STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS
OF A MARINE-NONMARINE PLIO-PLEISTOCENE SEQUENCE,
WESTERN SALTON TROUGH, CALIFORNIA

A Thesis
Presented to the
Faculty of
San Diego State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
in
Geology

by
Steven Michael Richardson
Fall 1984
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CHAPTER ONE

INTRODUCTION

Purpose of Study

The purpose of this study is to provide a detailed description and measurement of the marine-nonmarine Plio-Pleistocene sequence of strata in the upper Fish Creek Wash area of the Salton Trough. The detailed record includes a variety of stratigraphic, sedimentologic and paleontologic features which provides information to interpret the depositional environments and mechanisms. Based on these interpretations, depositional models depicting the paleogeography through time are presented.

Location and Accessibility

The Fish Creek Wash area is located in the Anza Borrego Desert State Park, California, along the western margin of the Salton Trough, west of the Fish Creek Mountains and south of the Vallecito Mountains. The Carrizo Badlands border the field area to the south and the Peninsular Ranges are approximately 20 miles to the west (Figure 1).

The field area is reached from San Diego by driving east on Interstate 8 to State Highway 79, following the signs to Julian. Turn west onto State Highway 78 in Julian, down Banner grade to Ocotillo Wells. Turn south onto Split Mountain Road and continue for 10 miles to an unimproved dirt road which turns right into Fish Creek Wash. Conditions are variable with summer thunderstorms causing flash floods.
Figure 1. Index map showing access to field area (lined box) via State Highway 78, Split Mountain Road and Fish Creek Wash.
through the normally dry wash. Four-wheel drive vehicles are recom-
mended, but a light truck is adequate.

Field Methods

Preliminary reconnaissance began in January 1984 with the study
of 1:12000 aerial photos courtesy of San Diego County Operations.
Field work began in February and continued through May 1984. An area
of approximately 15 square miles was mapped at a scale of 1:12000.
Base maps were compiled from parts of the Arroyo Tapiado and Harper
Canyon 7 1/2 minute quadrangle maps (Plate 1).

Excellent exposures facilitated the measurement of about 5,200
feet of continuous strata. This included 200 feet of the uppermost
Imperial Formation, 5,000 feet of the Palm Spring Formation and 350
feet of the Canebrake Conglomerate. An additional 4,500 feet of
laterally equivalent section was measured to illustrate lateral
variability of the vertical sequence of strata (Plate 2).

Stratigraphic sections were measured with a Brunton Compass and
Jacob Staff. Lithology of each unit was described and primary
sedimentary structures were noted with regard to their vertical po-
sition and horizontal continuity. Paleocurrent direction indicators
such as cross-bedding foreset azimuths, ripple crest orientations,
channel axes and parting lineations were recorded and corrected for
tectonic tilt where necessary according to Potter and Pettijohn
(1977). The Wentworth (1922) scale was used in the field for grain
size determination and colors were obtained from the Geological
Society of America Rock Color Chart (1980). Color of field
photographs are not true due to processing procedures.

Samples were collected for more detailed sedimentologic descriptions including petrographic analysis. A small collection of fossils was also collected for paleontologic identification.

Previous Work

Initial study of the region was made by Blake (1858) as a geologic reconnaissance project for the railroads. Blake reported the presence of fossils and the early studies of Gabb (1869), Arnold (1906), Mendenhall (1910), Kew (1914), and Hanna (1926) concentrated on the paleontology of the marine strata in the western Salton Trough.

The Cenozoic nomenclature of the western Salton Trough has long been the subject of debate and revision, beginning with Kew (1914), and continuing with Hanna (1926), Woodring (1932), Tarbet and Holman (1944), Tarbet (1951), Dibblee (1954), Durham and Allison (1961), Woodard (1963) and Woodard (1974). Detailed accounts of the history of the stratigraphic nomenclature of the region are provided by Pappajohn's (1980) study of the Neogene marine section at Split Mountain and Kerr's (1982) study of the Early Neogene nonmarine sedimentation of the western Salton Trough.

Previous paleontologic work and geophysical studies are discussed under the Age and Paleontology section of Chapter 2.

Structural Setting

The Salton Trough, considered to be the landward extension of the Gulf of California, is formed by rifting of Baja California from the Mexican mainland (Crowell and Sylvester, 1979). Rifting began about 4
to 5 million years ago during late Miocene to early Pliocene time (Larson, 1972; Sharp, 1982), however, presence of marine sediments near Yuma, Arizona suggests the encroachment of marine waters as early as 5.5 million years ago. This proto-Gulf of California probably formed in response to crustal thinning preceding the actual rifting of Baja California (Lucchitta, 1972).

A study by Johnson et al. (1983) revealed that the Fish Creek Wash area has undergone two distinct episodes of tectonism in the past 4 million years in response to rifting of the Gulf of California and movement along the San Andreas and related fault systems. An initial period of subsidence occurred from 4.0 million years ago to 0.9 million years ago corresponding to the rifting and development of the Gulf of California (Johnson et al., 1983). In the last 0.9 million years ago uplift has brought sediment buried 3 miles below sea level to 350 feet above sea level today and accounts for the dissected pediments observed in the area today.

In addition to uplift, the area has undergone 35 degrees of clockwise rotation in the past 0.9 million years (Johnson et al., 1983). No rotation of the area is recorded in the sediments prior to this since the time of deposition, approximately 4.0 million years ago. The clockwise rotation resulted from right-lateral displacement along related faults of the San Andreas fault system (Figure 2).

**Tectonic Implications**

Palinspastic restoration along right-lateral faults, suggests the field area has been displaced from the region of the modern Colorado
Figure 2. Structural setting of study area with related faults of the San Andreas fault system. After Johnson et al. (1983).
River delta to its present site. With this tectonic activity in mind, the interpretation of the rock record introduces an interesting variable to Walther's Law (Middleton, 1973). Rather than recording the lateral migration of depositional environments through time, the vertical sequence of strata has recorded the northward migration of the field area through delta, fluvial, and alluvial depositional environments. This unique situation is discussed more fully in Chapter 7.
CHAPTER TWO

STRATIGRAPHY

Nomenclature

The uppermost Imperial Formation, the Palm Spring Formation and its lateral and vertical equivalent, the Canebrake Conglomerate crop out in the field area.

The lowermost marine beds which were first defined by Kew (1914) as the Carrizo Creek Formation near Carrizo Mountain and later named the Imperial Formation by Hanna (1926), are composed of interbedded drab green sandstones and siltstones, with locally abundant marine macrofossil assemblages forming biostromal deposits.

The Palm Spring Formation was originally named by Woodring (1932) for the terrestrial beds that overlie the Imperial Formation on the north side of the Coyote Mountains. Dibblee (1954) reported the Palm Spring Formation to be about 4,800 feet thick at the type locality. Further to the north, at the Fish Creek Wash area, he reported a maximum thickness of 6,500 feet and that these rocks grade westerly into the Canebrake Conglomerate. Woodard (1974), however, re-defined the Palm Spring Formation in the Fish Creek Wash area to include more than 10,000 feet of interbedded sandstone, siltstone, mudstone, pebble conglomerate and fresh-water limestone.

The Canebrake Conglomerate, named after Canebrake Wash (Dibblee, 1954), is the coarse marginal conglomerate facies of the Palm Spring
and Imperial Formations. The type section reaches 7,000 feet in thickness at the southeastern base of the Vallecito Mountains four miles west of Fish Creek Wash (Dibblee, 1954).

For the purpose of this study, the formally named Imperial and Palm Spring Formations and Canebrake Conglomerate exposed in the field area have been informally divided into four mappable rock units (A, B, C and D), which are further subdivided into 11 distinctive lithofacies. The lithofacies are defined by grain size, color, bedding style, and sedimentary structures, which were readily identified in the field. The informal mappable units are defined by the presence or absence of distinguishing lithofacies. The correlation between the mappable units and formal rock unit names is shown in Figure 3. This informal classification best illustrates the cyclic and locally complex nature of the stratigraphy. Due to the recurrent nature of the deposits, the lithofacies are not restricted to any one rock unit and will be described as they occur in each unit.

It should be noted that recent terrace deposits are scattered throughout the field area at various elevations. They have been mapped (Plate 1), but will not be included in the following descriptions or discussions. The various levels of elevation reflect recent tectonism in the area.

**Descriptive Terminology**

As the sections were measured many characteristics of the strata were recorded to form as complete of a description as possible. These characteristics are divided into lithology and bedding. Lithology is
Figure 3. Correlation of stratigraphic nomenclature.
a well understood term and does not deserve any special definition. For this study, features of external bedding and internal bedding were used to describe the various lithofacies.

External bedding descriptions include thicknesses between bedding surfaces, shape of the beds, types of contacts with the overlying and underlying beds and the lateral and vertical distribution of the lithofacies within the rock units. Thickness terms will follow those of Reineck and Singh (1975).

Internal bedding will include primary sedimentary structures, with emphasis on vertical position within the beds. This will also include those structures found on the bedding plane surfaces such as, scouring, shrinkage cracks and ripple marks. Primary sedimentary structures will be classified according to Reineck and Singh (1975) or as otherwise noted, and cross-stratification will be described following Allen (1963). Sandstone and mudstone nomenclature follows that of Folk (1980).

Age and Paleontology

The age of the Imperial Formation has long been the subject of discussion. According to Quinn and Cronin (1984) soon after marine fossils were recorded by Blake (1858), Gabb (1869) studied molluscan fossils near Carrizo Creek and determined a Pliocene age. Arnold (1906) considered these rocks Miocene based on molluscan evidence and noted that the shallow water pectens were more like those in the modern Gulf of California than those found along the California coast. Kew (1914) studied echinoids in the Carrizo Creek area and gave them a
Miocene age. Vaughn (1917) considered the rocks Pliocene after his study of reef corals, which he compared with Neogene species from the Dominican Republic. Woodring (1932) described molluscs, echinoids, and foraminifera and assigned a Miocene age to the rocks.

More recent studies conducted by Stump and Stump (1972) and Ingle (1974) date the lower Imperial as middle Pliocene (planktonic foraminifera zones N20-N21). Terrestrial vertebrate fossils associated with marine fossils indicate the uppermost Imperial Formation to be late Pliocene in age.

Vertebrate fossils from the Palm Spring Formation have been studied by Downs (1957), Downs and Woodard (1961), Howard (1963) and Downs and White (1967). Over 90 vertebrate taxa of mammals, reptiles, amphibians and birds have been identified in the Fish Creek Wash area. Downs and White (1967) found three distinct faunas in the Vallecito-Fish Creek Wash area, the lowermost Layer Cake fauna, the middle Arroyo Seco fauna and the uppermost Vallecito Creek fauna which were later incorporated into a magnetic stratigraphy study.

