Earthquake clustering inferred from Pliocene Gilbert-type fan deltas in the Loreto basin, Baja California Sur, Mexico

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ABSTRACT

A stacked sequence of Pliocene Gilbert-type fan deltas in the Loreto basin was shed from the footwall of the dextral-normal Loreto fault and deposited at the margin of a marine basin during rapid fault-controlled subsidence. Fan-delta parasequences coarsen upward from marine siltstone and sandstone at the base, through sandy bottomsets and gravelly foresets, to gravelly nonmarine topsets. Each topset unit is capped by a thin shell bed that records marine flooding of the delta plain. Several mechanisms may have produced repetitive vertical stacking of Gilbert deltas: (1) autocyclic delta-lobe switching; (2) eustatic sea-level fluctuations; (3) climatically controlled fluctuations in sediment input; and (4) episodic subsidence produced by temporal clustering of earthquakes. We favor hypothesis 4 for several reasons, but hypotheses 2 and 3 cannot be rejected at this time. Earthquake clustering can readily produce episodic subsidence at spatial and temporal scales consistent with stratigraphic trends observed in the Loreto basin. This model is supported by comparison with paleoseismological studies that document clustering on active faults over a wide range of time scales. Earthquake clustering is a new concept in basin analysis that may be helpful for understanding repetitive stratigraphy in tectonically active basins.

INTRODUCTION

Gilbert-type fan deltas have been recognized as an important stratigraphic component of tectonically active marine basins (e.g., Colella, 1988; Gawthorpe and Colella, 1990; Dorsey et al., 1995). The stratigraphic architecture in these settings commonly consists of vertically stacked, coarse-grained deltaic parasequences that record repeated episodes of delta progradation and transgression. Previous studies have noted the significance of vertically stacked fan-delta successions and have tended to attribute parasequence stacking to episodic subsidence along the basin-bounding fault (e.g., Colella, 1988; Kazanci, 1988). These models raise, but do not thoroughly address, important questions regarding the style, scale, and cyclicity of seismicity on basin-controlling faults. In addition, other processes such as changes in eustatic sea level, climatically controlled variations in sediment input, and autocyclic switching of deltaic depocenters, have the potential to produce similar vertical stacking of fan deltas in active basins.

In this paper we explore these questions by examining a sequence of gravelly Gilbert-type fan deltas in the Pliocene Loreto basin. The Loreto basin provides an excellent opportunity to study controls on fan-delta deposition, because the tectonic and structural settings are well known, the stratigraphic architecture of fan deltas is revealed by detailed facies mapping and measured sections, and the sequence is temporally well constrained by existing high-precision age dates on two bounding tuffs (Umhoefer et al., 1994; Dor-

