. For the most part, the lithology of the cuttings for a given interval and the lithologies inferred from the geophysical logs are the same. In a few cases, however, the cuttings in the sample vials do not match the lithologies indicated by the geophysical logs, suggesting that caution should be used in analysis of the cuttings.

The amount of contamination of the cuttings from washing out of sediments farther up the well is variable and could be estimated with a moderate degree of certainty in monolithologic intervals. For example, cuttings of the monolithologic silicic tuff interval (8,478-9,032 ft) contain only an estimated 10 percent contaminant chips. The contamination in this interval is minimal because the overlying lower basin-fill units and Pantano Formation are relatively well consolidated. In addition, the second casing was set at 2,992 ft, just below the base of the loosely consolidated upper basin-fill units (figs. 2 and 3), which effectively eliminated contamination from these materials. In intervals directly below poorly consolidated sediments, such as the monolithologic pyroxene trachyte (9,504-10,026 ft) below the limestone conglomerate (9,032- 9,504 ft), contamination reaches as much as 50 percent.

Geophysical logs are invaluable in the interpretation of the stratigraphy and sedimentology of the cuttings, and provide much of the basis for structural interpretations. The logs were obtained by a commercial well-logging company, Schlumberger Well Services. Table 1 summarizes the logs run, and borehole and casing diameters; and plates 1-10 display the geophysical logs. The mud log (230-12,556 ft) provided useful estimates of relative amounts of lithologies present, comments on important textural and compositional variations, and information on drill bit sizes and drilling times.

Thickness estimates for faults and dikes interpreted from the geophysical logs are maximum values because the attitudes of the faults and dikes relative to the logging tools and well bore are not known. In general, the steeper the attitude, the thicker the feature will appear to be. Down section from the upper basin-fill units (which presumably are flat lying), thickness estimates of bedding and of stratigraphic units will be affected similarly if the units have been tilted.

English units rather than metric are used in this Open-File Report because depths in the original data (both cuttings and geophysical logs) are given in English units. Moreover, for this preliminary report it was not possible to reproduce the logs as digital illustrations with metric depth intervals.

Stratigraphic Nomenclature

Basin-fill units

The most comprehensive record of the stratigraphy of the Tucson basin is given by the Exxon State (32)-1 well (fig. 2). The record of the late Cenozoic sedimentary basin-fill units is particularly good because the well was drilled near the deep part of the basin as indicated by the residual-gravity anomaly map (Davidson, 1973). This location provides for a thick, relatively complete sedimentary section with few hiatuses or complicating influxes of locally derived sediment. In the upper 6,000-plus ft of sediments in the Tucson basin, we recognize four units that we informally designate as Units A and B of the upper basin fill and Units C and D of the lower basin fill.

The separation into upper and lower basin fill is based on age, degree of consolidation, and amount of deformation (figs. 2 and 3). In the southern Basin and Range Province of southeastern Arizona and southwestern New Mexico, upper basin-fill deposits generally are Pliocene and Pleistocene in age, poorly to moderately consolidated, flat lying or nearly so, and broken by only a few faults, most of which have relatively small displacement. Lower basin-fill deposits generally are middle to late Miocene in age, moderately consolidated, slightly to moderately deformed with dips of as much as 15° (higher adjacent to faults), and broken by numerous faults having small displacement and by some faults with very large displacement.

The areal distribution of the facies of both upper and lower basin-fill deposits indicates that they were deposited in basins having more or less the modern configuration. Clasts in upper basin-fill deposits were derived from adjacent ranges, whereas conglomerate beds in lower basin-fill deposits (particularly near the base of the units) commonly contain lithologies that are not present in the adjacent ranges and(or) do not contain lithologies that are locally abundant. This is a consequence of erosional stripping and demonstrates the greater age of the lower basin fill relative to the upper fill. In outcrops near basin margins, the contact between upper and lower basin-fill deposits commonly is sharply gradational or paraconformable. Examples of paired upper and lower basin-fill units in nearby basins are shown in table 2.

Although Davidson (1973) named two stratigraphic units in the Tucson basin (Fort Lowell Formation and Tinaja beds) that correlate, in part, with the upper and lower basin-fill deposits described above, we prefer to use the more general terminology of upper and lower basin fill in this report. The reasons for this are discussed below.

<u>Fort Lowell Formation</u>

Davidson (1973, p. E25-E30) defined the lower to middle Pleistocene Fort Lowell Formation on the basis of cuttings and core from the type section, which is a well located in Sec. 31, T. 13 S., R. 14 E. in the northern part of the Tucson basin near the Catalina foothills. Because the well is so close to the edge of the basin it is probably not representative of basin wide sedimentation and, in fact, Davidson stated (1973, p. E27) that the base of the formation is difficult or impossible to identify in the subsurface data of wells farther out in the basin.

Davidson estimated the thickness of the Fort Lowell Formation to be 300 to 400 ft and showed the base of the formation at a depth of about 350 ft in his cross section E-E′, (1973, plate 2) which was drawn through a well near the Exxon State (32)-1 well; and Anderson (1987, plate 1) showed the basal contact

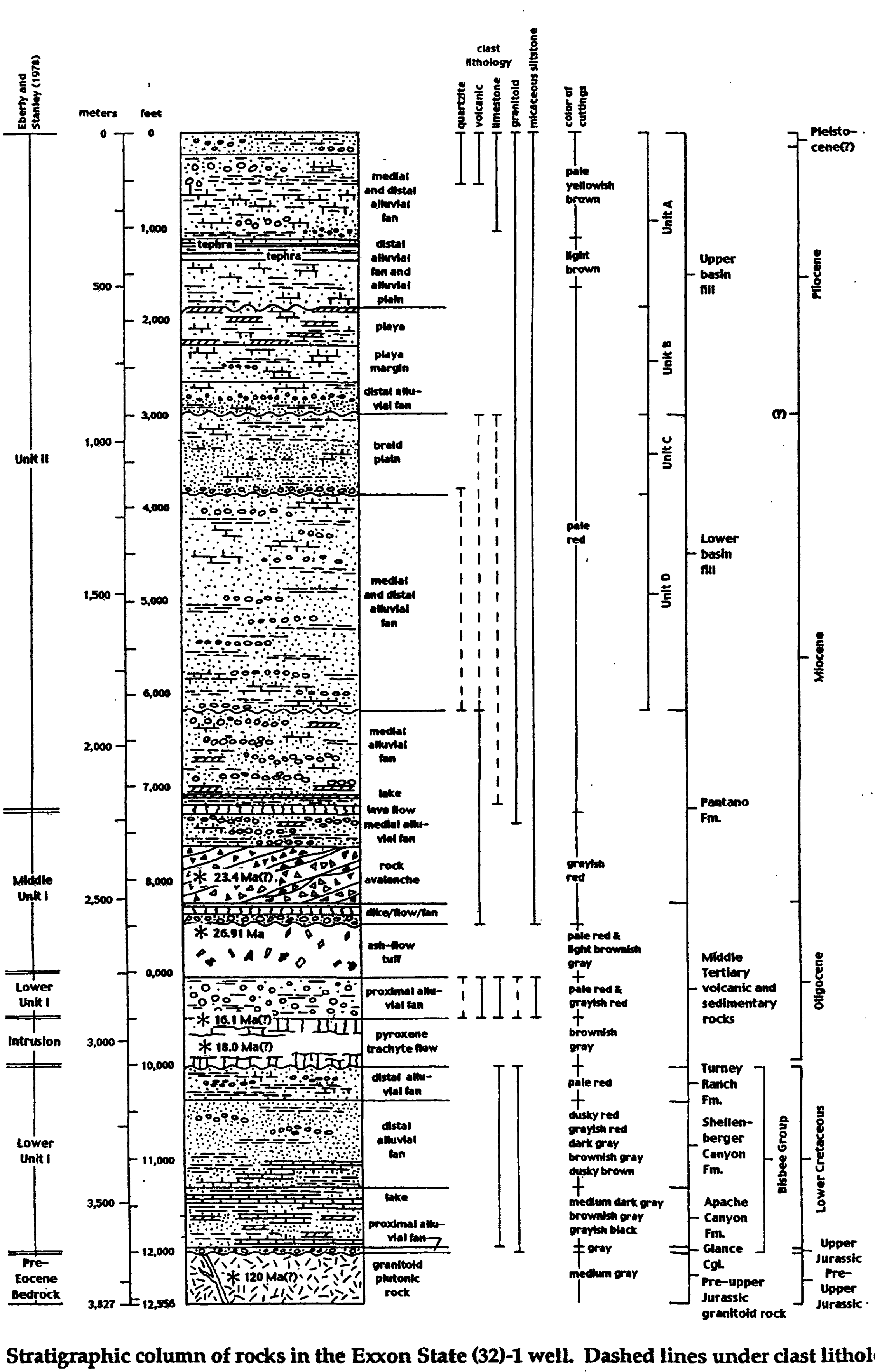

Figure 2. Stratigraphic column of rocks in the Exxon State (32)-1 well. Dashed lines under clast lithology heading indicate intervals where the lithology is rare. Queried radiometric dates are from Eberly and Stanley (1978); the date on the ash flow tuff was obtained in this study. The stratigraphic correlation of Eberly and Stanley (1978) for southwestern Arizona is shown at the left. In their correlation Unit II is basin fill; middle Unit I is middle Tertiary volcanic and sedimentary rocks; lower Unit I is the Pantano Formation.

