A submarine-fan valley-levee complex in the Upper Cretaceous Rosario Formation: Implication for turbidite facies models

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ABSTRACT

Outcrops of the Upper Cretaceous Rosario Formation along Arroyo San Fernando, Baja California Norte, Mexico, expose a continuous cross-sectional view through a submarine-fan valley-levee complex that is similar in scale to many modern submarine-fan valleys. This unusually complete exposure provides an opportunity to compare an ancient turbidite sequence with modern submarine-fan systems and to test some aspects of submarine-fan facies models.

The Arroyo San Fernando submarine-fan valley fill is 670 m thick and 5.5 to 7.5 km wide perpendicular to paleocurrent direction. The valley fill is bordered by >500-m thickness of levee deposits; these levees aggraded with the valley maintaining positive relief over the surface of the fan. The valley fill consists of coarse-grained channel deposits that alternate with fine-grained interchannel deposits. The channel deposits within the valley fill consist of both single (0.25–2 km wide and 10–50 m thick) and amalgamated (as much as 5 km wide and 45–210 m thick) channel deposits. The levee deposits that border the valley fill consist of interbedded sandstone and mudstone beds that are commonly slumped. These slumps slid both toward and away from the valley axis, indicating that slumping was due to positive relief and not solely to undercutting by channels within the valley. The valley system records an overall aggradation, with very little downcutting of the valley floor or undercutting of the levee walls by channels.

The Arroyo San Fernando submarine-fan valley has dimensions comparable to those of modern submarine-fan valleys. The channels within it are comparable in size to many inferred ancient submarine-fan valleys described in the literature and are the same size as channels within modern submarine-fan valleys. These data, together with facies relationships, may indicate that many ancient deep-marine deposits interpreted as submarine-fan valley fill only represent channels within a submarine-fan valley.

INTRODUCTION

Modern depositional systems provide important analogues for interpreting ancient deposits and developing actualistic models. Facies models for ancient turbidite systems, however, were developed primarily from ancient turbidite sequences, and the relationships between such tur-

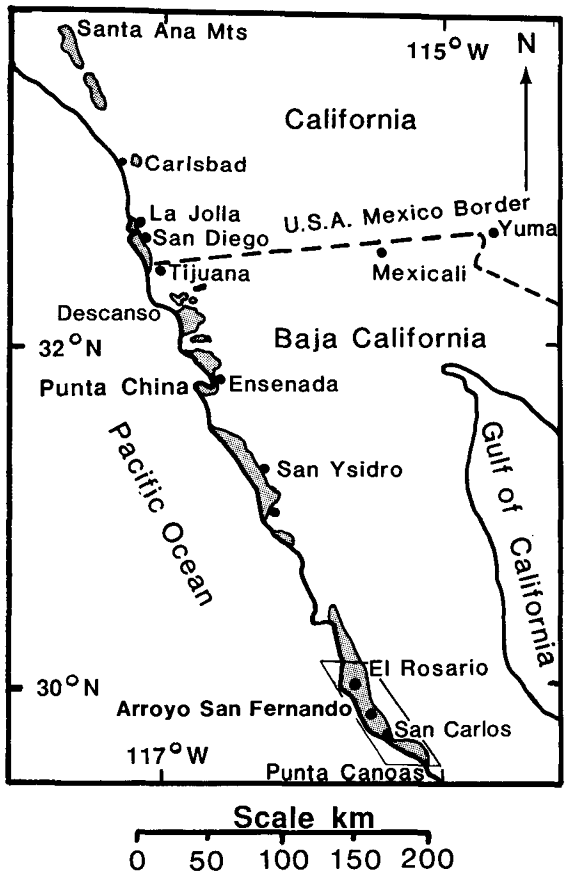


Figure 1. Location of exposed Upper Cretaceous forearc sedimentary rocks (stippled/gray pattern) in southern California (United States) and Baja California Norte (Mexico). Study area is located in the Rosario embayment; boxed area shown in Figure 3. Modified from Popenoe (1973).

Geological Society of America Bulletin, v. 102, p. 900–914, 12 figs., 2 tables, July 1990.

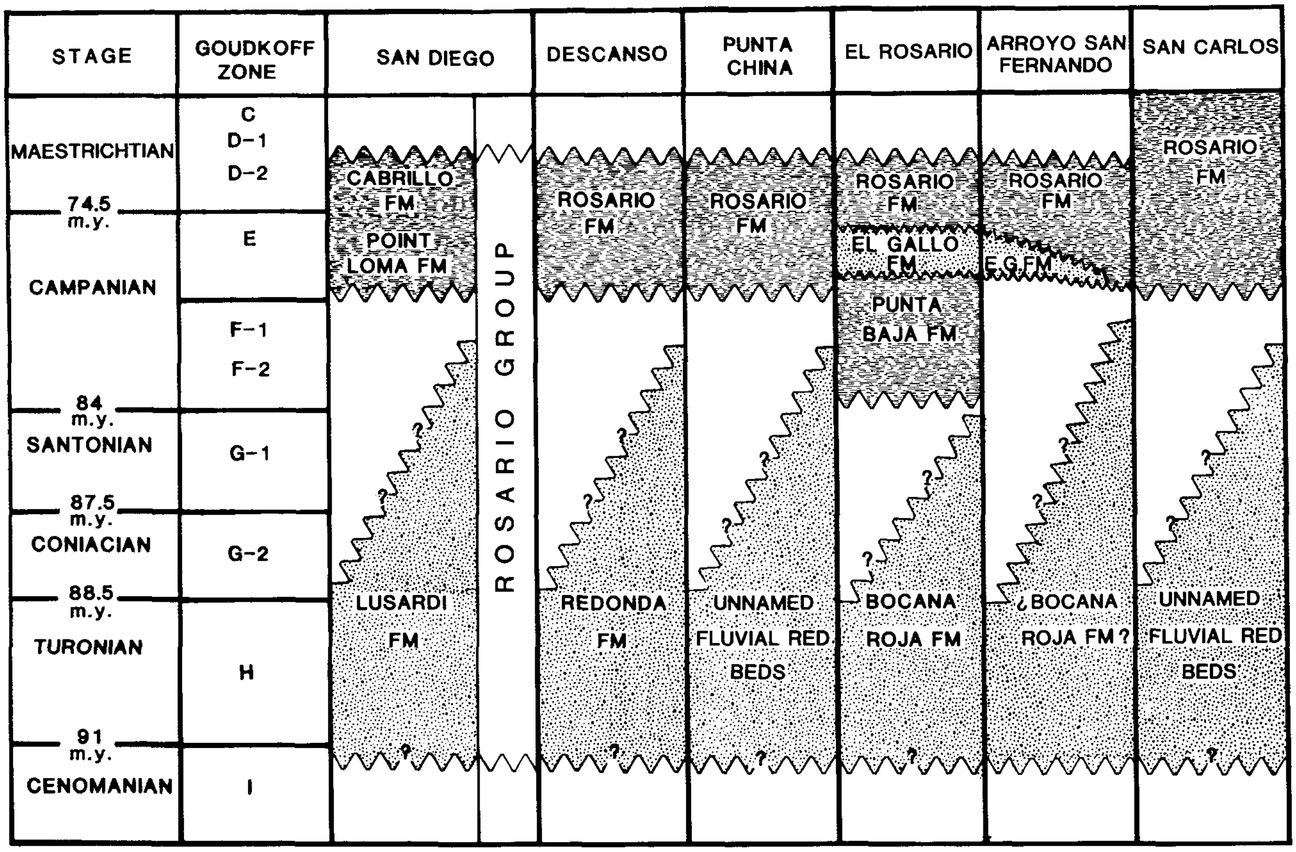
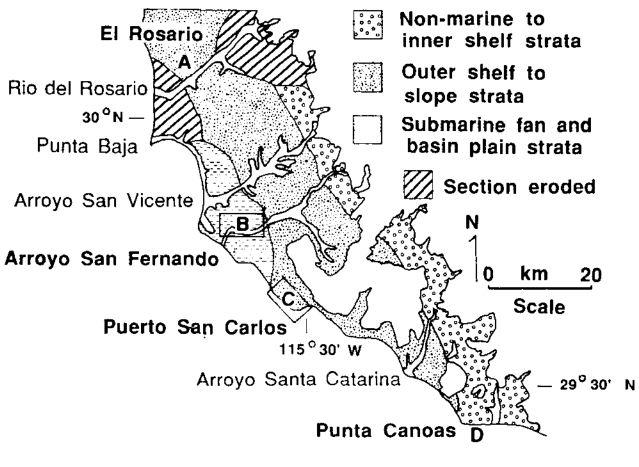


Figure 2. Regional stratigraphic chart for Upper Cretaceous sedimentary rocks of southern California and Baja California Norte (localities shown in Fig. 1). Dot pattern indicates nonmarine rocks, and dashed pattern indicates marine rocks.

bidite facies associations and related fan subenvironments from modern fans remain a matter of controversy (Nilsen, 1980; Normark and others, 1983/1984; Shanmugam and others, 1985).

