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Rapid development of gravelly high-density turbidity currents in marine Gilbert-type fan deltas, Loreto Basin, Baja California Sur, Mexico

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ABSTRACT

The Pliocene Loreto basin is an asymmetrical half graben located on the eastern margin of Baja California Sur, Mexico, which formed by rapid subsidence along the dextral-normal Loreto fault. The southern Loreto basin contains numerous, well exposed coarse-grained Gilbert-type fan deltas that were derived from the footwall of the Loreto fault. Detailed sedimentological study of individual foreset beds provides information about down-slope flow transformations of cohesionless sediment gravity flows in shallow water. Deposits of Gilbert-delta foresets consist of ungraded, normal-graded, inverse- to normal-graded, and bipartite conglomerate and sandstone. Lateral transitions in sorting, grading style and internal structure are commonly observed within individual beds, both across and down slope, suggesting heterogeneity within flows and a close relationship between high-density turbidity currents and gravel traction carpets. A conceptual model for flow transformation and deposition of high-density turbidity currents on Gilbert-delta foreset slopes is developed for Pliocene strata in the Loreto basin. In this model, ungraded cohesionless debris flows evolved rapidly down-slope into normal-graded gravelly turbidity currents. With continued down-slope transport, the gravel fraction collapses and becomes concentrated into a basal traction carpet undergoing laminar shear, and is over-ridden by a sandy turbulent suspension. The short distances (10–20 m) over which lateral transitions within single beds are observed indicate very rapid flow transformations (10–20 s) and rapid deposition of gravel traction carpets by frictional freezing on and near the base of the foreset slope.

INTRODUCTION

Gilbert deltas were first described from Lake Bonneville deposits (Gilbert, 1885), and for years were believe to be restricted to lacustrine settings (e.g. Stanley & Surdam, 1978). Gilbert-type fan deltas are a subset of fan deltas that are defined by their unique and highly constructional tripartite geometry of sub-horizontal topsets, steeply dipping foresets and sub-horizontal bottomsets (Fig. 1; Ethridge & Wescott, 1984). The occurrence of Gilbert deltas in marine settings has received attention only in the past 10–15 years (Postma, 1984; Postma & Roep, 1985; Colella *et al.*, 1987; Colella, 1988; Postma *et al.*, 1988a,b; Prior & Bornhold, 1988, 1990; Corner *et al.*, 1990; Massari & Parea, 1990; Dorsey *et al.*, 1995). Most of these studies have focused on either a general description of foreset facies or a specific example of a foreset bed as a means to characterize fan-delta front deposition. In general, topset deposition may be dominated by mass flows, fluvial traction sedimentation, and/or marine reworking, while

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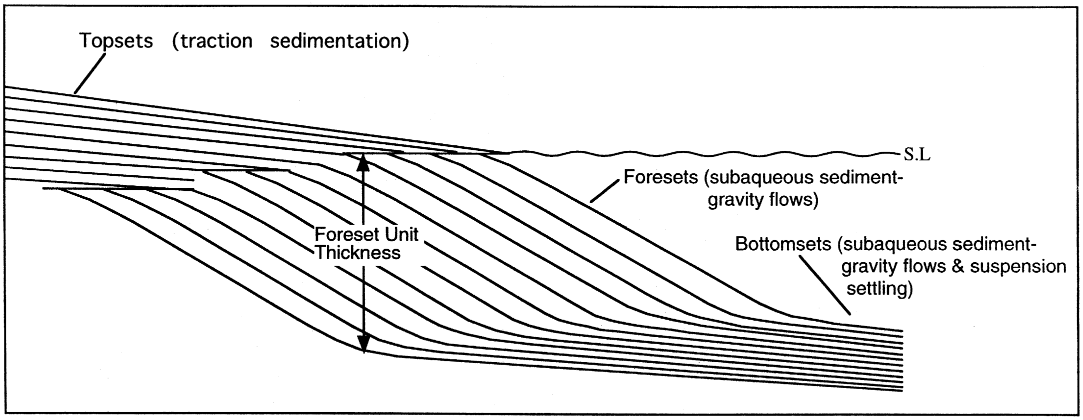


Fig. 1. Schematic representation of a classical Gilbert-type delta showing the tripartite geometry of sub-horizontal topsets, steeply dipping foresets and sub-horizontal bottomsets. Parentheses indicate the general depositional process(es) for each of the three parts of the Gilbert delta (modified from Postma & Roep, 1985).

foresets and proximal bottomsets are dominated by subaqueous sediment-gravity flows (Fig. 1). Suspension settling may be an important depositional process for distal bottomsets.

A recent review paper on transport and depositional processes operative on steep gravelly delta slopes emphasized the need for detailed study of these processes, especially with regard to foreset and bottomset deposits (Nemec, 1990). Deposition of foreset strata is commonly attributed to 'avalanching' (*sensu lato*) with no effort to interpret actual single-event mass-transport processes (Nemec, 1990). Sediment gravity flows commonly begin as slumps at the top of the foreset slope due to over-pressuring during sediment accumulation on the delta front (Postma, 1984). A variety of types of flow transformation are likely to occur down-slope from there. As slumps move down slope they evolve into flows with plastic behaviour (debris flows). Continued movement down slope results in further dilution of the flow, commonly resulting in transformation to a flow with fluidal properties, also known as a turbidity current (Postma & Roep, 1985; Nemec, 1990). Some recent studies, most notably by Postma *et al.* (1988a), have carried out detailed examination of foreset and bottomset deposits where the bottomsets have been deformed by submarine slides, slumps and sediment gravity flows. While these studies are important for better understanding of subaqueous deformation, there remains a need for detailed study of a wide range of single-event mass-transport processes that are common on subaqueous fan-delta slopes.

Subaqueous sediment gravity flows have received considerable attention over the past 30 years. The majority of this research focused on experimental studies and field observations that described and interpreted sedimentary structures and textures. This work has resulted in a broad understanding of the transport mechanisms in low-density and high-density turbidity currents in deep-sea settings (e.g. Middleton & Hampton, 1973; Lowe, 1979, 1982; Middleton, 1993). High-density turbidity currents are defined as flows having more than 10% of sediment by weight (Kuenen, 1966; Middleton, 1970). In flows containing a significant population of pebble- and cobble-sized clasts, the combined effects of fluid turbulence, hindered settling, matrix buoyant lift, and dispersive pressures resulting from grain-grain collisions commonly are involved in clast support (Lowe, 1982). Large clasts are more readily transported in relatively concentrated flows, and they are quickly deposited once sedimentation begins and particle concentration increases. Lowe (1982) developed a conceptual model for the development of gravel traction carpets at the base of high-density turbidity currents, in which clasts in the traction carpet layer are supported mainly by dispersive pressures resulting from grain-grain collisions. Experimental work by Postma *et al.* (1988b) confirmed the presence of a laminar inertia flow (gravel traction carpet) concentrated at the base of a faster-moving, lower-density turbulent suspension.

In spite of these advances, there have been few detailed field studies of the evolution and flow transformations of high-density turbidity currents and gravel traction carpets in shallow marine settings. Well exposed Gilbert-type fan deltas in the Pliocene Loreto basin (this paper) provide us with an excellent opportunity to study the evolution of high-density turbidity currents and gravel traction carpets in shallow water. These fan deltas are mud-poor and occur in a variety of sizes, with foreset-unit thicknesses ranging from 5 m to greater than 30 m. The paucity of mud in foreset deposits of this study probably results from low-density fresh-water plumes that carried suspended sediment out to sea. Thus, transport and deposition on Gilbert-delta slopes in the Loreto basin were dominated by processes involving cohesionless flows. The variety of foreset-unit thicknesses allows for analysis of processes at a variety of scales, and the smallest foreset units are similar in scale to small-scale experiments performed by Postma *et al.* (1988b). This allows us to make meaningful comparisons between experimental studies and field exposures of comparable deposits, where model predictions can be tested.

GEOLOGICAL SETTING AND STRATIGRAPHIC OVERVIEW

The Pliocene Loreto basin, located on the eastern margin of Baja California Sur, Mexico, formed in response to oblique rifting associated with opening of the Gulf of California (Fig. 2a; Moore & Buffington, 1968; Larson, 1972; Mammerickx & Klitgord, 1982; Lonsdale, 1989; Stock & Hodges, 1989). The basin is an oblique half graben bounded on the south-west by the Loreto fault, an oblique-slip dextral-normal fault (Fig. 2; Umhoefer *et al.*, 1994). The stratigraphy is characterized by pronounced westward thickening and coarsening of strata toward the Loreto fault, which controlled rapid westward tilting and subsidence during late Pliocene time. A pulse of very rapid basin subsidence (8 ± 5 mm year^{-1}) occurred during a short time interval from 2·46–2·36 Ma and acted as the primary control on formation of Gilbert deltas (Fig. 3; Dorsey *et al.*, 1995).