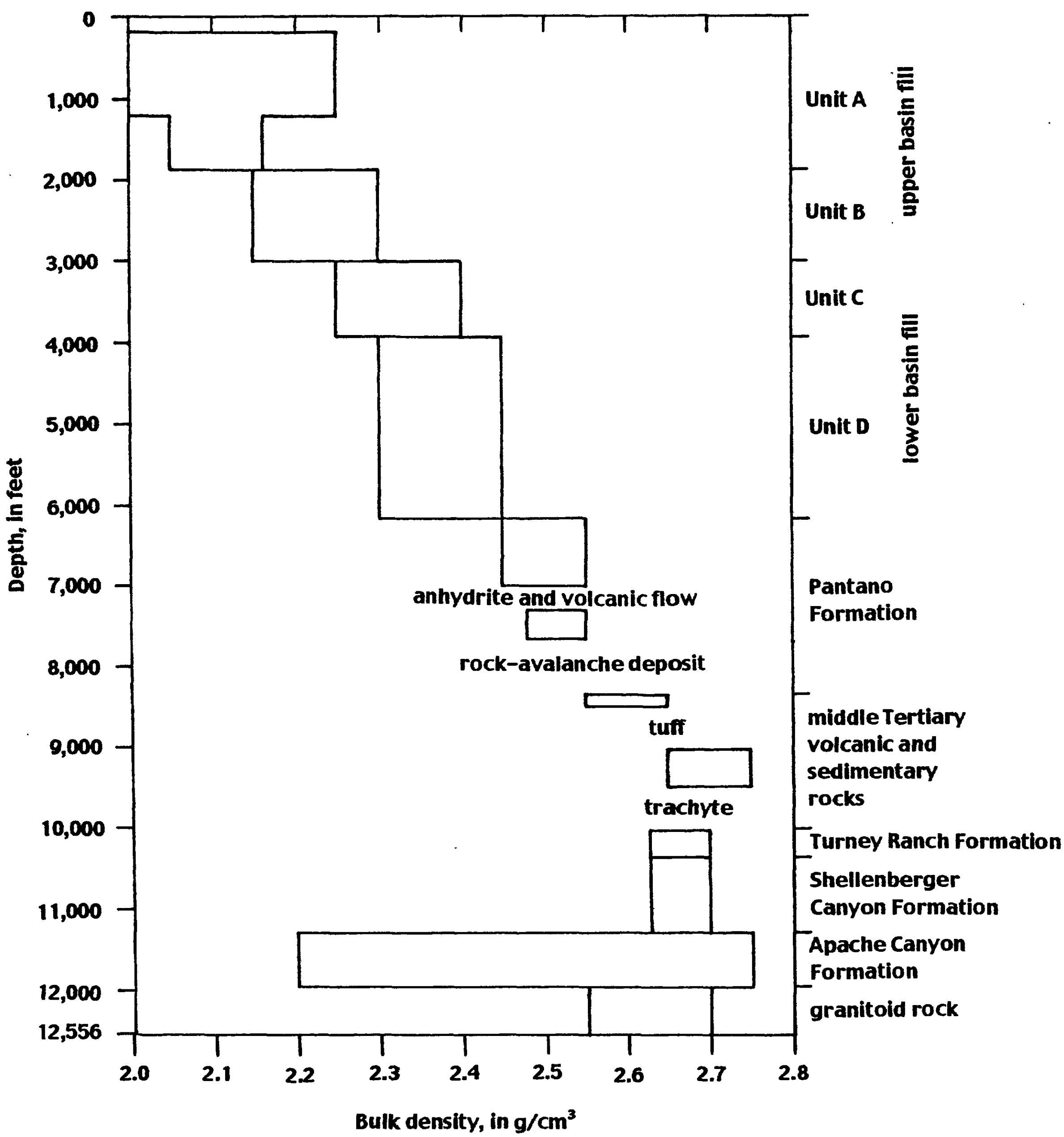

Figure 3. Bulk density of the sedimentary units in the Exxon State (32)-1 well. Boxes represent average high and low bulk density within each sedimentary unit interval. Volcanic units are labeled, but their bulk densities are not plotted because they are not age and depth dependent. Average bulk densities were estimated visually from the formation density logs (pls. 1-7).

Table 2. Names and ages (if known) of paired upper and lower basin-fill units in basins of southeastern Arizona and southwestern New Mexico

Basin	Upper basin fill	Lower basin fill	References
Upper Santa Cruz, Arizona	Unnamed (age not constrained)	Nogales Formation; middle to late(?) Miocene (younger than 13.23 Ma)	Simons, 1974; Gettings and Houser, 1997
Upper San Pedro, Arizona (south of Narrows)	St. David Formation; lower Pleistocene and Pliocene	Unnamed; pre-late Pliocene (age not constrained)	Brown and others, 1966; Gray, 1967; Johnson and others, 1975
Lower San Pedro, Arizona (north of Narrows)	not present	Quiburis Formation; middle(?) to late Miocene (5.35-6.43 Ma)	Smith, 1967; Scarborough, 1975; Lindsay and others, 1984; Reynolds and others, 1986
Safford, Arizona	111 Ranch beds; Pliocene	Midnight Canyon conglomerate; middle(?) to late(?) Miocene (probably younger than 16 Ma)	Richter and others, 1983; Galusha and others, 1984; Houser and others, 1985; Kruger and others, 1995
Alma, New Mexico and Arizona	Alma beds; Pliocene (younger than 5.6 Ma)	Keller Canyon conglomerate; middle Miocene (younger than 18.7 to older than 5.6 Ma)	Houser, 1987 & 1994

of the Fort Lowell at a depth of about 350 ft in the Exxon well in his cross section F-F'. Our study of the cuttings and geophysical logs of the Exxon well (fig. 2 and pl. 1) does not indicate any significant change in the sedimentary rocks near the depth of 350 ft or at any depth above a facies change at 1,120 ft in our stratigraphic Unit A (pl. 1). Redefining the Fort Lowell Formation to include all or part of the upper basin-fill interval in the Exxon well is beyond the scope of this preliminary report, so we have chosen to use the informal basin-fill terminology.

Tinaja beds

Davidson (1973, p. E20-E25) and Anderson (1987, p. 10-12) applied the informal term Tinaja beds (Cooper, 1973) to all basin-fill sedimentary rocks underlying the Fort Lowell Formation and overlying the Pantano Formation; to tilted and faulted sedimentary strata exposed at the edges of the Tucson basin; and to volcanic and volcaniclastic rocks as old as 26 Ma near the Tucson and Sierrita Mountains (lower Tinaja beds). In this usage the Tinaja beds span the time period of late Pliocene to early Oligocene.

We have three objections to use of the term Tinaja beds to designate basin-fill in the Tucson basin. (1) As defined by Davidson (1973), the Tinaja beds cover much too long a period of time for the term to be very useful as a stratigraphic designation. (2) More importantly, this time period includes two markedly different deformational phases recognized in the region; middle Tertiary volcanism and detachment faulting, and late Tertiary basin-range taphrogeny (Dickinson, 1991). The sedimentary rocks related to these two styles of tectonism are very different and are separated by a major hiatus. This second objection was Dickinson's (1999) reason for not applying the term Tinaja beds to tilted and faulted strata of the Catalina foothills at the north edge of the Tucson basin. (3) Sanidine crystals from an ash bed in the thick tuffaceous conglomerate unit north and west of Tinaja Peak (Cooper, 1973) yielded an $^{40}Ar/^{39}Ar$ age of 24.70 ± 0.19 Ma (Geochronological Research Laboratory, New Mexico Tech, Socorro, New Mexico) indicating that at the type locality, the Tinaja beds are age equivalents of the Pantano Formation rather than younger than the Pantano as Davidson assumed. Thus, we recommend restricting usage of the term Tinaja to rocks of the small early Miocene volcanic eruptive center on the southeast side of the Sierrita Mountains mapped by Cooper (1973) as the Formation of Tinaja Peak.

Upper Basin-Fill Deposits (0-2,980 ft)

The upper basin-fill sediments in the well can be separated into two units that reflect, from younger to older, (A) medial to distal alluvial fan facies and distal alluvial fan to alluvial plain facies, and (B) playa, playa margin and distal alluvial fan facies (fig. 2, pls. 1 and 2). We designate these as units A and B to avoid confusion with the numerical terminology used by Pashley (1966) and Eberly and Stanley (1978) to designate stratigraphic units in the basin. Similarly, we subdivide the lower basin-fill sequence into units C and D.

Unsampled interval (0-230 ft) -- lower Pleistocene(?) to upper Pliocene(?)

No cuttings were collected from the upper 230 ft of sediment in Exxon State (32)-1. Moreover, no geophysical logs were run in the upper 200 ft of the well because of the surface casing, which was set at 199 ft. Thus, no records exist for the first 200 ft of sediments penetrated in the well. The Quaternary and upper Tertiary geologic map of the Tucson 1° x 2° quadrangle (Pearthree and others, 1988) shows that relatively undissected basin-fill deposits are exposed at the well site. The location of the well on the eastern piedmont slope of the Tucson basin suggests that the upper 200 ft of these basin-fill deposits probably are medial to distal alluvial-fan facies. The age of the uppermost basin-fill deposits at the well site probably is early Pleistocene or late Pliocene (Pearthree and others, 1988).

Stratigraphic Unit A (230-1,856 ft) – lower Pleistocene(?) and upper(?) Pliocene

Unit A, the uppermost stratigraphic unit in the well for which there is a record, is a fluvial unit more than 1,626 ft thick that represents (1) medial to distal alluvial-fan facies (230-1,120 ft) overlying and grading to (2) distal alluvial-fan and alluvial-plain facies (1,120-1,856 ft). It consists chiefly of interbedded sandy conglomerate, pebbly sandstone, sandy siltstone, and unconsolidated calcareous sandy mud (fig. 2 and pl. 1).

The cuttings indicate that conglomerate clasts in the upper part of Unit A (230-1,120 ft) consist of limestone, both unaltered and chloritized granitoid lithics, and quartz. Chips of quartzite and intermediate composition volcanics are also present, but only to depths above 540 ft. The cuttings contain fragments of slightly indurated, calcareous micaceous siltstone and sandstone that presumably are interbedded with the conglomerate. Sand-size mineral fragments in the cuttings include quartz, muscovite, chlorite, epidote, and magnetite. The average dry color of the cuttings is pale yellowish-brown (10 YR 6/2).

The absence of quartzite and volcanic chips below 540 ft depth does not appear to coincide with any other major lithologic break in the cuttings or changes in the geophysical logs (fig. 2 and pl. 1). The influx of quartzite and volcanic chips above 540 ft probably reflects the beginning of drainage integration and(or) a change in the headwaters and sediment sources of one of the streams draining into this part of the Tucson basin, rather than a tectonic event or change in depositional environment within the basin. Assuming there has been no major change in the shape of the Tucson basin since the Pliocene, the source of the sediment at the well site during deposition of the upper part of Unit A probably was the northern end of the Santa Rita Mountains as it is today (fig. 1). This assumption is consistent with the absence of gneissic granitoid chips in the cuttings, indicating that the source did not include the mylonitic granitoid terrane of the Rincon and Santa Catalina Mountains.

