TECTONIC AND HYDROLOGIC CONTROLS ON CYCLIC ALLUVIAL FAN, FLUVIAL, AND LACUSTRINE RIFT-BASIN SEDIMENTATION, JURASSIC-LOWERMOST CRETACEOUS TODOS SANTOS FORMATION, CHIAPAS, MEXICO[1]

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ABSTRACT: The nonmarine Upper Jurassic–lowermost Cretaceous Todos Santos Formation of central Chiapas, Mexico, was deposited in half-graben basins formed during the early rifting stage of the southern Gulf of Mexico Basin. This formation consists of alluvial-fan, fluvial, and lacustrine sequences that were deposited under arid climatic conditions. Alluvial fans were built outwardly from the elongate basin margins by runoff that flowed transverse to the basin axis, whereas fluvial units were deposited by rivers that flowed parallel to the basin axis. Lacustrine deposition took place in a topographic depression adjacent to the basin margin. The presence of alluvial-fan and fluvial or lacustrine deposits in vertically stacked, cyclic megasequences hundreds of meters thick indicates that the basin topography changed through time. This cyclicity denotes that periodically fluvial or lacustrine environments occupied the basin-margin position and at other times alluvial-fan sedimentation occurred there. Cyclicity was caused by periodic changes from high to low rates of basin subsidene. The response of these three depositional environments to basin subsidence differed due to the unique hydrologic controls on sediment transport and deposition in each environment. Lakes were maintained by springs that emanated from the fractured fault margin and by fluvial discharge. Fluvial discharge and deposition resulted from precipitation or annual snowmelt anywhere in the river's expansive drainage basin, whereas alluvial-fan sedimentation occurred only when there was infrequent, significant precipitation in the small drainage basin from which fan sediment was derived. As a result of these hydrologic controls, the lacustrine or fluvial environments responded more quickly to periods of active tectonic subsidence and migrated over the fans to occupy the basin-margin depression. Aided by a decrease in basin subsidence, alluvial fans eventually prograded and displaced the fluvial or lacustrine environments away from the basin margin.

INTRODUCTION

Alluvial-fan, fluvial, and lacustrine depositional environments are characteristic of modern nonmarine rift and pull-apart basins, such as in the Basin and Range Province of the western United States (Hunt and Mabey 1966; Mulhern 1982; Osborne et al. 1982); the east African rift basins (Vondra and Burggraf 1978; Burggraf and Vondra 1982; Tiercelin 1984); the Dead Sea rift (Sneh 1979); the East Anatolian pull-apart basins in Turkey (Hempton and Dunne 1984); and the Salton Basin of southern California (Van de Kamp 1973). These basins most commonly have a strongly elongated shape, varying in width from 15 to 100 km and in length to hundreds of kilometers. They are characterized structurally by block faulting, typically forming half grabens, in which one side of the basin undergoes significantly more subsidence than the other. Alluvial fans are commonly built outwardly from the long, high-angle, fault-bounded basin margins by high-gradient feeder channels that flow transverse to the basin axis. Fan deposition is restricted to these basin margins, rarely extending outward from the fault more than 15 km (Heward 1978) and generally extending for less than 10 km (Anstey 1965). Fluvial sedimentation results from deposition in relatively lower-gradient rivers that are oriented longitudinally to the basin axis. Lakes are developed in topographic depressions that commonly are elongated parallel to the basin axis.

In ancient rift and pull-apart basin fills such as the Tertiary Ridge Basin of California (Link 1982, 1984; Link and Osborne 1982); the Miocene of the Rio Grande Rift of New Mexico (Cavazza 1985); the Devonian basins of Norway (Steel 1976; Steel et al. 1977) and Scotland (Wilson 1980); the Permo-Triassic North Minch Basin of Scotland (Steel and Wilson 1975); the Triassic-Jurassic basins of the eastern United States (Turner-Peterson 1980; LeTourneau 1985); and the Late Jurassic–earliest Cretaceous basins of the southern Gulf of Mexico region (this paper), basin-margin alluvial-fan and basin-axis fluvial-lacustrine deposits are found in vertically stacked *megasequences* (term following definition of Heward 1978) hundreds of meters thick. In these ancient basin-fill sequences, the basin-margin and basin-axis megasequences alternate vertically, resulting in large-scale cyclicity. This cyclicity in well-studied ancient rift and pull-apart basins is limited to the part of the basin fill deposited on the tectonically most active side of these ancient half grabens (Steel et al. 1977; Turner-Peterson 1980; Link and Osborne 1982). Such cyclicity indicates that periodically, the basin-axis fluvial-lacustrine environments occupied the basin-margin position, and that at other times alluvial-fan deposition took place there. This cyclicity in these ancient basin-fill sequences is generally thought to be caused by tectonism, with alternation between periods of active tectonic subsidence and periods of less active or negligible subsidence (Steel and Wilson 1975; Steel 1976; Steel et al. 1977; Heward 1978; Wilson 1980; Mack and Rasmussen 1984). The way in which alluvial-fan, fluvial, and lacustrine environments in extensional basins respond to varying rates of tectonic subsidence, however, is poorly understood.

The purpose of this paper is to present a detailed sedimentologic, stratigraphic, and tectonic analysis of exposures of the Upper Jurassic–lowermost Cretaceous Todos Santos Formation of central Chiapas, Mexico. This nonmarine formation was deposited in Late Jurassic–earliest Cretaceous half-graben basins that formed during the early rifting stage of development of the southern Gulf of

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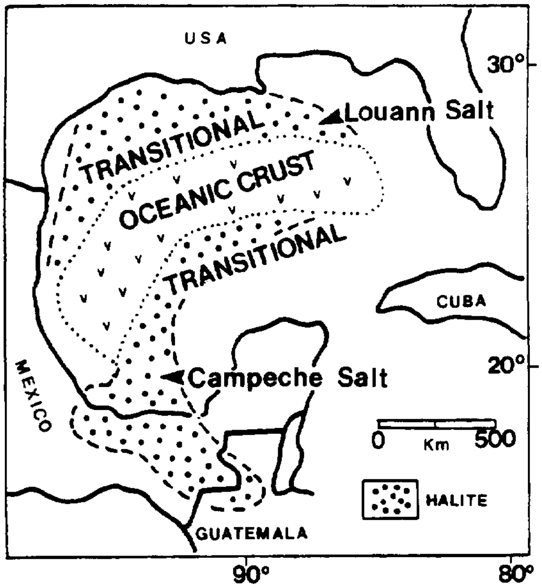

FIG. 1.—Distribution of crustal types and thick Jurassic evaporite deposits, Gulf of Mexico (from Buffler et al. 1980; location of evaporite deposits in Mexico and Guatemala is from Viniegra Osario 1981). Transitional crust consists of continental crust that was attenuated by rifting.

Mexico Basin (Blair 1986). The specific objectives of this paper are 1) to describe the distinctive sedimentologic and stratigraphic characteristics of the basin-margin alluvial-fan deposits and the basin-axis fluvial-lacustrine deposits; 2) to demonstrate the subenvironmental controls and the tectonic significance of vertical changes in stratigraphy within individual alluvial-fan megasequences; and 3) to identify the origin of, and controls on, cyclicity between basin-margin alluvial-fan and basin-axis fluvial-lacustrine megasequences based on a comparative analysis with modern analog basins of the southwestern United States.

BACKGROUND INFORMATION

Geological Setting

The Gulf of Mexico Basin formed as a result of Mesozoic rifting between the North American Plate and the Yucatán Block, as indicated by the presence of oceanic crust in the central Gulf, by the lack of a subduction zone along any of the boundaries of this oceanic crust, and by the presence of extended continental crust peripheral to this oceanic crust (Fig. 1; Buffler et al. 1980; Dickinson and Coney 1980; Salvador and Green 1980). Two thick Jurassic evaporite sequences, the Louann Salt Province in the northern Gulf and the Campeche Salt Province in the southern Gulf (Fig. 1), are contained within basins in areas of the Gulf that are underlain by extended continental crust (Buffler et al. 1980). Seismic data from the Campeche Salt Province demonstrate that salt and associated sedimentary rocks were deposited within half-graben rift basins (Buffler et al. 1980; Schlager et al. 1984). A residual magnetic anomaly map compiled by Martin and Case (1975) shows that the Campeche Shelf and the southwestern part of the Gulf are underlain by alternating elongate magnetic highs and lows (Fig. 2) interpreted to represent basement block horsts that are separated by sediment-filled grabens (Ensminger and Matthews 1972; Schlager et al. 1984). This conclusion was confirmed in the eastern Campeche Shelf by data from five wells drilled during Legg 77 of the Deep Sea Drilling Project (Schlager et al. 1984), and in southeastern Campeche Bay and in Tabasco and northern Chiapas by Petroleos Mexicanos wells (Viniegra Osario 1981). The presence of a widespread zone of alternating horsts and grabens suggests that the paleotopography of this region during rifting was similar to that of the present Basin and Range Province of the western United States. Elongate rift basins on the Campeche Shelf have a NNE-SSW orientation, whereas they trend N-S to NNW-SSE in the Campeche Bay area (Fig. 2). Viniegra Osario's (1981) Jurassic paleogeographic map of northern Central America, based mainly on Pemex well data, shows that the Campeche Salt and associated graben-fill deposits extend from the Campeche Shelf onto the Mexican mainland and into Guatemala (Fig. 1).

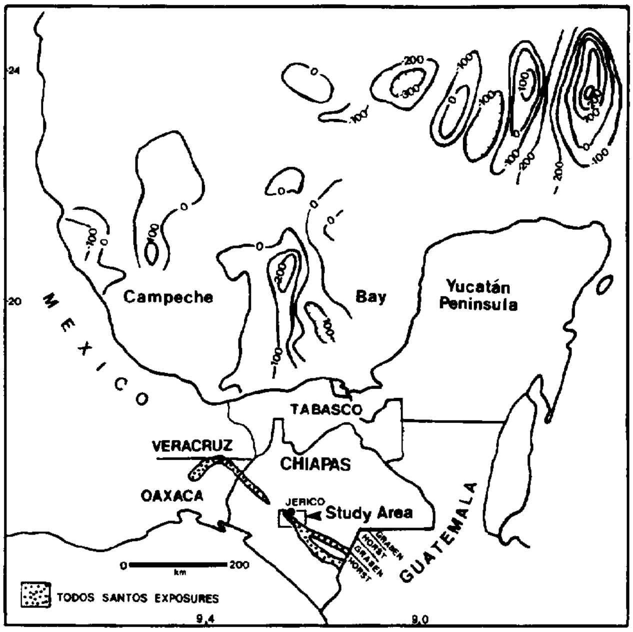

FIG. 2.—Magnetic anomaly map of the southern Gulf of Mexico (from Martin and Case 1975). Contour interval is 100 gammas. The location of Late Jurassic–earliest Cretaceous horsts and graben basins in western Guatemala is from Burkart and Clemons (1972). Todos Santos Formation exposures and the location of the study area near Jerico, Chiapas, are also shown.