This study focuses on the sedimentology and depositional processes of a thick package of footwall-derived Gilbert-type fan deltas (marginal marine and marine shelly sandstone and conglomerate in Fig. 2; Dorsey *et al.*, 1995). They are classified as fan deltas because they pass laterally up-transport into poorly sorted, massive and unfossiliferous alluvial-fan deposits that make up a continuous belt ≈1·5–2 km wide along the Loreto fault (Fig. 2). Bottomset and foreset strata of the Loreto fan deltas comprise marine deposits that are described in the following sections of this paper. Topset facies consist of massive to cross-stratified channel conglomerate and unfossiliferous to shelly sandstone with weakly developed palaeosols, which accumulated in a gravelly and sandy delta-plain setting. Facies of the proximal, upper delta plain (toward the south-west) display an increase in structureless, unstratified conglomerate deposited by debris flows. Thus, fan-delta plain deposits in the Loreto basin occupy the transition between nonmarine alluvial fans to the south-west and marine foreset slopes to the north-east (Fig. 2; Dorsey *et al.*, 1995). This close association of fault-bounded, mass flow-dominated alluvial fans (feeder system) passing laterally over a short distance into gravelly, fluvial-influenced delta plain deposits (topsets) and associated foreset and bottomset facies is a common feature of Gilbert-type fan deltas in tectonically active basins (Colella *et al.*, 1987; Colella, 1988; Postma, 1990). Fan deltas in the Loreto basin comprise 16 vertically stacked parasequences that are bounded by transgressive marine shell beds (Fig. 3), and they display systematic geometrical relationships between bottomset, foreset and topset deposits (e.g. Fig. 1).

PHYSICAL SEDIMENTOLOGY

Gilbert-delta deposits in the Loreto basin provide exposures of foreset and bottomset strata, which consist of interbedded pebble to pebble-cobble conglomerate, pebbly sandstone, and sandstone. The excellent exposure and outcrop accessibility within the study area permit detailed analysis of depositional processes in individual foreset beds on Gilbert deltas with varying foreset-unit thicknesses. The well understood stratigraphic architecture allows for analysis of foreset beds and depositional processes in relation to their stratigraphic distance below the contact between foreset and topset strata (Falk, 1996).

In this section we describe and interpret the physical sedimentology of several examples of foreset beds selected from a total of 58 different foreset beds studied in eight different Gilbert deltas. Data collection included analysis of grain size, bed thickness, bedding characteristics, internal structures, textures and lateral changes in these parameters. The Gilbert-type fan deltas described here are divided into two types: those with foreset-unit thickness greater than 20 m (larger Gilbert deltas) and those with foreset-unit thickness less than 15 m (smaller deltas).

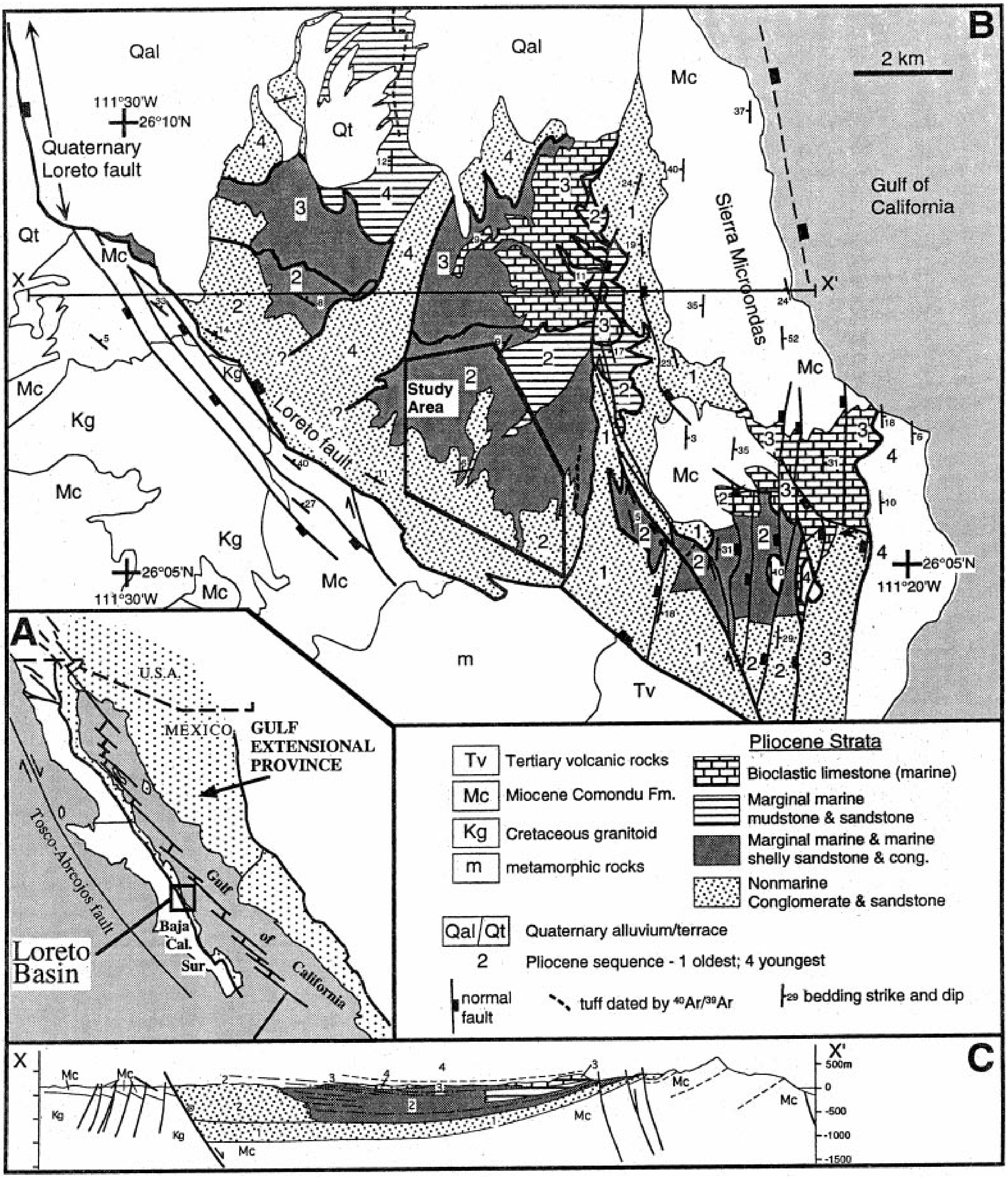


Fig. 2. (A) Regional tectonic map of Baja California and the Gulf of California showing location of the Loreto basin (adapted from Stock & Hodges, 1989). (B) Simplified geological map of the Loreto basin, showing distribution of major lithofacies, Pliocene sequences, south-western basin-bounding Loreto fault and the study area. (C) Cross-section across Loreto basin showing asymmetrical half-graben geometry. Location of cross-section shown in B.

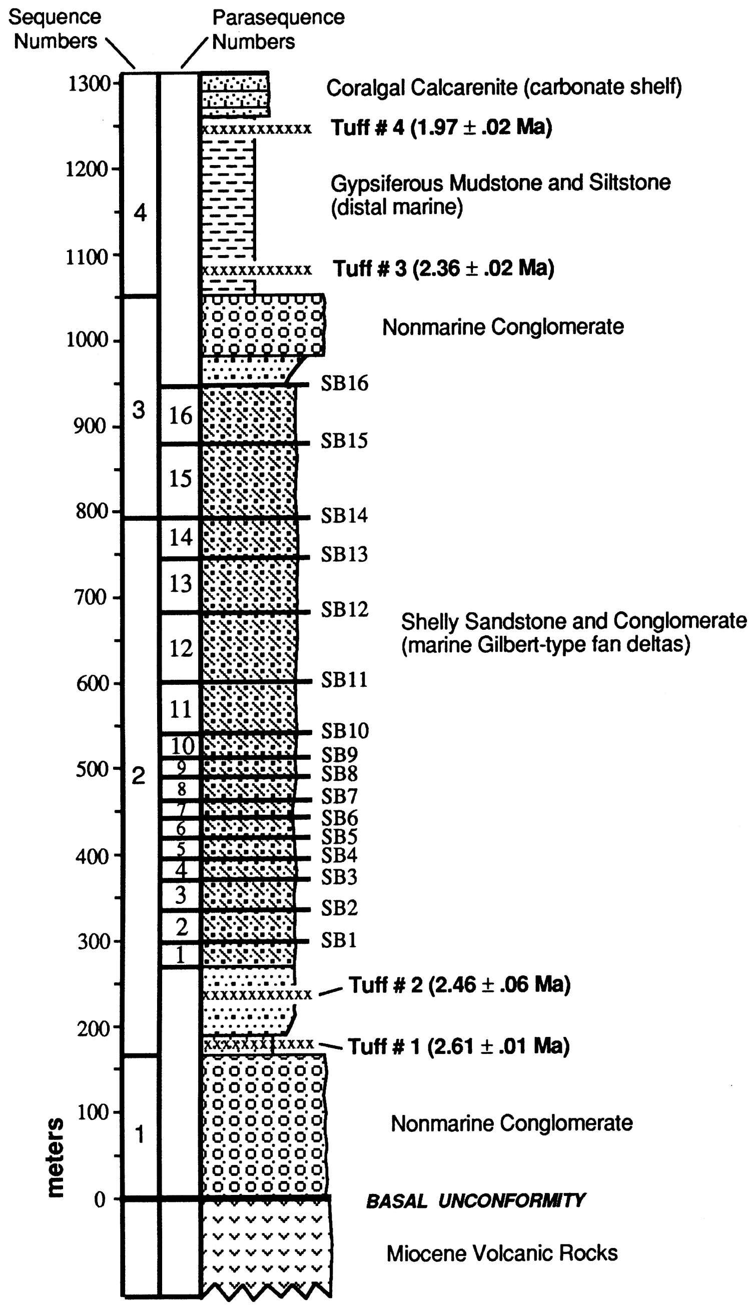


Fig. 3. Composite stratigraphic section for the Loreto basin, showing interbedded tuffs (#1 through #4) and hiatal molluscan shell beds (SB1 through SB16). Sequence and parasequence boundaries are shown in column on the left. Calculated rates of sediment accumulation (= subsidence rates) are shown on the right. Modified from Dorsey *et al.* (1995).