The density log (pl. 1) and figure 3 show that the bulk density of sediment in the upper part of Unit A varies considerably. The maximum range is from 1.85 to 2.45 g/cm^3, and the average is about 2.1 g/cm^3. The higher density peaks probably correspond to calcite cemented gravel beds as much as 5 ft thick; the areas of intermediate density probably correspond to slightly indurated, calcareous micaceous siltstone and sandstone in beds 5-10 ft thick interbedded with the gravel; and the low density areas correspond to unconsolidated, very calcareous sandy mud. There are a number of these muddy intervals, particularly 650-700 ft, where the cuttings are difficult to identify because of the muddy coating. The sonic log, induction electrical log, gamma ray log, and caliper log also demonstrate the relatively thin bedded, chiefly poorly consolidated, but highly variable nature of Unit A.

The contact of the upper part of Unit A with the lower part is gradational and coincides with a decrease in thin, relatively dense, moderately well cemented conglomerate beds accompanied by an increase in sandy lime mud. This change in lithology results in an overall decrease in the variability of the bulk density for the lower part of Unit A as shown on plate 1 and figure 3. The contact between the upper and lower parts of Unit A is further marked by the absence of limestone lithic chips below about 1,040 ft, and a color change from pale yellowish-brown (10 YR 6/2) to light-brown (5 YR 6/4) at 1,120 ft. The contact was chosen as 1,120 ft because the color change of the cuttings is fairly abrupt at this depth. The color changes again at 1,650 ft from light-brown to pale-red (5 R 6/2), following a trend to more reddish color with increasing age that is typical of upper Cenozoic continental sediments in the southern Basin and Range.

The lower part of Unit A extends from 1,120 ft to 1,856 ft, giving a thickness of 736 ft. It consists chiefly of light brown (5 YR 6/4) unconsolidated sandy lime mud and somewhat better indurated very fine-grained micaceous sandstone. Soft, light greenish-gray (5 GY 8/1) lime mudstone is present as a minor constituent. The only lithic fragments present are granitoid lithics and quartz; the only mineral chips are quartz, feldspar, muscovite, biotite, and chlorite. The granitoid lithics are actually just abraded quartz fragments that contain bits of mica or other small mafic mineral inclusions, implying that the source area for the granitoid clasts was either remote from the depositional area or was a mature weathered terrane. Clusters of 1-mm-long calcite crystals are common. The caliper log shows numerous washouts and the sediment is termed "very soft gummy" on the mud log.

Two intervals near the top of the lower part of Unit A (1,150-1,175 ft and 1,285-1,350 ft) show significant increases in radiation on the gamma ray log (from 80 to 100 API units for sediment above and below the intervals to as much as 160 API units for sediment within the intervals) that we attribute to volcanic ash beds (tephra) deposited with the sediment (pl. 1). White grains consisting of aggregates of clay and glass shards are present in cuttings from this interval, lending credence to our interpretation of the gamma ray log. The shape of the curves on the gamma ray log suggests that a few individual beds of relatively clean ash as much as 5 ft thick may occur within zones of reworked ash and sediment. The presence of interbedded tephra indicates a low energy depositional environment and supports our interpretation that the lower part of Unit A represents distal alluvial-fan and alluvial-plain facies sediments. Davidson (1973, p. E23) reported a 3-ft-thick bed of silty tuff that was cored in a well located about 2.5 mi northwest of the Exxon well. The elevation of the cored tuff is 1,185 ft, which is 340 ft and 540 ft lower than the tuffaceous intervals in the Exxon well.

The contact of the lower part of Unit A with Unit B is sharp and is evidenced by increases in bulk density and sonic velocity, and a decrease in conductivity (pls. 1 and 2; fig. 3). The increases in bulk density and sonic velocity of Unit B are important because they indicate that a significant amount of time must have elapsed between the deposition of Units A and B; long enough for diagenesis and compaction to increase the bulk density from 2.05-2.28 g/cm^3 to 2.15-2.30 g/cm^3.

The reason for the difference in conductivity of the two units is more difficult to interpret, but may be related to the presence of saline connate water and to variation in porosity associated with diagenesis. Plates 1 and 2 show that the conductivity of the alluvial-plain deposit sediments in the lower part of Unit A increases from about 120 millimhos/m to 350 millimhos/m in the 200-ft-thick interval above the contact with the gypsiferous playa deposit of Unit B. At the contact, the conductivity decreases abruptly to about 160 millimhos/m, then gradually increases throughout the playa deposit to about 400 millimhos/m in the underlying playa-margin deposit. The conductivity again begins to decrease near the bottom of the playa-margin deposit and is about 100-200 millimhos/m in the distal alluvial-fan deposit. We suggest that the observed increases in conductivity in the alluvial-plain and playa-margin deposits are caused by the presence of connate saline brine associated with the playa, which has had limited circulation through the more permeable sediments above and below the playa deposits.

<u>Stratigraphic Unit B (1,856-2,980 ft)</u> – middle(?) Pliocene to upper Miocene(?)

Unit B extends from 1,856 to 2,980 ft giving a thickness of 1,124 ft. The unit can be divided into three parts (fig. 2 and pl. 2): (1) gypsiferous sandy lime mud between 1,856 and 2,250 ft; (2) sandy lime mud with sparse gypsum from 2,250 to 2,640 ft; and (3) from 2,640 to 2,980 ft, sandy lime mud and poorly indurated muddy sandstone with minor pebble conglomerate beds. We infer the sequence to represent a 394-ft-thick gypsiferous muddy playa deposit, overlying 390 ft of playa-margin facies sediments, that in turn overlie 340 ft of distal alluvial-fan facies sediments.

The logs and cuttings (fig. 2 and pl. 2) indicate that the playa and playa-margin deposits constitute fairly uniform, poorly consolidated sediment sequences containing lime mud, and very fine- to medium-grained sand. The distal alluvial-fan deposits consist of sandy lime mud, increasing amounts (downward) of sandstone and slightly indurated pale-red calcareous micaceous siltstone , and a pebble conglomerate interval from about 2,760 to 2,810 ft. As in the fine-grained sediments in the lower part of Unit A, the only lithic fragments in Unit B are abraded granitoid lithics, indicative of a distant or deeply weathered source, and quartz.

We were not able to place the contact between Unit B (upper basin fill) and Unit C (lower basin fill) precisely because the bottom of the second casing was set at 2,992 ft, very close to the contact, and because geophysical logs were not run between 2,950 and 2,992 ft. Based on cuttings from this interval, we place the contact at 2,980 ft, which corresponds to the base of the muddy sediment of Unit B and the last occurrence downhole of gypsum and anhydrite. Over all, Unit C of the lower basin fill is slightly coarser grained than Unit B of the upper basin fill, and is better indurated and less calcareous. The better induration is shown by the density logs (pls. 2 and 3) and figure 3. The bulk density of the lower 700 ft of Unit B is 2.10 to 2.25 g/cm^3, whereas the bulk density of lower basin-fill sediments (Units C and D) averages 2.25 to 2.45 g/cm^3. The difference in consolidation apparently was immediately obvious to the drillers because they set the bottom of the casing about 10 ft below the contact of the two units.

Lower Basin-Fill Deposits (2,980-6,170 ft)

The lower basin-fill deposits are better indurated than the upper basin fill and are more deformed, as indicated by numerous faults identified on the geophysical logs, particularly the density and caliper logs (pls. 3 and 4). The lower basin fill consists of two members, both fluvial, designated C and D.

Stratigraphic Unit C (2,980-3,840 ft) – upper(?) Miocene

Unit C is a relatively fine-grained fluvial deposit about 860 ft thick that consists of the following down-hole sediment sequence: (1) interbedded sandstone and siltstone 280 ft thick (2,980 to 3,260 ft), (2) mostly sandstone with minor siltstone 480 ft thick (3,260-3,740 ft), (3) interbedded sandstone and siltstone 40 ft thick (3,740-3,780 ft), and (4) conglomerate 60 ft thick (3,780-3,840 ft). Cuttings from the two sandstone and siltstone intervals contain abundant chips of pale red (5 R 6/2) to grayish-orange-pink (5 YR 7/2) moderately well-indurated, slightly calcareous, micaceous sandy siltstone and very calcareous, micaceous muddy sandstone. The sandy siltstone is very similar to the sandy siltstone in Unit A except that it is better indurated and less calcareous. Lithic clasts in the cuttings are abundant granitoid chips and quartz, and rare volcanic chips and limestone. The mineral grains are quartz, feldspar, muscovite, biotite, chlorite, and magnetite. Some of the granitoid lithics are rounded quartz with included micas or mafic minerals, as in Units A and B, implying a source area that was distant or was a weathered terrane of low relief. However, the granitoid lithics also include subangular polycrystalline chips composed of quartz, feldspar, micas, and mafics, which implies a closer source. Rare malachite crusts and pyrite crystals suggest the presence of mineralized terrane in the source area. Small amounts of gypsum and anhydrite are present throughout this interval.

We interpret the depositional environment of Unit C for the most part to be a sandy braidplain. This is indicated by the relatively good sorting of sandstone and siltstone into well defined interbeds rather than the muddy, poorly sorted mix of the alluvial-plain and playa facies of Units A and B, and by the presence of only minor amounts of gypsum and anhydrite. The presence of a conglomerate zone 60 ft thick at the base of Unit C suggests that a significant unconformity exists between Unit C and the underlying Unit D. Lithic chips and mineral grains in the conglomerate are the same as elsewhere in Unit C, except for uncommon chips of quartzite that resemble Precambrian or Paleozoic lithologies of the region.

Faults are numerous throughout Unit C, as shown by thin sharply defined intervals of decreased bulk density on the density log (pl. 3). Ten individual faults and zones of faulting are recognized, in contrast to Units A and B, which show no identifiable evidence of faulting. The density log indicates that individual faults range from 2 ft to as much as 8 ft wide and that zones of faulting are as wide as 28 ft. The caliper and sonic logs show that most faults correspond to washed-out intervals and decreased sonic velocity, but a few show no wash outs or decrease in sonic velocity suggesting that, in some cases, fault zones might be brecciated and cemented. The gamma radiation log shows no pronounced increases in gamma radiation corresponding to faults, suggesting that there is little or no clayey fault gouge present.

