Highstand fans in the California borderland: The overlooked deep-water depositional systems

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ABSTRACT

Contrary to widely used sequence-stratigraphic models, lowstand fans are only part of the turbidite depositional record; our analysis reveals that a comparable volume of coarse-grained sediment has been deposited in California borderland deep-water basins regardless of sea level. Sedimentation rates and periods of active sediment transport have been determined for deep-water canyon-channel systems contributing to the southeastern Gulf of Santa Catalina and San Diego Trough since 40 ka using an extensive grid of high-resolution and deep-penetration seismic-reflection data. A regional seismic-reflection horizon (40 ka) has been correlated across the study area using radiocarbon age dates from the Mohole borehole and U.S. Geological Survey piston cores. This study focused on the submarine fans fed by the Oceanside, Carlsbad, and La Jolla Canyons, all of which head within the length of the Oceanside littoral cell. The Oceanside Canyon–channel system was active from 45 to 13 ka, and the Carlsbad system was active from 50 (or earlier) to 10 ka. The La Jolla system was active over two periods, from 50 (or earlier) to 40 ka, and from 13 ka to the present. One or more of these canyon-channel systems have been active regardless of sea level. During sea-level fluctuation, shelf width between the canyon head and the littoral zone is the primary control on canyon-channel system activity. Highstand fan deposition occurs when a majority of the sediment within the Oceanside littoral cell is intercepted by one of the canyon heads, currently La Jolla Canyon. Since 40 ka, the sedimentation rate on the La Jolla highstand fan has been >2 times the combined rates on the Oceanside and Carlsbad lowstand fans.

Keywords: submarine fans, sequence stratigraphy, sedimentation rates, shelf width, California borderland.

HIGHSTAND FANS AND THE CALIFORNIA BORDERLAND

Widely used sequence-stratigraphic models (e.g., Vail et al., 1977; Mitchum, 1985; Posamentier et al., 1988, 1991; Posamentier and Erksine, 1991) postulate that submarine-fan growth predominantly occurs during periods of sea-level lowstand, when rivers reach the outer continental shelf and entrench at the shelf edge. Contrary to these models, nearly half of the submarine canyons in the tectonically active California borderland are active at the present sea-level highstand (Normark et al., 2006). Highstand fan growth has been documented elsewhere by cable breaks and direct observations of sediment gravity flows in modern (i.e., Holocene) canyon-channels systems (e.g., Zaire Fan; Heezen et al., 1964; Khripounoff et al., 2003). An ancient highstand fan was interpreted from the Maastrichtian Lance–Fox Hills–Lewis sediment supply–dominated shelf margin in southern Wyoming by Carvajal and Steel (2006). This study provides a rare opportunity to quantify the volumes of submarine fans through sea-level fluctuation in order to challenge the nearly ubiquitous application of sequence-stratigraphic models.

The late Quaternary California borderland basins are separated by shallow sills and prominent ridges that trend subparallel to the northwest strike of the San Andreas fault zone. The eastern Gulf of Santa Catalina and San Diego Trough are tectonically active, elongate basins located in the inner California borderland (Fig. 1).