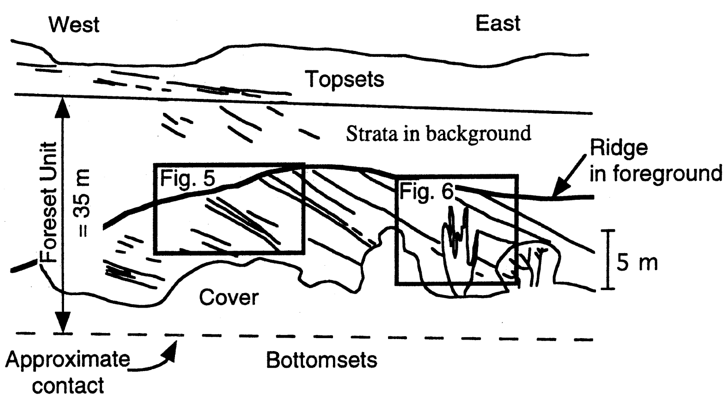


Fig. 4. Line drawing (from a photograph) of Gilbert-delta foresets and topsets within parasequence 13, showing the location of outcrops studied in example 1 (Figs 5 and 6). Strata in background are thicker than they appear in this sketch.

(A)

(B)

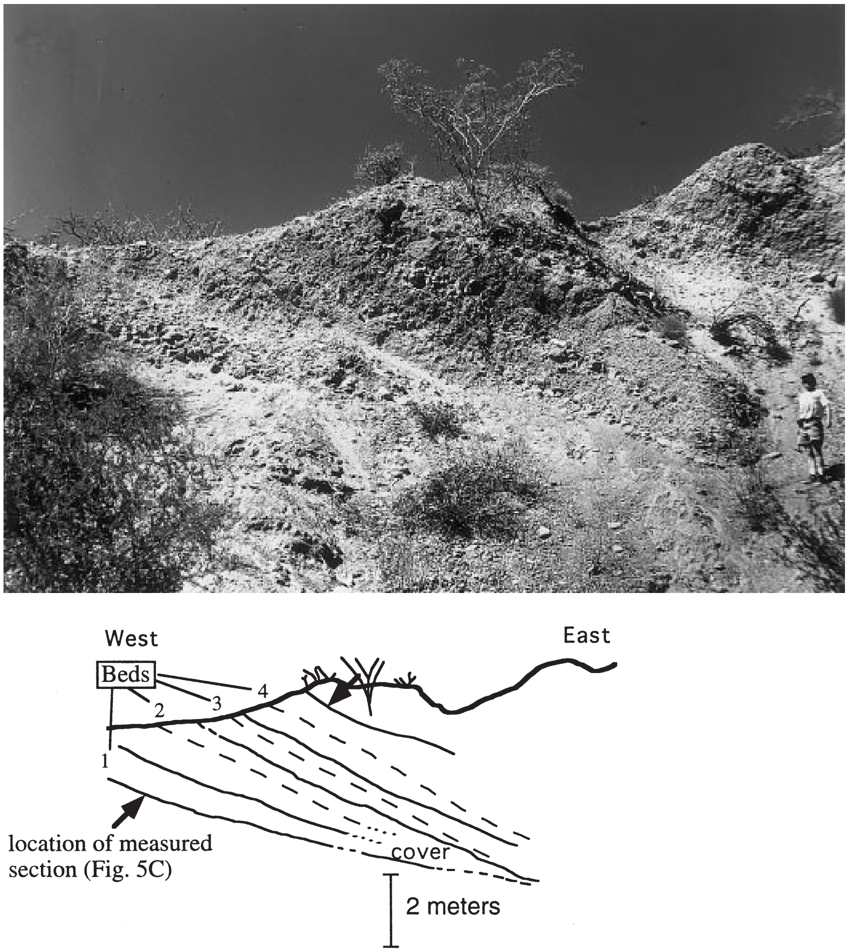


Fig. 5A,B. (A) Outcrop photograph of foreset beds (location is shown in Fig. 4). (B) Line drawing of A, showing contacts between four distinct beds (labelled 1 through 4). Dashed lines represent bipartite discontinuities between basal conglomerate and overlying pebbly sandstones. Note down-slope pinch-out of beds 1 and 2 and the basal parts of beds 3 and 4.

Larger Gilbert deltas (foreset unit > 20 m thick)

Example 1:

Description. Example 1 (Figs 4–6) illustrates a style of sedimentology that is commonly observed on Gilbert-delta foresets in the Loreto basin. Foreset beds in this example are situated between 20 and 30 m below the topset-foreset contact (Fig. 4). Because the topset-foreset contact is an approximate indicator of the palaeoshoreline, these two localities were deposited in at least 20–30 m of water depth. This corresponds to the lower part of foresets in a Gilbert delta whose foreset-unit thickness is ≈30–35 m (Fig. 4).

Figure 5 displays four well-defined foreset beds in this example. All beds exhibit a strong down-transport wedging geometry (Fig. 5A,B). Bed 1 exhibits normal grading while bed 2 exhibits an inversely graded basal conglomerate separated from an overlying pebbly sandstone by a sharp discontinuity (Fig. 5C). Bed 3 displays normal grading and a weakly defined bipartite discontinuity, and bed 4 displays a strong bipartite discontinuity (Fig. 5C).

In Fig. 6, we see a down-transport cross-sectional view of three beds that exhibit significant lateral changes. Bed 1 shows strong normal grading and is observed to pinch out in the down-transport direction. Beds 2 and 3 display lateral changes in their internal structure. In the upper left of Figs 6A and 6B, beds 2 and 3 are structureless, matrix-supported conglomerates. These matrix-supported conglomerates pass laterally down-slope into well-defined bipartite deposits that display an abrupt contact between a lower clast-supported basal conglomerate and an upper internally stratified pebbly sandstone (Fig. 6).

Interpretation. Bed 1 in Fig. 5 and bed 1 in Fig. 6 are interpreted to be deposits of fully mixed, gravelly high-density turbidity currents. Bed 2 (Fig. 5) is the deposit of a more evolved high-density turbidity current, in which the coarse-grained fraction settled into the basal layer

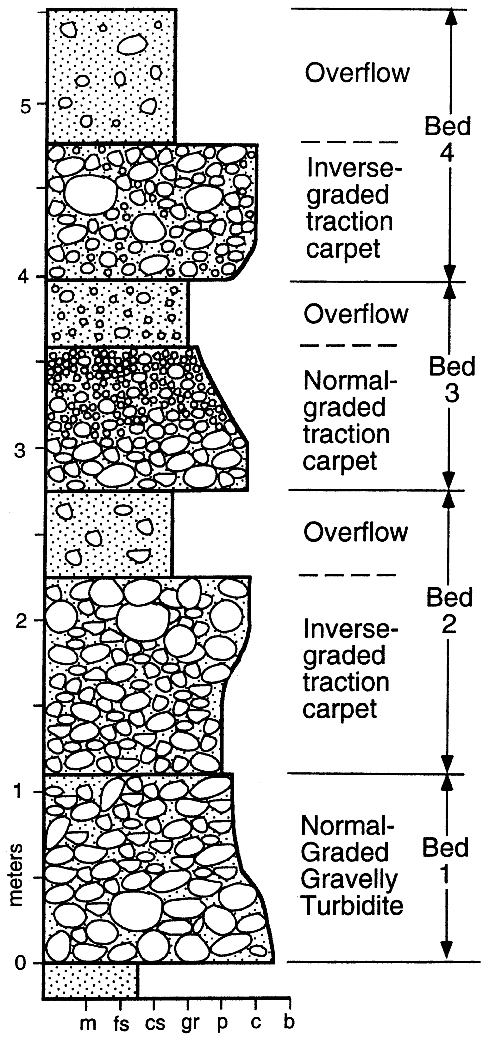


Fig. 5. (C) Stratigraphic measured section (location is shown in B), showing observed sedimentary structures and interpretations of transport processes.

to form a gravel traction carpet with an overflowing sandy turbulent suspension. Increased dispersive pressures in the gravel traction carpet is interpreted to be responsible for the inverse grading. The down-transport pinch-out of beds 1, 2 and 4, and the pinch-out of the basal conglomerate in bed 3 suggest rapid *en masse* deposition of gravel layers by frictional freezing, and bypassing of the sandy turbulent overflows.

Beds 2 and 3 (Fig. 6) present excellent examples of a down-transport lateral change in flow behaviour. The structureless, sand-matrix-rich and mud-free nature of the up-slope part of beds 2 and 3 suggest deposition of a cohesionless debris flow. The large disparity in clast sizes suggests that rapid clast segregation would have occurred if the flow had been turbulent. The bipartite nature of the down-slope parts of beds 2 and 3 (Fig. 6) indicates deposition by a high-density turbidity current comprising a gravel traction carpet with an overflowing sandy turbulent suspension (e.g. Lowe, 1982). This interpretation requires a very rapid down-transport flow transformation occurring over a distance of 20–30 m (Fig. 6). Another important aspect of Fig. 6 is the convex-up mound-like nature of the basal conglomerate in all three beds. This, combined with the down-transport pinch-out of gravel beds, suggests that these high-density turbidity currents deposited their gravel load *en masse* by frictional freezing on the foreset slope. This interpretation is similar to that developed for similar strata in Pleistocene gravels of southern Italy by Massari and Parea (1990), and is consistent with the argument that high-density turbidity currents rapidly collapse, probably in response to relatively minor changes in flow velocity (Middleton, 1970; Lowe, 1982; Nemec, 1990). Thus, in beds 2 and 3 (Fig. 6) we see evidence for rapid evolution of cohesionless debris flows into high-density turbidity currents which then rapidly deposited their basal traction carpets.

