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Stratigraphic, Sedimentologic, and Paleobotanical Investigations of Terrace Gravels, U.S. Army Yuma Proving Ground

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STRATIGRAPHIC, SEDIMENTOLOGIC, AND PALEOBOTANICAL INVESTIGATIONS OF TERRACE GRAVELS, U. S. ARMY YUMA PROVING GROUND

This study was developed under a joint program of U.S. Army Yuma Proving Ground, Environmental Sciences Directorate, and Northern Arizona University and Arizona Western College

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Cover: Petrified wood recovered from excavations for sewage lagoons on the U.S. Army Proving Ground

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The named investigators are but four of the many people who contributed to this project.

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EXECUTIVE SUMMARY

This report is the result of an investigation of petrified wood on the U.S. Army Yuma Proving Ground and includes studies of the stratigraphy, sedimentology, and paleobotany of terrace gravels with which it is associated.

During late Miocene time (approximately five million years ago) the vicinity of the Yuma Proving Ground became part of the Lower Colorado River extensional trough, a feature that extends as far north as Lake Mead. Sediments expressing a variety of depositional environments were deposited in this trough and now comprise the Cenozoic stratigraphic section for the region.

Evidence for the northward incursion of the Gulf is the presence of the Bouse Formation, a fossiliferous package of estuarine and lacustrine sediments.

Overlying the Bouse Formation are the Colorado River terrace gravels, marking the first occurrence of a through-going fluvial system. The terrace gravels on Yuma Proving Ground contain clasts of rock units that originated in the Grand Canyon on the Colorado Plateau. These gravels are Pliocene (< five million years) in age, indicating that at that time the Colorado River flowed through the area of Yuma Proving Ground, rather than along its present-day, more westerly channel. Included in the Colorado River gravels on Yuma Proving Ground is an occurrence of petrified wood unusual in its abundance, aesthetic appeal and state of preservation.

Petrified wood in the Colorado River sediments shows remarkable detail in its preservation and represents species that lived in the area of Yuma Proving Ground during Pliocene time. Preliminary taxonomic identification shows the presence of palm, walnut, and California bay laurel, among other species, which reflect environmental conditions quite different from those of the present. Petrographic analysis indicates that silica in the form of quartz is the primary replacement mineral. Since there is no evidence for burial of the wood by silica-rich volcanic ash or lavas (common agents of petrification), it is our working hypothesis that petrification took place as silica-rich waters of the Colorado River moved through the cells of the wood leaving the silica within.

A number of as-yet unresolved scientific questions of major scale and significance confront geologists in the southwestern United States. The origin and history of the Colorado River itself are open to debate, as are details of the opening of the Gulf of California. Comparison of the Pliocene Colorado River sediments and petrified wood at Yuma Proving Ground with those in the Diablo Formation at the Anza-Borrego Desert State Park in California allows an interpretation of the extent and direction of tectonic movement along the San Andreas fault system since the Pliocene (between 4 and 2.8 Ma). The presence of undisturbed deposits of Colorado River sediments and its included petrified wood are crucial to any future insights into such studies.

Over the years, wholesale removal of petrified wood by both individual and commercial collectors has clearly reduced the amount of this resource remaining in place, but to an extent that is not quantifiable. Military operations consistent with the mission of Yuma Proving Ground have had further effect.

As a fortuitously-sited and richly-endowed locality that has the potential to manage and control development and activities within its boundaries, Yuma Proving Ground is truly unique in its potential for preservation of scientific and aesthetic resources.

It is thus imperative that a management plan be developed and implemented so that future generations of appreciative lay persons as well as scientific investigators can benefit from those resources. Recommendations are presented.

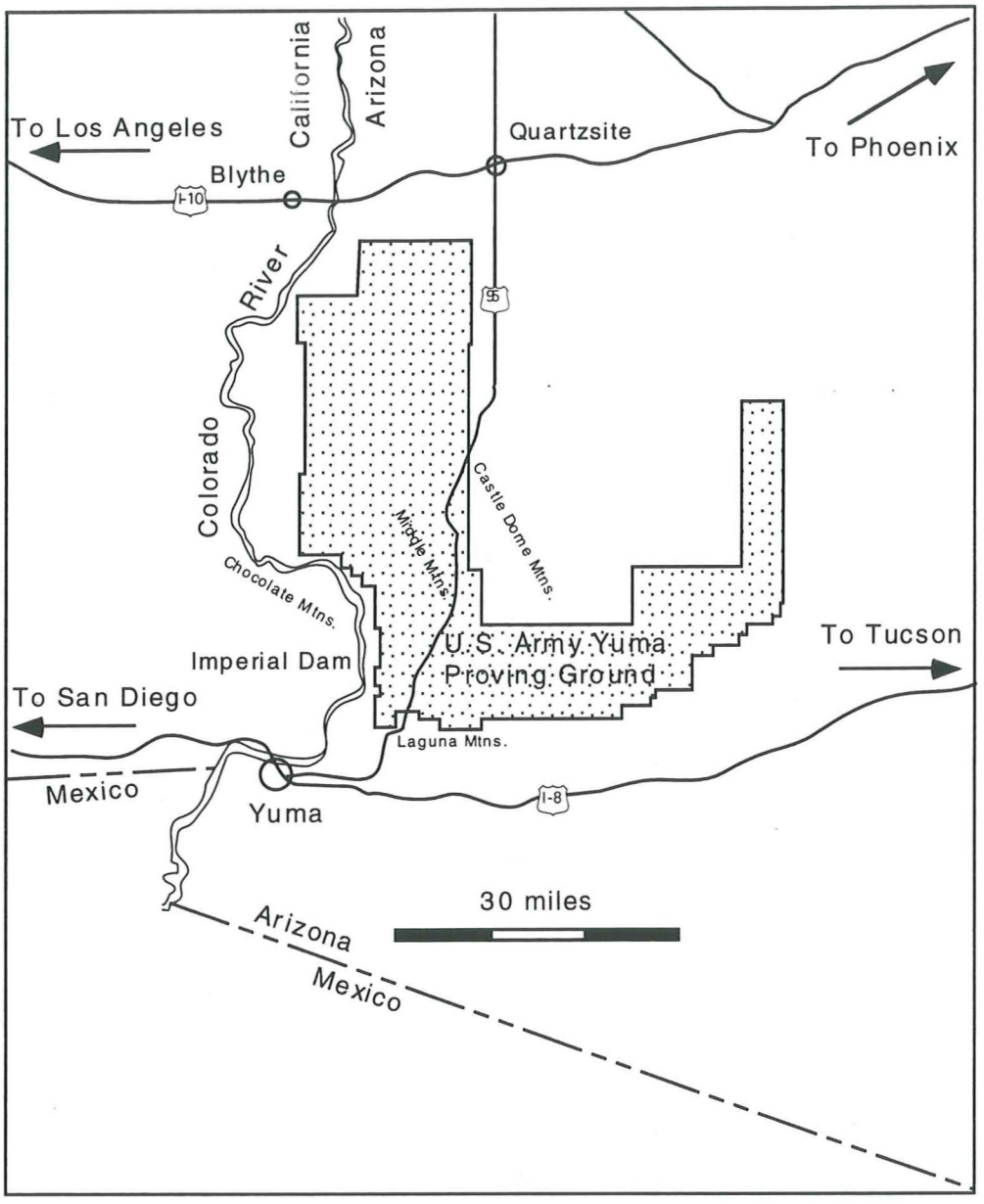


Figure 1.1 Location Map (after Ayres Associates, 1996).

1. INTRODUCTION

1.1 Significance of petrified wood

Although petrified wood in the Yuma Proving Ground area has been known for many years, during which time an unknown amount has been removed, the earliest record of scientific study was published in 1977. The significance of the petrified wood at Yuma Proving Ground may be evaluated from at least three different conceptual perspectives:

1) the petrified wood is a curious feature that is attractive to the general public and should be available to anyone who wants to collect it. This has been the management plan to date, as is indicated by the common knowledge of petrified wood in the possession of military personnel at Yuma Proving Ground and in the yards of many of the citizens of Yuma. We have also observed specimens in a rock shop at the southern entrance to the Petrified Forest National Park, where it is marketed as "petrified iron wood." A large petrified stump is on exhibit in the mineral museum of the Arizona Department of Mines and Mineral Resources.

2) the petrified wood is a unique natural resource that must be left undisturbed in the areas of occurrence. Even though desirable from a preservationist's perception, this concept would not allow collection for scientific examination and interpretation of the significance of the petrified wood.

3) the petrified wood is a scientifically significant natural resource that should be utilized by scientific researchers to interpret the vegetation and the climatic conditions that existed in the Yuma area at the time of its deposition during the early Pliocene. For example, the taxonomic identification of the plants that are preserved as petrified wood allows an interpretation of the paleoclimate of the Yuma area during the early Pliocene (Betts, 1987). Secondly, the comparison of the Pliocene Colorado River sediments and petrified wood at Yuma Proving Ground with those in the Diablo Member of the Pliocene Palm Springs Formation at the Anza-Borrego Desert State Park in California, allows an interpretation of the extent and direction of the tectonic movement of the San Andreas fault system since the Pliocene (between 4 and 2.8 Ma). Additionally, one publication in a scientific journal in Germany describes a bird (woodpecker) nest in a piece of petrified wood from the Yuma area. The argument that it is a woodpecker hole is convincing; however the specimen is erroneously attributed an Eocene age in that publication (Von Horst Bucholz, 1986).

1.2 Location

This study concentrates on the petrified wood and the wood-bearing sand and gravel deposits that underlie the southwestern portion of Yuma Proving Ground in the Laguna 15' Quadrangle.

The study area is located approximately forty kilometers north-northeast of Yuma, Arizona on the U.S. Army Yuma Proving Ground . The area is bounded by the Colorado River to the west, by the Middle Mountains to the east, the Chocolate Mountains of Arizona to the north, and by the Muggins and Laguna mountains to the south (Figure 1.1). The area is reached via Highway 95 and Laguna Dam and Martinez Lake roads. Additional access is provided by several secondary roads that cross the proving ground; however special permission from Yuma Proving Ground is required to use these since numerous hazards would threaten the safety of improperly prepared and advised users.

Plate 1.A is a LandSat image of the Yuma and Wellton-Mohawk area. The isolated light-colored region just northwest of the Yuma agricultural area depicts the striking contrast between Colorado River deposits and the adjacent dark-colored alluvial fan deposits. The dark colored regions are indicative of metamorphic and volcanic bedrock exposures and their alluvial fans in which extensive desert varnish has developed. The other lighter areas near Yuma include both Colorado River deposits and surficial eolian deposits. The southwest portion of the image reflects the low-iron content from granitic rocks and alluvial fans and appears with a slight reddish tinge.

1.3 Project Description

There are widespread terrace deposits of Colorado River-derived sand and gravel on the U.S. Army Yuma Proving Ground that are at elevations as much as 115 meters above the modern Colorado River near the Yuma Proving Ground. These gravels, herein referred to as Colorado River gravels are exposed along an arcuate trend that extends as much as 10 kilometers east of the present Colorado River, reaching from the east side of Martinez Lake southward into the valley between the Chocolate Mountains extension and the Laguna mountains.

The objectives of this study were to evaluate the occurrence of petrified wood that is abundant in these gravels, and to recommend a management plan for this paleontological resource. The scientific evaluation of the petrified wood required a comprehensive study of the wood-bearing sediments and interpretation of the depositional processes involved. The regional structural geology, regional stratigraphy, tectonic history, fluvial dynamics, and sedimentology, were discussed in the Master's thesis of Richard Betts that was completed as a part of this project. (An unbound copy was submitted to Delores Gauna on October 28, 1997, and two additional bound copies will be submitted when they are returned from the bindery.) This report will present an overview of the entire project, discuss the methodology, and emphasize the additional work that was done on the petrified wood, including its identification, paleoclimatic significance, and tectonic significance.

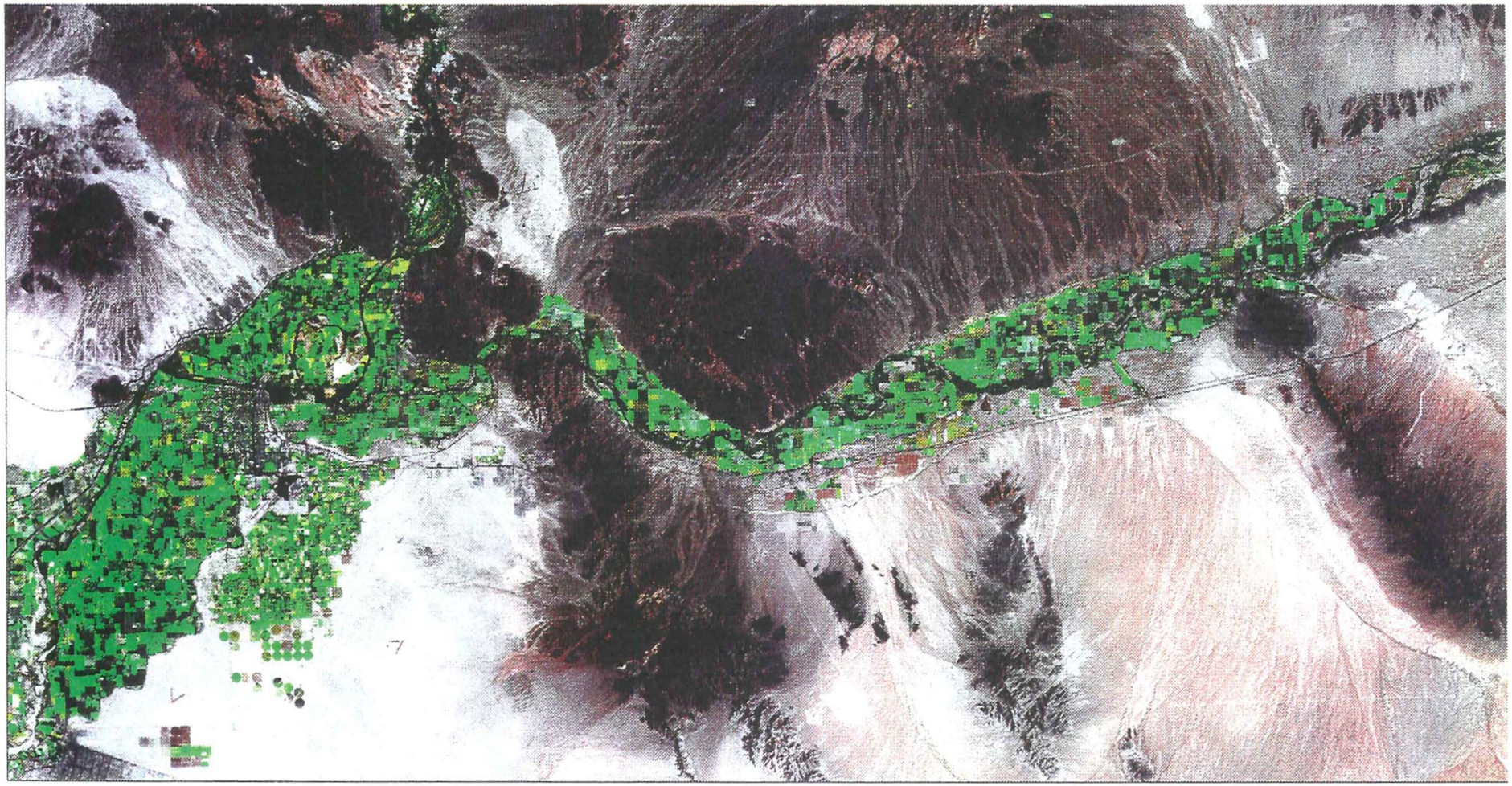
The stratigraphy and sedimentology of the Colorado River gravels on Yuma Proving Ground are described, and the depositional environments are

interpreted. The Colorado River gravels contact relations with the underlying Bouse Formation is described and interpreted. The known areal extent of the Colorado River gravels, both surface and subsurface, is mapped.

The Colorado River gravels at Yuma Proving Ground contain an unusual abundance of petrified wood. The primary emphasis of this report will be the description, identification and interpretation of this petrified wood. It is believed to be the silicified remnants of vegetation that grew in riparian habitats along the Colorado River during Pliocene time and therefore provides evidence for the paleoclimate of the area at that time. Another aspect of the problem is the analysis of the replacement process that resulted in the petrification of the wood.

Lower Colorado Region

PLATE 1.A



Yuma and Wellton-Mohawk Area - LandSat 5 TM - Bands 5 4 3 - 5/20/94

2. METHODOLOGY

On-site investigations began with an overflight of the Yuma Proving Ground to trace the extent of the terrace-forming Colorado River sediments. Geologic mapping and lithologic descriptions of the wood-bearing fluvial gravels followed. The extent and geometry of the wood-bearing gravels and the frequency and abundance of the petrified wood within them were determined through systematic field observations. Field observations of the gravels included:

- clast size measurement
- clast composition identification
- sedimentary structure identification
- imbrication direction measurement and analyses to determine paleocurrent directions
- search for datable material including vertebrate fossils

Clast compositions were identified and their sources determined by means of comparison with known outcrop lithologies within the drainage area of the Colorado River. Petrified wood occurrence, locations, relative abundance and compass orientations were recorded. Representative samples of the petrified wood specimens were collected for taxonomic identification. Throughout the on-site field investigation particular attention was paid to the presence or absence of datable material, including vertebrate fossils, none of which were found.

2.1 Data collection techniques

Because of the large area of study, data points for observations were spaced at the frequency of one per square kilometer, and located on the Laguna, Arizona & California, 15 minute topographic quadrangle at 1:50,000 scale. The base map that was provided by Yuma Proving Ground is Sheet 3149 IV, which is a Special Printing, and has served as the basis for the area maps in this report (Figures 2.1, 2.2, 2.3 and 2.4). Richard Betts' sample locations were assigned field designations of "A plus consecutive numbers" east of the 745000 UTM line, and of "B plus consecutive numbers" west of the 745000 UTM line. Additional field locations of data points observed by other members of the research team are designated "C plus consecutive numbers" (Appendix A). The UTM coordinates of each data point location are also shown in Appendix A. The samples of sediments and petrified wood that were collected by Betts are in the collections of Northern Arizona University. Additional samples that were collected by Dale Nations and Robert Swift are at Northern Arizona University, and those collected by Fred Croxen are in the collections of Arizona Western College.

2.1.1 composition, grain size, textures

Lithologic descriptions were recorded at each station of data collection. The term collection, as used here, refers to data collection, which may or may not include the physical collection of lithologic or petrified wood samples. At each data station a meter-square grid that consisted of a wire mesh of 100 ten-centimeter squares, was laid on the ground. At each of the 100 wire intersections, the clast, matrix, or petrified wood was observed. The clasts within each square meter of exposure were counted, sizes measured, roundness estimated, and identification made as to clast composition. A few of the localities included vertical exposures that allowed additional observations of in-situ sedimentary textures and structures, which allowed for interpretation of sedimentary processes and paleocurrent directions (Figure 2.2). The lithologic descriptions were recorded and each sample was classified in one of three categories: (1) Colorado River gravels, (2) Locally-Derived gravels and (3) matrix. The relative percentage of the three clast lithologies was recorded at each data collection point and are shown as pie diagrams in Figure 2.3.

2.1.2 petrified wood specimens

At each station of data collection the absence or presence, and relative abundance of petrified wood was recorded. See Table 2.1, Appendix A and Figure 2.4. The relative abundance of petrified wood within the square meter location point was estimated and noted in the data table as: A (abundant); C (common); U (uncommon); R (rare); or N (none). Disturbed surface areas of Colorado River gravels that exhibited no petrified wood, but where the wood is most likely absent because it has been collected, are indicated by N*(none, disturbed). In addition to the systematic sampling described previously, non-systematic collections of petrified wood were made for additional taxonomic study.

The most statistically significant collection was made during the excavation of three sewage lagoons in the Colorado River gravels deposit about 100 meters southwest of the Yuma Proving Ground airfield. Approximately 85,000 cubic yards of sediment was removed, from which 43 specimens (an approximate volume of one-half cubic meter) were salvaged by the construction crew (see cover photo). This sample was completely unbiased, and provides a measure of the three-dimensional distribution of the petrified wood in the Colorado River gravels. The recovered specimens were transported to Arizona Western College, where 31 of them were cut with a diamond saw so that representative samples could be taken to Northern Arizona University for additional preparation and study. Thirty of the lagoon samples, plus 13 others that were previously collected, were cut and polished in the Northern Arizona University rock laboratory in preparation for identification.

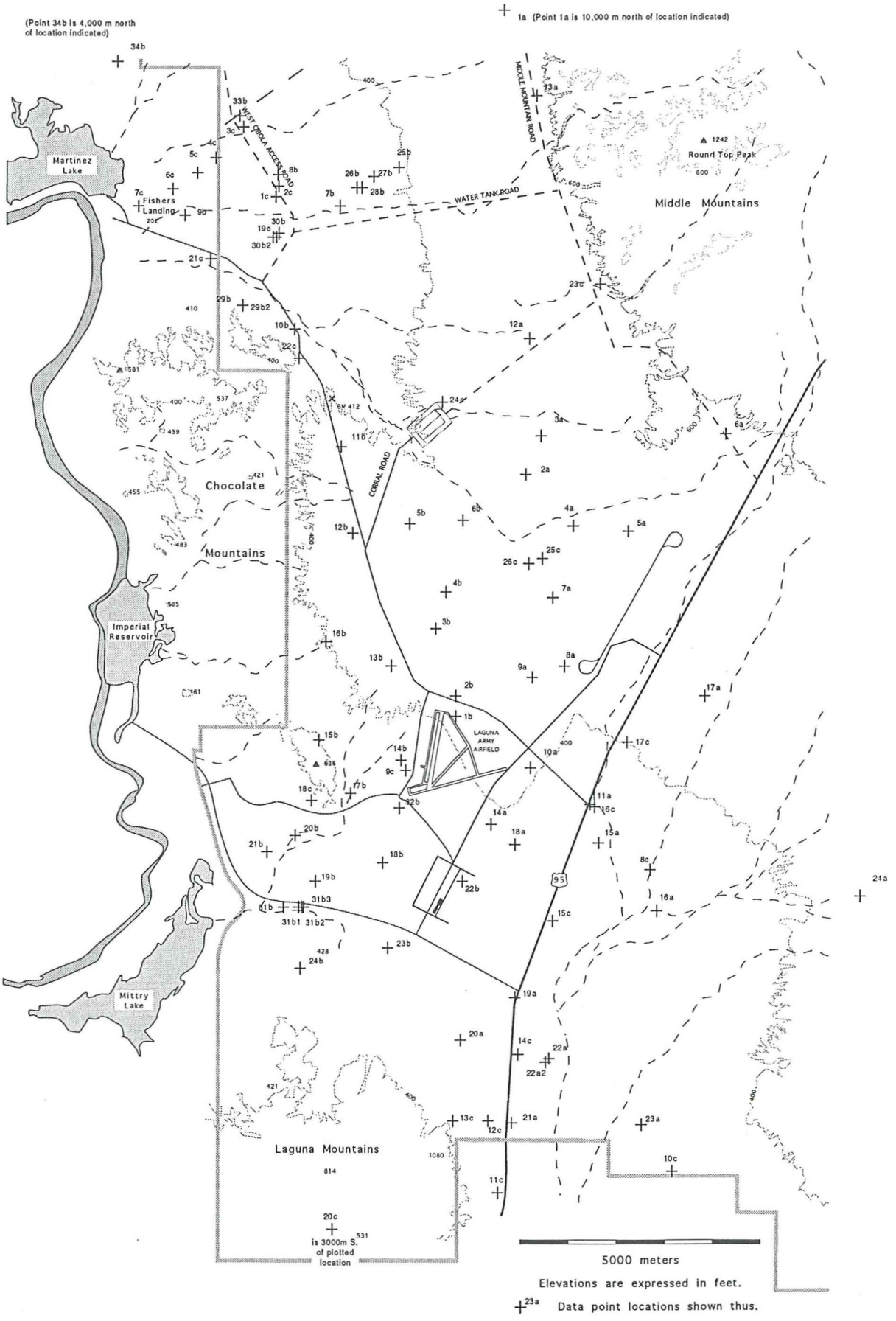


Figure 2.1 Map of the study area showing sample and data point locations.

Figure 2.2 Colorado River gravels in vertical wall of trench at locality 19C. Such exposures, which are rare at YPG, provide the best data on composition, grain size, texture, and sedimentary structures such as cross-bedding and imbrication.

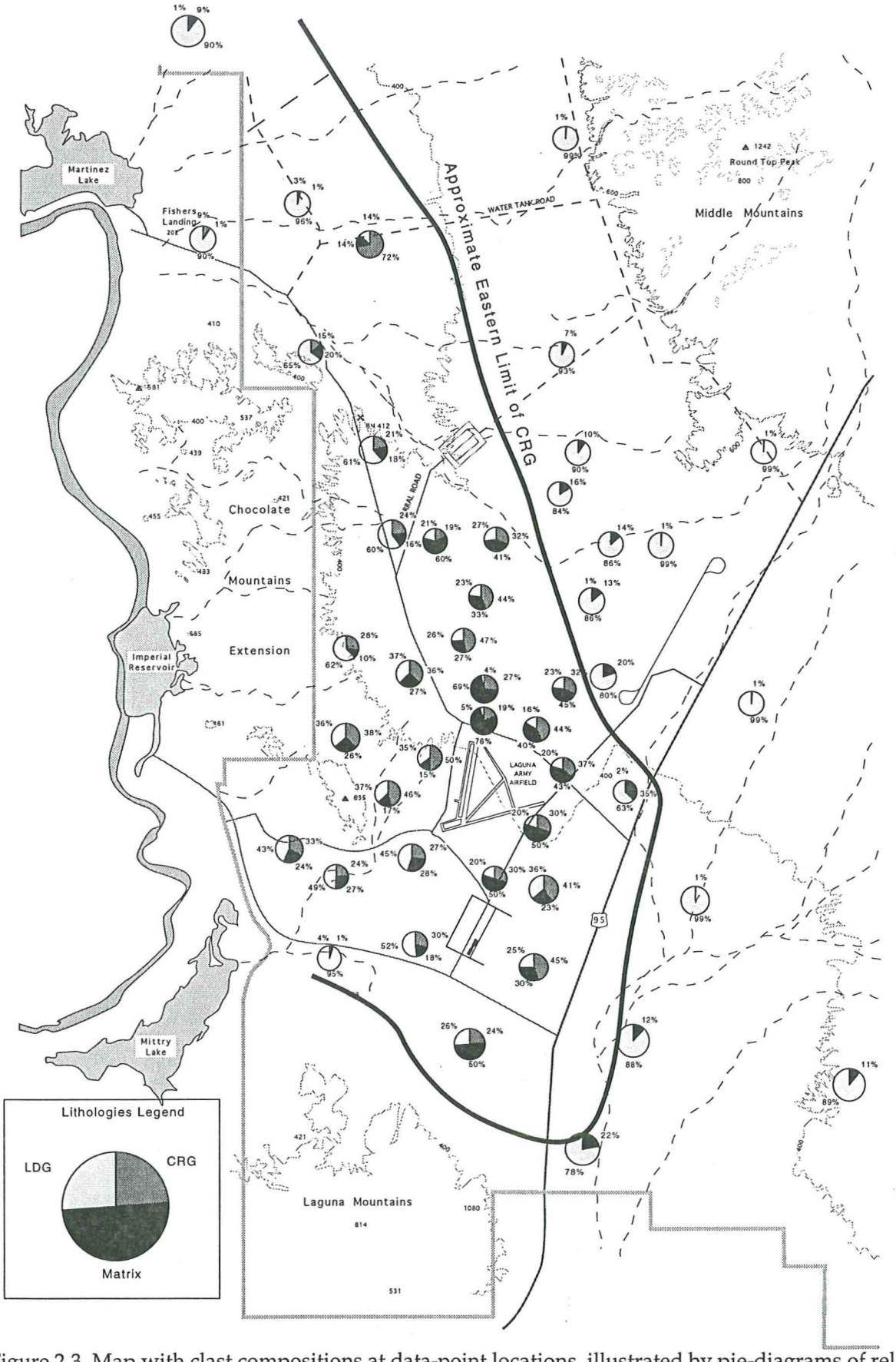


Figure 2.3 Map with clast compositions at data-point locations, illustrated by pie-diagrams of relative percentages of Colorado River gravels (CRG), locally-derived gravels (LDG), and matrix.