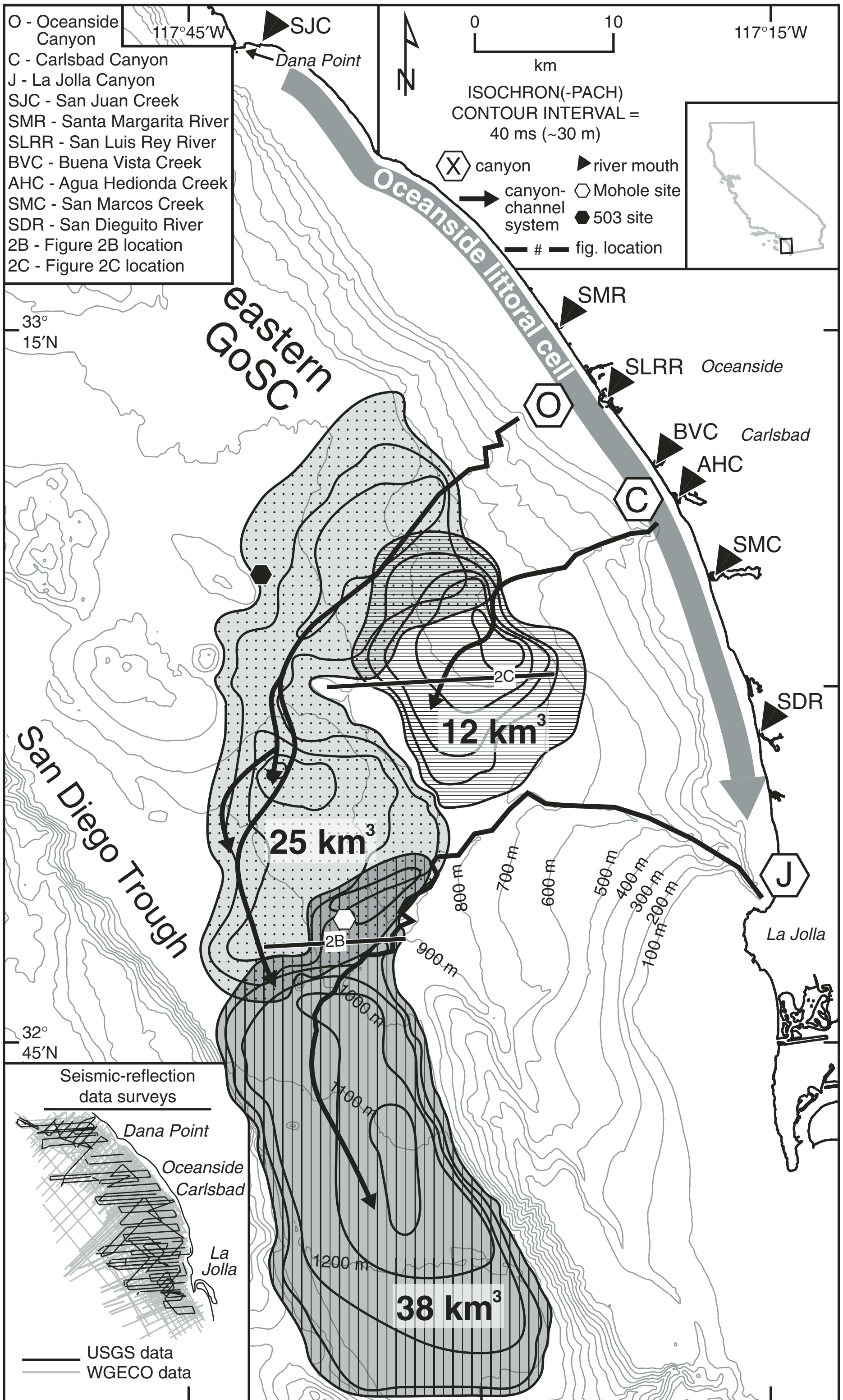
Three submarine canyon-channel systems supplied sediment to the southeastern Gulf of Santa Catalina and San Diego Trough since at least oxygen isotope stage (OIS) 3 (younger than 58 ka; Lambeck and Chappell, 2001). These are, from north to south, the Oceanside, Carlsbad, and La Jolla systems (Fig. 1). These systems have been overlooked by sequence stratigraphers, and only the La Jolla system has been studied in detail (Shepard and Buffington, 1968; Shepard et al., 1969; Piper, 1970; Normark, 1970; Graham and Bachman, 1983). The Oceanside and Carlsbad submarine fans received sediment from prominent fluvial systems, and their canyon heads are located at relatively wide segments of the continental shelf (Brownlie and Taylor, 1981; Fig. 1). The shelf width between the Oceanside Canyon head and the modern beach is ~6 km, whereas the distance between the Carlsbad Canyon head and the beach is ~2 km. The La Jolla fan lacks a prominent fluvial sediment contributor, and its canyon head has been incised across the continental shelf nearly to the modern beach (Fig. 1).

DATA AND METHODS

This study uses two-dimensional seismic-reflection profiles from WesternGeco multichannel geophysical surveys (W-3–75-SC, W-30–81-SC, W-31–81-SC, W-5–82-SC, and W-7–85-SC; U.S. Geological Survey, 2006) and U.S. Geological Survey multichannel and Huntec deep-tow boomer geophysical surveys (O-1–99-SC and A-1–00-SC; Normark et al., 1999; Gutmacher et al., 2000; Sliter et al., 2005) (Fig. 1).