Opdyke et al. (1977) sampled 150 sites in the Imperial and Palm Spring Formations. From these samples, the magnetic stratigraphy ranged from the Gilbert reversed epoch at the base to the Matayama reversed epoch at the top of the section. The ranges of 20 representative genera within the section were selected and used to define eight faunal events. The faunal events mark either the lowest or highest stratigraphic occurrence of a taxon correlated to the known paleomagnetic time scale (Figure 4). Based on magnetic stratigraphy data, the base of the lowermost Layer Cake fauna is marked by the
Figure 4. Magnetic stratigraphy and vertebrate fauna events. Modified from Johnson et al. (1983).
highest stratigraphic occurrence of the horse *Pliohippus* at about 3.8 million years ago near the Hemphillian-Blancan North American Mammal Age boundary (Lindsay et al., 1976).

The Arroyo Seco fauna lasted about 1.1 million years during Blancan time. Its base is marked by the lowest occurrence of the gopher *Geomys*, 3.3 million years ago and the top is marked by the lowest occurrence of the bear *Tremarctos* at 2.5 million years ago.

The Vallecito Creek fauna has a duration of either 0.8 million years or 1.5 million years depending on the interpretation of the normal magnetic event which occurs in the section. Four faunal datum events occur here which correspond to Late Blancan and Early Irvingtonian Land Mammal Ages (Lindsay et al., 1976).

The age of the Canebrake Conglomerate must be determined by its stratigraphic relationship. Within the field area, the Canebrake is laterally equivalent to the Imperial and Palm Spring Formations, forming a coarse-grained lateral facies between these formations and the basement rocks of the Vallecito Mountains. In addition, the Palm Spring Formation grades upward into the Canebrake Conglomerate. These stratigraphic relationships suggest that the age of the Canebrake Conglomerate ranges from Late Pliocene to Recent.
CHAPTER THREE

ROCK UNIT A

Lithologic Descriptions

Introduction

Rock Unit A, the lowest unit in the field area, forms a generally north-northwest trending section of multicolored mudstones, siltstones and minor sandstones of Lithofacies 1 through 5. Lithofacies 5 is a minor constituent of Rock Unit A and because its presence marks the transition between Units A and B, it will be discussed under Rock Unit B.

The base of Unit A was chosen as the first red- or pink-colored mudstone encountered going up section through the drab green-colored marine mudstones of the Imperial Formation between Fish Creek Wash and Loop Wash (measured section A-A', Plate 1). These marine mudstones persist above this contact and thus form a gradational marine-nonmarine transitional sequence. The upper contact with the overlying Unit B is gradational and defined when the thickly bedded sandstones of Lithofacies 5 dominate the marine mudstones. The formally defined gradational contact between the Imperial and Palm Spring Formations lies within Unit A.

Along the line of measured section A-A', Unit A is 300 feet thick and maintains this thickness to the south where it becomes covered by recent terrace deposits. To the north of section A-A', Unit A thins
gradually to approximately 175 feet before grading laterally into Unit D (Plate 1).

Structurally, Unit A is only slightly folded by the westerly plunging anticline and syncline which are the major deformation features in the western part of the field area. The beds generally dip shallowly to the west, averaging about 20 degrees.

The low-rolling-hill topography of Unit A is produced by the erosion of the poorly consolidated mudstones and siltstones, with the exception of the well indurated sandstone of Lithofacies 1 which forms protecting caprocks of steep linear ridges.

**Lithofacies 1**

**Lithology.** Lithofacies 1 is composed of fine, medium and coarse-grained fossiliferous sandstone. Fresh surfaces of the well-indurated sandstone are dark yellowish brown (10 YR 4/2), weathered outcrops are grayish brown (5 YR 3/2). The mostly arkosic framework grains are extremely poorly-sorted and subangular with subangular, pebble-sized granitic clasts associated with the coarse sandstone grains. The resistant nature of the lithofacies is produced by calcite cementation.

Oysters constitute a large percentage of the upper parts of the bed giving Lithofacies 1 a biostromal reef-like appearance. In addition to oysters, pectens and encrusting bryozoans are also present in varying positions and degrees of preservation (Figure 5).

**External bedding.** This lithofacies is exposed as a 3 to 5 foot bed
Figure 5. Lithofacies 1, oyster bearing section. Pencil is 5.5 inches long.
which forms a coarsening-upward gradational contact with the under-lying siltstone of Lithofacies 4. A sharp contact with Lithofacies 4 overlies the oyster-bearing upper surface of Lithofacies 1. The bed is laterally continuous for over 1 mile forming a continuous ridge through the field area (Plate 1). Weathering of the underlying un-consolidated siltstone creates unstable cliffs which collapse forming blocky talus surfaces on the east slopes of the ridge.

**Internal bedding.** Lithofacies 1 has a wide range of bedding styles within an overall coarsening-upward sequence. In a vertical section starting at the base of the bed, weak cross-stratification is present with intercalated parallel horizontal stratification and normal grading.

The cross-stratification appears as bidirectional planar cross-beds forming 1 foot sets. The sets are dominated by bottom and foreset layers as the topsets are truncated by the overlying layer. This style of cross-stratification is classified as alpha-type by Allen (1964).

Horizontal stratification, 1 inch thick is intercalated with and overlies the cross-stratification. Normal grading of fine- to coarse-grained sand separates the bedding surfaces. Local deposits of pebble-sized clasts are distributed within the coarse-grained sandstone forming poorly-sorted layers. Fragmented shell debris is also distributed within the coarser layers.

Concentrations of oyster shells are preserved in the upper parts of the bed. The oysters are found in a variety of preservation stages
and orientation. Locally, the shells appear to be preserved in living positions as articulated bivalves growing on top of one another. More commonly, the shells are disarticulated and fragmented forming a shell hash with the coarse-grained sandstone.

Only one oyster, *Ostrea vespertina*, and one pecten, *Pecten sp.*, and encrusting bryozoans were identified in this study. Woodard (1963) found a number of molluscan fossils in the upper Imperial Formation and identified them as *Ostrea heermanni*, *Aequipecten deserti*, *Anomia subcosta*, *Atrina stephensi*, *Turritella imperialis*, *Solenestrea fairbanks*, and *Enamilia carrizensis*.

A recent micropaleontological study by Quinn and Cronin (1984) found indurated oyster beds in the upper Imperial Formation to be dominated by two species of the foram *Elphidium*. Ostracod genera *Aurila*, *Hemicythere*, *Loxoconcha*, *Nesnesidea*, *Xestoleberis*, and *Perris-socytheridea* were also found and are characteristic of salinities between 15 and 30 parts per thousand.

Paleocurrent indicators are sparse, but five recorded orientations indicate bidirectional currents (Figure 6). Changing current strengths are suggested by wide range of grain sizes observed and the varying degrees of shell preservation.

**Lithofacies 2**

**Lithology.** Lithofacies 2 is composed of two distinguishable mudstones, a dusky green (5G 3/2) and a medium gray (N5) containing more than 50 percent silt or clay. Both mudstones are slightly calcareous and contain a high percentage of biotite and muscovite.
Figure 6. Paleocurrent Rose Diagram, Lithofacies 1. 30 degree class interval. Measurements taken from cross-bedding foreset azimuths. Dashed arrow is Plio-Pleistocene North before regional 35 degree clockwise rotation.
The green mudstones have a high organic content and unidentified plant material appears as oxidized orange fragments approximately 0.125 inches in diameter. Plant material was not observed in the gray mudstones. Both mudstones contain thin discontinuous well-sorted fine-grained sand lenses.

Gypsum occurs as thin interbeds approximately 0.25 inches in thickness throughout the green mudstones and weathers as slope talus which sparkles under reflected sunlight. Fibrous veins of interstitial gypsum are present in the concoidally fractured green mudstones.

Both the green and gray mudstones are friable and weather easily forming smooth rolling mounds where thicker sequences of interbeds are exposed. Weathering produces mud drapes locally covering the entire outcrop surface. Dusky green mudstones weather to grayson drab (5G 5/2) and medium gray mudstones weather to a medium bluish gray (5B 5/1).

External bedding. Both subfacies of Lithofacies 2 are vertically distributed throughout Unit A, but are more abundant near the base and subfacies usually occur as interbeds with each other as well as with the brown mudstones of Lithofacies 3. The interbedded packages reach a maximum thickness of approximately 10 feet. The individual beds rarely exceed 10 feet in thickness and average between 1 and 3 feet. The cyclicly bedded packages are laterally continuous over distances of 2,000 feet. Individual beds appear to be more discontinuous, but erosional features make them difficult to follow. Contacts with the
overlying and underlying strata are sharp and conformable, and do not appear to be erosional.

**Internal bedding.** The only internal bedding structures are sandy or silty lenses within the mudstone layers, which form thin, 1 inch thick, discontinuous lenses. Organic matter is abundant in the structureless mudstones. Lack of bedding and fragmented chaotically distributed plant matter may be the product of bioturbation, however, no burrows, tracks or trails were found. Mudcracks and other evidence of subaerial exposure are also absent.

No hard body fossils were found in this lithofacies, but Woodard (1965) reported two brackish water molluscs, *Ostrea vespartina* and *Anomia subcostata*, in gray calcareous siltstones and mudstones in the Palm Spring Formation south of the field area.

Paleocurrent indicators were not observed in Lithofacies 2.

**Lithofacies 3**

**Lithology.** Lithofacies 3 includes the moderate red (5 R 4/6) to the dark-reddish brown (10 R 3/4) calcareous mudstones. Again, as in Lithofacies 2, silt and clay amounts vary, but an overall mudstone compositional name is deserved. Petrographic analysis of a more clayey sample revealed an organic content of 5 to 10 percent, micaceous minerals and well-sorted silt laminations 0.125 inches thick. Red coloration is due to the alteration of iron bearing minerals to hematite. The mudstones weather to dusky red (5 R 3/4), poorly-consolidated "popcorn textured" surfaces forming smooth slopes over thick exposures. Fresh unweathered surfaces reveal conchoidal
fracturing of the more clayey facies whereas siltier facies develop a fissile texture. Calcite is present throughout the lithofacies in thin networks of irregular horizontal and vertical veinlets. Interstitial gypsum occurs low in the section as fibrous growths between fractures.

**External bedding.** The mudstones are distributed throughout Unit A and become increasingly abundant up section. Laterally the beds are found as both continuous and discontinuous lenses. The more continuous beds low in the section are associated with the green mudstones of Lithofacies 2, forming 5-foot packages of alternating mudstones. Discontinuous beds approximately 5 feet thick form lenses associated with siltstones of Lithofacies 4. Contacts with the underlying and overlying strata are sharp and distinct and do not appear to be erosional.

**Internal bedding.** Lithofacies 3 is structureless with rare internal bedding. Very thin laminations (0.04 inches) formed by concentrations of organic matter are present in the clayier facies. The laminations are sometimes disrupted to form ripple-like layers with random crest orientations.

No bioturbation, tracks or trails were found, but localized plant material is present which may suggest that bedding has been destroyed by vegetation, however, no root casts or molds are present. Desiccation cracks are absent here as in Lithofacies 2 and may have been obliterated by plant life. No paleocurrent indicators were seen in
the field, but the disrupted laminations suggest weak current activity.

Lithofacies 4

Lithology. Lithofacies 4 consists of unweathered light brown (5 YR 6/4) weathering to grayish orange (10 YR 2/4), poorly-sorted, calcite-cemented siltstone. The siltstone is very poorly consolidated, locally more deserving of the name silt. Limonite-bearing iron oxide concretions form brilliantly stained orange concretions around silicified wood.

