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Late Pleistocene channel–levee development on Monterey submarine fan, central California

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Abstract Much of the modern upper (proximal) Monterey fan is a channel–levee complex, the Upper Turbidite Sequence (UTS), that was deeply eroded after the channel breached a volcanic ridge to reach a deeper base level. Ages of sediment samples collected with the ALVIN submersible from the deepest outcrop within the channel–levee system, 390 m below the adjacent western levee crest, indicate that the UTS deposits accumulated at $\geq 1\ \mathrm{m\,ka^{-1}}$ during the last 500 ka. Neogene and Early Pleistocene sediment accumulation on the fan prior to the UTS was much slower ($<0.03\ \mathrm{m\,ka^{-1}}$), and underlying turbidite systems(?) had substantially different morphologic expression(s).

Introduction

The morphology of the upper Monterey fan is dominated by large-scale fan valleys, only one of which currently has a continuous gradient to a depositional lobe area (Fig. 1). The growth pattern of the fan has been investigated primarily through interpretation of seismic-reflection profiles and of side-scan sonar images that include both deep-tow high-resolution data and long-range GLORIA sonographs (Normark 1970; Hess and Normark 1976; Normark et al. 1985; EEZ-SCAN 84 Scientific Staff 1986; Gardner et al. 1991, 1996). These data indicate that shifts have occurred in the locus of deposition for mid- and lower-fan areas, as well as marked changes in the geometry of the channels on the upper fan. These "autocyclic" shifts cause changes in the surface morphology of the fan as depressions on the ocean crust are filled and elevated channel–levee complexes grow. Channel growth and possible channel piracy are thus key processes that control the morphology of the fan (Normark and Hess 1980; Normark and Gutmacher 1989). Erosional deepening of major fan valleys on the upper fan are related to changes in the position of the Monterey Canyon head as it migrates across the shelf in response to relative sea-level change and to a lowering of the base level for deposition on the lower fan (Normark 1970; Normark and Hess 1980). In this paper, the term "fan valley" is used with reference to specific, previously named features, e.g., Ascension fan valley, and the more generic term "channel–levee complex" is used when describing channel characteristics of, and depositional processes within, the larger fan valleys and their extensive overbank deposits.

The sequence of the changes in growth pattern for Monterey fan were mainly inferred from seismic-reflection and side-scan-sonar data, but the timing of these changes remains speculative without age control. No scientific drill sites exist that would allow direct determination of pre-Holocene sediment accumulation rates on the fan. The purpose of this study is to review existing interpretations of channel–levee development on the upper fan in light of an age constraint based on samples obtained with the submersible ALVIN in 1988. The dive samples are from an outcrop at the base of the western levee of the main channel–levee system (e.g., the Monterey fan valley; Fig. 1), within the area of maximum erosional downcutting on Monterey fan, and are used to establish the time frame for deposition and subsequent erosional deepening within the upper part of this channel–levee complex.

Geological setting and perspectives on fan growth rate

Upper Turbidite Sequence

Shepard (1966) delineated a large-scale, horseshoe-shaped meander loop in the main Monterey fan valley, upstream