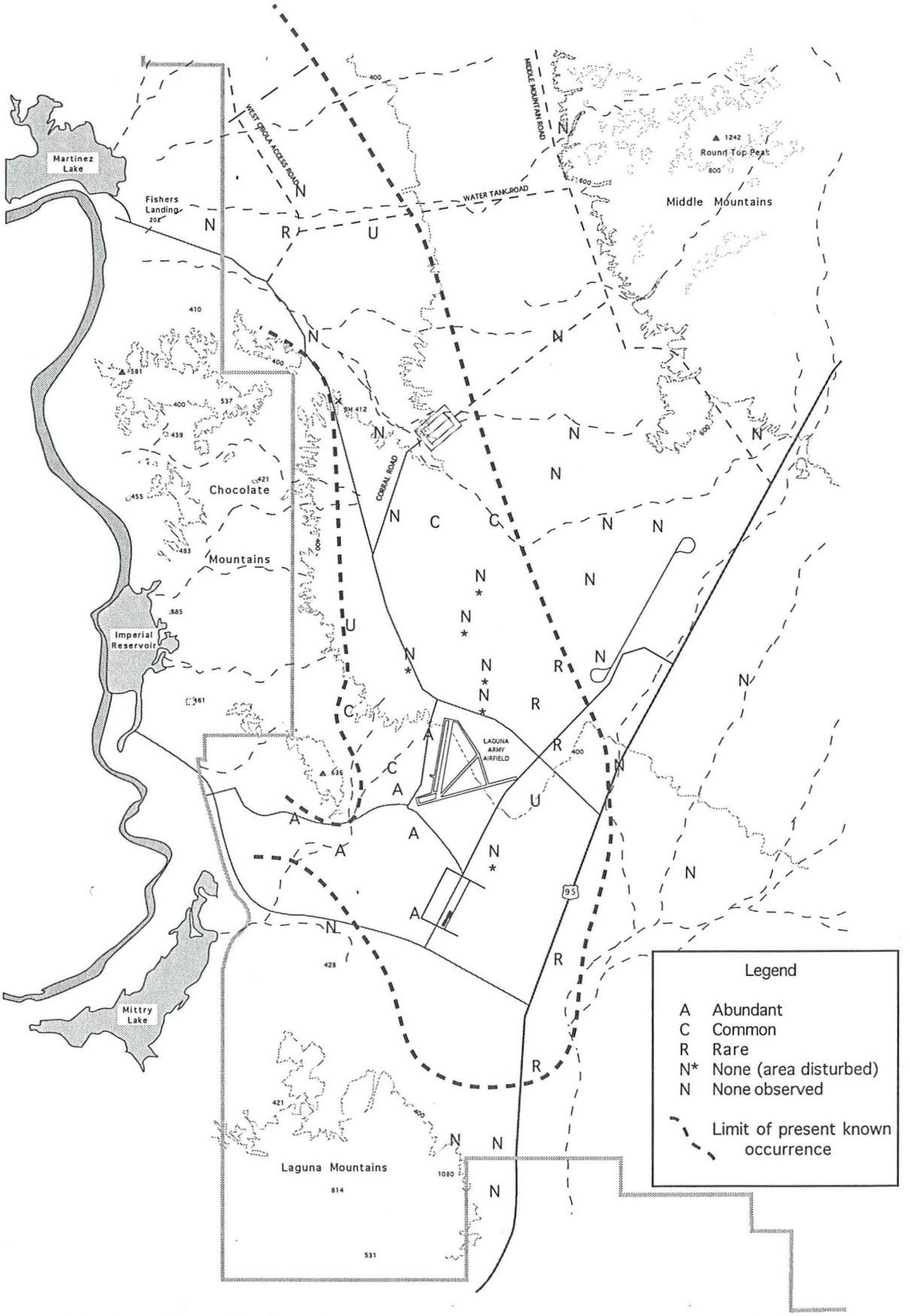


Figure 2.4 Map with petrified wood occurrence and relative abundance at data-point locations. Dashed line indicates present known limit of petrified wood occurrence on YPG.

2.1.3 paleocurrents

Where vertical exposures were accessible, clast imbrication directions were measured with a Brunton compass and recorded to illustrate the direction of transport of the particular clasts at that locality (Figure 2.5). At data collection locations where there were no vertical exposures to allow the measurement of imbrication or cross-stratification, the orientations of the long axes of undisturbed petrified wood specimens were measured as indicators of paleocurrent directions. This technique is based on the observation that floating or sunken logs and branches in modern streams tend to become aligned with current flow.

2.1.4 GPS

Traditionally, geologists determine their field locations from a topographic map. Contacts as well as short comments are annotated directly on the map, to be transcribed later. Low relief in many areas of the Yuma Proving Ground made accurate location determination by reference to topographic features difficult. However, fixing data-site locations was greatly facilitated through use of a Trimble *GeoExplorer* GPS loaned to the team by Yuma Proving Ground. Post-corrected field locations provided an accuracy sufficient to allow members of the team to confidently re-visit sites of particular interest. Hand-held instruments of lower precision were used to quickly determine locations while walking out contacts.

2.1.5 data management

Data acquired from various sources were entered on both PC and Mac operating systems and subsequently treated under a variety of applications. Processed information converged to a PowerPC 8500/120; and output from *Adobe Illustrator 6.0*, *Canvas 3.5* or *Microsoft Word 5.1* was to a LaserWriter Select 360 at 600 dpi. (Though available, later versions of *Canvas* and *Word* were found to be too cumbersome to justify their use.)

A number of data streams were employed, of which eight are representative:

- Appropriate parts of the Special Printing of Laguna, Arizona, 1:50,000 were scanned, saved as PICT files, then opened under *Canvas* and saved in *Canvas* format. Numbers, shapes and lines generated by Canvas were used to overlie major cultural features. *Adobe Streamline* allowed the investigators to autotrace some of the streams and contour lines shown on our maps; others were simply traced in by hand. A 1000 meter grid registered on the Laguna map's UTM zone 11 data allowed accurate positioning of field sites. The result was a versatile Base Map, combinations of whose 12 or more layers could be combined to illustrate specific concepts.

- In order to display locations of field sites on the Base Map, UTM coordinates provided by the GPS or lifted from field maps were entered into *Microsoft Word* (Table 2.1, Data Point Locations and Summary of Observations) and then saved as text-only files. Registration points consisting of four sets of UTM coordinates bounding the study area were added. *GeoView*™ mapped these out in accurate relative positions. The saved file was pasted into *Canvas* as a layer which was then stretched and compressed as required to register with the Base Map's grid. Plotted locations on the Base Map fell within tolerance of their known relationship to road junctions, watercourses, etc.

- For creation of the pie diagrams, numerical field data were entered first into *Microsoft Word*, then copied into *Microsoft Excel* which generated the pies. Individual pie diagrams were saved as PICT files, opened under *Canvas* and placed on their own layer of the Yuma Proving Ground Base Map created earlier.

- After entry into word, imbrication data were saved as text only files readable by RockWare's *Rosy*®, which created the rose diagrams and output them as PICT files. Again, these were placed in their own layer of the Yuma Proving Ground Base Map.

- DEMs (digital elevation models) of the El Centro and Salton Sea (1:250,000) sheets were ftp'd from the USGS web site and after conversion by *USGS Convert* were manipulated under *VistaPro*. This application allowed the investigators to examine several "what if?" situations regarding river levels contemporaneous with petrification of the wood on Yuma Proving Ground. Although interesting, the results were neither conclusive nor directly related to the work at hand and so are not included with this report.

- Prints from black and white photographs were scanned in to *Adobe Photoshop*. After cropping, exposures were balanced with the *IntelliHint* plug-in. Following addition of captions, the files were printed from *Adobe Illustrator*.

- For creation of the ground water chemistry map, cultural features and mountain ranges were first digitized in UTM Zone 11 coordinates from the Laguna 15' 1:50000 map using RockWare's *Digitize*®. Ground water chemistry data were provided by the U. S. Bureau of Reclamation Yuma Area Office chemistry lab and maintained in *Microsoft Excel* . The final map was completed using Golden Software's *Surfer*®, to generate the contours, plot the well locations and overlay the digitized features.

- The lithologic and geophysical well logs were created using *GeoTechnical Graphic System* software by GeoTechnical Graphics. Data were provided by recent U.S. Bureau of Reclamation well logs and older drillers logs.

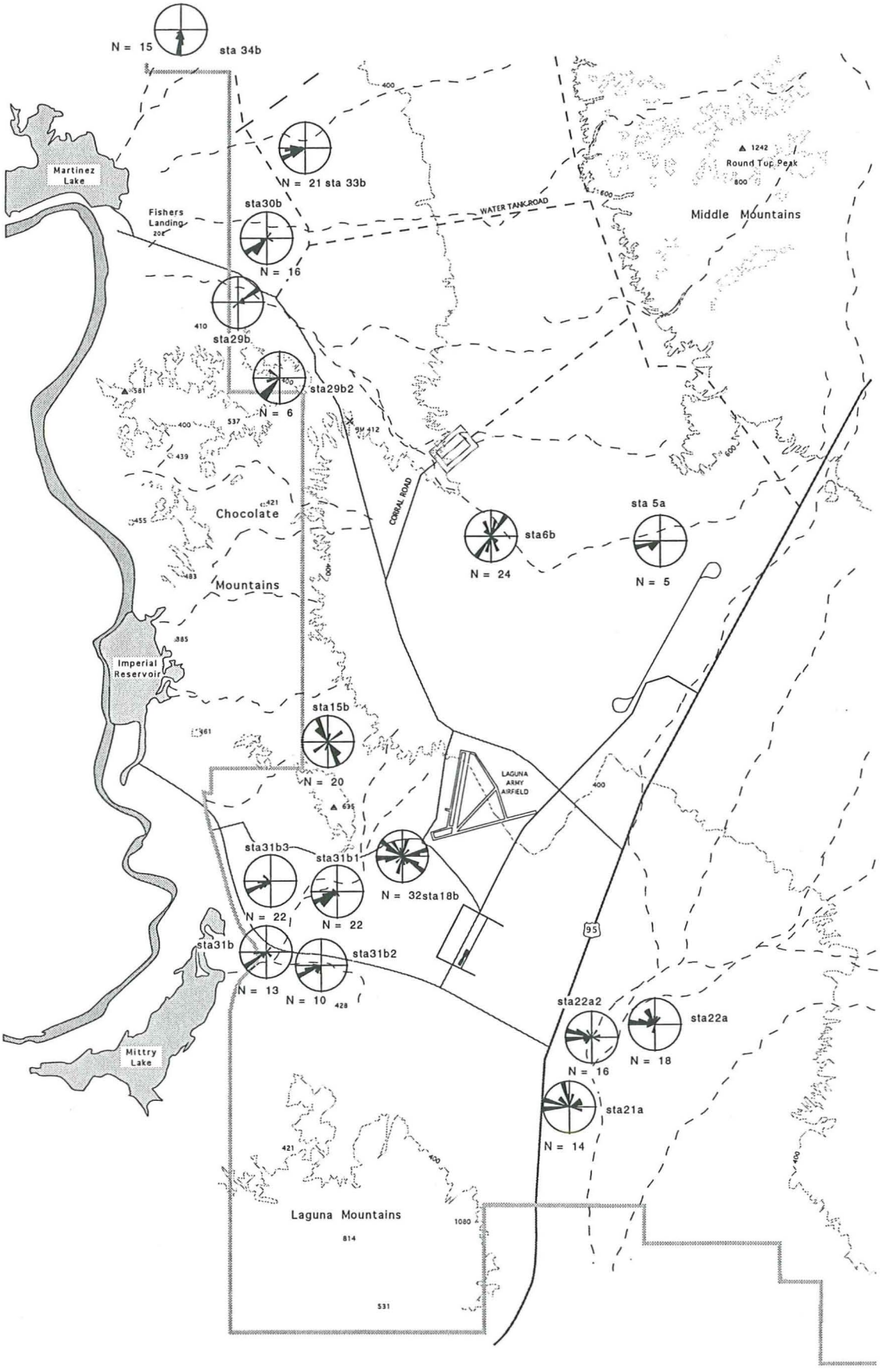


Figure 2.5 Map with paleocurrent directions in Colorado River gravels at data-point locations, as illustrated by rose-diagrams.

3. GEOLOGIC SETTING

3.1 Topography

The area of primary interest for this study consists of a gently-contoured valley approximately six kilometers wide and trending along a north-south axis. To its east the valley is bounded by the rugged Middle Mountains, which rise precipitously to 1242 feet at Round Top Peak; and on the west by a hilly area of dissected bedrock whose maximum elevation is 635 feet west of the Laguna Army Airfield. For convenience, members of the research team considered the western hilly area as an isolated fragment of the Chocolate Mountains, that lie to the west of the Colorado River. (The name "Chocolate Mountains" was apparently popular with early visitors to the area and has been applied by cartographers to several ranges in the California-Arizona border region.)

The hilly Chocolate Mountain area was primarily of interest to the investigators in its capacity of serving to limit extent of Colorado River gravels to the west. Alluvial fans of Locally-Derived gravels radiate from this source of detritus as well as from the Middle Mountains, providing a desert valley topographically typical of the Basin and Range province.

A small rise in the valley, Flat Hill (elevation 539 feet), serves to divert runoff from the Middle Mountains either to the north, where it can join the Colorado River at Martinez Lake (elevation 184 feet); to the south where it joins Castle Dome Wash, flowing between the Muggins and Laguna mountains to join the Gila River; or to the west, where several arroyos thread through the hilly Chocolate Mountains.

The relatively high flat surfaces of sand and gravel on which most of the Yuma Proving Ground is built consist of river terraces formed by the deposition of Colorado River sediments (Plate 3A).

Laguna Dam Road and the road connecting Laguna Army Airfield follow a west-trending valley from a point southwest of Flat Hill to the Colorado River, roughly delineating a drainage which presumably served as the main channel of the Colorado River at the time petrified wood was being formed.

In all, the topography is typical of southwestern fault-block terrain that has been shaped under arid and occasionally windy conditions punctuated by episodic torrential rains that result in sheet-flooding on low-relief surfaces and flash-flooding of washes.

3.2 Structural and tectonic setting

3.2.1 Basin and Range Province

The Yuma Proving Ground is located within the southern part of the Basin and Range Province. Down-faulted grabens that began to subside during the Basin and Range Disturbance (~19 Ma) have been the sites of accumulation of extensive deposits of clastic and volcanic sediments that were eroded from the adjacent elevated ranges. The associated volcanic activity along the active boundary faults contributed large volumes of lava and ash to the basin fill sequences. There were extended periods of interior drainage, in which thick deposits of lacustrine carbonates and evaporites accumulated. Most of these basins are buried by Quaternary alluvium, and their Tertiary rocks are known only from wells that have been drilled into them for water, oil or mineral exploration.

3.2.2 Gulf of California

In the Yuma basin and lower Colorado River area, rifting of the North American Plate during the late Miocene resulted in the encroachment of marine water along the Lower Colorado River extensional trough that extended northward to the Lake Mead area.

The Bouse Formation and older Miocene marine sediments of the Yuma area were deposited during a late Miocene-Pliocene marine invasion of the Gulf of California (Smith, 1970; Olmsted et al., 1973; Metzger et al., 1973). The Bouse Formation that is exposed on Yuma Proving Ground south of Laguna Dam Road consists of sediments ranging from conglomerates to mudstones. (Elsewhere, shoreline deposits of stromatolitic limestone, barnacles, foraminifera, and echinoids are evidence of a marine depositional environment for the Bouse Formation.)

The older marine sediments beneath the Bouse Formation in the Yuma area began to accumulate in the proto-Gulf of California by late Miocene time. The Gulf was formed by the eastward migration of the actively-spreading Pacific and North American plate boundary after 17 million years ago and caused a lowering of base level, affecting the lower Gila River drainage by about 8 million years ago (Shafiqullah and others, 1980).

The Gulf expanded northward at least to the Needles area by the end of the Miocene, where it is represented by the latest Miocene to Pliocene marine/estuarine sediments of the Bouse Formation. Low areas extended to the lake Mead area where the Hualapai Limestone Member of the Muddy Creek Formation was deposited in an estuary or saline lake near sea level (Blair and others, 1979; Lucchitta, 1979).

Plate 3.A View of typical exposure of Colorado River gravel terrace surface. Oblique sunlight reflects from the shiny patina of desert varnish that coats the clasts of Colorado River gravels and locally-derived gravels.

3.2.3 the Lower Colorado River trough

The Colorado River gravels at Yuma Proving Ground and other localities in the vicinity record the first arrival of the Colorado River in the Yuma area. Their age has not been dated directly, but can be bracketed between a 5.5 Ma tuff in the basal Bouse Formation (Shafiqullah et al, 1980) and 3.8 Ma volcanics that overlie the Colorado River gravels in the Lake Mead area.

Precise dating for the Colorado River gravels would be a major contribution to understanding the evolution and tectonic history of the entire Southwest but to date no study, including this one, has found materials—such as vertebrate remains, volcanic rocks—appropriate for dating by conventional means. The emerging cosmogenic dating technology (discussed further in section 4.3.2) offers promise for pinpointing the date, but it must be stressed that dates so obtained will be valid only for undisturbed specimens.

3.2.4 tectonic implications of the study

On the Yuma Proving Ground in the Lower Colorado River extensional trough, Pliocene fluvial terraces stand approximately 115 meters above present river elevation. Several explanations, tectonic activity among them, have been offered to account for this change in river level and are summarized in Section 4, which deals with the Colorado River.

As further described in that same section, Colorado River sediments convey a distinct signature. A comparison of petrified woods and Colorado River sediments from Yuma Proving Ground with those of the Fish Creek-Vallecito Basin provides significant evidence for right-lateral strike-slip movement along the San Andreas Fault system over the past five million years.

3.3 General stratigraphy

The stratigraphic sequence in the Yuma Proving Ground area is underlain by Pre-Tertiary basement metamorphic and igneous rocks that are exposed in the Chocolate, Laguna, Muggins and Middle mountains (see Figure 3.1).

The Cenozoic stratigraphy of the Lower Colorado River trough and the Yuma Basin, as documented by Metzger (1968), Olmsted et al. (1973), Buising (1988, 1990), Lombard (1993), and Sherrod and Tosdal (1991) includes the following stratigraphic units in ascending order: 1) nonmarine sedimentary rocks; 2) Older Marine sedimentary rocks and the contemporary Kinter Formation; 3) other nonmarine sedimentary rocks (or Osborne Wash Formation); 4) Bouse Formation; 5) Colorado River gravels and Locally-Derived alluvial gravels, and 6) Quaternary alluvium. In the study area the Bouse Formation is exposed in a limited area near the Yuma Proving Ground Main Administrative area. The

Colorado River gravels overlie the Bouse Formation and form the widespread terraces in the area (Figure 3.3). The Locally-Derived gravels occur as broad fans around bedrock outcrops and interfinger with the Colorado River gravels. The Quaternary alluvium is confined to modern drainage channels. Figure 3.2 illustrates the generalized stratigraphic relationships in the study area.

The stratigraphic position and facies descriptions of the Colorado River gravels that overlie Bouse Formation on the Yuma Proving Ground correlate particularly well with similar deposits that were described in detail by Buising (1988, 1990; 1993) along the length of the Colorado River from the Gulf of California northward to the Lake Mead area.

3.3.1 nonmarine sedimentary rocks

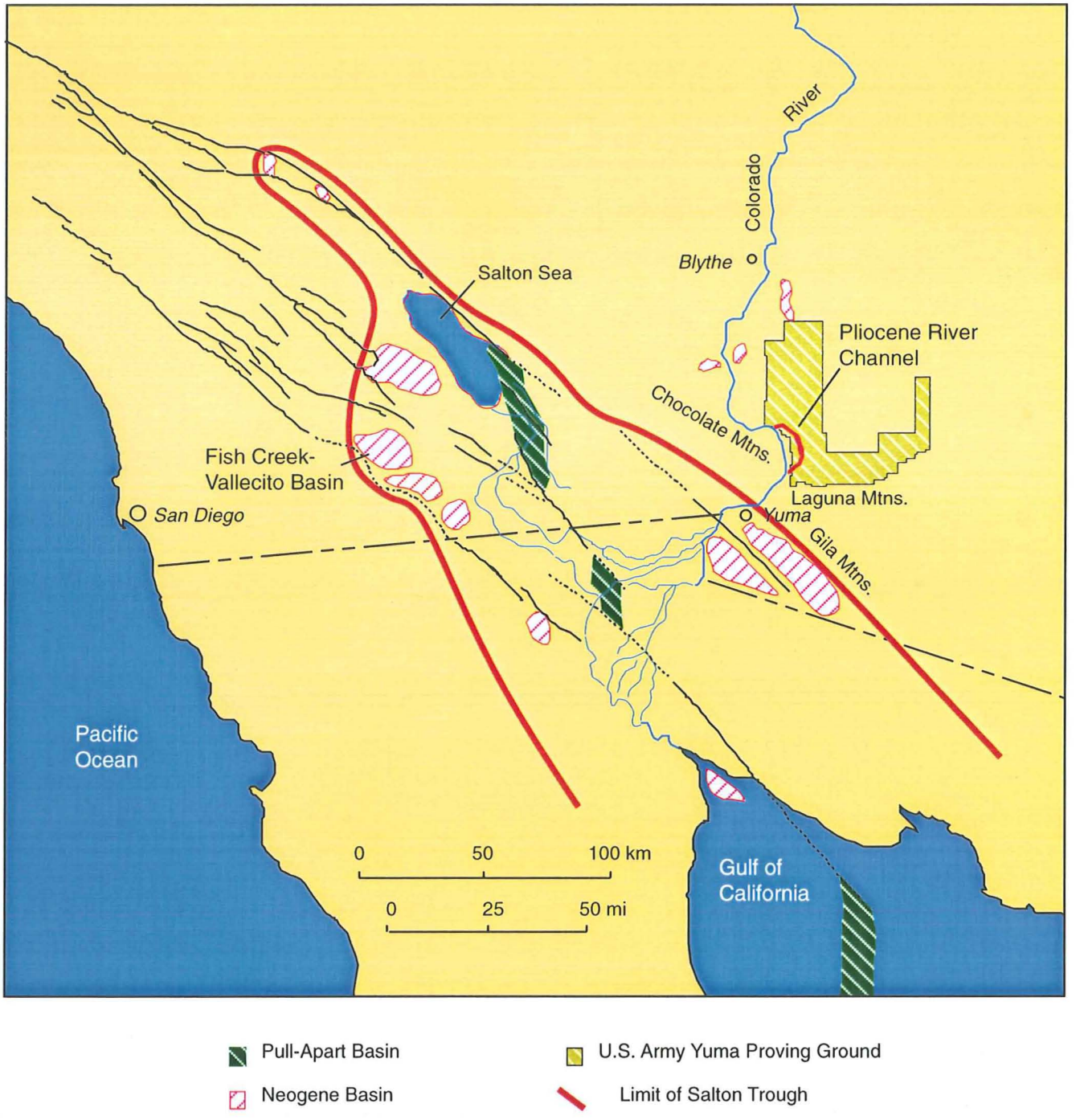
Nonmarine sedimentary rocks are reported by Lombard (1993) to unconformably overlie the pre-Tertiary crystalline basement rocks (Figure 3.4). Lombard (1993) revised Olmsted et al.'s (1973) original description of this unit by also including what was classified as the lower member of the Kinter Formation. The nonmarine sedimentary rocks (red-beds) of Lombard (1993) consist of conglomerate, sandstone and mudstone (in part of lacustrine origin), to sedimentary breccia and boulder conglomerate. The unit is reported to be at least 100 meters thick and moderately deformed; bedding generally dips 13 to 45 degrees (Lombard, 1993). The nonmarine sedimentary rocks are not exposed in the Yuma Proving Ground area; however, Lombard (1993) reported outcrops in the Laguna Mountains, and suggested that the unit is Eocene to Oligocene in age, based on stratigraphic position. This age was corroborated by Sherrod and Tosdal (1991) who reported a K-Ar date of 33 Ma on plagioclase in Chocolate Mountain volcanics that overlie the nonmarine sedimentary rocks (Figure 3.2).

3.3.2 older marine sedimentary rocks

The Older Marine Sedimentary Rocks were described by Olmsted et al. (1973) as fairly well-indurated, fine-grained sandstone, to siltstone and claystone. They intertongue with the uppermost portion of the nonmarine sedimentary rocks. The unit is reported to be moderately deformed and more than 1000 feet thick in the Yuma area. Olmsted et al. (1973) did not report an age with certainty; however, based upon the stratigraphic position of these beds it was suggested they intertongue with the nonmarine beds of the Kinter Formation of Miocene age (Figure 3.2).

3.3.3 Kinter Formation

The Kinter Formation is a sequence of nonmarine, predominantly coarse-grained sedimentary rocks, and minor intercalated beds of tuff and ash (Olmsted et al., 1973; Lombard, 1993). At its type section the Kinter Formation is divided



3.1 Map of tectonic and geographic features that illustrate the location and significance of Yuma Proving Ground relative to the late Neogene evolution of the Lower Colorado area. Depicted are: mountain ranges, Gulf of California, Salton trough, strike-slip faults of the San Andreas fault system, and the Fish Creek-Vallecito basin (modified from Winker and Kidwell, 1986; Abbott, 1997).

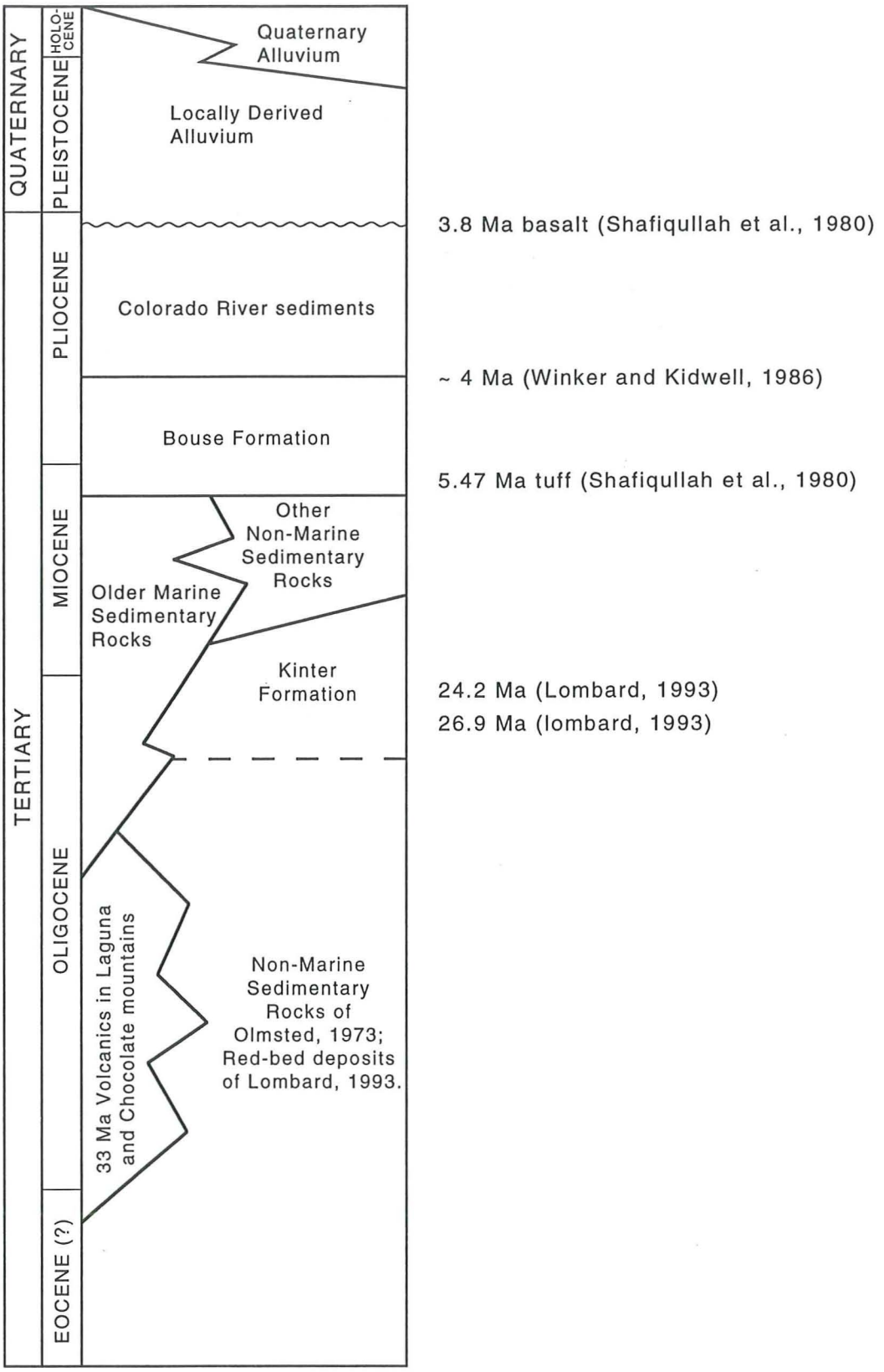


Figure 3.2 Composite stratigraphic column of the Lower Colorado River extensional corridor. Adapted in part from Olmsted et al. (1973), Buising (1988), Lombard (1993).

into two members: a lower member composed of unsorted breccia and tongues of arkosic sandstone and mudstone; and an upper member composed of conglomerate and arkosic sandstone and mudstone. The Kinter Formation is reported to unconformably overlie parts of the nonmarine sedimentary rocks (Figure 3.4) and is upper Oligocene (?) to lower Miocene in age based upon K-Ar dates of 23.0, 24.2 and 26.9 Ma on interbedded tuffs (Olmsted et al., 1973; Lombard, 1993)(Figure 3.2).