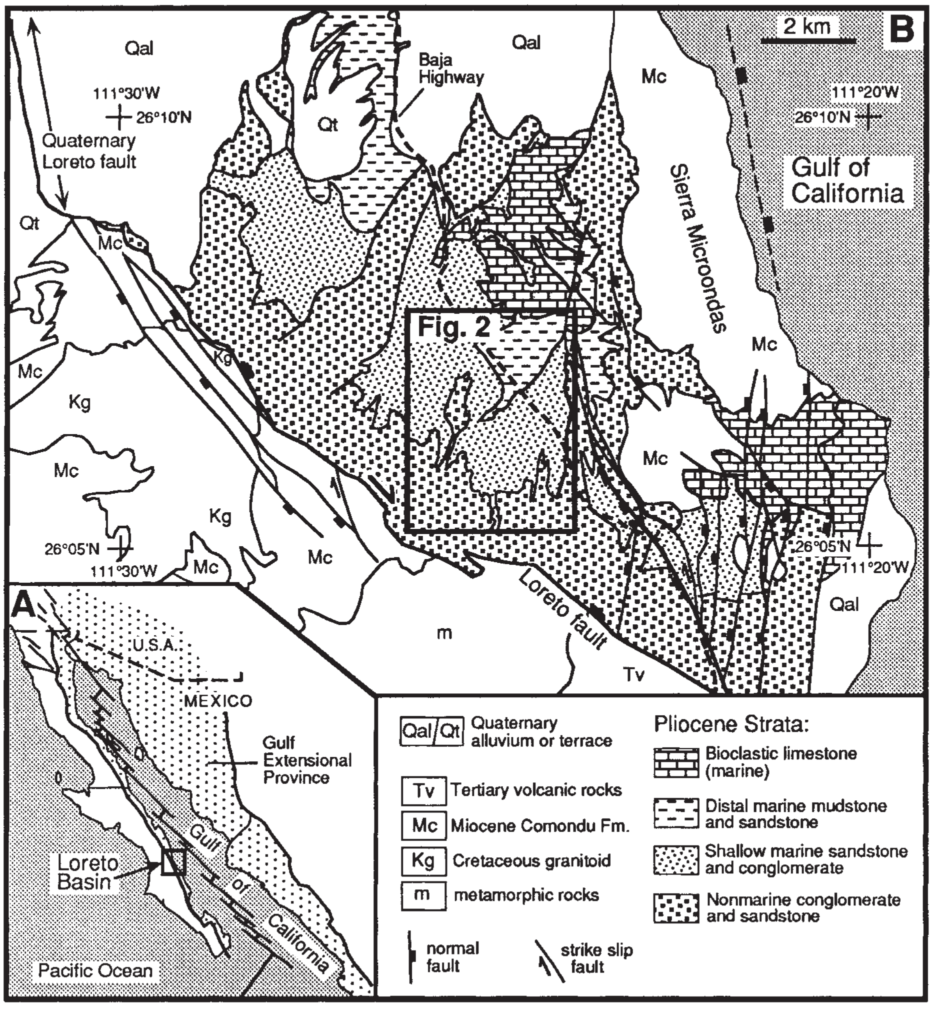

Figure 1. A: Location and tectonic setting of Loreto basin. B: Geologic map of Loreto basin, showing location of study area (Fig. 2).

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sey et al., 1995; Falk, 1996). In this paper we call attention to the necessary direct links between any model for faulting controls on fan-delta cyclicity and implications for paleoseismicity. We suggest that temporal clustering of earthquakes is a reasonable hypothesis to explain the observed spatial and temporal patterns of episodic subsidence, which appears to have controlled accumulation of stacked fan deltas in the Loreto basin.

GEOLOGIC SETTING AND STRATIGRAPHIC DATA

The Pliocene Loreto basin, an oblique half-graben basin located on the western margin of the Gulf of California, formed by asymmetric subsidence along the dextral-normal Loreto fault (Fig. 1; Umhoefer et al., 1994). The basin was rapidly filled with >1200 m of nonmarine, deltaic, and marine deposits, including a heterolithic assemblage of conglomerate, sandstone, and mudstone that accumulated in Gilbert-type and shelf-type fan deltas (Fig. 1B; Dorsey et al., 1995; Falk, 1996). Pronounced westward thickening of the section and abrupt lateral transitions from nonmarine to marine facies provide evidence for westward tilting and filling of the basin during subsidence on the Loreto fault. Gilbert-type fan deltas lie stratigraphically between tuffs 2 and 3, dated as 2.46 ± 0.06 Ma and 2.36 ± 0.02 Ma, respectively (Umhoefer et al., 1994). Decompacted thicknesses combined with tuff ages show that the Gilbert deltas accumulated during a short period (~100 000 yr) of very rapid subsidence (8 ± 5 mm/yr).

This study focuses on gently dipping, well-exposed, footwall-derived Gilbert-type fan deltas and associated marine and nonmarine facies, the stratigraphic architecture of which is revealed in a north-south facies panel (Fig. 2). The panel is ~540 m thick and 3600 m wide, and the south edge of the panel is ~1 km north of the Loreto fault. Stratigraphy in this area consists of nonmarine conglomerate and sandstone in the south that pass laterally through Gilbert-type fan deltas into marine sandstone in the north (Fig. 2). These Gilbert-type fan deltas comprise progradational, coarsening-upward parasequences consisting of (in ascending order): heavily bioturbated, massive, marine siltstone; well-bedded, sandy turbidites (bottomsets); bedded and stratified marine conglomerate and sandstone with primary dips of 15° to 25° (foresets); and marginal-marine to nonmarine conglomerate and sandstone (topsets) (Fig. 2B). Each Gilbert-delta topset unit is capped by a laterally continuous marine shell bed (average thickness = 1 m), which records a hiatus in sediment delivery, rapid marine transgression, and submergence of the underlying deltaic plain to shallow-marine depths (10–30 m) (Fig. 2; Dorsey et al., 1995; Falk, 1996). Parasequences 1–10 are 20–35 m thick, and parasequences 11–16 are 46–78 m thick. Paleocurrent data record overall transport toward the north, parallel to the facies panel (Fig. 2B; Falk, 1996).