These basal Mesozoic units are exposed in the Sierra de los Cuchumatanes in northwestern Guatemala and along the northern flank of the Sierra Madre del Sur in the adjacent southeastern Mexican state of Chiapas (Fig. 2; Richards 1963; Clemons and Burkart 1971; Anderson et al. 1973; Lopez Ramos 1975). These exposures consist of a lower nonmarine clastic unit called the Todos Santos

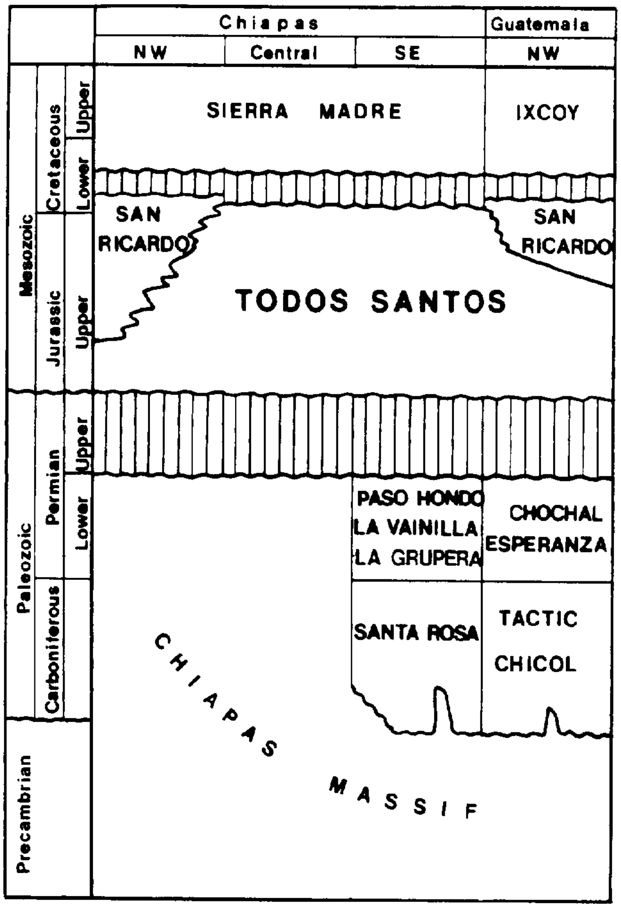

FIG. 3.—Stratigraphic column for exposures in Chiapas, Mexico, and in northwestern Guatemala (from Thompson and Miller 1944; Richards 1963; Clemons and Burkart 1971; Anderson et al. 1973; Hernandez Garcia 1973; Castro Mora et al. 1975; Blair 1986).

Formation, which is conformably overlain by, and interfingers with, nearshore marine clastics, carbonates, and evaporites of the San Ricardo Formation (Fig. 3; Sapper 1894; Richards 1963; Blair 1986). Thin, andesitic volcanic rocks are locally present at the base of the Todos Santos Formation (Castro Mora et al. 1975; Blair 1981, 1986). The Todos Santos–San Ricardo sequence ranges from early Late Jurassic to earliest Cretaceous (Neocomian) in age (Richards 1963; Clemons and Burkart 1971; Anderson et al. 1973; Castro Mora et al. 1975; Alencaster 1977; Blair 1981, 1986; Michaud 1984). The Todos Santos and lower San Ricardo are coeval, and interfinger in the subsurface with thick marine halite deposits of the Salina Formation (Imlay 1953; Castillo Terjero 1955; Contreras and Castillon 1968; Viniegra Osario 1971, 1981; Meyerhoff *in* Bishop 1980; Blair 1986).

The Todos Santos Formation nonconformably overlies Precambrian and Paleozoic igneous and metamorphic massif rocks throughout most of Chiapas, and locally in Guatemala (Fig. 3; Richards 1963; Anderson et al. 1973; Castro Mora et al. 1975; Lopez Ramos 1975). This massif in Chiapas is dominated by an exposed Permian granitic batholith (Damon et al. 1981) that intruded Precambrian metamorphic rocks (Lopez Ramos 1975). In southeastern Chiapas and in northwestern Guatemala, the Todos Santos overlies with angular unconformity a Carboniferous to Lower Permian sequence of marine strata (Fig. 3; Gutierrez-Gil 1956; Clemons and Burkart 1971; Hernandez Garcia 1973; Anderson et al. 1973; Litke 1975). This Upper Paleozoic sequence is composed of the Santa Rosa, Grupera, La Vainilla, and Paso Hondo Formations in Chiapas (Thompson and Miller 1944; Hernandez Garcia 1973), and the Tactic, Chicol, Esperanza, and Chochal Formations in Guatemala (Clemons and Burkart 1971). The Todos Santos–San Ricardo package throughout the region is unconformably overlain by Albian to Turonian carbonates of the Sierra Madre Formation (Clemons and Burkart 1971; Castro Mora et al. 1975; Blair 1986).

Previous Paleoenvironmental and Paleotectonic Work

Exposures of the Todos Santos Formation in northwestern Guatemala are interpreted to be the product of alluvial-fan, fluvial, and lacustrine deposition (Lattimore 1962; Richards 1963; Anderson 1969; Anderson et al. 1973; Litke 1975). Richards (1963), who studied the Todos Santos in western Chiapas, suggested that it was deposited there in "pediment," fluvial, and lacustrine environments. The lateral association of the Todos Santos with widespread evaporites of the Salina and San Ricardo Formations (Imlay 1953; Castillo Terjero 1955; Contreras and Castillon 1968; Viniegra Osario 1971, 1981; Meyerhoff *in* Bishop 1980; Blair 1986), and the presence of halite casts (Litke 1975), indicates that this formation was deposited under regionally arid climatic conditions.

The Todos Santos Formation in Guatemala is interpreted to have been deposited in fault-bounded grabens or half grabens (Anderson 1969; Burkart and Clemons 1972; Anderson et al. 1973; Litke 1975). Isopach maps of the Todos Santos exposures in northwestern Guatemala demonstrate the existence of linear, northwest-trending, thick graben fills separated by horst blocks (Fig. 2; Burkart and Clemons 1972; Anderson et al. 1973).

Location and Methods of Study

A northwest-trending, 11-km-wide belt of previously unstudied exposures of the Todos Santos Formation located near Jerico, in central Chiapas (Figs. 2, 4), is the subject of this investigation. These exposures unconformably overlie granitic rocks of the Chiapas Massif and are unconformably overlain by the middle Cretaceous Sierra Madre Formation (Fig. 4). Five stratigraphic sections, including the Finca San Antonio, Highway 83, Jerico, Quebrada Colorada, and Ramal Embalse sections, were measured and analyzed in detail. Two reconnaissance sections, one at Finca Santa Yerba, and one at Presa de la Angostura (Fig. 4), were also examined. Most major units could be traced laterally between these seven sections. The formation has a maximum thickness of 1,350 m in the study area, and thins to 250 m as a result of the removal of the upper Todos Santos at the overlying un-

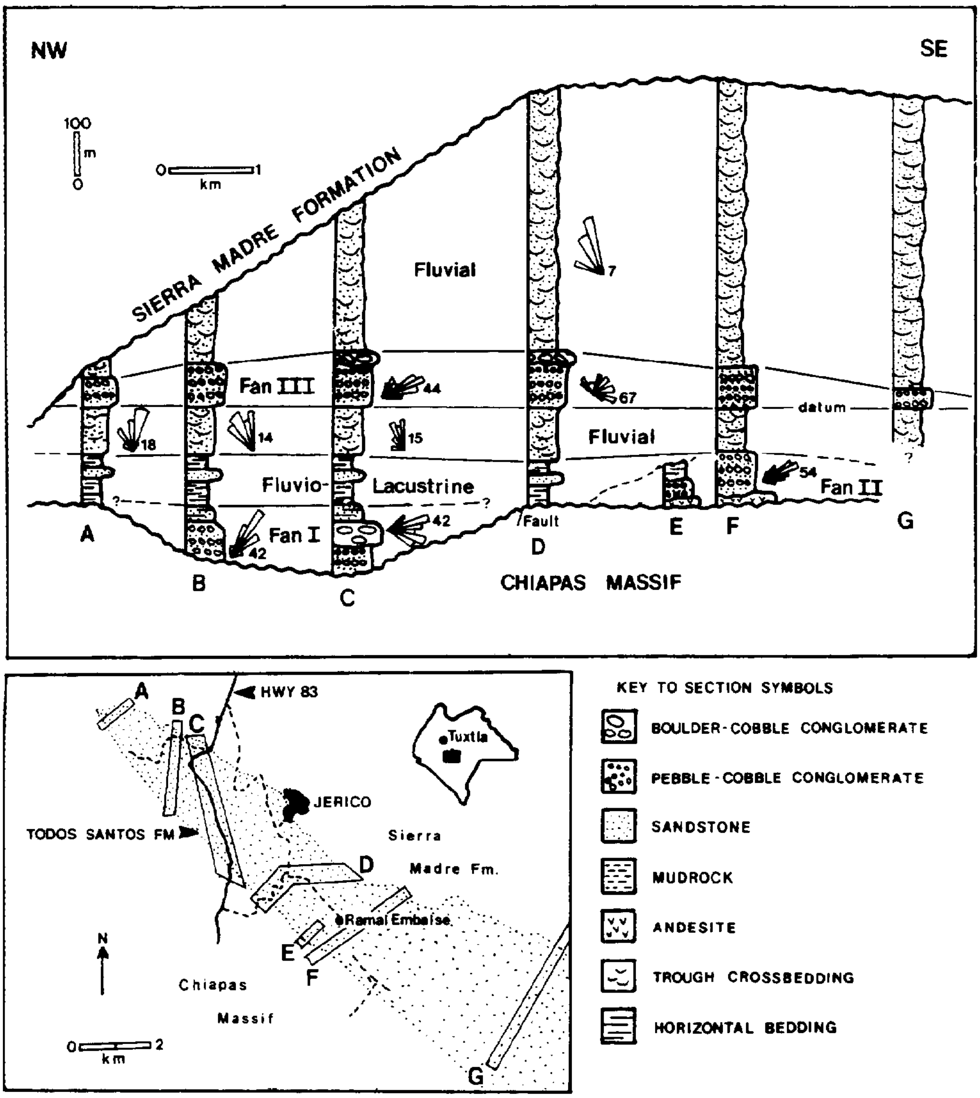

FIG. 4.—Cross-section of exposures of the Todos Santos Formation in central Chiapas. Rose diagrams are constructed from paleocurrent data obtained from clast imbrication in the conglomerate deposits, and from trough crossbedding in the fluvial deposits. Number of paleocurrent readings indicated adjacent to rose diagrams. Sections include A = Finca Santa Yerba; B = Finca San Antonio; C = Highway 83; D = Jerico; E = Quebrada Colorada; F = Ramal Embalse; G = Angostura. Location map of sections is also shown. Datum is the base of the Fan III deposits.

conformity (Fig. 4; Blair 1986). Provenance studies indicate that these Todos Santos exposures were derived primarily from the Permian granitic rocks (85–95%), and secondarily from the Late Paleozoic sedimentary rocks (0–5%) and andesitic volcanic rocks (5–10%) similar to those found in the basal part of the formation (Blair 1986).