Example 2:

Description. This example is from the same foreset unit that was described in example 1, but the foreset beds in this example are near or at the topset-foreset contact (Fig. 7). Figure 8 displays an across-transport view of three gravelly foreset beds located less than 8 m below the topset-foreset transition (Figs 7 & 8). The lowest bed is 43 cm thick, including a 22 cm basal pebble conglomerate overlain sharply by sandstone (Fig. 8). The middle bed is a 50 cm-thick inverse-to-normal graded conglomerate on the left side, but on the right shows development of a discontinuity between a basal pebble-cobble conglomerate and an overlying pebbly sandstone unit (Fig. 8). Finally, the upper bed is a 70 cm-thick pebble-cobble-boulder conglomerate that shows well developed normal grading (Fig. 8).

Figure 9 displays a well exposed down-transport view of gravelly foresets deposited in less than 3 m water depth. Figure 9C is a measured section through these deposits which shows three distinct beds. Bed A consists of a normal-graded and channelized conglomerate with the basal contact displaying up to 30 cm of erosional relief; bed B is an internally stratified conglomerate; and bed C is another pebble-cobble conglomerate that exhibits strong normal grading (Fig. 9C).

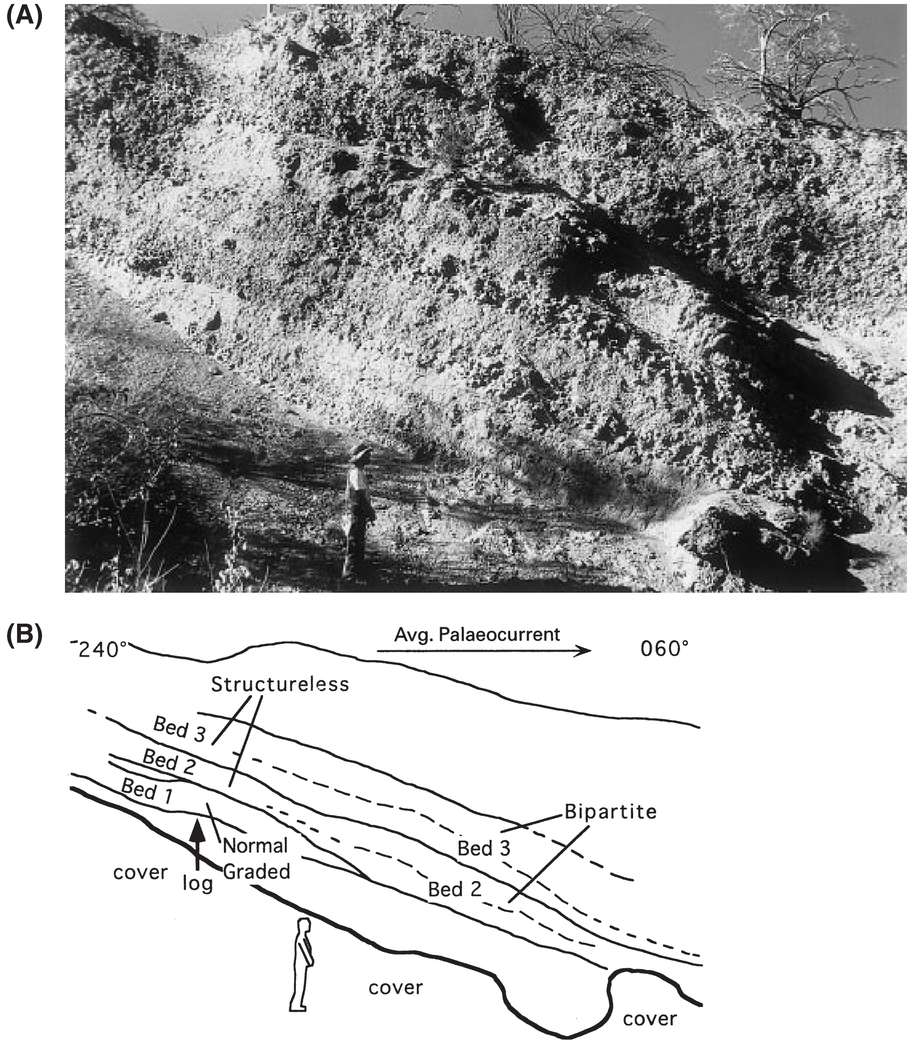
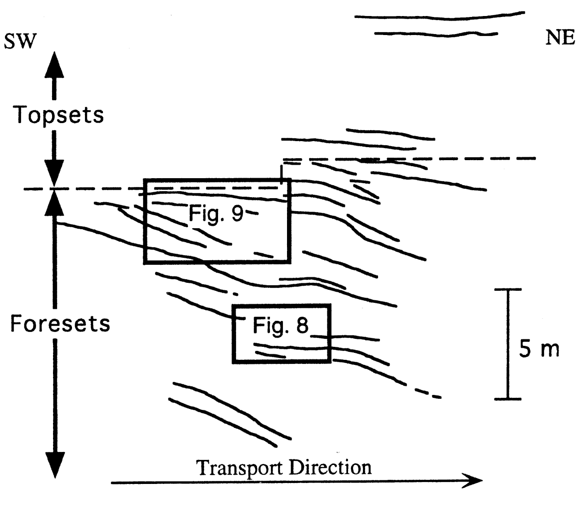


Fig. 6. (A) Outcrop photograph showing down-transport exposure of foreset beds. Location is shown in Fig. 4. (B) Line drawing of A, showing three beds and structural interpretation. Bed 1 is normal-graded and pinches out down-slope; beds 2 and 3 pass laterally down-slope from structureless, matrix supported, sand-rich conglomerates into well developed bipartite deposits. Basal traction carpets thin down-slope.



Interpretation: The three beds in Fig. 8 are typical deposits of gravelly high-density turbidity currents, displaying well-developed examples of bipartite discontinuities, normal grading and inverse to normal grading. It is significant that these features developed only 6 m below the topset-foreset transition, in 6 m of water depth. With a primary dip of 25°, that implies that these deposits travelled in the subaqueous environment less than 20 m before being deposited. This suggests a very short distance and short time for development of well organized structures indicative of evolved high-density turbidity currents.

Fig. 7. Line drawing (from a photograph) of the upper foresets and topsets of a Gilbert-delta within parasequence 13, showing the location of outcrops studied in example 2. Transport is to the right (NE). Apparent flattening of foreset dips within and above box for Fig. 8 results from a corner on the outcrop and is not real.

Fig. 8. Outcrop of three foreset beds orientated perpendicular to transport direction, ≈5–7 m below the topset-foreset contact. Transport is into the photo (NE). Collectively these beds display a variety of sedimentary structures including normal grading (upper bed), inverse to normal grading (middle bed), inverse grading (lower bed) and bipartite discontinuities (lower and middle bed). Location of photograph is shown in Fig. 7. Jacobs staff is divided into 10-cm intervals.

(A)

(B)

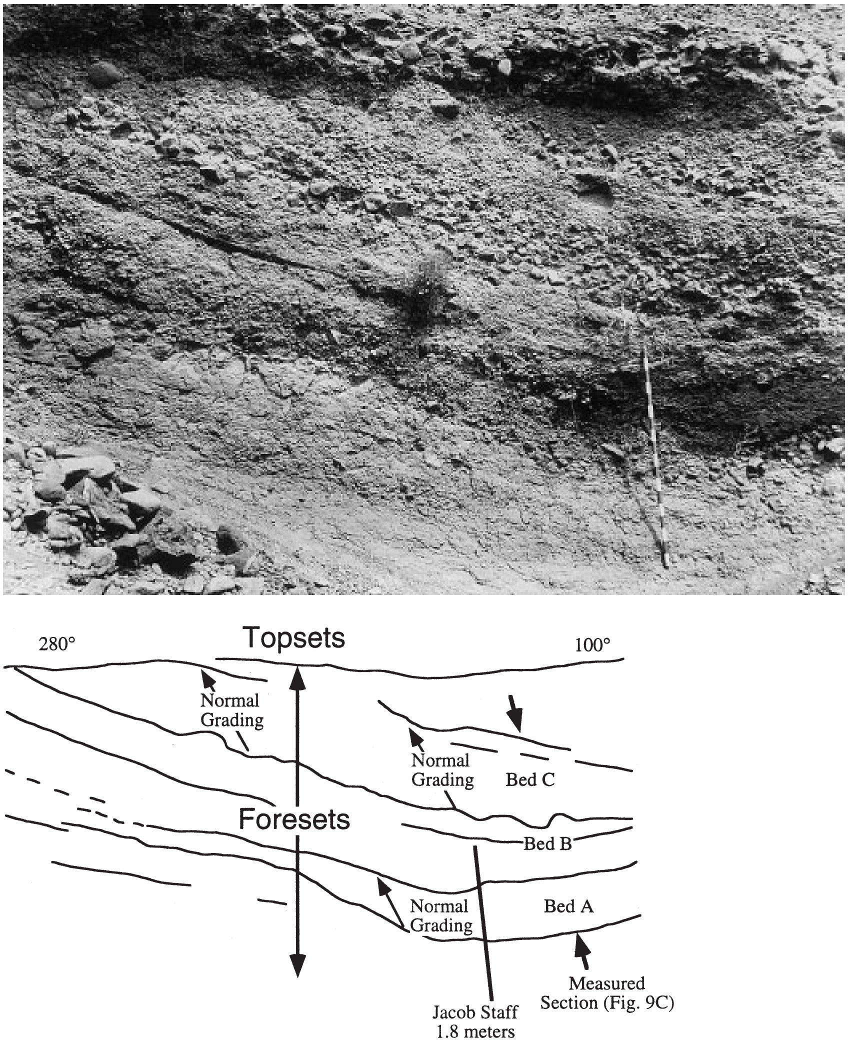


Fig. 9A,B. (A) Outcrop of foreset beds directly below the topset-foreset transition (location shown in Fig. 7). Transport is to the right (NE). Jacob staff is divided into 10-cm intervals. (B) Line drawing of A, showing topset-foreset contact, beds A, B and C, and location of measured section.