The thickness of Unit C penetrated in the well (860 ft) may not be an accurate measure of its true thickness for several reasons: (1) zones of faulting at both the top and bottom of the unit could have cut out some of the section; (2) faults within the unit may have repeated part of the section; and (3) as a result of the faulting, the unit is probably tilted 10° to 15°, which increases the apparent thickness.

<u>Stratigraphic Unit D (3,840-6,170 ft)</u> – upper(?) and middle Miocene

Unit D of the lower basin fill is a 2,330-ft-thick sequence, pale red in color (5 R 6/2), consisting of mud, siltstone, sandstone, and conglomerate that varies from poorly consolidated to moderately consolidated over short distances. We interpret the depositional setting to be medial to distal alluvial fan, similar to the upper part of Unit A. Lithics in the cuttings consist of abundant granite and quartz, and rare quartzite, limestone, and volcanics. Granitoid lithics are of two types: abraded quartz fragments containing bits of mica and mafic inclusions, and angular polycrystalline fragments of quartz and feldspar with micas and mafic minerals, indicating both distant and nearby sources for the granitoid clasts. The mineral grains are quartz, feldspar, muscovite, biotite, and chlorite. Chips of pale red (5 R 6/2) well indurated, noncalcareous, micaceous sandy siltstone, and calcareous, micaceous muddy sandstone are abundant. Gypsum is present, but uncommon, between 3,840 and 4,410 ft.

The geophysical logs (pl. 4) indicate that the sequence can be separated into three parts based on degree of consolidation. The upper 890 ft of Unit D (from 3,840 to 4,730 ft) and the lower 420 ft (from 5,750 to 6,170 ft) show extreme variations in density, sonic velocity, and resistivity and the caliper log shows that the well diameter was greatly enlarged due to washouts in these two intervals. The presence of numerous thin beds of unconsolidated calcareous mud interbedded throughout the more normal, moderately well-consolidated siltstone, sandstone, and conglomerate beds is a reason for the highly variable degree of consolidation.

The cuttings and the mud log show that the 1,020-ft-thick middle interval (4,730 to 5,750 ft) contains siltstone, sandstone, and conglomerate similar to the upper and lower intervals, but contains little unconsolidated mud. This paucity of unconsolidated mud is evidenced on the geophysical logs (pl. 4) which show that the middle interval has a much more uniform bulk density (2.3-2.4 g/cm^3), sonic velocity (85-100 microseconds/ft), and resistivity (3-5 ohm-m), and, thus, gives a more realistic indication of the typical degree of consolidation to be expected of lower basin-fill deposits at this depth in the basin.

The geophysical logs (pl. 4) show that Unit D is highly faulted, perhaps more so than Unit C. There are four zones of faulting from 50 ft to more than 100 ft wide, but individual faults are more difficult to identify because of the variable consolidation of Unit D. As with Unit C, the faulting and probable tilting of Unit D cause the thickness of the unit penetrated in the well to be only an approximation of its true thickness.

The contact between Unit D and the upper conglomerate of the underlying Pantano Formation is sharp, and on the geophysical logs (pls. 4 and 5) is characterized by several distinct signatures: (1) an increase in bulk density from about 2.35 to 2.55 g/cm^3 (fig. 3); (2) an increase in resistivity from about 2 to 10 ohm-m; (3) an increase in sonic velocity from 90 to 80 microseconds/ft; and (4) little change in gamma radiation (about 100 API units). The washouts and muddy sediment typical of Unit D of the lower basin fill cease abruptly at 6,170 ft. The presence of abundant volcanic chips in the Pantano Formation (fig. 2) further serves to differentiate it from the lower basin fill, which contains only rare volcanic chips. The sharpness of the contact, the markedly dissimilar characteristics on the geophysical logs of Unit D and the upper Pantano Formation, and the absence on the logs of sharp peaks that might indicate a fault at the contact, all suggest that the contact is probably an erosional unconformity representing a considerable hiatus.

Pantano Formation (6,170-8,256 ft) – lower Miocene and upper Oligocene(?)

In road cuts, clay quarries, and natural outcrops in Cienega Gap (fig. 1) about 11 to 15 mi east of the site of the Exxon State (32)-1 well, the Pantano Formation is well exposed and has been described by Brennan (1957), Finnell (1970b), and Balcer (1984). An andesite flow near the middle of the Pantano, exposed where the Southern Pacific railroad bridge and Pantano Road cross Cienega Creek, has been dated at 24.93 $\pm$ 2.6 Ma (K-Ar on plagioclase; Shafiqullah and others, 1978). The Pantano Formation in Exxon State (32)-1 is broadly similar to the formation in surface exposures, in that both are syntectonic deposits of alluvial fans, rock-avalanches, and volcanic flows in a region of middle Tertiary extension. However, significant differences exist that reflect the local tectonic setting of the two sites at the time of deposition.

In Exxon State (32)-1, the 2,308-ft-thick interval assigned to the Pantano Formation consists of two parts: (1) a 1,472-ft-thick well-consolidated gypsiferous, muddy conglomerate (6,170-7,642 ft) containing an andesite(?) flow in the lower half; and (2) a 614-ft-thick sequence we infer to be a series of rock-avalanche deposits composed chiefly of intermediate-composition volcanic rocks (7,642-8,256 ft). The overall color of the cuttings darkens gradually from pale-red (5 R 6/2) at 6,170 ft to grayish-red (5 R 4/2) by 7,300 ft.

Conglomerate, Mudstone, and Andesite flow (6,170-7,642 ft)

The geophysical logs (pl. 5) show the Pantano conglomerate and mudstone to be uniformly well consolidated except for a few broad areas of minor washouts, and a poorly consolidated interval between 7,000 and 7,200 ft, which contains gypsum and a 12-ft-thick bed of anhydrite. Few faults are in evidence on the logs for this part of the Pantano compared to the number interpreted for the overlying lower basin fill. A possible explanation for this may be that fault breccia and gouge has been recemented in the better indurated Pantano conglomerate so the faults are not as obvious on the logs. The geophysical logs and the composition of lithics and mineral grains in the cuttings allow the conglomerate, mudstone, and andesite of the Pantano Formation to be described in four parts:

(1) 6,170 to about 7,000 ft. The conglomerate in this interval is inferred to be a medial alluvial-fan deposit. It contains abundant volcanic clasts and common granitoid clasts interbedded with well-consolidated pale-red (5 R 6/2) slightly calcareous to noncalcareous, slightly gypsiferous, micaceous shale, and muddy calcareous micaceous sandstone. The bulk density ranges from 2.35 to 2.65 g/cm^3 with an average of about 2.50 g/cm^3 (pl. 5, fig. 3). Lithic clasts consist of angular quartz fragments, quartz with mica and mafic inclusions, granitoid chips of various kinds (unaltered; with red feldspar; pink chloritized; epidotized), abundant gray volcanic chips of probable intermediate composition, and rare limestone chips. Mineral grains in the cuttings consist of muscovite, biotite, chlorite, epidote and two types of quartz (angular, or rounded with frosted or polished surfaces).

(2) about 7,000 to 7,197 ft. This is a poorly consolidated muddy evaporite interval that contains a 12-ft-thick anhydrite bed between 7,098 and 7,110 ft. The depositional environment may have been a transgressive/regressive sequence of distal alluvial fan, playa margin, and short-lived lake. Cuttings in the interval are coated with mud and the caliper log (pl. 5) shows that the diameter of the well washed out from 11 in. to as much as 15 in. The bulk density is variable; ranging from 2.25 to 2.60 g/cm^3 (the bulk density of the anhydrite bed is 2.90 g/cm^3). Lithic and mineral chips in the cuttings are the same composition as in the overlying better-consolidated conglomerate. Chips of interbedded shale and sandstone include greenish-gray (5 GY 6/1) to light-olive-gray (5 Y 6/1) calcareous micaceous shale in addition to pale-red shale and sandstone.

The cuttings, density log, and sonic log indicate that the grain size, bedding, and consolidation of the sediment vary considerably over short distances in the evaporite interval. The electrical log, however, shows that the resistivity of the part of the interval between 7,080 and 7,180 ft is fairly constant at about 3 ohm-m (except for the anhydrite bed which is 100 ohm-m). This may indicate that the pore space of both fine-grained and coarse-grained lithologies in this interval is filled with saline connate water.

(3) 7,197 to 7,290 ft. This interval contains the densest rock encountered thus far in the well, nearly 2.70 g/cm^3, and is inferred to be a volcanic flow of intermediate composition. The geophysical logs (pl. 5) show that rock properties in the interval (bulk density, sonic velocity, and resistivity) are similar to those of the intermediate volcanic rock in the inferred rock-avalanche deposit below (7,642-8,256 ft) and in the intermediate-composition volcanic flow between 8,282 and 8,376 ft.

The contact between the volcanic flow of interval 3 and the overlying evaporite interval may be a fault. This is suggested by the density and sonic logs, which both show a sharp downward spike at 7,197 ft. There is probably also a fault or a flow breccia near the middle of the interval at 7,242 ft as shown by a sharp decrease in sonic velocity and resistivity at this depth. Thus, the 93-ft-thick interval is inferred to consist of one or more faulted intermediate-composition volcanic flows. However, cuttings from this interval indicate that it should be conglomerate of virtually the same composition as intervals 1 and 2. Because the geophysical logs are not likely to be in error, it is more likely that the cuttings were not collected from this 93-ft-thick interval or that the cuttings contain a very large amount of contamination.

(4) 7,290 to 7,642 ft. Conglomerate clasts in this interval are mostly volcanic as in interval 1 of the conglomerate, however, the volcanic clasts are more varied in composition and many are propylitically altered. Granitoid clasts are sparse to rare, as are rounded detrital quartz grains. The interval is still slightly gypsiferous. The overall color of the chips has darkened to grayish red (10 R 4/2). The bulk density is fairly constant at 2.50 g/cm^3, about the same as interval 1, but lower than the overlying intermediate-composition flow (interval 3).