FACIES ASSOCIATIONS AND DEPOSITIONAL ENVIRONMENTS

The Todos Santos Formation in the study area consists of four distinct facies associations: A) crossbedded, pebbly, granular, coarse sandstone and sandy, pebbly, granule conglomerate; B) mudrock with rare limestone; C) lenticular, fine sandstone and horizontally bedded, fine sandstone and mudstone; and D) massive or horizontally bedded, sandy, boulder, cobble, and pebble conglomerate and coarse sandstone. Thin volcanic flows and tuffs also occur locally. The inferred paleoenvironments represented by these facies associations were determined by examination of 1) the individual facies types and their paleocurrents; 2) the stratigraphic interrelationship of the facies; 3) the regional context of the deposits; and 4) by sedimentologic comparison with modern analog environments.

Facies Association A: High-Gradient Fluvial Deposits

The pebbly, granular sandstone and sandy, pebbly granule conglomerate facies association most typically displays trough-crossbedding (Fig. 5a) or broad, lenticular bedding (Fig. 5b). Less common are horizontally bedded and planar-crossbedded sets of pebbly, granular, coarse sandstone. Trough-crossbedded sets, which range from

0.1 to 1.0 m in thickness, were deposited over trough or channel-shaped scours (Fig. 5a, b). These scours range from 1.0 to 3.0 m in width and 0.5 to 2.0 m in depth. Textures vary abruptly both vertically and laterally due to the abundance of these scour surfaces. Some of the erosional surfaces are outlined by a mudstone drape (Fig. 5b), which probably represents deposition of suspended load during the waning stage of a sedimentation event. The presence of drapes indicates that these erosional features were not always filled with sediment during the same event in which they were formed. The preservation of mudstone drapes probably was caused by rapid sedimentation during the subsequent depositional event. The localized presence of abundant mudstone rip-up clasts at the base of many scour fills (Fig. 5b) demonstrates that deposition of mud drapes was common but that these drapes typically were reworked. Laterally widespread, thin accumulations of pebbles, which occur along horizontal surfaces that truncate crossbedding, are also present within these deposits (Fig. 5c).

Petrified conifer logs and limbs, preserved by calcification, carbonization, and silicification, are common within these deposits (Fig. 5c). The logs are as much as 20 cm in diameter and 3 m in length. They are generally oriented perpendicular to the direction of crossbed foresets and are concentrated along distinct, local, stratigraphic horizons.

This facies association is interpreted to have been deposited by high-gradient, possibly ephemeral, braided streams that experienced great fluctuations in discharge. Deposition occurred mainly during high discharge events by lateral and vertical accretion along with channel cutting and abandonment. The laterally widespread, thin pebble accumulations (Fig. 5c) are interpreted to represent deflation lags that formed from the removal of sand by wind erosion to produce a desert pavement. These deflation lags probably formed during intervals of time when the dry, unconsolidated, braided-stream deposits were exposed to wind erosion. Such lags were later scoured locally by subsequent discharge events (Fig. 5c). By analogy with modern sedimentologic and meteoric characteristics of extensional basins of the Basin and Range Province of the southwestern United States, the conifer logs in the Todos Santos Formation are interpreted to have been transported to the basin during major flood events by streams flowing from the adjacent uplands. Conifer forests probably occurred at higher elevations in the adjoining horst block, where precipitation was higher.

Facies Association B: Lacustrine Deposits

The mudrock with rare limestone facies association consists mainly of nonbioturbated, laterally persistent, horizontally interstratified gray to brown claystone and brown, very fine, sandy siltstone (Fig. 6a). The claystone units, which make up 70 percent of this facies association, are 0.2 to 3.0 m thick and are massive or thinly laminated. The very fine, sandy siltstone units make up 25 percent of this facies association and occur mainly in thin to thickly laminated sets 10 to 50 cm thick. Less common

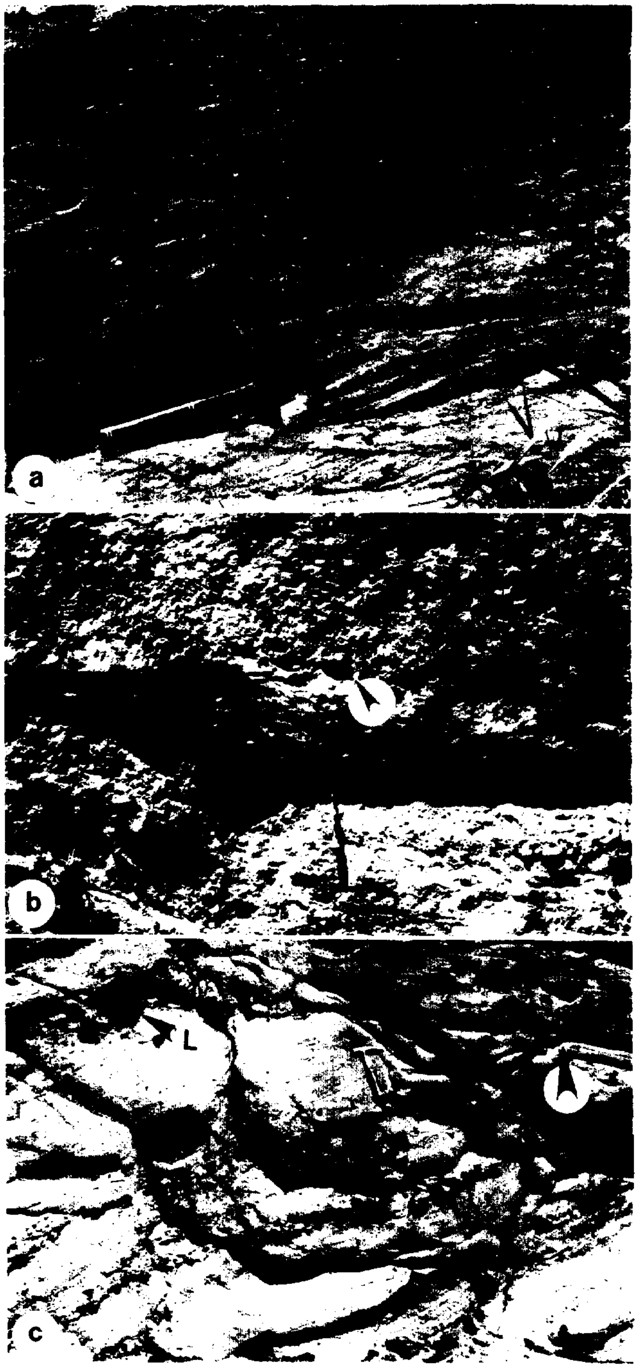

FIG. 5.—Views of the high-gradient, longitudinal fluvial deposits. a) Trough-crossbedded sets of pebbly coarse sandstone are very common. b) A thin claystone drape outlines an abandoned channel which was later filled by a sequence of sandstone and pebble conglomerate. Mudstone rip-up clasts are abundant near the base of the channel-fill conglomerate (arrow). c) Two horizontal pebble deflation lags interpreted to be desert pavement surfaces are present. The upper one is truncated in the right part of the photograph by an erosional surface (arrow). Conifer logs (L) are also present.

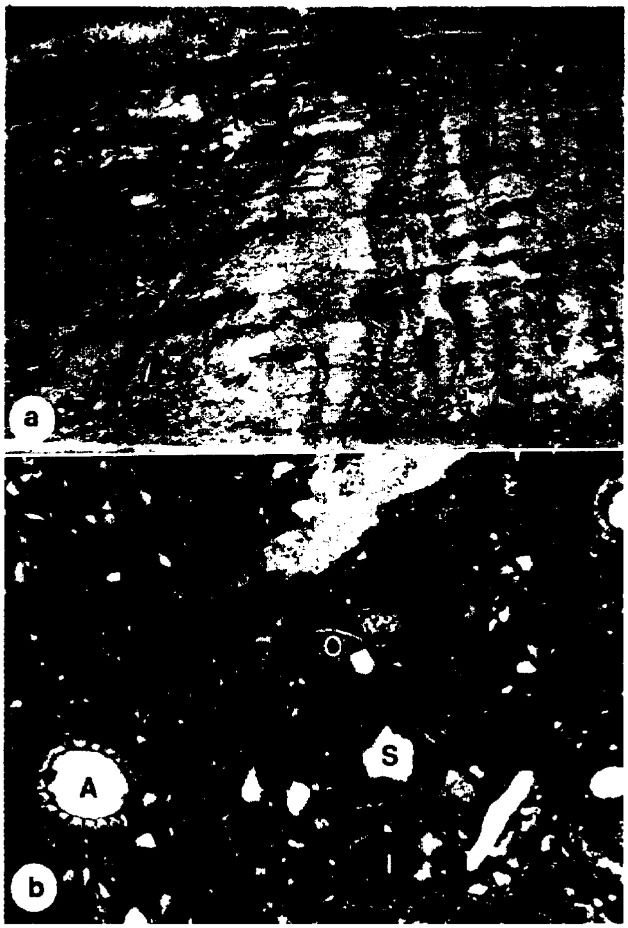

FIG. 6.—Views of the lacustrine deposits. a) Overview of horizontally interbedded claystone and sandy siltstone. b) Photomicrograph of a sample from a lacustrine carbonate bed. Charophytic algal gyrogonites (A), ostracode fragments (O), intraclasts (I), and quartz sand (S) are locally abundant. Labeled algal gyrogonite is 0.75 mm across.

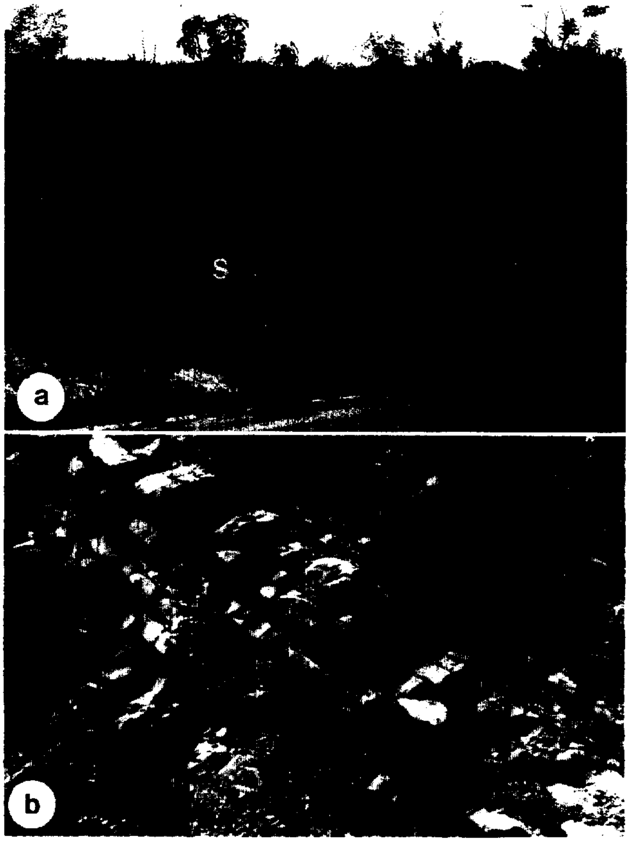

FIG. 7.—Views of the low-gradient fluvial deposits. a) Large-scale channel sandstone deposits that partly filled a major (10-m-wide) channel-shaped erosional scour (S). b) Close-up of horizontally bedded overbank sandstone deposits which are separated by mudstone beds.

are small-scale trough-crossbedded sets of similar thickness. The siltstone sets commonly are capped by current ripples, whereas load casts and rare flute casts are present at the base of these units where they overlie claystone. Contacts between siltstone and adjacent claystone units invariably are sharp (Fig. 6a). Carbonaceous plant material and mica flakes are commonly concentrated along bedding planes. Rare, thin volcanic ash beds are also present. The remaining five percent of this facies association consists of discontinuous interbeds of limestone up to 10 cm thick. These beds consist mainly of lime mudstone, whereas intraclasts, ostracode, and charophytic algal fragments are locally abundant (Fig. 6b).