Ground truth of submarine fan lithologies and ages was determined from 16 piston cores (3–5 m below seafloor, mbsf) collected during U.S. Geological Survey cruises O-2–99-SC and A-1–03-SC, and a deeper core (>70 mbsf) collected during experimental drilling into the La Jolla fan for Project Mohole (1958–1966; Inman and Goldberg, 1963; U.S. Geological Survey, 1999, 2003; Fig. 1). Records of box cores from the Scripps Institution of Oceanography Francis P. Shepard archives and published literature were also examined (Emery and Bray, 1962; Shepard and Einsele, 1962; Piper, 1970).

The Mohole core provides a calibrated radiocarbon age of 40 ka at 70 mbsf (Inman and Goldberg, 1963). The calibrated age was calculated following Shackleton et al. (2004). U.S. Geological Survey piston core 503 has a suite of calibrated radiocarbon ages, the oldest being 45 ka at 4 mbsf (U.S. Geological Survey, 1999; Fig. 1). The availability of radiocarbon ages in core 503 allows for estimation of the depth of a 40 ka seismic-reflection horizon on Oceanside fan. The 40 ka seismic-reflection horizons from the two core sites were correlated across the study area (Fig. 2). Time thickness values (two-way traveltime, ms) were determined across a nearly uniform grid between two isochronous seismic-reflection horizons. The thickness values were converted from two-way traveltime (ms) to depth (m) based on a compressional sound velocity of 1600 m/s (Hamilton et al., 1956). Bulk sediment volumes were calculated by integrating bulk sediment thicknesses across fans (Fig. 1). The bulk volumetric sedimentation rates on the fans since 40 ka were calculated by dividing the bulk sediment volumes by the durations of canyon-channel system activity (Fig. 1). The likely minor effects of sediment compaction were neglected.



Fan (since 40 ka)	Area (km²)	Average sediment thickness (m)	**Bulk volume (km³)**	Duration of activity (k.y.)	**Sedimentation rate (km³/k.y.)**
Oceanside	538	46	**25**	27	**0.9**
Carlsbad	208	59	**12**	30	**0.4**
La Jolla	521	72	**38**	13	**2.9**

Figure 1. Bathymetric map of prominent canyon-channel system sediment contributors to southeastern Gulf of Santa Catalina (GoSC) and San Diego Trough, and submarine-fan bulk sediment volumes since 40 ka. Lower left: Geophysical survey tracklines from Normark et al. (1999), Gutmacher et al. (2000), Sliter et al. (2005), and U.S. Geological Survey (2006). Bottom: Bulk sediment volume and accumulation rate calculations since 40 ka. U.S. Geological Survey piston core sites are available from U.S. Geological Survey CMG O-2–99-SC Metadata (U.S. Geological Survey, 1999), and CMG A-1–03-SC Metadata (U.S. Geological Survey, 2003). Bathymetry is from Gardner and Dartnell (2002). WGECO—WesternGeco.

FAN SYSTEM ACTIVITIES, SEDIMENT VOLUMES, AND ACCUMULATION RATES

The availability of sedimentation rates since 40 ka allows for interpretation of canyon-channel system activity (Fig. 2). These age calculations are compared to Lambeck and Chappell's (2001) sea-level curve (Fig. 2).

The Oceanside system activated at 45 ka, and shut down at 13 ka. The Carlsbad system became active before 40 ka, and shut down after the OIS 2–1 transition at 10 ka (Lambeck and Chappell, 2001). The shutdowns are based on the ages of hemipelagic mud draping the Oceanside and Carlsbad channels (Fischer et al., 1992; U.S. Geological Survey, 1999). The Oceanside and Carlsbad systems were active during sea-level lowstand (Fig. 2).

There have been two prominent periods of La Jolla system activity. The first period shut down at 40 ka during OIS 3 marine regression (Lambeck and Chappell, 2001). The second period of La Jolla system activity initiated at 13 ka. The La Jolla system remains active during the present sea-level highstand (Piper, 1970) (Fig. 2).

The bulk sediment volume of the La Jolla highstand fan is nearly equal to the combined bulk sediment volumes of the Oceanside and Carlsbad lowstand fans since 40 ka (Fig. 1). The long-term bulk volumetric sedimentation rate on La Jolla fan is >2 times the combined rates on the Oceanside and Carlsbad fans (Fig. 1).