Petrographic analysis reveals a framework grain composition of rounded quartz (65 percent), potassium feldspar (20 percent), plagioclase feldspar (10 percent) minor amounts of altered biotite and muscovite, and opaque grains of magnetite. The quartz grains show overgrowth rims.

External bedding. The siltstones are distributed throughout Unit A and form laterally continuous and discontinuous beds ranging from 2 to 15 feet in thickness. Laterally continuous beds are traceable over distances of about 2,000 feet while discontinuous beds cover 200 feet before pinching out laterally into mudstones of Lithofacies 3. Contacts are sharp and conformable, with both underlying and overlying lithofacies.

Internal bedding. The poorly consolidated siltstone shows no internal bedding, however, concretions reveal relic bedding of horizontal thin laminations (0.1 inches). This phenomena suggests
that the concretions are secondary in nature formed by percolating ground water after deposition and not calcrete nodules reflecting paleosol horizons.

**Depositional Environments**

**Introduction**

Rock Unit A represents both marine and nonmarine depositional environments. Where rivers enter oceans or seas, sediment-laden fluvial currents decelerate and the sediment load is deposited. If the sediment load is very high or if basinal processes such as waves, tides and currents are not sufficient to disperse the sediment, delta lobes will develop.

No single depositional model of delta processes can sufficiently account for the variability of modern deltas. Fisher et al. (1969) distinguished two types of modern deltas: high constructive deltas dominated by fluvial processes and high destructive deltas dominated by waves, tides and/or currents. Galloway (1975) proposed three models which define fluvial-, wave- and tide-dominated delta systems as the end members of a continuous spectrum of depositional environments.

Meckel (1975) pointed out that the modern Colorado River delta region in the northern Gulf of California is subject to extreme tidal ranges, up to 35 feet, and strong tidal currents. However, the ancient Colorado River delta may have been a more fluvial-dominated system as damming upstream has caused sediment supply to be severely
limited in the delta region today (Thompson, 1968).

Unit A is characterized by a wide range of shallow marine and delta plain facies representing the ancestral Colorado River delta.

**Lithofacies 1.** Lithofacies 1 represents a restricted, brackish water marine environment. The ostracod and oyster fauna suggests a constant input of freshwater to produce the salinity conditions favored by those species.

This type of depositional environment is similar to those occurring in the modern Mississippi River delta in interdistributary channel regions described by Coleman et al. (1964). As crevasse splays break out of the main distributary channel, sediments are deposited in the interdistributary bay in the form of sand bars. The bars prograde into the bay to produce local shoaling, and proximal facies overlie distal facies forming coarsening-upward sequences. Where numerous crevasse splays develop close to one another a laterally continuous front will develop producing a sub-delta lobe. These sub-delta lobes have been documented in the Mississippi River delta by a number of authors including Coleman and Gagliano (1964), Gagliano et al. (1971), and Gagliano and Van Beek (1975). Deposition continues until the bay is filled with sediment or the crevasse splay mouth is clogged whereupon the sub-delta is abandoned. At this point subsidence, compaction and coastal processes produce large bays where oyster beds may develop.

The coarsening-upward sequence of Lithofacies 1 may have been produced by these prograding delta lobes. Bidirectional cross-
laminations in the basal part of the bed are the product of tidal currents on the distal portion of the lobes. Normal grading indicates waning current activity and the very coarse detritus near the top of the layer may have been deposited during storms. These intense periods of precipitation and erosion could also choke the crevasse splay mouth with sediment resulting in the abandonment of the sub-delta.

The oyster beds were developed during a relatively quiet period where favorable living conditions prevailed. Rapid deposition periodically disrupted these conditions transporting the shells with coarse-grained sand and pebble clasts and depositing the poorly-sorted fragmented shell debris. These high energy conditions could have been caused by storm waves entering the normally quiet embayment.

The angular shaped clasts suggest a nearby source for the gravel associated with the fragmented shells. These were probably derived from adjacent highlands and introduced directly into the basin during storm events and reworked by currents or tides. A proximal adjacent highland source area is also suggested by the lateral gradation of Unit A into Unit D to the north at the base of the Vallecito Mountains (Plate 1).

**Lithofacies 2.** The green and gray mudstones of Lithofacies 2 represent supratidal deposition between distributary channels on the delta plain. These mudflats require periodic influxes of sea water to supply the minerals needed to form the gypsum layers. The lack of thick, well developed gypsum deposits may indicate that evaporation
took place in small local depressions where short lived pools formed. The clarity and purity of the gypsum indicates these pools were removed from any sediment deposition during periods of evaporation.

Thompson (1968) described supratidal areas in the modern Colorado River delta to occur approximately 50 feet above the lowest sub-tidal zone. The area supports little vegetation and is subject to marine water invasion only during exceptionally high spring tides and storm tides. Topographic lows up to 5 miles long and 15 miles wide form salt pans filled with sea water once or twice a year. Both gypsum and halite form evaporite sequences in the depressions. Gypsum dominates the fringes with halite forming in the center of the lowlands. Thompson (1968) also stated that evaporite sequences are restricted to these supratidal areas.

Meckel (1975) found a faunal assemblage of brackish water ostracods living in the supratidal area of the modern Colorado River delta similar to those found in gray gypsiferous mudstones sampled by Quinn and Cronin (1984) in the upper Imperial and lower Palm Spring Formations stratigraphically equivalent to Rock Unit A.

Mudcracks are not present and may have been destroyed by vegetation on the mud flat surface. The lack of vegetation on the modern delta plain suggests that climatic factors may have changed since the late Pliocene time when plant life thrived in this region. This will be discussed in Chapter 4.

Lithofacies 3. The red and brown mudstones of Lithofacies 3 were deposited on interdistributary mudflats on the delta plain. In
fluvial-dominated deltas, enclosed shallow water environments are found on the delta plain and are periodically flooded during high water stands of the river. Proximal to the channels, crevasse splay and levee deposits are found, but the central areas, farthest from the channels will be dominated by finer-grained mudstone deposits. The infilling of the interdistributary area provides a platform for vegetation growth (Elliott, 1974).

The macerated plant material found in the mudstones of Lithofacies 3 may represent the preservation of nonwoody grasses in a marsh environment. Coleman and Gagliano (1964) described the marsh surface in the Mississippi River delta region to approximate the mean high tide level. This suggests that these areas are inundated with marine waters during exceptionally high tides and storm events. This periodic influx of sea water could have supplied the evaporite mineral, gypsum, found as interstitial deposits in Lithofacies 3 low in the section.

Plants probably destroyed any mudcracks which might have provided evidence of subaerial exposure.

**Lithofacies 4.** Lithofacies 4 lacks sedimentary structures which suggest depositional processes, but the stratigraphic associations with Lithofacies 3 and 5, along with the petrified wood and petrographic data make an interpretation possible.

The increased abundance of Lithofacies 4 up section in the more terrestrial environment on the upper delta plain suggests a fluvial origin of the lithofacies. Lack of channelized depositional features
such as scour surfaces, lag deposits or fining-upward sequences indicates Lithofacies 4 may be the product of overbank and crevasse splay deposition.

The presence of quartz overgrowths on the coarse-silt-sized grains suggests a second cycle of deposition. The quartz grains of Lithofacies 5 also contain quartz overgrowths and were presumably derived from the Colorado Plateau, then transported and deposited here by the Colorado River system. In addition to this, the siltstones are stratigraphically associated with Lithofacies 3 which has been interpreted as overbank deposits of fluvial distributary channels on the delta plain of an ancient river system.

The presence of fossilized wood in Lithofacies 4 may be interpreted in two ways. One, large sections of trees may represent tree trunks which suggest that the sediment was deposited into the living areas of the trees. This is also suggested by the apparent horizons of large pieces of fossilized wood. On the other hand, the majority of the fossilized wood is fragmented, averaging less than 1 foot in length and 5 inches in diameter. No wood was found in place and this fragmentation suggests transportation, which could have taken place within the fluvial system as floating debris. With flooding, the river may top its banks depositing the finer suspended sediment load and floating wood debris as crevasse splay and over-bank deposits on the upper delta plain or flood plain. Transportation within fluvial channels is also indicated by the presence of wood within the channel sandstone of Lithofacies 5 suggesting the latter interpretation more
viable.

The petrified wood has been identified as ironwood by Dibblee (1954). Ironwood is common today in the Colorado Desert below the 2,000 foot elevation (Collins, 1976).
CHAPTER FOUR

ROCK UNIT B

Lithologic Descriptions

Introduction

Rock Unit B conformably overlies Unit A with the basal contact arbitrarily defined where the sandstone units of Lithofacies 5 begin to dominate the green and gray mudstones, Lithofacies 2, of Unit A (Plate 1). This unit is equivalent to Woodard's (1974) lower Palm Spring Formation.

Unit B is 2,400 feet thick along measured section A-A' and B-B' (Plate 2) and maintains this thickness throughout the generally north-northwest strike of the beds. Dips range from 10 to 25 degrees within the unit and gentle folding occurs in the northern and central areas of the field area along the west-dipping anticline and syncline.

Laterally, the unit grades northward into the sandstone and conglomerate facies of Rock Unit D near the base of the Vallecito Mountains. Terrace deposits unconformably overlie much of Unit B in the northern portion of the field (Figure 7). To the south, the beds are well exposed and extensive erosion has weathered the outcrops into low rolling hills (Plate 1).

Unit B is dominated by fining-upward sequences of Lithofacies 3, 4 and 5 with Lithofacies 2 also present in the bottom half of the unit. The upper half is almost exclusively composed of Lithofacies 3
Figure 7. Terrace deposits unconformably overlying Rock Unit B.
and 5 forming stacked sequences of cyclic deposition. The top of the unit is defined where the coarser grained sandstones of Lithofacies 7 appear.

Lithofacies 1 is not found in Unit B. The highest stratigraphic occurrence of the coarse-grained oyster bearing sandstone is near the base of Unit A.

The gray and green mudstones of Lithofacies 2 are rare in Unit B, becoming increasingly rare up section. They are lithologically identical to that described in Unit A with the exception of the absence of gypsum. Where the mudstones occur, they are usually associated with the mudstones of Lithofacies 3, forming thin, laterally continuous interbeds of 1 foot thickness.

The mudstones of Lithofacies 3 are present throughout Unit B with the same lithology described in Unit A. The most significant difference is the presence of desiccation cracks forming polygonal areas filled with the overlying sedimentation unit. The mudstones are associated with Lithofacies 5 forming the uppermost depositional unit of a fining-upward sequence. The overlying unit scourds the underlying mudstone incorporating mud chips of Lithofacies 3 into the basal lag deposit.

Beds are 3 to 5 feet thick where they form the top of coarsening-upward sequences. Thicker units of stacked mudstone layers also occur and average about 10 feet thick. Most beds are laterally continuous over distances of 2,000 feet. Locally, thicker discontinuous beds pinch out and grade into the siltstones of Lithofacies 4 within a few hundred feet.
No fossils or paleocurrent indicators were found in Lithofacies 3 of Unit B.