3.3.4 Osborne Wash Formation

The Miocene to Pliocene Osborne Wash formation consists of lithologically-variable clastic deposits that are found throughout the Lower Colorado River trough (Olmsted et al., 1973; Buising 1990)(Figure 3.2). The strata consist of coarse, angular, poorly-sorted conglomerate interpreted by Buising (1990) as alluvial fan deposits, that were formed by erosion of local highlands (Figure 3.4). Buising (1990) described abundant reverse and reverse-to normal-graded, matrix-supported conglomerates, which suggest deposition dominated by debris-flow processes. The deposits range from flat-lying to gently-tilted and were deposited on essentially modern topography. No direct evidence is documented for a through-going, integrated, regional drainage system during deposition (Buising, 1990). Trace amounts of far-traveled detritus apparently reached the northern end of the proto-Gulf basin, suggesting that through-going drainage may have fed it very early in its history. The Osborne Wash Formation is capped by a yellow sandstone that interfingers with the overlying basal carbonate of the Bouse Formation. This sandstone also marks the transition from a sedimentary environment dominated by sediment gravity flows to one dominated by dilute flow, traction and scour processes (Busing, 1990).

3.3.5 Bouse Formation

The Bouse Formation was originally named and described by Metzger 1968). Shafiqullah et al. (1980) reported a K-Ar age of 5.47 Ma for a vitric tuff in the basal carbonate of the Bouse Formation. This date indicates a late Miocene age (Figure 3.2).

Although Spencer and Patchett (1997) have suggested that $^{87}Sr/^{86}Sr$ ratios from the Bouse Formation are indicative of a lacustrine origin, the preponderance of evidence indicates that the Bouse is of marine origin; that perspective is adopted for purposes of this discussion.

Buising (1988, 1990), Lucchitta (1979), and Metzger (1968) each described the Bouse Formation as evidence of a Miocene marine transgression. The late Miocene to early Pliocene age Bouse Formation (Metzger, 1968) is comprised of sediments that may have been deposited during a marine incursion that extended as far north as Needles and possibly Lake Mead. Buising (1988, 1990) proposed that the

Bouse Formation and bracketing units, including the Colorado River gravels, record the evolution of the northern proto-Gulf of California and lower Colorado River (Figure 3.4). The marine sediments of the Bouse Formation are evidence of this marine embayment. The kinematics for creation of the accommodation space are not yet understood.

The basal carbonate of the Bouse Formation, which overlies the Osborne Wash Formation, indicates that the northern proto-Gulf of California was a carbonate basin early in its history and that significant volumes of far-traveled detritus did not begin to arrive until later in the history of the embayment (Buising, 1990).

Buising (1988, 1990) recognized two time-equivalent, interfingering lithofacies associations in the formation. The first association, referred to as the basin-margin association, is comprised of stromatolitic tufa deposits interbedded with a variety of carbonate and terrigenous-clastic lithofacies. The depositional environment of this association had already been interpreted by Metzger (1968) as marine shoreline. Smith (1970) reported the presence of marine foraminifera, including *Globigerina sp.*, providing further evidence that this area was at one time connected with the ocean. Buising (1993) described sedimentary structures that are evidence of tidal influence.

The second association, the basin-fill association, is divided by Buising (1988, 1990) into two informal upper and lower "members." The lower member consists of bedded clastic limestone with interbeds of coquina and is interpreted as estuarine. Barnacles, foraminifera, and ostracods have been reported from this member (Smith, 1970; Buising, 1988, 1990).

The upper member of the basin-fill is a deltaic and terrigenous-clastic sequence of fine-grained muds, silts, sands, and pebbly sands containing evidence of tidal action. There is evidence of plant bioturbation in the muds and silts, suggesting periodic sub-aerial exposure. The terrigenous-clastic input includes cobble-to-boulder breccia derived from adjacent highlands (Buising 1988, 1990).

In contrast to the widespread Colorado River gravels, exposures of the Bouse Formation on Yuma Proving Ground are limited. Neither the basin-margin association nor the lower estuarine member of the basin-fill association has been observed in outcrop within the Yuma Proving Ground study area. Here it is limited to the upper member of the basin-fill association, with exposed thicknesses of up to 10 meters. These exposures consist of poorly consolidated, calcareous siltstone and mudstone, which overlie one meter of very fine-grained, poorly consolidated, arkosic sandstone. The calcareous siltstone and mudstone commonly vary in color between green, tan, pink, and white over vertical distances of less than 0.5 cm to greater than 1 meter. Horizontal color variations are visible on a larger scale and are less common. In the study area, a yellow siltstone fills a channel cut into a white siltstone. The sandstone, siltstone, and mudstone all show evidence of plant bioturbation with root molds

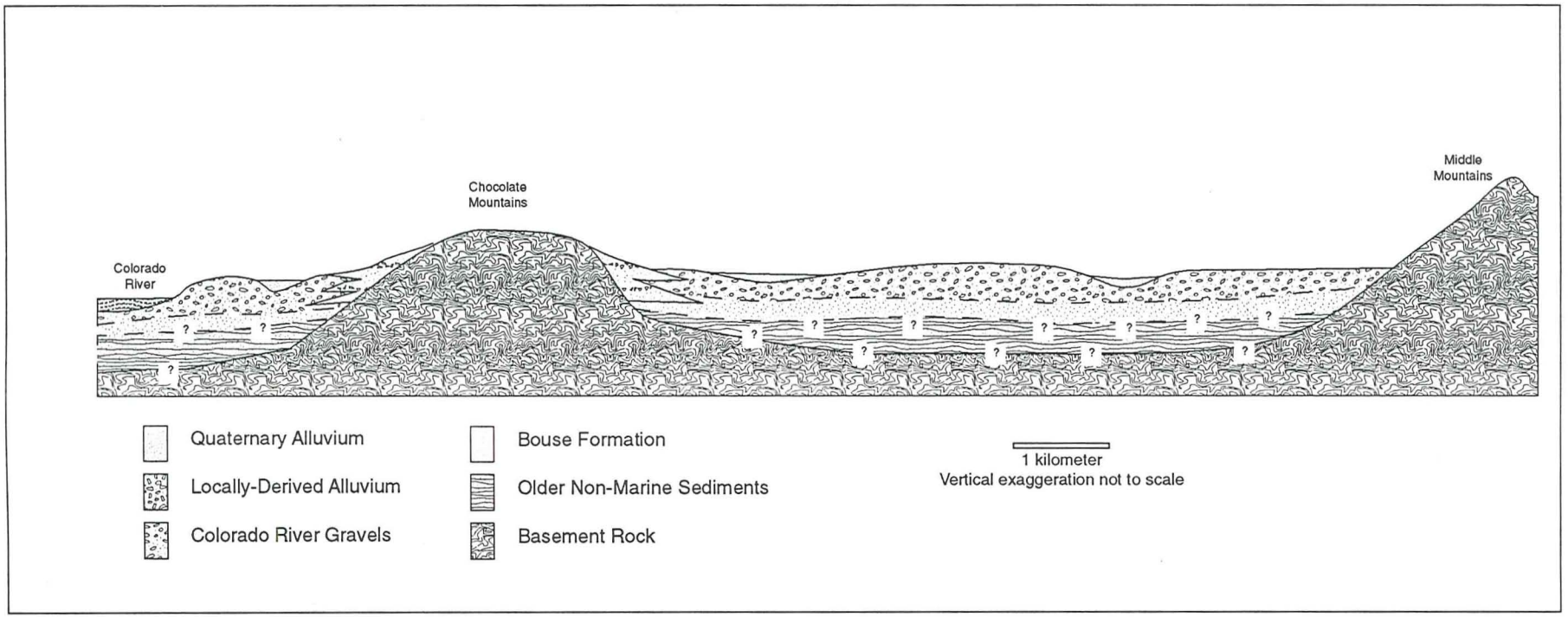


Figure 3.3 Idealized east-west cross-section across the study area on the Yuma Proving Ground from the Colorado River to the Middle Mountains, showing the relationship between the pre-Tertiary basement, Bouse Formation, Colorado River gravels, Locally-Derived gravels, and Quaternary Alluvium (adapted in part from Buising, 1988, and Olmsted et. al., 1973).

less than 1 millimeter in width and commonly 3 cm in length. None of the original organic tissue is preserved, and the molds are evidenced by their iron oxide fillings. Throughout the sequence, gypsum veins are found in random orientations. These veins are most likely secondary fracture fillings that formed in desiccation cracks during subaerial exposure. The upper contact of the Bouse Formation varies from conformable to unconformable with the overlying Colorado River gravels. Where the contact between the Bouse and Colorado River gravels is exposed in the study area, the gravels are of highly variable thickness.

On Yuma Proving Ground the fine-grained nature of the Bouse Formation, its planar bedding, and the absence of cross-bedding, bars, and flaser or lenticular bedding, all suggest a very low-energy environment of deposition dominated by suspension sedimentation. The planar bedding, suspension sedimentation, bioturbation, and cut-and-fill structures support an environment without significant wave or tidal influence (Miall, 1984). Instead, Miall interprets environments that exhibit each of the above-listed characteristics as delta plain environments in which the distributary channels are separated by interdistributary flood plains. Therefore, the portion of the Bouse Formation exposed in the study area probably represents such a delta plain.

In the Exxon No. 1 Yuma-Federal well, the Bouse Formation grades upward from predominantly marine shale with a few thin sandstone and siltstone members, through a transition zone of fine-grained nonmarine sediments, into the sand and gravel of the Colorado River sediments. The Bouse Formation of Miocene-Pliocene age is extensive along the length of the Gulf of California embayment and documents the opening of the Gulf of California (Metzger et al., 1973).

The overlying Colorado River gravels mark the first occurrence of a through-going fluvial system above the Bouse Formation sediments.

3.3.6 Colorado River sediments

Metzger (1968), Lucchitta (1979), Olmsted et al. (1973), and Buising (1988, 1990) have all discussed the Colorado River gravels. Buising (1988, 1990) gave the Colorado River gravels the most attention and described them in the context of an upper bracketing-unit above the Bouse Formation (Figure 3.3). Buising (1988, 1990) described the lithologies and sedimentary structures of the Colorado River gravels at several localities along the Colorado River between California and Arizona. These descriptions correlate well with the gravels found on Yuma Proving Ground (Figure 3.4; Plate 3.B.1). Buising asserted that these gravels mark the first progradation of the fluvial system into what was previously the deltaic and estuarine system of the Gulf of California.

The present course of the Colorado River is not believed to have existed prior to ten million years ago. Lucchitta (1972, 1989) proposed that drainage from what is today the Basin and Range Province flowed northeasterly into large lakes on the Colorado Plateau until about 18 million years ago, when displacement along the Grand Wash fault topographically separated the two provinces. The main stem of the Colorado River in the Rocky Mountains is thought to have flowed west into the headwaters of the White River and down a course through the Uinta structural basin. Due to early Miocene Basin and Range extension the river's westward course was interrupted, and not until late Miocene time did it breach the mountain barriers to become established in the present-day Lake Mead area. Since the late Miocene, between 3.8 and 5.5 Ma, the river drained into the Bouse embayment where estuarine or lacustrine conditions prevailed (Lucchitta, 1972; Shafiqullah et al., 1980).

3.3.7 Locally-Derived gravels

The Locally-Derived gravels (Figure 3.2) consist of clasts of bedrock eroded from nearby mountains, such as the Middle Mountains and Laguna Mountains (Figure 3.3). The gravels occur in broad fans that prograde from the mountain ranges over parts of older units. The clasts are predominantly angular, and range from 2 cm to 4 cm (in distal exposures) to boulder size (in proximal locations)(Plate 3.B.2). Clast lithologies, identified by Barnett (1972), reflect those of the surrounding mountains, and include gneiss, andesite, rhyolite, granite, and diorite. Desert pavement and varnish commonly are well developed on surface exposures of this unit.

Clast imbrication data also indicate transport from the local mountains, which supports local derivation. The paleocurrent directional data collected in this unit are tabulated in Appendix A and illustrated in the form of rose diagrams in Figure 2.5. Inspection of the rose diagrams indicates that these gravels were eroded from the nearby mountains. Additionally, vertical exposures indicate that deposits thicken and coarsen toward the mountains (Figure 3.3). No petrified wood was observed in association with these gravels. Present-day drainage features trend approximately east-west across much of the study area, and dissect the Locally-Derived gravels, the underlying Colorado River gravels and the Bouse Formation.

3.3.8 Quaternary alluvium

The youngest unit in the area of study is the Quaternary alluvium (Figure 3.2). It is unconsolidated and comprises the bed material in present-day washes and arroyos. Clast lithologies include reworked Colorado River gravel, Locally-Derived gravel, and Bouse Formation.

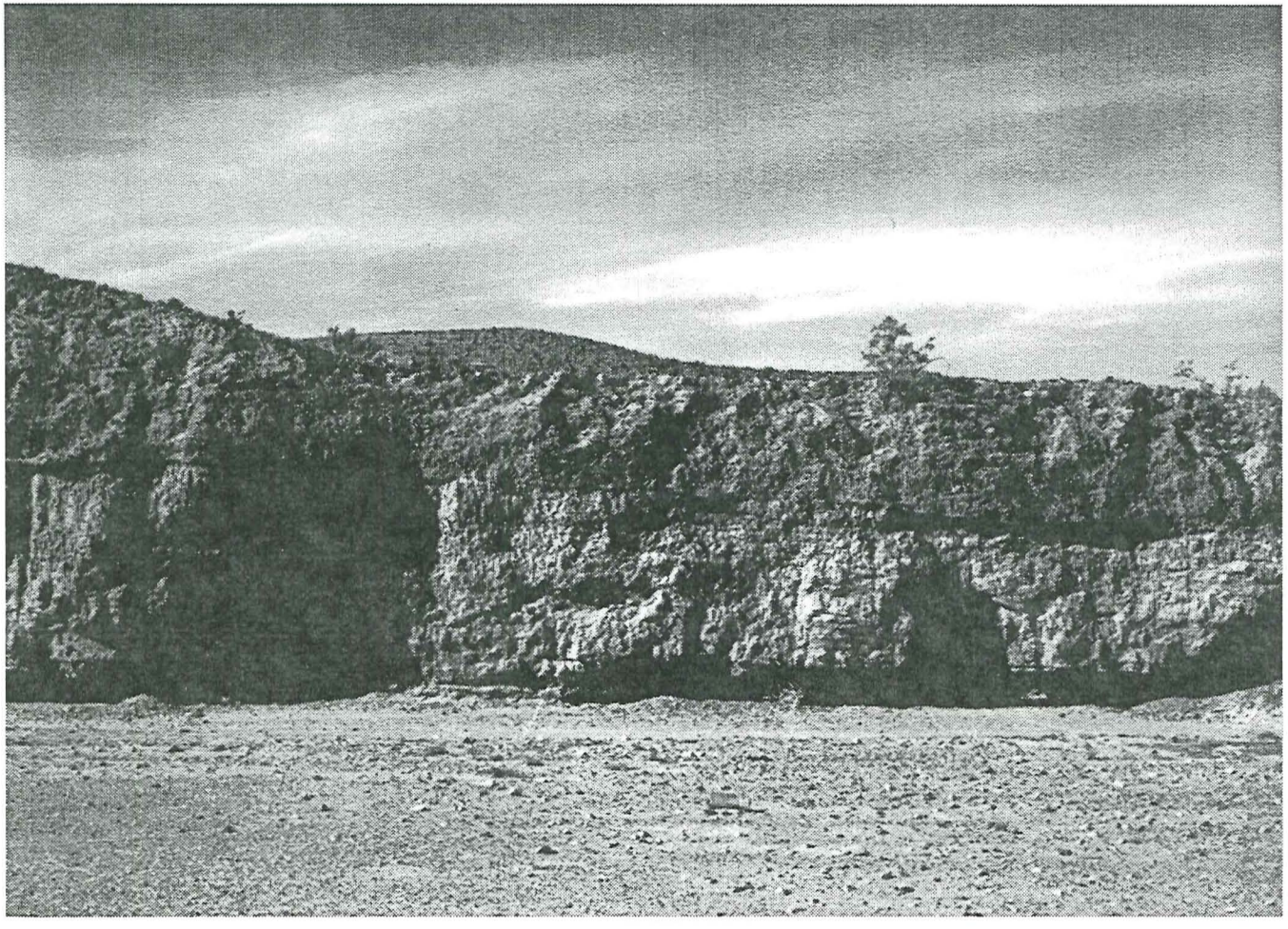


Figure 3.4 Vertical exposure of Colorado River sediments in wash south of Laguna Dam Road. Note contact between overlying coarse, petrified wood-bearing gravels with fine-grained fluvial sequence beneath.

Plate 3.B.1 Typical surface exposure of Colorado River gravels. Most data-point locations were of this type, where the matrix has been removed by deflation leaving the clasts clearly visible.

Plate 3.B.2 Typical surface exposure of mixed CRG, LDG, matrix, and associated petrified wood; note desert varnish over all clasts and petrified wood.

4. COLORADO RIVER SEDIMENTS

4.1 Description and evidence for Colorado River origin

The Colorado River gravels on the Yuma Proving ground are a broad, flat-lying, and unconsolidated sheet-like deposit (Plate 3.A). They are exposed at the surface throughout the study area, except adjacent to local bedrock hills and mountains where alluvial fans of Locally-Derived gravels prograde out over the Colorado River gravel sheets and interfinger with them at depth (Figure 3.4). The Colorado River gravels occur at elevations of up to sixty meters above the present river level at Yuma Proving Ground, and other exposures of Colorado River sediments are widespread beyond the area into California and Mexico (Figure 4.1).

The gravel is matrix-rich and matrix-supported, where the mean clast size is less than five centimeters; and clast supported where the mean clast size exceeds five centimeters. The matrix is medium- to fine-grained quartz sand. Desert pavement and varnish are well developed on undisturbed surface exposures of the gravel (Plate 3.A).

4.1.1 clast composition

Clast counts were conducted at 58 localities in the field area. One hundred points on a grid at equal spacing of ten centimeters were classified as either matrix, Locally-Derived gravels, or Colorado River gravels. These results are illustrated in Table 2.1. The compositional percentages have been plotted in Figure 2.3 as pie diagrams in the position of their respective localities of collection.

Clast lithologies include: fine-grained, brown-to-purple quartzite; red, yellow, and black chert; dark-brown, crinoidal cherty-limestone; tan, medium- to fine-grained quartz sandstone; and gray crinoidal dolomite. The chert and limestone lithologies are similar to the Mississippian Redwall Limestone and Permian Kaibab Formation exposures on the Colorado Plateau. The quartz sandstone is similar to the Permian Coconino Sandstone found on the Colorado Plateau. The dolomite could be derived from the Devonian Martin Formation. Quartzite is a very common lithology and is similar to the Shinumo or Mazatzal Quartzite. These clast compositions indicate a Colorado Plateau source (Plate 3.B.2).

Petrified wood in Colorado River gravels

The Colorado River gravels at the Yuma Proving Ground contain an unusual concentration of petrified wood (Plate 3.B.2). It occurs in varying abundance, commonly as pieces twenty-five centimeters to forty centimeters in length and rarely reaching two meters. The wood preserves excellent surficial detail including angularity, except in a single locality where a rounded piece of petrified

wood was found in gravels with a mean clast size greater than five centimeters. In only a single instance has a piece of petrified wood been observed below the surface; this may be due to the lack of vertical exposures, especially as wood has been recovered from the subsurface during construction excavations, such as the sewage lagoons west of the airfield.

4.1.2 grain size, roundness and sorting

Clast sizes commonly range from 0.25 centimeters to ten centimeters, but some clasts are as large as 25cm in diameter. Clasts are typically well-rounded and moderately sorted, suggesting a distant source (Figure 2.2; Plate 4.A.1).

4.1.3 paleocurrent indications

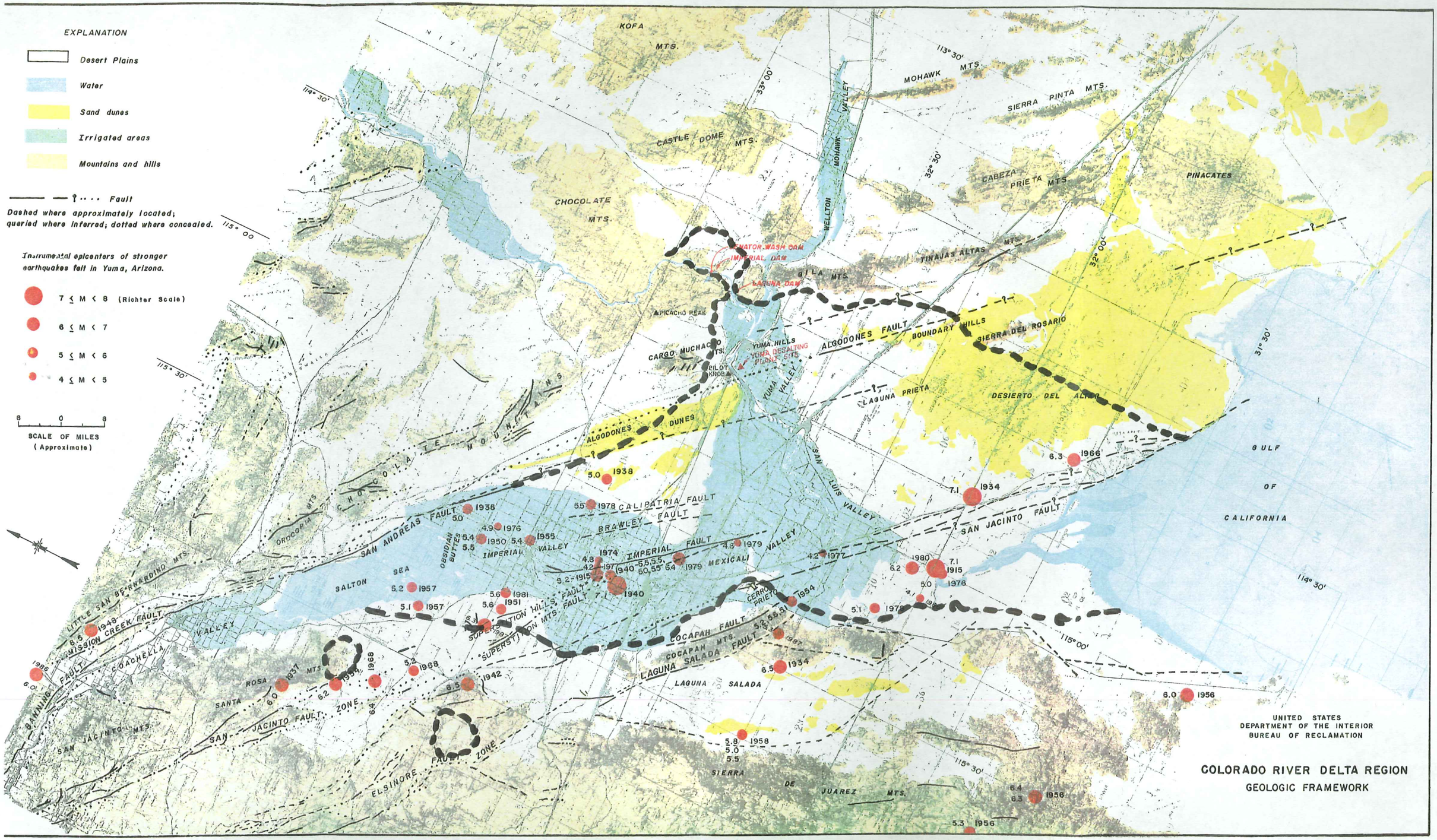
The Colorado River gravels display trough cross-bedding on a scale from ten centimeters to fifty centimeters. Colorado River gravel-filled channels are scoured into both the Colorado River gravels internally, and the top of the Bouse Formation. These cut-and-fill structures range in size from twenty centimeters to several meters in depth and width. Where vertical exposures are visible, the Colorado River gravels display excellent clast imbrication.

The availability of paleocurrent indications was limited by the lack of vertical exposures of the Colorado River gravels. Clast imbrication directions and/or wood orientations were measured at eighteen of 58 data collection localities to interpret the flow direction of the Pliocene Colorado River in the study area. Where clast imbrication was visible, the direction was measured with a Brunton compass (Plate 4.A.2).

Four of the paleocurrent measurements were based on the orientations of the longest axis of petrified wood specimens, which were also measured with a Brunton compass. Wood orientations were measured only in areas free from signs of disturbance such as scars in the desert pavement. Paleocurrent observations are tabulated in Appendix A and the paleocurrent directions are illustrated by rose diagrams in Figure 2.5. Discussion and interpretations of the significance of these data are discussed in section 4.4 of this report.

This pattern of observations indicates that the Pliocene Colorado River flowed in a southerly direction through the valley between the Chocolate Mountains, Middle Mountains, Muggins Mountains and Laguna Mountains. The variation in flow directions, which is evident in the pie diagrams, is typical of sediment-choked braided streams (Reading, 1986).

FIGURE 4.1



KNOWN or INFERRED EXTENT of PLIO-PLEISTOCENE COLORADO RIVER GRAVELS

Plate 4.A.1 Nations (left) and Harmon examining Colorado River gravels at locality 19C and collecting quartzite clasts for cosmogenic dating; YPG helicopter and crew in background.

Plate 4.A.2 Colorado River gravel in vertical trench wall at locality 19C, with imbrication of flat pebbles showing a southerly transport direction.

4.2 Regional setting

4.2.1 extent of Colorado River Gravels on Yuma Proving Ground

The surficial extent of the Colorado River gravels on Yuma Proving Ground is indicated by the distribution of the Colorado River gravel symbols at data-point locations shown in pie-diagrams and the heavy black line on Figure 2.3. The areal extent of the gravels is largely limited to within ten kilometers east of the present course of the Colorado River (Figure 2.3). Subsurface information from well logs supports these findings and shows that the Colorado River gravels do not extend east of the Middle Mountains.