We can estimate the average frequency (or repeat time) of deltaic parasequences by using the tuff ages described above. The lower tuff (tuff 2 of Umhoefer et al., 1994) is seen near the base of the facies panel (Fig. 2B), and tuff 3 is stratigraphically above the top of the panel. The age difference between the two tuffs is 100 000 ± 80 000 yr. There are 16 parasequences of variable thickness (including 3 more above area of Fig. 2B) preserved between the two tuffs. This gives an average frequency of 6250 ± 5000 yr per parasequence. The actual duration of any parasequence may vary significantly from the average, and if we include subcycles (e.g., 10a, 12a, 12b, and 12c in Fig. 2) the calculated average frequency would be even shorter. This simple analysis reveals very rapid, high-frequency production of Gilbert-type fan deltas in the Loreto basin.

INTERPRETATION OF FAN-DELTA CYCLES

Each parasequence was produced by rapid progradation of gravelly fan deltas 1–2 km into the shallow-marine basin; each shell bed formed during a sharp reduction in sediment accumulation, submergence of the delta plain, and rapid transgression of the shoreline back toward the Loreto fault. Advance and retreat of fan deltas were controlled by large changes in the balance between the rate of sediment input (which may be internally or externally controlled) and the rate of basin subsidence, possibly modulated by fluctuations in eustatic sea level. In this section we evaluate four processes that could have controlled episodic growth and abandonment of Loreto fan deltas.

1. Repetitive stacking of fan deltas may have resulted from autocyclic channel avulsions and delta-lobe switching superimposed on steady rapid subsidence. Lobe switching is common in delta systems, and detailed stratigraphy in these delta-plain deposits indicates that channel switching was active. This hypothesis predicts that Paleocurrent directions should vary substantially from one parasequence to the next, because the direction of input would have to change in order to shift deltaic lobes laterally to different depocenters through