Rock-avalanche deposit (7,642-8,256 ft)

Cuttings from this 614-ft-thick interval consist chiefly of intermediate-composition volcanic rocks. Propylitic alteration of the volcanics is uncommonly present and there are rare chips of copper-bearing minerals. Chips in the upper part of the interval, above about 7,800 ft, are grayish-red (5 R 4/2) and blackish-red (5 R 2/2); below about 7,800 ft, they are medium-dark-gray (N 4), medium-light-gray (N 6), and brownish-gray (5 YR 4/1). Pale-red (5 R 6/2), micaceous, calcareous shale and sandstone are present in amounts of 10 to 50 percent (also present are minor amounts of light-greenish-gray (5 GY 7/1) shale similar to the pale-red shale). Sparse gypsum is present below about 8,000 ft. Quartz is sparse and consists of both angular fragments and well-rounded to spherical grains. The shale, sandstone, gypsum, and quartz grains in the cuttings probably are contamination from uphole washouts.

Recognition of the sedimentary component of the cuttings as contamination implies that a significant amount of the volcanic chips in the cuttings probably are contamination also.

We infer this interval to be a sequence of thirteen rock-avalanche deposits composed of intermediate-composition volcanic rocks. This inferrence is based on unique patterns shown by the geophysical logs in this interval (pl. 5) and their likely correspondence with physical properties that might be expected of rock-avalanche bodies. Rock-avalanche bodies have been described by many other workers (for example Shreve, 1968; Kreiger, 1977; Yarnold and Lombard, 1989; Yarnold, 1993) and are relatively common in lower Miocene syntectonic sedimentary rocks in southeastern Arizona (Creasey, 1965; Kreiger, 1977). One of the occurrences described by Yarnold and Lombard (1989) is the Cross Hill rock-avalanche deposit at the top of the Pantano Formation in Cienega Gap (fig. 1).

Rock-avalanche deposits are very large volume, tabular or lensoid megabreccia bodies, commonly monolithologic, that begin as giant rockfalls and traverse down several kilometers of relatively gentle slopes at high speed. Other than the opinion that water probably is not involved, there is little consensus on the medium of support that allows for high-speed nonturbulent transport of the megabreccia bodies, preservation of relict stratigraphy within the megabreccia, and little disturbance of the substrate. Various mechanisms have been proposed by Kent (1966), Shreve (1968), Hsu (1975), and Melosh (1983).

Four characteristics of rock-avalanche megabreccia bodies are important in the context of this report: (1) they are comprised of pervasively shattered, fresh rock; (2) they are commonly monolithologic and consist of identifiable lithologic units with relict stratigraphy preserved; (3) the breccia is dense, for the most part, being composed of a tight mosaic of angular fragments (crackle breccia) or fragments separated from each other by thin bands of comminuted rock (jigsaw breccia) (Krieger, 1977); and (4) the unconfined tops of some megabreccia bodies consist of rotated clasts (Kreiger, 1977, fig. 13), which would have the effect of reducing the bulk density of the rock.

The inferred rock-avalanche deposits in Exxon State (32)-1 appear as a sequence of thirteen asymmetrical humps on the geophysical logs (pl. 5). The thickness of individual humps ranges from 32 to 76 ft, for an average thickness of about 50 ft. Individual humps are densest in their bottom two-thirds (2.65 to 2.75 g/cm^3) and tail off upward to bulk densities of 2.25 to 2.50 g/cm^3. We interpret the thirteen humps to be thirteen separate rock-avalanche megabreccia deposits, each composed of dense crackle and jigsaw breccia in their bottom part and grading upward to unconfined tops characterized by less dense breccia having rotated clasts. Both the geophysical logs and the abundance of volcanic chips in the cuttings and show that the more dense parts of the humps are composed of intermedieate-composition volcanic rocks. Although it is possible that the less dense parts of the humps could be composed of sedimentary rocks entrained in the rock-avalanche deposit or of vesicular volcanic flow tops, the cuttings show no systematic variations, either in the amount of the shale and sandstone component (probably contaminants) or in vesicular volcanic chips, that correspond to the depth intervals of the humps.

There are no examples in the literature of rock-avalanche deposits similar to the aggregate of thirteen deposits that we infer here. Beratan (1998) presented evidence that numerous small-volume rock-avalanches are generated along nearly vertical transfer faults and that less numerous large-volume rock-avalanche deposits are generated from the over steepened upper plate of detachment faults. However, the examples given of small-volume rock-avalanche deposits in these settings indicate thay are interbedded with debris-flow and braided-stream deposits and that most are about 6 ft thick. Therefore, we infer that although the avalanche deposit in the Exxon well is made up of thirteen small- to moderate-volume rock-avalanche deposits, the apparent absence of sedimentary conglomerate interbedded with the avalanche deposits indicates that they were emplaced closely in time and actually constitute a single event. Taken as a whole, based on the measured thickness of 614 ft for the rock-avalanche deposit interval in the well, the avalanche deposit in the Pantano is classified as a very large-volume rock-avalanche deposit.

The source of the rock-avalanche deposit is not known. The rock-avalanche event probably was associated with extension on the Catalina detachment fault (Dickinson, 1991) to the north and east of the present well site, but both middle Tertiary and Laramide age intermediate-composition volcanic rocks were widely distributed in the region in early Miocene time. The highland that supplied the volcanic rock of the deposit is either buried beneath the Pantano Formation and basin-fill sedimentary rocks or the volcanic rocks have been removed by erosion.

One of the whole-rock K-Ar dates (23.4 $\pm$ 0.6 Ma) reported by Eberly and Stanley (1978) was obtained on selected cuttings taken within the inferred rock-avalanche deposit. The location of the dated interval, 7,940-7,960 ft, is shown on plate 5 where, based on geophysical characteristics, it appears to be within the upper part of one of the megabreccia deposits. The date is queried because of the presence of a significant amount of contaminant chips of both sedimentary rocks and volcanic rocks in the rock-avalanche interval. Many of the contaminant volcanic chips could be of weathered conglomerate clasts eroded from the rock-avalanche deposit itself. The contaminant chips would appear similar to chips of the avalanche deposit, but could have lost argon and, thus, would give erroneously young ages. If the age is accurate, however, the rocks of the rock-avalanche deposit must be older than the part of the Pantano Formation in which they were emplaced.

Middle Tertiary volcanic and sedimentary rocks (8,256-10,026 ft) – lower Miocene(?) and Oligocene

This 1,770-ft-thick interval consists of a diverse group of rocks with uncertain correlation to surface units. It contains the following rock units (fig. 2, pl. 6): (1) lamprophyre(?) dike; (2) intermediate-composition lava flow; (3) conglomerate; (4) crystal-lithic ash-flow tuff; (5) limestone conglomerate; and (6) pyroxene trachyte flow.

<u>Lamprophyre(?) dike (8,256-8,280 ft)</u> – early Miocene or late Oligocene

This 24-ft-thick interval is defined by relatively high gamma radiation of 160 API units, and resistivity of 60 ohm-m; both higher than the intermediate-composition volcanic rocks above and below the interval (pl. 6). The bulk density and sonic velocity (2.55 g/cm^3 and 65 microsec/ft) are slightly lower than the volcanic rocks. We interpret this interval to be a K-feldspar biotite lamprophyre dike (minette) based on the high gamma radiation. The bulk density of 2.55 g/cm^3 is consistent with this interpretation because lamprophyre dikes commonly are deuterically altered which reduces the density of the rock. The interval of high resistivity is only about 12 ft thick, and is centered within the high gamma radiation interval. This geometry may indicate the presence of chilled margins enclosing the dike.

Although the geophysical logs are consistent with our interpretation of this interval containing a dike, the cuttings are not. The cuttings in the interval consist of about 50 percent pale-red and greenish-gray shale and sandstone and 50 percent intermediate-composition volcanic chips; similar to the conglomerate in the Pantano Formation. The discrepancy probably indcates that the cuttings are not from this interval.

Biotite lamprophyre dikes are found in the southern part of the Santa Catalina Mountains (Force, 1997), where they cut mylonitic fabric and are undeformed. This relationship indicates that lamprophyre dikes 20 mi north of the well site are younger than the middle Tertiary mylonitization of the Catalina core complex (Dickinson, 1991).

<u>Intermediate-composition lava flow (8,280-8,376 ft)</u> – lower Miocene or upper Oligocene

We infer that the rocks in this 96-ft-thick interval are intermediate-composition volcanic rocks based chiefly on the bulk density of about 2.70 g/cm^3 (pl. 6). The cuttings contain mostly chips of volcanic rocks with only 10-20 percent shale and sandstone (probably as contaminants). An 8-ft-thick zone of low density, low sonic velocity, and low resistivity at 8,310 ft is interpreted to be a fault. The caliper log shows that the well diameter was enlarged considerably in this zone, which may indicate that the volcanic rocks are highly fractured.

<u>Conglomerate (8,376- 8,478 ft)</u> – lower Miocene or upper Oligocene

This conglomerate interval is 102 ft thick and contains intermediate-composition volcanic chips and more than 50 percent pale-red and greenish-gray shale and sandstone chips. The shale chips are still micaceous and calcareous, but are noticeably harder than the shale higher in the well. This is verified by comparison of the bulk density of the conglomerate overlying the rock-avalanche deposit in the Pantano Formation (about 2.50 g/cm^3, pl. 5) with the bulk density of this conglomerate, which is about 2.55 to 2.60 g/cm^3 (pl. 6., fig. 3). Based on the higher bulk density, it appears that this conglomerate is probably a significantly older stratigraphic unit than the conglomerate in the Pantano Formation

The contact of the conglomerate with the underlying tuff is very sharp on the geophysical logs and could be either a fault or a depositional contact on an erosional surface. The contact is probably depositional because the bottom 20 ft of the conglomerate contains 10-20 percent chips of tuff, and the gamma radiation log shows that the radiation level of the conglomerate gradually increases in the lower 30 ft toward the contact with the tuff (pl. 6).