4.2.2 thickness of Colorado River Gravels

In the study area, the Colorado River gravels range in thickness from a few centimeters (only a single clast-layer deep) to at least 10 meters. The Colorado River sediments, including sand and silt, are known to be 100 m thick (Figure 4.2). Available subsurface data consist of exploration and water production well logs provided by Yuma Proving Ground and the U.S. Bureau of Reclamation (see Appendix B). Several of the logs were older driller's logs containing general lithologic descriptions while others contained both detailed lithologic and geophysical information. However, none of the logs contain descriptions of the lithology of the gravel-sized clasts encountered at various depths making interpretation of the base of Colorado River deposits difficult. Figure 4.2 is a preliminary east-west stratigraphic cross-section of the Yuma Proving Ground Main Post and Test Directorate. The cross-section was compiled using lithologic descriptions, geophysical logs and the Geologic Map of the Laguna Dam 7.5 Minute Quadrangle (Olmsted, 1972).

The cross-section indicates a thick channel of Pliocene Colorado River sediments that intertongue locally derived alluvium and overlie pre-Colorado River non-marine deposits including the Kinter Formation (see Figure 3.2 for a descriptive stratigraphic column). None of the subsurface logs appears to have encountered Bouse Formation which is partially exposed in washes near Main Post. Exploration wells MAA#1 and MAA#2 were drilled about 2 kilometers from Bouse exposures but, perhaps in the case of MAA#2, not drilled deep enough to intersect the Bouse contact or the Bouse is missing from those sections.

The Colorado River gravels overlie the Bouse Formation on the Yuma Proving Ground. The lower contact with the Bouse Formation varies from gradational to sharp, the latter occurring where Colorado River gravel-filled channels were scoured into the top of the Bouse. Gravel-filled channels are also common within the Colorado River gravels (Figure 3.3). The Colorado River gravels are generally exposed at the surface, with no evidence of overlying sediment or rock

units. In a few exposures near their depositional limits, the Colorado River gravels are covered by, mixed with, and interfinger with, the Locally-Derived gravels (Figure 3.4; Plate 3.B.2). These gravels are coarse and angular, and reflect the lithologies of the surrounding mountains.

4.2.3 extent of Colorado River Gravels outside Yuma Proving Ground

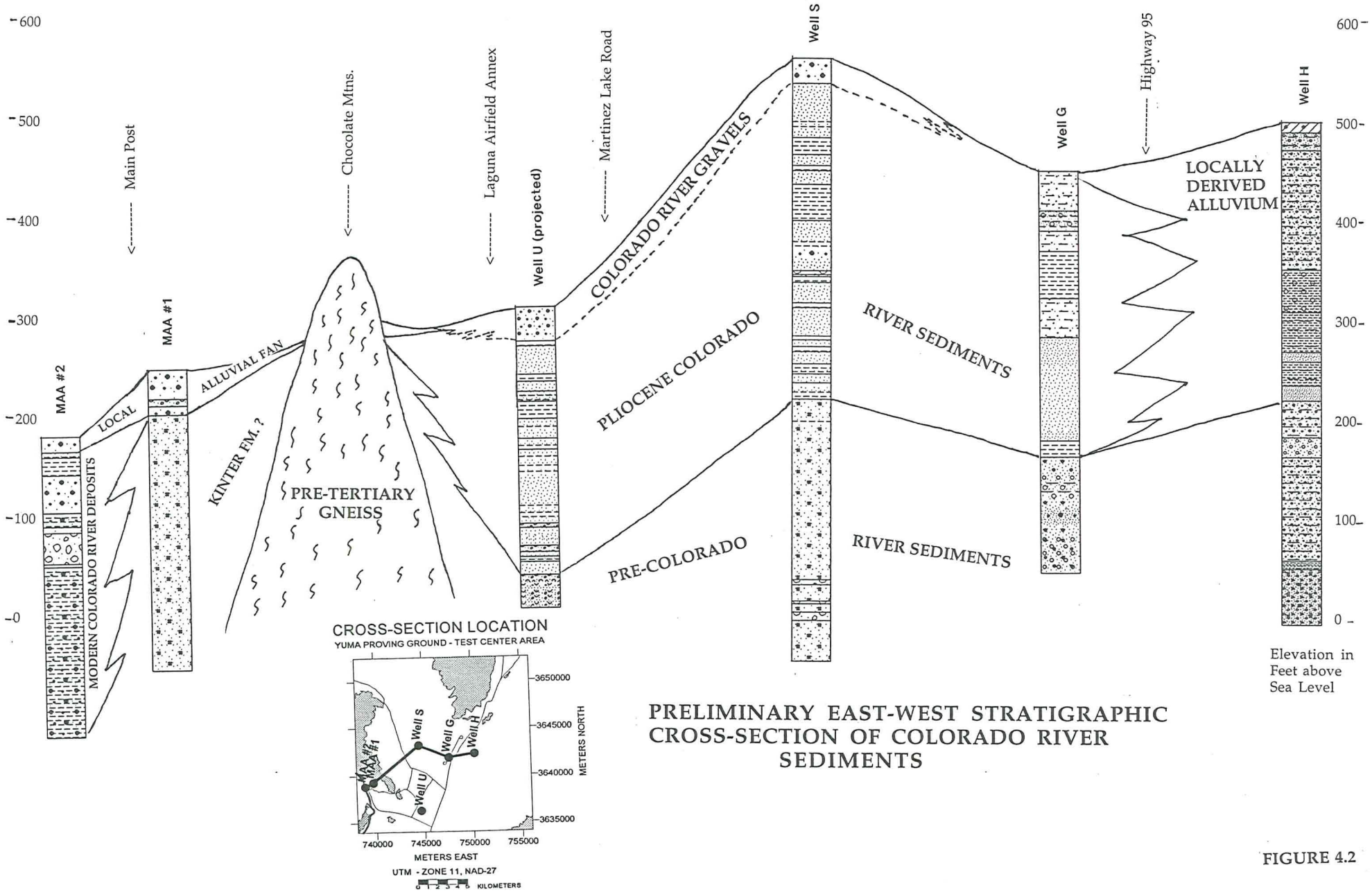
South and west of Yuma Proving Ground where the river passes through Yuma into Mexico, Colorado River gravels can be found at further distances from the existing river channel. The extent of these Plio-Pleistocene exposures is shown on Figure 4.1 by the heavy dashed line. In some cases modern eolian deposits cover Colorado River gravels between exposures and the line has been drawn across them to reflect the aerial extent.

The Colorado River terrace deposits near Yuma contain occasional small pieces of petrified wood that often exhibit rounding by secondary transport. It is presumed that most of this wood is reworked from older deposits such as those at Yuma Proving Ground since: 1) the fossil wood is exposed downstream, 2) the size and concentration of petrified wood is greatly diminished from that of Yuma Proving Ground and, 3) most samples show some degree of rounding.

Near the head of the Gulf of California early to middle Pleistocene Colorado River gravels have been tectonically raised in the vicinity of Golfo de Santa Clara, Sonora by the active San Jacinto - Cerro Prieto Fault system. These deposits contain a diverse Irvingtonian vertebrate fauna and abundant petrified wood (Shaw, 1981).

4.2.4 Anza Borrego State Park, CA

Figures 3.1 and 4.1, and Plates 4.B.1 and 4.B.2, depict the exposures of Pliocene Colorado River sediments in the Anza Borrego State Park. Remeika and Fleming (1995) and Abbott (1997) point out the Colorado River deposits in the Vallecito and Borrego Badlands and the significance of their tectonic offset. Clasts from the Borrego Badlands recently provided by Paul Remeika for inspection by Croxen reveal a Colorado Plateau affinity. Included in the clasts are dark brown chert, light brown quartzites and limestones containing crinoid and bryozoan fragments that are lithologically similar, but finer grained, than the gravels at the Yuma Proving Ground.



PRELIMINARY EAST-WEST STRATIGRAPHIC CROSS-SECTION OF COLORADO RIVER SEDIMENTS

FIGURE 4.2

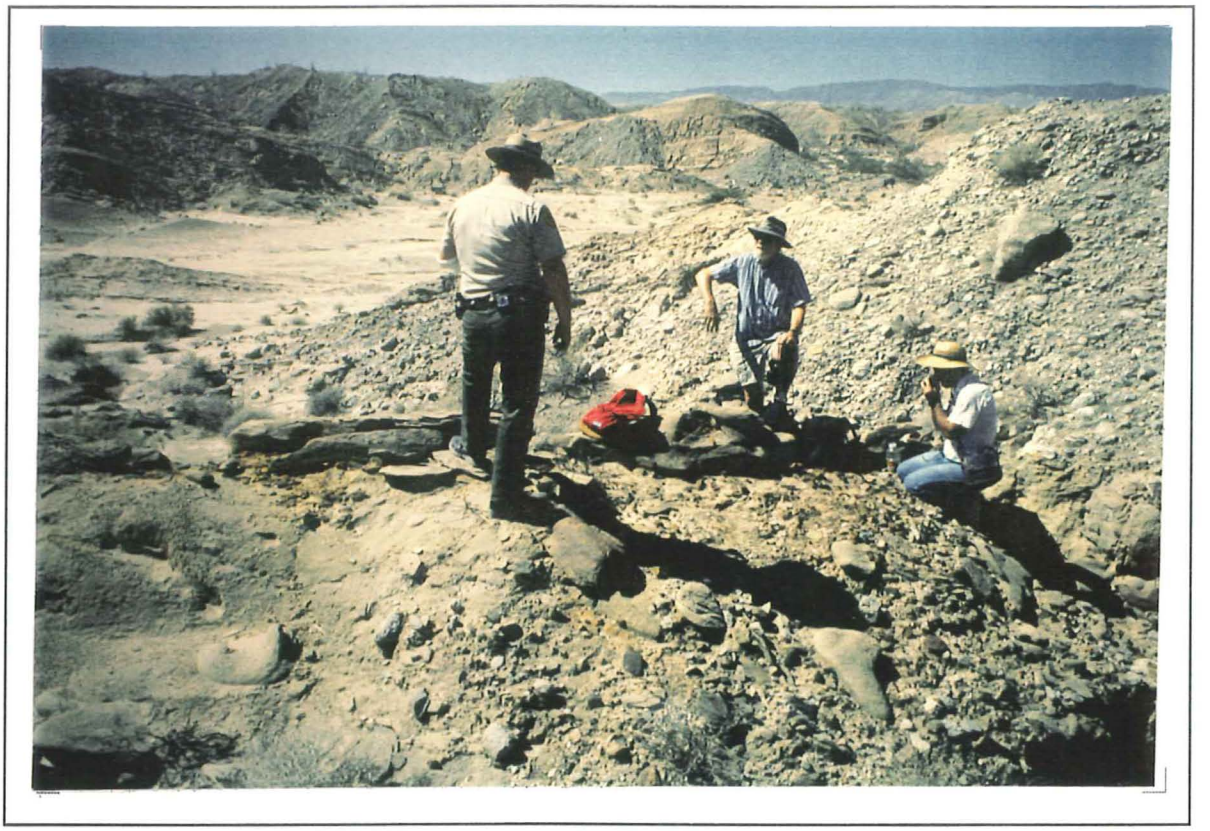
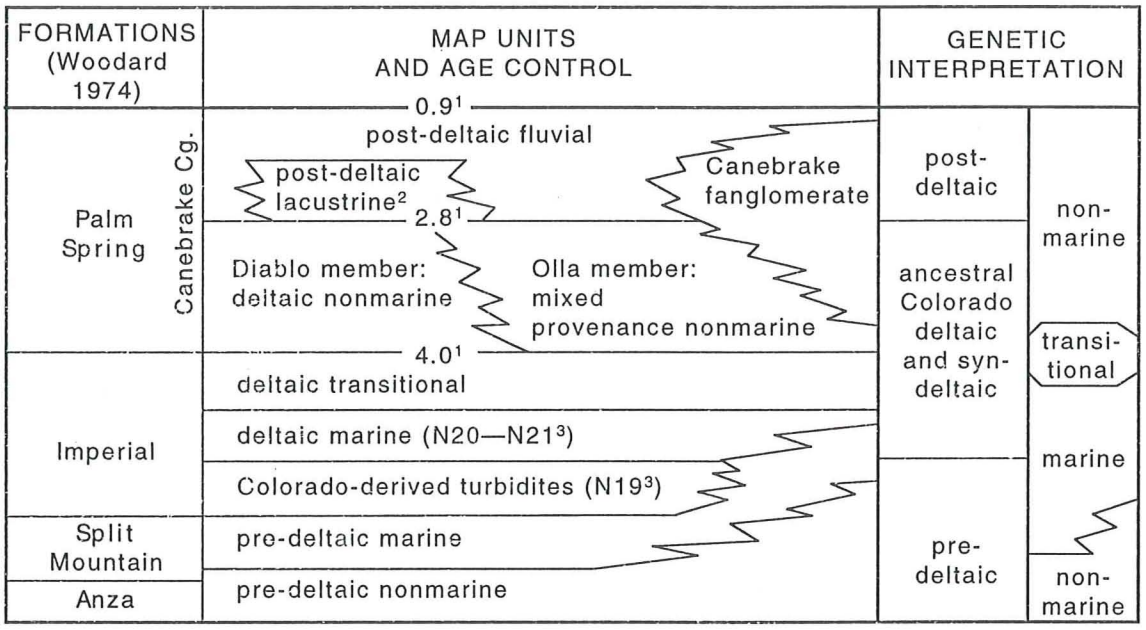


Plate 4.B.1 Remeika, Swift and Croxen examining petrified wood in delta-plain deposits of the Colorado River delta, Pliocene Diablo Mbr. of the Palm Spring Fm., Fish Creek-Vallecito basin, California.

Plate 4.B.2 Pro-delta sediments and cliff-forming channel sands of the Pliocene Colorado River delta in the Fish Creek-Vallecito basin. The petrified wood-bearing delta-plain deposits are not visible in this photograph.



[1]magnetostratigraphic ages in Ma (Johnson et al.,1983; P. Remeika, 1985, written comm.)
[2]2.3±0.4 Ma, fission-track age on zircon from air-fall tuff (Johnson et al., 1983)
[3]planktonic foraminiferal zones (Stump, 1972)

Figure 4.3 Stratigraphic column in the the Fish Creek-Vallecito area (from Winker and Kidwell, 1986).

4.3 Age and correlation of Colorado River sediments

4.3.1 bracketing technique

On the basis of similar lithology and stratigraphic position, the Bouse Formation and the Colorado River gravels on Yuma Proving Ground can be correlated with the same units that have been dated elsewhere along the Colorado River and in the Salton Trough to the west. Even though no datable materials, e.g. interbedded volcanic rocks, have been found with the Colorado River gravels at Yuma Proving Ground, they do occur to the north in the Lake Mead area and to the west in the Fish Creek-Vallecito Basin (Figure 4.3). By lateral correlation of the Colorado River gravels into those areas, it is possible to determine the age of the sediments at Yuma Proving Ground by the "bracketing technique."

4.3.2 K-Ar dates in Yuma, Lake Mead and Fish Creek-Vallecito Basin

Lucchitta (1979) reported the Colorado River gravels overlying the Bouse Formation in deposits that extend from the Gulf of California to at least as far north as Parker, Arizona. Buising (1990) correlated the Colorado River gravels of the lower Colorado River between Parker and Yuma, Arizona with similar deposits to the north. The Colorado River gravels exposed at Sandy Point, Lake Mead, are overlain by a basalt flow dated at 3.79 Ma (K-Ar, whole rock) (Shafiqullah et al., 1980). Outcrops in the Grand Wash area, Lake Mead are overlain by a basalt flow dated at 3.80 Ma (K-Ar, whole rock) (Shafiqullah et al., 1980). A K-Ar date of 5.5 Ma on tuff that is interbedded with basal carbonate member of the Bouse Formation provides a maximum age of the Colorado River gravels (Shafiqullah, et al, 1980; Buising, 1988, 1990). These dates bracket the age of the gravels between 3.8 and 5.5 Ma. This is consistent with an estimated ~4 Ma date (based on paleomagnetic chronology by Johnson et al, 1983) of the first arrival of distally-derived Colorado River sediments in the Diablo Formation in the Vallecito-Fish Creek basin in California (Winker and Kidwell, 1986). The top of the Diablo Member is the stratigraphically highest occurrence of Colorado River-derived sediments in the Fish Creek-Vallecito Basin, where it is estimated at 2.8 Ma (Winker and Kidwell, 1986). Therefore, the time interval of deposition of the Colorado River delta at Fish Creek-Vallecito Basin was between ~4 and 2.8 Ma, which defines a duration of 1.2 million years.

4.3.3 paleontological correlation

The common occurrence of the same plant taxa in the petrified wood found in the Colorado River gravels at Yuma Proving Ground and in the Colorado River delta sediments at Fish Creek-Vallecito Basin are evidence of correlation of these

deposits. Based on this correlation, the age of the Colorado River gravels at Yuma Proving Ground can be more precisely defined as between ~4 and 2.8 Ma.

Also, the change of direction of the Colorado River from the Yuma Proving Ground area to its present channel that cuts across the southeastern end of the Chocolate Mountains, must have occurred since 2.8 million years ago.

4.3.4 cosmogenic dating attempts

Two attempts have been made to collect Colorado River gravels clasts for cosmogenic dating of the upper surface of the Colorado River gravel terrace deposit. On May 5, 1997, Thure Cerling and Cassie Fenton (University of Utah), Ted Melis and Bob Webb (U.S. Geological Survey) went in the field with us to collect basaltic clasts that are potentially datable by Helium (^3He) isotopes. They collected samples at location 19C, both from the surface and at a depth of 1m below the surface in the exposed trench at that locality. These samples have not been processed yet, therefore no results are available to report (Melis, pers. com., January, 1998). They also observed a high alluvial fan surface with well-developed desert varnish, at the northeastern corner of the Laguna Mountains. No Colorado River gravels were present at that locality, therefore no samples were taken for dating.

On October 28, 1997, Russell Harmon collected several quartzite pebbles from the surface at location 19C, and was going to send them to Paul Bierman for cosmogenic dating utilizing the beryllium (^{10}Be) technique (Plate 4.A.1). These samples have not been analyzed, and there are no results to report at this time (Bierman, pers. com., January, 1998).

These data might be applicable to the dating of the Colorado River gravels since there is no indication that the surface has been covered since the gravel was deposited, and therefore the date of the age of the surface might be equal to the age of the gravel. However any undetected erosion from the surface would decrease the validity of the age (Bierman, pers. com., January, 1998). Since the age of the Colorado River gravels is reasonably well-known by bracketed radiometric dates, the validity of the cosmogenic date could be evaluated. This would be a possible test for the cosmogenic dating technique, which is being utilized in dating debris flow surfaces along the Colorado River in the Grand Canyon area (Webb et al., 1996).

4.4 Evidence of Colorado River origin

In addition to the clast compositions of the Colorado River gravels that indicate a Colorado Plateau source, there are several published examples of reworked Cretaceous fossils in Colorado River sediments, that could only have come from the Mancos Shale in New Mexico, Colorado and Utah.

Merriam and Bandy (1965), identified detrital specimens of seven species of Upper Cretaceous foraminifera in the Palm Springs Formation, which had been reworked from the Upper Cretaceous Mancos Shale of the Colorado Plateau. They noted that these fossils are also found in the modern Colorado River delta, upper Pleistocene lacustrine sediments of the Borrego and Brawley formations, the Pliocene Imperial Formation of southern California, and in the modern Colorado River delta in Lake Mead. They concluded that "the Colorado River began depositing sediment in the Gulf of California at least as early as the Pliocene or latest Miocene. Deposition, which has been continuous since then, has fluctuated between marine and fresh water conditions as determined by structural events and shifting of distributaries. The bulk of the sediment occupying the basin extending from the Salton Sea to the Gulf of California has been imported by the Colorado River."

According to Lucchitta (1979), no Mancos-type foraminifera have been found in the Bouse Formation. This suggests that the ancestral Colorado River did not flow into the Bouse depositional basin until after the Bouse Formation was deposited. The Colorado River gravels at Yuma Proving Ground in the Yuma area, therefore are the record of the first arrival of the Colorado River to the Salton Trough.

Similar paleontological evidence of the Colorado Plateau origin of Colorado River sediments is found in the Colorado River delta deposits of the Fish Creek-Vallecito Basin, California (Figure 3.1). The reworked specimens of the Cretaceous palynomorphs *Proteacidites* spp. and *Aquilapollenites* spp. from the Upper Cretaceous Mancos Shale indicate that the southern Colorado Plateau was being eroded by early Pliocene, and the northern Plateau by 3.9 Ma. (Remeika and Fleming, 1995).

Gastil et al. (1996) demonstrated that Colorado River-derived sediments can be differentiated from locally derived sediments on the basis of their magnetic signature. This is because the plutonic rocks of eastern California are magnetite-poor, and the rocks exposed in the drainage area of the Colorado River are magnetite-rich. The difference can be detected by a hand-held magnetic susceptibility meter.

4.5 Depositional environment of Colorado River Gravels

The transition from the very fine-grained Bouse Formation to the Colorado River gravels represents a large energy increase. Trough cross-bedding, clast size and roundness, and channel cut-and-fill structures indicate that the Colorado River gravels were deposited in a fluvial environment. Clast compositions indicate a Colorado Plateau source of the gravels, which are mixed along the depositional margin with locally derived gravels. These clast compositions and the ratios between Colorado River gravels, Locally-Derived gravels and matrix are indicated by pie diagrams on Figure 2.3. The flow directions, as indicated by

paleocurrent indicators, are depicted in rose diagrams on Figure 2.5. They exhibit a range of variation, yet a dominant direction of flow is indicated for each observation station. The imbrication directions in the Colorado River gravels indicate a southerly direction of transport in a Colorado River fluvial system that flowed around the southeastern end of the California Chocolate Mountains. The Colorado River gravels are not observed on the surface or in drill logs east of the Middle Mountains, which suggests the Colorado River did not flow east of the Middle Mountains. Buising (1993) observed similar paleocurrent indications in other areas, as "predominantly southwesterly to southeasterly transport, with rare outcrops indicating northeasterly transport".

Areas in which Colorado River gravel clast size exceeds 5 cm may represent the high energy channel environment. At a locality just west of 7B (Figure 2.1) the Colorado River gravels are over 10 meters thick, clast-supported, and the mean clast size approaches 10 cm. The sediments observed in the area of 7B are believed to be those deposited in the thalweg (main channel) of the Pliocene Colorado River. The Colorado River gravels here show a southerly transport direction and are visible in part over at least three kilometers along an east-west line. Erosion to the north and burial of the gravels by the Locally-Derived gravels to the south have made it difficult to trace the position of the thalweg in those areas. Deposits that show a mean clast size less than 5 cm also show a higher percentage of matrix and indicate lower energy areas of the fluvial system, such as those found in broader flat reaches or along channel margins. The occurrence of petrified wood is consistent with these findings, as there is little wood in the high-energy environments, and the single piece found at locality 7B is small (9cm), and well rounded. Instead, petrified wood is concentrated in the lower-energy environments of sedimentation, presumably closer to the banks from which trees may have been removed, and are more likely to have sunk and been buried there.

Gravelly and sandy fluvial deposits commonly form in braided-stream environments, while sandier deposits are commonly the product of meandering systems (Reading, 1986). The coarse Colorado River gravels then suggest the Pliocene Colorado river in this area was a braided system. It is proposed that the Pliocene Colorado River in this area was a bedload-dominated, sinuous-channel system. Therefore, it is likely that the process of lateral channel migration is largely responsible for the broad Colorado River gravels distribution in the study area. The dominance of coarse-grained sediment and the large-scale of bedforms indicate a high-energy system (Buising, 1993)

Areas where the deposits are matrix-dominated (>50%) with pebble-size clasts, are interpreted as lower energy environments. It is likely that in many of these areas, coarser deposits of the laterally migrating thalweg exist below the surface. This occurs as the channel accretes laterally, leaving behind abandoned coarse-grained channel fill deposits, which are subsequently covered by finer-grained deposits, a process of vertical accretion. Together the processes of lateral and vertical accretion are diagnostic of a migrating system (Reading, 1986). The Pliocene Colorado River had the competency to carry some clasts that are >25 cm in diameter, probably during periods of accentuated flow velocities caused by storm events or other high seasonal runoff.

4.6 Changes in course of Colorado River

Following deposition of Colorado River gravels at Yuma Proving Ground as recently as 2.8 Ma, the Colorado River changed course and followed a new channel across the southeastern end of the (California) Chocolate Mountains, which was at or below the aggradational river deposit at the time. Since then, the River has cut its channel as much as 115 m below its level when it was flowing through the Yuma Proving Ground area. Betts (1997) discussed possible fluvial dynamic processes that may have caused the course change.

5. PALEOBOTANY OF THE COLORADO RIVER GRAVELS

5.1 Occurrence

The Colorado River gravels found on Yuma Proving Ground contain an unusual concentration of petrified wood. The wood occurs only in the Colorado River gravels and not with the Locally Derived gravels (Figure 5.1). The localities in the study area where wood has been found are identified in Figure 2.4, which also shows qualitative observations of wood abundance, summarized with notations of frequency of occurrence as: abundant, common, uncommon, rare, none, and none* (which denotes a disturbed area). The wood is most abundant where matrix percentage exceeds 25% (Figure 2.3). These areas represent relatively lower energy environments such as the channel margin.

5.2 Preservation and petrification

It is a common observation that dead wood will ordinarily decompose within a few years. In this process fungi metabolize the cellulose, hemicellulose, and lignin in the wood's vascular network (Kaarik, 1974).

However, in certain instances dead woody material and its histological detail can be preserved as part of the fossil record. For the preservation of wood to occur, decomposing microbial activity must be halted (Browning, 1963). This can only happen in environments where specific conditions, dependent upon moisture, temperature, aeration, pH, and sedimentary setting, can be achieved (Browning, 1963). Because most of the organisms responsible for decomposition, such as fungi, require oxygen for respiration, the most important of the conditions essential for the preservation of wood in nature is the absence of oxygen (Browning, 1963).

An interesting confirmation of the rapid deterioration of wood has occurred in our own collection of modern wood specimens collected for comparison with Yuma Proving Ground petrified wood. A sample of desert ironwood from near the Yuma Proving Ground area was moved to Northern Arizona University, where it was deposited in the comparative collection. About one week later, when the dry specimen was next observed, a significant portion of it had been reduced to "sawdust" by a boring insect, which is still working on it today. Presumably if it had been kept saturated with silica-rich water, this process of decomposition would have been prevented.

5.2.1 volcanic activity

One common set of conditions leading to petrification is volcanic activity. Hot, fine-grained volcanic material raining down on trees is capable of destroying microorganisms which might otherwise lead to decomposition. Fine-grained ash settling at the right temperature and rate can encapsulate trees without igniting them or even knocking them down, leaving standing, preserved trees. Volcanic ash is also silica-rich and can contribute the replacing mineral material required in the petrification process. The Yellowstone region exemplifies this mode of preservation.

In the Petrified Forest National Park and vicinity, recently-downed trees accumulated in swampy environments upon which ashfalls acted to facilitate petrification during the Triassic Period (240 Ma).

The absence of overlying sediment or ash in the study area suggests other modes of petrification must be examined.

5.2.2 sub-aqueous petrification

Nearly all of the Yuma Proving Ground petrified wood specimens show intricate detail in preservation of cell structure. The replacement mineral in the petrified wood has been identified as quartz (Knauth, pers. comm., 1995). In this case, silicification probably occurred in the depositional environment of the Pliocene Colorado River channel. The good preservation of morphologic detail and lack of abrasion in the majority of specimens indicate that they have not been transported and are therefore locally derived from the riparian habitats of the Pliocene Colorado River channel and its tributaries. There have been several published studies of the process of sub-aqueous petrification of wood, which are briefly discussed below.

Ninety-five per cent of the total weight of moisture-free wood is made up of cellulose, hemicellulose, and lignin (Browning, 1963). Browning further reported that cellulose is the principal constituent of softwoods and hardwoods, comprising 40 and 50 per cent of the total moisture-free weight respectively, and provides the framework for wood structure. As woody plants grow they create a cellulose framework, and the hemicellulose and lignin are deposited in and among the framework as an encrusting and strengthening matrix.