The lithologic characteristics of Lithofacies 4 in Unit B are similar to those found in Unit A. However, fossilized wood fragments are more abundant throughout Rock Unit B. Here, many horizons of concentrations of wood fragments are found including some large branching trunks 5 feet in length and 2.5 feet in diameter.

The beds are poorly consolidated with abundant iron oxide concretions. Lateral continuity varies from wedging units 10 feet thick and 100 feet in length to thinner 5 foot thick laterally continuous beds.

**Lithofacies 5**

**Lithology.** Lithofacies 5 consists of pale-yellow orange (10 YR 8/6), poorly consolidated, but locally well indurated, well-sorted, subrounded, fine- to coarse-grained sandstone. Petrographic analysis puts Lithofacies 5 into the feldspathic litharenite classification of Folk (1980). Framework grains consist of 60 percent subrounded quartz grains, 25 percent rounded and sericitized feldspar 10 percent muddy sedimentary rock fragments and 5 percent biotite and opaque heavy minerals. Quartz overgrowths indicate a reworked sediment source (Figure 8). The sedimentary rock fragments are mud chips probably derived from a nearby source. Cementation is produced by calcium carbonate and alteration of a muddy matrix into a weak phyllitic cement.
Figure 8. Lithofacies 5, photomicrograph showing second cycle quartz grains with overgrowth rims. Original grain surface is outlined by dots. Crossed Nicols, Field of view is 2.5 millimeters.
The lithology of Lithofacies 5 varies vertically. Near the base of Unit A lag deposits commonly contain fragmented shell debris. The shell debris becomes increasingly rare up section until it is completely absent. The sandstone bodies generally fine upward above the coarse-grained lag into fine- and very fine-grained sandstone.

**External bedding.** Lithofacies 5 is vertically distributed throughout Rock Unit B (Plate 2). In the lower part of Unit B, the sandstone bodies are laterally continuous over several thousand feet and are 10 to 30 feet thick. In the middle and upper parts of the unit, Lithofacies 5 is thicker, 30 to 60 feet, and lateral continuity is decreased forming wedge-shaped sandstone bodies averaging about 1,000 feet in length. In the northern part of the field area, the lithofacies is somewhat coarser grained near the gradational contact with Rock Unit D. Lithofacies 5 is usually overlain by Lithofacies 3, as either a gradational contact or a sharp nonerosional contact. This overlying mudstone is commonly overlain by a sandstone body of Lithofacies 5 forming a cyclic sequence of deposition.

**Internal bedding.** The internal bedding sequence of Lithofacies 5 is complex. It is neither laterally continuous within a single sandstone body, nor is it the same among sandstone bodies at different stratigraphic levels within the unit. However, there are common features which identify Lithofacies 5 in Unit B.

Lithofacies 5 is a generally fining-upward sequence, beginning with a flat, erosional basal scour contact, overlain by coarse-grained
sandstone fining-upward into fine-grained sandstone with a variety of sedimentary structures including cross-bedding, horizontal, convolute and ripple laminations.

Flat basal scour faces are found in all observable outcrops and are locally obscured by muddy stucco-like layers. A basal lag deposit occurs just above the scour surface and contains varied lithologies ranging from coarse-grained sand to pebbly gravel. Mud rip-up clasts are present, varying in size from small chips to pebble-sized clasts. The larger clay balls are associated with the finer grained lag deposits whereas the smaller mud chips were deposited with coarser sediment. An underlying mudstone is not always present and in this case the mud chips and clasts were probably derived upstream or the mudstone layer has been completely scoured away.

A variety of cross-bedding is present above the basal lag deposits. Large-scale epsilon cross-stratifications (Allen, 1963) are found as solitary sets and cosets 6 inches to 1 foot in height. The epsilon-type cross-bedding is characterized by low-angle foresets covering large distances 5 to 10 feet within the set (Figure 9).

Medium and large scale trough cross-stratification is also present. Viewed on a vertical surface parallel to the inferred flow direction, erosional surfaces form a series of upwardly truncated concave-upward arcs (Figure 10). The thickness of each set is approximately 8 inches to 1 foot with average widths of 2 feet. On a vertical section perpendicular to flow, the set boundaries are nearly parallel, similar to tabular cross-stratification (Figure 11), but rare three-dimensional views provide clear evidence for classifi-
Figure 9. Lithofacies 5, epsilon-type cross-bedding. Jacob staff is 5 feet long.
Figure 10. Lithofacies 5, trough-shaped cross-bedding looking parallel to flow direction. Shoe is 1 foot in length.
Figure 11. Lithofacies 5, trough-shaped cross-bedding looking perpendicular to flow direction. Jacob staff is 5 feet.
Climbing ripple laminations and horizontal laminations overlie the cross-stratified layers. The climbing ripple laminations are classified as small scale kappa- or lambda-type of Allen (1963). McKee (1965) described two types of ripple laminae: in-phase and in-drift, with transitions between the two types. Ripple laminae in-phase is characterized by ripple crests lying directly above one another whereas ripple laminae in-drift show crest migration away from a directly overlying relationship. The climbing ripples observed fall under the in-phase type with little or no crest migration (Figure 12). Ripple laminae in-drift were not seen in Unit B.

Horizontal stratification is by far the most abundant sedimentary structure seen in Lithofacies 5 and commonly occurs above the cross-stratification replacing the ripple laminations or intercalated with the ripples. Laminae thicknesses range from 0.125 inches to about 1 inch. The laminae are formed by silt-sized heavy mineral or micaceous mineral concentrations.

Rare occurrences of convolute bedding within the lithofacies locally incorporate the overlying unit to form spectacular large scale flame structures. The small convolutes are poorly defined with heights of 1 to 2 inches. One large scale convolute reaches a height of over 1 foot incorporating an interbedded mudstone (Figure 13).

As mentioned earlier, the fossils present in Lithofacies 5 include shell fragments low in the section and wood fragments throughout the unit.
Figure 12. Lithofacies 5, climbing ripple in-phase type. Lens cap is 2 inches in diameter.
Figure 13. Lithofacies 5, flame structure. Shovel is 2.5 feet long.
Paleocurrent direction indicators from cross-bedding foreset azimuths, ripple-crest orientations and trough cross-bedding axes suggest a general current direction from the northeast to the southwest (Figure 14).

Depositional Environments

Introduction

Rock Unit B strata represent the transition from the lower delta plain environment of Unit A to an upper delta plain, fluvial-dominated environment. The shift to an almost exclusively nonmarine depositional environment is recorded in measured section A-A' by the up-section decrease of marine fossils and lithofacies and an up-section increase in the fluvial deposition of Lithofacies 3 and 5 (Plate 1).

Lithofacies 1. The absence of Lithofacies 1 indicates that marine conditions, if any, did not last long enough for oyster beds to develop. The presence of shell debris, however, suggests that either the oyster beds were located basinward and the shells were transported landward to the depositional site of lower Rock Unit B sediments during storm events, or the shells represent oyster beds reworked by the fluvial system as the sea regressed. It is probable that both processes occurred simultaneously during the deposition of lower Unit B sediments.

Lithofacies 2. Rare exposures of Lithofacies 2 are limited to the lower half of the unit. The beds are generally thinner, although
Figure 14. Paleocurrent Rose Diagram, Lithofacies 5, Rock Unit B. 30 degree class interval. Measurements taken from cross-bedding foreset azimuths, trough axes and ripple crest orientations. Dashed arrow is Plio-Pleistocene North before regional 35 degree clockwise rotation.
lateral continuity is maintained over similar distances seen in Unit A. The main difference is the absence of gypsum. The thinness of the beds may indicate relatively shorter periods of marine incursions onto the delta plain. The marine conditions could have been the product of eustatic sea level rises, but the thinness of beds and short period of incursions make such an interpretation unlikely. Delta distributary abandonment would be a more probable model for development of the stratigraphic relationships of Lithofacies 2.

Abandonment of a distributary channel of a delta lobe causes subsidence (Gagliano et al., 1971) because pore water pressure decreases within the sediment upon abandonment. During this period, marine conditions could invade onto the low gradient delta plain without the intermixing of marine and nonmarine sediments. The meandering distributary system would eventually return and deposit fluvial sediments over the marine unit as seen in the field area.

Lithofacies 3. The red and brown mudstones of Unit B represent mud flat overbank sediments deposited in the interdistributary areas of the delta plain environment low in the section. Higher in the section, the mudstones become cyclic and are interpreted as overbank deposits in a fluvial flood plain nonmarine environment.

In the lower half of the unit, Lithofacies 3 is locally interbedded with the marine mudstones of Lithofacies 2. No desiccation cracks are present indicating subaerial exposure was nonexistent or minimal at best. The great lateral extent of the beds suggest a broad flat surface of deposition and the thin laminations of well-sorted
silt-sized grains suggest winnowing by weak current action. Similar sediments have been described by Thompson (1968) to occur in the transition zone between intertidal mud flats and higher subaerially exposed flats of the modern Colorado River delta region. Here, silt and clay are supplied by flood waters as suspended load. Reworking and resuspension occur during rising tidal cycles which sort out the silt, forming well-sorted laminations within the mud.

Higher in the section of Unit B, the mudstones become thicker and are cyclicly deposited with the channel sandstones of Lithofacies 5. The polygonal-shaped filled mud cracks are direct evidence of subaerial exposure. Where mud cracks are absent, rip-up clasts of mudstone are found in the basal channel lag of the overlying sandstone bodies. Scoured mud-cracked surfaces could have been the source of the mud rip-up clasts providing additional evidence for subaerial exposure.

The association of the mudstones with underlying and overlying sandstone bodies suggests they are the final product of fining-upward sequences typical of point-bar deposition (Visher, 1972). The finest grained sediment is deposited as overbank suspended load during high water stands. The silts and clays form the capping vertically accreted sediment over the laterally accreted point-bar deposits.

Very thick mudstone layers found within Unit B represent channel-fill deposits. These deposits are formed where meander bends migrate into each other and flow is cut off producing an abandoned meander. Overbank flooding produces oxbow lakes until eventually the area is
filled with fine overbank sediments (Miall, 1982).

Rare plant material within the mudstone beds and absence of root casts suggest a sparse flood-plain vegetation. This is likely due to climatic factors and/or depositional and erosional features which limited the preservation of such material.

Calcite veins and layers do not appear to be calcrete deposits of paleosols. Their random orientation and distribution were produced by percolating ground waters subsequent to deposition and burial.

**Lithofacies 4.** The similar lithology and stratigraphic characteristics of Lithofacies 4 here in Unit B with those described in Unit A suggest a similar depositional environment. In Unit B, however, the abundant fossilized wood along stratigraphic horizons, possibly in place, suggests the siltstone was deposited into the living areas of the ironwood trees and therefore implies a nonmarine interfluvial channel environment.

**Lithofacies 5.** Lithofacies 5 represents channel deposits produced by meandering distributaries. Point-bar deposits record the lateral migration of meandering streams and rivers with deposition occurring on the inside bank of the meander by means of lateral accretion. This produces a distinct vertical succession of lithologies and sedimentary structures similar to those seen in Lithofacies 5. The vertical sequence of lithologies and sedimentary structures are the products of initially strong currents which gradually wane through time. This accounts for the generally fining upward sedimentation and the sequence of sedimentary structures representing successively lower
flow regimes.