The widespread extent of this facies association (> 9 km along strike), the lack of desiccation features, and the lack of evaporite deposits despite the arid climate setting suggest that it was deposited in a large, perennial lake. The presence of charophytic algal remains in the carbonates indicates that at the time of their deposition, shallow lake conditions existed (Murphy and Wilkinson 1980; Dean and Fouch 1983). The abundance of claystone indicates that the primary mode of sedimentation was of suspended material. Sandy siltstone deposition probably occurred when an influx of coarser sediment was transported to the lake by a rainfall event. The erosive bases of some of the siltstone beds indicate that this material was in part transported to the lake bottom by tractive forces, whereas the current ripples present on the top of the siltstone beds probably formed during the waning depositional phase, or by wind-generated waves. The common presence of current ripples on the tops of siltstone beds, the preponderance of claystone deposits, and the presence of charophytic algal carbonates suggest that the lake varied from shallow to deep enough to be below wind-generated wave base throughout much of its existence.

Facies Association C: Low-Gradient Fluvial Deposits

Facies Association C is made up of lenticular, fine sandstone and horizontally bedded, fine sandstone and mudstone. The lenticular, fine sandstone bodies have a northwest-trending ribbon geometry and vary in thickness from 0.5 to 2.0 m and in width from 5.0 to 15.0 m. They overlie major scour surfaces (Fig. 7a) formed by erosion into either other lenticular sandstone bodies, horizontally bedded siltstone and mudstone, or lacustrine deposits. Within the lenticular units are horizontal bedding and small-scale trough-crossbedding. Mud rip-up clasts are abundant at the base of these sand bodies, and rarely, slump structures are present near some of their margins.

The horizontally bedded fine sandstone and mudstone units (Fig. 7b) occur lateral to and between the lenticular sandstone units. The sandstone sets are 10 to 20 cm thick, display horizontal and ripple stratification, and have sharp, planar boundaries (Fig. 7b). Intervening siltstone and mudstone beds, which contain mica flakes and carbonaceous leafy plant fragments, are 5 to 10 cm thick and typically are laminated or massive. Rare vertical to oblique burrows (from insect larvae?) 2 to 5 cm long and 0.3 cm in diameter are also present.

This facies association is interpreted to represent a low-gradient fluvial channel and overbank depositional environment. The pronounced erosional surface at the base of the lenticular channel sandstones indicates that these channels were formed during major erosional events, whereas slumps present along some of the channel margins suggest that lateral cutting also occurred. The horizontally bedded, fine sandstone and mudstone facies that occurs lateral to the channel sandstones was deposited at times of overbank flooding. The prevalence of mudrock and fine sandstone in this facies association suggests that this fluvial system was of relatively low gradient.

These low-gradient fluvial deposits are both overlain and underlain by lacustrine deposits (Fig. 4). The presence of this low-gradient fluvial sequence above lacustrine deposits indicates that the lake was terminated, either by sediment filling or by a lowering of lake level, and that the fluvial system that originally occupied this area traversed the flat lake-bed surface. The fact that the low-gradient fluvial deposits are overlain by a second lacustrine interval indicates that either lake level rose dramatically or that the area was subsided tectonically.

Facies Association D: Alluvial-Fan Deposits

The boulder, cobble, and pebble conglomerate with sandstone facies association consists primarily of two distinct conglomeratic facies and one sandstone facies interpreted to have resulted from deposition on alluvial fans as sheetfloods and within incised channels. Three distinct fan megasequences (labeled I, II, and III on Fig. 4) are present.

Proximal Sheetflood Deposits.—The most common facies in this association consists of cobble-pebble conglomerate that is sharply interstratified with fine, pebbly, granular, coarse to very coarse sandstone (Fig. 8a, b, c). Interstratification can be seen regardless of outcrop orientation, indicating that the beds have planar geometries. The conglomerate beds are 5 to 80 cm thick and consist of imbricated, clast-supported cobbles and pebbles (Fig. 8b). Within an individual bed the conglomerate clasts are moderately to well sorted (Fig. 8c), with minor amounts of sand occupying the interstices between the clasts. Modal grain size of individual conglomerate beds varies from fine pebbles to cobbles, but without any overall vertical trend. The conglomerate beds commonly overlie a planar to slightly scoured surface (Fig. 8b, c), whereas the tops of these beds are usually planar. Individual conglomerate beds laterally pinch-out, extending 1 to 5 m before onlapping adjacent beds. Paleocurrent data obtained from coarse pebble or cobble-clast imbrication demonstrate that the sediment-dispersal pattern had high variance (170°). The sandstone interbeds, which are poorly sorted, fine, pebbly, granular, and coarsely to very coarsely grained, occur as 5 to 20 cm thick sets of planar, wavy, to slightly inclined laminations (Fig. 8c). Bedding is apparent due to the segregation of fine pebbles or granules from sand. The bases of the sandstone beds are slightly irregular, having filled the topographic lows between pebbles or cobbles at the top of the underlying conglomerate (Fig. 8c). The tops of the sandstone beds vary from planar to slightly erosional (Fig. 8c). Individual sandstone beds extend laterally from 1 to 10 m (Fig. 8a) and are commonly terminated by erosional truncation.

This interbedded conglomerate-sandstone stratification is attributed to deposition caused by lateral expansion of unconfined water flows that sheetflooded across part of an alluvial-fan surface. *Sheetflooding* (usage here follows Hogg's [1982] definition) occurs on alluvial fans where a water flow becomes unchannelized or unconfined (Bull 1972). This lack of confinement occurs at the fan apex unless there is a channel incised into the proximal part of the fan. In this later case, sheetflooding begins farther down-fan where the incised channel ends at a place Hooke (1967) named the *intersection point* (Fig. 9). The interpretation that the interbedded conglomerate and sandstone facies of the Todos Santos Formation formed by sheetflooding on alluvial fans is based on the fact that deposits with identical characteristics (Fig. 8d) were produced by a recent catastrophic sheetflood event on the modern Roaring River fan in Rocky Mountain National Park, Colorado (Blair 1987). The single sheetflood event on the Roaring River fan produced as many as 15 gravel-sand couplets in a deposit as much as 2 m thick by supercritical flow on a 2–4°-dipping fan surface (Blair 1987). By analogy with the hydrologic conditions required to form the gravel and sand sheetflood deposits on the Roaring River fan, the identical sheetflood deposits of the Todos Santos fans are considered to be the result of sedimentation on the fan surfaces by supercritical flow during low-frequency, high-discharge events. Despite the suggested low frequency of these depositional events (perhaps one per hundreds to thousands of years), these sheetflood deposits dominate the stratigraphic record of the Todos Santos fans, making up all of the conglomeratic part of Fan II, and most of Fans I and III (Fig. 4).

The thick sheetflood units in the Todos Santos fans contain stratigraphic breaks where calcretes (caliches) or channel-fill deposits are present. The calcrete horizons attest to long periods of nondeposition at the fan surface (Gile and Hawley 1966). Channel-fill deposits within the Todos Santos sheetflood sequences, which consist of a channel-shaped lag accumulation of the coarsest clasts present in the sheetflood deposits, have a maximum thickness of 0.5 m and a maximum width of 2.0 m. Chan-

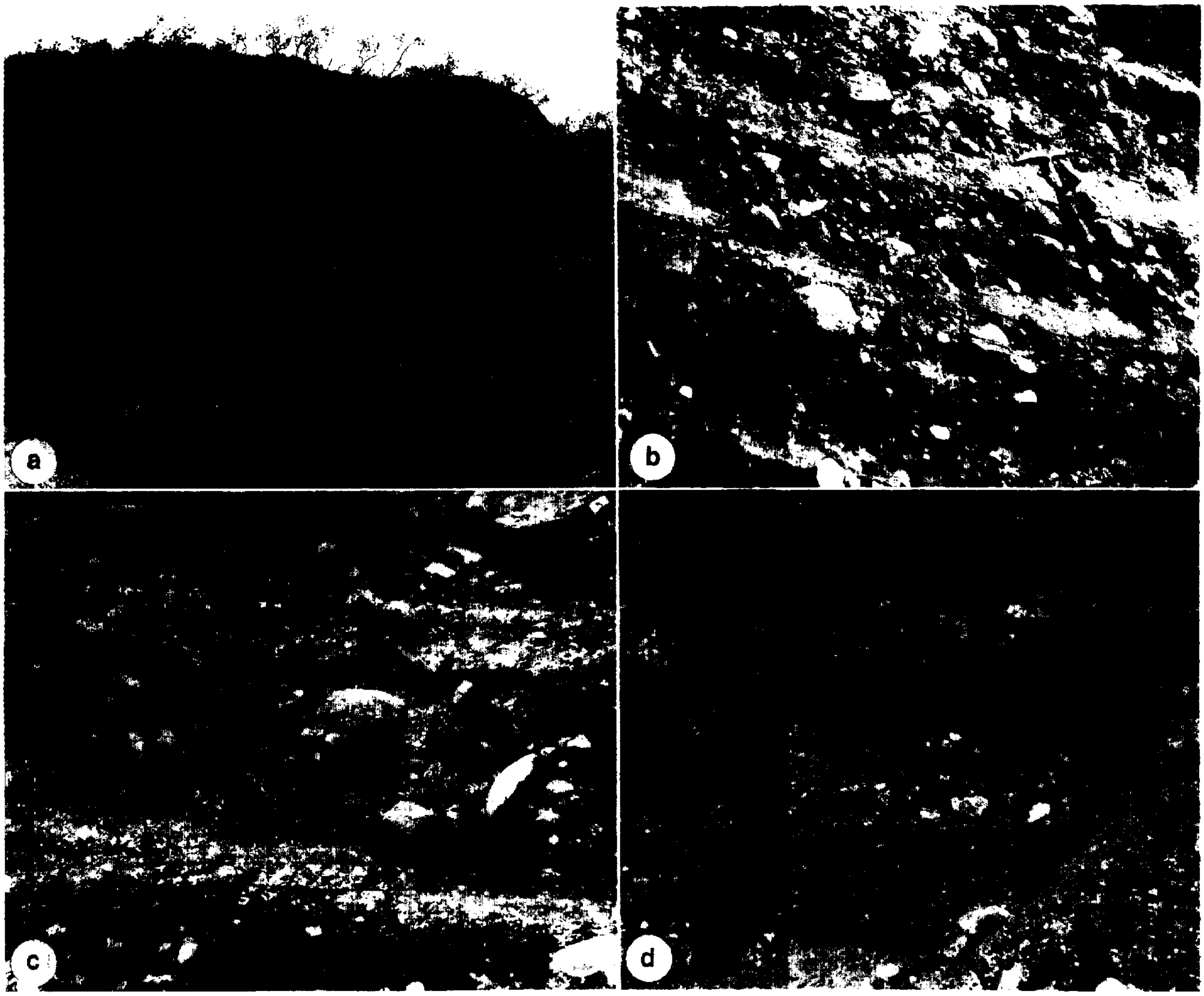

FIG. 8.—Views of the alluvial-fan sheetflood deposits. a) Overview of 30 m exposure of interbedded sandstone and conglomerate. b) Imbricated pebble-cobble conglomerate beds 5 to 80 cm thick are separated from sandstone beds along sharp boundaries. c) The base of the conglomerate beds is slightly eroded, whereas the tops are usually planar. Interstratified sandstone beds are poorly sorted, fine, pebbly, granular, and coarsely to very coarsely grained, and they display horizontal to slightly inclined bedding. View is of section about 0.5 m thick. d) Interstratified gravel and sand couplets which were deposited on 15 July 1982 during a modern sheetflood event on Roaring River alluvial fan in Colorado.

nel fills of this kind formed on the Roaring River fan years after the catastrophic sheetflood depositional event as a result of the erosional reworking of the surface of the sheetflood deposits by noncatastrophic discharge to form braided distributary channels (Blair 1987). By analogy, these channel-fill features in the Todos Santos fan deposits are interpreted to be a preserved remnant of the reworking of the surface of the sheetflood deposits by noncatastrophic discharge during periods of general nondeposition.