Silicic Tuff (8,478-9,032 ft) – upper Oligocene

This interval is a 554-ft-thick crystal-lithic tuff containing biotite and quartz in the upper 82 ft (8,478-8,560 ft), and chiefly quartz and opaque oxide in the bulk of the unit. Biotite books collected between 8,478 and 8,560 ft yielded an $^{40}Ar/^{39}Ar$ age of 26.91 $\pm$ 0.18 Ma (Geochronological Research Laboratory, New Mexico Tech, Socorro, New Mexico). Between 8,930 ft and the base of the unit at 9,032 ft, the tuff contains andesitic lithic fragments, in addition to quartz and opaque oxide. The color of the tuff varies from pale red (5 R 6/2) to light brownish-gray (5 YR 6/1). The basal vitrophyre (9,008-9,032 ft) is 24 ft thick and consists of moderate orange-pink (10 R 7/4) waxy-appearing altered glass. The presence of a basal vitrophyre indicates that the tuff probably was emplaced as an ash flow rather than an ash fall.

Both the geophysical logs (pl. 6) and examination of the cuttings indicate that the tuff is relatively homogeneous and shows no sharp discontinuities, except at the top of the vitrophyre. The characteristics that define the tuff are high gamma radiation (as much as 240 API units) and lack of washouts. The caliper log indicates that the well diameter in the tuff interval was fairly constant at 10 to 11 in. Minor variation in the bulk density suggests that the tuff may be a compound cooling unit having a less dense lower part below 8,800 ft (about 2.40 g/cm^3), and a more dense upper part above 8,800 ft (about 2.45 g/cm^3), overlain by a nonwelded zone at the top about 50 ft thick. The tuff's thickness and our interpretation that it was emplaced as a single compound cooling unit suggest that the tuff was derived from a nearby caldera-forming eruption.

Although ash-flow tuffs this thick commonly are welded, no traces of fiamme were seen in the cuttings. However, the apparent absence of fiamme could be a function of the small size of the chips. The regular sinusoidal pattern seen on the sonic log (pl. 6) in three intervals (8,720-8,760 ft; 8,840-8,910 ft; 8,935-8,980 ft) may correspond to the sonic properties of densely welded tuff. This pattern is also seen on the sonic log in the trachyte interval deeper in the well, between 9,504 and 10,026 ft, and in the granitoid rock near the bottom of the well.

Limestone Conglomerate (9,032-9,504 ft) – Oligocene(?)

This interval is a 472-ft-thick moderately well-indurated conglomerate that is composed chiefly of clasts of Paleozoic(?) limestones, with subordinate clasts of reddish andesite or dacite (some propylitically altered), grayish-red quartzite, and granitoid rocks. The overall color of the cuttings is speckled pale red (10 R 6/2) and grayish red (10 R 4/2). Chips of pale-red (5 R 6/2) and greenish-gray (5 GY 6/1) micaceous, calcareous shale and sandstone are common. The dominance of limestone clasts is demonstrated by the density log (pl. 6) which shows that the bulk density of the conglomerate is about 2.60 to 2.75 g/cm^3. Figure 3 shows that the limestone conglomerate is denser in part than the underlying Lower Cretaceous Turney Ranch and Shellenberger Canyon Formations of the Bisbee Group, although the presence of micaceous shale interbeds in the limestone conglomerate indicates that the conglomerate is Tertiary rather than Cretaceous.

The caliper and gamma-radiation logs suggest that the conglomerate may consist of two slightly different facies with a gradational contact between them at about 9,245 ft. The caliper log indicates that the well diameter was considerably enlarged by washouts in the upper facies, from 10 in. to 13 or 14 in., and that the conglomerate washed out uniformly not preferentially (as in shaly interbeds, for example). The gamma radiation of the upper facies ranges from about 60 to 90 API units, whereas the lower facies shows a more uniform gamma radiation of about 60 API units. Small differences in the density, sonic, and induction logs for the two facies, show that the lower facies is slightly better indurated.

Two well defined faults occur at 9,199 and at 9,459 ft; they are characterized by sharp decreases in bulk density, sonic velocity, and resistivity. Although the contact of the limestone conglomerate with the overlying tuff is very sharp, the presence of the basal vitrophyre in the tuff suggests that it is not a fault contact.

Pyroxene trachyte (9,504-10,026 ft) – Oligocene(?)

This 522-ft-thick unit is identified as a pyroxene-bearing trachyte based on the combination of high K_2O content as indicated by the gamma-radiation log (pl. 6), and the presence in cuttings of pyroxene phenocrysts and porphyritic texture with large euhedral tabular feldspar crystals. Assuming the gamma-radiation log is measuring mostly K_2O content, then the K_2O content of the trachyte (140 to 160 API units) is about midway between that of the intermediate-composition volcanic rocks (80 to 120 API units) in the Pantano Formation, which are probably high-K (pl. 5), and that of the silicic tuff (200 to 240 API units) (pl. 6).

Eberly and Stanley (1978) reported two whole-rock K-Ar dates from the trachyte (16.1 and 18.0 Ma), and because both dates were younger than the 23.4 Ma age obtained by them from rocks higher in the well, they interpreted the younger dates to be from an intrusive dike or sill. This was a reasonable interpretation, considering that magmas of trachyte composition are highly viscous and are commonly emplaced as dikes, plugs, or short, thick flows. The cuttings provide no clues as to whether the trachyte is an intrusion or a flow and evidence of the geophysical logs is not unequivocal. The balance of the evidence leans toward the trachyte being a thick extrusive flow, however, which requires the 16.1 and 18.0 Ma dates reported by Eberly and Stanley (1978) to be anomalously young (discussed below).

Evidence for a flow origin of the trachyte is shown by the geophysical logs (pl. 6). Zones at the top and bottom of the trachyte interval have lower bulk density, sonic velocity, and resistivity than the main body of trachyte. The zone at the top is about 70 ft thick and the one at the bottom is about 25 ft thick; both are much thicker than would be expected from chilled contacts. The differences in thickness of the two zones are consistent with the zone at the top being a subaerial, brecciated flow carapace, and the bottom zone being an annealed basal flow breccia. A sharp decrease in bulk density and sonic velocity near the middle of the top zone (pl. 6) may represent a boundary between two carapace slabs.

Assuming the trachyte body is a flow, the K-Ar dates obtained by Eberly and Stanley (1978) must be in error, because the new $^{40}Ar/^{39}Ar$ age reported in this paper for biotite from the overlying silicic tuff (which is about 500 ft higher in the well than the trachyte) is 26.91 $\pm$ 0.18 Ma. The most likely cause for errors in the K-Ar whole-rock dates is contamination of the selected cuttings with similar appearing lithologies from weathered conglomerate clasts. Selected cuttings from 9,498 to 9,508 ft yielded an age of 16.1 $\pm$ 0.6 Ma. However, the geophysical logs (pl. 6) show that the first 6 ft of the sampled interval are in the overlying limestone conglomerate, and inspection of the cuttings show that the sampled interval as a whole contains about 50 percent limestone chips as contamination from the limestone conglomerate. Therefore, there is a strong possibility that the selected cuttings may have contained volcanic chips from the overlying limestone conglomerate unit, similar in appearance to the trachyte. The second interval sampled by Eberly and Stanley (1978), from 9,751 to 9,850 ft in the central part of the trachyte, yielded an age of 18.0 $\pm$ 2.0 Ma. While the cuttings in this interval are less contaminated than those higher in the trachyte, the contamination is still significant, and the relatively large standard deviation makes this age suspect.

An additional indication that contamination of the selected cuttings by weathered clasts probably was the cause of the anomalously young dates for the trachyte interval is given by Eberley and Stanley's (1978) description of the rock unit. They called it a varicolored, porphyritic andesitic basalt. Our inspection of the cuttings showed that the trachyte is distinctive, uniformly light gray, fine grained, and contains large tabular feldspar phenocrysts. Numerous varicolored volcanic chips are present and have been washed in from uphole.

Bisbee Group (10,026-12,001 ft) – Lower Cretaceous and Upper Jurassic

The Bisbee Group was described and named by Ransome (1904) for exposures in the Mule Mountains in Cochise County, Arizona (fig. 1). The formations recognized in the Mule Mountains (southeastern facies) are the basal Glance Conglomerate and overlying Morita Formation, Mural Limestone, and Cintura Formation. In the Empire and Whetstone Mountains (northwestern facies), 50 mi northwest of the Mule Mountains and 15 to 30 mi southeast of the well site, the Bisbee Group is comprised of five formations that are partly correlative with strata in the Mule Mountains as time equivalent facies (Tyrrell, 1957; Schafroth, 1965; Finnell, 1970a). They are the basal Glance Conglomerate and overlying Willow Canyon Formation, Apache Canyon Formation, Shellenberger Canyon Formation, and Turney Ranch Formation. The Bisbee Group ranges in age from uppermost Jurassic to lowermost Cretaceous for the Glance Conglomerate (Bilodeau and others, 1987) through Lower Cretaceous for the Turney Ranch Formation (Archibald, 1987).

In the Exxon well, we correlate the 1,975-ft-thick interval of shale, thin-bedded limestone, and conglomerate from 10,026 to 12,001 ft (beneath the middle Tertiary volcanic and sedimentary rocks and overlying the granitoid rock at the bottom of the well) with sedimentary rocks of the Bisbee Group. Except for the fact that each formation in the section is much thinner than in sections of the Bisbee Group in the Empire and Whetstone Mountains, the lithologies we interpret from the cuttings and geophysical logs correlate reasonably well with the Bisbee Group in those ranges, although we did not recognize the Willow Canyon Formation.

The reason for the relatively thinner section in Exxon State (32)-1 may be found in the geometry of the Late Jurassic-Early Cretaceous Bisbee basin. The Bisbee Group was deposited in the Bisbee basin, which consisted of a series of northwest-trending en-echelon extensional subbasins at the northwestern end of the Chihuahua trough (a northwest-trending rift basin related to the opening of the Gulf of Mexico) (Bilodeau, 1982). Two possible causes for the thin Bisbee section in the well are related to the location of the well in the Bisbee basin.