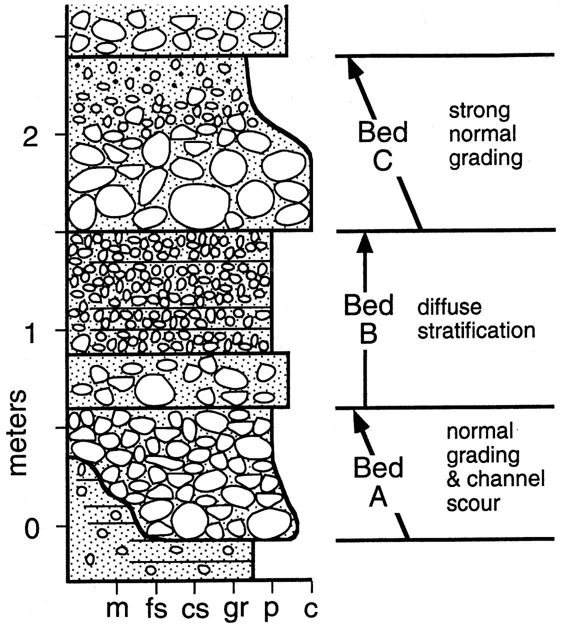


Fig. 9. (C) Measured section of the three beds shown in B showing sedimentary structures.

Beds A and C in Fig. 9 are interpreted as single-event deposits, while bed B probably represents an amalgamated deposit of several cohesionless debris flows. Most significant is the normal-graded deposit of bed C, in which normal grading can be followed up-transport virtually to the topset-foreset transition (Fig. 9A,B). This suggests almost instantaneous development of a high-density turbidity current at the top of the Gilbert-delta slope.

Example 3:

Description. Figure 10 shows four short measured sections, A, B, C and D, within a single foreset bed. The foreset bed is located ≈15 m below the topset-foreset boundary of a Gilbert-type fan delta having a foreset unit ≈30 m thick. Beginning at location A, the foreset bed is bipartite, with a lower normal graded conglomerate separated from an upper sandstone along a sharp discontinuity (Fig. 10). The basal conglomerate displays up-slope dipping

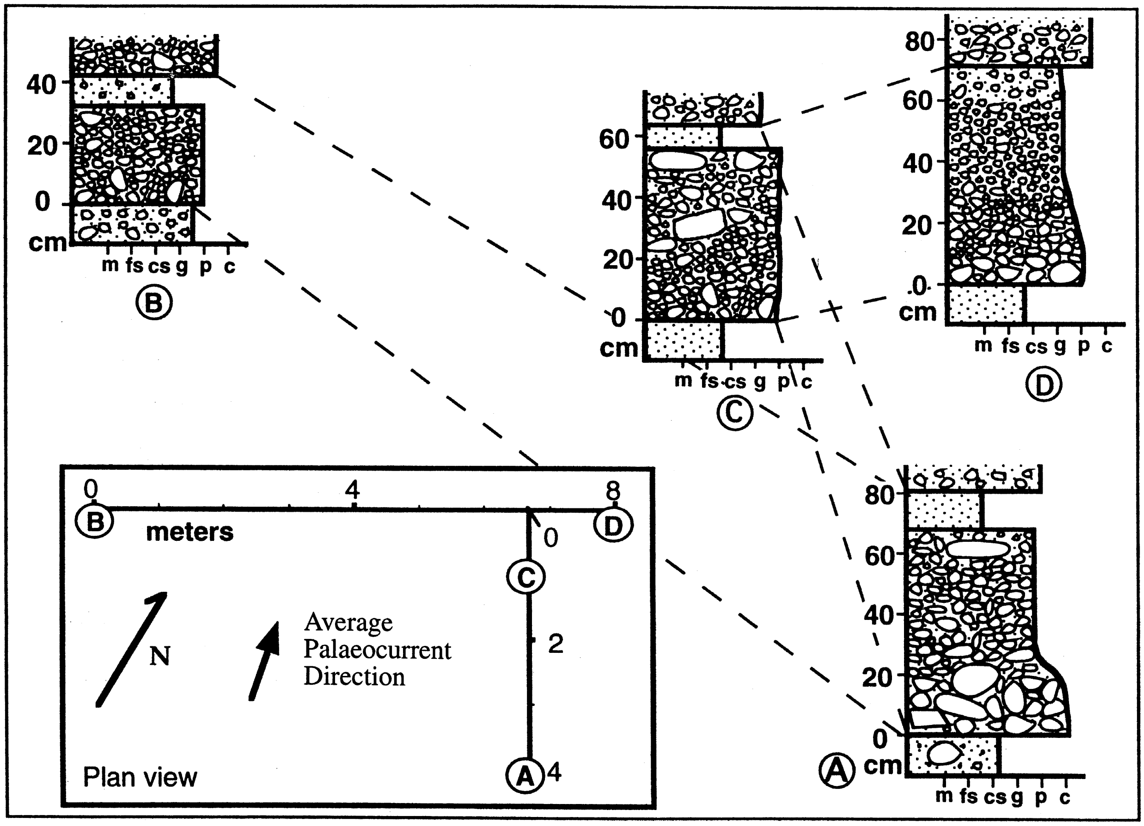


Fig. 10. Four short measured sections from a single bed in the foresets of a Gilbert-delta located in parasequence 12. Measured sections show the variability of structures possible within the deposit of one flow. Insert is a plan view showing the exact location of each section and their orientation relative to the averaged palaeocurrent data. Dashed lines show how the sections were correlated. This bed is ≈15 m below the topset-foreset transition.

a(p)a(i) clast imbrication. Down-transport 3 m, at location C, the deposit still exhibits a bipartite discontinuity but the basal conglomerate is ungraded. Isolated outsized clasts are observed at both localities A and C and the deposits between them (Fig. 10). Location B is similar to A and C except that the basal conglomerate is thinner. Location D exhibits no bipartite discontinuity but does display normal grading (Fig. 10).

Interpretation: The bed in example 3 is interpreted to have been deposited by a gravelly high-density turbidity current. This example shows important lateral variations in grading style and textures within a single deposit, and illustrates that flow characteristics can change within a few metres in both down-transport and across-transport directions. Hence, all four of these locations, though separated by only metres, display a range of grading and thicknesses that existed within a single flow just prior to deposition. Similar lateral changes in grading in Pleistocene gravel deltas in southern Italy were observed 'within a few meters of each other and with no clear systematic trend' (Massari & Parea, 1990; p. 319).

The outsized clasts observed at and between locations A and C (Fig. 10) are similar to those described by Postma *et al.* (1988b). In their analysis, they concluded that outsized clasts are transported along the rheological interface between the basal inertia flow (traction carpet) and the lower-density faster-moving turbulent overflow. As the inertia-flow layer freezes, outsized clasts may become partially submerged but are unlikely to drop to the base of the traction carpet. The bipartite nature of this deposit combined with placement of outsized clasts at or near the bipartite discontinuity support this interpretation.

Smaller Gilbert deltas

This section presents three examples of deposits found within gravelly foreset beds of relatively small Gilbert-type fan deltas (foreset unit less than 15 m thick). Thinner foreset packages, where exposed, have the advantage of permitting analysis of the complete foreset unit from the topset-foreset contact into proximal bottomsets.

Example 4:

Description. Figure 11 shows a Gilbert delta whose foreset unit is 9 m thick. In this example, structureless poorly sorted sand-rich conglomerate and matrix-supported pebbly sandstone (upper left, Fig. 11B) pass laterally down-transport into well bedded, normal-graded sand-poor conglomerates and sandstones (lower right, Fig. 11B). The gravelly deposits exhibit dramatic down-transport pinch-out both near the topset-foreset boundary and at the foreset-bottomset transition (Fig. 11B). Conglomerate beds display normal grading, a(p)a(i) clast fabrics, and one exhibits a bipartite discontinuity. The observed down-slope distance from the structureless pebble-cobble conglomerate to the well bedded organized conglomerates is less than 10 m.

Interpretation. This example illustrates a rapid lateral down-slope change in bedding characteristics that is commonly observed in foresets of the Loreto basin. The increase in well defined bedding contacts and the pronounced down-transport changes in structures within the deposits reflects a change in the behaviour of sediment-gravity flows, evolving from cohesionless debris flows into fully turbulent high-density turbidity currents. The short distance over which this change occurs provides evidence for very rapid flow transformation, similar to examples 1 and 2.