Harlow (1970) has reported that waterlogged, undecomposed wood has been recovered from stagnant lake bottoms after a hundred years or more. Wood over 4,500 years old has been recovered from anaerobic muds and found to be histologically intact as well as recognizable as to botanical taxa (Bailey and Barghoorn, 1942; Barghoorn, 1949). One reason these specimens have been preserved is that the water-logging expels entrapped air while maintaining the

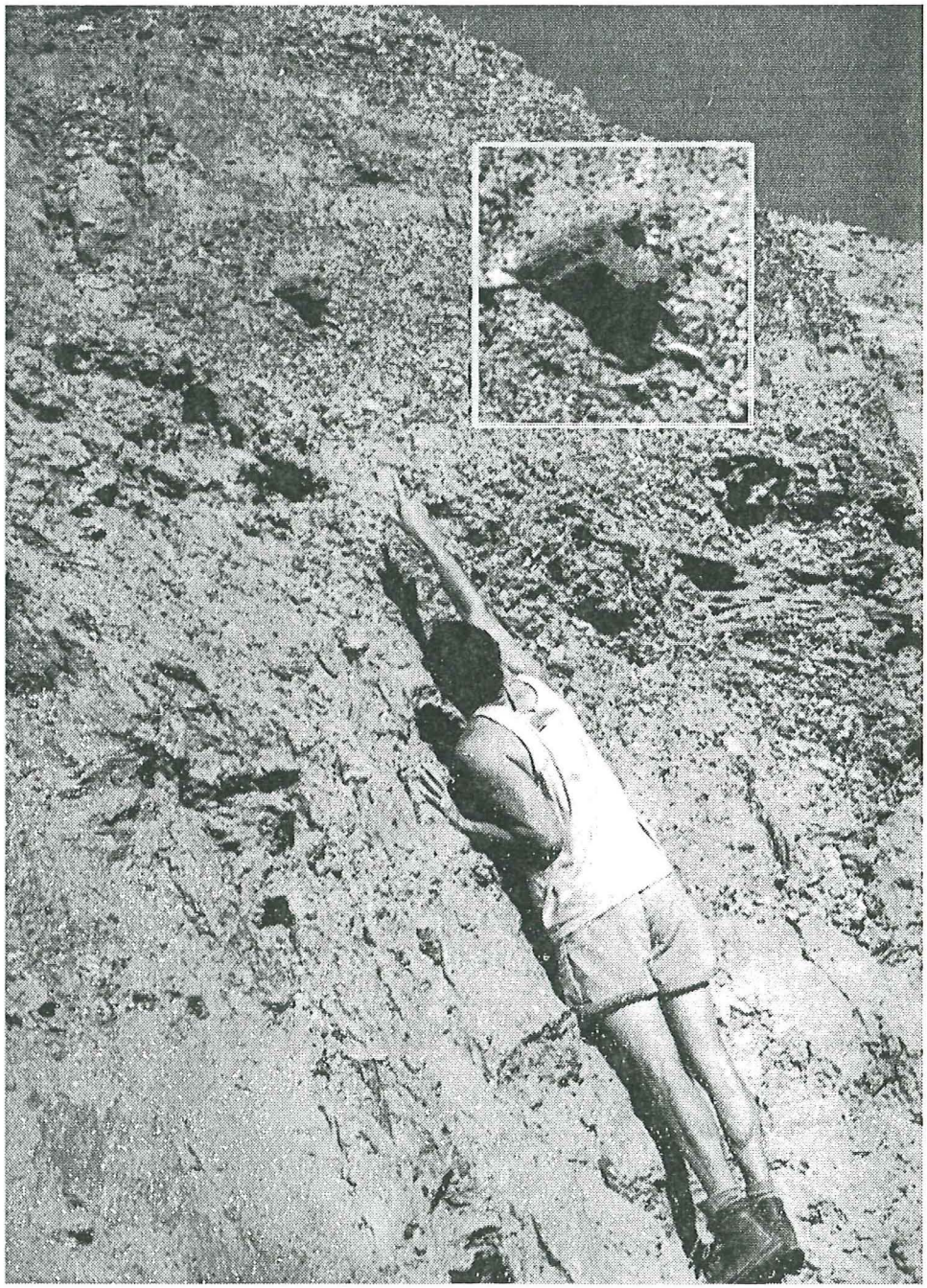


Figure 5.1 Betts pointing to a petrified log being eroded from the Colorado River gravels south of Laguna Dam Road; inset shows detail of the log. This discovery constitutes the only observed occurrence of wood beneath a ground surface that had not been influenced by human activity.

wood in a swollen and plastic state (Browning, 1963). When wood exists in this waterlogged state, maximum permeability is also achieved which allows for the transport and dispersal of soluble minerals such as silica into and through the wood (Browning, 1963).

Barghoorn (1960) suggested that the tendency of vascular wood tissue to act as a depository for silica is the result of the potential for hydrogen bonding that exists between soluble silica and the ligno-cellulosic/hemicellulosic complexes that make up the bulk of wood. The semi-rigid nature of the plant cell- wall retains its internal structure and permeability which then allows for the infiltration of siliceous fluids (Rolfe and Brett, 1969). Once the siliceous fluids have penetrated the wood, petrifaction proceeds not as a 'molecule-for-molecule' replacement but instead as a process of impregnation, where the wood substance serves as a template for silica deposition (St. John, 1927; Arnold, 1941; Barghoorn, 1960; Schopf, 1971).

The concentration of aqueous silica needed to petrify organic material would not even need to be of ore-forming concentrations if preservation were to take place within a time period of ten years (Demko, pers. comm., 1995). Silicification has been reported to begin in as little as twenty-four hours when wood samples are placed in a solution of 5,000 -10,000 ppm of sodium metasilicate (Sigleo, 1978). A much more dilute concentration, similar to drinking water would be sufficient for petrification to occur over a period of ten years or more (Demko, pers. comm., 1995). It is very common for silicification to occur at relatively early stages in the burial history of the enclosing sediment, at depths of zero to ten meters (Carson, 1991). Logically, if wood is not petrified within a few years of the death of the plant, it must inevitably decay.

5.3 Petrification of Yuma Proving Ground wood

In the case of the petrified wood in the Colorado River gravels at Yuma Proving Ground, silicification appears to have occurred in the Colorado River gravels without deep burial, because there is no field evidence that the gravels were buried by other sediments or by volcanic ash, and almost all of the petrified wood studied was found at the surface of the Colorado River gravels deposit. Only one specimen was observed in a buried position by the investigators (Figure 5.1), but excavation for the sewage lagoons uncovered large amounts of petrified wood a short distance below the present-day land surface.

Sustained contact with aqueous silica is essential to the process of petrification (Carson, 1991). This explains why no petrified wood is found with the Locally-Derived gravels which, as suggested by their morphology, were transported by ephemeral flow processes. The Colorado River appears to have been a continuing source of water and may have been the source of the silica in the petrified wood. The present Si concentration of Colorado River water at Imperial Dam averages 9.0 ppm, and is even higher (32.6 ppm) in the ground water in

wells at the Yuma Proving Ground (Figure 5.2). These concentrations apparently were adequate to preserve the wood in the Pliocene Colorado River sediments (Table 5.1 and Table 5.2 in Appendix C).

Dissolved silica in the Colorado River is most likely derived from weathering and devitrification of local volcanic rocks in the numerous mountain ranges that the Colorado River traverses along its southern course. The even greater concentrations in groundwater basins is most likely derived from weathering of bedrock in surrounding hills and mountains.

When dead wood becomes water-logged it maintains maximum permeability and the water can transport and disperse soluble silica throughout the wood (Browning, 1963). When the Pliocene flora in the study area died and became submerged and water-logged in Colorado River water, the water could penetrate the interstices of the wood and disperse soluble silica for deposition, resulting in the silicification and preservation of the petrified wood that is found on the Yuma Proving Ground.

In summary, the most likely sequence of events in the Yuma Proving Ground area has been: growth of trees in a riparian habitat; inundation of the trees by ephemeral flooding events by waters which rapidly subsided; trees in backwaters became waterlogged without significant transport; silica-rich river waters replaced the cell structure; the river course changed, leaving the silicified trees and associated gravels in dry localities that eventually deflated to produce the present-day desert surfaces.

5.4 Identification

Because the petrified wood was locally derived, taxonomic identification can provide insights into Pliocene environments and climate in the lower Colorado River region. Even though many specimens have been collected in past years, essentially no previous work has been done to identify the petrified wood or explain its occurrence within the Colorado River gravels on the Yuma Proving Ground (Plate 5.A).

A representative suite of 60 specimens of petrified wood was collected from Yuma Proving Ground for purposes of identification (Plate 5.B). The identification of the petrified wood has been challenging because there is no well-documented technique for the identification of plant taxa on the basis of cell anatomy.

5.4.1 scanning electron microscopy

Our first attempt at identification was to examine cell-wall morphology by scanning electron microphotography of specimens. Preparation of the Yuma Proving Ground petrified wood was done at Northern Arizona University,

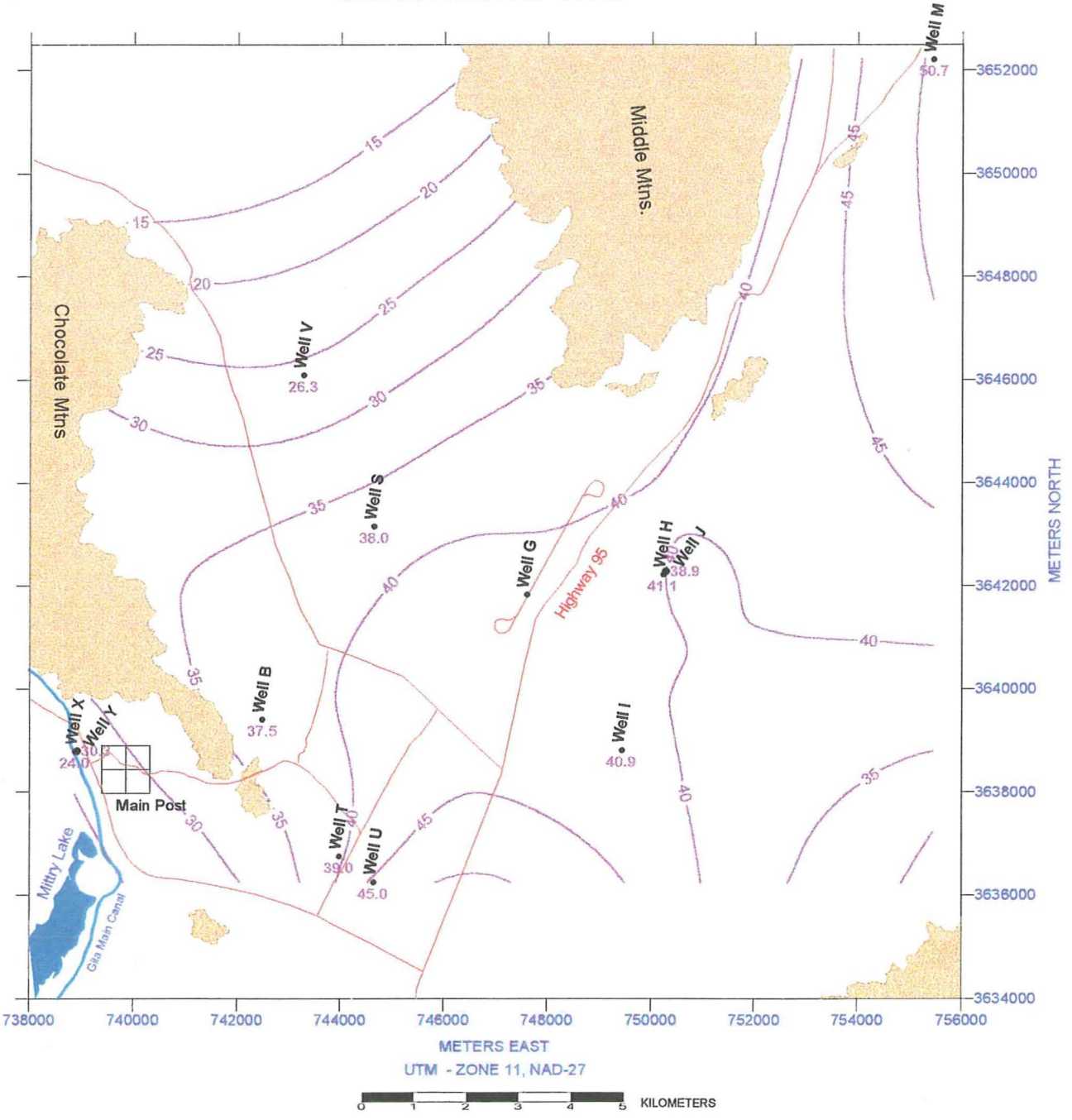
FIGURE 5.2

SILICA IN GROUND WATER

YUMA PROVING GROUND - TEST CENTER AREA

• Sampled Well and Silica in PPM
33.7

CONTOUR INTERVAL = 5 PPM



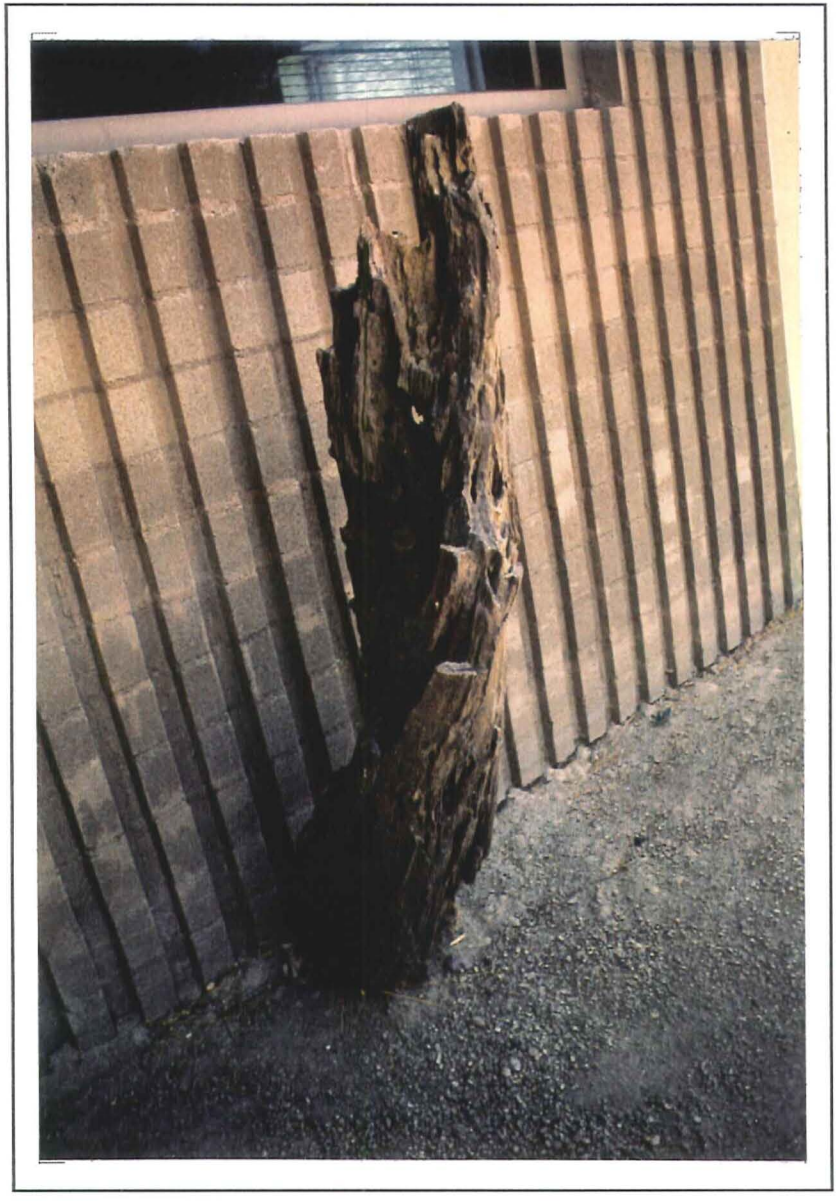


Plate 5.A.1 Petrified *Umbellularia* (bay laurel) tree that was collected from the Colorado River gravels near the YPG Airfield, and restored to a standing position at the entrance to the Range Operations Center.

Plate 5.A.2 Nations and Croxen examining the Range Operations Center petrified tree. Its identification is based on the cell structure observed on polished surfaces of a small chip taken from its base.

Plate 5.B.1 Sewage lagoons near the YPG airbase. This is the data-point location 9C, from which 43 specimens of petrified wood were collected by the excavation contractor.

Plate 5.B.2 Gauna, Croxen, and Nations, transferring the specimens of petrified wood from the sewage lagoon excavation to Arizona Western College for diamond-saw cutting and storage.

where the specimens were SEM-photographed in the Department of Biological Sciences by Marilee Sellers. The specimens and photographs were examined and, based on wood anatomy, identified by Dr. Owen Davis at the University of Arizona as: palm, cottonwood, conifer, and a variety of undifferentiated dicotyledenous angiosperms (Table 5.3).

Dr. Davis also expressed the opinion that, even though some of the SEM photos show images of pits and rays, the identification of much of the material on that basis was prohibited by quartz deposits on cell walls (Davis, pers. com., 1995).

Based on his petrographic analysis of specimens, Dr. Paul Knauth at the Geology Department, Arizona State University, confirmed that the replacement silica was in the form of quartz, rather than opal, which is more to be expected in specimens of this relatively young age (Knauth, pers. com., 1996). Dr. Knauth expressed the opinion that the implications of this observation are worthy of further investigation.

5.4.2 comparison to contemporary specimens

The most successful technique for identification of the Yuma Proving Ground petrified wood has been that developed by Paul Remeika at the Anza Borrego Desert State Park, Borrego Springs, California. Mr. Remeika utilizes the gross anatomy of petrified wood (i.e. patterns of cell arrangement in rings, rays and cortical cells) in comparison with the patterns in the wood of modern plant taxa.

Cut and polished specimens of the Yuma Proving Ground petrified wood (Plate 5.C) were taken to Anza Borrego and compared directly with the identified specimens in the collection of Paul Remeika. Upon examination of the Yuma Proving Ground specimens, Remeika observed that they were remarkably similar to the petrified wood that he has collected from the Colorado River-derived delta plain deposits in the Diablo Member of the Lower Pliocene Palm Spring Formation in the Vallecito-Fish Creek Basin of the Anza-Borrego State Park, California, the occurrence of which is described in Remeika and Fleming (1995). He assisted us in the preliminary identification of representative specimens in our collection as laurel, walnut, and palm, as well as several specimens of other types of dicotyledenous angiosperms that he could not identify to genus.

For independent confirmation of the identifications, Robert Larson, Professor of Forestry at Northern Arizona University, and a wood anatomy specialist, examined a representative sample of the Yuma Proving Ground specimens and confirmed the identification of *Umbellularia* (laurel), *Juglans* (walnut) and palm. He did not have appropriate comparative material needed for further identifications at this time (Larson, pers. comm., 1998). All the specimens that Larson examined were identifiable as angiosperms, mostly dicotyledonous, but with the monocotyledons represented by palm. Larson was impressed with the

Table 5.3 Record of preparation and identification of Yuma Proving Ground Petrified wood. Specimens that were collected, but not cut and prepared for identification are not listed in this table.

SAMPLE NUMBER	SAMPLE LOCALITY	TENTATIVE IDENTIFICATION	Length (cm)	Max. Diam (cm)	Comment	MODERN ANALOG
YPG000	YPG19C	*Umbellularia sp*	78	25	part of 13' long tree	laurel
YPG001	YPG19C	*Umbellularia sp*	93	23		laurel
YPG002	YPG19C	identification pending	85	42	22 cm I.D., root?	
YPG003	YPG19C		53	23	missing	
YPG004	YPG19C	dicot, gen & sp indet(type 1)	72	14	hollow, animal burrow?	dicot
YPG005	YPG19C	*Umbellularia sp*	81	20	15 cm I.D.,root?	laurel
YPG006	YPG19C	*Umbellularia sp*	68	17		laurel
YPG007	YPG19C	*Umbellularia sp*	60	15		laurel
YPG008	YPG19C	*Juglans sp*	50	14		walnut
YPG009	YPG19C	*Umbellularia sp*	39	14		laurel
YPG010	YPG19C	*Umbellularia sp*	56	15	10 cm I.D.,root?	laurel
YPG011	YPG19C	*Umbellularia sp*	41	12		laurel
YPG012	YPG19C	*Juglans sp* (Larson id)	15	18	fragment	walnut
YPG013	YPG19C	identification pending	47	16		
YPG014	YPG19C	identification pending	46	22		
YPG015	YPG19C	identification pending	33	11		
YPG016	YPG19C	*Umbellularia sp*	34	14		laurel
YPG017	YPG19C	identification pending	29	13		
YPG018	YPG19C	*Umbellularia sp*	22	16		laurel
YPG019	YPG19C	*Umbellularia sp*	33	11		laurel
YPG020	YPG19C	*Umbellularia sp*	37	10		laurel
YPG021	YPG19C	*Umbellularia sp*	fragment			laurel
YPG022	YPG19C	*Juglans sp*				walnut
YPG023	YPG19C	*Umbellularia sp*				laurel
YPG024	YPG19C	*Umbellularia sp* (Larson id)				laurel

Table 5.3 (concluded)

SAMPLE NUMBER	SAMPLE LOCALITY	TENTATIVE IDENTIFICATION	Length (cm)	Max. Diam (cm)	Comment	MODERN ANALOG
YPG027	YPG19C	identification pending				
YPG029	YPG19C	*Umbellularia sp*				laurel
YPG030	YPG19C	*Umbellularia sp*				laurel
YPG032	YPG19C	*Umbellularia sp*				laurel
YPG035	YPG19C	dicot, gen & sp indet				dicot
YPG039	YPG19C	*Umbellularia sp*				laurel
YPG040	YPG19C	*Juglans sp*	fragment			walnut
YPG19C	YPG19C	dicot, gen & sp indet(type 1)				dicot
YPG7B	YPG7B	monocot (palm)				
YPG9A	YPG9A	identification pending				
YPG18A	YPG18A	*Umbellularia sp*				laurel
YPG18B	YPG18B	monocot (palm)				
YPG20A	YPG20A	dicot, gen & sp indet(type 3)				dicot
YPG21B	YPG21B	*Umbellularia sp*				laurel
YPG21B2	YPG21B	monocot (palm)				
YPG22A	YPG22A	*Umbellularia sp*				laurel
YPG25B	YPG25B	*Umbellularia sp*				laurel
YPG26B	YPG26B	identification pending				
YPG27B	YPG27B	identification pending				
YPG31B	YPG31B	dicot, gen & sp indet(type 3)				dicot
no number	random	dicot, gen & sp indet(type 4)				dicot
no number	random	dicot, gen & sp indet(type 4)				dicot
no number	random	*Populus* (Davis id., 1995)				cottonwood
no number	random	conifer (Davis id., 1995)				conifer

quality of preservation of the petrified wood, and expressed the opinion that additional preparation and study of these specimens will certainly result in more precise identifications. Nine representative specimens from the Yuma Proving Ground material have been cut, polished and thin sectioned for additional detailed study under the microscope, which will probably result in more precise identifications in future studies.

Specimens of modern ironwood, mesquite, paloverde, juniper and pine have been collected, cut and sanded for comparison of their cell structures with that preserved in the Yuma Proving Ground petrified wood. With one exception, there is no indication that any of these common taxa in the present-day Yuma area or adjacent higher elevations are represented among the petrified wood specimens. The one exception is palm, which is indigenous to the Palm Canyon area of the Kofa Mountains 40 miles from the study area. And Axelrod (1950) recognized *Washingtonia* (fan palm) in the Miocene rocks of the Big Sandy basin, 135 miles northeast of Yuma Proving Ground.

Although there is a need for additional study to determine more precise taxonomic assignments, these preliminary identifications indicate that the Yuma Proving Ground collection includes laurel, cottonwood, walnut, palm, and conifer, and a variety of undifferentiated dicotyledenous angiosperms. Approximately 90% of the identified specimens were laurel; the tabulated results are shown in Table 5.3.

5.4.3 earlier identifications questioned

Two other identifications of petrified wood from the Yuma area, presumably in the Colorado River gravels, have been published but in our opinion, are unreliable. Lee and Zavada (1977), identified petrified wood from the Pliocene of the Yuma basin, as paloverde (*Cercidium* or *Parkinsonia*). However, this identification is likely to be in error, because the occurrence of this genus would be ecologically inconsistent with the taxa that we report herein and believe are more reliably identified. We are attempting to find their study materials for re-examination.

The petrified wood from the Yuma area that contains the fossil woodpecker nest, referred to earlier, was identified as "a species close to *Acacia* (Leguminosae)" by Von Horst Bucholz (1986). We also believe this identification to be probably in error because it would be ecologically inconsistent with the taxa that we recognize.

We believe that both of these identifications were unduly influenced by comparison with the plant taxa that currently grow in the area, and are adapted to very arid environments.

Plate 5.C.1 Collection of petrified wood from sewage lagoons, being prepared for cutting by Croxen at Arizona Western College.

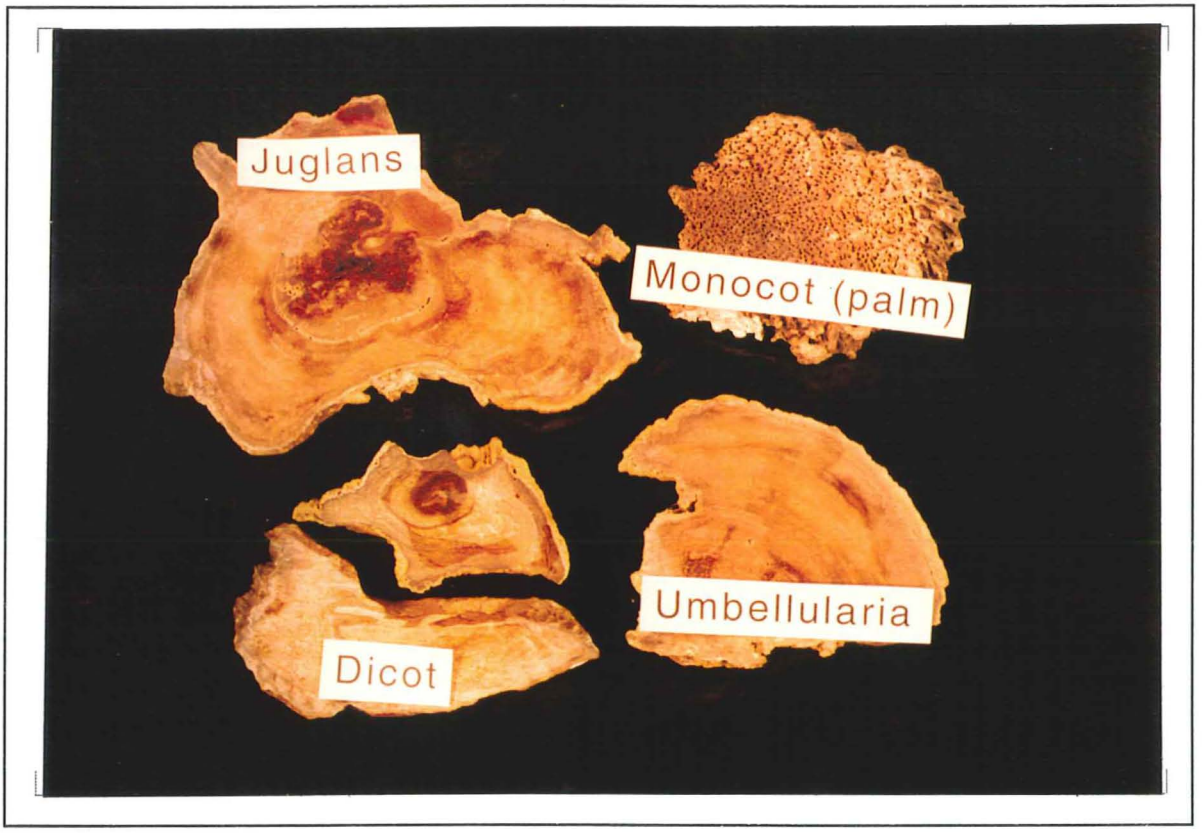


Plate 5.C.2 Cut specimens of YPG petrified wood, showing the cell structure that is visible on cut and polished surfaces that were prepared in the rock lab at Northern Arizona University.

