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ORIGINAL RESEARCH PAPER

Late Pleistocene to Holocene sedimentation and hydrocarbon seeps on the continental shelf of a steep, tectonically active margin, southern California, USA

Amy E. Draut · Patrick E. Hart · Thomas D. Lorenson · Holly F. Ryan · Florence L. Wong · Ray W. Sliter · James E. Conrad

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Abstract Small, steep, uplifting coastal watersheds are prolific sediment producers that contribute significantly to the global marine sediment budget. This study illustrates how sedimentation evolves in one such system where the continental shelf is largely sediment-starved, with most terrestrial sediment bypassing the shelf in favor of deposition in deeper basins. The Santa Barbara–Ventura coast of southern California, USA, is considered a classic area for the study of active tectonics and of Tertiary and Quaternary climatic evolution, interpretations of which depend upon an understanding of sedimentation patterns. High-resolution seismic-reflection data over >570 km^2 of this shelf show that sediment production is concentrated in a few drainage basins, with the Ventura and Santa Clara River deltas containing most of the upper Pleistocene to Holocene sediment on the shelf. Away from those deltas, the major factor controlling shelf sedimentation is the interaction of wave energy with coastline geometry. Depocenters containing sediment 5–20 m thick exist opposite broad coastal embayments, whereas relict material (bedrock below a regional unconformity) is exposed at the sea floor in areas of the shelf opposite coastal headlands. Locally, natural hydrocarbon seeps interact with sediment deposition either to produce elevated tar-and-sediment mounds or as gas plumes that hinder sediment settling. As much as 80% of fluvial sediment delivered by the Ventura and Santa Clara Rivers is transported off the shelf (some into the Santa Barbara Basin and some into the Santa Monica Basin via Hueneme Canyon), leaving a shelf with relatively little recent sediment accumulation. Understanding factors that control large-scale sediment dispersal along a rapidly uplifting coast that produces substantial quantities of sediment has implications for interpreting the ancient stratigraphic record of active and transform continental margins, and for inferring the distribution of hydrocarbon resources in relict shelf deposits.

Keywords Continental shelf · Fluvial sediment · Hydrocarbon seeps · Southern California

Introduction

Styles of sedimentation on continental shelves influence the economic potential, geohazard risk, and vulnerability to anthropogenic environmental contamination of many coastal regions worldwide. Understanding patterns of sediment dispersal and deposition from small, steep, mountainous watersheds is particularly important in regional and global sedimentology because 10^1–10^4 km^2 watersheds along mountainous coasts collectively have a proportionately greater importance for global sediment production than do larger rivers (Milliman and Syvitski 1992). In this paper, we examine a new, high-resolution seismic record of continental-shelf sedimentation along ~120 km of mountainous, tectonically active coastline in southern California, USA. These data, collected as part of the U.S. Geological Survey (USGS) California seafloor mapping program and a collaborative study of hydrocarbon seeps by the USGS and U.S. Minerals Management Service, elucidate 10s-km-scale sedimentation patterns that have proceeded since late

A. E. Draut (✉)
U.S. Geological Survey, 400 Natural Bridges Drive, Santa Cruz, CA 95060, USA
e-mail: adraut@usgs.gov

P. E. Hart · T. D. Lorenson · H. F. Ryan · F. L. Wong · R. W. Sliter · J. E. Conrad
U.S. Geological Survey, 345 Middlefield Rd., Menlo Park, CA 94025, USA

Pleistocene time along a steep, tectonically active margin that is important to many tectonic and climatic investigations. By comparing sediment thickness and volume on the shelf with estimates of watershed sediment yield, the efficiency of sediment trapping on this shelf versus bypass into deeper basins can be investigated.

Geologic setting

Shallow geophysical profiles were collected on the northern continental shelf of the Santa Barbara Channel, a body of water separating mainland California from the Channel Islands (Fig. 1). Off the shelf, the Santa Barbara Basin (as deep as 600 m) forms the western, offshore continuation of the east–west trending Ventura Basin. This basin, cut by numerous west- and northwest-trending reverse faults, is structurally part of the Western Transverse Ranges province, a coherent crustal block that has been rotating clockwise since Miocene time as the North American continental margin accommodates transform motion of the adjacent Pacific Plate (e.g., Atwater 1970; Yeats 1988; Jackson and Molnar 1990; Nicholson et al. 1994; Sorlien et al. 2000). The east–west orientation of the Transverse Ranges, including the actively uplifting Santa Ynez Mountains onshore of our study area, is anomalous among dominantly northwest-trending structures associated with the San Andreas Fault system, the main trace of which lies ~60 km inland from this coast (e.g., Yerkes and Lee 1987). Modern uplift rates onshore of the study area are estimated to be 0.4–10 mm/year (Gornitz et al. 1997; Sylvester 2000).

The continental shelf bordering the north and east side of the Channel is typically 10–20 km wide and receives most of its sediment during winter rain events. Drainage basins in the Santa Ynez Mountains are small (10^1–10^4 km^2) and steep, reaching elevations consistently >1,100 m within 5–10 km of the coast. Most coastal watersheds have ephemeral, seasonal flow; landslides and debris flows are not uncommon, especially during winter rains that follow summer wildfires. Rainfall averages ~400 mm/year near Santa Barbara, nearly all of which falls in winter. Owing to rapid uplift, easily erodible lithologies, and agricultural practices, sediment yield from watersheds of these Western Transverse Ranges is as much