Flat-based erosional contacts are common in meandering streams where migration produces scouring pools which erode at a fairly constant level (Allen, 1964). The initial scour surface is produced by turbulent currents which undercut the outside bank of the channel causing bank failure and slumping. The bank material falls into the thalweg of the channel and either remains as large blocks or is broken up into smaller pieces and transported down stream as channel lag deposits. Rip-up clasts derived directly from the underlying sediment are also present indicating that initial currents scoured the base of the channels as well.

The preservation of the larger mud balls is probably due to the cohesive nature of the mud as well as the absence of gravel-sized grains which surely would have ground the softer mud pieces into finer grained particles as the bed load material was transported. Channel lag deposits grade upward into a variety of cross-bedded layers.

Epsilon cross-bedding of Allen (1963) is very good evidence for deposition by lateral accretion and point-bar deposition. Trough cross-stratification signifies the migration of dune-shaped bed forms (Harms and Fahnestock, 1965) which occur under upper flow regimes where initial current velocities are high. The trough-shaped cosets also indicate unidirectional flow typically found in fluvial environments.

Trough cross-stratification grades upward into both ripple laminated layers and more commonly planar horizontal bedding. The
development of climbing ripples in-phase requires that much sediment is available in suspension so that the ripples build upward rather than migrating forward. This also calls for fairly constant current velocities and any deviance from these conditions will preclude the development of the structures (Reineck and Singh, 1975). The poorly developed climbing ripples in Lithofacies 5 suggest current velocities and sedimentation rates were fluctuating through time.

Horizontal laminations have generally been thought to represent upper flow regimes for fine-grained sand sizes (Harms and Fahnestock, 1965). However, Reineck and Singh (1975) indicated that much of the horizontal bedding found in point-bar deposits is produced by deposition of suspension clouds due to decreases in turbulence or current velocity changes. With the fine-grained nature of Lithofacies 5, suspension deposition is likely to have produced the horizontal bedding.

Convolute laminations are also present and occur as isolated destructions of the bedding surface. These are interpreted to be slumping structures of water laden sediment produced during subaerial exposure at low water stages (Conybeare and Crook, 1968).

The final product of the point-bar deposition is the overbank mudstones of Lithofacies 3. These represent the lowest current velocities as the finest particles are deposited out of suspension.

This sequence of sedimentary structures is not always present and in some places ripple laminations are replaced by massive bedding or horizontal laminations. These discrepancies from the classic point bar model are not surprising and simply point out the variability of
fluvial systems under different hydrologic conditions and sediment supply.

Channel morphology may be interpreted from bed thicknesses and lateral continuity. Visher (1972) stated that the thickness of the point-bar deposit is equal to the depth of the average flood channel. In this case, channel depths ranged from 10 to 30 feet low in the section and up to 60 feet near the top of Unit B. This is consistent with a study by Sykes (1937) in which fluvial channels in the Colorado River delta plain were found to scour up to 32 feet during floods. The scoured area was then rapidly filled during waning flood conditions. Meckel (1975) cored the modern Colorado River delta plain and found variable thicknesses of point bar deposits up to 100 feet. He also determined that point-bar sequences on the lower delta plain were thinner than those found in an upper delta plain environment. The difference was attributed to smaller channel size and lower gradients on the lower delta plain.

This relationship is applicable to Unit B where Lithofacies 5 becomes thicker up section, thereby suggesting a shift from a lower delta plain to an upper delta plain depositional environment. This shift may have been caused by tectonic uplift of the area, falling sea level, or a combination of both mechanisms operating simultaneously.

The type of channel pattern is a function of both geomorphological criteria such as gradient and channel flow as well as sedimentologic features such as grain size and sediment availability (Jackson, 1978). The fairly low gradient of the delta plain environment and the fine-
grained sediment source resulted in a meandering stream channel morphology. This is also indicated by the lateral continuity of Lithofacies 5. The degree of sinuosity or meandering may not be determined, but a relatively higher sinuosity system produced the more laterally continuous, thinner, sandstone bodies found in lower Unit B. The thicker less continuous beds of upper Unit B represent a relatively lower sinuosity stream system. This relationship may also be attributed to higher gradients on the upper delta plain environment.

An ancient Colorado River source for the Palm Spring Formation has been suggested by Merriam and Bandy (1965). They found displaced and weathered Cretaceous forams presumably derived from the Cretaceous Mancos Shale of the Colorado Plateau. The presence of rounded overgrowths on the detrital quartz grains of Lithofacies 5 further supports this idea. Sanderson (1984) stated that overgrowth represents the remnants of cement adhering to a grain's surface from a previous sedimentary cycle. A number of possible source areas of the reworked quartz grains exist within the Colorado Plateau.
CHAPTER FIVE

ROCK UNIT C

Lithologic Descriptions

Introduction

Unit C conformably overlies Unit B with the basal contact arbitrarily defined where the sandstone beds of Lithofacies 7 first appear (Plate 1). Maximum thickness of approximately 2,650 feet occurs in the central part of the area and the unit thins to a minimum thickness of about 1,100 feet towards the north. This unit is equivalent to the middle Palm Spring Formation.

Unit C is structurally deformed by west plunging (15 degrees) asymmetrical anticline and syncline structures in the central and northern part of the field area. Dips range from 15 degrees on the southern limb of the anticline to 75 degrees between the two structures near Olla Wash (Plate 1).

Laterally, Unit C grades northward into the sandstone facies of Unit D near the base of the Vallecito Mountains. To the west, Unit C grades upward into Unit D and the contact is defined where coarser, pebbly sandstone of Unit D begins to predominate over the finer lithofacies of Unit C.

Unit C is dominated by the multistoried sandstones of Lithofacies 7 and the laterally equivalent beds of Lithofacies 6. Lithofacies 8 appears as lenticular sandstone bodies in the middle of the unit and
Lithofacies 3, 4 and 5 are minor constituents. Lithofacies 3, 4 and 5 are rarely exposed in the lower and middle sections of Unit C and become more abundant near the top of the section (Plate 2).

Lithofacies 3 is lithologically similar to that described in Units A and B. It is associated with the fining-upward sequences of Lithofacies 5 and in addition is interbedded with mudstones of Lithofacies 6. Beds are generally 1 to 2 feet thick, and never exceed 5 feet in thickness. Lateral continuity varies from a few hundred feet to over a thousand feet.

Lithofacies 4 is rarely exposed in Unit C. Where it is found, petrified wood is not ubiquitous as it was in Units A and B. Lithologically, Lithofacies 4 remains the same as that described previously except concretions are more abundant and locally appear near the top of the beds. The siltstones appear to be laterally less continuous and could only be followed over distances of about 100 to 200 feet.

Lithofacies 5 is found as laterally discontinuous beds approximately 500 to 1,000 feet wide and 5 to 25 feet thick, which grade laterally into the mudstones of Lithofacies 3. One excellent exposure along Fish Creek Wash, south of Sandstone Canyon is composed of a sequence of climbing ripples grading upward into horizontal laminations. The climbing ripples are preserved as laminae in-phase grading into laminae in-drift (Figure 15). The ripple laminae in-drift is seen as two types: one in which only the lee side is preserved and the other in which both the lee and stoss sides are preserved. Joplin
Figure 15. Lithofacies 5, climbing ripples in-drift type. Lens cap is 2 inches in diameter.
and Walker (1968) interpreted the transition from one type to the other as the result of decreasing suspended load to bedload ratios. Laterally, a plan view of this bed reveals strongly undulatory or weakly linguoid shaped small current ripples (Figure 16). Ripple wavelengths average about 6 inches with heights of 1 to 2 inches. Other sedimentary structures include trough shaped cross-stratification as seen in Unit B, ripple laminations and horizontal laminations; parting lineations are also present on well exposed horizontally bedded surfaces.

Paleocurrent indicators give a closely grouped set of orientations spreading over 60 degrees revealing paleocurrents generally flowing from the northwest to the southeast (Figure 17).

**Lithofacies 6**

Lithofacies 6 is actually made up of two distinct subfacies, a sandstone and mudstone. However, because they always occur as inter-bedded units they have been grouped as a single lithofacies.

**Lithology.** The sandstone subfacies is a light gray (N7) fine- to coarse-grained, moderately-sorted, subangular, locally conglomeratic, highly micaceous feldspathic litharenite. Calcite cement produces locally resistant beds, but the majority of the sandstone is weakly indurated by a phyllitic matrix. The local conglomeratic stringers contain pebble-sized subangular granitic clasts. Weathered surfaces are yellowish orange (10 YR 6/6) due to the alteration of iron bearing minerals to hematite.

The fresh, dark-greenish gray (5 GY 4/1), weathering to dark-
Figure 16. Lithofacies 5, strongly undulatory ripple surface. Notebook is 11 x 14 inches.
Figure 17. Paleocurrent Rose Diagram, Lithofacies 5, Rock Unit C. 30 degree class interval. Measurements taken from cross-bedding foreset azimuths, trough axes, ripple crest orientations and parting lineations. Dashed arrow is Plio-Pleistocene North before regional 35 degree clockwise rotation.
greenish gray (5 G 4/1), mudstones appear as nonfissile sandy mudstones and fissile clayey mudstones. Both are highly micaceous showing a distinct linear orientation of the biotite and muscovite grains.

**External bedding.** The sandstone and mudstone are distributed throughout Unit C as laterally discontinuous units pinching and wedging with the sandstones of Lithofacies 7. As a result of this stratigraphic relationship, Lithofacies 7 is more abundantly distributed in the northern and southern portions of the field area.

The sandstone forms beds from a few inches to not more than 10 feet thick. The beds are wedge shaped and extend laterally anywhere from 10 feet to over 1,000 feet.

The mudstones range from 1/8 of an inch to 3 inches thick. The thinner layers form partings between sandstone beds and locally show desiccation cracks. The thicker mudstones are interbedded with thin sandstone beds, forming layers up to 10 feet thick.

Together the mudstone and sandstone interbeds form thinning (fining) and thickening (coarsening) upward sequences depending on the mudstone:sandstone ratio (Figure 18). The interbedded units are anywhere from 1 foot to 25 feet thick.

**Internal bedding.** As mentioned before, the mudstone is both fissile and nonfissile has desiccation cracks and is infilled by the overlying sandstone. Thicker mudstones are either fissile or non-fissile depending upon the amount of silt-sized grains inhibiting fissility. The sandstone is mostly massive and structureless.
Figure 18. Lithofacies 6, sandstone-mudstone interbeds overlain by Lithofacies 7.
However, local conglomerate stringers, ripples and horizontal laminations break the monotony of the massive beds. Conglomerate stringers form lag deposits marking the base of channels.

Bioturbation locally destroys any bedding characteristics in the interbedded units. Horizons of intensely burrowed layers are well preserved on freshly weathered outcrops (Figure 19). Two distinct trace fossil assemblages were recorded. The smaller, more common passively filled burrows are unlined, vertically oriented and is 0.125 inches in diameter and 0.75 inches in length with a curved base. The second type of burrow is larger and less common. They are vertically oriented, unlined, 0.5 inches in diameter and 1 to 3 inches in length. Here again, the base of the burrow is curved. Both actively and passively filled burrows were observed in addition to escape type structures. Neither of the burrow types have been identified on a generic basis. However, their distribution does reflect sporadic sedimentation rates where slow sedimentation rates allowed the organisms to thrive only to be destroyed by a sudden influx of sediment.