5.4.4 petrified wood elsewhere in the Colorado River Gravels

The closest and most thoroughly documented occurrence of petrified wood outside of the immediate study area is found in the Diablo Member of the Palm Spring Formation in the Anza-Borrego Desert State Park, California .

The Diablo Member consists of massive crossbedded arenites, siltstones and mudstones that are dark brown, tan and maroon with fossiliferous gray limestone lenses. It is dated at 4.1-2.8 Ma and contains abundant petrified wood that is very similar in appearance, type of preservation, and taxonomic composition (Plate 4B; Tables 5.3 and 5.4). Investigations by Remeika, Fleming, and others (Remeika et al., 1988; Remeika and Fleming, 1995) have led to an interpretation of the Fish Creek-Vallecito Basin area as having been covered by a dominant California laurel forest with cottonwood and walnut interspersed along the deltaic/fluvial distributional sites (Remeika et al., 1988). Since that area of Colorado River delta-plain deposition was juxtaposed to the Pliocene Colorado River channel at Yuma Proving Ground as recently as 2.8 Ma (Winker and Kidwell, 1986), then the Yuma Proving Ground area would have been located in the same climatic zone.

The petrified palm of Yuma Proving Ground has not been identified to genus; but Remeika and Fleming (1995) recognized *Sabal* cf. *S. miocenica* Axelrod, and palm (genus and species indeterminate) from the Diablo Member.

Populus (cottonwood) has also been identified in the Diablo Member of the Pliocene Palm Springs Formation in California (Remeika and Fleming, 1995), which was previously identified by Davis (pers. com., 1995) in our Yuma Proving Ground collections.

For comparison purposes, the taxonomic list from the Diablo Formation (Carrizo Local Flora) includes eleven taxa that are assignable to seven families, based on tracheid cell structure are listed in Table 5.4 (Remeika and Fleming, 1995).

Petrified woods which are common to both the Pliocene Colorado River channel sediments at Yuma Proving Ground and the Pliocene Colorado River delta at Fish Creek-Vallecito Basin are: *Umbellularia* sp., *Juglans* sp., *Populus* sp., and palm.

FOSSIL SPECIES	ALLIED LIVING SPECIES
Arecaceae	
Genus and species indeterminate	monocot (palm)
Sabal cf. S. miocenica Axelrod	*S. urseana* (palm)
Cupressaceae	
Juniperus sp. indet.	*Juniperus sp.* (juniper)
Hippocastanaceae	
Aesculus sp.	*A. californica* (California buckeye)
Juglandaceae	
Juglans pseudomorpha Condit	*J. californica* (California walnut)
Lauraceae	
Persea coalingensis Axelrod	*P. podadenia* (avocado)
Umbellularia salicifolia Axelrod	*U. californica* (bay laurel)
Oleaceae	
Fraxinus caudata Dorf	*F. oregona* (Oregon ash)
Salicaceae	
Populus sp. indet.	*Populus sp.* (cottonwood)
cf. P. alexanderi Dorf	*P. trichocarpa* (black cottonwood)
Salix sp. indet.	*Salix sp.* (willow)
S. gooddingii Ball	*S. gooddingii* (Dudley willow)

Table 5.4 Carrizo Local Flora Taxonomic List (from Remeika & Fleming, 1995)

5.5 Age interpretations

Because the wood is locally derived and only occurs with the Colorado River gravels, the age of the wood is inferred from that of the host gravels, which has been bracketed between 3.8 to 5.47 Ma in the Lower Colorado River extensional trough from Lake Mead to Milpitas Wash in the Yuma area (Shafiqullah et al, 1980; Buising, 1988). The age can be further refined by correlation, based on similar taxa of petrified wood in Colorado River sediments, with the Pliocene Colorado River delta-plain deposit in the Diablo Member of the Palm Spring Formation, which has been dated at 4.1 to 2.8 Ma (Winker and Kidwell, 1986; Remeika and Fleming, 1995)

5.6 Paleoclimatic significance of petrified wood at Yuma Proving Ground

The taxonomic identification of the petrified wood in the Colorado River gravels on the Yuma Proving Ground as *Umbellularia* sp. (laurel), *Juglans* sp. (walnut), *Populus* sp. (cottonwood), and palm (genus and species indeterminate), allows an interpretation of the climate in the Yuma Proving Ground area during the Pliocene. This assemblage of plant taxa consists of the same taxa, at the generic level, as that described as the Carrizo Local Flora from the Colorado River delta-plain sediments in the Diablo Member of the Pliocene Palm Spring Formation, Fish Creek-Vallecito Basin, Anza-Borrego Desert State Park, California (Remeika and Fleming, 1995). Remeika et al. (1988) also identified cooler-weather taxa such as *Persea podadenia* (avocado), *Fraxinus oregona* (Oregon ash), and *Salix gooddingii* (Dudley willow) in the Carrizo Local Flora. Some of these taxa may be present, but as-yet unidentified, in the Yuma Proving Ground Pliocene flora. Since that area of Colorado River delta-plain deposition was juxtaposed to the Pliocene Colorado River channel at Yuma Proving Ground as recently as 2.8 Ma (Winker and Kidwell, 1986), then the Yuma Proving Ground area would have been located in the same climatic zone.

The paleoclimatic significance of the Carrizo Local Flora has been interpreted by Remeika et al. (1988) as "a temperate climate with ocean influence and predominantly winter rainfall in this region during the Lower Pliocene Epoch". Comparisons of the plant assemblage with living analogs suggests vegetation similar to a dominant California laurel forest with cottonwood and walnut interspersed along the deltaic/fluvial distributional sites (Remeika et al., 1988). The paleoclimatologic significance of this plant assemblage is that of a coastal environment similar to the present southern California coast.

For such a maritime climate to have existed in the area of deposition of the Colorado River gravels in the Yuma Proving Ground area during the Pliocene,

the California Coast Ranges must not have been present to create the rain shadow effect that creates the arid climatic conditions that exist in the Yuma area today. The area must have received greater rainfall, and experienced cooler temperatures than the present arid climate in the Yuma area. Winograd et al. (1985) suggested that uplift of the Sierra Nevada and Transverse Ranges during the Pleistocene blocked inland-bound Pacific storm systems that provided moisture to the southwestern United States during the Pliocene.

The average annual rainfall today in the Yuma area is approximately 2.8 inches. The greater amount of moisture in the mid-Pliocene could have provided the necessary 5 to 7 inches of additional rainfall that was needed to support the Yuma Proving Ground Pliocene local flora in the study area. These interpretations are supported by studies of stable isotopic compositions of pedogenic carbonate in the Pliocene-Pleistocene St. David Formation of southeastern Arizona by Smith (1994), and Smith et al. (1993), which indicated that southeastern Arizona and the southwestern United States were wetter and cooler between 3.2 and 2.8 Ma.

6 TECTONIC SIGNIFICANCE

6.1 Tectonic significance of Colorado River gravels at Yuma Proving Ground

Winker and Kidwell (1986) determined from south-trending paleocurrent measurements in the Colorado River delta-plain sediments of the Diablo Member of the Palm Spring Formation in the Fish Creek-Vallecito Basin that the delta was formed in the Gulf of California between ~4 and 2.8 million years ago (Figure 4.3). They calculate that the delta has moved 130 km to the northwest since 2.8 Ma, along component faults of the San Andreas system (Figure 3.1). This amount of movement is the distance from the Fish Creek-Vallecito Basin delta to the point where the Pliocene Colorado River channel at the Yuma Proving Ground near where it would have entered the Salton Trough and supplied its Colorado Plateau-derived sediment load to the delta (Figure 3.1).

The contact between the Bouse Formation and the Colorado River sediments at Yuma Proving Ground must coincide with the first occurrence of the Colorado River sediments in the Fish Creek-Vallecito Basin area at ~4 Ma, because Yuma Proving Ground was the location of the channel as it flowed toward the Pliocene Colorado River delta.

The discovery that the Pliocene Colorado River gravels at Yuma Proving Ground contains the same taxa of petrified wood (this report) as previously reported at in the Colorado River delta-plain at Fish Creek-Vallecito Basin (Remeika and Fleming, 1995), indicates that both sedimentary units were deposited in the same fluvial system.

This supports and confirms that the Colorado River delta at Fish Creek-Vallecito Basin was deposited at the southeastern margin of the Salton Trough, and since 2.8 Ma was tectonically translated 130 km to the northwest along the San Andreas fault system to its present location (Winker and Kidwell, 1986). Figuratively restoring the delta to its 2.8 Ma position, places it contiguous with the mouth of the Pliocene Colorado River about 30 km southwest of the Yuma Proving Ground, where the river would have crossed the present location of the Algodones fault, which defines the eastern tectonic margin of the Salton Trough (Winker and Kidwell, 1986).
The recognition of the Pliocene Colorado River channel (this paper), and its relation to the location of the Pliocene Colorado River delta in the Fish Creek-Vallecito Basin (Winker and Kidwell, 1986), obviates the need for a marine Imperial basin as large as was postulated by Smith (1970).

6.2 Possible causes for base-level change

As indicated by the large volume, coarse grain size and large scale of bedforms, the Pliocene Colorado River compared with that of the modern river, must have had a greater volume and velocity of water. This could have been accomplished in three ways: 1) by increasing the gradient by tectonic uplift of the upper end of the river; 2) lowering the base level to which the river was flowing, or 3) by increasing the volume of water to the system. There is evidence that all of these factors were at play during the Pliocene.

6.2.1 tectonic uplift

The evidence that tectonic uplift in the upper part of the Lower Colorado River extensional trough has been discussed mostly by Lucchitta (1979), and is based primarily on the interpretation of the Bouse Formation as marine-estuarine sediments that provide a Pliocene sea-level datum. (Smith, 1970; Buising, 1993). The evidence for this interpretation is based on deposits of stromatolitic limestone, barnacles, foraminifera, and echinoids as evidence of a marine depositional environment. Additional evidence for marine or estuarine environments was based on wave and tide-formed sedimentary structures in the Bouse Formation (Buising, 1993). Marine and/or estuarine environments extended to the Needles area and possibly to the Lake Mead area during the late Miocene (Lucchitta, 1979; Blair and others, 1979). Low areas extended to the Lake Mead area where the Hualapai Limestone Member of the Muddy Creek Formation was deposited in an estuary or saline lake near sea level (Blair and others, 1979; Lucchitta, 1979). The Bouse Formation presently occurs at elevations as high as 550 m above sea level about 100 km north of Parker, which implies that amount of regional uplift since it was deposited.

Spencer and Patchett (1997) proposed a different interpretation of the environment of deposition of the Bouse Formation, based on geochemical analysis of the carbonates and invertebrate shells in the Bouse Formation. the $^{87}Sr/^{86}Sr$ ratio from the marl and shells of the Bouse Formation is consistent with that observed in nonmarine water (specifically Colorado River water) and revealed no evidence of sea-water influence. It is interpreted as indicating a lacustrine depositional environment for the Bouse Formation that occurred in a series of isolated topographic basins within the Colorado River trough. These include the Muddy Creek basin in the Lake Mead area, and the Parker, Blythe and Cibola subbasins (Spencer and Patchett, 1997). The Bouse Formation was deposited in these basins before the Colorado River transected them to become a through-flowing drainage to the south in the Salton Trough. It typically grades upward from calcareous sediments at the base, through silts, sand and gravel, which reflects southward progradation of the Colorado River delta front (Spencer and Patchett, 1997). Even if this is correct, and the Bouse was deposited

above sea level in the Pliocene, some tectonic or base-level change must have occurred to initiate the through-flowing drainage of the Colorado River to the Yuma Proving Ground area (and its Fish Creek-Vallecito Basin delta), by ~4 Ma, and its continued degradation of the Colorado River gravels to the present 115 m below the Yuma Proving Ground terrace gravels.

Although the evidence of the cause is not definitive, and there is some question about the marine environment of the Bouse Formation, it is undeniable that broad-scale erosion of the Colorado Plateau is necessary to explain the record of coarse-grained, Colorado Plateau-derived sediments in the Yuma Proving Ground area, beginning ~4 million years ago. The uncertainty of evidence of tectonic uplift causing the deposition, and then degradation, of the Colorado River gravels, still needs to be resolved, possibly by an independent technique.

6.2.2 eustatic sea level change

Citing evidence from the literature, Betts (1997) suggests that the downcutting was caused by climate-induced eustatic changes. The growth and retreat of the Earth's glacial margins is largely responsible for shifting sea levels. The ice sheets of the Pliocene were relatively small compared to today's (Dowsett et al., 1994); therefore, sea level would have been higher. Haq et al. (1987) reported sea level stands as much as sixty meters higher in the Pliocene than today (Figure 6.1). Since the Colorado River gravel terrace at Yuma Proving Ground is about 115 m above the present River level, the sixty-meter drop in sea level from the Pliocene to today could account for some of the degradation of the Colorado River channel due to the greater eroding power of the increased gradient. The Pliocene Colorado River must have been very near base-level, since the Fish Creek-Vallecito Basin delta was only about 30 km to the southwest of Yuma Proving Ground at that time. The Colorado River, which terminates in the Gulf of California, has lengthened its course by a distance equal to the distance the shrinking sea has receded. Therefore the Colorado River would have prograded into an area that was previously dominated by marine deposition. This transition could explain the occurrence of Colorado River gravels overlying the marine-estuarine Bouse Formation, and seems to be best supported by the evidence.

6.2.3 paleoclimatic change

The fossil plant assemblage found in the Colorado River gravels at Yuma Proving Ground (discussed in Part 5) indicates that this area was wetter in the Pliocene than today (Dowsett et al., 1994). Wet or humid climates produce a higher degree of chemical weathering and runoff, which would have resulted in higher flow volumes and velocities that could account for the transport of the coarse bedload that was deposited at Yuma Proving Ground.

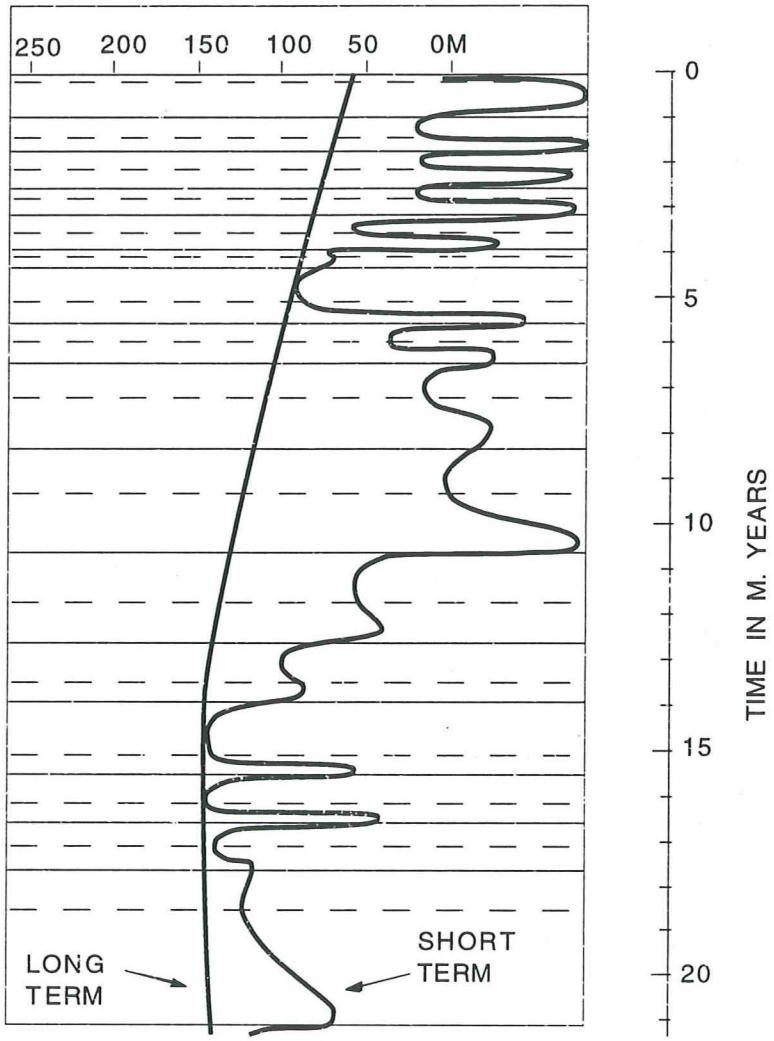


Figure 6.1 Eustatic sea level curve (from Haq et al., 1987).

7. SUMMARY

The southwestern portion of the U.S. Army Yuma Proving Ground lies on gravel and sand terrace deposits that contain abundant petrified wood. Field mapping and analysis indicate that the sand and gravel was deposited by the Colorado River and contains pebble, cobble and even boulder-size clasts that could only be transported by a river much more powerful than the modern river. The compositions of the clasts are identifiable as quartzite, dolomite, and chert fragments eroded from rock units that are only exposed on the Colorado Plateau, i.e. the Grand Canyon. The Colorado River gravels overlie the Bouse Formation, which was deposited in marine-estuarine environments in the Gulf of California embayment, possibly as far north as Lake Mead, before the Colorado River began flowing into the Gulf. The Colorado River gravels at Yuma Proving Ground, therefore are the first record of the Colorado River flowing into the Gulf of California. The age of the Colorado River gravels at Yuma Proving Ground has been determined to be between 5.5 and 3.8 million years, based on correlation with radiometrically dated underlying and overlying volcanic rocks in the Milpitas Wash and Lake Mead areas.

More precise age interpretation has been accomplished by identification of four genera of plant taxa in the petrified wood fossil assemblage at Yuma Proving Ground, and correlation with that of the Carrizo Local Flora in the Colorado River delta-plain deposits in the Diablo Member of the Pliocene Palm Spring Formation in the Fish Creek-Vallecito Basin, Anza-Borrego Desert State Park, California. The age of the Diablo Member has been determined to be between 3.8 and 2.6 million years, therefore the Colorado River gravels at Yuma Proving Ground, must have been deposited during that time interval.

It had been previously determined, based on composition of the sediments and sedimentary structures, that the sediments of the Diablo Member were deposited in the Colorado River delta-plain that was located at the head of the Gulf of California, and since 2.8 Ma has been moved along the San Andreas fault system, 130 km to its present position. The direct correlation of the Colorado River gravels at Yuma Proving Ground with the Colorado River delta-plain deposits in the Fish Creek-Vallecito Basin, based on the common occurrence of plant taxa represented by petrified wood in both areas, proves the juxtaposition of the two areas between 3.8 and 2.6 Ma. Furthermore, it defines the position of the Pliocene Colorado River channel at Yuma Proving Ground, and establishes it as a piercing point of the Algodones fault, about 30 km southwest of Yuma Proving Ground where the channel enters (by projection) the Salton Trough.

The modern Colorado River now flows in a different channel that is 10 km to the west and is 115 m lower than the Pliocene channel deposit at Yuma Proving Ground. The change in the course of the river since 2.8 Ma and its subsequent downcutting of the new channel was the result of increased gradient and eroding

power. This could have been the result of tectonic uplift of the headward portion of the river, or eustatic lowering of sea level. There is evidence that both of these events occurred.

Petrified wood and its associated gravels on Yuma Proving Ground are pivotal to a fuller explanation of the geologic history of the Colorado River and the Southwest and must be preserved for further study.

8. RECOMMENDED MANAGEMENT PLAN

Petrified wood that occurs on the United States Army Yuma Proving Ground is of great significance to the scientist but also holds exceptional appeal for the collector. These two aspects of its nature are inherently in conflict. While the casual collector may feel that "just one piece" won't be missed, the undisturbed field relationships of in situ petrified wood provide the only completely reliable evidence for geologists and paleobotanists. As described in this report, distribution of the wood, its areas of varying concentration, and its precise relationships to its surroundings provide insights into not only origin of the wood itself but for reconstructing the geologic history of the entire southwestern United States and northern Mexico.

In the course of their investigations, it became clear to project staff that virtually everyone on Yuma Proving Ground was aware of the petrified wood and that no one considered collecting it to be in any way improper. On the contrary, as soon as our interest in the wood became known people were eager to share their observations *and their collections* with us. Simply making it known to honest and well-intentioned people that removing or disturbing petrified wood is having a detrimental effect will deter most from continuing to do so. Others, including tourists and passers-by may only be constrained by implementation of a formal policy, but in the interim considerable damage might be averted by *requesting* compliance with an as-yet-to-be-announced policy.

As well as small-scale removal by casual collectors, large-scale removal of petrified wood has occurred for commercial purposes (Plate 9.A). Additionally, by their very nature certain types of military operations are conducive to disruption of the terrain on which they are conducted. Thus it becomes apparent that a management plan reconciling the various potential uses of the Yuma Proving Ground and its petrified wood should be designed and implemented.

8.1 Legal basis and precedents

Army Regulation 200-4 of 22 January 1998 (Table 8.1) applies specifically to Army installations and activities. Under its provisions the collection, removal or disturbance of scientifically significant fossilized remains (such as petrified wood) are prohibited without a permit issued by the USACE District Real Estate Office on approval of the installation commander. Violation of this regulation subjects the violator to civil or criminal penalties, including forfeiture of vehicles and equipment used in connection with the violation.

Headquarters
Army Regulation 200-4
Department of the Army
Washington, D.C.
22 JANUARY 1998

Cultural Resources Management. (This regulation supersedes AR 420-40 Historic Preservation, 15 May 1984.)

History. This publication is a revision of AR 420-40, originally printed 15 May 1984.

Summary. This regulation has been revised to update the Army's policy for managing cultural resources to meet legal compliance requirements and to support the military mission. Cultural resources are: historic properties as defined in the National Historic Preservation Act (NHPA) , cultural items as defined in the Native American Graves Protection and Repatriation Act (NAGPRA), archeological resources as defined in the Archeological Resources Protection Act (ARPA), sacred sites as defined in Executive Order (EO) 13007 to which access is provided under the American Indian Religious Freedom Act (AIRFA), and collections as defined in 36 CFR 79 Curation of Federally-Owned and administered Collections. Requirements set forth in NEPA, NHPA, ARPA, NAGPRA, AIRFA, 36 CFR 79, EO 13007, and Presidential Memorandum on Government to Government Relations with Native American Tribal Governments define the basis of the Army's compliance responsibilities for management of cultural resources. Regulations applicable to the Army's management of cultural resources include those promulgated by the Advisory Council on Historic Preservation (ACHP) and the National Park Service (NPS).

Applicability.
a. This regulation applies to the Active Army, the Army National Guard (ARNG), the US Army Reserve and to all installations and activities under control of the Department of the Army by ownership. lease, license, public land withdrawal, or any similar instrument. Specifically it applies to:
(1) Army installations and activities;
(2) Army National guard federal installations, activities and sites supported with federally appropriated funds or subject to federal approval;
(3) Installations and activities, or portions thereof, that are in full-time or intermittent use by the US Army Reserve or Reserve Officers Training Corps;
(4) Real property of other Federal, State, and local agencies and private parties used by the Army, Army Reserve, or Reserve Officers Training Corps under license, permit, lease, or other land and/or facility use agreement.

2-6. Antiquities Act of 1906 / Archeological Protection Act of 1979 (ARPA) / Archeological and Historic Preservation Act of 1974 (AHPA)
a. The Antiquities Act of 1906 and ARPA prohibit the excavation, collection, removal, and disturbance of archeological resources (as defined by ARPA) and objects of antiquity (as referenced in the Antiquities Act) on federally-owned Army property without a permit issued by the USACE District Real Estate Office on the approval of the installation commander. Violation of ARPA may result in the assessment of civil or criminal penalties and forfeiture of vehicles and equipment that were used in connection with the violation.
b. Paleontological Resources. Paleontological Resources are scientifically significant fossilized remains, specimens, deposits and other such data from prehistoric, non-human life. The AHPA specifically provides for the survey and recovery of scientifically significant data which may be irreparably lost as a result of any alteration of the terrain from any federal construction projects, or federally licensed project, activity, or program. Any installation paleontological resource management requirements will be integrated into ICRMPs and will establish and include installation policy for limitation of collection and removal of paleontological resources. Known paleontological resources will also be addressed in any NEPA documentation prepared for actions that may impact or cause irreparable loss or destruction of such resources.
(1) When an institution finds, or is notified in writing by an appropriate authority that its activities may cause irreparable loss or destruction of scientifically significant paleontological resources, the installation commander will notify the Secretary of the Interior in writing and will provide information concerning the activity IAW AHPA. Such notification may be incorporated as part of the NEPA public review and comment process for the subject activity.
(2) Upon notification by the installation that scientific data may be irrevocably lost or destroyed by a proposed field activity, the Secretary of the Interior shall, if he determines that such data are significant and after reasonable notice to the installation responsible for the activity, conduct or cause to be conducted a survey and other investigation of the affected area and recover and preserve such data. AHPA provides installation commanders the authority to assist the Secretary of the Interior with funds for surveys or other activities to recover significant scientific data, but such financial assistance is not required. Likewise, installation commanders may choose to undertake such professional survey and recovery activities themselves with funds appropriated to the project, program, or activity. Such project requirements shall be programmed in the Environmental Program Requirements report.

Table 8.1 Army Regulation 200-4

Plate 9.A.1 Gift and rock shop near Petrified Forest National Park which offers YPG petrified wood for sale.

Plate 9.A.2 Petrified wood from YPG that is offered for sale as "Arizona petrified ironwood" at the gift and rock shop near the Petrified Forest National Park.

Investigations leading to this report have made it clear that petrified wood as well as the undisturbed Colorado River gravels and desert surfaces associated with it, contain "scientifically significant data." Thus it is apparent that the legal basis for preservation of Yuma Proving Ground's petrified wood is already in place.

Nevertheless, the investigators feel that coordination of Yuma Proving Ground's policy with policies affecting surrounding lands and the people frequenting them will be of mutual benefit to Yuma Proving Ground and to neighboring land and resource managers—under the proposed management plan a single pamphlet summarizing regional guidelines would be appropriate, describing to area visitors localities where collecting is permitted as well as where it is not. Rockhounds and casual collectors alike would thereby be presented with alternatives instead of mere prohibitions. For that reason a brief outline of regulations pertaining to non-Yuma Proving Ground lands follows:

Arizona's rock, mineral, and fossil collectors must adhere to rules and regulations established by owners of the lands on which they wish to collect. Prior to collecting, rockhounds should determine ownership of the lands they intend to visit and familiarize themselves with the regulations that apply to collecting on those lands. Site-specific land-ownership maps may be consulted at the recorder's office in the county in which they intend to collect. Arizona's lands are managed by the federal government (Bureau of Land Management, U.S. Forest Service, or the Bureau of Indian Affairs), state government (School and Institutional Trust Lands Administration), and private owners (including local governments). Rockhounding permits are required to collect on some government lands, and permission is required to collect on private lands.

8.1.1 federal lands

About 72% of Arizona's lands are managed by the federal government. Most of this land is open to collecting except for National Parks, National Monuments, Indian Reservations, military reservations, dam sites, wildlife refuges, and wilderness areas.

Bureau of Land Management (BLM) Lands:

The casual collector may take small amounts of petrified wood, invertebrate and plant fossils, gemstones, and rocks from unrestricted federal lands without obtaining a special permit if collection is for personal, non-commercial purposes.

Collectors of petrified wood on BLM land are subject to slightly different rules. Collecting for personal use has a maximum limit of 25 pounds plus one piece per day but cannot exceed more than 250 pounds per calendar year. Use of explosives

and/or power equipment is forbidden. A group of collectors may not pool their limits to remove a single, large specimen.

Collection in large quantities or for commercial purposes requires a permit, lease, or license from the BLM.

Collecting on National Park Service or Native American lands is prohibited.