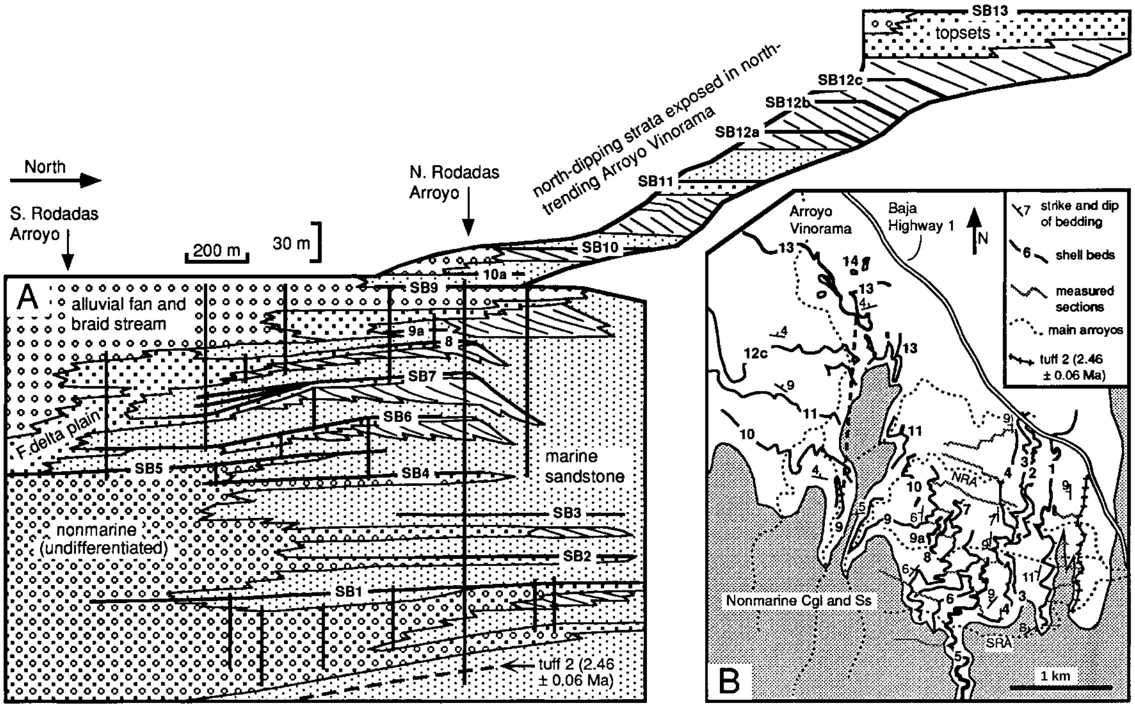

Figure 2. A: North-south facies panel showing detailed stratigraphic architecture of Gilbert-type fan deltas in southern Loreto basin. SB1 through SB13 are 0.5–1.0-m-thick shell beds that cap topset units. Vertical lines are detailed measured sections. B: Map of nonmarine facies (shaded), marine facies (white), and numbered shell beds that define fan-delta parasequences in southern Loreto basin. NRA is north Rodadas Arroyo; SRA is south Rodadas Arroyo. Dashed north-south line is line of projection used for constructing upper part of facies panel (A).

time. However, Paleocurrent data collected from foreset strata reveal overall uniform northward transport, the greatest variations occurring within rather than between foreset units (Falk, 1996). We therefore do not favor this hypothesis.

2. Transgressive-regressive cycles in the Loreto basin may have been produced by high-frequency eustatic sea-level fluctuations superimposed on steady, rapid basin subsidence. In this hypothesis rising sea level causes sediment to be trapped close to the fault-bounded mountain front, resulting in sediment starvation and rapid deepening. During a sea-level fall, a balance between the rate of eustatic fall and the rate of basin subsidence could produce a relative stillstand, causing rapid progradation of fan deltas. Rapid sea-level changes (Heinrich events) are known to have occurred with a frequency of 4000–8000 yr during Pleistocene time (Bond et al., 1992; Broeker, 1994; Blanchon and Shaw, 1995; Dokken and Hald, 1996), and polar glaciation was initiated by about 3.2 Ma (Cronin et al., 1996). Thus, high-frequency eustatic fluctuations could have operated during late Pliocene time. This model appears to be contradicted by the fact that foreset units average 15–20 m high, and range up to ~60 m (area above that in Fig. 2B), substantially greater than the small magnitude of Heinrich eustatic events (≤5 m). However, rapid background subsidence should amplify the stratigraphic thickness produced by a eustatic sea-level rise, and could match the scale of the Loreto fan deltas for eustatic rises lasting 2000–4000 yr. We therefore consider this mechanism to be plausible.

3. A third hypothesis involves climatically controlled variations in sediment yield superimposed on relatively steady, rapid basin subsidence. In this model, variations in sediment discharge are produced by wet-dry shifts in local climate that may be driven by global climate cycles. Wet periods produce high sediment discharge and delta progradation, and dry periods produce slow sediment input and transgression. Numerical modeling by Paola et al. (1992) showed that rapid variations in sediment input to a steadily subsiding basin can cause abrupt progradation and backstepping of coarse-grained facies. Model simulations by Koltermann and Gorelick (1992) showed that the progradation and retreat of alluvial fans near the Hayward fault during the past 600 000 yr could have been produced by varying sediment discharge in response to glacioclimatically controlled variations in rainfall and stream discharge. However, fluctuations modeled by Koltermann and Gorelick (1992) varied at an ~100 000 yr frequency, substantially slower than the Loreto example. Furthermore, climatically controlled reduction in sediment yield would be unlikely to produce abrupt marine drowning events recorded in delta-capping shell beds, and should instead produce gradational delta abandonment and fining-upward trends. Although climatic fluctuations are known to occur at high frequencies that can match the temporal scale of the Loreto Gilbert deltas, there is little evidence to indicate that the magnitude of these climate perturbations could be great enough to produce the large variations in rainfall necessary to effectively turn on and off strongly progradational fan-delta systems. For these reasons we do not favor this model.