The comparison of modern and ancient turbidite systems is difficult because they are observed at greatly different scales (Normark and others, 1983/1984; Mutti and Normark, 1987). Geophysical studies of modern submarine fans have resulted in descriptions of the morphology, geometry, and internal structure, on the scale of hundreds of meters to tens of kilometers, of submarine-fan subenvironments. The relationships of sedimentary facies to subenvironments of modern fans, however, are poorly constrained owing to limited penetration of piston cores and paucity of drill-core data (Kulm and others, 1973; Damuth and Kumar, 1975; Stow, 1981; Cleary and others, 1985; Normark and Piper, 1985; Bouma and others, 1985b; Nelson and Maldonado, 1988). Studies of ancient submarine fans consist primarily of detailed descriptions of vertical successions, whereas descriptions of lateral facies relationships are commonly limited to outcrop distances of a few hundred meters or less. This results in uncertainties in assigning turbidite facies associations to the subenvironments that have been defined from modern submarine fans.

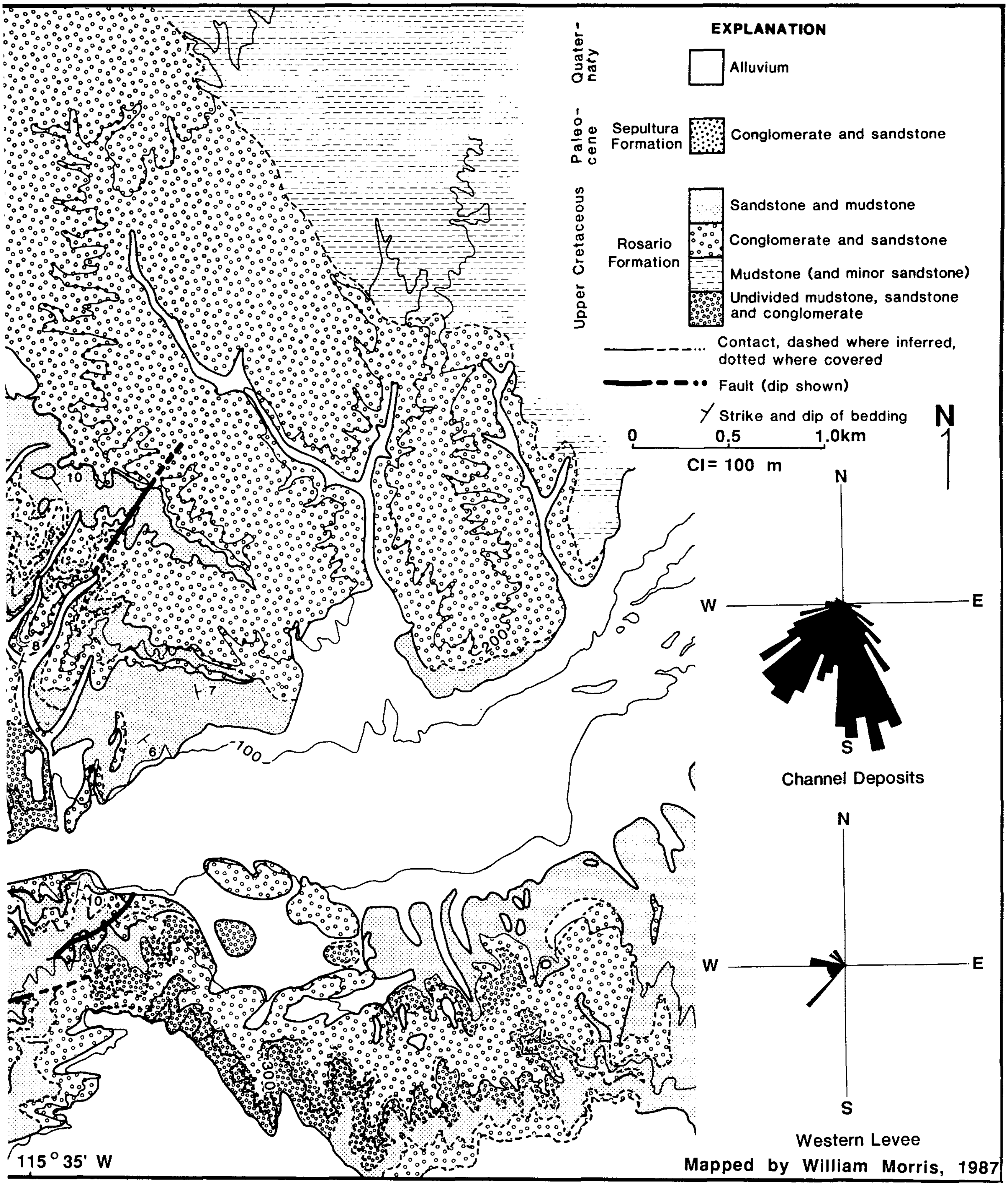
Figure 3. Generalized facies map of the Rosario embayment (Fig. 1). The embayment is divided into three facies belts that show the predominant paleodepositional environment during latest late Campanian (?) to early Maestrichtian time. Specific areas referred to in the text are marked A, B, C, and D. Boxed area at Arroyo San Fernando shown in Figure 4; boxed area at Puerto San Carlos shown in Figure 3 from Morris and Busby-Spera (1988).



The Upper Cretaceous Rosario Formation, exposed along Arroyo San Fernando, is an ancient submarine-fan valley-levee complex[1] with

[1]The terminology used in describing submarine-fan systems varies. We follow the usage of Normark (1978), referring to the largest channel-like feature laterally bounded by thick, extensive levee deposits as a "submarine-fan valley"; smaller channel-like features confined within the valley are termed "channels."

Figure 4. Geologic map of the Arroyo San Fernando area. The Paleocene Sepultura Formation overlies the Rosario Formation with angular unconformity, and the base of the Rosario Formation is not exposed at this locality. The Rosario Formation is here divided into (1) fine-grained deposits (interbedded sandstone and mudstone), (2) coarse-grained deposits (interbedded conglomerate and sandstone), and (3) mudstone with minor sandstone. Interbedded coarse-grained and fine-grained deposits that are either too poorly exposed or thin (<5 m) to be mapped are undivided. Sandstone and mudstone beds in the western and southeastern margin of the map are commonly slumped and represent levee



deposits, whereas the fine-grained and coarse-grained deposits in the center of the map represent valley fill (Fig. 5). The mudstone beds (with minor sandstone beds), exposed only in the easternmost edge of the field area, record abandonment of the valley-levee complex (see text). Paleocurrent directions in the channel deposits are south-southeast in the basal part and south in the upper part of the valley fill, whereas the western levee deposit shows a paleocurrent direction to the west. (Note overlap in center.)

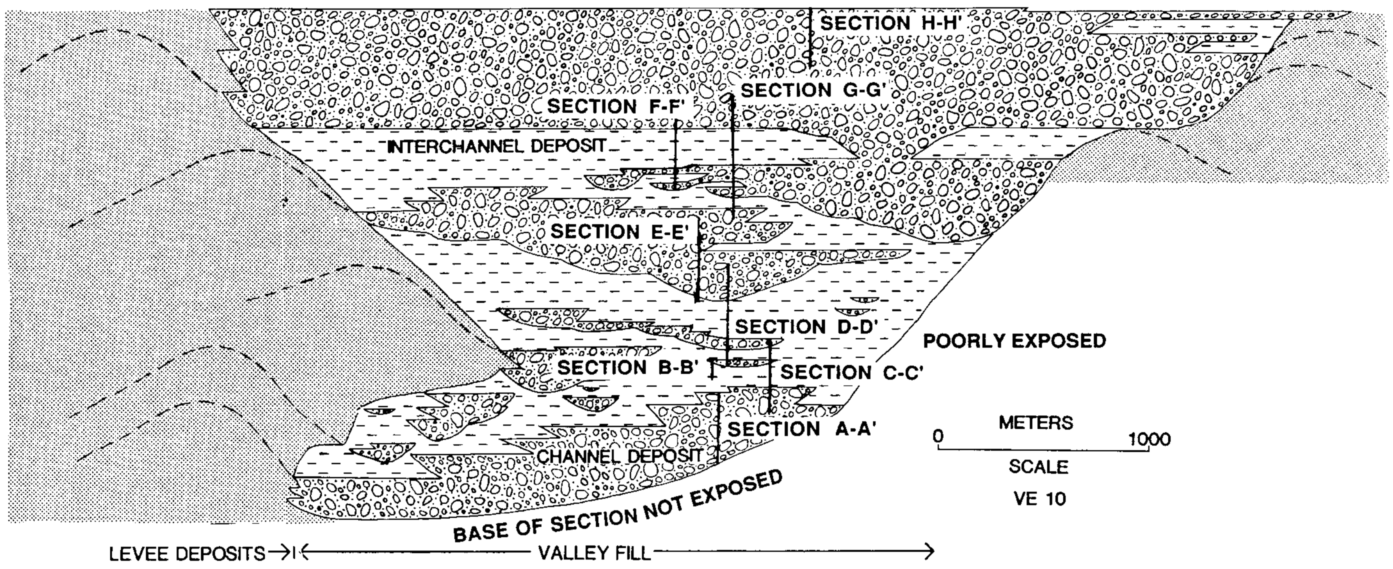


Figure 5. Cross section of the Arroyo San Fernando submarine-fan valley-levee complex (see Fig. 4; paleocurrent direction directly out of the page for all but the uppermost channel deposit, which is an oblique view). The valley fill is composed of channel and interchannel deposits that interfinger with levee deposits that border the valley. The positions of measured sections are projected onto the cross section. The sections were hung from a set of sandstone beds below the uppermost channel deposit that appear continuous throughout the field area.

nearly continuous exposure, comparable in cross-sectional vertical dimension and width to modern submarine-fan valley-levee systems. This complex provides an example of an ancient submarine-fan valley that can be compared to modern submarine-fan valleys and allows comparison of some aspects of submarine-fan facies models used in interpretation of ancient turbidite systems.