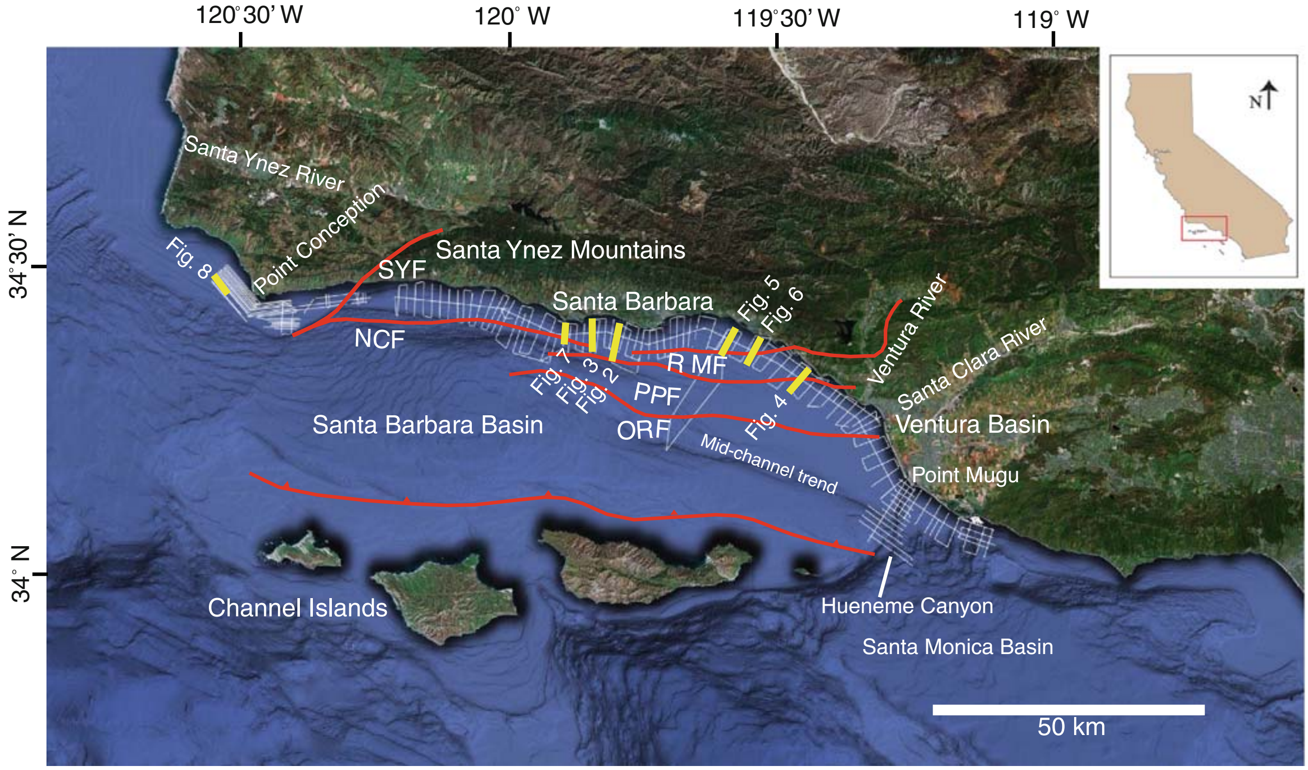


Fig. 1 Location map showing the study area on the southern California coast (base image courtesy of Google Inc.). Ship tracks along which Chirp and mini-sparker seismic-reflection profiles were collected are shown in white, with *arrows* indicating seismic lines shown in Figs. 2, 3, 4, 5, 6, and 7. Profiles west of 120°20′W were obtained in 2002 (Normark et al. 2003); profiles east of 120°20′W were obtained in 2007 and 2008 (Sliter et al. 2008). The Santa Ynez Mountains, onshore, are part of the Western Transverse Ranges tectonic province, which experiences rapid uplift; sediment yield from these coastal watersheds is, accordingly, substantially greater than in surrounding areas. Major faults are indicated: *NCF* north channel fault, *RMF* Red Mountain fault, *PPF* Pitas Point Fault, *ORF* Oak Ridge Fault, *SYF* Santa Ynez Fault (south branch). Locations of seismic lines shown in Figs. 2, 3, 4, 5, 6, 7, and 8 are indicated

as an order of magnitude greater than in surrounding areas of California (Warrick and Mertes 2009).

Coastal morphology along the study area northwest of the Ventura River valley consists of alternating bluffs and narrow beaches, some of which have been altered by jetties and other engineered structures. To the southeast, the Ventura and Santa Clara Rivers feed the largest sediment deposits in the study area, forming connected deltas. The Ventura and Santa Clara Rivers have drainage area 585 and 4,220 km^2, respectively, and, before dams were built in the mid-twentieth century, delivered an average of approximately 5.9×10^6 tons of sediment to the ocean annually (Warrick 2002; Warrick and Mertes 2009). With dams currently in place, the two watersheds contribute $\sim 4.7 \times 10^6$ tons of sediment to the ocean annually (USGS, unpublished data; Slater et al. 2002); large floods can, however, produce sediment discharge several orders of magnitude higher than the mean annual load (e.g., Drake et al. 1972).

Subtidal shelf currents in the eastern Santa Barbara Channel flow dominantly northwest (in contrast to the larger California Current, which flows southeast farther offshore), comprising a large counterclockwise eddy generated by interaction with coastline topography; in the littoral zone, however, longshore drift is dominantly toward the southeast (Drake et al. 1972, 1985; Hickey 1992; Bray et al. 1999; Noble et al. 2002; Brocatus 2008; Barnard et al. 2009). The shelf is largely wave-dominated, although the Channel Islands and Point Conception shelter the study area from high wave energy unless the incident swell approaches from due west. Fair-weather wave base along the shelf south of Point Conception is estimated to be 10–25 m (Drake et al. 1985; Slater et al. 2002). A small tidal range ($\sim$2 m) and the lack of constrictions in coastal geometry preclude strong tidal currents.

Fine sediment has accumulated in the Santa Barbara Basin at rates high enough to help produce some of the best-preserved paleoclimate records in the world (>1 m/ky in Pleistocene and Holocene time; Behl and Kennett 1996). The active tectonics of the basin cause sedimentary units of varying ages to be exposed at the sea floor; recent and ongoing paleoclimate studies have sampled sediment as old as upper Pliocene in the limbs of an anticline known as the "mid-channel trend" (Fig. 1; Nicholson et al. 2006). The Santa Barbara Basin area is widely considered an excellent site to study the interaction of sedimentary and tectonic processes.

Previous work

Previous mapping of shelf sediment in this area by Fischer et al. (1983), Slater et al. (1987, 2002), and Sommerfield et al. (2009) produced generalized maps of sediment thickness overlying a regional unconformity. Dahlen et al. (1990) used seismic-reflection profiles to map upper Pleistocene to Holocene sediment on the Ventura–Santa Clara River deltas up to $\sim$10 km NW of the Ventura River mouth (Fig. 1). Their study identified two wave-cut terraces of late Pleistocene age now buried within the delta sediments, and estimated 17 and 40 m of Quaternary shelf-sediment displacement by the Oak Ridge and Pitas Point Faults, respectively (Dahlen et al. 1990). Slater et al. (2002) estimated a total shelf sediment volume of 22 km^3 for the region from Point Conception to Point Mugu (Fig. 1), dominated by deltaic deposits from the Ventura and Santa Clara Rivers. Other studies have traced the dispersal of flood sediment from coastal rivers across this shelf and into the Santa Barbara Basin on various time scales, describing oceanic conditions that redistribute sediment seasonally (Drake et al. 1972), developing a conceptual model for sand and mud dispersal mechanisms (Warrick and Farnsworth 2009), and using flood deposits to refine regional climatic history (Escobedo and Behl 2007). In a detailed study of beach sediment distribution and grain size, Barnard et al. (2009) assessed trends in beach width and morphology between Santa Barbara and Ventura, quantifying the effects of El Niño-Southern Oscillation (ENSO) cycles and human alterations of the shoreline.

In the western part of our study area, Fisher et al. (2005) used shallow seismic-reflection profiles, correlated with ^{14}C ages from Ocean Drilling Program (ODP) Site 893, to determine ages of 8–10 ka for major failure episodes on the large Goleta landslide complex. Fisher et al. (2005) proposed that relict Quaternary sediment, oversteepened by uplift along an anticline in the Santa Barbara Basin and affected by fluid flux associated with hydrocarbons, could undergo additional failure in future submarine landslides, causing tsunamis (Greene et al. 2006). Numerous other investigations by industry scientists have generated detailed seismic reflection and refraction data for this area, much of which is proprietary because Miocene and Pliocene strata on the shelf and in the Santa Barbara Basin contain actively producing hydrocarbon fields.

Methods

Data were acquired in 2007–2008 using SIG mini-sparker and Edgetech Chirp 512 instruments aboard the *R/V Zephyr*. The area covered by that survey spanned approximately 100 km of coastline and included shore-perpendicular transects spaced 1–2 km apart that extended offshore as far as the 3-mile ($\sim$5 km) limit of California state waters (Fig. 1). Water depth in the survey area was generally between 45 and 120 m, but as deep as 200 m off Santa Barbara (Fig. 1) and, in the southeastern part of the study area, typically 35–40 m over the Santa Clara and Ventura

River deltas. Sub-bottom acoustic penetration ranged from tens to several hundred meters, and varied by location.

The Edgetech 512 Chirp subbottom profiling unit (“fish”) consists of a source transducer and an array of receiving hydrophones housed in a 500-lb fish towed at a depth of several meters. The 50 ms swept-frequency (500 Hz–4.5 kHz) acoustic source signal was recorded by hydrophones located on the bottom of the fish. The mini-sparker system used a 500 J high-voltage electrical discharge that creates a source with greater power and lower frequency than the Chirp and was received by a towed 15-m-long hydrophone streamer. Depending on water depth, the sources for either system were fired at 1–4 times per second, which, at a normal survey speed of 4–4.5 knots, gives a data trace every 2.0–0.5 m. The data from each system were digitally recorded in standard SEG-Y format with Triton Subbottom Logger (SBL) PC-based software that merges seismic reflection data with differential GPS navigation data. Digital sampling for the Chirp data was at 10 kHz, and was 16 kHz for the mini-sparker data. Differential global positioning system (GPS) position fixes were written into the seismic data trace headers. Seismic-reflection profiles collected in 2007 and 2008 are available in standard SEG-Y geophysical format, and as JPEG and TIFF images linked to Google Earth^{TM} software, from the online data report by Sliter et al. (2008).