If the well is located close to the northwest end of the Bisbee basin and, thus, close to the northwestern extent of rifting, the basin may not have subsided as much here as farther to the southeast. Risley (1987) suggested that the Chihuahua trough extended as far to the northwest as the Tucson Mountains (fig. 1) and that the Lower Cretaceous alluvial-fan and lacustrine-delta facies sediments of the Amole Arkose were deposited in it. This implies that the well is not located at the northwestern end of the Bisbee basin. However, the facies of the Amole Arkose seem to be considerably different from those of the northwestern facies of the Bisbee Formation, so the Amole may have been deposited in a different subbasin than were the sediments of the Exxon well.

A second factor that could have resulted in a thinner Bisbee section in the well was the tectonic shape of the Bisbee subbasin. Soreghan (1999) has shown that the Bisbee subbasin in the Empire and Whetstone Mountains was a half graben, deeper on the northeast side, and that the thickness of the Apache Canyon Formation is a function of its depositional site in the half graben; being thickest near the northeastern border fault where the graben was deepest. Because all the formations in the Exxon well are thin, we can safely infer that the well probably is not in the deepest part of the basin. Also, because the coarse-grained Glance Conglomerate is very thin and the Willow Canyon formation is missing, we can infer that the well probably is not near the border fault.

We recognized a significant difference between Cenozoic sedimentary rocks and sedimentary rocks of the Bisbee Group in the Exxon well. Very fine-grained muscovite flakes are present in all shale and mudstone cuttings of the Cenozoic sedimentary rocks, but are absent in shale and mudstone chips of the Bisbee interval.

Turney Ranch Formation (10,026-10,384 ft) - Lower Cretaceous

In exposures in the Empire and Whetstone Mountains, the Turney Ranch Formation has been described as a thick- to thin-bedded repetitive fluvial sequence of pale-red calcareous shale and siltstone, and light pinkish-gray and pale yellowish-orange sandstone (Shafroth, 1965; Finnell, 1970a; Archibald, 1987). Lenses of arkosic pebble conglomerate contain chert, quartzite, and light-colored volcanic clasts. The thickness ranges from more than 3,200 ft in the Whetstones to more than 1,000 ft in the Empire Mountains.

The geophysical logs (pl. 7) indicate that the 358-ft-thick interval we interpret to be Turney Ranch Formation in Exxon State (32)-1 consists of uniformly well-consolidated rock with an average bulk density of about 2.65 g/cm^3, gamma radiation of about 80 API units, average sonic velocity of about 60 to 65 microseconds/ft, and average resistivity of about 20 to 40 ohm-m. There are no sharp spikes in any of the logs that might indicate faulting, and the caliper log shows no washed-out intervals. Although these characteristics could be representative of an intermediate-composition volcanic rock instead of a consolidated sedimentary rock, the absence of a sinusoidal pattern on the sonic log suggests the interval is not a homogeneous crystalline rock. In addition, volcanic chips in the cuttings are only common to rare.

The lithology of the Turney Ranch Formation in the well is difficult to determine from the cuttings, which contain considerable uphole contamination. Limestone chips that are common to abundant indicate most of the contamination is from washouts in the limestone conglomerate interval higher in the well (9,032-9,504 ft). Pale-red nonmicaceous mudstone and sandstone chips are distinctive and probably are representative of the Turney Ranch. Other mineral grains and lithic chips (granitoid, volcanic, limestone) could be from either conglomerate lenses in the Turney Ranch Formation or contamination from the higher limestone conglomerate.

We use two main criteria for correlating the inferred Turney Ranch interval in Exxon State (32)-1 with sections in the Empire and Whetstone

Mountains: (1) the increased bulk density of the sedimentary rocks compared to the overlying middle Tertiary units, indicating that the unit is significantly older, and (2) the presence in the cuttings of pale-red, nonmicaceous mudstone and sandstone chips similar to the lithologic descriptions of the Turney Ranch Formation in outcrop. However, because the well site is 15 to 30 mi east of Turney Ranch exposures in the Empire and Whetstone Mountains, it is possible that the Turney Ranch Formation interval penetrated in the well had a different source area and may contain clasts of different lithology than at the type locality. Thus, some of the limestone chips may come from conglomerate clasts in the Turney Ranch Formation rather than from uphole contamination.

Shellenberger Canyon Formation (10,384-11,310 ft) – Lower Cretaceous

In the Empire and Whetstone Mountains, the Shellenberger Canyon Formation consists of about 4,000 ft of shale, siltstone, and sandstone (Tyrrell, 1957; Schafroth, 1965; Finnell, 1970a; Archibald, 1987). About two-thirds of the section is sandstone, and some of the sandstone beds in the upper half contain thin lenses of pebble conglomerate. Most of the shale and siltstone beds and a few limestone beds are in the lower half. The predominant colors of the strata are shades of red, gray, olive, brown, and green.

In Exxon State (32)-1, we correlate the 926-ft-thick interval from 10,384 to 11,310 ft with the Shellenberger Canyon Formation. As in the inferred Turney Ranch Formation interval, the cuttings contain considerable contamination from washouts higher in the well; however, the interval contains semi-indurated to indurated chips of sandstone, mudstone, and waxy shale in distinctive colors of dusky red (5 R 3/4), grayish red (5 R 4/2), dark gray (N3), brownish gray (5 YR 4/1), and dusky brown (5 YR 2/2). These colors are similar to those described in the literature for the Shellenberger Canyon, and are differerent from those of the overlying Turney Ranch Formation and underlying Apache Canyon Formation.

The geophysical logs (pl. 7) show that the characteristics of the Shellenberger Canyon Formation generally are similar to those of the Turney Ranch Formation, but the Shellenberger Canyon contains many thin clay-rich(?) zones of low bulk density, more numerous in the lower part of the unit. The average bulk density is about 2.65 g/cm^3, with spikes as low as 2.05 g/cm^3. The average gamma radiation is 80 to 100 API units, with spikes as high as 140 API units corresponding, in part, to the low bulk density spikes. The sonic velocity is 65 to 75 microseconds/ft, slightly slower than the Turney Ranch Formation, with low-sonic-velocity spikes corresponding to low-bulk-density spikes. The resistivity of the Shellenberger Canyon formation is also lower than that of the Turney Ranch Formation, averaging about 8 to 20 ohm-m.

The thin zones of low bulk density probably are caused by faults, some of which may be bedding-plane faults in shaly intervals. This is suggested by the presence of lens-shaped slickensided waxy shale fragments in the cuttings. The slickensided shale fragments are inferred not to be an artifact of drilling, because they are not found in any other intervals containing fine-grained sedimentary rocks.

Apache Canyon Formation (11,310-11,948 ft) – Lower Cretaceous

The interval inferred to be the Apache Canyon Formation is 638 ft thick and the cuttings show that it consists of dark-gray to medium-dark-gray (N 3 to N 4) shale, brownish-gray (5 YR 4/1) calcareous sandstone, and grayish-black (N 5) limestone. Minor amounts of gypsum are present from 11,600 to 11,820 ft, and the dark-gray shales in the lower part of the Apache Canyon interval contain sparse pyrite. An unidentifiable carbonaceous plant fossil was seen on a brownish-gray shale chip.

The density log (pl. 7) shows that the Apache Canyon varies greatly in bulk density (from 2.0 to 2.8 g/cm^3) across intervals of a foot to as much as 10 ft wide. Fissile shale is probably responsible for the lowest density and limestone for the highest density. The caliper log shows numerous wash outs, particularly in the vicinity of the gypsiferous interval between 11,580 and 11,840 ft, where the well diameter washed out from about 8 in. to as much as 16 in. These characteristics indicate that the unit is thin-bedded, lithologically variable, and not uniformly consolidated.

Studies of the Apache Canyon Formation in the Whetstone Mountains (Tyrrell, 1957; Archibald, 1987) and in the Empire Mountains (Schafroth, 1965; Finnell, 1970a) indicate that it is primarily a lacustrine deposit composed of thin-bedded to laminated limestone, shale, and minor sandstone, which grades laterally and vertically (down section) to coarser-grained alluvial-fan facies of the Willow Canyon Formation and the Glance Conglomerate. The lithology of the Apache Canyon Formation interpreted from the well cuttings is very similar to exposures of the Apache Canyon in the Empire Mountains as described by Schafroth (1965) and Finnell (1970).

Finnell estimated the Apache Canyon to be more than 1,600 ft thick and Schafroth measured a thickness of 870 ft. However, the interval apparently is only 628 ft thick in Exxon State (32) -1. Part of the difference may be in the placement of the contact of the Apache Canyon with the overlying Shellenberger Canyon Formation. Schafroth and Finnell both placed the contact above the last significant limestone sequence. In the well, the contact was placed at 11,310 ft, which is just above the highest occurrence of black limestone chips and corresponds to the top of the interval of highly variable density as shown on the density log. It is also likely the basal part of the Apache Canyon may be missing in the well due to the apparent fault contact with the underlying Glance Conglomerate.

The gypsiferous interval in the well is at about the right place and thickness to be correlative with a gypsum bed and overlying gypsiferous sequence exposed in the Empire Mountains. In the well the interval begins about 110 ft above the base of the Apache Canyon and is about 260 ft thick (pl. 7). In outcrop, the gypsum zone begins about 200 ft above the base of the Apache Canyon and is about 100 ft thick (Schafroth, 1965; Finnell, 1970a).

Glance Conglomerate (11,948-12,001 ft) – Lower Cretaceous and Upper Jurassic

We interpret a 53-ft-thick interval consisting of interbedded medium-dark-gray (N 4) calcareous shale, brownish-gray (5 YR 4/1) sandstone, and conglomerate containing unaltered to slightly chloritized granitoid clasts and medium-gray (N 5) limestone to be the Glance Conglomerate. The granitoid chips increase in abundance downward toward the top of the underlying granitoid basement(?) rock at 12,001 ft, from sparse at 11,950 ft to about 20 percent of the sample at 11,990 ft. Some granitoid chips in the interval directly overlying the granitoid rock (11,990-12,000 ft) contain chalky weathered-looking feldspar. Limestone chips are rare to sparse, indicating that limestone clasts in the conglomerate are relatively sparse. This is suggested also by the density log (pl. 7), which shows that the density of the of the conglomerate assigned to the Glance is about the same as that of the granitoid rock (2.60-2.65 g/cm^3). Thus, the Glance penetrated in the well is probably a granitoid-clast conglomerate with a gray shale and sandstone matrix. It can be correlated with the upper granitoid-clast conglomerate member of the Glance described in the northern part of the Empire Mountains by Finnell (1970a) and Bilodeau and others (1987).