Lithofacies 7

Lithology. Fine-, medium-, and coarse-grained sandstones make up Lithofacies 7. Sandstone grains are moderately well-sorted and angular. Petrographic analysis reveals a framework grain composition of 50 percent quartz, 45 percent feldspar and 5 percent lithic fragments. Varietal minerals of biotite and muscovite make up about 10 percent and 3 percent, respectively of the whole rock sample. Sixty-
Figure 19. Lithofacies 6, burrow horizons. Pencil is 5.5 inches long.
five percent of the feldspars are plagioclase and the remaining 35 percent are of potassium. Lithic fragments are mainly plutonic in origin with a few sedimentary rock fragments present. Biotite and muscovite grains are aligned parallel to the bedding surfaces. Intraformational mudstone clasts form a basal lag deposit along with locally abundant pebble-sized, angular granitic clasts.

**External bedding.** The very thickly bedded Lithofacies 7 forms discontinuous lenticular sandstone bodies. Thicknesses of these units, from the basal scour to the capping desiccated mudstone partings, range from 3 to 20 feet, averaging about 10 feet (Figure 20). Laterally, the lenses grade into the sandstone and mudstone interbeds of Lithofacies 6 over distances of 100 to 500 feet.

Lateral distribution of Lithofacies 7 is not uniform within the field area. The thickest accumulation occurs in the Sandstone Canyon area and thins dramatically to the north and south (Plate 2).

**Internal bedding.** Between the capping mudstones separating the sandstone bodies, a distinct sequence of sedimentary structures is seen. A basal scoured surface is overlain by coarse-grained material which includes intraformational mudstone clasts and granitic pebbles. Large-scale trough cross-stratification occurs in the lower parts of the beds (Figure 21), with depths of 2 to 3 feet and widths of 5 feet across. Foreset angles of inclination range from 20 to 35 degrees. The trough cross-stratification grades upward into horizontal and ripple laminations. Horizontal laminations range from 0.25 to 1 inch thick. Poorly-developed ripple laminations form thin, 1 inch layers
Figure 20. Lithofacies 7, thickly-bedded sandstone and desiccated mudstone partings. 5 foot Jacob staff in lower center.
Figure 21. Lithofacies 7, large-scale, trough-shaped cross-bedding. Cap is 8 x 6 inches.
within the horizontal laminations (Figure 22).

Paleocurrent direction indicators reveal general flow directions from the northwest (Figure 23).

**Lithofacies 8**

**Lithology.** Lithofacies 8 occurs as two distinct subfacies, a finer grained sandstone and coarser grained conglomerate, and will herein be referred to as Lithofacies 8a and 8b respectively.

Lithofacies 8a is a fine- to medium-grained sandstone. Fresh surfaces are medium-dark gray (N4) weathering to olive gray (5 Y 3/2). Sandstone composition is 45 percent quartz, 35 percent feldspar, 15 percent lithic fragments of plutonic origin, 5 percent biotite and muscovite and less than 1 percent heavy mafic minerals. The grains are moderately-sorted, angular and calcite cemented. Thin mud rip-up clasts are locally incorporated into the base of the beds.

Lithofacies 8b consists of poorly-sorted pebble- to boulder-sized, randomly distributed conglomerate clasts and well-sorted, granule-sized clasts, both in an olive gray (5 Y 3/2) sandy mudstone matrix. The clasts are subrounded and mostly granodiorite with rare gneisses and schists. Conglomerate layers are capped by thin mudstone partings.

**External bedding.** Lithofacies 8a and 8b occur as a lense-shaped sandstone bodies approximately 1 mile long and 300 feet thick between sandstone Canyon and Oilla Wash. These lithofacies grade laterally and vertically into Lithofacies 7. Lithofacies 8a forms channelized sandstone lenses ranging from a few feet to over 100 feet in length.
Figure 22. Lithofacies 7, poorly-developed ripple laminations. Pencil is 5.5 inches long.
Figure 23. Paleocurrent Rose Diagram, Lithofacies 7, Rock Unit C. 30 degree class interval. Measurements taken from cross-bedding foreset azimuths, trough axes, ripple crest orientations and clast imbrications. Dashed arrow is Plio-Pleistocene North before regional 35 degree.
Channel depths are 6 inches to 2 feet. The lithofacies are often interbedded with thin, 0.125 inch mudstone layers. Lithofacies 8b forms distinct sheet-like deposits of uniform thickness over 100 feet long and 1 foot thick. The beds grade laterally into the sandstones of Lithofacies 8a forming interbeds. The beds are separated by thin, 0.125 inch mudstone layers.

**Internal bedding.** The internal bedding of Lithofacies 8a and 8b displays a variety of sedimentary structures. Channelized deposits of Lithofacies 8a reveal large scale sand waves, cut and fill structures and reactivation surfaces (Figure 24). Thin mudstone layers cap the channels indicating waning current velocities. The mudstones have desiccation cracks infilled with the overlying sandstone. Extreme desiccation is also preserved as curled mudstone flakes in situ (Figure 25).

Channel lag deposits occur in a few sandstone layers of Lithofacies 8b. Conglomerate lag infills erosional depressions with pebble-to-boulder sized clasts. Flow directions are indicated by clast imbrication and sediment shadows formed down current around the clasts (Figure 26).

Normal and reverse grading dominates the gravel conglomerates of Lithofacies 8b. The two types of grading appear in single beds where basal fine-grained layers reversely grade upward into very coarse-, granule- and pebble-sized grains in the middle of the bed. This, in turn grades normally into fine-grained sediment and mudstone at the top of the bed (Figure 27). These sequences suggest that the beds
Figure 24. Lithofacies 8a, channel reactivation features. Jacob staff is 5 feet long.
Figure 25. Lithofacies 8a, in situ curled mudstone layer.
Figure 26. Lithofacies 8b, boulder-sized clasts. Note imbrication. Jacob staff is 5 feet long.
Figure 27. Lithofacies 8b, debris flow deposits. Note reverse-normal grading below hammer. Hammer is 1 foot in length.
represent individual depositional events. Conglomerates containing randomly oriented pebble-sized clasts in fine sand and mud matrix are also present.

Paleocurrent direction indicators such as channel axes and clast imbrication reflect currents carried sediment in a generally northwest to southeast direction (Figure 28).

**Depositional Environments**

**Introduction**

The laterally and vertically changing facies relationships within Unit C suggest actively migrating adjacent depositional systems contributing sediment into the basin simultaneously.

**Lithofacies 3.** Lithofacies 3 represents overbank flood plain deposits related to the fluvial system of Lithofacies 5. This is indicated by the similar stratigraphic relationships between the two lithofacies as those seen in Unit B. The thinner nature of the beds suggest flooding was less intense during the deposition of Unit C relative to Unit B or that the mudstones in Unit C represent deposition farther away from the flooding channels where overbank muds would be thinner and more widespread. The latter theory is supported by the interbedding relationship of Lithofacies 3 with Lithofacies 6 which represents a different depositional system. Desiccation cracks indicate subaerial exposure.

**Lithofacies 4.** Lithofacies 4 is again difficult to interpret because of the lack of diagnostic sedimentary structures. However,
Figure 28. Paleocurrent Rose Diagram, Lithofacies 8. 30 degree class interval. Measurements taken from cross-bedding foreset azimuths, channel axes and clast imbrication. Dashed arrow is Pliocene-Pleistocene North before regional 35 degree clockwise rotation.
the same stratigraphic relationships with the meandering stream and overbank deposits of Lithofacies 5 and 3 suggest a similar origin of crevasse splay deposition.

The rare occurrence of Lithofacies 4 suggests that stream morphology became less sinuous, possibly due to a higher gradient. Rare fossilized wood suggests that either the source of wood was depleted or that the ironwood no longer thrived near the fluvial system.

Lithofacies 5. The meandering fluvial system depositing Lithofacies 5 meandered in, out and back into the area during the time Unit C was being deposited. This is indicated by its relative abundance low and high in the section and its scarcity in the middle of the unit. The associated Lithofacies 3 and 4 also follow this pattern. It is not unusual for a meandering system to migrate several miles. For example, the modern Colorado River meander belt is 4 to 5 miles wide (Meckel, 1975).

The vertical relationship of Lithofacies 5 with Lithofacies 7 and 8 indicates the two depositional systems were operating as individual environments. Current directions and petrology also support this theory, as no mixing of the different source sediments was revealed.

Lithofacies 6. The similarities of lithologies, lateral gradation and vertical proximity suggest a close relationship between the channelized sandstones of Lithofacies 7 and the laterally equivalent Lithofacies 6. The interbedded sandstones and mudstones reflect rapidly changing flow velocities and sediment availability. Such conditions could occur along adjacent margins of an actively migrating
braided stream where sediment-choked stream channels are periodically abandoned.

The fining-upward sequence of interbeds represents waning current velocities and sediment supply at the site of deposition. The gradual decrease in current strength could occur as channels are choked off by sediment from upstream, which is rapidly deposited during waning flood stages. A sudden influx of sediment from another source may also produce these features. As the stream is choked off, downstream sediment supply is limited to finer and finer grained material producing the fining upward sequence seen in Lithofacies 6.

Under these less energetic conditions, a favorable living habitat enabled burrowing organisms to flourish, as seen in the burrowed horizons of Lithofacies 6. However, these conditions were short-lived and sudden influxes of sand, probably during storm events, buried the organisms thriving on and beneath the mud surfaces. Upon burial, the animals tried to make it back up to the sediment-water or sediment-air interface thus producing escape burrows.

Coarsening-upward sequences indicate increasing stream velocities as channels migrated laterally into the marginal areas. Mud-dominated layers are overlain by increasingly sandier units and finally the main actively migrating channel deposits of Lithofacies 7. The coarsening-upward sequence may not necessarily be caused by channel migration. The unplugging of choked-off channels upstream could cause the area to become part of the main active channel system.

The local pebble conglomerates indicate periodic high energy
conditions within small channels. The clasts are similar to those found in Lithofacies 7 and 8 suggesting the interfingering and lateral proximity of the two depositional environments.

**Lithofacies 7.** Lithofacies 7 is composed of a series of fining upward cycles characteristic of a braided stream depositional environment. A number of vertical profile models for braided stream environments have been proposed by Miall (1977), Cant and Walker (1978), Cant (1978), and Rust (1978), and these models are based on sedimentologic features such as gravel to sand ratios and vertical sequences of sedimentary structures. Of these, Lithofacies 7 best fits the sandy South Saskatchewan River model of Cant and Walker (1978).