Example 5:

Description: This example contains the most complete and well exposed Gilbert delta in the study area, exhibiting an across-transport view of Gilbert-type topsets, foresets and proximal bottomsets (Fig. 12A). Foresets at this locality are divided into upper foresets and lower foresets. This division is based on a decrease in gravel in the lower foresets relative to the upper foresets, and a change in the nature of the deposits. The upper foresets at this locality are typified by very poorly sorted and crudely bedded matrix-rich pebble conglomerate and pebbly sandstone (Fig. 12B). Although bedding contacts are difficult to identify in the upper foresets, weak internal stratification can be observed. The lower foresets consist of well bedded and organized, normal graded, inversely graded, and bipartite deposits of matrix-poor conglomerate and sandstone. Conglomerate clasts are better sorted and more closely packed than in conglomerates of the upper foresets, and sandstones contain fewer pebbles than in the upper foresets. Proximal bottomsets consist of planar-tabular bedded, normal-graded sandstones and thin pebble horizons with rare gravel-filled scours (Fig. 12C).

Interpretation: The deposits at this locality provide additional information about the evolution of flows down the slope of Gilbert-type fan-delta foresets. Upper foresets record deposition of cohesionless debris flows, while the lower

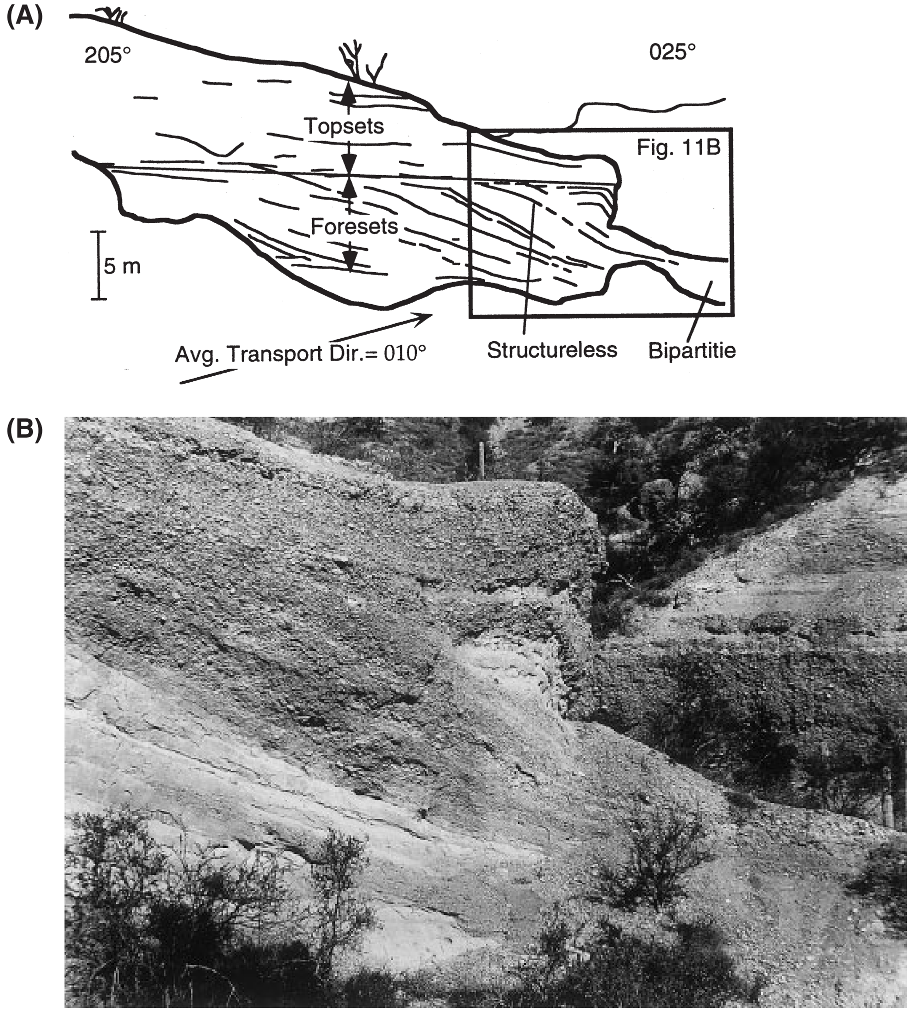


Fig. 11. (A) Line drawing (from a photograph) of a Gilbert delta with a foreset-unit thickness of 9 m found within parasequence 9. Box shows location of photograph in Fig. 11B. (B) Outcrop photograph showing crudely bedded sandy, matrix-rich conglomerate that passes laterally downslope into well bedded, normal-graded conglomerates and bipartite deposits. Jacob staff on left is 1·8 m long.

foresets record deposition of high-density turbidity currents and development of gravel traction carpets. Proximal bottomsets record deposition of both high- and low-density turbidity currents. The previous examples illustrated down-transport changes over short distances in individual foreset deposits. The deposits in this example are important because they provide a vertical stratigraphic record of systematic variations in foreset and proximal bottomset deposits which are controlled by the distance of transport down the steep gravelly fan-delta front.

Indistinct bedding on lower foresets

The next two examples illustrate indistinctly bedded gravel-rich sandstones and conglomerates found on the lower foresets of large Gilbert-deltas (≈30 m). Indistinct bedding, especially on the lower foresets, is problematic because it is difficult to place these structures in the context of a general model for evolution of gravelly turbidity currents.

Example 6:

Description. Figure 13A is a photo-overlay sketch of a Gilbert delta whose foreset unit is about 30 m thick. Lower foresets consist mostly of sand-rich, crudely to-moderately stratified pebbly sandstone with very diffuse bedding (Fig. 13B) (upper foresets were not observed at this locality). Except for a 35-cm thick clast-supported bed, conglomerate at this locality is mostly matrix-supported. Weak, discontinuous bedding displays low-angle truncations produced by downslope pinch-out geometries, similar to previous examples (e.g. Figs 5B, 6B). Down-transport 5 m from the lower half of this outcrop, stratification improves significantly with the development of thin, discreet, weakly graded conglomerate and pebbly sandstone beds. Up-transport 10 m, the internal stratification observed in Fig. 13B is even more diffuse.

Interpretation. These deposits are difficult to interpret. The stratification observed in Fig. 13B

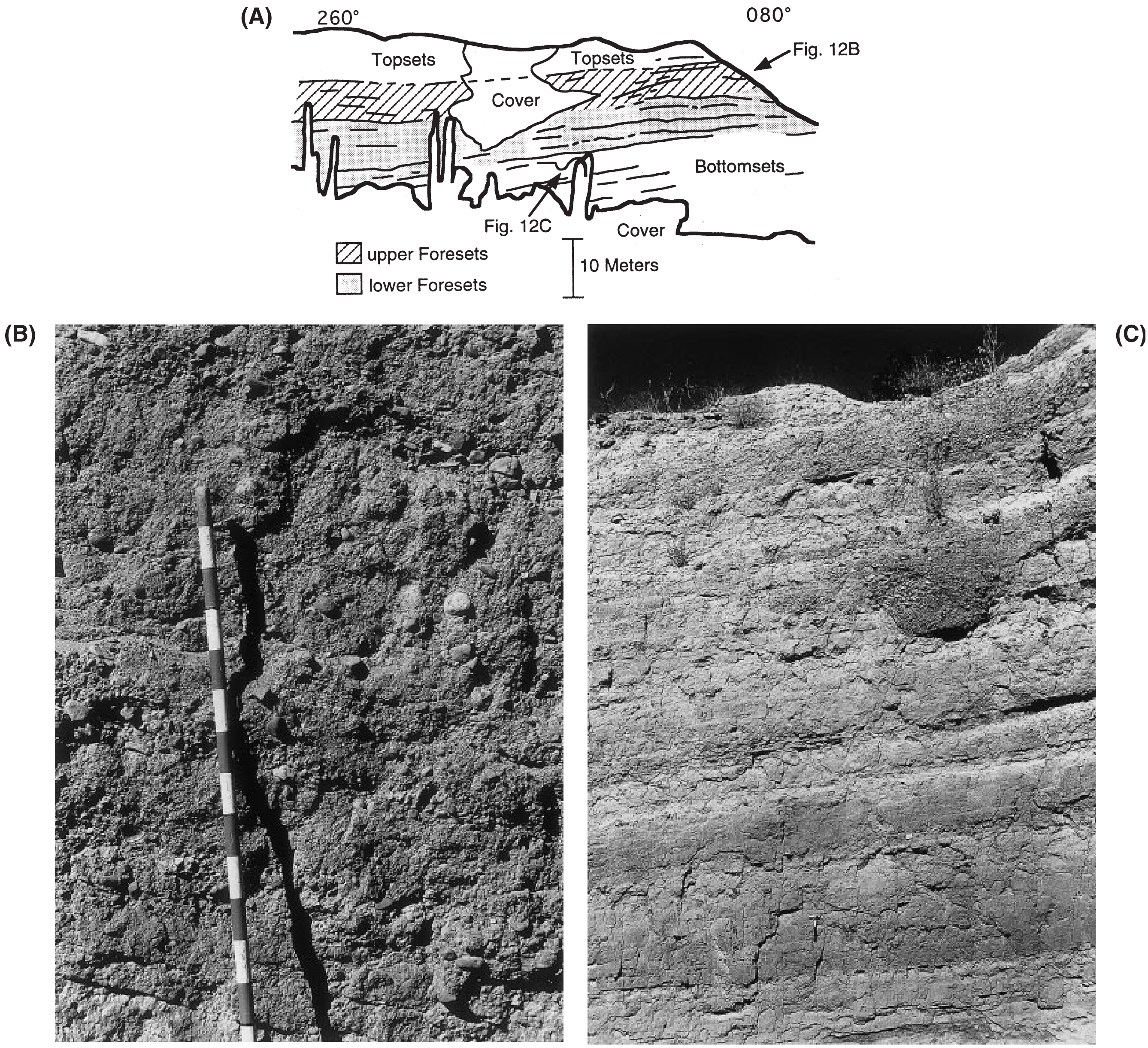


Fig. 12. (A) Line drawing from a photograph of a Gilbert delta within parasequence 6. Foresets have been divided into an upper and lower division. Upper foresets consist of crudely bedded matrix-rich pebble conglomerates (Fig. 12B), and lower foresets consist of well bedded, normal graded, inverse graded and bipartite deposits. Transport is into the page (N). (B) Outcrop of upper foresets showing weakly developed bedding in poorly sorted sand-matrix-rich pebble conglomerate. Location of photograph is shown in A. Jacob staff is divided into 10-cm intervals. (C) Outcrop of proximal bottomsets dominated by well bedded normal-graded sandy turbidites. Thin pebble horizons are seen at the base of some of the turbidites. Upper part of photograph shows strong channel scouring in pebble conglomerate. Conglomerate in deepest channel exhibits inverse to normal grading. Location of photograph is shown in (A). Hammer (lower centre of photo) is 32·5 cm long.