REGIONAL STRATIGRAPHY

The Rosario Formation constitutes the upper part of a belt of Upper Cretaceous sedimentary rocks that are discontinuously exposed along the Pacific Coast of southern California and Baja California del Norte for a distance of almost 500 km (Fig. 1; Beal, 1948; Gastil and others, 1975). These strata were deposited along the east side of the west-facing Peninsular Ranges forearc basin complex (Bottjer and Link, 1984) and onlap the Upper Jurassic to Upper Cretaceous Peninsular Range batholith (Beal, 1948; Gastil and others, 1975; Silver and others, 1975).

The basal section of the Peninsular Ranges forearc basin complex is a nonfossiliferous, nonmarine deposit with a formational nomenclature that varies by location (Fig. 2) and may range in age from Cenomanian to early Campanian (Kilmer, 1963; Flynn, 1970; Nordstrom, 1970). These strata are unconformably overlain by Campanian to early Maestrichtian nonmarine to deep-marine strata that include the Rosario Formation (Beal, 1948; Kilmer, 1963; Nilsen and Abbott, 1981; Yeo, 1982; Morris, 1987). Paleocene and Eocene deposits unconformably overlie the Cretaceous strata (Gastil and others, 1975) except near San Carlos (Fig. 1) where the contact appears conformable.

The Rosario Formation consists of nonmarine, shallow-marine, and deep-marine sedimentary rocks (Kilmer, 1963; Gastil and others, 1975; Nilsen and Abbott, 1981, 1984; Yeo, 1982, 1984). Near San Diego and Ensenada (Fig. 1), the Rosario Group shows a retrogradational (shoreface to slope and basin-plain environments) to progradational (basin-plain to outer-fan to mid-fan to inner-fan environments) sequence (Nilsen and Abbott, 1981, 1984; Yeo, 1982, 1984). The type area of the Rosario Formation, at El Rosario (Figs. 1 and 3), consists of deep-marine slope deposits that grade upward into outer-shelf deposits (Patterson, 1978).

The Rosario embayment (Fig. 3) is the most areally extensive (3,600 km^2) and by far the best-exposed segment of the Peninsular Ranges forearc basin complex. Sedimentation units as thin as a few meters can be mapped for a distance of several kilometers, whereas sediment sequences tens of meters thick crop out continuously for distances of tens of kilometers. Postdepositional faults are few, with minor offsets, allowing us to trace facies changes across the basin, from nonmarine and inner-shelf through outer-shelf and slope to deep basinal paleodepositional environments (Fig. 3). Paleodepositional systems we have mapped in detail in the Rosario embayment include (1) submarine canyon and slope deposits at San Carlos (Fig. 3, locality C, Morris and Busby-Spera, 1988), (2) a confined fan-delta complex at Punta Canoas (Fig. 3, locality D, unpub. data of Morris and Busby-Spera), and (3) the submarine-fan valley-levee complex described in this paper (Fig. 3, locality B).

STRATIGRAPHY AND SEDIMENTOLOGY OF THE ARROYO SAN FERNANDO AREA

The Rosario Formation in the Arroyo San Fernando area (Fig. 1) consists of deep-marine deposits that unconformably overlie the El Gallo Formation (Fig. 2) and are unconformably overlain by conglomerates of the Paleocene Sepultura Formation (Fig. 4). Benthic foraminifera and nannofossils indicate that the Rosario Formation, in the Arroyo San Fernando area, ranges from the late Campanian to middle Maestrichtian in age (Mark Filewicz and Sarah Downs, 1988, personal commun.).

Beds of the Rosario Formation in the Arroyo San Fernando area form a north-northeast–south-southwest– to east-northeast–west-southwest–striking homocline that dips from 5° to 15° to the east (Fig. 4). Attitudes vary near faults or in large paleoslumps. Faults are uncommon and appear to have normal displacement, commonly of less than 10 m. One fault, located near the western edge of the study area, appears to have a vertical displacement of approximately 100 m and extends southward for a distance of

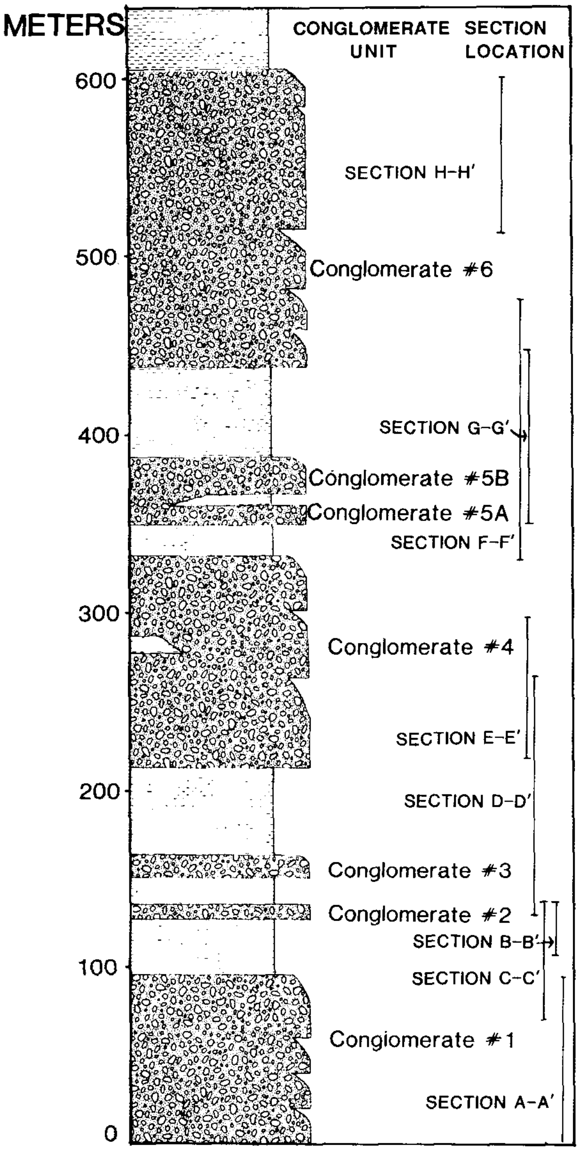


Figure 6. Composite stratigraphic section of the valley fill, showing relative thickness of coarse-grained (channel deposits) and fine-grained (upper channel deposits and interchannel deposits) units. The positions of the stratigraphic sections in Figure 8 are shown on the right-hand side of this figure.

16 km to the San Carlos area (Morris and Busby-Spera, 1988).

We interpret the Rosario Formation, along Arroyo San Fernando, as an ancient submarine-fan valley-levee complex. The complex consists of coarse-grained (largely conglomerate and sandstone) and fine-grained (largely sandstone and mudstone) deposits that are grouped into two subenvironments (Figs. 4 and 5): (1) the valley fill, consisting of interbedded coarse-grained and fine-grained deposits, and (2) levee deposits, consisting of fine-grained deposits with slumps. The valley fill grades laterally into the levee deposits (Figs. 4 and 5). Valley-abandonment deposits, consisting mainly of mudstones with minor sandstone, drape the valley-levee complex.

Valley Fill (Channel and Interchannel Deposits)

The width of the submarine-fan valley fill at Arroyo San Fernando (perpendicular to paleocurrent directions) varies upsection from 5.5 to 7.5 km and is at least 670 m thick (Figs. 4 and 5). The valley fill consists of (1) interbedded conglomerate and sandstone units, interpreted as channel deposits, and (2) interbedded sandstone and mudstone units, interpreted as either the upper parts of channel deposits or interchannel (overbank and terrace) deposits. Both the channel and interchannel deposits laterally interfinger with the levee deposits (Fig. 5).

Channel deposits in the valley fill include both single and amalgamated channel deposits (Figs. 6 and 7). Single channel-fill deposits are cut into and overlain by fine-grained deposits. The single channel deposits are 10 to 50 m thick and 0.25 to 2 km wide (perpendicular to paleocurrent directions) and show either no vertical sequence trend or a single upward-fining sequence of beds (Figs. 6 and 8). The amalgamated channel deposits range from 45 to 210 m thick and as much as 5 km wide and commonly contain several upward-fining sequences of beds (Figs. 6, 8, and 9).