Horizons consisting of channel-fill conglomerates or calcretes allow separation of the sheetflood units into depositional events. However, intervals in the Todos Santos sheetflood deposits as much as 25 m thick remain inseparable. These units indicate that either up to 25 m of sediment were deposited during one depositional event or, perhaps more likely, that multiple sheetflood events occurred without the preservation of any noncatastrophic units between them.

Distal Sheetflood Deposits.—A sandstone facies up to 60 m thick is found in association with the conglomeratic sheetflood deposits in the Todos Santos Formation. This facies consists primarily of laminated, slightly pebbly, medium to very coarse sandstone. Stratification is visible due to the segregation of coarse and fine sand grains into alternating laminations. Heavy minerals and parting lineations are common along bedding-plane surfaces. Small-scale cross-stratification and ripple bedding make up a small part of this unit.

This facies is interpreted to represent deposition primarily by upper-flow-regime sheetflooding on the distal margin of alluvial fans beyond the location of gravel

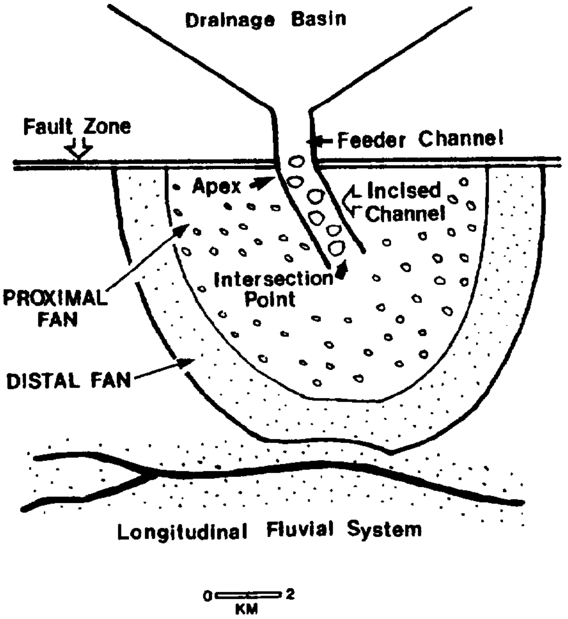

FIG. 9.—Diagram of typical subenvironments found on modern alluvial fans derived from granitic rocks. Distal sheetflood sandstones will only be preserved where they are not reworked by a longitudinal fluvial system. Model based on the Roaring River alluvial fan, Colorado (Blair 1987) and on modern fans in Death Valley and Owens Valley, California, visited by the writer.

sheetflood deposition (Fig. 9) similar to the Roaring River fan (Blair 1987). These sheetflood sandstone units were probably deposited during the major, low-frequency sheetflood sedimentation phases that resulted in deposition of gravel up-fan. This facies corresponds to the "sandflat" deposits of other workers (e.g., Hardie et al. 1978).

The distal sheetflood deposits are only preserved at the top of Fan I and lateral to Fan II (Fig. 4). In both cases where they are preserved in the Todos Santos fans, the sheetflood sandstone deposits are overlain by lacustrine deposits. They are not present where the fans are overlain or laterally associated with fluvial deposits. Distal sheetflood sandstone deposits were not preserved where the fans are bounded vertically or laterally by high-gradient fluvial deposits, apparently because the high-gradient fluvial systems were capable of reworking the distal sheetflood deposits, but the lake waters were not.

Incised-Channel Deposits.—Thirty- to fifty-meter-thick, crudely stratified, clast-supported cobble to boulder conglomerate comprises the second conglomeratic facies present in the Todos Santos fan deposits (Fig. 10a). Elongate clasts in these conglomerate beds are well imbricated and have intermediate axial lengths as large as 0.4 m. Individual beds, which range in thickness from 0.5 to 2.0 m, can be distinguished due to imbrication, changes in clast size, and by the presence of sandstone interbeds (Fig. 10a). Horizontal to planar-crossbedded, tabular- to wedge-shaped, pebbly, coarse sandstone beds are associated with this conglomerate facies (Fig. 10b).

This facies, which is much more coarsely grained and

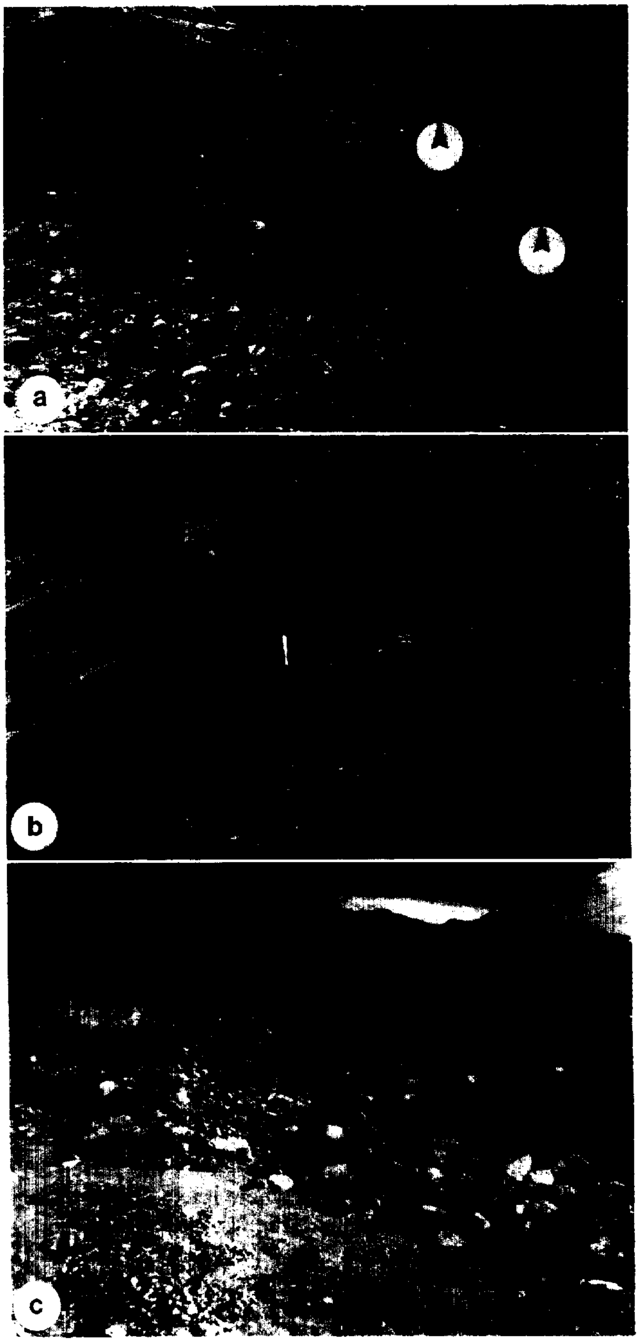

FIG. 10.—Views of alluvial-fan incised-channel deposits. a) Exposure of thick, crudely bedded, pebble, cobble, and boulder conglomerate. Bedding can be distinguished by changes in clast size and because of the occurrence of sandstone beds (arrows). b) View of thick conglomeratic sequence containing two wedge-trough sets of coarse sandstone. c) Sediments within incised channel of a modern alluvial fan derived from a granodioritic source, Death Valley, California. The sediment consists mainly of transversely imbricated cobble and boulder gravel. Sand occurs as deposits lateral to the gravel bedform. Note the finer-grained sheetflood deposits (S) in the channel cut.

is more thickly bedded than the sheetflood conglomeratic deposits, is interpreted to represent deposition within large channels that were incised into the proximal sheetflood alluvial-fan deposits, similar to those found on modern incised fans (Fig. 10c). These incised-channel deposits are more coarsely grained and contain a smaller percentage of sandstone beds than the sheetflood deposits because of the higher competency that is maintained due to confinement of the flood discharge within a channel. Transportation of the transversely imbricated, coarse gravel clasts took place in these channels as rolling bedload during rapid, large storm discharge where highly turbulent, upper-flow-regime conditions were reached, whereas the finer sediment fraction was transported farther down-fan, where it was deposited by sheetflooding below the intersection point. Variation in available clasts in the source area, or in stream power due to differences in flood intensity, or in differences in flood stage resulted in variations in grain size of the bedload (Fig. 10a, c). Pebbly sandstone beds in both the modern fan channels and in the Todos Santos fan deposits probably represent deposition during waning flood stage, or by less catastrophic discharge events. Wedge-planar and wedge-horizontal sets result from lateral accretion to the low-relief gravel bedforms or bars (Fig. 10c). Preservation of this finer material may be dependent upon early cementation or rapid sedimentation and minimal time for reworking during the next depositional event.

BASIN-FILL ARCHITECTURE AND DEPOSITIONAL MODEL

Facies analysis demonstrates that the Todos Santos basin-fill sequence at Jerico consists of fluvial, lacustrine, and alluvial-fan deposits (Fig. 4). The thickness and lateral continuity of each of these deposits are highly variable. Two pebbly, sandy, high-gradient fluvial megasequences are present, both of which are laterally persistent throughout the 11-km-wide outcrop belt (Fig. 4). The lower one is 110 m thick, whereas the upper one is 700 m thick. Only one lacustrine low-gradient fluvial megasequence is present. It has a maximum thickness of 140 m and is laterally continuous throughout the Jerico area except in the southeastern part, where it terminates against an alluvial-fan megasequence (Fig. 4). The three alluvial-fan megasequences that are present (labeled I, II, and III on Fig. 4) vary in maximum thickness from 80 to 130 m. All three pinch out laterally over distances of 2 to 12 km into fluvial or lacustrine deposits (Fig. 4). These geometries, combined with analysis of the alluvial-fan facies, indicate that each megasequence consists of the deposits of a single, uncoalesced fan. The individual fans are separated vertically by fluvial or lacustrine deposits, except for the base of Fan I, which rests on granite, and the base of Fan II, which rests on a 10-m-thick sequence of andesitic flows and breccias. Vertical alternation between alluvial-fan megasequences and fluvial or lacustrine megasequences results in cycles hundreds of meters thick.