DISCUSSION: CONTROLS ON DEEP-WATER SEDIMENTATION

Placed in temporal and geographic context, seismic-reflection–based interpretations indicate that shelf width between the canyon head and the littoral zone is the primary control on canyon-channel system activity (Fig. 3). During the latest Pleistocene interval of low sea level (ca. 20 ka), the Oceanside and Carlsbad canyon heads received sediment from fluvial systems that extended across the subaerially exposed continental shelf, and captured sediment from

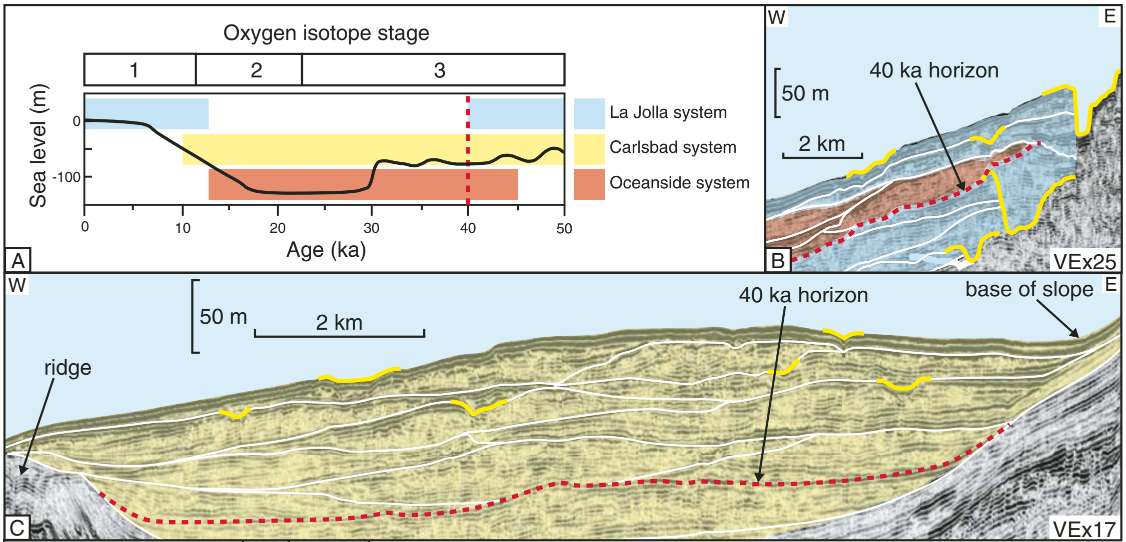
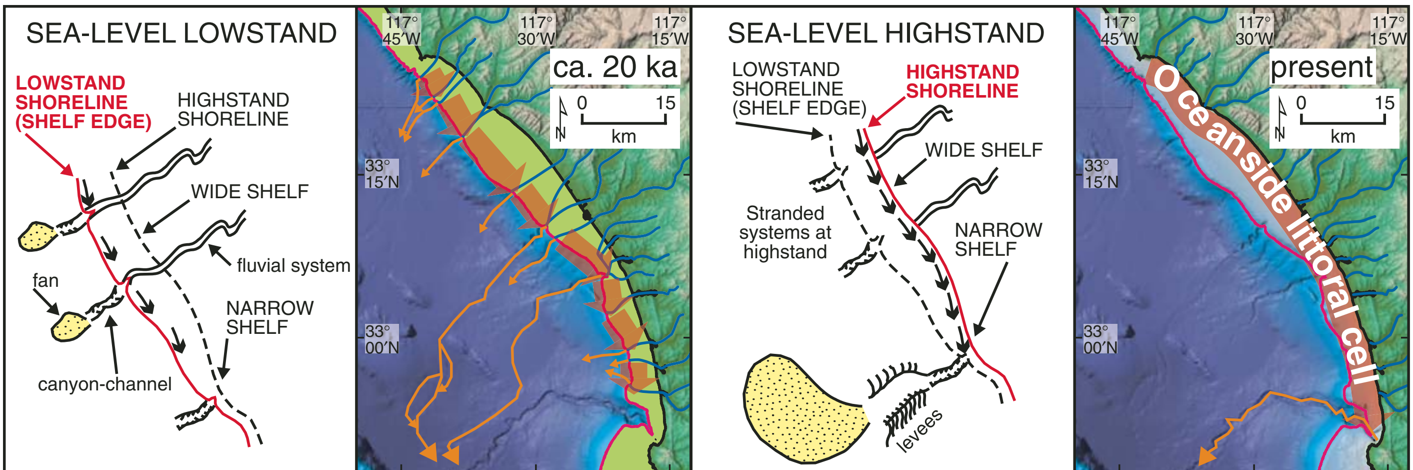