could represent numerous different flow events, or internal stratification produced by surging within a single-event deposit. The observation that bedding becomes better developed down-transport as the conglomerate passes laterally into several graded deposits indicates that the stratification represents amalgamated beds of several different gravelly turbidity currents. Massari and Parea (1990) described and interpreted deposits that closely resemble this example. Similarly, they interpret the diffusely stratified facies as deposits of traction carpets that formed at the base of multiple, highly concentrated supercritical flows.

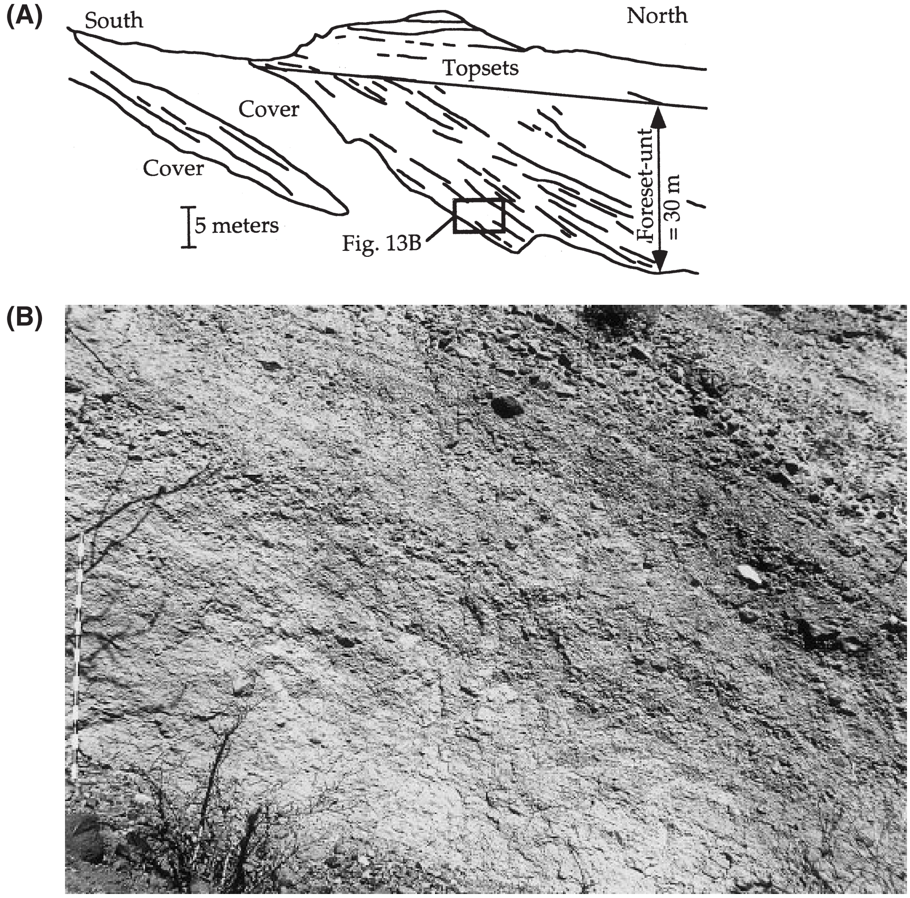


Fig. 13. (A) Line drawing (from a photograph) of a Gilbert delta within parasequence 13. Transport is to the right (N). (B) Outcrop of indistinct bedding with discontinuous stratification. Jacob staff on left is divided into 10-cm intervals.

Example 7:

Description. This example (Fig. 14) provides important information regarding the nature of indistinct bedding in lower foresets. The topsets and upper foresets overlying these foresets have been eroded away at this locality, but a nearby measured section indicates that these foresets were deposited in about 20 m of water. Figure 14 displays an observable stratification defined by zones of more highly concentrated pebbles and cobbles in an otherwise sand-rich pebble conglomerate. Of six recognizable bedding contacts, only one is laterally continuous (Fig. 14). Foreset beds nearby and the same distance below the topset-foreset contact contain well-bedded, normal-graded and bipartite pebble conglomerates that pass laterally down-transport into structureless sand-rich pebble conglomerates that exhibit crude stratification.

Interpretation. As in the previous example, we want to know whether weak stratification in Fig. 14 records numerous individual depositional events or surging pulses within a single flow. Beds nearby suggest that, up-slope from the beds in question, deposition of the gravel-rich basal part of numerous flows resulted in bypassing of turbulent pebbly sandy overflows. The pebbly sandstone deposits of these overflows, when stacked and amalgamated, are likely to contain crude stratification. Hence, stratification in these indistinctly bedded conglomerates appears to represent amalgamated deposits of numerous structureless pebbly high-density turbidity currents. Rather than suggesting a less evolved flow, weak internal stratification may be produced by pebbly sand-rich overflows that bypassed basal gravel traction carpets deposited by frictional freezing higher up on the foreset slope. In example 6, indistinct bedding was shown to become better developed down-transport, suggesting that these flows continued to evolve and became segregated into organized high- and low-density turbidity currents. This resembles the repetitive cyclic processes for high-density turbidity currents described by Lowe (1982).

Fig. 14. Outcrop of indistinct bedding defined by dominantly discontinuous horizons of alternating clast-rich and sand-rich horizons. Outcrop is located in parasequence 13, ≈20 m below the topset-foreset contact. Hammer (lower centre) is 32·5 cm long.

TRANSPORT AND DEPOSITIONAL MODEL

A synthesis of the above observations leads to the development of a generalized conceptual model for the rapid evolution and deposition of high-density turbidity currents on the steep slopes (foresets) of Gilbert-type fan deltas in the study area (Fig. 15). The lack of mud in the foresets and proximal bottomsets suggests that

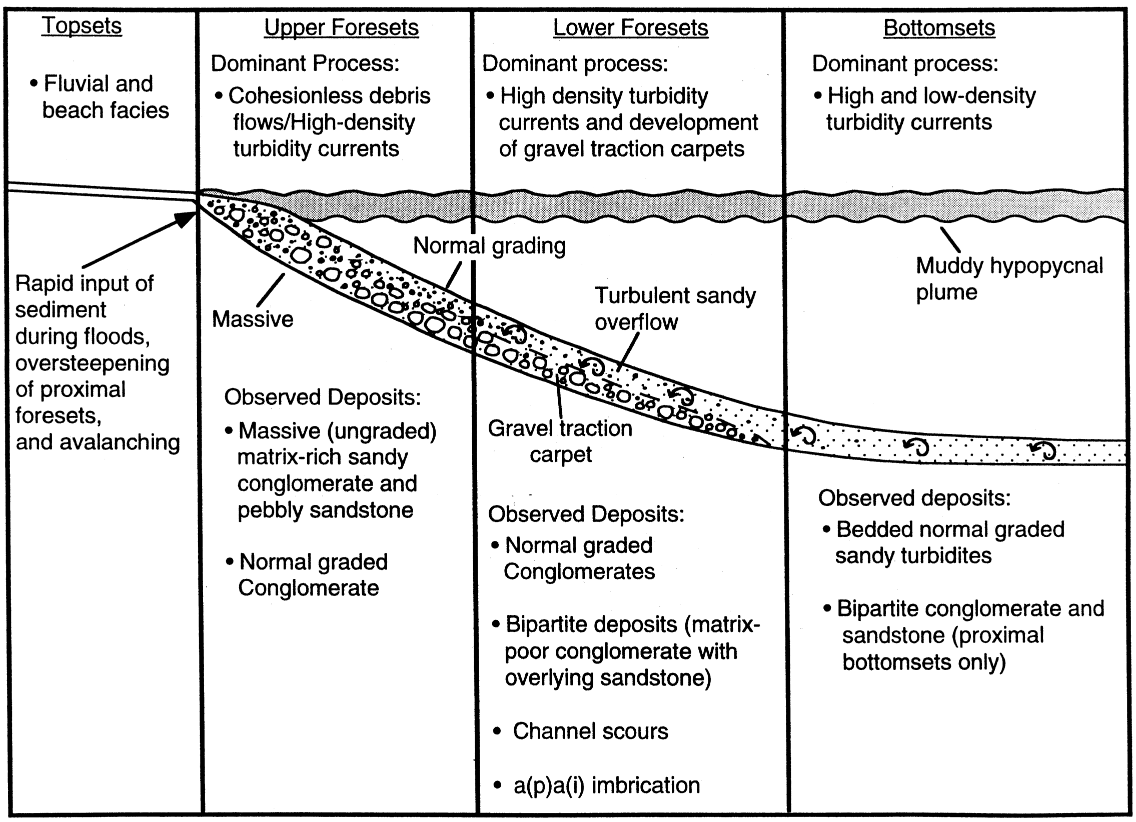


Fig. 15. Conceptual model for the development of high-density turbidity currents on the steep slopes of Gilbert-type fan deltas in the Loreto basin. See text for discussion.