Rock, mineral, and fossil collecting on lands managed by the U.S. Forest Service requires a permit. Although collecting is allowed in most districts and permits are free, collecting rules vary among districts.

8.1.2 state lands

Arizona state law protects petrified wood as a 'paleontological feature' from random collection on state lands. Arizona Revised Statutes (41 A.R.S. 853) declares that petrified wood is the official fossil of the State of Arizona. The law states that "no person, except when acting as a duly authorized agent by the state, shall excavate in or upon any paleontological feature situated on lands owned or controlled by the state of Arizona, or any agency thereof." Any person found in violation of this article is considered guilty of a Class II misdemeanor, which carries a maximum jail sentence of four months, and shall forfeit to the Arizona State Museum all articles and materials discovered, collected, excavated or offered for sale or exchange, together with all photographs and records relating to such objects.

Most state-owned property is managed by the School and Institutional Trust Lands Administration (Trust Lands) and a Rockhounding Permit is required to collect mineral specimens on these lands. A fee is charged for the annual permit. Rockhounds may collect up to 25 pounds plus one piece per person per day, up to a maximum of 250 pounds per year. Collectors cannot operate in state and local parks.

To remove rock, mineral, or fossil specimens from state lands, commercial collectors must also follow specific regulations, and apply for mineral leases. Materials such as building stone, limestone, gemstones, and volcanic materials are commonly collected by amateur collectors with permits but require leases for commercial collectors. Permits and fee information are obtained from the State Land Department.

8.1.3 private lands

To access or collect on privately owned lands, collectors must contact and obtain permission from the owners prior to entering the property.

8.2 Recommendations

To preserve the unique occurrence of petrified wood on Yuma Proving Ground it is recommended that Yuma Proving Ground enact a base policy to protect it. Policy development should be initiated immediately but fully considered, developed, revised as needed, and implemented over time.

Phase I

Pending the consideration, development and implementation of a complete formal policy, Legacy Administrator (Gauna) or her designee(s) upon receipt of required authorization by "Yuma Proving Ground Administration" (in this text construed to include both Military Commanders and appropriate Civil counterparts) will:

- Issue an immediate appeal to Yuma Proving Ground employees, residents and visitors. The appeal will inform all concerned of existing state and federal policies that appear to prohibit collection of petrified wood. "Amnesty" will be declared and a no-retribution policy guaranteed for existing collectors and their holdings. Voluntary compliance is urged on the basis of rational arguments for such a policy rather than upon threat of possible penalties.
- Initiate information dissemination. Post signs (preferably ones that can be modified to reflect Phase II changes) along roads. Prepare news releases to inform newspapers, local schools and outdoor groups of the need to protect petrified wood on Yuma Proving Ground.

Phase II

Within the shortest possible time Yuma Proving Ground administration will:

- Officially designate petrified wood along with its associated desert pavement and Colorado River gravels as important natural resources.
- Direct that, to the extent possible, all base operations—particularly those involving vehicular traffic—will be conducted in areas least likely to further disturb petrified wood and Colorado River gravels (Figures 2.3, 2.4), pending further development of policy.
- Declare a moratorium, prohibiting the collection or disturbance of petrified wood along with its associated desert pavement and Colorado River gravels except by people acting under permit to do so.
- Continue Phase I voluntary appeals with addition of potential teeth. Announcements could parallel seat-belt campaigns which inform motorists of the benefits of seat-belts but add "...and it's the Law!"
- Expand information dissemination programs.
- Establish an Action Committee consisting of Yuma Proving Ground administrators and military leaders (and/or their designees), scientists, school personnel, and representatives of rockhound and outdoor groups.

Phase III

This Action Committee will:

- Refine the maps provided by this report to identify specific areas that can be designated as one of the following:
  a. undisturbed areas from which all trespass and disturbance is prohibited without express written permission.
  b. light to- moderately-disturbed areas that should will restricted access but might be sites for limited, controlled visitation by the public.
  c. disturbed areas and localities beyond the limits of the Colorado River gravels in which military operations and/or public access could be encouraged and concentrated.
- Establish a working relationship with the USACE District Real Estate Office to ensure compatibility of emerging policy with established procedures.
- Recommend a permitting process which recognizes that much petrified wood has already been taken, so as to seriously limit permitted takings, and grant permits solely for clearly-defined academic/scientific purposes.
- Determine the nature and extent of specimens already collected so that the majority of permit-seekers can obtain already-collected wood.
- Recommend penalties, such as forfeiture and fines, for the violation of this base policy.

As each component is developed and submitted, Yuma Proving Ground administration will either accept, promulgate and implement it or else refer it back for further study. As appropriate, the pro tem policies of Phase II will be modified or supplanted by permanent policy. All Base personnel will be kept aware of the developing policy and opportunities to participate in policy formation; security personnel will be trained in enforcement procedures.

Phase IV

The Action Committee and/or its sub-committees will continue to increase the effectiveness of preservation efforts through avenues which might include:

- Assemble accurate and informative information regarding the natural heritage, history and resources of Yuma Proving Ground.
- Further disseminate this information through no-cost avenues, such as articles submitted to publications of the State Geologist, Arizona Science Teachers Association, etc.
- Contact managers of Regional, State and National sites (such as Petrified Forest National Park) and other Military Installations regarding successful awareness and informational programs.
- Develop petrified wood, Colorado River gravels and paleobotany pages linked to the Yuma Proving Ground home page and also available to keyword searches.
- Explore avenues for funding expanded public relations and informational/educational projects based on natural resources of Yuma Proving Ground. (Potential funding opportunities include but would not be limited to Heritage or Eisenhower grants, NSF Informal Education programs, etc.)
- Develop partnerships with regional school districts, Indian tribes, land managers, and interest groups.
- Enhance the existing nature trail near the Main Post by pointing out features of the landscape and desert surface and stressing the importance of preserving these.
- Develop additional roadside exhibits and self-guided walks. Informative displays along the roadsides could describe the significance of the petrified wood and would lead to better understanding of the reasons underlying restrictions on land use. Exhibit sites might well include areas of historical interest, such as WW II cantonments, where historical perspectives would be combined with observation of the fragility and non-resilience of desert surfaces.
- Design and construct permanent indoor displays, and traveling outreach exhibits (slide and video presentations, guest speakers, etc.)
- Collect feedback from the various audiences and use it to enhance the effectiveness of dissemination efforts.

- Encourage further scientific efforts directed toward identifying wood taxa and their significance.
- Establish a procedure for evaluating the effectiveness of the Yuma Proving Ground petrified wood policy. Periodically review the effectiveness of the policy and submit results and recommendations to Yuma Proving Ground Administration.

Based on their own observations as well as reports from the Action Committee, Yuma Proving Ground Administration will periodically review the petrified wood policy and the results of its implementation.

This plan or a similar one will help to preserve and protect the unique petrified wood resources of Yuma Proving Ground for the enjoyment and education of future generations.

9. REFERENCES

Abbott, P.L., 1997, Miocene and Pliocene sedimentation history, Split Mountain, Anza-Borrego Desert State Park, California, p. II-1-II-19, *in* Deen, P., C. Metzler and A. Trujillo (editors), 1997, Geology and Paleontology of the Anza-Borrego Region, California: Field Trip Guidebook for the National Association of Geoscience Teachers, Far Western Section 1997 Spring Field Conference.

Arnold, C A., 1941, The petrification of wood: The Mineralogist, v. 9, p. 323-353.

Axelrod, D.I., 1950, The evolution of desert vegetation in western North America; Carnegie Institute of Washington Publication 590, p. 215-306.

Bailey, I.W., and E.S. Barghoom, 1942, Identification and physical condition of the stakes and wattles from the fishweir: In Johnson, F. (editor), Papers of the Robert S. Peabody Foundation for Archaeology, v. 2, p. 2-89

Barghoorn, E.S., 1949, Paleobotanical studies of the fishweir and associated deposits: In Johnson, F. (ed.), Papers of the Robert S. Peabody Foundation for Archaeology, v. 4, p. 49-83.

Barghoorn, E.S., 1960, Petrifaction: In McGraw-Hill Encyclopedia of Science and Technology, v. 10, p. 42.

Barnett, F., 1972, Soils Map of The U.S. Army Yuma Proving Ground: out of print, source unknown.

Betts, W.R., 1997, Stratigraphic, Sedimentological, and Paleobotanical Investigations of Terrace Gravels, U.S. Army Proving Ground: Master's thesis, Northern Arizona University, Flagstaff, 84 p.

Blair, W. N., 1978, Gulf of California in Lake Mead area of Arizona and Nevada during late Miocene time: American Association of Petroleum Geologists Bulletin, v. 62, no. 7, p. 1159-1170.

Blair, W.N., J.P. Bradbury, and R.L. Oscarson, 1979, Upper Miocene Hualapai limestone member from the proto-Gulf of California at Lake Mead, Arizona, p. 285-292: *in* Newman, G.W. and H.D. Goode, editors, Basin and Range Symposium and Great Basin Field Conference: Rocky Mountain Association of Geologists.

Browning, B.L., 1963, The composition and chemical reactions of wood: In Browning, B.L. (editor), Chemistry of Wood, Wiley, p. 57-101.

Buising, A. V., 1988, Depositional and tectonic evolution of the northern proto-Gulf of California and lower Colorado River: Ph.D dissertation, University of California, Santa Barbara, 196 p.

Buising, A. V., 1990, The Bouse Formation and bracketing units: Journal of Geophysical Research, v. 95, no. B12, p. 20,111-20,132.

Carson, G., 1991, Silicification of Fossils: Taphonomy: Plenum Press, New York, 560 p.

Davis, O. K., 1995, Personal Communication, University of Arizona, Department of Geology, Tucson, Arizona.

Deen, P., C. Metzler and A. Trujillo (editors), 1997, Geology and Paleontology of the Anza-Borrego Region, California: Field Trip Guidebook for the National Association of Geoscience Teachers, Far Western Section 1997 Spring Field Conference,

Demko, T. M., 1995, Personal Communication, University of Arizona, Department of Geology, Tucson, Arizona.

Dowsett, H., R. Thompson, J. Barron, T. Cronin, F. Fleming, , S. Ishman, , R. Poore, D. Willard, , & T. Holtz, Jr., 1994, Joint investigations of the middle Pliocene Climate I:PRISM paleoenvironmental reconstructions: Global and Planetary Change, v.9, p. 169-195.

Earth Resources Stewardship at the Department of Defense Installations, 32 CFR 229.

Gastil, R.G., D.L. Kimbrough and P.L. Abbott, 1996, Arrival of the Colorado River in the Salton Trough defined by magnetic susceptibility: South Coast Geological Society Guidebook 24, p. 203-208.

Haq, B.H., J. Hardenbol, & P.R. Vail, 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156- 1167.

Harlow, W.M., 1970, Inside Wood: American Forestry Association, Washington, DC , p. 120.

Kaarik, A.A., 1974, Decomposition of Wood: *in* Dickinson, C.H. and G. Pugh (editors), Biology of Plant Litter Decomposition, v.l: Academic Press, New York, pp. 129-174.

Knauth, P. L., 1995, Personal Comrnunication, Arizona State University, Department of Geology, Tempe, Arizona.

Lee, M.R. and M. Zavada, 1977, Report of a late Tertiary petrified wood from Yuma County, Arizona: Arizona-Nevada Academy of Science, v. 12, p. 21-22.

Lombard, J. P., 1993, Tertiary stratigraphy of the Laguna Mountains, Yuma County, Arizona: *in* Sherrod, D. R. and J.E. Nielson, editors, Tertiary Stratigraphy of Highly Extended Terranes, California, Arizona, and Nevada: U. S. Geological Survey Bulletin 2053, p. 203-215.

Lucchitta, I., 1979, Late Cenozoic uplift of the southwestern Colorado Plateau and adjacent Lower Colorado River Region: Tectonophysics, v. 61, p. 63-95.

Lucchitta, I., 1989, History of the Grand Canyon and of the Colorado River in Arizona, p. 701-715: *in* Jenney, J.P., and Reynolds, S.J., editors, 1989, Geologic Evolution of Arizona: Arizona Geological Society Digest 17 .

Merriam, R. and O.L. Bandy, 1965, Source of upper Cenozoic sediments in Colorado River delta region; Journal of Sedimentary Petrology, v. 35, no. 4, p. 911-916.

Metzger, D.G., 1968, The Bouse Formation (Pliocene) of the Parker-Blythe-Cibola Area, Arizona and California: United States Geological Survey Professional Paper 600-D, p.D126-D136.

Metzger, D.G., O.J. Loeltz, and B. Irelan, 1973, Geohydrology of the Parker-Blythe-Cibola area, Arizona and California: U.S. Geological Survey Professional Paper 486-G, 130 p.

Miall, A.D., 1984, Principles of Sedimentary Basin Analysis: Springer-Verlag, New York, 490 p.

Olmsted, F.H., 1972, Geology of the Laguna Dam 7.5 minute quadrangle, Arizona and California: U.S. Geologoical Survey Quadrangle Map GQ-1014, scale 1:24,000.

Olmsted, F.H., O.J. Loeltz, & B. Irelan, 1973, Geohydrology of the Yuma Area, Arizona and California: U. S. Geological Survey Professional Paper 486-H, 227 p.

Panshin, A.J. and C. de Zeeuw, 1980, Textbook of Wood Technology, 4th edition; McGraw-Hill Book Company, 722 p.

Reading, H.G., 1986, Sedimentary Environments and Facies: Blackwell Scientific Publications, London, 615 p.

Remeika, P. and R.F. Fleming, 1995, Cretaceous palynoflora and Neogene angiosperm woods from Anza-Borrego Desert State Park, California: Implications for Pliocene climate of the Colorado Plateau and age of the Grand Canyon: *in* Remeika, P. and A. Sturz (editors), 1995, Paleontology and Geology of the Western Salton Trough Detachment, Anza-Borrego Desert State Park, California; Field Trip Guidebook and Volume for the 1995 San Diego Association of Geologist's Field Trip to the Anza-Borrego Desert State Park, Volume 1, 88 p.

Remeika, P., I.W. Fischbein, & S.A. Fischbein, 1988, Lower Pliocene petrified wood from the Palm Spring Formation, Anza Borrego Desert State Park, California: Review of Paleobotany and Palynology, v. 56, p. 183-198.

Remeika, Paul and Anne Sturz (editors), 1995, Paleontology and Geology of the Western Salton Trough Detachment, Anza-Borrego Desert State Park, California; Field Trip Guidebook and Volume for the 1995 San Diego Association of Geologists Field Trip to the Anza-Borrego Desert State Park, Volume 1, 88 p.

Rolfe, W., and D. Brett, 1969, Fossilization processes, p. 213-244: *in* Eglinton, G., and M. Murphy (editors), Organic Geochemistry: Methods and Results; Springer-Verlag, New York.

Schopf, J.M., 1971, Notes on plant tissue preservation and mineralization in a Permian deposit of peat from Antarctica: American Journal of Science., v. 271, p. 522-543.

Shafiqullah, M., P.E. Damon, D.J. Lynch, S.J. Reynolds, W.A. Rehrig, , & R.H. Raymond, 1980, K-Ar geochronology and geologic history of south-western Arizona and adjacent areas, p.201-260: *in* Jenney, J.P. and C. Stone, editors, Arizona Geological Society Digest, v.12, 322 p.

Shaw, C. A., 1981, The Middle Pleistocene El Golfo local fauna from northwestern Sonora, Mexico: Master's thesis, California State University, Long Beach, 141p.

Sherrod, D. R. and R. M. Tosdal, 1991, Geologic setting and Tertiary structural evolution of southwestern Arizona and southeastern California: Journal of Geophysical Research, v. 96, no. B7, p. 12,407-12,423.

Sigleo, A., 1978, Organic Geochemistry of silicified wood, Petrified Forest National Park, Arizona: Geochimica et Cosmochimica Acta, vol. 42, p. 1397-1405.

Smith, G. A., 1994, Climatic influences on continental deposition during late-stage filling of an extensional basin, southeastern Arizona: Geological Society of America Bulletin, v. 81, p. 1411-1420.

Smith, G. A., Y. Wang, T.E. Cerling, & J.W. Geissman, 1993, Comparison of a paleosol-carbonate isotope record to other records of Pliocene - early Pleistocene climate in the western United States: Geology, v. 21, p. 691-694.

Smith, P., 1970, New Evidence for a Pliocene marine embayment along the Lower Colorado River Area, California and Arizona: Geological Society of America Bulletin, V. 81, no. 4, pp. 1411-1420.

Spencer, J.E. and P.J. Patchett, 1997, Sr isotope evidence for a lacustrine origin for the upper Miocene to Pliocene Bouse Formation, Lower Colorado River trough, and implications for timing of Colorado Plateau uplift: Geological Society of America Bulletin, v. 109, no. 6, p. 767-778.

Spencer, J., & S. Reynolds, 1991, Tectonics of Mid-Tertiary extension along a transect through west-central Arizona: Tectonics, v.10, no. 6.

St. John, R., 1927, Replacement vs. impregnation in petrified woods: Journal of Geology, v. 35, p. 729-739.

Von Horst Buchholz, 1986, Die Hohle eines Spechtvogels aus dem Eozan von Arizona, USA (Aves, Piciformes); Verhandlungen des Naturwissen-schaftlichen Vereins in Hamburg, p. 5-25.

Webb, R.H., T.S. Melis, T.W. Wise and J.G. Elliott, 1996, "THE GREAT CATARACT" Effects of Late Holocene Debris Flows on Lava Falls Rapid, Grand Canyon National Park and Hualapai Indian Reservation, Arizona: U.S. Geological Survey Open-File Report 96-460, 96 p.

Wernicke, B., 1992, Cenozoic extensional tectonics of the U.S. Cordillera, p. 553-581*in* Burchfiel, B. C., P. W. Lipman and M. L. Zoback, editors, The Cordilleran Orogen: Conterminous United States Geological Society of America, The Geology of North America, G-3, Boulder Colorado.

Winker, C.D. and S.M. Kidwell, 1986, Paleocurrent evidence for lateral displacement of the Pliocene Colorado River delta by the San Andreas fault system, southeastern California: Geology, v. 14, p. 788-791.

Winker, C.D. and S.M. Kidwell, 1996, Stratigraphy of a marine rift basin: Neogene of the western Salton Trough: Pacific Section SEPM Book 80, p. 295-336.

APPENDIX A

Data Point Locations and Summary of Observations

Table 2.1 Data Point Locations and Summary of Observations

Station	UTM E	UTM N	Wood Present?	Wood Abundance	CRG Present?	CRG %	Average CRG Clast (cm)	Matrix %	LDG %	Mean Imbrication Direction	Number of Points
1A	45235		yes	rare	yes	44	0.5 - 1	40	16		
2A	45760	45320		none				16	84		
3A	46100	46180		none				10	90		
4A	46761	44280		none				14	86		
5A	47880	44160		none				1	99	62°	6
6A	49914	46200		none				1	99		
7A	46329	42760		none	yes	1	2 - 5	13	86		
8A	46577	41330		none				20	80		
9A	45916	41090	yes	rare	yes	32	2 - 5	45	23		
10A	45890	39205	yes	rare	yes	37	0.5 - 1	43	20		
11A	47120	38420		none	yes	2		35	63		
12A	45842	48205		none*				7	93		
13A	45974	53315		none				1	99		
14A	45085	38005	yes	uncommon	yes	30	0.5 - 2	50	20		
15A	47300	37615	yes	uncommon	yes/ Deltaic	80	2 - 5	15	5		
16A	48500			none				1	99		
17A	49485	40715		none				1	99		
18A	45590	37580	yes	uncommon	yes	41	2 - 5	23	36		
19A	45564	34380	yes	uncommon	yes	45	2 - 5	30	25		
20A	44460	33490	yes	rare	yes	24	2 - 4	50	26		
21A	45520	31720		none				22	78	217°	14
22A	46300	33090		none				12	88	258°	18
22A2	46210	33000	yes	rare	yes	yes	2 - 4			235°	16
23A	48200	31700		none				11	89		
24A	52706	36510		none					yes		

Table 2.1 Data Point Locations and Summary of Observations (continued)

Station	UTM E	UTM N	Wood Present?	Wood Abundance	CRG Present?	CRG %	Average CRG Clast (cm)	Matrix %	LDG %	Mean Imbrication Direction	Number of Points
1B	44315	40290		none*	yes	19	0.25 - 3	76	5		
2B	44335	40695		none*	yes	27	0.25 - 1	69	4		
3B	43920	42100		none*	yes	47	2 - 5	27	26		
4B	44125	42890		none*	yes	44	2 - 6	33	23		
5B	43335	44300	yes	common	yes	19	2 - 6	60	21	185° (wood orient.)	9
6B	44490	44390	yes	common	yes	32	2 - 5	41	27	147° (wood orient.)	12
7B	41870	51000	yes	uncommon	yes	72	2 - 5	14	14		
8B	40552	51650		none	yes	3		1	99		
9B	38601	50790		none	yes	9		1	90		
10B	40889	48390		none	yes	15		20	65		
11B	41879	45905		none	yes	21		18	61		
12B	42127	44105		none	yes	24		16	60		
13B	42960	41310		none*	yes	36	2 - 5	27	37		
14B	43185	39340	yes	abundant	yes	50		15	35		
15B	41475	39775	yes	common	yes	38		26	36	216° (wood orient.)	13
16B	41560	41800	yes	uncommon	yes	28		10	62		
17B	42130	38645	yes	common*	yes	46		17	37		
18B	42781	37190	yes	abundant	yes	27		28	45	285° (wood orient.)	16
19B	41400	36790	yes	abundant	yes	24		27	49		
20B	40944	37750		none	yes	trace			yes		
21B	40350	37400	yes	abundant	yes	33		24	43		
22B	44459	36800		none*	yes	30	0.5 - 2	50	20		
23B	42875	35400	yes	abundant	yes	30	2 - 5	18	52		
24B	41052	34980		none	yes	<5			yes		
25B	43100	51800	yes	rare	yes	trace			yes		
26B	42200	42200	yes	rare					yes		
27B	42550	51370	yes	common*	yes	45	2 - 5	10	45		

Table 2.1 Data Point Locations and Summary of Observations (continued)

Station	UTM E	UTM N	Wood Present?	Wood Abundance	CRG Present?	CRG %	Average CRG Clast (cm)	Matrix %	LDG %	Mean Imbrication Direction	Number of Points
28B	42300	51610	yes	common*	yes	55	2 - 5	25	20		
29B	39810	48900		none					yes	78°	10
29B2	39810	48900		none	yes	yes	7			238°	6
30B	40550	50330	yes	rare	yes	yes	5 - 7			196°	16
30B2	40450	50330		none	yes	yes	7			198°	21
31B	40700	36220	yes	abundant	yes	45	2 - 4	10	45	206°	13
31B1	41050	36220	yes	abundant	yes	45	2 - 4	10	45	238°	22
31B2	41070	36220	yes	abundant	yes	45	2 - 3	10	45	233°	10
31B3	41130	36220	yes	abundant	yes	45	2 - 4	10	45	247°	22
32B	43148	38340	yes	rare*	yes	59	2 - 3	31	10		
33B	39747	52880		none						249°	21
34B	37185			none	trace					186°	15
1C	40510	51180			yes						
2C	40570	51410							100		
3C	39815	52650							100		
4C	39250	52000							100		
5C	38890	51680							100		
6C	38370	51350	yes		yes						
7C	37650	49990			yes						
8C	48370	37060							100		
9C	43290	39140	yes	common	yes						
10C	48845	30715							100		
11C	45230	30260							100		
12C	45030	31760							100		
13C	44305	31760							100		
14C	45640	33080	yes		yes				yes		
15C	46460	35950	yes		yes						
16C	47215	38390	yes		yes						
17C	47890	39750							100		
18C	41300	38500							100		

Table 2.1 Data Point Locations and Summary of Observations (concluded)

Station	UTM E	UTM N	Wood Present?	Wood Abundance	CRG Present?	CRG %	Average CRG Clast (cm)	Matrix %	LDG %	Mean Imbrication Direction	Number of Points
19C	40580	50410	yes	common	yes						
21C	39150	49870			yes						
22C	40890	47795			yes						
23C	47400	49390							100		
24C	44040	46870							100		
25C	46110	43590							100		
26C	45860	43485			yes						
27C	43180	45890			yes						

* Site was clearly disturbed.

APPENDIX B

Selected Well Logs on Yuma Proving Ground

GEOLOGIC LOG OF DRILL HOLE

Feature: Pilot Hole Project: YPG State: Arizona

Hole: MAA #1 Location: C-6-21 32 bdcd NAD 27 Conus UTM Coords. N: 3639288 m E: 739744 m

Begun: 1/26/95 Finished: 1/30/95 Ground Elev: 245 ft Drilled Depth: 300 ft

Stem Logged By: E.Kandl Log Depth Datum: Ground surface

Geophysical Logs: SP,SPtR,Gamma Depth to Water: 79.24 ft Water Surface Elev: 165.76 ft

Run By: E.Kandl Water Level Measured on: 2/15/95

Other Logs: Stem Log Reviewed by:

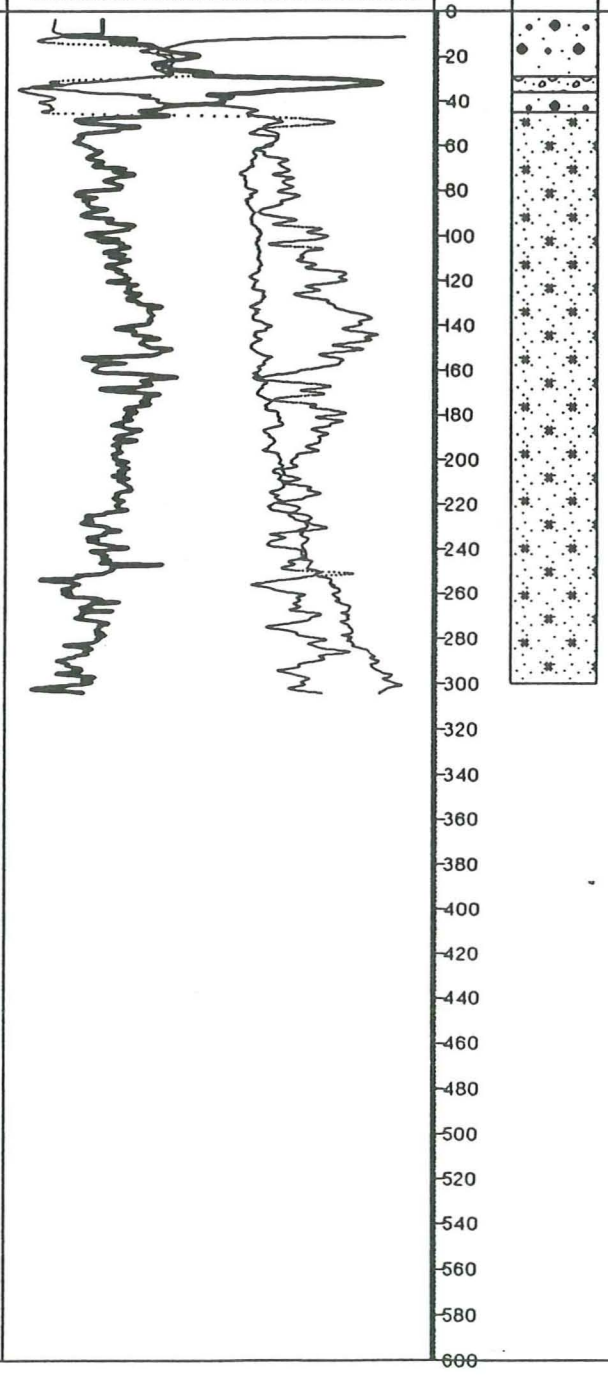
Notes on Drilling Method, Equipment, Hole Size, Mud Loss, Casing, Caving, Completion, Etc.

Driller:C.Craig
Helpers:R.Torres
J.Zohovetz

Method: Mud rotary using a 5 1/8" tricone bit to 250'. Switched to drag bit 250-260'. Switched to button bit 260-300'.