4. Our preferred hypothesis calls for episodic subsidence on the Loreto fault to explain transgressive-regressive fan-delta cycles. We suggest that progradation occurred during times of slow subsidence, when the rate of sediment input exceeded the rate at which accommodation space was being produced. During pulses of rapid subsidence, surface gradients on feeder alluvial fans were reduced by back tilting, high subsidence rates outpaced sediment delivery to the basin, and rapid transgression and drowning of the fan-delta plain occurred. Episodic subsidence on basin-bounding faults has been used to explain vertical stacking of Gilbert-type fan deltas in other active basins (e.g., Kazanci, 1988; Colella, 1988; Gawthorpe and Colella, 1990), but previous models have not explained how single earthquakes could produce tens of metres of subsidence. To resolve this problem, we propose a model in which short bursts of very rapid subsidence are produced by temporal clusters of earthquakes (multiple slip events occurring over a short time interval; Fig. 3A). In this model, earthquake clusters alternate with seismically quiet intervals when subsidence is slow, the ratio of sediment input to subsidence is high, and delta progradation occurs (Fig. 3B).

We favor the earthquake clustering hypothesis for several reasons. First, it is obvious that rapid fault-controlled subsidence was the main influence on the Loreto basin during the period in question. Deposition of Gilbert-type fan deltas was restricted to the brief interval of very rapid subsidence, and thus the very existence of the Gilbert deltas can be attributed to extremely rapid subsidence (Dorsey et al., 1995). From this we infer that the stratigraphic architecture was controlled by temporal variations in the controlling parameter, subsidence. The high variability in thickness of Loreto fan deltas suggests that deposition was episodic rather than periodic, which argues against a periodic sub-Milankovitch climate mechanism. If episodic subsidence on the Loreto fault was the main control on sedimentation, the height of Gilbert deltas appears to require short bursts of rapid subsidence at a magnitude greater than what can be produced by fault slip during single earthquake events. In this case, temporal clustering of earthquakes is required to produce the necessary scale of episodic subsidence.

EVIDENCE FOR EARTHQUAKE CLUSTERING

Evidence for earthquake clustering is revealed in studies of paleoseismicity. Using high-precision radiocarbon dating, Sieh et al. (1989) developed a refined chronology for the San Andreas fault at Pallett Creek over the past ~1500 yr. They determined that earthquakes occur in clusters: events within each cluster are separated by several decades, but the period between clusters is 200–300 yr. This conclusion is supported by other studies of the San Andreas fault (Jacoby et al., 1988; Grant and Sieh, 1994) and the San Gabriel fault (Lee and Schwarcz, 1995). The Wasatch fault zone displays well-documented temporal and spatial patterns of earthquake clustering: six large slip events occurred between 1500 and 400 yr B.P. at a recurrence interval of 220 yr, significantly shorter than the long-term recurrence interval of ~400 yr (Schwartz, 1988; Machette et al., 1991, 1992; McCalpin and Nishenko, 1996). Machette et al. (1992) suggested that there may be causal links between periods of high fault slip rate (earthquake clusters) and deep-water cycles in the Pleistocene Lake Bonneville.

In the Dead Sea graben, the Pleistocene Lisan Formation contains a 50 000 yr record of seismicity consisting of laminated sediments and mixed layers (seismites) formed by earthquake shaking and liquefaction (Marco et al., 1996).