Two scales of channelization are recognized within the valley fill. These are (1) first-order channels that are the same size as the single channel deposits and (2) second-order channels that are tens of meters wide and several meters

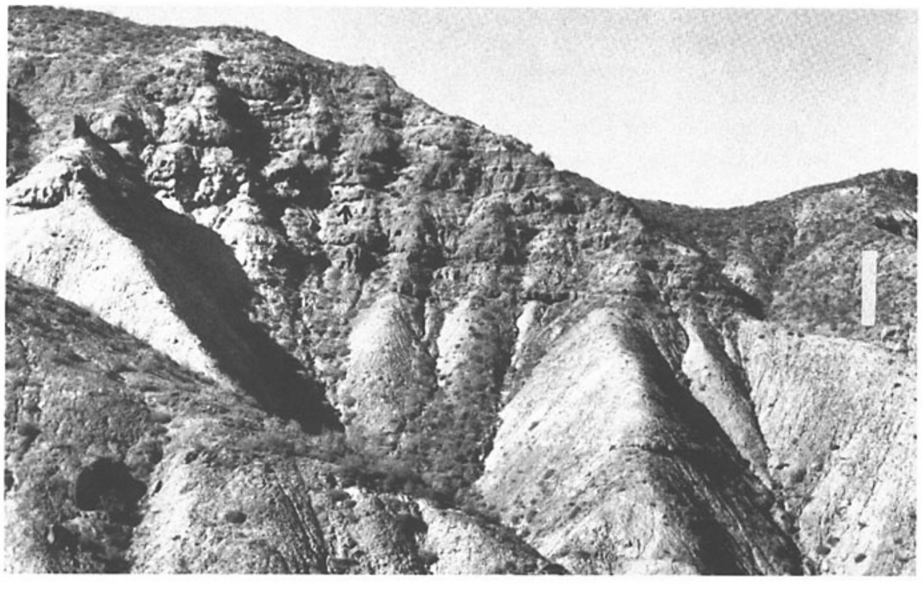


Figure 7. Amalgamated channel deposits from conglomerate 4 (Fig. 6). Channel 1 is approximately 20 m thick. Black arrows mark the boundaries of the individual channels. White scale bar represents ~10 m.

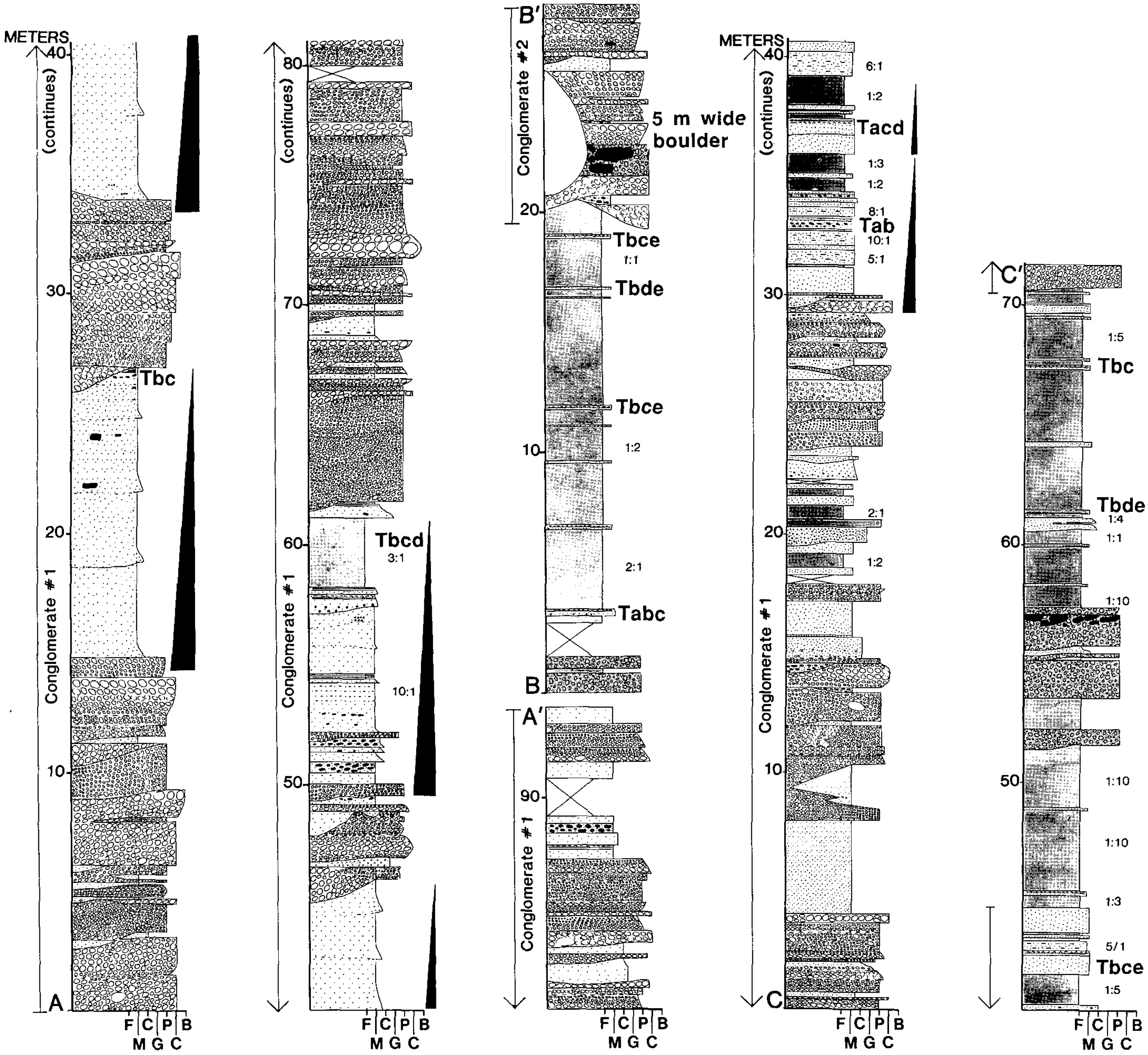


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Figure 8. Measured stratigraphic sections of the Arroyo San Fernando valley fill. Positions of measured sections given in Figures 5 and 6. For key, see Figure 8C.

deep. First-order channels are cut as much as 10–20 m into the underlying deposits, except for the channel at the base of conglomerate 6, which has cut 50 m into fine-grained deposits (Fig. 6). Epsilon cross-stratification within some first-order channel deposits records lateral channel migration. Relationships between first-order channel and interchannel deposits suggest two types of paleomorphology: (1) erosional channels with both banks cut into interchannel deposits and (2) depositional channels with at least one bank that laterally interfingers with interchannel deposits and may show epsilon cross-stratification (for example, Fig. 5 in Mutti and Normark, 1987).

The channel deposits consist primarily of interbedded clast-supported conglomerate and sandstone beds, with lesser matrix-supported conglomerate beds and rare mudstone beds (Table 1). Conglomerate beds fill some channels entirely or occur in the lower half of some channels with sandstone beds occupying the upper part and margins of channels, commonly forming an upward-fining sequence of beds (Fig. 8). Matrix-supported conglomerate beds are most common near the base of channel deposits (Fig. 8A, sections B–B′ and C–C′, and Fig. 8B, sections D–D′ and E–E′) owing to scouring of the fine-grained substrate during channel initiation. Matrix-supported conglomerate beds can also

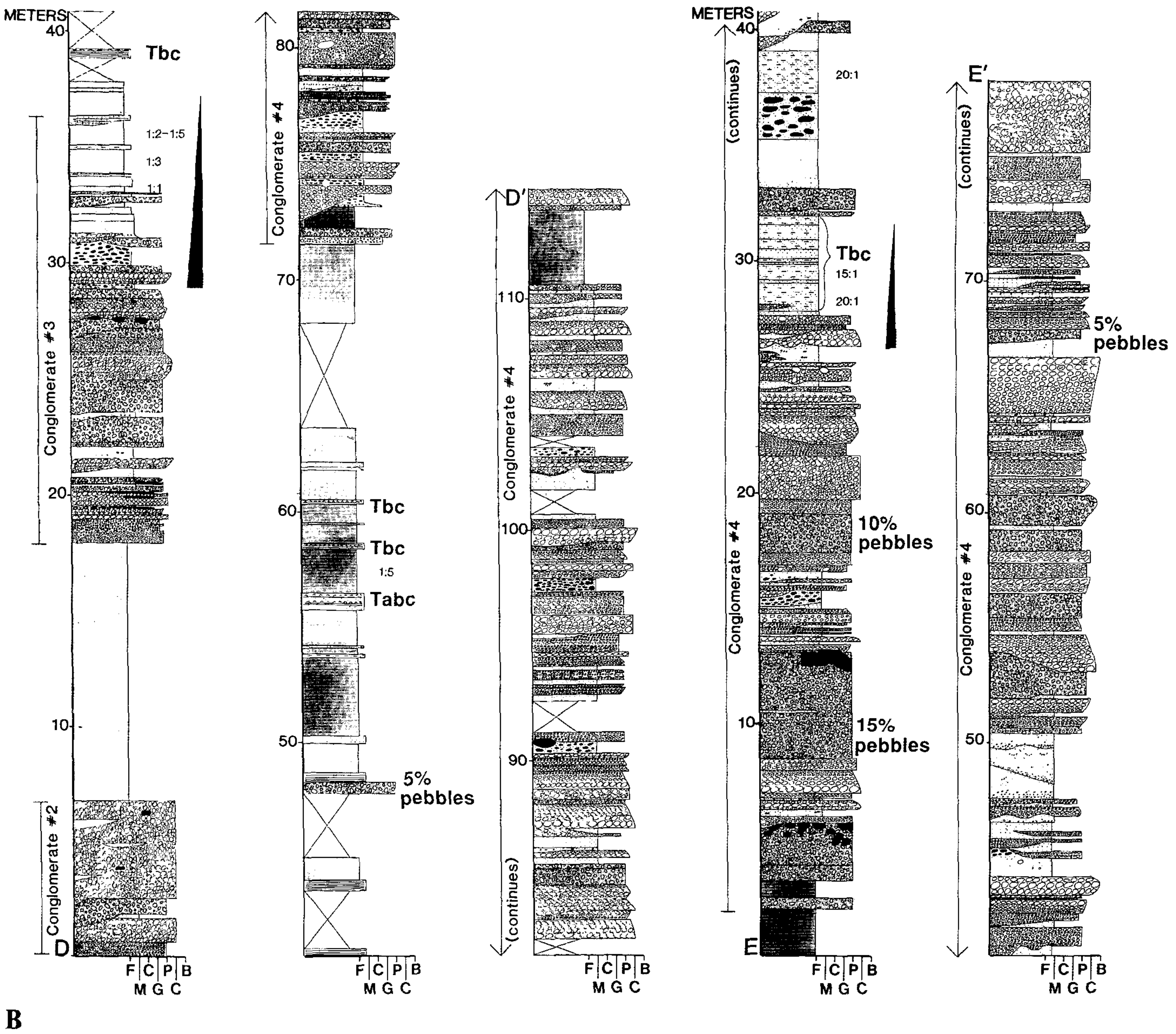


Figure 8. (*Continued*).