To extend our regional assessment of sedimentation patterns, this study also utilized data collected in 2002 by the USGS and Minerals Management Service in the vicinity of Point Conception (Fig. 1), using the same Chirp system described above. Methods of data collection and processing from that cruise, on the *M/V Auriga*, can be found in Normark et al. (2003). In total, the seafloor area represented by the data sets discussed here covers >570 km^2, at line spacing that ranges from 0.25 km around Point Conception to 1–2 km over the rest of the study area.

To interpret late Pleistocene to Holocene sedimentation patterns, and to produce a resulting isopach map (discussed below), reflection two-way travel times were picked along the sea floor and a regional unconformity in seismic profiles and were output to a geographic information system (GIS) mapping program. Location and elevation data were gridded and contoured using an inverse distance weighted algorithm (Liszka 1984); two-way reflection times were converted to depth using a sound velocity of 1,500 m/s for the water column and 1,600 m/s for the interval between the seafloor and the unconformity.

Results

Examples of Chirp and mini-sparker transects are shown in Figs. 2, 3, 4, 5, 6, 7, and 8. It is apparent in many of the profiles that the most recent sediment deposits on the continental shelf in the study area lie in unconformable contact with older deposits beneath (e.g., Fig. 2). The geophysical data are of sufficient quality that sedimentary architecture within the deposits above the unconformity can be discerned; rather than the commonly described acoustically transparent layer (e.g., Hogarth et al. 2007), these youngest sediments include clinoforms clearly visible in some profiles (Fig. 3) and subhorizontal bedding in others (Fig. 4). Below the unconformity, sedimentary bedding generally dips offshore along the northern Santa

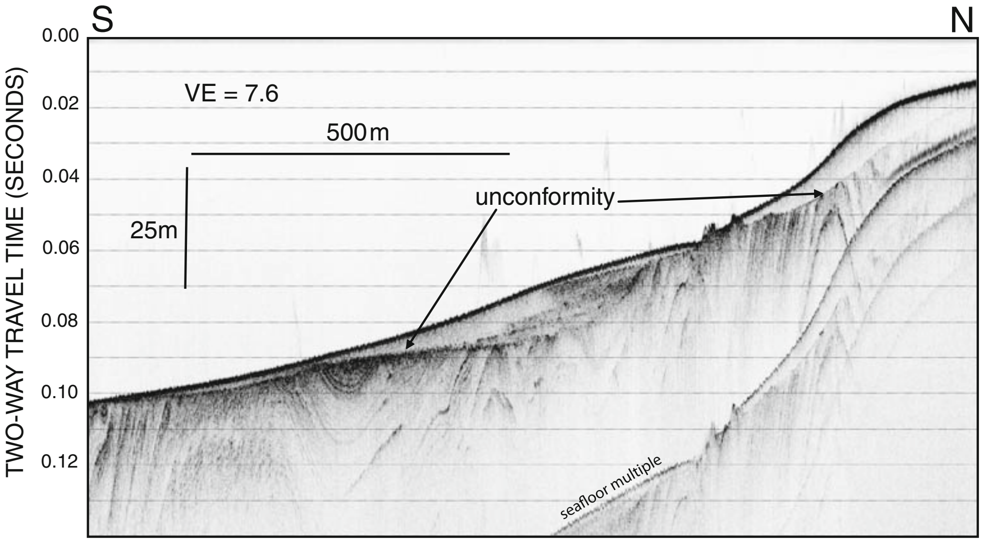
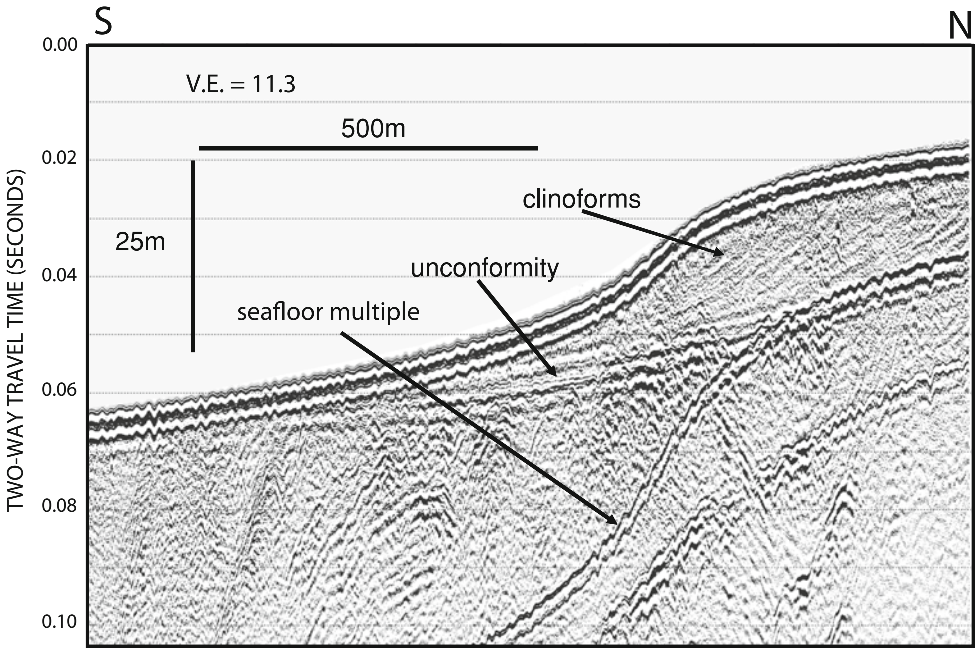


Fig. 2 Chirp profile (number SBC-122 from Sliter et al. 2008) showing upper Pleistocene and Holocene sediments overlying an unconformity that persists throughout the southern California shelf. Complex structure, including bedrock folds, is visible beneath the unconformity. Location shown on Fig. 1. Vertical exaggeration = 7.6

Fig. 3 Example of a mini-sparker profile (number SB-148 from Sliter et al. 2008) in which sediment above the unconformity, rather than being acoustically transparent, contains visible clinoform geometry. Location shown on Fig. 1. Vertical exaggeration = 11.3



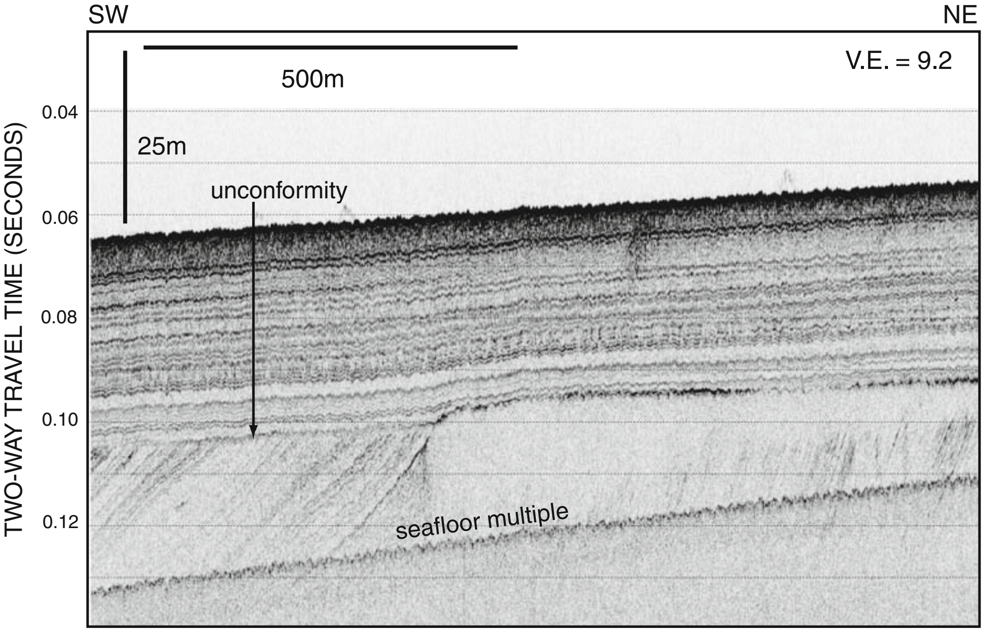


Fig. 4 Detail from Chirp profile SBC-84 (Sliter et al. 2008) showing the regional unconformity. Late Pleistocene to Holocene sediment here does not show clinoform geometry but is bedded parallel to the unconformity surface. Bedding (of Tertiary sedimentary rocks) beneath the unconformity dips offshore. Location shown on Fig. 1. Vertical exaggeration = 9.2

Barbara Channel shelf (Figs. 4, 7), with more complex structure also visible in many of the transects (e.g., anticlines and synclines in Fig. 2, a broad syncline in Fig. 5, and a fault in Fig. 6).