The Todos Santos Formation in the study area is interpreted to have been deposited in an elongate rift basin simlar to those in the southeastern Gulf of Mexico and in northwestern Guatemala that have been identified by seismic, magnetic, and isopach studies (Fig. 2). The presence of preserved, thick alluvial-fan deposits denotes the existence of an ancient tectonic basin margin. Fluvial and lacustrine environments are commonly associated with alluvial fans in extensional basins. Paleocurrent data obtained from crossbedding present in the two high-gradient fluvial megasequences demonstrate that both were deposited by a river system that flowed northwestward, with relatively low (40°) variance (Fig. 4). Paleocurrent data from the alluvial-fan deposits, obtained from pebble, cobble, and boulder imbrication, indicate that all three fans were built by runoff that flowed toward the northeast, but with high (170°) variance (Fig. 4). The dominant paleocurrent direction in the fan deposits is nearly perpendicular to that of the fluvial deposits. Based on paleocurrent data, lithofacies analysis, and comparative analysis with modern analog basins, it is interpreted that the fluvial sequences were deposited by rivers that flowed northwestward, oriented parallel to, or longitudinally down the basin axis, whereas the fans were deposited by runoff that flowed transverse to the basin axis, outward from the basin margin (Fig. 11). The presence of the lacustrine sequence demonstrates that during one period of Todos Santos deposition in the Jerico area, the basin contained a large lake system (Fig. 11), indicating that this area was a topographic depression. Basal volcanic rocks in the Jerico area may have been emplaced as a result of structural development of this graben basin.

Basin architectural analysis and paleocurrent data show that the graben basin in which the Todos Santos Formation was deposited in central Chiapas had a NW-SE orientation. This trend is similar to the elongate basins identified in northwestern Guatemala and in the southern Bay of Campeche (Fig. 2).

CAUSE AND TECTONIC SIGNIFICANCE OF COARSENING- AND THICKENING-UPWARD FAN MEGASEQUENCES

Fan III and the conglomeratic part of Fan I display pronounced coarsening- and thickening-upward motifs (Fig. 12). These trends result from the occurrence of incised-channel deposits stratigraphically above the proximal sheetflood deposits of Fans I and III. Conglomerate beds increase in thickness from 5–80 cm to 50–200 cm, and in grain size from cobbles-pebbles to cobbles-boulders as a result of this subenvironmental change. Sandstone beds are much less common overall and are 25–50 cm thick in the incised-channel deposits, as opposed to 5–20 cm thick in the sheetflood deposits. The overall coarsening- and thickening-upward trends are not gradual but occur abruptly along major erosional surfaces that represent entrenchment of large channels into the underlying sheetflood deposits (Fig. 12). More gradual upward-coarsening trends are apparent within the sheetflood deposits. Fan II, which consists solely of sheetflood deposits, does not display any thickening-upward trends and only subtle coarsening-upward trends (Fig. 12). A slight lateral decrease in maximum conglomerate clast-size can also be detected within the sheetflood deposits of Fan III (Fig.

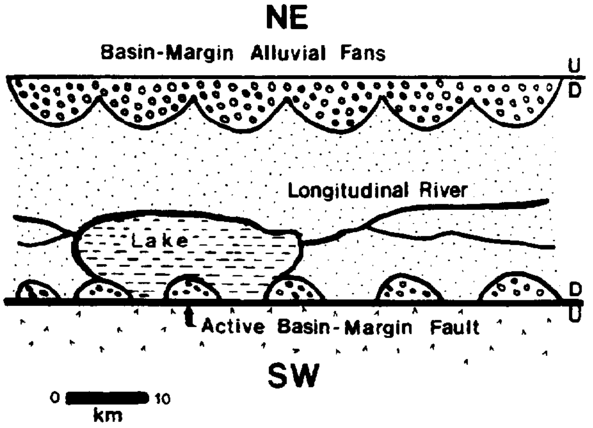

FIG. 11.—Depositional model for half-graben extensional basin nonmarine sedimentation based on modern extensional basins of the southwestern United States. The Jerico exposures are interpreted to represent units that were deposited along the active basin margin in a setting similar to the southwest side of this model.

13). The Fan I coarsening-upward sequence is overlain by a thin, fining-upward trend resulting from a vertical change in fan subenvironments from incised-channel to distal sheetflood deposits (Fig. 12).

The coarsening- and thickening-upward trends are not present everywhere on Todos Santos Fans I and III. The widespread exposures of Fan III allowed examination of the lateral extent of these motifs. This examination revealed that the incised-channel deposits occur above the sheetflood deposits only in the thicker, central part of the fan body (Fig. 13) and that they are absent along the thinner fringes of the deposit. This distribution indicates that the thicker, topographically higher part of the fan is most likely to be the site of channel entrenchment. The development of incised channels on the Todos Santos Fans I and III moved the locus of sheetflooding downfan. Thus, the vertical change in fan stratigraphy from sheetflood deposits to incised-channel deposits is indicative of fan progradation.

A variety of factors causing entrenchment of the most proximal part of fans has been identified or hypothesized, including climatic change (e.g., Lustig 1965), achievement of a geomorphic threshold (Weaver and Schumm 1974; Weaver 1984), or intrinsic sedimentologic factors (see Heward 1978, for a review of these). Heward (1978) considered these factors to be important when examining fan sequences 1–10 m thick, which he considered to be the result of fan behavior of short to moderate duration. The occurrence of incised-channel deposits at the top of 100+-m-thick fan megasequences in the Todos Santos Formation suggests that the control on the development of fan-head incision on them resulted from long-term fan behavior. Postulated long-term controls on fan-head incision include a) incision through a build-up of sediment in the proximal part of the fan as a result of the capture of the fan-feeder channel by a channel eroding headward on an abandoned segment of the fan (Denny 1967) or by lobe switching not involving stream capture (Blair 1987); b) incision of the fan-head area as a result of continued down-cutting in the source area, and subsequently, on the upper fan (Eckis 1928); and c) from tectonic tilting or

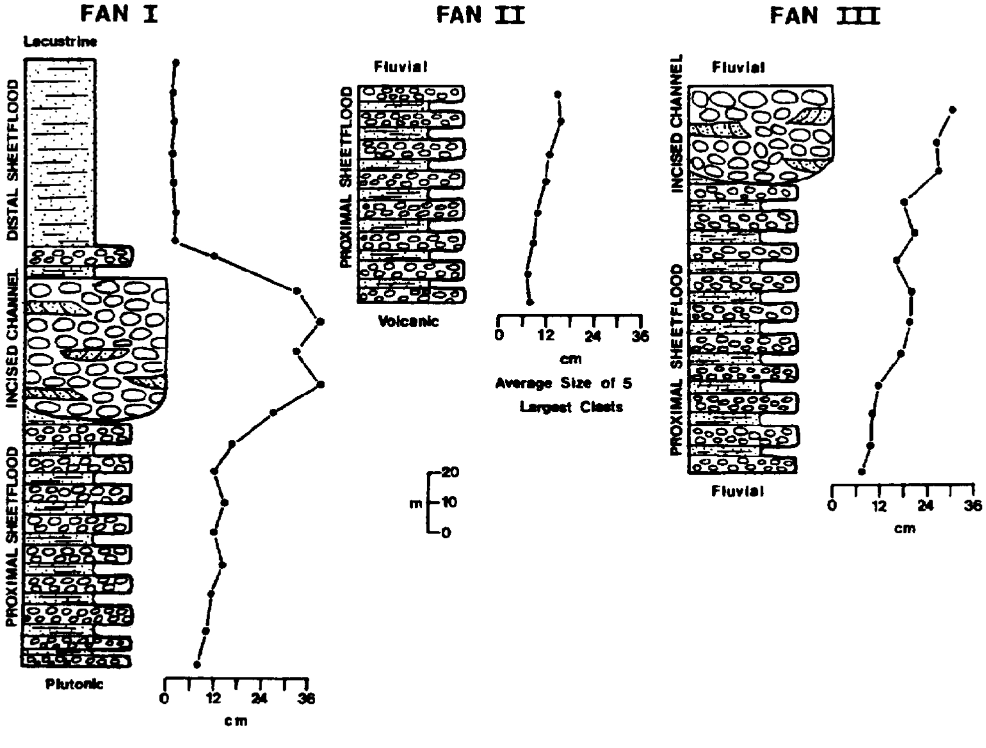

FIG. 12.—Vertical profile sequences for Fans I, II, and III. Coarsening- and thickening-upward motifs in Fans I and III result from a change from sheetflood to incised-channel deposition. A thin fining-upward sequence at the top of Fan I results from deposition of distal sheetflood deposits above the incised-channel deposits.

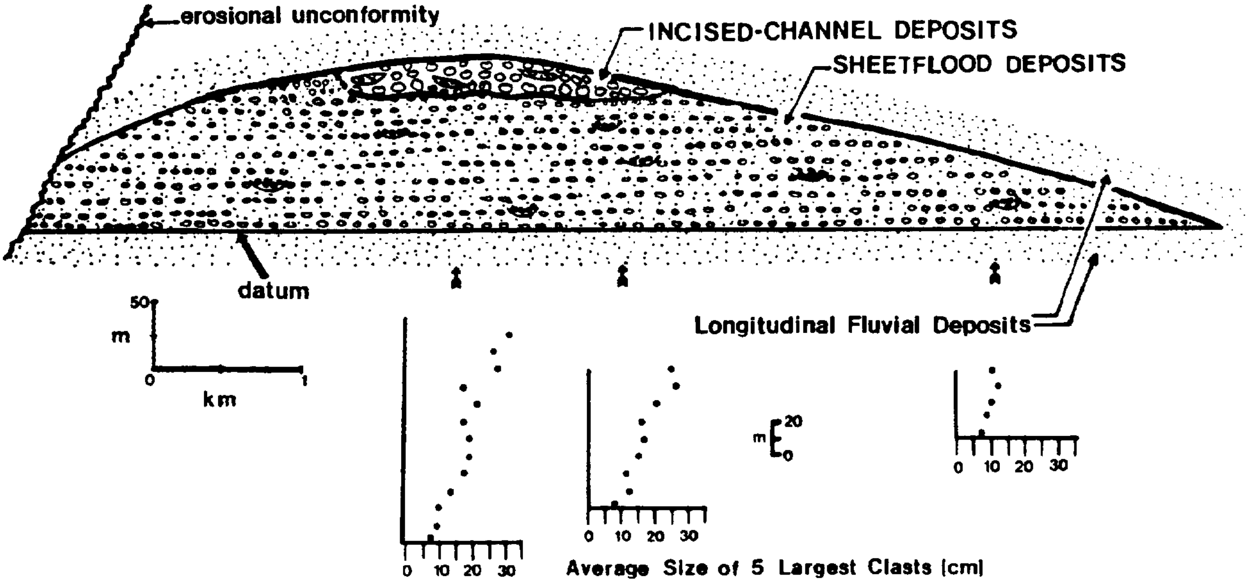

FIG. 13.—Distribution of sheetflood and incised-channel sequences on the Todos Santos Fan III. Incised-channel deposits occur above the sheetflood deposits only in the central, thickest part of this fan. Slight lateral fining of maximum clast size within the sheetflood deposits can also be seen.

uplift of fault slices containing the proximal part of the fan (Hooke 1972). The third factor, tectonic uplift or tilting of the proximal fan, would probably not produce a preservable incised-channel deposit, as uplift would result in erosion of this part of the fan. The two remaining causes probably are not exclusive, as downcutting in the source area implies that erosion is greater than tectonic uplift, and thus, as a result, aggradation of the fan-head area would be taking place.