occur well above the base of channel deposits (Fig. 8B, sections D–D′ and E–E′, and Fig. 8C, section G–G′). These may have resulted from the erosion of interchannel mudstone beds during lateral migration of a channel (Bouma and Coleman, 1985). Interchannel sandstone and mudstone locally occur as slump-folded horizons, or slump blocks at the base of channels, indicative of outer bank erosion.

Both clast- and matrix-supported conglomerate beds occur within the channel deposits. Clast-supported conglomerate beds are graded and ungraded (Fig. 8). Outsized subangular boulders, as much as 8 m long (Fig. 8A, section B–B′), of limestone and volcanic breccia locally occur with the clast-supported conglomerate beds and are interpreted as lag deposits. The matrix of the clast-supported conglomerate beds consists primarily of fine- to medium-grained sand with minor mud-sized particles. Matrix-supported conglomerate beds are predominantly ungraded and have a matrix of mud- and sand-sized particles. The percentage of matrix and mudstone clasts commonly increases upward within conglomerate beds.

Sandstone beds within the channels are predominantly very thick to medium bedded (Fig. 8). Massive and normal-graded sandstone beds are commonly interstratified with the conglomerate beds and also occur at the base of the upward-fining sequences that overlie the conglomerate beds (Fig. 8A, section A–A′, Fig. 8B, section D–D′, and Fig. 8C, section F–F′. Planar-laminated sandstone beds and sandstone beds with Bouma divisions are most common in the upper part of the upward-fining sequences that overlie the conglomerate (Fig. 8A, sections A–A′ and B–B′, and Fig. 8B, sections D–D′ and E–E′). These sandstone beds become interstratified upward with mudstone and pass gradationally upward and laterally into interchannel deposits or are erosionally overlain by conglomerate and sandstone beds within a channel deposit.

Interchannel deposits in the valley fill consist of laterally extensive sequences of interbedded, very thin- to medium-bedded sandstone and mudstone beds (Fig. 10) with lower sandstone-mudstone ratios than in the channel deposits (Table 1). These interchannel deposits interfinger with, or are erosionally truncated by, the channel deposits. Interchannel deposits range from less than 5 m thick (as a lens in conglomerate unit 4, see Fig. 6) to more than 60 m thick (between conglomerate units 5 and 6, see Fig. 6). Sandstone-mudstone ratios generally decrease upward from the tops of channel deposits and are lowest in the section between conglom-

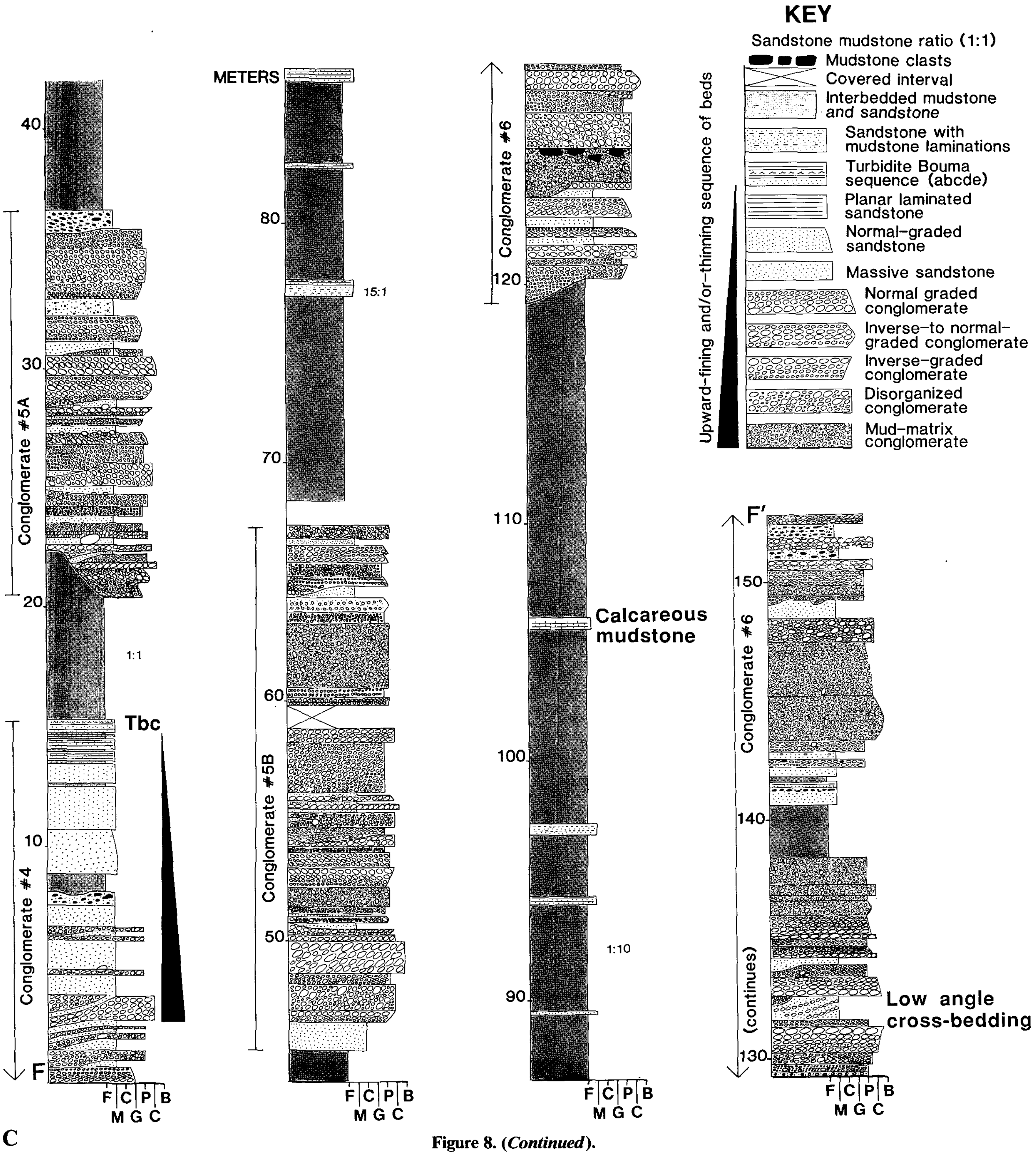


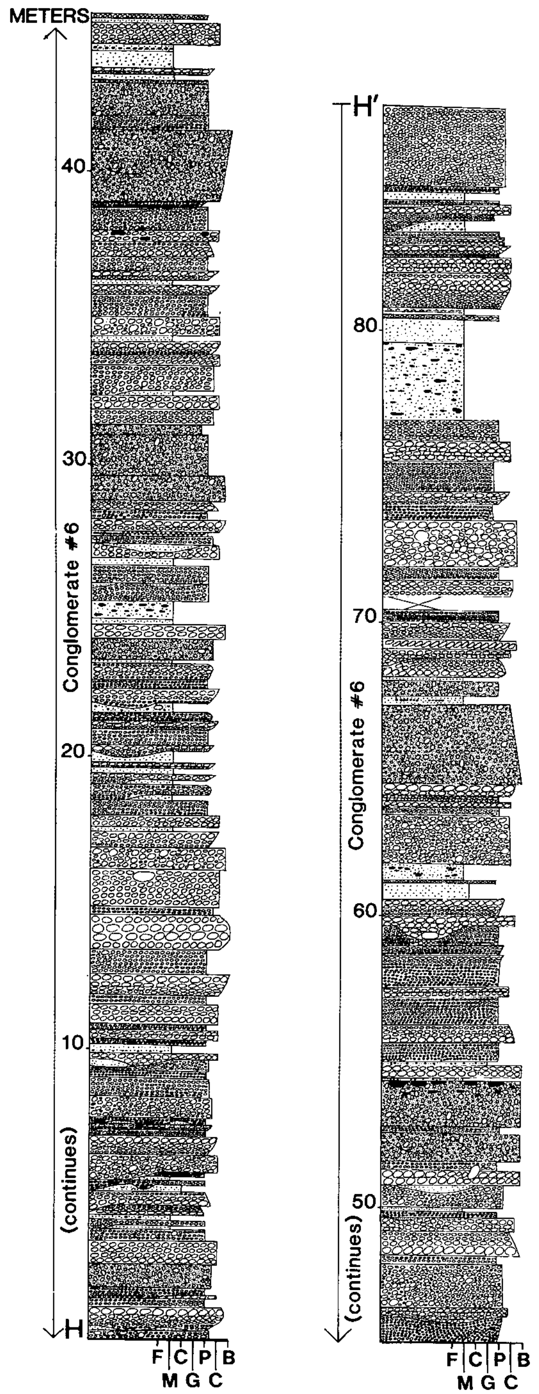
Figure 8. (*Continued*).

erate units 5 and 6 (Fig. 8). The thin to medium-thick sandstone beds consist largely of either a Bouma sequence, with and without the basal Bouma division (Bouma, 1962), or are planar bedded, whereas the very thin-bedded sandstone beds are commonly either ripple laminated or a Bouma sequence without the basal Bouma division. Interchannel conglomerate beds are nonchannelized and lobate in form.