Figure 2. Submarine fan seismic-reflection profiles. A: Sea-level curve modified from Lambeck and Chappell (2001). B: Seismic-reflection profile showing La Jolla fan (shaded blue) and channels (bold yellow lines), and Oceanside fan (shaded red). C: Seismic-reflection profile showing Carlsbad fan (shaded yellow) and channels. White lines are boundaries of depositional lobe and overbank elements. Lower section shows interpreted canyon-channel system activity and corresponding sea levels. See Figure 1 for seismic-reflection profile locations. VE—vertical exaggeration.

Event	Age (ka)	Sea level (m)
Oceanside system initiation	45	-65
Oceanside system shutdown *	13	-75
Carlsbad system shutdown *	10	-45
Ancient La Jolla system shutdown	40	-78
Modern La Jolla system initiation	13	-75

* Seismic-reflection- and sediment-core–based interpretations supported by Fischer et al. (1992)



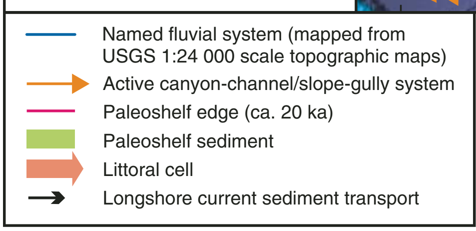


Figure 3. Summary diagrams and paleogeographic reconstructions illustrating influence of shelf width between canyon heads and littoral zone on canyon-channel system activity. Bathymetry is from Gardner and Dartnell (2002).

numerous littoral subcells. The segmentation of the Oceanside littoral cell into subcells substantially reduced longshore drift–transported sediment contributions to the La Jolla Canyon head, which lacked a prominent fluvial sediment contributor and shut down (Fig. 3).

During the Holocene transgression and highstand (after 11.5 ka; Lambeck and Chappell, 2001), longshore drift–transported sediment bypassed the Oceanside and Carlsbad canyon heads, and contributed to the La Jolla Canyon head (cf. Shepard, 1963). Fluvial systems were unable to reach the Oceanside and Carlsbad canyon heads across the wide, drowned shelf, and contributed almost exclusively to the Oceanside littoral cell or small coastal lagoons rather than directly to canyon heads (although sediment retention in small coastal lagoons is volumetrically insignificant in southern California; Uncles and Smith, 2005) (Fig. 3).

The discrepancy between long-term bulk volumetric sedimentation rates (i.e., the sedimentation rate on the La Jolla highstand fan is >2 times the combined rates on the lowstand fans; Fig. 1) is a result of discounting the deep-water sediment contributions from less prominent lowstand active canyon-channel systems. For example, Figure 3 shows numerous relatively small sources of sediment to deep water active during sea-level lowstand. The sediment volumes from many small sources cannot be accounted for with the current data.

CONCLUSION

This study provides a rare opportunity to compare sediment volume fluctuation to deep water through sea-level variation during the latest Quaternary. Revisiting the overlooked La Jolla highstand fan and examining the less-studied Oceanside and Carlsbad lowstand fans yields new insight into controls on deep-water coarse-clastic sediment distribution. Contrary to widely used sequence-stratigraphic models, lowstand fans are only part of the turbidite depositional record, and this analysis reveals that a comparable volume of coarse clastic sediment has been deposited in California borderland deep-water basins regardless of sea level. Early sequence-stratigraphic models were developed along passive margins with relatively wide continental shelves, where relative sea level has a greater influence on sediment delivery to submarine canyons. Along the tectonically active California margin, the narrow shelf between the canyon head and the littoral zone allows nearly half of the canyons to remain active at the present sea-level highstand (Normark et al., 2006). Since 40 ka, the sedimentation rate on the La Jolla highstand fan has been >2 times the combined rates on the Oceanside and Carlsbad lowstand fans.

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