The stratigraphic sequence of Lithofacies 7 begins with a scoured base with mudstone intraclasts and pebble clasts overlain by trough-shaped cross-bedding. Cant and Walker (1978) described the base of the deepest channels of the South Saskatchewan to be littered with mud intraclasts derived from undercutting of the banks of the flood plain during high water stands. High water stands could also account for the locally distributed pebble clasts of Lithofacies 7 when high energy conditions prevailed. The clasts may have merely been transported down stream from the upper reaches of the fluvial system or they could represent the introduction of sediment from Lithofacies 8, in which similar clasts are found. No direct evidence of this was seen, but stratigraphic relationships indicate the two lithofacies were deposited by adjacent environments.

The channels of the South Saskatchewan are floored by sinuous
crested dunes (Cant and Walker, 1978). Harms and Fahnestock (1965) found that trough-shaped cross-beds, similar to those found at the base of Lithofacies 7, are produced by the migration of dune bedforms.

Overlying the large trough cross-beds of Lithofacies 7 are horizontally stratified, massive and ripple-laminated interbeds. This vertical sequence of sedimentary structures deviates from Cant and Walker's (1978) model. However, the deviation does not necessarily mean a break in the correlation, but reveals the variability of fluvial conditions. When relating this model, to an example in the rock record, Cant (1978) stated that it is based on only a few examples and is therefore only a general model.

Cant and Walker (1978) found medium-grained sand flat deposits of planar cross-bedded units developed by the migration of sand waves oblique to the flow directions. Interbedded with these were horizontal and ripple-laminated layers.

The lack of planar cross-bedding in Lithofacies 7 may be due to flow velocity and grain size differences between the two fluvial systems. Harms et al. (1975) found that for fine-grained sand, horizontal bedding develops on a flat bed when flow velocities are too great for sand waves or dunes to develop. This is also demonstrated in the Bijou Creek model (Miall, 1977) where flash floods produce high energy conditions in an ephemeral stream environment. It may therefore be inferred that Lithofacies 7 was deposited under higher energy, more ephemeral stream conditions than those in the South Saskatchewan.

Capping the cycles are mudstone layers. Desiccation cracks indicate subaerial exposure as channels are filled and abandoned.
during waning current velocities.

Average minimum flow depths may be approximated by the thickness of the trough cross-beds multiplied by two. The trough sets average 2 feet in thickness suggesting channel flow depths of 4 feet. Channel widths average 250 feet for a width to depth ratio of 62.5. Braided streams are characterized by high width/depth ratios, normally greater than 40 (Miall, 1982).

**Lithofacies 8.** The variety of stratification observed in Lithofacies 8 suggests deposition under a wide range of hydrodynamic conditions which determined bedding thickness, grain size distribution, and types of contacts with the underlying and overlying strata. The wide variety of depositional processes responsible for such sedimentation occurs on alluvial fan surfaces as defined by Bull (1972).

Hooke (1967) described an idealized fan profile to consist of a fan apex from which channels radiate. A main channel is commonly incised into the fan and emerges onto the fan surface at the intersection point. A depositional lobe occurs below the intersection point as the slope gradient decreases.

Several types of fan deposits are recognized by Bull (1972). These include fluid flow, low viscosity stream channel and sheet flood deposits and high viscosity debris flows. Lithofacies 8a and 8b are interpreted to have been deposited by a spectrum of alluvial fan processes.

The fine- to medium-grained locally conglomeratic sandstones of
Lithofacies 8a are characteristic of small, shallow braided distributaries on the distal portions of fans. The thin, low angle trough cross-beds are the product of migrating sand dunes (Harms and Fahnestock, 1965). Minimum flow depths ranged from 2 to 3 feet.

The boulder trains found in Lithofacies 8a suggest periods of very high energy which transported proximal material down the fan into the lower fan environment. This may occur with the incision of the upper fan channels into the lower fan region below the previous point of intersection (Reading, 1978).

Cut and fill structures provide evidence for the actively migrating nature of the stream channels. This is due to the high gradient of the fan surface and possible arid climate contributing to ephemeral conditions at the time of deposition.

Subaerial exposure is indicated by the thin mudstone layers showing desiccation cracks. This again is evidence for waning current velocities and ephemeral conditions.

Both the extremely poorly sorted conglomerates and graded conglomerates of Lithofacies 8b are the product of debris flows. Blackwelder (1928) was the first to recognize debris flows on alluvial fans. Prerequisites for the development of debris flows are a source area which weathers to produce fine debris, and steep slopes which promote rapid erosion and run off. The debris flows move as variably dense and viscous masses (Reading, 1978).

Bull (1972) pointed out that the thickness and internal structure of debris flows vary as changes in fluid content affect the matrix
strength. The thicker, poorly-sorted, randomly oriented conglomerate of Lithofacies 8b was deposited as a more viscous, less fluidized flow than the thinner, graded units. The reverse and normal grading within a single sedimentation unit is typical of debris flows. Nilsen (1982) reported that many beds deposited by debris flows coarsen upward in their lower part and fine upward to the top of the bed, similar to the thinner, granule conglomerates of Lithofacies 8b.

Lateral shifting of the locus of deposition on the fan surface accounts for the lateral and vertical interbedding of Lithofacies 8 with Lithofacies 6 and 7. Stratigraphic relationships suggest that alluvial fan deposits migrated in and out of the braided stream or river environment. This surging of the fan system may reflect tectonic or climatic changes.
CHAPTER SIX

ROCK UNIT D

Lithologic Descriptions

Introduction

Rock Unit D, equivalent to the Canebrake Conglomerate of Dibblee (1954), is wedge-shaped, lies on the basement rocks of the Vallecito Mountains to the north and grades laterally into Units A and B. It was not possible to determine whether Unit D forms a fault contact or a nonconformity with the basement rock. In the northwest part of the field area, Unit D is laterally and vertically gradational with Unit C.

Only 350 feet of Unit D was recorded along measured section D-D' because of topographic restrictions (Plate 2). In the north the top of the unit is in contact with the basement rock. To the west the unit extends out of the field area attaining an undetermined thickness.

This youngest unit is only slightly deformed by the anticline and syncline plunging beneath its exposures. Dips range from 5 degrees to 30 degrees.

Rock Unit D consists of three lithofacies, including two sandstone dominated facies and a conglomerate facies.
Lithofacies 9

**Lithology.** Lithofacies 9 occurs as very light-gray (N8) medium-to coarse-grained locally conglomeratic sandstones. The sandstones are composed of poorly-sorted, angular framework grains consisting of 25 percent quartz, 35 percent feldspar (mostly plagioclase) and 40 percent plutonic rock fragments. The clasts consist mainly of granodiorite, bordering on tonalite, with varying percentages of gneissic and schistose rock also present. Calcite cement is variable, but locally strong giving these beds a very resistant nature.

**External bedding.** The sandstone beds form individual sedimentation packages with sharp erosional contacts. These beds first appear in Unit C 1,200 feet below the contact with Unit D in measured section D-D' (Plate 2). They are described here, however, because of their lithologic affinities with the other lithofacies of Rock Unit D. Thicknesses range from 1 to 3 feet and are laterally continuous at the outcrop scale of about 100 feet. Unfortunately, the northwestern part of the field area is extensively covered with recent terrace deposits which make lateral continuity difficult to record. One well-exposed bed was traced approximately 1,500 feet (Plate 1).

**Internal bedding.** Internally, Lithofacies 9 contains planar cross-bedding as solitary sets 1 to 2 feet in height. These structures are classified as alpha or beta cross-stratification of Allen (1964). Horizontal laminations 0.25 inches think dominate the sandier, less conglomeratic layers.
Only three paleocurrent direction indicators were recorded due to the limited exposure and indicate a wide range of transport directions measurements (Figure 29).

Lithofacies 10

**Lithology.** Lithofacies 10 consists of pale-yellowish brown (10 YR 6/2) fine- to medium-grained, locally conglomeratic sandstone. Grains are poorly-sorted, angular and feldspathic. Lack of cement makes for a very friable texture which weathers to a same yellow brown color. Pebble-sized clasts are granodiorite.

**External bedding.** External bedding in Lithofacies 10 is poorly exposed due to the friable nature of the outcrops. Thicknesses were estimated by the distances between discontinuous pebble stringers and range from 6 inches to 5 feet. Discontinuous mudstone layers are also present suggesting fining upward sequences between partings.

Lithofacies 10 forms a laterally and vertically gradational contact with Unit C. A 350 foot section of it was measured in the upper reaches of Olla Wash (Plate 2). This represents only a part of the entire thickness that forms the Mud Palisades (Plate 1). To the east Lithofacies 10 is juxtaposed against Lithofacies 11 in a high-angle fault contact.

**Internal bedding.** Discontinuous beds of 1 to 10 feet are delineated by pebble-sized strings of conglomerate. Mud chip rip-up clasts are also present near the base of the bedded sandstone.
Figure 29. Paleocurrent Rose Diagram, Lithofacies 9. 30 degree class interval. Measurements taken from cross-bedding foreset azimuths. Dashed arrow is Plio-Pleistocene North before regional 35 degree clockwise rotation.
Bedding styles are restricted to horizontal laminations 0.5 to 1.0 inches in thickness.

**Lithofacies 11**

**Lithology.** This lithofacies is composed of clast and matrix-supported conglomerates. Clasts range in size from pebbles to boulders with cobble-sized clasts predominating (Figure 30). Hand sample and petrographic analyses reveal a high proportion of granodiorite clasts. A small percentage of schists and gneissess are also present. The clasts are subangular to rounded with igneous clasts ellipsoidal in shape and metamorphic clasts rectangular. Sorting of the clasts is poor and imbrication is absent.

The matrix-supported conglomerates contain poorly-bedded sandstones of arkosic composition. Grain sizes vary from silt to medium-grained sand. Calcium carbonate forms a weak cement for the poorly sorted, subangular grains. The color is similar to Lithofacies 9, very-light gray (N8). Thin mudstone interbeds are also present.

**External bedding.** External bedding is poorly defined. Lithofacies 11 is not recorded in any of the measured sections and is best seen in the steep cliffs bordering Fish Creek Wash in the northernmost part of the field area. The cliff walls are formed by massive clast-supported conglomerates with intercalated matrix-supported layers north of the fault contact with Lithofacies 10.

**Internal bedding.** Lithofacies 11 is poorly-stratified and
Figure 30. Lithofacies 11, matrix- and clast-supported conglomerate.
bedding surfaces are weakly delineated by thin discontinuous sandstone layers interbedded with both matrix- and clast-supported conglomerates. Bed thicknesses range from 2 to 15 feet, averaging about 10 feet. Stacking of the beds produces the thick exposures seen along Fish Creek Wash.

**Depositional Environments**

**Introduction**

The coarse-grained, conglomeratic lithology and stratigraphic distribution of Unit D strongly suggests an alluvial fan environment marginal to the deltaic and fluvial deposits of Rock Units A, B, and C.

**Lithofacies 9.** The sedimentology and sheet geometry of lithofacies 9 indicates a sheetflood origin of deposition. Bull (1972) and Nilsen (1982) attributed sheet flood deposits to surges of sediment-laden water spreading out from channels on the fan surface producing rapidly shifting distributary channels which coalesce to form the sheet-like geometry. Varying paleocurrent directions recorded at different stratigraphic levels reflect various paleoslopes of the fan surface.