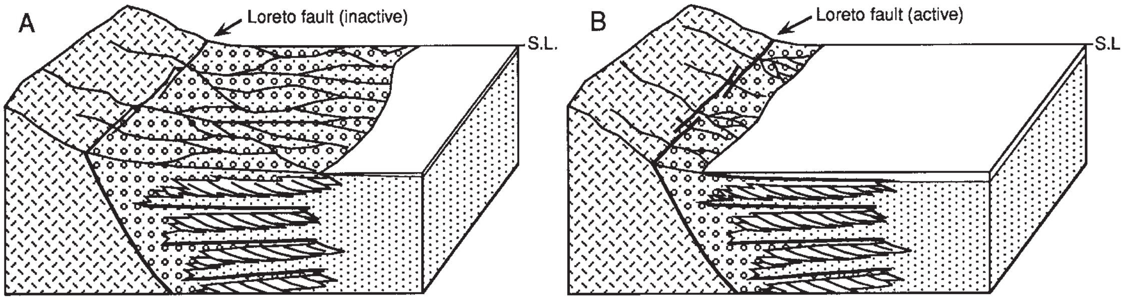

Figure 3. Proposed model for accumulation of Gilbert-type fan deltas during episodic subsidence produced by clustering of earthquakes on Loreto fault. A: Quiet interval—slow subsidence and fan-delta progradation. B: Earthquake cluster—rapid subsidence, transgression, and submergence of preexisting fan-delta plain.

TABLE 1. FREQUENCY OF TEMPORAL CLUSTERING ON SOME KNOWN FAULTS

Fault or fault zone	Fault type	Duration of clusters	Time between clusters	Estimated frequency	Ref.
Xiaojiang F.Z.	strike slip	3-10 k.y.	18-24 k.y.	30-40 k.y.	1
Dead Sea Graben	normal & ss	~ 10 k.y.	~ 10 k.y.	~ 20 k.y.	2
Qued Fodda Fault	thrust	~ 1 k.y.	1000s of yr	1000s of yr	3
Lost River Fault	normal	100s of yr	1000s of yr	1000s of yr	4
Loreto Fault	**oblique slip**	**?**	**?**	**6 ± 5 k.y.**	**5**
Wasatch Fault	normal	500+ yr	1-2 k.y.	2-3 k.y.	6
San Andreas Fault	strike slip	~ 200 yr	~ 200 yr	~ 400 yr	7
North China T.P.	strike slip	30-40 yr	275 yr	~ 300 yr	8
San Gabriel Fault	strike slip	~ 40 yr	40-160 yr	100-200 yr	9

References: (1) Xu and Deng (1996); (2) Marco et al. (1996); (3) Swan (1988); (4) Schwartz (1988); (5) this paper; (6) Machette et al. (1992); (7) Sieh et al. (1989); (8) Xu and Deng (1996); (9) Lee and Schwarcz (1995). F.Z. = fault zone; ss = strike slip; T.P. = tectonic province.

Uranium-series dating of aragonite showed that earthquakes in the Dead Sea occurred in clusters lasting ~10 000 yr, separated by quiet periods of similar length (Marco et al., 1996). In China, a 32 000 yr record from the Xiaojiang fault zone shows that earthquakes have occurred in clusters that last 3000–6000 yr, separated by quiet intervals of 18 000–24 000 yr (Xu and Deng, 1996). In the North China tectonic province, earthquake clusters lasting several decades are separated by quiet periods of 200–300 yr (Xu and Deng, 1996). In the eastern Mediterranean region, dating of coseismically uplifted shorelines shows that ~10 earthquakes occurred in a brief time interval between the fourth and sixth centuries A.D. (Pirazzoli et al., 1996). The repeat time calculated for episodic subsidence on the Loreto fault falls within the wide range of frequencies calculated for earthquake clustering in these and other fault zones (Table 1).

CONCLUSIONS

We propose that vertically stacked Gilbert-type fan deltas in the Loreto basin were produced by episodic subsidence on the basin-bounding Loreto fault. This mechanism has been used in other studies to explain vertical stacking of fan deltas, but previous models have not attempted to explain episodic subsidence in terms of nonlinear earthquake recurrence. Although alternate hypotheses cannot be ruled out, earthquake clustering is a reasonable mechanism that can produce episodic subsidence at temporal and spatial scales consistent with stratigraphic patterns observed in the Loreto basin. Recent paleoseismic studies indicate that earthquake clustering may govern the behavior of many fault systems; it therefore represents a potential control on repetitive stratigraphy in tectonically active basins.

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