The development of incised channels during long-term fan behavior and resulting fan progradation can thus be used to indicate that the rate of erosion surpassed the rate of tectonic subsidence, and thus, to indicate a change from active tectonic basin subsidence to relative tectonic quiescence. This relationship has been discussed by Eckis (1928), Denny (1967), Hooke (1972), and Heward (1978), and is well illustrated by the modern fans of Death Valley, California. In southeastern Death Valley, small (radial length of 1 km or less), uncoalesced fans are being deposited outwardly from an active fault scarp that has 500 m of relief (Fig. 14). These fans lack incised channels, and runoff becomes unconfined at the fan apex. Runoff flowing through the feeder channels to these fans has not been able to erode more than a narrow 10-m-wide canyon through the uplifted block adjacent to the fan apex (Fig. 14). This relationship confirms that the rate of basin subsidence is greater than the rate of erosion in the drainage basin and, subsequently, is greater than the short-term rate of fan sedimentation. As long as this disparity is maintained, fan building will be limited to vertical aggradation in the proximal part of the fan, near the apex, where unconfinement of flow will continue to occur (Fig. 15a). Only when the rate of tectonic subsidence decreases will the rate of drainage-basin erosion and vertical-fan aggradation become larger than the rate of tectonic subsidence. Thus, it is during periods of relative tectonic quiescence that erosion will be able to increase the size of the drainage basin by lateral cutting and down-cutting. Movement of this sediment will result in a build-up of the proximal part of the fan, initiation of fan progradation by entrenchment of the proximal-fan deposits, and a shift of the locus of deposition down-fan (Fig. 15b). Continued down-cutting in the drainage basin without additional tectonic subsidence will lower the level of the drainage basin and the feeder channel below the level of the proximal-fan deposits and enhance incision (Eckis 1928). Under these conditions, the only active area of fan sedimentation in the proximal fan would be within the incised channels. An illustration of this stage of fan sedimentation is the modern fans that are prograding outward from the Panamint Mountains in southwestern Death Valley. This side of Death Valley is undergoing significantly less subsidence than the active eastern side (Hunt and Mabey 1966; Hooke 1972). These coalesced fans are significantly larger than those of the eastern side, having radial lengths of as much as 10 km, and have large, incised channels in the proximal areas (Denny 1965; Hooke 1972).

TECTONIC AND HYDROLOGIC CONTROLS ON CYCLIC BASIN-MARGIN ALLUVIAL-FAN AND BASIN-AXIS FLUVIAL-LACUSTRINE DEPOSITION

Cyclicity between basin-margin alluvial-fan and basin-axis fluvial-lacustrine megasequences in ancient rift basins has been attributed to tectonic controls (Steel and Wilson 1975; Steel et al. 1977; Wilson 1980; Gloppen and Steel 1981; Cavazza 1985; LeTourneau 1985), or to climatic controls (LeTourneau 1985). The climate model provided by LeTourneau (1985) for the origin of cyclic megasequences is considered by the writer to be unsub-

FIG. 14.—View of small fan that is being deposited outward from a 500-m-high fault scarp in southeastern Death Valley, California. Insignificant downcutting in drainage basin has resulted in a 50-m-high, 10-m-wide canyon feeding to the fan apex.

stantiated because it assumes that debris flow and laminated sandstone deposits are indicative of "arid" climates, and that crossbedded sandstone is indicative of "humid" climates. Well-dated, stacked, lacustrine-fluvial and alluvial-fan megasequences that have been studied in the east African rift basins provide more useful insight into the role climate has in the development of such deposits. Tiercelin (1984) discussed a package of basin-fill deposits from the Afar rift of Ethiopia that consists of 300 m of lacustrine and fluvial deposits that are overlain by alluvial-fan deposits. Likewise, Vondra and Burggraf (1978) discuss a similar sequence from the Gregory rift in northern Kenya that consists of a 325-m package that begins with lacustrine and fluvial deposits and is capped by alluvial-fan deposits. Both of these single couplets of lacustrine-fluvial and alluvial-fan megasequences were deposited during the last 4.0 Ma (Pliocene to Recent), a duration of time that included numerous major climatic changes (e.g., Hays et al. 1976; Cerling et al. 1977). These examples suggest that major climatic change is not an important factor in the development of the large-scale cyclicity found in these rift-basin-fill deposits.

Large-scale cyclicity between basin-margin alluvial-fan megasequences and basin-axis fluvial-lacustrine megasequences thus is attributed in this interpretation solely to alternations between periods of active tectonic subsidence and periods of less active or negligible subsidence. Most commonly, others have concluded that deposition of alluvial fans takes place during periods of active tectonic subsidence as a result of the rejuvenation of relief in the adjacent, uplifted horst block and that finer-grained facies are deposited over the fans as a result of erosional reduction of relief in the source area (Steel and Wilson 1975; Wilson 1980; Van Houten 1978; Mack and Rasmussen 1984; Cavazza 1985). However, in many modern, tectonically active basins such as in southeastern Death Valley, basin-axis fluvial-lacustrine environments occur adjacent to the active fault scarp despite thousands of meters of vertical relief in the adjoining horst block (Hunt et al. 1966). This example illustrates that the sedimentological response to tectonic subsidence in extensional basins is more complex than simply associating periods of coarsest-grained sedimentation to periods of time during which structural relief is maximum. The nature of the response of alluvial-fan, fluvial, and lacustrine environments in extensional basins to periodic tectonic subsidence and tectonic quiescence will be elaborated by comparing the sedimentologic and stratigraphic features of the Todos Santos Formation with the sedimentologic and hydrologic features of well-studied, modern, extensional basins of the arid to semiarid southwestern United States, which serve as modern analogs.

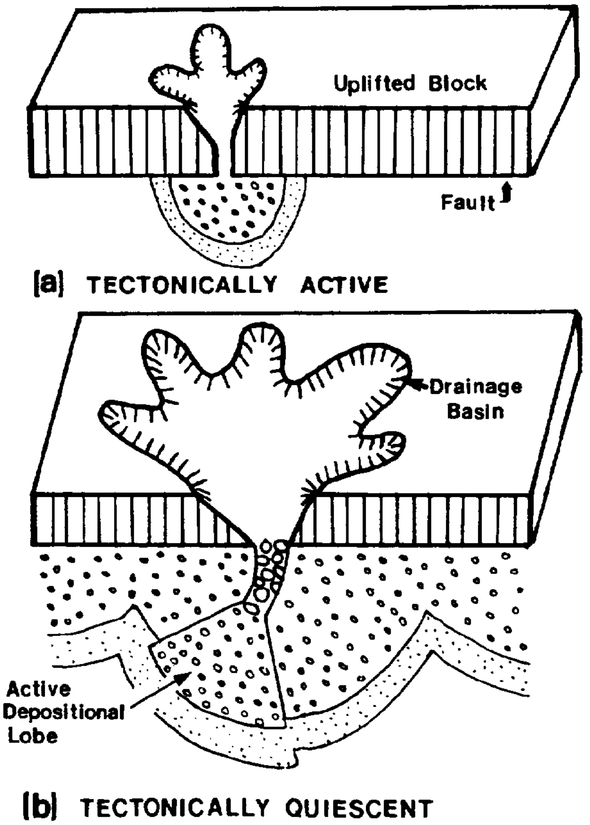

FIG. 15.—Diagram illustrating the response to the alluvial-fan environment to tectonism. a) During periods of active tectonic subsidence, fan deposition is characterized by sheetflooding at the fan apex. b) When drainage-basin erosion and fan sedimentation surpass the rate of tectonic subsidence during periods of relative tectonic quiescence, incision of the proximal fan occurs and the locus of sheetflooding is moved down-fan, resulting in fan progradation. Based on Eckis (1928), Denny (1967), Hooke (1972), and Heward (1978).

The stratigraphically lowest package of rocks in the Todos Santos Formation consists of proximal sheetflood, distal sheetflood, and incised-channel deposits of Fan I (Fig. 4). Deposition of Fan I took place over an unconformable surface upon batholithic granitic rocks of the Chiapas Massif. Prior to Todos Santos sedimentation, Upper Paleozoic rocks and an unknown volume of plutonic rocks were eroded from this site, indicating that this region was a highland prior to rift-basin development. Deposition of 75 m of sheetflood deposits of Fan I rep-

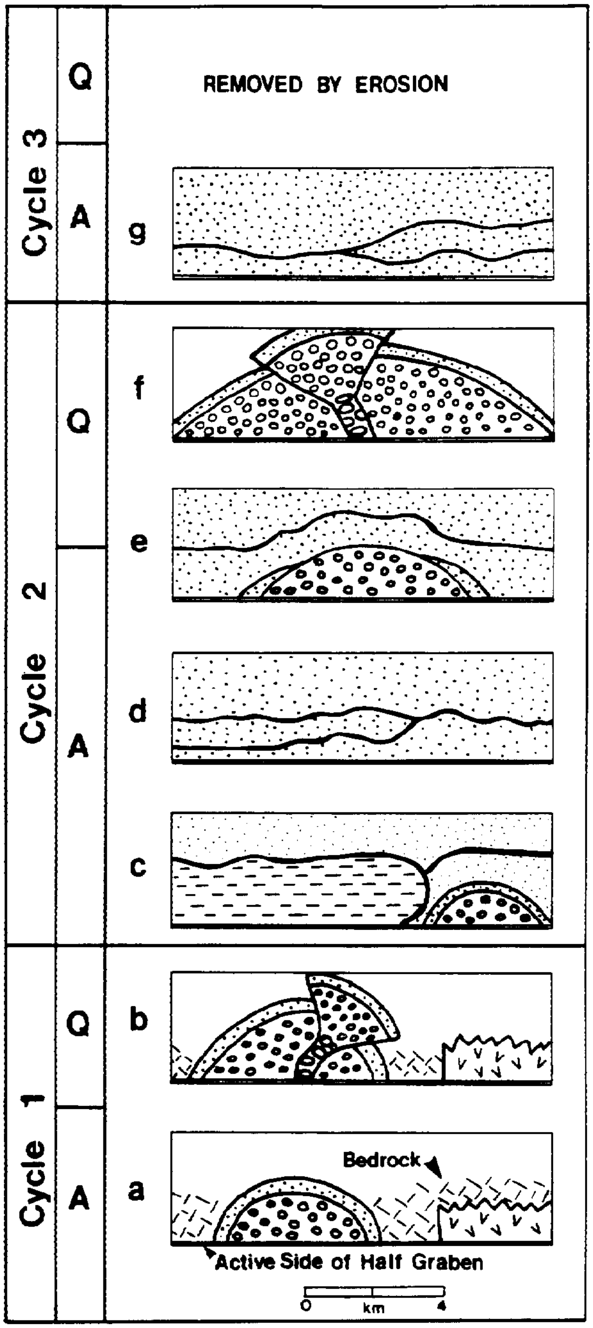

FIG. 16.—Paleogeographic map views demonstrating the tectono-sedimentological history of the Todos Santos Formation, central Chiapas, Mexico. a) In response to the first phase of tectonic subsidence, deposition of Fan I begins. Volcanic activity is also generated by this tectonic event. b) Fan I progrades during the first tectonic quiescent phase. c) In response to initiation of the second phase of tectonic subsidence, Fan II locally develops, but most of the study area is transgressed by a lake system. d) With continued subsidence, a longitudinal fluvial system develops over both Fan II and the lacustrine deposits. e) With further continued subsidence, Fan III deposition begins over the longitudinal fluvial deposits. f) Fan III progrades during the second phase of tectonic quiescence. g) In response to the third phase of tectonic subsidence, a longitudinal fluvial system is developed above the subsiding Fan III deposits.