Completion: Backwash valve, 20' of 2" pvc screen, 280' of 2" pvc pipe.

Stickup of 6" surface casing is .6 above ground and 1.6' above land surface. 2" pvc casing is flush with top of surface casing even 1/4" higher.



Interpretation (based on all logs)

0-29' (SP) GRAVELLY SAND
Coarse sand with sub angular to sub rounded gravel up to 1"

29-36' (GP) SANDY GRAVEL
As above except less sand.

36-45' (SP) GRAVELLY SAND
Similar to material found above

45-300' (SP-SC) CEMENTED SAND/CLAYEY SAND
Coarse sand and fine gravel either cemented or with a clay matrix. Slow drilling. Relatively little clay in cuttings. Material is somewhat cohesive. Slow drilling. Zones of slightly more clay or cementation throughout.

GEOLOGIC LOG OF DRILL HOLE

Feature: Pilot Hole Project: YPG State: Arizona

Hole: MAA #2 Location: C-6-21 31 dacdl NAD 27 Conus UTM Coords. N: 3638868.9 m E: 738910.7 m

Begun: 2/2/95 Finished: 2/7/95 Ground Elev: 182 ft Drilled Depth: 300 ft

Stem Logged By: E. Kandl Log Depth Datum: Ground surface

Geophysical Logs: SP,SPtR,Gamma Depth to Water: 25.34 ft Water Surface Elev: 156.66 ft

Run By: E.Kandl Water Level Measured on: 2/15/95

Other Logs: Stem Log Reviewed by:

Notes on Drilling Method, Equipment, Hole Size, Mud Loss, Casing, Caving, Completion, Etc.

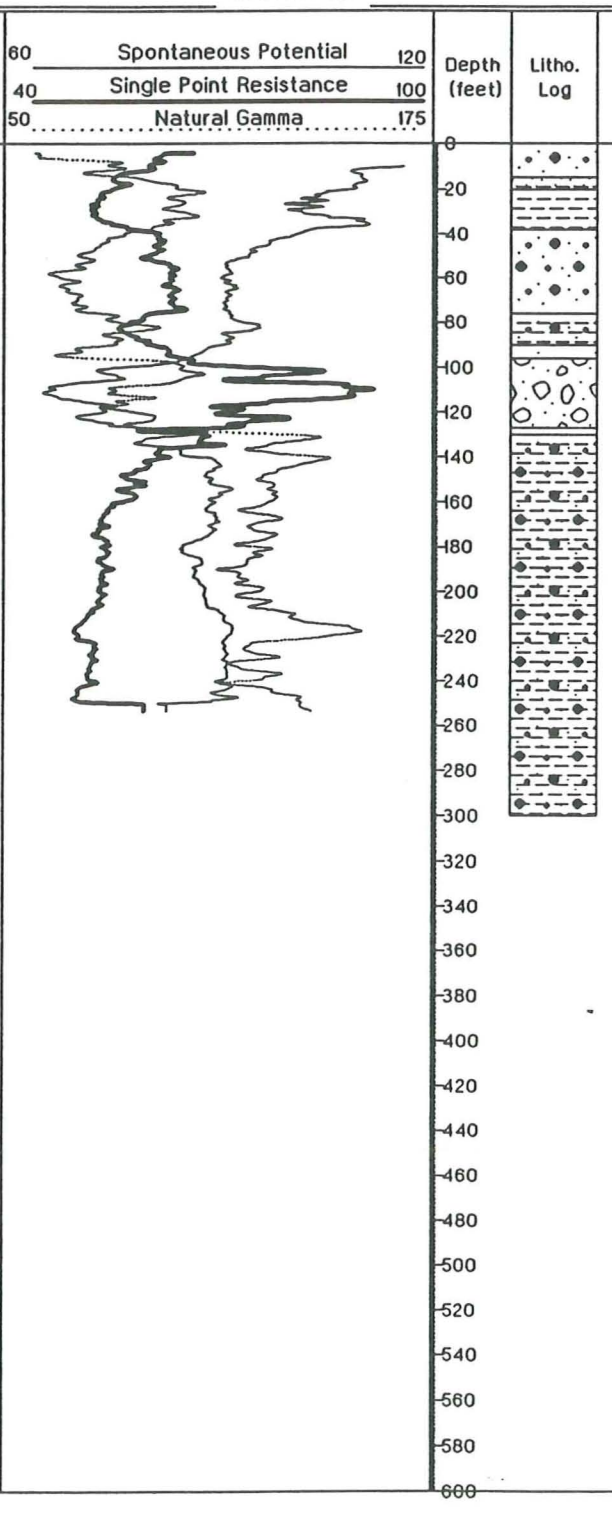
Driller: C.Craig, R.Torres
Helper:J.Zohovitz

Method: Mud rotary using a 5 5/8" tricone bit. Switched to drag bit 20-40' and 220-300'.

Hole caved at 250' preventing geophysical logging of last 50'.

Completion:Casing suspended to 130'. Backwash valve, 20' of 2" pvc screen, 110' of 2" pvc pipe.

Stickup of 6" surface casing is 1.4' above surrounding land surface. 2" pvc casing is 2" below top of 6" casing.



Interpretation (based on all logs)

1-15' (SP) GRAVELLY SAND
Coarse sand and gravel. Gravel is sub-angular to rounded, up to 1".

15-20' (SC) CLAYEY SAND
Very sticky clayey sand

20-38' (CH) CLAY
Fat clay. Tricone bit does not drill, only push through. Less fat around 30' but becomes fat again just below.

38-76' (SP) COARSE SAND-GRAVELLY SAND
Coarse sand with small gravel. Granular.

76-90' (SC) CLAYEY, GRAVELLY SAND
Similar to above material except with higher clay content. Sticky.

90-96' (SP) GRAVELLY SAND
Similar to material above without as much clay.

96-127' (GP) GRAVEL Angular to rounded gravel up to 1". Much ground up material. Few whole pebbles.

127-130' (CL) CLAY

130-300' (SC) CLAYEY, GRAVELLY, SILTY SAND
A mixture of materials slightly alternating in proportions with depth. Material is mainly a coarse sand and fine gravel with varying amounts of silt and clay.

GEOLOGIC LOG OF DRILL HOLE

Feature: YPG Water Supply Project: Dynamometer Course Well State: Arizona

Hole: WELL "G" Location: (C-6-20) 19acd NAD 27 Conus UTM Coords. N: 3641825.1 m E: 747602.4 m

Begun: 1958 Finished: December 8, 1958 Ground Elev: 450 ft Drilled Depth: 400 ft

Stem Logged By: Log Depth Datum: Land Surface

Geophysical Logs: Depth to Water: 292 ft ft Water Surface Elev: 158 ft ft

Run By: Water Level Measured on:

Other Logs: Reviewed by:

Notes on Drilling Method, Equipment, Hole Size, Mud Loss, Casing, Caving, Completion, Etc.	No Geophysical Log	Depth (feet)	Litho. Log	Interpretation (based on all logs)
		0		0 - 20 ft: Sand and Clay
		20		20 - 40 ft; Sand and Hard Clay
		40		40 - 60 ft; Sand, Clay, Gravel
		60		70 - 80 ft; Sand and Clay
		80		80 - 127 ft; Hard Clay
		100		
		120		
		140		127 - 166 ft; Sand and Clay
		160		
		180		166 - 195 ft; Sand
		200		195 - 259 ft; Quicksand
		220		
		240		
		260		259 - 269 ft; Sand
		280		269 - 285 ft; Clay
		300		285 - 302 ft; Quicksand, some Gravel
		320		302 - 311 ft; Sand, Pebbles
		340		311 - 326 ft; Sand, Clay, Pebbles
		360		326 - 335 ft; Quicksand, Pebbles
		380		335 - 353 ft; Sand, Pebbles
		400		353 - 363 ft; Quicksand, Pebbles
		420		363 - 400 ft; Sand, Pea Gravel
		440		
		460		
		480		
		500		
		520		
		540		
		560		
		580		
		600		

GEOLOGIC LOG OF DRILL HOLE

Feature: YPG Water Supply Project: Yuma Test Station State: Arizona

Hole: WELL "H" Location: (C-6-20) 21 bcaa NAD 27 Conus UTM Coords. N: 3642220.4 m E: 750224.1 m

Begun: March 25, 1959 Finished: April 20, 1959 Ground Elev: 500.39 ft Drilled Depth: 500 ft

Stem Logged By: Edward Rose - Geologist Log Depth Datum: Land Surface

Geophysical Logs: Depth to Water: 322 ft Water Surface Elev: 178 ft ft

Run By: Water Level Measured on:

Other Logs: Reviewed by:

Notes on Drilling Method, Equipment, Hole Size, Mud Loss, Casing, Caving, Completion, Etc.

DRILLER: Evans Bros., Lancaster, Calif.

WELL CONSTRUCTION: 27 ft. of 28" surface casing. 502 ft of 14" steel casing with the following configuration: 0-262' - blank casing; 262 - 478' of perforated casing with louver shaped apertures; and from 478- 502' - blank casing with bull-nose plug.

LOCATION: N 688,470.2 and E 323,453.9: Arizona Coordinate System West.

PUMP TEST DATA: Water Temp. = 104 F (40 C). Static water level at start of test pumping = 330'. After 1 1/2 hours at a rate of 500 GPM with a maximum drawdown of 16 feet measured.

DRAWDOWN DATA:

Flow (GPM)	Drawdown (ft)
170	5
230	7
325	10
450	13
500	16

RECOVERY: Recovered to 330' in 1 min. 15 sec.

No Geophysical Log

Depth (feet) / **Litho. Log**

Interpretation (based on all logs)

0 - 10 ft; Silty Gravel

10 - 28 ft; Sandy Gravel with some clay

28 - 148 ft; Fine Gravel and coarse Sand with clay streaks

148 - 190 ft; Sandy Clay and Gravel with streaks of firm clay

190 - 230 ft; Clay with lenses of gravelly sand

230 - 240 ft; Sand

240 - 264 ft; Clay with lenses of gravelly sand

264 - 279 ft; Sand

279 - 315 ft; Fine Gravelly Sand with streaks of firm clay

315 - 335 ft; Sandy Gravel

335 - 438 ft; Fine Gravel and Coarse Sand with lenses of clay

438 - 446 ft; Clay gray, soft with friable sand grains

446 - 502 ft; Gravelly Sand; coarse and well cemented

GEOLOGIC LOG OF DRILL HOLE

Feature: Pilot Hole Project: YPG Water Supply State: Arizona

Hole: WELL "S" Location: T.6 S. R.21 W. Sec. 23 baca (est.) NAD 27 Conus UTM Coords. N: 3643139.6 m E: 744511.1 m

Begun: 04/06/94 Finished: 04/12/94 Ground Elev: 561 ft Drilled Depth: 600 ft

Stem Logged By: E. Kandl Log Depth Datum: Ground Surface

Geophysical Logs: SP, SPtRes, N Gamma Depth to Water: 384.5 ft Water Surface Elev: 176.5 ft

Run By: E. Kandl Water Level Measured on:

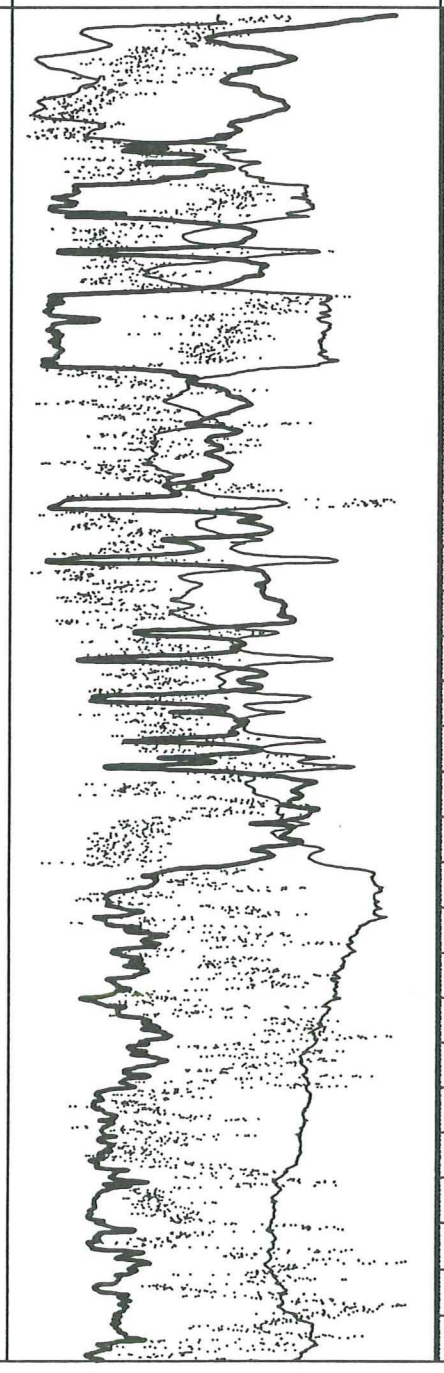
Other Logs: Reviewed by:

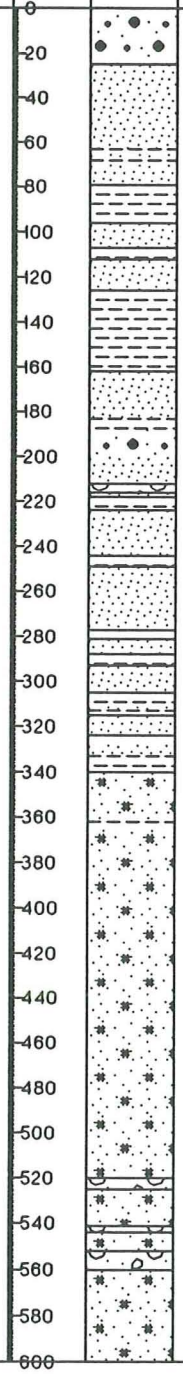
Notes on Drilling Method, Equipment, Hole Size, Mud Loss, Casing, Caving, Completion, Etc.

Driller: C. Craig
Helpers: R. Torres, J. Zohovetz

Method: Mud rotary using a 5.25" tricone bit to a depth of 490'. 5.25" drag bit was used from 490' to 600'.

Note: Hole is 3' south of first hole which was abandoned after 430' was drilled. The drill stem broke off approximately 50' down the hole and could not be retrieved.





Interpretation (based on all logs)

0-25' (SP) GRAVELLY SANDS
Medium to coarse sand with abundant small gravel. Sand is cemented places.

25-79' (SP) SAND
Medium to coarse sand. Fast drilling. Small clay layers between 60' and 70'.

79-96' (CL) CLAY
Tan to pink/brown clay. Slow drilling

96-107' (SP) SAND

107-112' (CL) CLAY

112-126' (SP) SAND

126-162' (CL) CLAY

162-212 (SP) SAND
Sand with a small clay zone at 183-188'. Sand may be gravelly around 190'. Heavy mud loss noted around 200'. Drill bit advanced appoximately 2 feet in 2 seconds at 198'.

212-216' (GP) GRAVEL
Difficult to determine characteristics of gravel due to poor recovery of cuttings.

218-224' (CL) CLAY

224-244' (SP) SAND

244-249' (CL) CLAY

249-277' (SP) SAND

277-281' (CL) CLAY

281-288' (SP) SAND

288-293' (CL) CLAY

293-305 (SP) SAND

305-315' (CL) CLAY
Interbedded clay and sand

315-324' (SP) SAND

324-340' (CL) CLAY Interbedded clay and sand

340-520' (SP) SAND
Cemented sand. Some portions containing clay. Sand is medium to coarse with abundant fine gravel.

340-520' (SP) SAND
Cemented sand. Some portions containing clay. Sand is medium to coarse with abundant fine gravel.

520-560' (SP-GP) SAND AND GRAVEL
Cemented sand with gravel layers. It is unknown if gravel layers are also cemented. Gravel layers defined by drilling characteristics and geophysics. Good cuttings were difficult to obtain.

560-600' (SP) SAND
Cemented gravelly sand

GEOLOGIC LOG OF DRILL HOLE

Feature: Pilot Hole Project: YPG Water Supply Well State: Arizona

Hole: WELL "U" Location: (C-7-21) 11 bdcb NAD 27 Conus UTM Coords. N: 3636253 m E: 744642 m

Begun: 10/18/93 Finished: 10/18/93 Ground Elev: 306 ft Drilled Depth: 300 ft

Stem Logged By: E.Kandl Log Depth Datum: Ground Surface

Geophysical Logs: SP, SptRes., N.Gamma Depth to Water: 161.21 ft Water Surface Elev: 144.8 ft

Run By: E.Kandl Water Level Measured on: 2/2/94

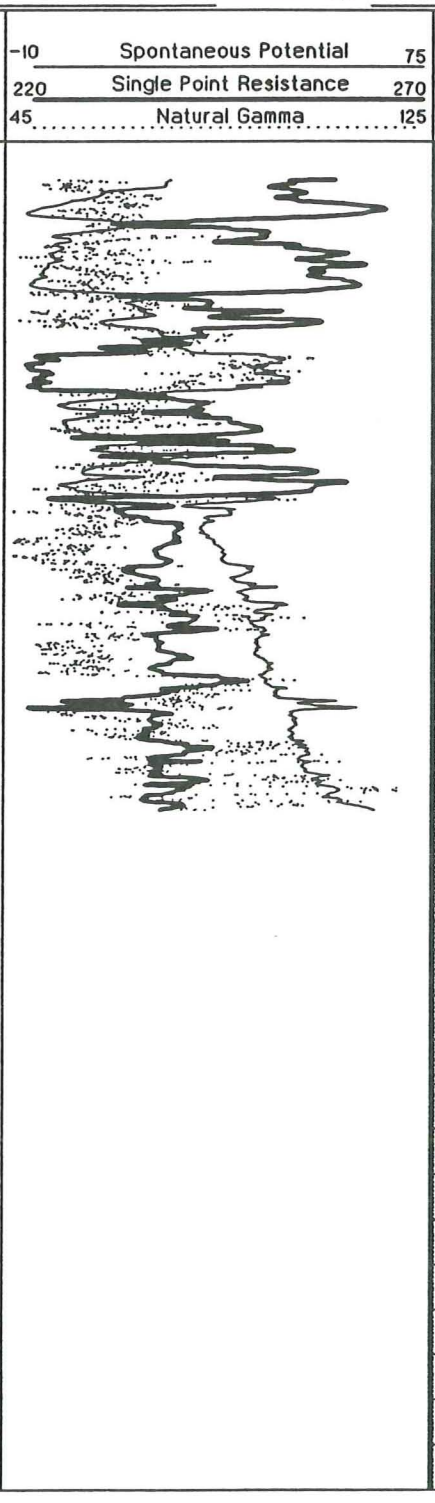
Other Logs: Reviewed by:

Notes on Drilling Method, Equipment, Hole Size, Mud Loss, Casing, Caving, Completion, Etc.

Method: Mud Rotary
Driller: C.Craig
Bit: 5.25" Tricone
Completion: From bottom to top; 6' of 12" stainless steel (ss) casing, 30' of 12" ss screen, 20' of 12" ss casing, 50' of ss screen, 200' of 12" mild steel casing.

Drilling Time Log

Interval	Minutes
20-40	6
40-60	8
60-80	9
80-100	14
100-120	15
140-160	11
160-180	10
180-200	7
200-220	13
220-240	11
240-260	12
260-280	14
260-300	16



Interpretation (based on all logs)

0-34' (SP) GRAVELLY SAND

34-39' (CL) CLAY

39-67' (SP) SAND

67-74' (CL) CLAY

74-84' (SP) SAND

84-94' (SC) CLAYEY SAND

94-111' (CL) CLAY

111-131' (SP) SAND
Mainly fine to medium sand with clay interbeds

131-142' (CL) CLAY
Clay with sand interbeds

142-216' (SP) SAND

216-220' (GP) GRAVEL

220-238' (SP) SAND
Sand becoming gravelly around 230'

238-244' (GP) GRAVEL

244-249' (SP) SAND

249-254' (CL) CLAY
Clay with sand interbed

254-267' (SP) SAND

267-300' (SP-GP) SAND AND GRAVEL
Interbedded sand and gravel

APPENDIX C

Chemical Analyses of Colorado River at Imperial Dam
and Ground Water - Yuma Proving Ground area

TABLE 5.1

COLORADO RIVER 1997

	CHEMICAL ANALYSES OF COLORADO RIVER AT IMPERIAL DAM																
Date Collected	Na	K	Ca	Mg	HCO_3	Cl	SO_4	NO_3	**SiO_2**	B	F	Ba	Sr	pH	TDS Evap.	TDS Sum.	EC mslemens/cm
1/6/97	148	4.4	88.6	29.8	196	142	316	1.3	**10.0**	0.19	0.40	0.110	1.250	8.26	942	837	1370
1/21/97	142	4.7	88.0	30.2	184	140	310	1.0	**9.8**	0.18	0.41	0.102	1.220	8.27	876	817	1280
2/3/97	115	5.2	80.2	29.3	170	105	277	1.3	**8.9**	0.14	0.54	0.111	1.150	8.25	728	706	1120
2/17/97	106	4.8	79.9	28.6	170	107	264	1.4	**9.2**	0.12	0.34	0.119	1.150	8.27	722	685	1110
3/3/97	108	5.2	80.5	28.3	167	111	260	1.4	**8.6**	0.14	0.33	0.112	1.150	8.34	764	686	1110
3/17/97	109	4.9	79.4	28.6	168	109	265	1.2	**8.1**	0.13	0.36	0.110	1.120	8.27	720	688	1130
4/7/97	114	3.1	72.1	24.2	170	103	261	1.5	**7.3**	0.13	0.35	0.103	1.050	8.26	724	670	1120
4/21/97	111	4.0	75.5	25.8	165	100	264	1.1	**7.4**	0.13	0.34	0.102	1.080	8.28	746	671	1110
5/5/97	113	5.1	76.1	24.2	170	103	262	1.3	**6.2**	0.13	0.33	0.133	1.090	8.32	710	675	1110
5/19/97	134	4.4	85.6	27.7	171	98	276	1.0	**8.0**	0.14	0.34	0.101	1.060	8.29	694	719	1110
6/2/97	119	4.6	80.9	24.9	173	107	275	1.2	**7.7**	0.13	0.39	0.109	1.120	8.29	756	706	1150
6/16/97	103	4.5	80.2	28.5	172	100	268	0.9	**8.7**	0.13	0.31	0.107	1.110	8.33	764	679	1130
7/7/97	114	4.5	76.5	29.4	173	96	267	0.8	**8.5**	0.13	0.36	0.103	1.070	8.31	720	683	1100
7/21/97	122	4.0	78.3	29.5	174	101	265	0.8	**8.8**	0.13	0.36	0.102	1.090	8.29	718	696	1110
8/4/97	115	5.1	75.2	28.1	163	95	257	0.8	**8.7**	0.12	0.42	0.104	1.060	8.23	702	666	1070
8/18/97	121	5.5	76.7	28.7	168	86	266	0.8	**8.7**	0.12	0.26	0.108	1.060	8.25	686	677	1060
9/2/97	135	4.1	78.8	30.6	171	104	283	1.6	**9.2**	0.14	0.41	0.107	1.100	8.20	728	731	1100
9/15/97	93	4.8	78.8	30.4	166	82	254	1.2	**9.6**	0.14	0.35	0.097	1.080	8.26	682	636	1030
10/6/97	136	5.0	87.6	30.5	187	111	299	0.6	**11.0**	0.16	0.43	0.113	1.190	8.32	782	774	1220
10/20/97	107	4.8	81.9	28.5	184	112	270	0.7	**9.8**	0.14	0.43	0.102	1.120	8.32	746	706	1200
11/3/97	128	4.3	81.0	28.5	181	104	271	0.9	**9.4**	0.14	0.31	0.104	1.100	8.28	746	717	1160
11/17/97	130	4.3	87.7	38.3	187	115	296	0.9	**10.6**	0.20	0.38	0.098	1.150	8.27	808	775	1200
12/1/97	121	4.3	87.5	37.9	182	102	278	0.9	**10.3**	0.30	0.41	0.102	1.210	8.29	756	732	1180
12/15/97	127	4.2	91.1	32.4	195	115	301	0.9	**10.5**	0.21	0.39	0.103	1.260	8.31	842	779	1270
AVERAGE	120	4.6	81.2	29.3	175	106	275	1.1	**9.0**	0.15	0.4	0.107	1.127	8.28	753	713	1148
Values in Parts per Million																	

TABLE 5.2

YPG Wells - Chemical Analyses

		CHEMICAL ANALYSES OF GROUND WATER - YPG AREA																				
	Location - UTM NAD-27																					
Well	Zone 11 in Meters		Date																	TDS	TDS	EC
Name	Easting	Northing	Collected	Na	K	Ca	Mg	CO_3	HCO_3	Cl	SO_4	NO_3	SiO_2	B	F	Fe	Ba	Sr	pH	Evap.	Sum.	mslemens/cm
Well B	742490	3639400	6/18/97	234	4.2	31.0	1.2		61	238	131	5.1	**37.5**	0.55	6.37	0.01	0.044	0.330	8.13	766	719	1320
Well H	750224	3642220	6/12/97	345	5.2	26.6	0.4	0.5	85	342	189	2.7	**41.1**	0.85	7.80	0.01	0.031	0.418	8.34	1020	1000	1790
Well I	749430	3638810	6/12/97	319	4.5	36.8	1.0		36	336	213	5.2	**40.9**	0.72	5.43	0.02	0.033	0.432	6.52	988	980	1690
Well J	750280	3642280	6/12/97	312	5.8	29.5	0.4		83	349	168	2.2	**38.9**	0.74	7.78	0.05	0.047	0.475	8.26	986	955	1740
Well K			6/17/97	376	4.8	210.0	9.6	0.6	15	533	532	12.5	**11.8**	0.61	1.98	0.02	0.055	2.580	8.47	1840	1700	2820
Well L			6/11/97	211	5.6	33.6	3.1		110	233	162	9.0	**33.7**	0.61	4.37	0.08	0.029	0.348	8.07	790	750	1350
Well M	755449	3652207	6/11/97	195	3.3	8.7	0.4	2.6	1.6	155	107	4.6	**50.7**	0.50	9.94	0.27		0.086	8.54	600	590	1010
Well R			6/10/97	387	2.0	12.3	0.3	10	29	234	464	4.0	**16.0**	1.73	6.52	0.62	0.017	0.181	9.20	1180	1150	1940
Well S	744650	3643150	6/19/97	225	4.1	20.4	0.7		104	250	136	4.5	**38.0**	0.55	7.37	0.09	0.040	0.235	8.23	788	738	1370
Well T	743975	3636750	6/18/97	243	4.3	23.7	0.1		97	261	135	4.1	**39.0**	0.56	7.56	0.01	0.040	0.254	8.00	806	767	1400
Well U	744642	3636253	2/1/94	267	3.9	25.1	0.7		98	282	143	3.9	**45.0**	0.58		0.07	0.066	0.254	8.17	812	820	1400
Well V	743274	3646089	6/17/97	234	2.9	16.6	0.9	7.6	61	212	148	0.8	**26.3**	0.55	6.16	0.30	0.020	0.293	8.60	708	686	1210
Well W			6/19/97	136	5.1	93.6	27.3		190	116	301	0.8	**18.7**	0.14	1.39	0.06	0.019	1.310	8.08	844	794	1270
Well X	738876	3638786	6/19/97	203	5.6	95.4	21.5		173	216	326	2.1	**24.0**	0.30	2.02		0.023	1.320	7.95	1060	981	1650
Well Y	738920	3638795	6/19/97	380	7.0	89.8	16.8		217	351	434	8.6	**30.3**	0.65	3.53		0.023	1.330	8.01	1520	1430	2410
Well Z			6/19/97	162	5.1	99.8	23.3		210	131	331	0.8	**29.6**	0.17	1.92	0.02	0.019	1.470	8.05	958	888	1440
AVERAGE				264	4.6	53.3	6.7		98	265	245	4.4	**32.6**	0.61	5.34	0.12	0.034	0.707	8.16	979	934	1613
Values in Parts per Million																						