Levee Deposits

Slumped, interbedded sandstone and mudstone beds that border the valley fill and interfinger with channel and interchannel deposits are interpreted herein as levee deposits (Fig. 5). These deposits are >500 m thick and are exposed on the west, northwest, and southeast sides of the field area, with the best exposures along Arroyo San Fernando (Fig. 4).

Slump features include block rotation and translation, broken horizons, and slump-folded horizons, bounded above and below by undisturbed, flat-lying strata. A zone of shear several meters thick is common at the base of slump blocks (Fig. 11). Paleoslump directions, determined from rotation of slump blocks and orientation of slump folds, are both to the east (into the valley) and to the west (directly away from the valley). The largest recognized rotated slump block (>80 m thick and 0.5 km wide) slid away from the submarine-fan valley. The existence of slumps that moved both away from and toward the valley indicates a positive topographic fea-



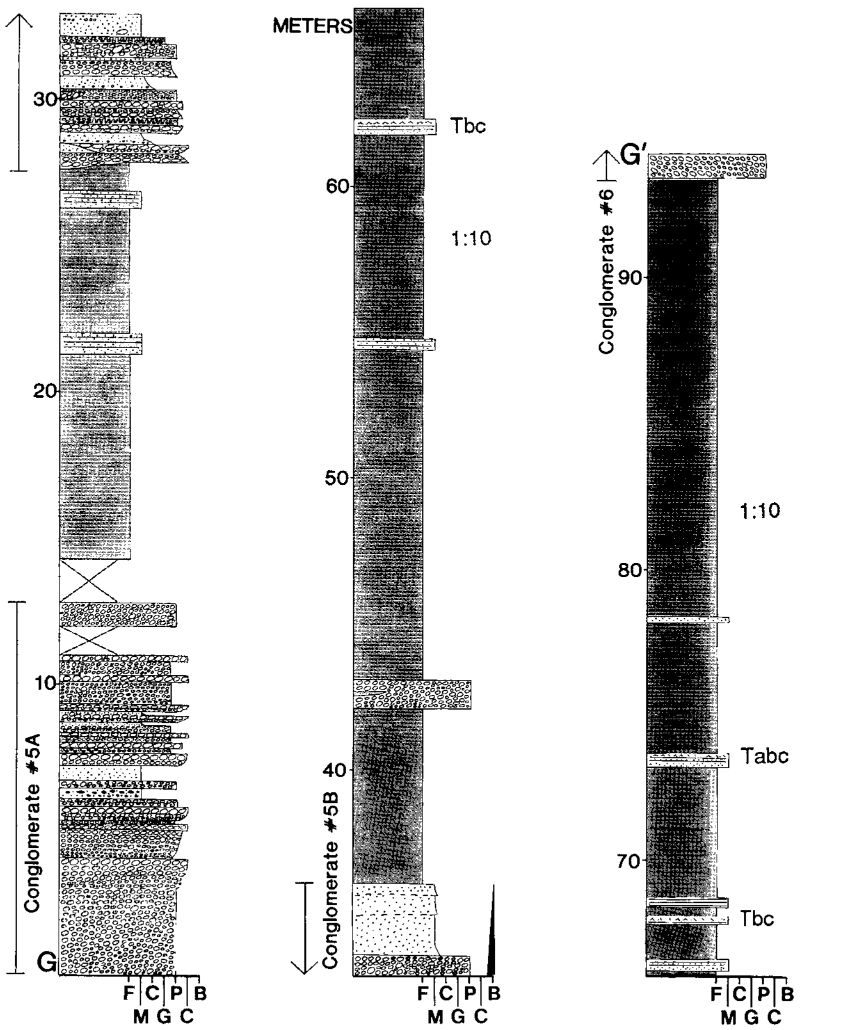


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Figure 8. (*Continued*).

TABLE 1. LITHOLOGY AND SEDIMENTARY FEATURES OF SUBMARINE-FAN VALLEY-LEVEE COMPLEX

	Valley fill		Levee deposits
	Channel deposits	Interchannel deposits	
Predominant lithology	Conglomerate and sandstone	Sandstone and mudstone	Mudstone and sandstone
	Base—Cg:Ss ratio, 1:1; Ss:Ms ratio, 20:1. Fining-upward sequence—Cg:Ss ratio, <1:7; Ss:Ms ratio, 20:1 to 3:1	Ss:Ms ratio, 3:1 to 1:10, average 1:1	Ss:Ms ratio, average 1:1 to 1:2
Geometry of sedimentary sequences	Channelized—10–50 m thick, 0.1 to 2 km wide. Fining-upward sequence—5–15 m thick	Nonchannelized, several kilometers wide	Nonchannelized. Large slumps, several (0.08 by 0.5 km)
Turbidite facies (*sensu* Mutti and Ricci Lucchi, 1978)	Base—facies A, B, and F. Fining-upward sequence—facies C, with lesser D and B	Facies D and G	Facies D, E, and G
Sedimentary features	Graded and ungraded conglomerate, sand matrix and clast-supported, lesser mud matrix and matrix supported. Massive sandstones with and without mudstone clasts; normal graded sandstone with granules common at the base. Fining-upward sequence—very thick- to medium-bedded, planar-laminated sandstones, Bouma sequence with and without the basal Bouma division, uncommon massive sandstone	Medium- to very thin-bedded sandstone, planar laminated, Bouma sequence with and without the basal Bouma division; very thin sandstones, ripple laminated or turbidites without basal Bouma division	Thick- to very thin-bedded sandstone; sedimentary structures similar to those of interchannel deposits except that medium- to thick-bedded sandstones are more common

TABLE 2. DIMENSIONS OF MODERN AND ANCIENT SUBMARINE-FAN SYSTEMS

Dimensions of modern submarine-fan valley* fills

Name	Width (km)	Fill thickness (m)	Reference
1 Loma Sea valley	1.5	200–500	Graham and Bachman, 1983
2 Newport Valley	0.9	75	Graham and Bachman, 1983
3 La Jolla Valley,	1.5–2.7	80–240	Graham and Bachman, 1983
4 Ebro Valley	0.5–6.0	150–200	Nelson and Maldonado, 1988
5 Tuffs abbysal valley	3.5	150	Hamilton, 1967
6 Rhone Fan valley	1.0–3.0	600–700	Droz and Bellaiche, 1985

Dimensions of ancient inner-fan valley* fills

Name	Width (km)	Fill thickness (m)	Reference
1 Doheny Channel	0.2	40+	Normark and Piper, 1969
2 Marnosa-Arenacea	0.5–1.5	10–50	Ricci Lucchi, 1985
3 Hecho Turb	1–3	30–50	Mutti, 1985a
4 Delaware Basin	0.4	15+	Jacka and others, 1968
5 Shale Grit Formation	1+	<50	Walker, 1966

Morphology of modern submarine-fan valleys*

Name	Width (km)	Depth (m)	References
1 Bengal Fan	0.9–15	95–329	Emmel and Curray, 1985
2 Indus Fan	<9.3	>100	Kolla and Coumes, 1985
3 Amazon Fan	1–3	75–300	Damuth and Flood, 1985; Damuth and others, 1988
4 Mississippi Fan	3.1–12	52–300	Bouma and others, 1985a
5 Rhone Fan	1–3	50–75	Droz and Bellaiche, 1985
6 Ebro Fan	0.5–6	38–376	Nelson and others, 1985
7 Laurentian Fan	1.4–7	34–250	Piper and others, 1985
8 La Jolla Fan	1–1.2	160	Graham and Bachman, 1983
9 Wilmington Fan	<7	20–50	Cleary and others, 1985
10 Delgada Fan	1.9–4.9	56–98	Normark and Gutmacher, 1985
11 Astoria Fan	1–2	82–146	Nelson, 1985
12 Magdalena Fan	—	>100	Kolla and Buffler, 1985
13 Monterey Fan	2.3–3.7	55–280	Normark and others, 1985
14 Navy Fan	1–5	15–70	Normark, 1978; Normark and Piper, 1985
15 Ascension Fan	8	—	Normark, 1978
16 Chile Trench axial valley	1–5	50–200	Thornburg and Kulm, 1987
17 Cascadia	0.6–4.5	40–320	Carter, 1988
18 Bounty	1–2	150–650	Carter, 1988
19 Vidal	0.5–1.5	100–220	Carter, 1988
20 Maury	3–10	100–300	Carter, 1988
21 Cap-Ferret Fan	4–6	300–400	Cremer and others, 1985

Morphology of channels and thalwegs within modern submarine-fan valleys

Name	Width (km)	Depth (m)	Reference
1 Wilmington Valley	0.5–1.5	—	Cleary and others, 1985
2 Rhone Valley	0.5–0.6	40–50	Droz and Bellaiche, 1985
3 Navy Valley	0.2–0.5	8	Normark, 1978
4 Ascension Valley	—	20	Normark, 1978
4 Ascension Valley	—	20	Normark, 1978

*Terminology as in Normark (1978).

ture (levee) and that slumps were not just the result of undercutting by channels. The maximum thickness of a listric slide block (>80 m) provides a minimum value for the relief of the levee.