The granitoid-clast conglomerate member of the Glance Conglomerate in the northern Empire Mountains is as much as 2,625 ft thick, whereas the interval interpreted to be the Glance in Exxon State (32)-1 is only 53 ft thick. This difference can be attributed to normal variation in the thickness of the Glance. The Glance Conglomerate varies greatly in thickness throughout its outcrop area, and in the northern Empires thins toward the south to as little as 1 m thick as it interfingers laterally with the Willow Canyon and Apache Canyon Formations (Finnell, 1970a; Bilodeau and others, 1987).

Zones of low density rock (2.1 g/cm^3) about 10 ft thick at both the top and bottom of the Glance Conglomerate interval are inferred to be shear zones associated with faults (pl. 7). Resistivity peaks on the induction log within the shear zones suggest that the actual faults are about 2-3 ft wide. It is not possible to estimate how much of the Glance section may have been cut out by the faults, but the thicknesses of the inferred shear zones implies that they are major structures. The fault at the top of the Glance may account for the absence of the Willow Canyon Formation and for the contact with the overlying Apache Canyon Formation being sharp rather than gradational as reported elsewhere by Bilodeau and others (1987). The basal fault may account for there not being a larger percentage of granitoid clasts directly above the contact with granitoid rock.

Granitoid rock (12,001-12,556 ft, TD) – pre-Cretaceous

Between 12,001 ft and the total depth of 12,556 ft, Exxon State (32)-1 penetrated 555 ft of equigranular granitoid crystalline rock, termed quartz monzonite by Eberly and Stanley (1978). In the present report, this rock is termed granitoid because of the difficulty of differentiating granitoid compositions based on examination of cuttings. On the geophysical logs (pl.

7) and the mud log, the top of the granitoid rock appears to be at 12,001 ft, although Eberly and Stanley placed it a little lower, at 12,008 ft.

Eberly and Stanley (1978) reported two ages for the granitoid rock: a K-Ar whole-rock age of 61 Ma, which they said was a reduced age, and a Rb-Sr whole-rock age of 120 $\pm$ 60 Ma. Although the contact of the overlying Upper Jurassic(?) or Lower Cretaceous Glance Conglomerate with the granitoid rock may be faulted, it was probably depositional originally as evidenced by the weathered granitoid chips at the base of the Glance. Thus, the granitoid rock must be older than the Glance. As the Cretaceous-Jurassic boundary is about 138 Ma, it follows that the granitoid rock must be older than 138 Ma. It may correlate with the Triassic or Jurassic granitoid rocks of the Sierrita Mountains (Cooper, 1973); or it may correlate with either the Middle Proterozoic Oracle Granite of the Santa Catalina and Rincon Mountains (1,351 to 1,430 Ma; Reynolds and others, 1986) or the similar age Continental Granodiorite of the Santa Rita Mountains (Drewes, 1971). In a cross section on the Rincon Valley geologic map, Drewes (1977) inferred the crystalline rocks in the bottom of the Exxon well to be a thrust faulted sequence of Precambrian diabase, Pioneer Shale, and Rincon Valley Granodiorite, and Cambrian Bolsa Quartzite.

The cuttings consist of about 50 percent granitoid rock and 50 percent shale, sandstone, and limestone presumably washed in from above during drilling from poorly-consolidated intervals of the Apache Canyon Formation. The granitoid chips are white, gray, pink, red, or pale green, and are composed of quartz and feldspar along with muscovite, biotite, or chlorite. Mafic minerals are rare. All the granitoid chips show mild chloritic alteration, which gives the cuttings a pale greenish cast; however, chloritic alteration is less conspicuous in the interval from about 12,390 to 12,450 ft. Feldspar in the lithic chips in this interval is pink to red.

The geophysical logs (pl. 7) show that, although the characteristics of the granitoid rock are fairly uniform, a moderate amount of variation exists, and there may be two different igneous bodies separated by a fault. Over all, the bulk density varies from about 2.55 to 2.70 g/cm^3; the average gamma radiation is about 120 API units; the interval transit time on the sonic log averages about 60 microseconds/ft; and the resistivity is high, between 30 and 300 ohm-m in the upper part of the granite and rising to more than 1,000 ohm-m in the part of the granite below the fault.

There is evidence in the geophysical logs (pl. 7) for several dikes and a fault. Two small lamprophyre(?) dikes about 4 ft wide are tentatively identified at 12,060 ft and 12,132 ft. They correspond to increases in bulk density of 0.1 g/cm^3, lower resistivity, and peaks on the gamma ray log to about 160 API units. A feature at 12,154 ft, interpreted to be a pegmatite dike about 8 ft wide, corresponds to a gamma ray peak of 320 API units. The sonic, density, and induction logs show no corresponding peaksfor this interval in the well, which implies that, except for its high gamma-radiation level, the dike is very similar in composition and physical characteristics to the granitoid rock surrounding it.

A 10-ft-wide interval of low-bulk-density rock between 12,430 and 12,440 ft may be caused by a fault zone. The caliper log shows that considerable rock was washed out over a vertical distance of 50 ft centered on the inferred fault zone. The cuttings in this washed out interval drop from an average of about 50 percent granitoid rock to about 20 percent granitoid rock and 80 percent dark-gray shale, black pyritic limestone, and grayish-red sandstone. It is likely that the abundant cuttings of shale, limestone, and sandstone in the interval are derived from a 20-ft-thick tectonic slice of sediment inferred to be the Apache Canyon Formation that was caught in the fault zone.

The bulk density of the rock in the faulted interval is as low as 2.30 g/cm^3 whereas the density of the granitoid rock is about 2.58 to 2.63 g/cm^3 above the interval and 2.63 to 2.68 g/cm^3 below the interval. The difference in density of the rock on either side of the inferred fault suggests the juxtaposition of two slightly different granitoid bodies. In addition, the rock below the faulted interval has a higher sonic velocity and reisitivity than the rock above. The sinusoidal pattern of the sonic log is slightly more pronounced and regular in the granitoid rock below the fault than in that above, which may indicate a difference in the crystalline homogeneity of the two igneous bodies.

SUMMARY

In this discussion we summarize the geologic events that affected the Tucson basin in the vicinity of the Exxon State (32)-1 well site, to the extent that we are able to interpret them from study of the well data. The principal events are listed numerically from oldest to youngest. References are given in the main text.

1. Emplacement of the granitoid crystalline rock, probably in Middle Proterozoic time (1,400 Ma). This is the age shown for similar granitoid basement rock overlain by sedimentary rocks of the Bisbee Group in the Rincon Mountains, Cienega Gap, and the Empire Mountains to the east of the well site (Reynolds, 1988). The granitoid rock is not mylonitic.
2. Probable deposition and subsequent erosion of Paleozoic marine sedimentary rocks. At the well site at least, Paleozoic rocks are absent, but based on exposures in the surrounding mountains, they probably are present in scattered fault blocks beneath the basin.
3. Northeast-southwest directed extension, beginning in latest Jurassic time and continuing through the Early Cretaceous, associated with rifting of the northwest-trending Chihuahua trough and formation of the Gulf of Mexico. This extension created the Bisbee basin, a series of block-faulted, asymmetrical subbasins in which fluvial, lacustrine, and marine sedimentary rocks of the Bisbee Group were deposited. The section of Bisbee Group rocks in the well is somewhat thinner than sections to the southeast indicating either a northwestward shallowing of the subbasin and(or) that the well was not drilled through the depositional axis of the

subbasin. This may have been a time when Paleozoic rocks were eroded from horst blocks.

4. Late Cretaceous to middle Tertiary hiatus.
5. Magmatism and northeast-southwest directed crustal extension during the middle Tertiary. Dickinson (1991) has discussed the middle Tertiary tectonism of the region. The stratigraphic section in the Exxon well for this period consists chiefly of 522 ft of pyroxene trachyte, 472 ft of limestone conglomerate, and 554 ft of ash-flow tuff. The presence of nearly 500 ft of limestone conglomerate implies that a small basin had developed in the vicinity of the well, and the presence of 554 ft of ash-flow tuff indicates that a caldera forming eruption occurred nearby. The only radiometric date in the well that we consider to be reliable is a $^{40}Ar/^{39}Ar$ date of 26.91 Ma from the ash-flow tuff.
6. Detachment faulting during the middle Tertiary (Dickinson, 1991). The Pantano Formation is inferred to be a syntectonic deposit of an extensional basin on the upper plate of the Catalina detachment fault. In contrast to the Pantano Formation exposed in Cienega Gap where there is a rock avalanche deposit at the top of the section, in the Exxon well, there is a rock-avalanche deposit at the bottom of the Pantano Formation. Assuming that rock-avalanches in this setting are derived from the upper plate of detachment faults, the relative stratigraphic position of the two avalanche deposits may indicate eastward migration of the Catalina detachment fault and associated break away faults during deposition of the Pantano in this area.
7. Early Miocene to middle Miocene hiatus.
8. Basin-range tectonism (Dickinson, 1991). The Tucson basin contains more than 6,000 ft of basin-fill sedimentary rocks, about equally divided between lower-basin fill and upper basin-fill deposits. The age of the basin fill is not constrained because no datable materials have been found. An approximate age for the base of the lower basin-fill deposits is given by a bimodal volcanic sequence at the base of the Nogales Formation in the upper Santa Cruz Valley dated at 13.23 Ma. The minumum age of the upper basin-fill deposits is late Pliocene to early Pleistocene based on ages of deposits in nearby basins.

The basin-fill units are deposits of alluvial fans and playas. The chief differences between the lower and upper basin fill are that the lower basin fill is better consolidated and is significantly faulted whereas the upper basin fill does not appear to be faulted at all in the well. The boundary separating the upper and lower basin-fill units has regional tectonic significance because a similar boundary can be recognized in a number of basins in Arizona and New Mexico (table 2). It represents a recognizable hiatus of perhaps a few million years and signals a change in tectonic activity.

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