The sheetflood deposits represent the most distal site of alluvial fan deposition as they flowed out onto the valley floor intertonguing with the fluvial sediments of Rock Unit C. This is consistent with Bull's (1972) observation of sheetflood deposits below the intersection point on the distal portions of a modern fan system.
Lithofacies 10. Lithofacies 10 represents main distributary channel deposits and sheetflood deposits. Near the intersection point, migrating channels responding to tectonics and sediment supply produced a stacked sequence of channelized deposits and sheetflood deposits seen in Lithofacies 10. Similar rates of uplift of the source area and subsidence of the adjacent basin accounts for the thick accumulation (350 feet) of mid-fan sediments.

Lithofacies 11. The poorly-bedded, pebble-, cobble- and rare boulder-sized conglomerates were deposited in a proximal fan environment. Rapid erosion of a nearby source produced deposition at the fan apex by channel filling and debris flows. The crudely-stratified conglomerates are similar to Miall's (1978) Scott type of braided stream sequence typical of proximal alluvial fan deposits.

However, some discrepancies, such as lack of clast imbrication and the presence of interbedded sandstone layers suggest the possibility of deposition by debris flows within channels near the fan apex. Heavy rainfall or stream flow could then obscure the characteristics of a debris flow origin by winnowing the matrix away in the clast supported conglomerates. Intermittent stream flow is suggested by the sandstone lenses.

The proximal fan environment is also suggested by the contact with the adjacent basement rocks. The compositional similarity and angularity of the clasts provide additional evidence for a nearby source and, therefore, a proximal environment of deposition.
Chapter Seven

Paleogeography

Regional Discussion

The development of the Salton Trough began with crustal extension and rifting associated with opening of the Gulf of California. Down-dropped fault blocks developed in response to the rifting and Lower Neogene continental sediments were deposited into the depressions as described by Kerr (1982, 1984). This was followed by the incursion of marine waters and the development of a delta system at the mouth of the Colorado River. These marine deposits of the Imperial Formation have been described by Bell (1980) and Pappajohn (1980) and represent some of the underlying sediments of those described in this study.

Based on magnetic anomalies and seismic data, the development of the Gulf of California produced numerous pull-apart basins within a ridge-transform fault system (Larson, 1972). With continued rifting, right-lateral strike-slip movement began on the San Jacinto and Elsinore fault zones. This compounded the right-lateral displacement along the already active San Andreas fault system.

Crowell and Sylvester (1979) pointed out that in the last 3 to 4 million years about 40 miles of combined slip along the Elsinore and San Jacinto fault zones and about 110 miles of displacement along the San Andreas has taken place for a total of approximately 150 miles of displacement. Upon palinspastic reconstruction, the field area lies...
in the vicinity of the modern day Colorado River Delta. This suggests that the delta region has been relatively stationary since Plio-Pleistocene time. Displacement along the right-lateral fault systems accounts for the up-section stratigraphic shift from marine to non-marine depositional environments. However Woodard (1974) suggests presence of brackish-water molluscs throughout the Palm Spring Formation indicates that deposition occurred near sea level and sedimentation rates approximated the rate of basin subsidence (Johnson et al., 1983).

Field Area Interpretation

Within the field area, paleocurrent data and vertical and lateral distribution of lithofacies assemblages suggest complex and dynamic paleogeographic settings through time. Paleocurrent directions used for the palinspastic reconstructions have been corrected for the tectonic rotations discussed in Chapter 1.

Beginning with Rock Unit A, deposition took place on the upper delta plain surfaces very near sea level. Delta morphology was probably between the fluvial- and tidal-dominated type models. This accounts for the development of restricted brackish-water environments of Lithofacies 1, which are usually associated with fluvial-dominated deltas. Here, active migration of the distributary channels produce bays suitable for the establishment of oyster reefs.

Continued shoaling and lateral migration of the distributary channels, probably in an eastward direction, could have then produced the tidal-dominated delta plain environment. Lithofacies 2, 3, and 4
represent such deposits where gypsiferous sediments are found in supratidal regions and over-bank deposits laid down during flood conditions are reworked by tidal currents, similar to those found in the modern tidal-dominated mouth of the Colorado River.

Simultaneously, alluvial fans were forming at the base of the Vallecito Mountains, represented by the laterally gradational relationship between Units A and D. Figure 31 shows the paleogeographic reconstruction during this time of deposition.

Tectonic uplift and/or recession of the shoreline is reflected by the terrestrially dominated lithofacies of Unit B. Actively migrating meandering distributions of the Colorado River account for the cyclic deposition of the point-bar sequences and crevasse splays seen in Lithofacies 3, 4, and 5. Intermittent marine influxes are indicated by the presence of Lithofacies 2 low in the member. These may have been the result of eustatic sea level changes, but are more likely the result of the abandonment and subsequent subsidence of distributary channel lobes. Continued deposition of alluvial fan sediments adjacent to the flood plain is shown in Figure 32.

During the time of deposition of Unit C, new sediment sources were introduced. Low in the unit, the rarity of Lithofacies 3, 4, and 5 suggest the shifting of Colorado River distributaries, possibly to the east while deposition occurred mainly by braided streams (Lithofacies 6 and 7). Paleocurrent indicators and petrographic analysis suggest transport from a fairly close, northwestern source rich in biotite and plagioclase feldspar. Granodiorite and tonalite
Figure 31. Paleogeographic reconstruction during deposition of Rock Unit A.
Figure 32. Paleogeographic reconstruction during deposition of Rock Unit B.
igneous rock types of the eastern Penninsular Range to the west were a probable source area.

The alluvial fan sediments of Lithofacies 8 were deposited in mid to lower fan surface environments. The vertical and lateral relationship with the braided stream deposits suggest progradation of the fan system onto the valley floor adjacent to the braided streams. The sudden influx of alluvial sediment could have caused the choking of streams interpreted to have produced Lithofacies 6. Apparently, alluvial fan deposition was not continuous which accounts for the vertical interbedding of the two lithofacies assemblages (Figure 33).

High in Unit C, the reappearance of Lithofacies 3, 4, and 5 indicate the probable westward migration of the Colorado River distributaries back into this area of the flood plain. In addition, sheet-flood deposits of Lithofacies 9, made their way onto the floodplain from the adjacent alluvial fans at the base of the Vallecito Mountains (Figure 34).

The lithofacies of Unit D represent the development of alluvial fans building out from the base of the Vallecito Mountains contemporaneous with the deposition of Units A, B, and C, as shown in the previous paleographic reconstructions. With continued infilling of the Salton Trough, alluvial fan deposits prograded onto the valley floor overlying the fluvial sediments of Unit C (Figure 35).

An arid to semi-arid paleoclimate is indicated by evaporite deposits (Lithofacies 2) and the torrential rains needed to produce debris flows (Lithofacies 8) on alluvial fan surfaces. Lack of root
Figure 33. Paleogeographic reconstruction during deposition of lower Rock Unit C.
Figure 34. Paleo-geographic reconstruction during deposition of upper Rock Unit C.
Figure 35. Paleogeographic reconstruction during deposition of Rock Unit D.
casts and the presence of mud cracked surfaces imply sparse vegetation often associated with arid to semi-arid conditions similar to the climate of the area today.

Downs and White (1961), however, found a variety of faunal evidence in the Palm Spring Formation indicating locally wooded and open grassland environments during middle Pleistocene. These contrasting paleoclimate indicators suggest the climate was not nearly as dry and arid as it is today and the area received sufficient rainfall in sometimes large amounts for the development of grasslands on the floodplain and to produce debris flows on the adjacent alluvial fans.
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ABSTRACT
Abstract

The uppermost Imperial Formation, Palm Spring Formation and Cane-brake Conglomerate represent marine to nonmarine sediments which filled the Salton Trough during the late Pliocene to middle Pleistocene time. Mapping of 15 square miles and measurement of 5,200 feet of continuous strata and 4,500 of laterally equivalent section enabled the recognition of four vertically gradational rock units. Within these Rock Units A through D, 11 lithofacies were identified which represent cyclicly deposited sediments not restricted to any particular rock unit. Depositional environments of the rock units were interpreted by the vertical and lateral stratigraphic relationships and sedimentary structures and paleocurrent data recorded within the lithofacies.

Rock Unit A, equivalent to the uppermost Imperial Formation and the lowermost Palm Spring Formation, is composed of marine-fossil-bearing sandstone (Lithofacies 1), gypsiferous mudstone (Lithofacies 2), and nonmarine mudstone and siltstone (Lithofacies 3 and 4), respectively. These rocks were deposited from an eastern source in the Colorado River delta system in brackish-water, restricted bay and interdistributary mudflat environments.

Rock Unit B is equivalent to the Palm Spring Formation and consists of cyclicly deposited, fining-upward sandstone (Lithofacies 5) interbedded with Lithofacies 3 and 4, with rare deposits of Lithofacies 2. Petrographic analysis reveals quartz overgrowth rims
suggesting a second cycle origin. Sedimentation occurred as meandering distributary point-bar deposits on the upper delta plain and lower flood plain Colorado River system.

Rock Unit C, equivalent to the Palm Spring Formation, is dominated by multistoried, locally conglomeratic sandstone (Lithofacies 7) and laterally equivalent interbedded sandstone and mudstone (Lithofacies 6), both deposited by braided streams from a western source. Alluvial fan sediments ((Lithofacies 8) migrated onto the flood plain from the northwest in debris flows and stream channels. Subsequently, the Colorado River system migrated back into the area depositing the point-bar sequences found high in the section of Rock Unit C.

Equivalent to the Canebrake Conglomerate and laterally gradational to Rock Units A, B, and C is Rock Unit D, which represents alluvial fan sediments (Lithofacies 9, 10, and 11) deposited along the base of crystalline highlands adjacent to the flood plain.

Palinspastic reconstruction of the region along right-lateral faults associated with the rifting of the Gulf of California, to the time of deposition, beginning 3 to 4 million years ago, places the area in the vicinity of the modern day Colorado River delta. This suggests that the delta system has been relatively stationary and accounts for the sedimentologic similarities between some of the lithofacies and the modern deposits of the Colorado River flood plain and delta and adjacent regions.
PLATE 1: GEOLOGIC MAP OF FISH CREEK WASH AREA

Stratigraphy and Depositional Environment of a Pliocene marine -nonmarine sequence, Western Salton Trough, California

Steven Michael Richardson
Stratigraphy and Depositional Environm{ent} of a Pliocene-Pleistocene marine-nonmarine sequence, Western Salton Trough, California

Steven Michael Richardson

PLATE 2: MEASURED SECTIONS

ROCK UNIT D
ROCK UNIT C
ROCK UNIT B
ROCK UNIT A

EXPLANATION

Vertical Scale 1" = 100'

Legend:
1. Marine fauna-bearing intervals
2. Marine oozes
3. Marine glauconite
4. Marine sediments with plant remains
5. Marine tufa
6. Marine tuff with sandstone intercalations
7. Marine siltstones with sandstone intercalations
8. Marine conglomerates with sandstone intercalations
9. Marine conglomerate
10. Marine breccia
11. Marine tuff
12. Marine sandstones
13. Marine conglomerates
14. Marine breccias
15. Marine tuffs
16. Marine oozes
17. Marine faunas

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