Natural hydrocarbon seeps occur in the study area and were imaged in a number of seismic profiles. Seeps occur both as gas plumes and as tar mounds on the sea floor. Gas seeps, such as the large Trilogy Seep (Fig. 7), are apparent as bubble plume zones that each cover 10–100 m^2 at the sea surface. Tar mounds containing a mixture of tar and sediment form bathymetric highs with as much as 5 m relief above the surrounding sea floor (Fig. 8). The presence of tar composing these mounds was confirmed by grab samples and images from a towed video camera; tar-seep extent was analyzed by using both the Chirp data and high-resolution seafloor imagery collected by Fugro

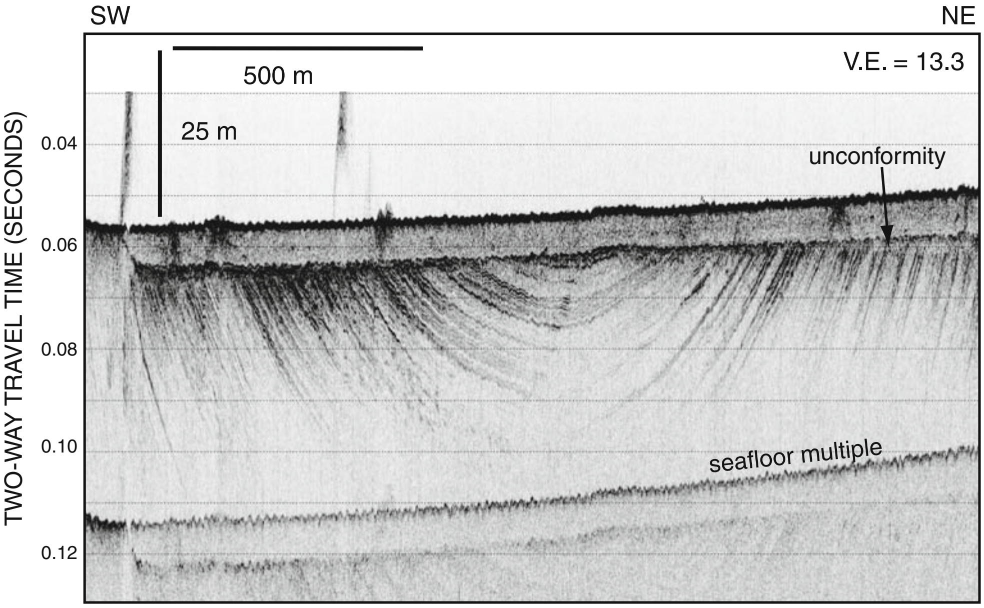


Fig. 5 Detail from Chirp profile SBC-96 (Sliter et al. 2008) showing sediment overlying the regional unconformity, beneath which Tertiary sedimentary rocks are folded into a syncline. Location shown on Fig. 1. Vertical exaggeration = 13.3

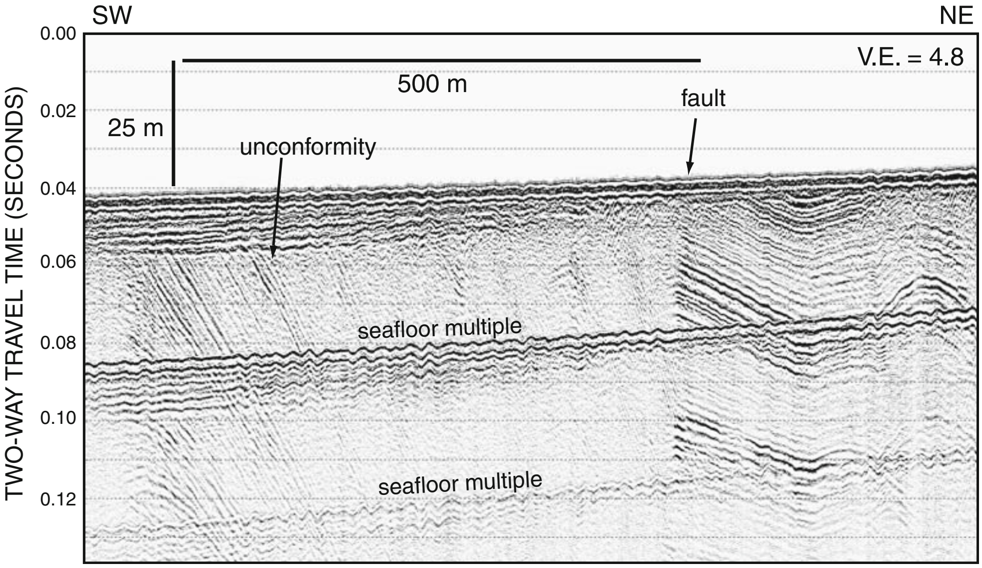


Fig. 6 Detail from mini-sparker profile SB-99 (Sliter et al. 2008), showing seaward-thickening late Pleistocene and Holocene sediment overlying the regional unconformity. Beneath the unconformity, bedrock structure includes a steeply dipping fault (the Red Mountain Fault) and a conjugate fold pair at the *right* (shoreward) side of the image. Location shown on Fig. 1. Vertical exaggeration = 4.8

Pelagos using Reson multibeam echo sounders (data not yet publicly available).

An isopach map of sediment overlying the regional unconformity is shown in Fig. 9, generated from the Chirp and mini-sparker data. The delta of the Ventura and Santa Clara Rivers is apparent as the thickest sediment body (>40 m); a smaller deposit, ~30 m thick and covering a substantially smaller area than the Ventura–Santa Clara deltas, occurs at the mouth of Gaviota Creek (Fig. 9). Away from these depocenters at the mouth of the three largest watersheds on this coast, thinner sediment bodies (<20 m thick, with the geometry of low-relief mounds) tend to occur opposite coastal embayments (e.g., immediately west of Coal Oil Point, between Goleta Point and Santa Barbara, and east of Santa Barbara), with little or no accumulation opposite coastal promontories. Figure 10 shows topography of the transgressive surface above which late Pleistocene to Holocene deposition occurred. Tar-seep