Sandstone and mudstone beds of the levee deposits are similar to interchannel deposits except that medium- to thick-bedded massive sandstone beds are more common (Table 1). Paleocurrent data from the levee sandstone beds indicate a westerly direction of sediment transport, almost perpendicular to the paleocurrents in the channel deposits (Fig. 4).

Valley-Abandonment Deposits

The valley-abandonment deposits consist of mudstone beds with minor sandstone beds and are exposed in the east side of the field area, capping the valley fill and possibly the levee deposits (Fig. 4). Within the field area, this unit is more than 100 m thick. The sandstone beds are nonchannelized and consist largely of very thin to medium-thick beds. Most of the sandstone beds contain the Bouma sequence without the basal division. The sandstone-mudstone ratio is generally less than 1:4. No slumps were recognized in this deposit. Similar mudstone facies have been identified from piston cores taken within abandoned modern submarine-fan valleys (Nelson and Maldonado, 1988).

COMPARISON OF THE ARROYO SAN FERNANDO SUBMARINE-FAN VALLEY-LEVEE COMPLEX TO MODERN SYSTEMS

The deep-marine deposits along Arroyo San Fernando are similar in size and spatial arrangement to the morphologic expression of many modern submarine-fan valley-levee systems. The width and thickness of the ancient submarine-fan valley fill at Arroyo San Fernando is similar to widths and thicknesses of many modern submarine-fan valley systems (Fig. 12; Table 2). Channel deposits in the Arroyo San Fernando submarine-fan valley are comparable in size to the widths and depths of channels within modern submarine-fan valleys (Table 2). Lastly, the levee deposits adjacent to the Arroyo San Fernando submarine-fan valley are similar in thickness, lithology, and soft-sediment deformation features to modern submarine-fan levees (discussed below).

Modern submarine-fan valleys range from less than 1 to 15 km wide and commonly show a general decrease in valley width downfan (Barnes and Normark, 1983/1984; see compilation chart). Mud-rich fans such as the Indus, Mississippi, and Bengal fans have the largest submarine valleys, as much as 15 km wide, whereas mixed-sediment or sand-rich fans (see

Figure 9. Two upward-fining sequences of beds within an amalgamated channel deposit. Each of these upward-fining sequences contains a basal section of interbedded conglomerate and sandstone that grades upward into sandstone and finally into interbedded sandstone and mudstone. White scale bar represents ~4 m.

Shanmugam and others, 1988) in active-margin settings have submarine-fan valleys less than 10 km wide (Fig. 12; Table 2). The Arroyo San Fernando submarine-fan valley is a coarse-grained depositional system in an active-margin setting, and its width (5.5 to 7.5 km) lies within the range of modern submarine-fan valleys in active-margin settings.

Shallow channels within modern submarine-fan valleys are commonly tens of meters deep and several hundred meters wide (Table 2). These dimensions are similar to those of the single channel deposits in the Arroyo San Fernando submarine-fan valley fill.

The thickness of fill of modern submarine-fan valleys, as estimated from interpretation of seismic reflection profiles, ranges from 75 to 700 m (Table 2), the thicker sequences being the product of vertical aggradation of the valley-levee system (Droz and Bellaiche, 1985; Nelson and Maldonado, 1988; Manley and Flood, 1988). The thickness of the Arroyo San Fernando submarine-fan valley fill (670 m) lies within the upper range of modern submarine-fan valley-fill thicknesses. Vertical aggradation of the La Jolla submarine-fan valley has resulted in stacking of channelized sandstone and gravel bodies that are encased in fine-grained overbank deposits (Bachman and Graham, 1985). Stacked channel and interchannel deposits also resulted from vertical aggradation of the stable main valley at Arroyo San Fernando.

Modern submarine-fan levee deposits consist of interbedded hemipelagic sediment and fine-grained turbidites that are commonly slumped (Nelson and Nilsen, 1974; Anderson and others, 1986). They are commonly tens to hundreds of meters thick (Nelson and Nilsen, 1974; Walker, 1984; Shanmugam and others, 1985; Barnes and Normark, 1983/1984; see compilation chart). Stow (1981) has measured slopes of 8° and 2°, respectively, for the upper valley margin and the slope off the back of levees. The steep slopes of levees along the submarine-fan valley margin result in slump blocks sliding perpendicular to, both toward and away from, the channel axis. The slumping of levee deposits perpendicular to the submarine-fan valley has been documented from levee deposits along the Ebro and Rhone submarine-fan valleys (Droz and Bellaiche, 1985; Nelson and Maldonado, 1988), with the largest slumps on the outer slopes of the Rhone submarine-fan valley (Droz and Bellaiche, 1985). The levee deposits at Arroyo San Fernando consist of interbedded sandstone and mudstone beds, have at least 80 m vertical relief, and show sedimentary facies and slump development similar to those of modern levee deposits.

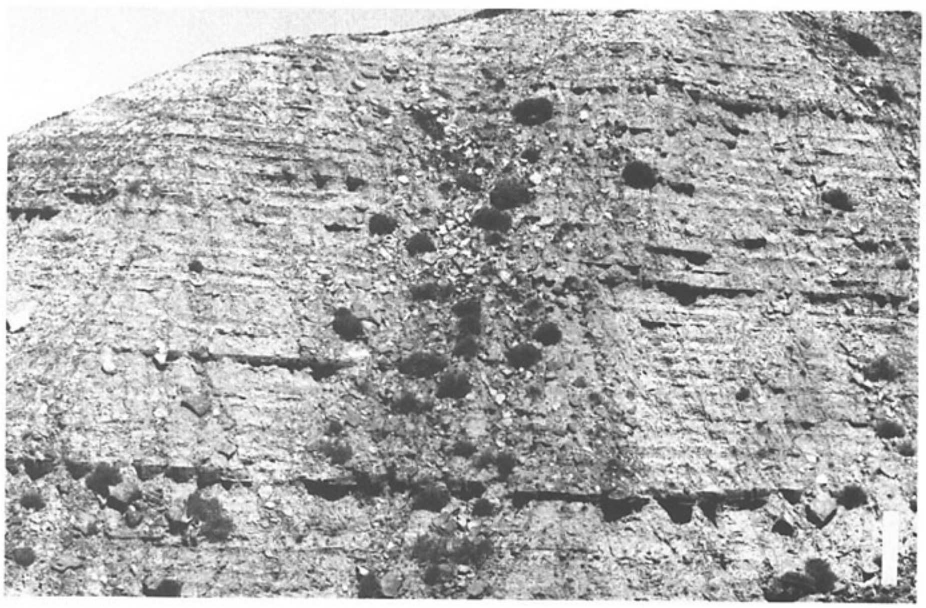


Figure 10. Interchannel deposits. These deposits consist of interbedded mudstone and fine- to medium-grained sandstone beds. Medium- to thick-bedded sandstone beds are largely Bouma sequence turbidites or planar laminated, with lesser massive beds. Very thin to thin-bedded sandstone beds are either ripple laminated or Bouma sequence turbidites without the basal division. A systematic trend of either an upward-thinning or -thickening sequence of beds is not present. White scale bar represents ~1.5 m.

COMPARISON OF CHANNEL DEPOSITS IN THE VALLEY FILL TO OTHER ANCIENT INNER-FAN VALLEY FILLS

Channel deposits *within* the Arroyo San Fernando valley fill have cross-sectional dimensions, sedimentary facies, and vertical facies trends similar to several deposits interpreted in the literature as ancient inner-fan valley fills. These relationships indicate that many ancient inner-fan valley fills may instead only represent