fluvial floods deposited their coarse material at the marine–nonmarine interface, while the fine-grained fraction was carried seaward in suspension by hypopycnal plumes (Elliott, 1986). Rapid input of sediment from fluvial channels during floods resulted in over-steepening of the proximal foresets and avalanching (*sensu lato*; Nemec, 1990). The abundance of structureless sand-matrix-rich sandy conglomerate and pebbly sandstone argues for deposition by cohesionless debris flows on the upper foresets. Cohesionless debris flows quickly evolved down-slope into organized high-density turbidity currents (Fig. 15). Where good down-transport exposures exist, this transformation is shown to occur over a distance of less than about 20 m. With an estimated flow velocity of about 100 cm s^{-1} (e.g. Postma *et al.*, 1988b), this probably occurred in less than 20 s. Flow transformation often occurred high in the foresets, resulting in a down-transport increase in normal-grading, bipartite discontinuities, and a(p)a(i) imbrication (Fig. 15). This transformation probably resulted from an increase in the fluid content and velocity of the flow, allowing for increased grain movement and the onset of turbulence. An important aspect of flow evolution is the collapse of the gravel fraction to form a basal gravel traction carpet, which behaved as a nonturbulent concentrated clast dispersion at the base of a less dense sandy turbulent suspension (Lowe, 1982; Postma *et al.*, 1988b). Once these bipartite high-density turbidity currents developed, the basal gravel layer was rapidly deposited by frictional freezing on the foresets. The overflowing sandy turbulent suspension continued down the foreset slope, possibly repeating the segregation process if the slope was sufficiently high and long. Amalgamated overflow deposits probably produced the indistinct bedding observed in lower foresets. Many of the sandy overflows were transported beyond the steep delta slope. These overflows developed into low-density turbidity currents that produced normal-graded sandy turbidites on the bottomsets (Fig. 15). Finally, increased down-slope movement incorporated more ambient fluid, further decreasing the density of the flow.

One important issue is whether the foreset beds record *en masse* deposition or gradual grain-by-grain aggradation. If the sediments are deposited *en masse* then they represent a snapshot in time of the internal structure of the flow. If, however, these deposits record a period of gradual deposition over time, then they do not represent the internal structure of the flow. The latter is probably the case for sandy turbidites, as normal grading in turbidites is usually attributed to grain by grain traction sedimentation (Lowe, 1979, 1982; Middleton, 1993). However, for the gravel fraction, deposition commonly occurs either *en masse* or at least by very rapid frictional freezing with high rates of aggradation (Lowe, 1982). This interpretation appears to be correct for Gilbert deltas in Loreto basin, based on the common observation that the gravel fraction is deposited preferentially on foreset slopes. If deposition occurred during the waning part of the flow or gradually throughout the flow, a large quantity of gravel should bypass the foresets and accumulate in the proximal bottomsets. This is observed in bottomset deposits of other systems (Colella *et al.*, 1987; Nemec, 1990), but it was seldom observed in this study. Instead, convex-up geometries and down-transport pinch-out of many gravel deposits suggest rapid, *en masse* deposition of gravel by frictional freezing on the steep foresets prior to reaching the bottomsets. Moreover, the high incidence of a(p)a(i) imbrication in basal gravel layers suggests the action of high shear stresses between the flow and the bottom of the bed, indicating the presence of high frictional forces that would cause gravelly flows to freeze quickly.

DISCUSSION

Gravel clasts within high-density turbidity currents may be supported by the combined effects of fluid turbulence, hindered settling, matrix buoyant lift and dispersive pressures that result from grain-grain collisions (Lowe, 1982). As a gravel traction carpet forms at the base of a high-density turbidity current, the role of fluid turbulence decreases while hindered settling, matrix buoyant lift and dispersive pressures become more important as sediment-support mechanisms (Lowe, 1982). Fully developed traction carpets are pseudo-laminar flows commonly associated with overflowing lower-density turbulent flows (Shanmugam, 1996). High shear stresses necessary to maintain grain dispersions are provided by both the down-slope component of gravity acting on gravel clasts and by the faster-moving turbulent overflow (Postma *et al.*, 1988b). In fluvial high-density flood flows, the shear stresses imparted to the gravel traction carpet by the turbulent overflow may be sufficient to drive gravel traction carpets on very low slopes (Todd, 1989).

The observed structures and textures and the rapid down-slope flow transformations in the Loreto basin allow for discussion of the major grain-support mechanisms. The common occurrence of normal grading in gravelly deposits suggests that fluid turbulence was an important grain-support mechanism. Many of the gravel traction carpets display weak to well developed normal grading which indicates that, especially in the early part of flow evolution, fluid turbulence was an important mechanism of clast support. Common ungraded and inversely graded conglomerate beds indicate that inter-grain dispersive pressures also commonly played an important role in particle support in gravel traction carpets. Lateral across-transport transitions from bipartite deposits into normal-graded deposits suggest that fluid turbulence capable of entraining gravel clasts commonly disrupted a co-evolving gravel traction carpet, perhaps due to large powerful eddies in a poorly organized upper part of the flow. Although gravel traction carpets are not turbulent (Shanmugam, 1996), they evolve from and represent the collapsed gravel concentration of high-density turbidity currents. The down-slope pinch-out of traction carpet layers, combined with the observation that most traction carpets are restricted to foresets while bottomsets are dominated by sandy turbidites, indicate that the combination of shear stresses applied by the turbulent overflow and the down-slope component of gravity acting on clasts were capable of transporting gravel traction carpets only on short steep slopes. It appears from these relationships that foreset slopes were required to sustain transport of gravel traction carpets.

In this study we observed no compelling evidence for submarine slumping or sliding, such as internally deformed zones, slump scars produced by slope failure, or associated liquefaction features. Instead, low-angle erosional truncations within foreset and bottomset strata are associated with shallow channel scours that formed at the base of high-energy turbidity currents. Resedimentation of gravelly sediment is common in other Gilbert-delta systems (Postma & Roep, 1985; Colella *et al*., 1987; Postma *et al*., 1988a), but appears to have been unimportant in the Loreto Gilbert-type fan deltas. We interpret this to be the result of very low clay content and a dominance of noncohesive sediments in the system, which resulted from a combination of arid climate and very rapid mechanical weathering in the footwall source. We infer that slope oversteepening and onset of avalanching probably occurred during floods when large amounts of gravel were delivered to the delta front over a short time interval (several days). This interpretation is supported by observed sigmoidal (gradational) contacts between topset and foreset deposits, in which flood-deposited topset gravel units pass laterally without interruption down-transport into upper-slope gravelly turbidites or debris flow deposits. During floods, there would be little or no time for significant storage of oversteepened sediment in the upper delta slope. Instead, it appears that sediment was transferred quickly from flood flows in the delta plain to sediment-gravity flows in the subaqueous slope during single flood events, and therefore slumping, sliding, and resedimentation did not play a major role in initiation of sediment gravity flows in the Loreto Gilbert delta slopes.

Finally, the studied deposits and inferred transport processes are similar for a wide range of foreset-unit thicknesses, indicating that organized high-density turbidity currents evolved rapidly in very shallow water (<5m). Conglomerate and sandstone deposits in even the smallest Gilbert delta (≈5 m thick) contain normal grading, inverse to normal grading and one or several bipartite deposits. Importantly, the smallest Gilbert deltas in the Loreto basin are similar in scale to small-scale flume experiments (4 m long, 25° dip, 1·7 m high) carried out by Postma *et al.* (1988b). The results of their experiments suggested that high-density turbidity currents with basal gravel carpets can become fully developed in very shallow water (<2m). Observations and interpretations presented in this paper support this conclusion and provide an important link between experimental and field studies of transport processes active in gravelly turbidity currents.

CONCLUSIONS

Foreset deposits of Gilbert deltas in the Loreto basin display a variety of sedimentary structures that record deposition by high-density turbidity currents in the steep delta slope. Normal-graded gravels and bipartite deposits are found in the shallow-water portion of larger Gilbert deltas (foreset-unit thicknesses >20 m) and on smaller Gilbert-deltas, suggesting that high-density turbidity currents evolve rapidly after entering the foreset slope. Sedimentologic data provide evidence for flow transformations from cohesionless debris flows into high-density turbidity currents occurring over short distances. Very short distances of lateral transitions indicate very rapid (≤20 s) transformation from poorly organized cohesionless debris flows into well organized high-density turbidity currents with basal traction carpets. The gravel traction carpets are interpreted to develop at the base of high-density turbidity currents in which the coarse fraction settled to the base of the flow to form a basal laminar inertia flow. The gravel fraction is preferentially restricted to steep delta slopes, suggesting rapid deposition due to frictional freezing. Indistinct bedding in sandy conglomerate on the lower foresets of larger Gilbert-deltas represents amalgamated deposits of turbulent overflows that bypassed their accompanying traction carpets. Commonly, these turbulent overflows continued to evolve down-slope, developing a new basal traction carpet and repeating the evolutionary process of a bipartite flow.

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