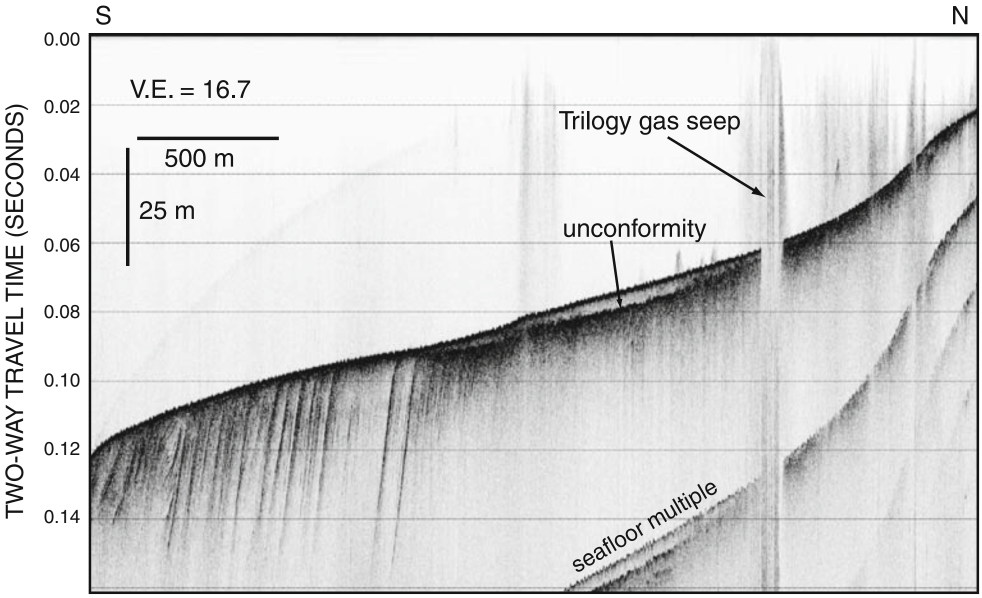


Fig. 7 Chirp profile SBC-148 (Sliter et al. 2008). In addition to showing bedrock beneath and younger sediment above the regional unconformity, this profile shows a large natural gas seep (Trilogy Seep) and several smaller seeps (at the *right side* of the image) that obscure strata. These gas seeps are manifested at the sea surface by plumes of bubbles covering >100 m^2. Location shown on Fig. 1. Vertical exaggeration = 16.7

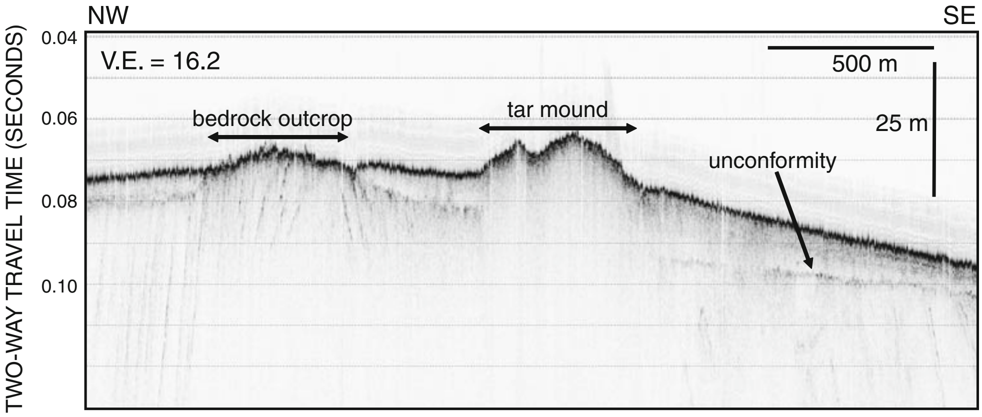


Fig. 8 Detail of Chirp profile SS02-09 (Normark et al. 2003) obtained southwest of Point Conception. At the *left side* of the image, bedrock outcrops at the sea floor, and steeply dipping bedding is visible. On either side of the bedrock outcrop, the regional unconformity is visible with sediment overlying it. In the center of the image, a bathymetric high is formed by a natural tar seep. The seafloor mound, elevated >1 m above the surrounding sea floor, is likely composed of tar and sediment; the hydrocarbon seep obscures the structure of the unconformity beneath it, and it is not known how deep beneath the sea floor the seep originates. The presence of tar was confirmed by grab sampling near this and other, similar mounds in the area. Seeps along coastal California originate from the Miocene Monterey Formation (Peters et al. 2008). Location shown on Figs. 1 and 10. Vertical exaggeration = 16.2

extent is indicated in Figs. 9 and 10; the minimum thickness of tar mounds off Point Conception is mapped in detail in Fig. 11.

Discussion

Continental-shelf sedimentation in southern California reflects interactions of tectonic activity, eustatic sea-level change, and erosion and deposition of sediment from local sources (as elsewhere along this active margin; cf. Orange 1999). Upper Pleistocene to Holocene sedimentary deposits on the shelf between Point Conception and Ventura are defined by their unconformable contact with underlying deformed, tilted strata. The regional unconformity apparent in Figs. 2, 3, 4, 5, 6, 7, and 8, which we use to define the base of sedimentary “overburden” mapped in Figs. 9 and 10, formed largely as a result of tectonic deformation of

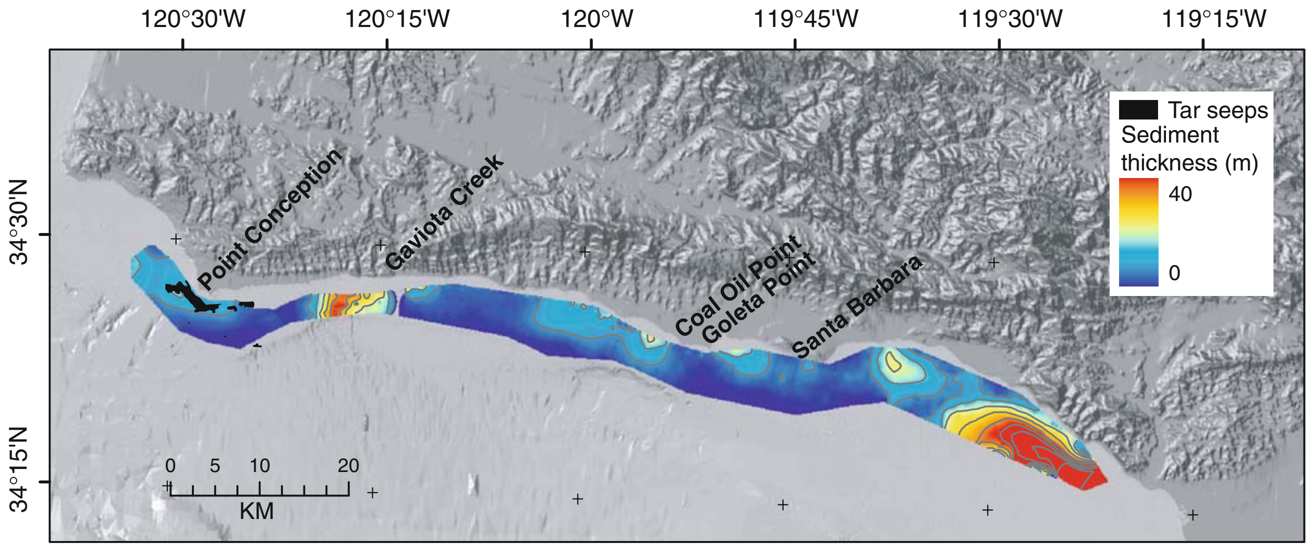


Fig. 9 Isopach map showing thickness of upper Pleistocene to Holocene sediment overlying the regional unconformity; the contour interval is 4 m. In the southeastern part of the study area, sediment from the connected Ventura and Santa Clara River deltas thins to the northwest (downdrift). The shelf west of the deltas is largely sediment-starved, with the only other fluvially controlled depocenter occurring at 120°17′W, just downdrift of the mouth of Gaviota Creek (the largest watershed on this coast after those of the Ventura and Santa Clara Rivers). The rest of the shelf in this area contains little sediment above the regional unconformity, with minor depocenters concentrated opposite coastal embayments (e.g., depocenters occur immediately west of Coal Oil Point, between Goleta Point and Santa Barbara, and east of Santa Barbara). In contrast, bedrock is exposed at or near the sea floor opposite coastal headlands. *Blackened* areas off Point Conception indicate the presence of tar seeps. The total area covered by tar seeps is ~8.5 km^2