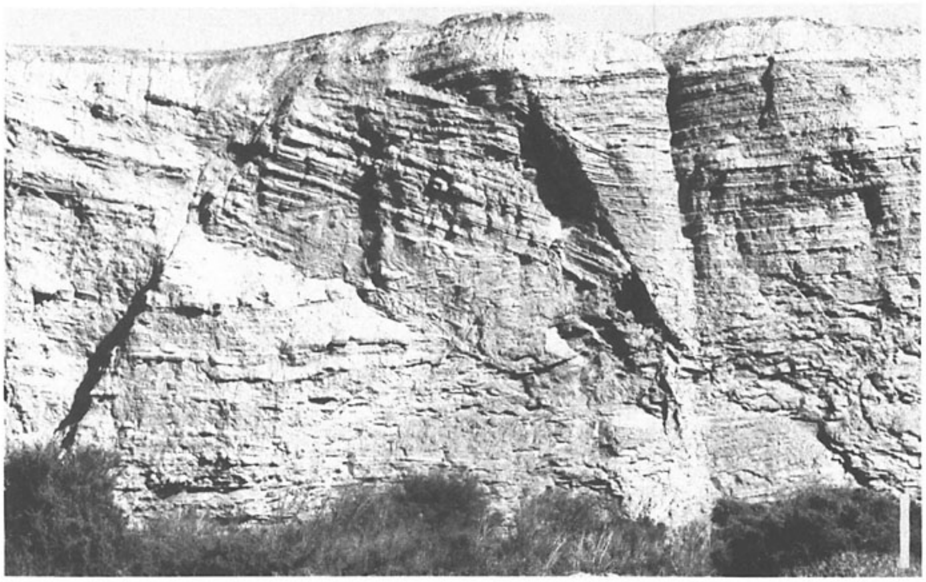


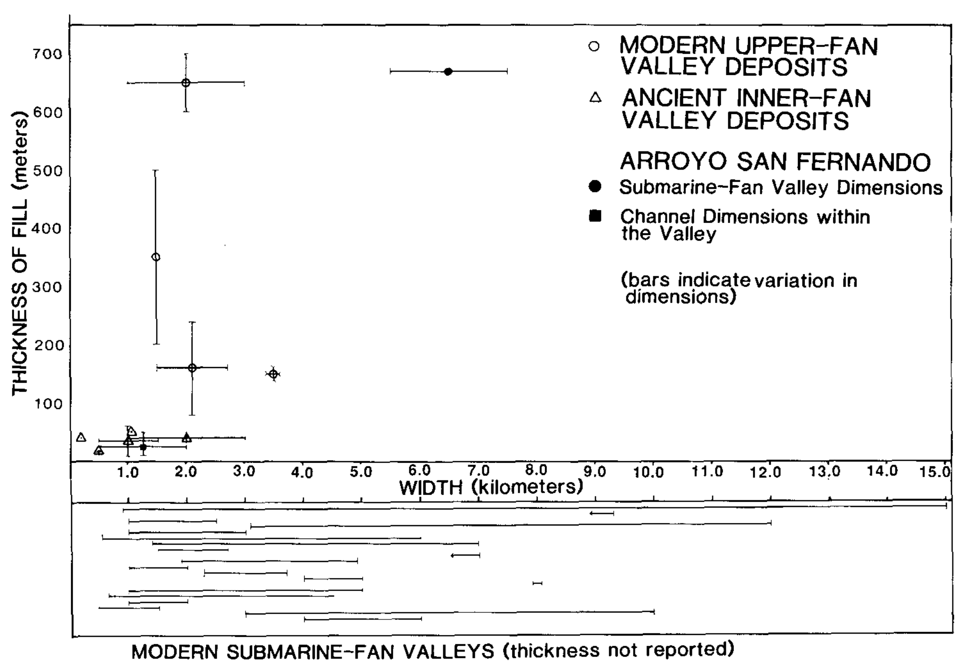
Figure 11. A 20-m-thick slump block in the levee deposits. This slump block is enclosed in semiparallel beds, indicating that this block formed by soft-sediment slumping. Below the large slump block are several horizons of smaller slide blocks and soft-sediment folds. White scale bar represents ~6 m.

channel deposits within a larger submarine-fan valley fill (see also Mutti, 1985b; Mutti and Normark, 1987).

The cross-sectional dimensions of interpreted ancient inner-fan valley fills range from 0.5 to 3 km wide and less than 50 m thick (Table 2). These dimensions are similar to those of individual channel deposits within the Arroyo San Fernando submarine-fan valley fill; however, they are as much as an order of magnitude smaller than the cross-sectional dimensions of the Arroyo San Fernando submarine-fan valley fill and modern submarine-fan valley fills (Table 2). We suggest, as have Mutti and Normark (1987), that an unusually continuous exposure is required to identify a feature as large as an entire submarine-fan valley-levee complex in the ancient record.

The channel deposits in the Arroyo San Fernando valley fill consist of turbidite-facies assemblages (*sensu* Mutti and Ricci Lucchi, 1978) that are similar to many other ancient deep-marine conglomerate and sandstone inner-fan valley fills. Basal channel conglomerate and sandstone beds are composed primarily of turbidite facies A with lesser facies B and F. Similar examples include the Great Valley Sequence, Butano Sandstone, Wheeler Gorge Conglomerate, Cabrillo Formation and Ferrelo turbidite system of California, the Gottero turbidite system in Italy, the Pesaguero Fan in Spain, the Kongstad turbidite system in Norway, the Cap Enrage Formation in eastern Canada, and the Rosario and Valle Formation in Baja California (Fisher and Mattinson, 1968; Nelson and Nilsen, 1974; Rupke, 1977; Ingersoll, 1978; Nilsen and Abbott, 1981, 1984; Yeo, 1982, 1984; Hein and Walker, 1982; Patterson, 1984; Walker, 1984; Howell and Vedder, 1985; Nilsen and Abbate, 1985; Pickering, 1985). The upward-fining sequence of sandstone beds

Figure 12. Graph of depth versus width for modern and inferred ancient inner-fan valley deposits reported in the literature (data summarized in Table 2). Also plotted on this graph are the dimensions of the Arroyo San Fernando submarine-fan valley and of the channels within it. (See footnote in Introduction for definition of the terms "valley" and "channels" used here.) Note that the dimensions of the Arroyo San Fernando submarine-fan valley-levee complex are similar to those of modern submarine-fan valleys, whereas a single channel deposit within the Arroyo San Fernando submarine-fan valley-levee complex has a size similar to those of deposits interpreted in the literature as ancient inner-fan valleys. These relationships, and facies relationships discussed in the text, may indicate that many deep-marine deposits interpreted as inner-fan valleys simply represent channels within a submarine-fan valley.



commonly overlies the basal conglomerate-sandstone section at Arroyo San Fernando; these are composed primarily of turbidite facies B and C at the base, and facies D at the top. Similar deposits occur in the Wheeler Gorge Conglomerate (Walker, 1984) and the Cap Enrage Formation (Hein and Walker, 1982). The upward-fining sequences in the Arroyo San Fernando submarine-fan valley resulted from channel migration and channel switching.

CONCLUSIONS

The deep-marine deposits along Arroyo San Fernando represent a submarine-fan valley-levee complex that has many features in common with modern submarine-fan valley-levee systems. These similarities include (1) valley width, (2) valley-fill thickness, (3) presence of channels within the valley, (4) channel dimensions, (5) a thick levee sequence that borders the valley, and (6) a stable, vertically aggrading valley-levee system.

The submarine-fan valley-levee complex at Arroyo San Fernando differs sedimentologically from other deep-marine environments such as submarine ramp, submarine canyon, or middle-fan channel environments. Submarine ramp environments have conglomeratic facies and channel dimensions similar to those of submarine-fan valleys, but they lack levee deposits and a central axis of sedimentation (Chan and Dott, 1983; Heller and Dickinson, 1985). Submarine canyon fills may resemble those of submarine-fan valley fills (Mutti and Ricci Lucchi, 1978; Howell and Normark, 1982; Shanmugam and Moiola, 1988); however, submarine canyons are erosional features several hundred meters deep, and they are not bordered by levee deposits (for examples, see McHargue and Webb, 1986). The fine-grained slope deposits into which a submarine canyon is cut are commonly slumped, but slump directions are parallel to the sediment transport directions in the canyon (Field and Clarke, 1979; Nardin and others, 1979; Howell and Normark, 1982), whereas slump directions on levees are perpendicular to sediment transport in the submarine-fan valley (Droz and Bellaiche, 1985). Middle-fan channels are arranged in a radiating pattern, and middle-fan aggradation is accomplished by shingling of channel-levee deposits over a broad region (Droz and Bellaiche, 1985; Damuth and others, 1988); channels within submarine-fan valleys, in contrast, are restricted to a narrow region and stack vertically as the fan grows (Normark, 1970; Graham and Bachman, 1983; Droz and Bellaiche, 1985). Additionally, conglomerate deposits are rare in middle-fan environments (Nelson and Nilsen, 1974).

The Arroyo San Fernando submarine-fan valley fill and modern submarine-fan valley fills are as much as an order of magnitude wider and thicker than other ancient deep-marine deposits interpreted as inner-fan valleys. These inferred ancient inner-fan valleys are comparable in size to channels *within* the Arroyo San Fernando submarine-fan valley and to channels within modern submarine-fan valleys. Comparison of the Arroyo San Fernando submarine-fan valley-levee complex to modern submarine-fan valley-levee systems and ancient inner-fan deposits indicates to us that many ancient deep-marine deposits interpreted as inner-fan valley fills may only represent channel deposits within a much larger submarine-fan valley-fill complex.

ACKNOWLEDGMENTS

Funds for this project were furnished by National Science Foundation Grant EAR86-18771 (Busby-Spera) and an Arco Research Grant (Morris).

The writers thank James Boles and Pat Abbott for helpful discussions. The writers appreciate the service rendered by Unocal in preparation of microfossil samples. Micropaleontologic work by Mark Filewicz and Sarah Downs is deeply appreciated. Critical reviews by William Normark and Martin Link were very helpful.

Special thanks go to Scott Renger and Joe Acaba for field assistance and to Doug Smith, James White, and Nancy Riggs for editing earlier versions of the manuscript.

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Manuscript Received by the Society May 19, 1989
Revised Manuscript Received October 20, 1989
Manuscript Accepted October 27, 1989