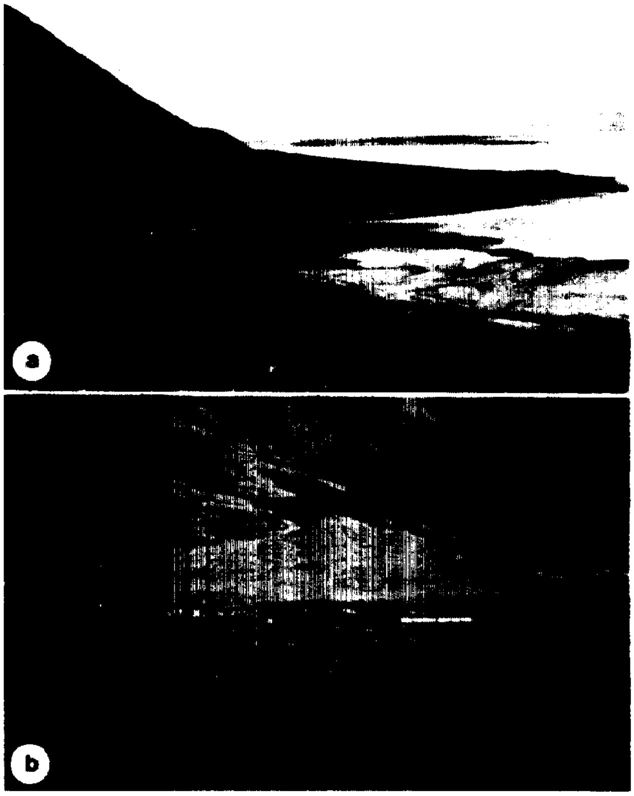

FIG. 17.—a) View from southeastern Death Valley, California. A lacustrine system is developed adjacent to the active fault scarp. Small, widely spaced, uncoalesced alluvial fans are also being deposited outward from this fault scarp. Highway on fans for scale. b) View of modern alluvial fans near Winnemucca, Nevada. In foreground annual snowmelt discharge is passing through the longitudinal Humboldt River. This discharge is generated 300 km away due to snowmelt in the high mountains where this river originates. Alluvial fans at the basin margin in the background remain dry and inactive.

resents the initial response to basin subsidence in the study area (Fig. 16a). Emplacement of volcanic flows in the southeastern part of the study area (Fig. 4) probably also occurred during this initial tectonic subsidence event. Deposition of incised-channel deposits above the Fan I sheetflood deposits indicates that fan progradation was occurring and that a period of tectonic quiescence followed the initial period of tectonic subsidence (Fig. 16b).

Deposition of Fan II over volcanic flows in the southeastern part of the study area took place during the second cycle of tectonic subsidence. The more widespread response to this same phase of subsidence was the establishment of a lake system over both Fan I and bedrock (Figs. 4, 16c). The development of a lake environment over an alluvial-fan deposit indicates that enough tectonic subsidence (hundreds of meters) occurred to create a topographic depression over an alluvial-fan deposit which, during its deposition, was topographically the highest part of the sedimentary basin.

A similar response to active tectonic subsidence is taking place in southeastern Death Valley. Lake sedimentation is occurring immediately adjacent to the active fault except locally, where small alluvial fans are being deposited (Fig. 17a). Lacustrine deposition in Death Valley is the primary sedimentary response to tectonism rather than alluvial-fan deposition, despite thousands of meters of structural relief, due to the different hydrologic controls on lake versus fan sedimentation. Alluvial-fan deposition takes place only when there is significant precipitation in the small (< 1 km^2) drainage basins from which fan sediment is derived. These precipitation events are apparently of very low frequency; without enough time for numerous significant precipitation events, fan building does not occur regardless of the amount of structural relief. In contrast, the lake system in Death Valley is maintained by water that emanates from springs that are present along the active fault scarp, as well as from surface runoff (Hunt et al. 1966). Discharge from the individual springs is significant, varying from less than 260 to 21,000 liters per minute (Hunt et al. 1966). The springs are common along the active fault scarp because of the development of fracture systems in the bedrock as a result of fault activity. Thus, tectonic subsidence in half-graben basins can readily initiate basin-margin lakes by both creating a topographic depression and by forming a fracture system through which groundwater can flow easily. Water is also brought to the Death Valley lake basin by surface runoff through two ephemeral longitudinal river systems. Discharge through these rivers, which drain an area of 23,300 km^2, occurs intermittently in response to day- to week-long periods of wet weather (Hunt et al. 1966). For example, in February 1969, runoff resulting from three consecutive days of warm rains combined with snowmelt discharge from the Panamint Mountains added 3×10^{12} m^3 of water to the lake, flooding 200 km^2 to an average depth of 0.3 m (Hunt 1975). Thus, due to different hydrologic controls, lake sedimentation is relatively constant, whereas fan sedimentation occurs only in response to infrequent periods of significant precipitation in the fan-drainage basins. Because of this disparity, deposition of as much as 350 m of clay and evaporite has occurred in the Death Valley lake basin in close proximity to the active basin-margin fault (Hunt and Mabey 1966), whereas only widely spaced, uncoalesced fans with radial lengths less than 1 km have been built (Fig. 17a).

In the Todos Santos Formation, both the lacustrine megasequence and the Fan II megasequence were subsequently overlain by 110 m of longitudinal fluvial deposits (Figs. 4, 16d). This event is considered to have resulted from the same subsidence phase that caused the lacustrine and Fan II megasequences to form. A lake system is sustained only as long as the topographic depression is maintained. The Todos Santos lake system was terminated either by filling or by lowering of the water level, and a longitudinal fluvial system became established at the basin-margin position. When this happened, deposition in the Todos Santos Formation changed to vertical aggradation by this river system. The lack of incised channel deposits at the top of the Fan II megasequence indicates that fan progradation did not occur, supporting the conclusion that deposition of the longitudinal fluvial megasequence that overlies both this fan and the lacustrine deposits was caused by continued basin subsidence rather than by a phase of tectonic quiescence.

Sedimentation of the longitudinal fluvial deposits in response to continued basin subsidence rather than alluvial-fan deposits was caused by the different hydrologic controls on these two depositional environments. Water in the longitudinal fluvial system, like the lacustrine system, is derived from precipitation that mostly does not fall at the site of deposition. Fan sedimentation takes place only when there is a significant low-frequency depositional event in the small drainage basin from which fan sediment is derived, whereas longitudinal fluvial deposition results from precipitation or annual snowmelt events anywhere in the expansive drainage basin. Furthermore, less significant precipitation or discharge can cause abundant transport and deposition of sediment in the longitudinal fluvial system, unlike in the fan systems, due to the finer grain size of the sediment. Large, perennial longitudinal fluvial systems are common in modern rift basins such as the Humboldt River in northern Nevada, and the Rio Grande in Colorado and New Mexico. Both of these rivers experience large annual discharge as a result of snowmelt from the high mountains in which these rivers originated (Fig. 17b). This discharge can cause high annual sediment transport and deposition in the longitudinal river system, whereas the topographically higher alluvial fans remain dry and inactive (Fig. 17b).

The Fan III megasequence in the Todos Santos Formation was also deposited during the same period of subsidence that included the lacustrine, lower longitudinal fluvial, and Fan II deposits (Figs. 4, 16e). The Fan III megasequence was probably initiated by a low-frequency, high-discharge event that produced a significant accumulation of sheetflood deposits. By continued aggradation, the Fan III sequence continued to increase in size and eventually caused the longitudinal fluvial system to migrate laterally away from the fault scarp.

The second phase of tectonic basin subsidence terminated with the deposition of the Fan III megasequence. Growth of Fan III into the longitudinal river valley and the development of incised-channel deposits indicate that fan progradation was occurring, and that sedimentation rates were higher than the rate of subsidence. This represents the onset of the second phase of tectonic quiescence in the basin (Fig. 16f).

The third phase of tectonic subsidence is represented by deposition of the upper longitudinal fluvial megasequence over the Fan III deposits (Figs. 4, 16g). Subsidence was substantial because at least 700 m of longitudinal fluvial deposition took place. Deposition of a sequence this thick at the basin margin suggests that a large river, perhaps similar to the Rio Grande, must have occupied the basin at this time. The unconformity at the top of this sequence (Fig. 4) indicates that any additional sedimentary rocks, if deposited, were subsequently removed prior to deposition of the Albian Sierra Madre Formation.

Three tectonic cycles are represented in the Todos Santos Formation in the study area. Each cycle includes sedimentation that occurred during a period of tectonic subsidence followed by a period of relative tectonic quiescence. The first cycle is represented by sedimentation of 125 m of the proximal sheetflood and incised-channel deposits of the Fan I megasequence. The second cycle resulted in deposition of the 490-m-thick distal sheetflood deposits of Fan I, all of Fan II, the lacustrine megasequence, and the lower longitudinal fluvial megasequence, and is capped by the Fan III deposits. The third cycle included deposition of as much as 700 m of longitudinal fluvial deposits.

The hydrologic-tectonic model presented here implies that alluvial-fan deposits that are capped by incised-channel deposits do not necessarily indicate the onset of active tectonic subsidence but, instead, are indicative of a period of tectonic quiescence. Furthermore, in the Todos Santos Formation, and perhaps in other similar types of basin fills, the onset of active basin subsidence can best be ascertained where longitudinal fluvial or lacustrine megasequences initially become deposited over alluvial-fan deposits. Steel et al. (1977) and Gloppen and Steel (1981) suggested a similar interpretation for the stacked basin-axis and basin-margin sequences found in the Devonian Hornelen Basin of Norway.

CONCLUSIONS

Vertically stacked cyclic megasequences of alluvial-fan and fluvial or lacustrine deposits like those in the Todos Santos Formation occur in the tectonically most active side of half-graben extensional basins as a result of periodically changing rates of basin subsidence. The response of the alluvial-fan, fluvial, and lacustrine environments deposited under arid climatic conditions to variations in tectonic subsidence differs due to the unique hydrologic controls on sediment transport and deposition in each of these environments. The lake systems are maintained by springs emanating from the active fault zone, or by discharge in the fluvial system. Discharge in the fluvial system results from precipitation or snowmelt in its expansive drainage basin. Alluvial-fan sedimentation takes place only when rare, significant precipitation occurs in the small drainage basin from which sediment is derived. Because of these disparities, fluvial and lacustrine environments respond more quickly than the fan environment to tectonic subsidence and will migrate to the basin-margin depression during periods of active subsidence. Eventually, alluvial-fan deposition will resume at the basin margin. Aided by lower rates of tectonic subsidence, the fans will ultimately prograde and displace the fluvial-lacustrine environments basinward.

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