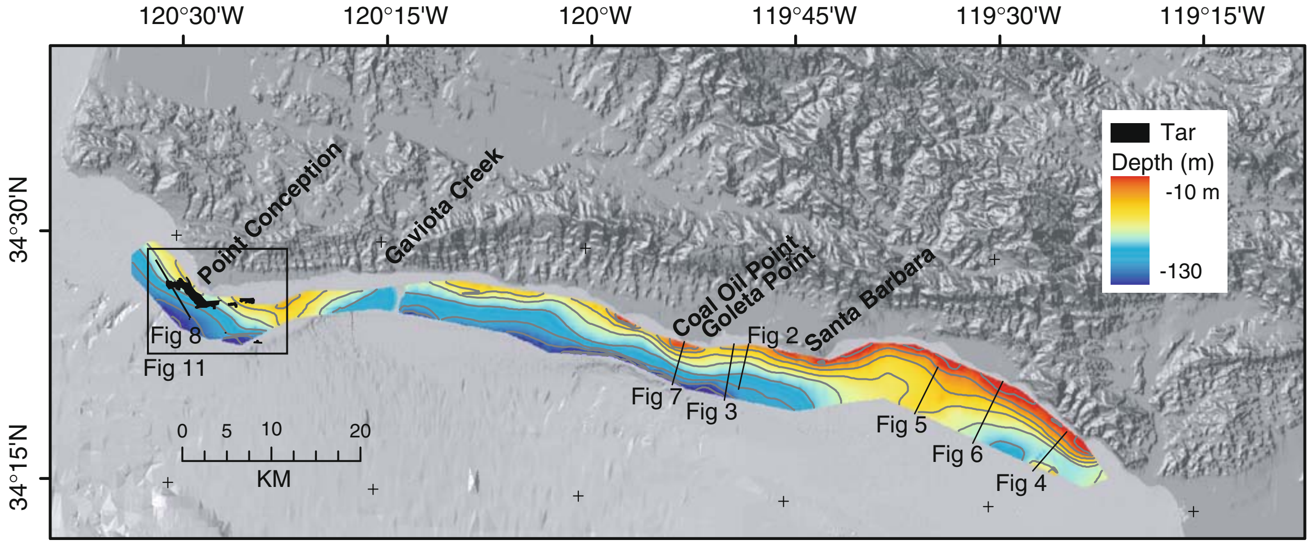


Fig. 10 Map showing depth from the sea floor to the regional unconformity (transgressive surface) above which we define the upper Pleistocene and Holocene sedimentary package illustrated in Fig. 9. The contour interval is 10 m. *Blackened* areas off Point Conception indicate tar seeps. Locations of profiles shown in Figs. 2, 3, 4, 5, 6, 7, and 8 are indicated; the *box* shows the area of Fig. 11

this margin that caused subaerial exposure. Beneath the unconformity, thick (>6,000 m) marine and non-marine Tertiary and Pleistocene sedimentary units (also now exposed onshore; Dibblee and Ehrenspeck 1986, 1987, 1988; Minor et al. 2007) attest to rapid subsidence of the Ventura Basin then, on the order of 1 km/my (Yeats 1978). In late Pleistocene time, rapid subsidence of the northern part of the Ventura Basin was replaced by uplift and subaerial exposure, forming the regional unconformity. Tectonic tilting has caused rapid uplift of the margin onshore (as much as 10 mm/year) and corresponding subsidence on the shelf, allowing renewed marine sediment deposition above the unconformity (Yeats 1977, 1978; Yerkes and Lee 1987; Yerkes et al. 1987).

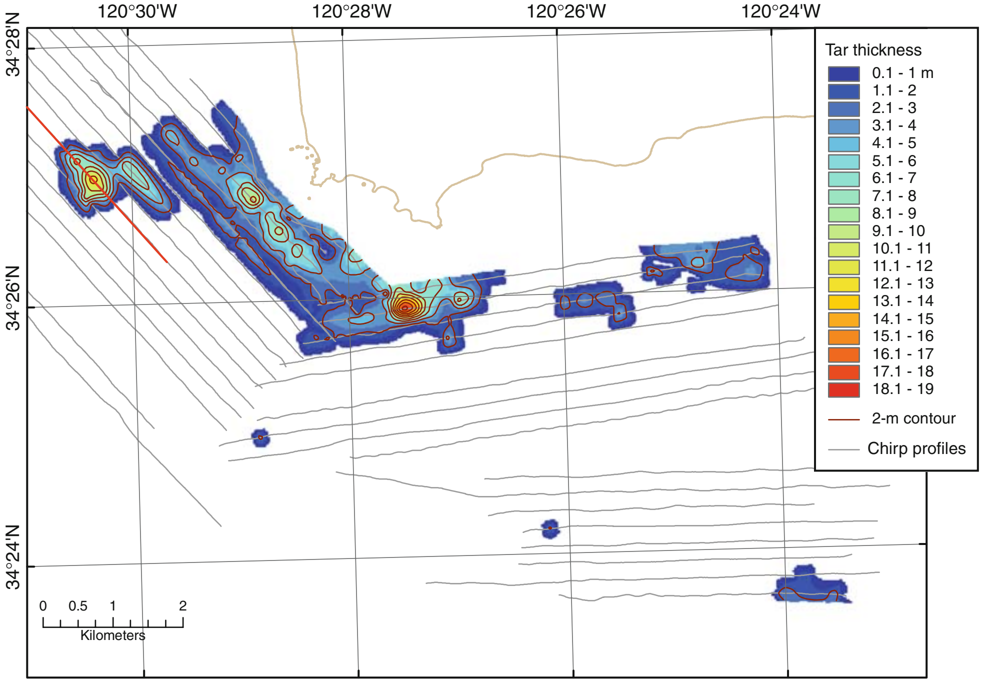


Fig. 11 Thickness of mounds off Point Conception interpreted as natural tar seeps. Mounds likely contain sediment and tar. Thickness is given as minimum values, and was inferred by using Chirp profiles to measure the height of the bathymetric highs relative to the surrounding sea floor (as in Fig. 8). The true thickness of the tar deposit formed at each seep site could be much greater, but is not readily apparent in the Chirp images. *Gray lines* show ship tracks along which Chirp profiles were surveyed (Normark et al. 2003); the track in *red* is profile number SS02-09, shown in Fig. 8

Superimposed on the substantial tectonic activity of this coastline have been Pleistocene and Holocene eustatic sea-level fluctuations and migration of the Santa Clara River mouth (Dahlen et al. 1990), both of which affect the supply of fluvial sediment to the Santa Barbara shelf. The relative roles of eustatic and local (tectonic) sea-level changes on sedimentation patterns in this region, both of which affected accommodation space available for sediment storage, are complex (Sommerfield et al. 2009) and have not yet been precisely differentiated. During Pleistocene lowstand, the Santa Clara River mouth was south of its present position, supplying sediment to Santa Monica Basin via Hueneme submarine canyon (Dahlen et al. 1990; Normark et al. 1998). Even during the present highstand, the supply of fluvial sediment to the Santa Barbara shelf is affected by littoral drift of sand from the Ventura and Santa Clara River mouths toward the southeast, where hyperpycnal flows transport much of it through Hueneme Canyon into Santa Monica Basin (Normark et al. 1998). Finer, muddy sediment tends to take a different path: traveling farther offshore from the river mouths than does the sand, outside the littoral drift zone and onto the shelf, where it moves northwest in dilute hypopycnal plumes or is transported off the shelf via wave-induced gravity currents (Wiberg et al. 2002; Warrick and Farnsworth 2009).

The sedimentary package overlying the regional unconformity was identified by Dahlen et al. (1990) as containing upper Pleistocene to Holocene material. Radiocarbon dates from the shelf south of our study area (Santa Monica and San Pedro Bays; Sommerfield and Lee 2003) corroborate this, having yielded ages of 13–10 cal year BP for strata just above the unconformity; sediment was not collected or dated during our study, and the age uncertainty precludes differentiation of late Pleistocene and Holocene material. Above the unconformity, sedimentation patterns show substantial spatial variability. In the southeastern part of our study area, delta sediment 10s of m thick from the Ventura and Santa Clara Rivers overlies the unconformity (present there as a disconformity, with little or no tilting of the beds beneath it), and thins to the northwest, apparently shaped by the northwestward subtidal currents on the shelf (Fig. 9). In the thickest part of the delta, nearest the Ventura and Santa Clara River mouths, the base of delta sediment was not readily resolvable in our data set; the sediment thickness mapped in Fig. 9 extends only as far southeast as could be confidently resolved from our data. Active displacement along the Oak Ridge and Pitas Point Faults exerts some control over sedimentary architecture (cf. Dahlen et al. 1990), with the Pitas Point Fault appearing as a growth structure on seismic profiles of the eastern shelf (Sliter et al. 2008) and implying ~10 m of associated offset within the young sedimentary package. Fault control on recent and active shelf sedimentation is not uncommon in southern California (Hogarth et al. 2007). We do not see evidence for substantial structural control of recent sedimentation in our study area west of ~119°20′W, perhaps owing in part to the grid spacing of seismic lines or to the contouring algorithms applied.

West of 119°35′, farther downdrift of the Ventura and Santa Clara River sediment sources, the character of shelf sedimentation changes substantially. The shelf between 119°35′ and north of Point Conception is relatively sediment-starved. Although this part of the shelf has been described as having accommodation space that greatly exceeds sediment supply (Slater et al. 2002; Sommerfield et al. 2009), this occurs not because sediment supply is low (it is in fact very high; Warrick and Mertes 2009), but because most fluvial sediment supplied to the shelf is not stored there long before being transported either into the deeper Santa Barbara Basin, where accumulation rates are some of the highest known in the world (Schwalbach and Gorsline 1985; Behl and Kennett 1996), or into Santa Monica Basin forming Hueneme Fan and other deposits (Normark et al. 1998). The thickest recent sediment deposit on the shelf west of the Ventura–Santa Clara deltas, and the only one clearly associated with a coastal watershed, occurs at 120°20′W, just west of the mouth of Gaviota Creek. As the only watershed in this part of the coast to extend north of the main Santa Ynez mountain range, Gaviota Creek has the third-largest drainage basin (52.2 km^2) in the study area (after the Ventura and Santa Clara watersheds; Warrick and Mertes 2009). The size, shape, and sediment yield of the Gaviota Creek watershed, as well as the continental shelf at the depocenter receiving its sediment, are influenced by the northeast-trending South Branch Santa Ynez fault, which comes onshore near the mouth of Gaviota Creek (Fig. 9). The Gaviota Creek shelf depocenter is confined within <10 km of its source, partly because a bathymetric high (centered on 120°22′W; Fig. 10) would hinder transport west of there. West of that, around Point Conception and to the northwest, the shelf again has little sediment above the regional unconformity; our seismic data indicate that sediment from the Santa Ynez River (Fig. 1), which debouches north of Point Conception, does not form thick deposits near Point Conception. Sediment in that region locally interacts with tar seeps to form the mounds shown in Fig. 8 (discussed below).

Efficiency of sediment retention on the shelf

By comparing the total volume of sediment stored on the shelf in this region with estimates of watershed sediment yield, we can estimate the proportion of terrestrial sediment discharge stored on this part of the southern California shelf and thus the efficiency of off-shelf sediment transport. Slater et al. (2002) estimated that ~22 km^3 of upper Pleistocene to Holocene sediment (above the regional unconformity) is presently stored on the shelf between Point Conception and Point Mugu, most of which is in the Ventura and Santa Clara deltas. Using a bulk density range of 1,650–1,750 kg/m^3 for shelf deltaic sediments, Slater's volume estimate is equivalent to 3.63–3.85 × 10^{10} t; for the following calculations, we use this mass based on Slater's volume rather than generate a revised estimate from our data because the base of the Ventura-Santa Clara delta was better resolved by Slater et al. (2002). Suspended-sediment data obtained by Warrick (2002) indicated that under the modern climate regime and before dams were built in the watersheds, the Ventura and Santa Clara Rivers would have delivered an average of ~5.9 × 10^6 t of sediment annually to the ocean. Based on that estimate, given that transgression across the regional unconformity occurred 13–10 ka (Sommerfield and Lee 2003), the sediment mass stored on the shelf above the unconformity between Point Conception and Point Mugu would be equivalent to ~6150–6530 years' worth of sediment discharge from those two rivers; in other words, 47–65% of the late Pleistocene to Holocene sediment yield from the Ventura and Santa Clara watersheds would remain on the shelf today. This estimate does not account for differences in topography between 13 ka and today; watershed size and shape at that time are not known in detail. If transgression in fact began earlier locally (i.e., if sediment immediately above the unconformity in the study area were to be found older than 13 ka), then sediment retention on the shelf would have been less efficient than indicated by the above estimate.

However, because southern California had a wetter climate in Holocene time than today (Sommerfield et al. 2009), using watershed sediment yield measured only during the relatively wet interval 1969–1999 probably allows a more accurate calculation of shelf sediment storage. In those wetter decades, the Ventura and Santa Clara watersheds together yielded an annual average of ~1.5 × 10^7 t, based on measurements from individual smaller basins in which sediment yield varies by two orders of magnitude (Warrick and Mertes 2009). Estimating based on those wetter-decade sediment yields, the sediment mass stored on the shelf above the unconformity between Point Conception and Point Mugu is equivalent to ~2500–2700 years' worth of sediment discharge from the Ventura and Santa Clara Rivers. Additional sediment contributions from small coastal watersheds in the Santa Ynez Mountains have not been precisely quantified, but their total output is far less than that of the Ventura–Santa Clara basins (Warrick 2002). Assuming transgression across the regional unconformity began 13–10 ka, we conclude that ~20–27% of the late Pleistocene to Holocene sediment yield from the Ventura and Santa Clara watersheds remains on the shelf today whereas the majority is stored in deeper basins. This latter estimate is reasonably similar to a sediment budget that was estimated using a radioisotope geochemical record in deposits of the Eel River, a flood-prone watershed on the tectonically active margin of northern California; there, a maximum of 20% of the fluvial sediment supply accumulates on the shelf, with the remainder transported into deeper water (Sommerfield and Nittrouer 1999).

Sedimentation controlled by wave interaction with coastal geometry

The strongest influence on shelf sediment distribution away from the mouths of the three largest coastal watersheds is apparently interaction of wave-driven sediment transport with large-scale (10 km) coastal geometry. Patterns of late Pleistocene to Holocene sedimentation show depocenters opposite broad embayments in the coastline, and thinner or no accumulation opposite topographic headlands such as those formed by Goleta Point, Coal Oil Point, Santa Barbara, and other promontories (Fig. 9). Such a sedimentation pattern indicates that deposition and reworking over much of this shelf are controlled largely by incident-wave refraction. Depocenters that correspond to coastal embayments are thinner than the delta sediments at the mouths of the three largest watersheds, with maximum sediment thickness less than 20 m. This sedimentation pattern, largely controlled by wave interaction with coastal geometry, dominates along >80 km of the coast, ending only where delta sediment from the Santa Ynez River has accumulated (north of ~34°37′N; Slater et al. 2002).

The apparent importance of wave interaction with coastline geometry in controlling sediment distribution on this shelf indicates that time scales of sediment mixing (reworking by waves) are shorter than time scales of accumulation. Although the northern Santa Barbara Channel is sheltered by the Channel Islands, storm wave base must still extend as deep as the entire continental shelf (>100 m) often enough that sediment is redistributed into the depocenters in Fig. 9 well before it becomes too deeply buried to be mobilized by wave energy. This is consistent with estimates of a 10-year recurrence interval in southern California for storms that mobilize sediment across the entire shelf width, whereas inner to middle shelf sediment could be mobilized by storms annually (Wiberg et al. 2002).

Winter storms are the source of both the highest wave energy and greatest fluvial sediment input to the California shelf. Drake et al. (1972), studying the fate of flood sediment from the Ventura and Santa Clara Rivers, found that material moved rapidly northwest from the river mouths, with 70% of flood-delivered sediment initially deposited at depths <30 m. Of that, sand was initially deposited in a belt 1–2 km from shore extending northwest (finer material was distributed more widely); observations of Santa Clara River floods in 1997 and 1998, which involved hyperpycnal sediment transport, also supported this initial depositional pattern concentrated within ~1 km of the river mouth (Warrick et al. 2004).

Warrick et al. (2004) observed that substantial flood-sediment transport on the shelf near the Santa Clara River mouth occurs via nepheloid layers, and inferred that nepheloid layers were likely also the dominant means by which mud moves off-shelf. Similar processes likely operate northwest of the river mouths, though with smaller sediment quantities; over the relatively sediment-starved shelf where we infer wave-controlled distribution of sediment deposits, wave action probably causes nepheloid layers to form that move sediment off-shelf into Santa Barbara Basin by gravity-driven flow, leaving relatively little material to comprise the thin shelf deposits opposite coastal embayments (Fig. 9). Consistent with this, Drake et al. (1972) attributed to wave-induced resuspension and transport their observation that, ~3 years after major floods, fine-sediment distribution on the shelf largely resembled its pre-flood condition. Such rapid wave reworking of flood deposits is characteristic of California shelf processes (cf. Eel River observations and modeling by Wheatcroft et al. 1997; Zhang et al. 1999; Fan et al. 2004). Flood sediment that moves off the shelf into the Santa Barbara Basin forms distinctive gray, fine-grained deposits there. These basin deposits have been used to reconstruct high-resolution records of flood frequency over late Pleistocene to Holocene climatic regimes (Escobedo and Behl 2007). The utility of these deposits for reconstruction of individual flood events further indicates that fluvial sediment has a short residence time on the shelf before moving offshore to the deeper basin.

This seismic data set highlights a unique style of sedimentation: wave reworking of shelf sediment into depocenters controlled by large-scale coastal geometry, on a steep, tectonically active margin. Although small, steep, uplifting coastal watersheds are prolific global sediment producers and this coastline is no exception, this study illustrates how sedimentation evolves in a portion of one such tectonic system that is relatively sediment-starved. Even though this coast is sheltered from the highest incident wave energy, wave interaction with coastal geometry is still the controlling factor in shelf sedimentation away from a few isolated river mouths (nearer the Ventura and Santa Clara river mouths, the influence of currents is evident in the shape of nearshore deltas). That so little recent sediment accumulates on much of the shelf is especially notable given that the erodible lithologies, rapid uplift, and agricultural land use in the Western Transverse Ranges fronting this coastline produce 2–10 times greater sediment yield than occur in surrounding areas of California (Warrick and Mertes 2009). Rather than accumulate on the shelf, sediment largely bypasses this region in favor of longer-term deposition in the deeper Santa Barbara and Santa Monica Basins. Nevertheless, understanding the processes that control sediment distribution over 100 s km^2 scales in such a tectonic setting has implications for how the ancient stratigraphic record of continental shelves is interpreted, and for how hydrocarbon resources may be distributed in relict shelf deposits.

Natural hydrocarbon seeps

As shown in Figs. 7 and 8, seismic-reflection images of the continental shelf in this area allow a detailed look at natural seeps of gaseous and solid hydrocarbons that interact with the upper Pleistocene to Holocene sedimentary package. These hydrocarbons are products of deep burial of Miocene Monterey Formation sedimentary rocks (Normark et al. 2005; Lorenson et al. 2007; Peters et al. 2008), and along some parts of this shelf are commercially extracted. The presence of tar seeps breaching the sea floor as mounds and extrusive features in this area has been known to the research community for some time (Vernon and Slater 1963) although their thickness and extent have not previously been quantified at the level of detail attempted here (Fig. 11).

Natural gas seeps are manifested at the sea surface by plumes of bubbles, some of which cover $>100\ \text{m}^2$ (e.g., Trilogy Seep, Fig. 7), that locally hinder settling and deposition of sediment. Where present, even some gaseous zones that do not breach the sea floor obscure seismic-reflection images of the strata. Pockmarks associated with gas emission are visible in bathymetric images (Eichhubl et al. 2002).

Whereas some of the tar seeps are found in areas of bare rock outcrops at the sea floor (i.e., exposure of the transgressive surface shown in Fig. 10 that forms the regional shelf unconformity), many active seeps occur as mounds that consist of tar and sediment (Seanz 2002). The mounds, which form bathymetric highs surrounded by unconsolidated sediment, range in size from a few meters across to large accumulations that can exceed 1 km in width and 5 m in height above the sea floor. Within the study area they occur primarily south and west of Point Conception, where numerous tar seeps are active and cover an irregular area of approximately 8.5 km^2; one tar seep alone there reaches a maximum thickness of 10 m and covers ~2 km^2. Figure 11 shows the minimum thickness of all tar deposits mapped in the vicinity of Point Conception, obtained by analyzing the Chirp records discussed here, side-scan sonar data (Normark et al. 2003, 2005), and multibeam imagery of the seafloor. We estimate the minimum thickness of each tar mound to be the difference between its height above the sea floor and the (time-converted) sea-floor depth. Areal extent of each mound (Fig. 11) was estimated from its appearance on side-scan images and its length on the Chirp record. The entire volume of tar and sand represented by the area in Fig. 11 is estimated to be $31 \times 10^6\ \text{m}^3 \pm 20\%$, a volume equivalent to 26×10^7 barrels of crude oil.

The locations and abundance of hydrocarbon seeps in the northwestern Santa Barbara Channel are significant not only because of their resource potential but also because active venting of natural gas in this region, which is controlled by subsurface structure—fault and fold geometry—can be a contributing factor in the genesis of tsunamis (Eichhubl and Boles 2000; Eichhubl et al. 2002). Tsunamis, several of which have occurred in historic times along the Santa Barbara coast, can be triggered by earthquakes and landslides particularly on slopes destabilized by hydrocarbon fluid flux; the potential for future tsunamis is of concern in this region (Fisher et al. 2005; Greene et al. 2006).

Conclusions

High-resolution seismic-reflection profiles on the southern California continental shelf between Ventura and Point Conception illustrate 10 s-km-scale patterns of late Pleistocene to Holocene sedimentation along this steep, tectonically active margin that is important to many tectonic and climatic investigations. Since late Pleistocene time, sediment has accumulated locally on a transgressive surface that forms a regional unconformity on this shelf; in some areas, interaction of the young sedimentary package with natural gas and tar seeps is apparent. Northwest of the Ventura and Santa Clara River mouths, which provide the largest regional sediment source and form connected deltas, shelf sedimentation is largely controlled by the interaction of wave energy with coastline geometry. Depocenters containing sediment <20 m thick exist opposite broad coastal embayments, whereas relict material (bedrock beneath the regional unconformity) is exposed at the seafloor opposite coastal headlands.

Although steep, rapidly uplifting coasts such as this are prolific sediment-producing areas that contribute significantly to the global sediment budget, this study provides an example of relative sediment starvation within such a system. The shelf in this region is largely a zone of sediment bypass, with as much as 80% of fluvial sediment moving off-shelf into the deeper Santa Barbara Basin (and also, particularly the sand fraction, transport into the Santa Monica Basin via Hueneme submarine canyon). Understanding the factors that control sediment dispersal in such a setting is necessary for accurate interpretation of the stratigraphic record along relict active and transform margins, with implications for tracing associated hydrocarbon resources.

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