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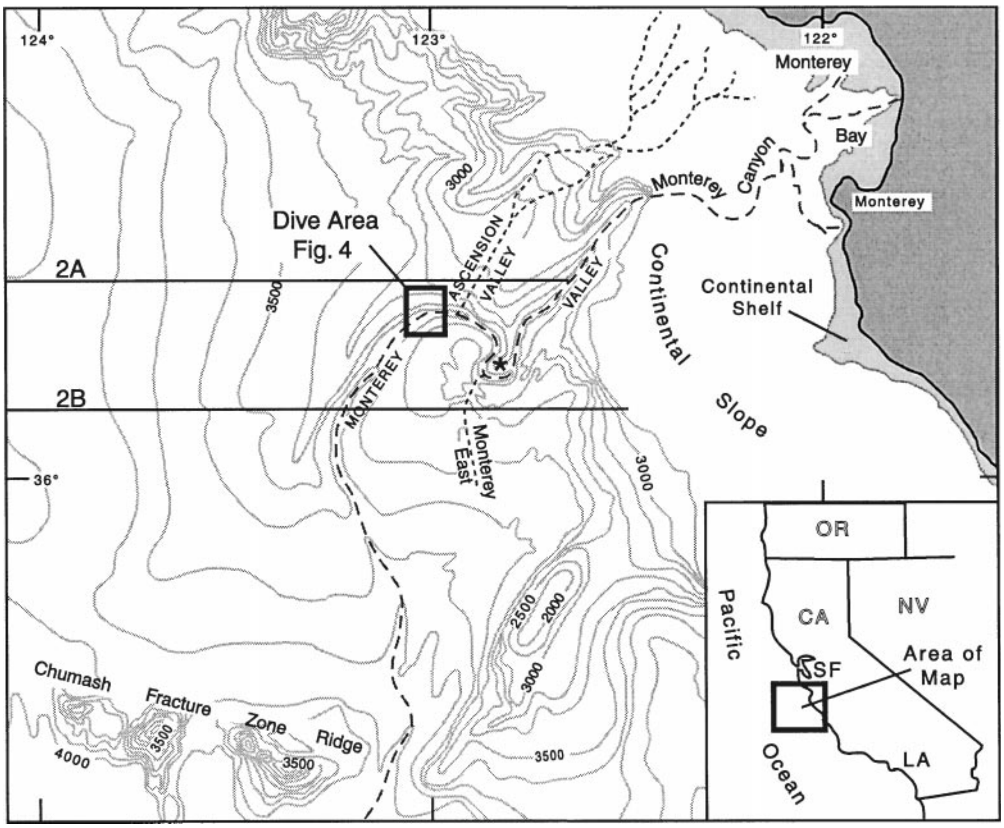

Fig. 1 Generalized bathymetry of the northeastern part of Monterey fan showing the valley systems. Open box shows the dive area detailed in Fig. 4. Tracklines for seismic-reflection profiles of Fig. 2 that bracket the study area are shown. Star denotes the center of the large horseshoe-shaped meander. Modified from Normark et al. (1980)

from its confluence with the Ascension fan valley. Normark (1970) obtained seismic-reflection profiles in the area of the meander that showed turbidite deposition in the upper part of the sediment pile to involve two separate leveed–channel systems (Fig. 1). Subsequent deeper-penetration seismic-reflection data show that the distinctive turbidite depositional characters are generally most common in the upper part of the sediment column east of 124°W longitude (Fig. 1) (Normark and Gutmacher 1989; Normark et al. 1985; EEZ-SCAN 84 Scientific Staff 1986). This dominantly turbiditic interval is denoted as the Upper Turbidite Sequence (UTS), and its morphologic expression dominates the upper fan (Fig. 2). The UTS is as much as 500 m thick under the western levee crest of the Monterey and Ascension valleys on the upper fan, but it thins radially downfan. The UTS wedges out (downlaps) on older sediment 70–90 km west of the levee crest of Monterey fan valley (Figs. 1 and 2A and B). The UTS thins to less than 150 m just north of the Chumash Fracture Zone (CFZ). Farther west, available seismic-reflection profiles suggest that older (pre-UTS) turbidite intervals came from a more northerly source than the Ascension and Monterey Canyon systems (Fildani 1993). The sediment underlying the UTS includes both turbiditic and acoustically transparent intervals (Fig. 2C and D).

The present relief of the UTS is dominated by the fan valleys extending from the Monterey and Ascension canyons and by at least one major discontinuous channel–levee feature termed Monterey East (Fig. 1). The relief between levee crest and channel floor along the main Monterey fan valley southwest of the meander loop is nearly 400 m. The truncation of bedding imaged by the seismic-reflection profiles shows that the channel in the area south and west of the horseshoe meander was erosionally deepened by as much as 300 m (Figs. 2 and 3). The erosional deepening is generally limited to the channel reach between the mouth of Monterey Canyon at the base of the continental slope and the CFZ ridge (Fig. 1), and the downcutting probably resulted from headward erosion within the Monterey channel–levee complex. Headward erosion might reflect a lengthening of the Monterey Canyon in response to rising sea level (Normark 1970), but it is more likely that erosion was initiated when turbidity currents were first able to flow directly to the deeper sea floor south of the CFZ (Normark and Hess 1980).

Another estimation of the depth of erosional downcutting southwest of the horseshoe meander is based on a comparison between the levee-crest/channel-floor relief of the Ascension and Monterey fan valleys north and south of their confluence. The western levee of the Ascension fan valley forms a single, continuous sedimentary ridge with the western levee of the Monterey fan valley below their confluence (Fig. 1). The width, thickness, and internal structure of the levee sequence, as well as the down-channel depth profile along the levee crest, show no

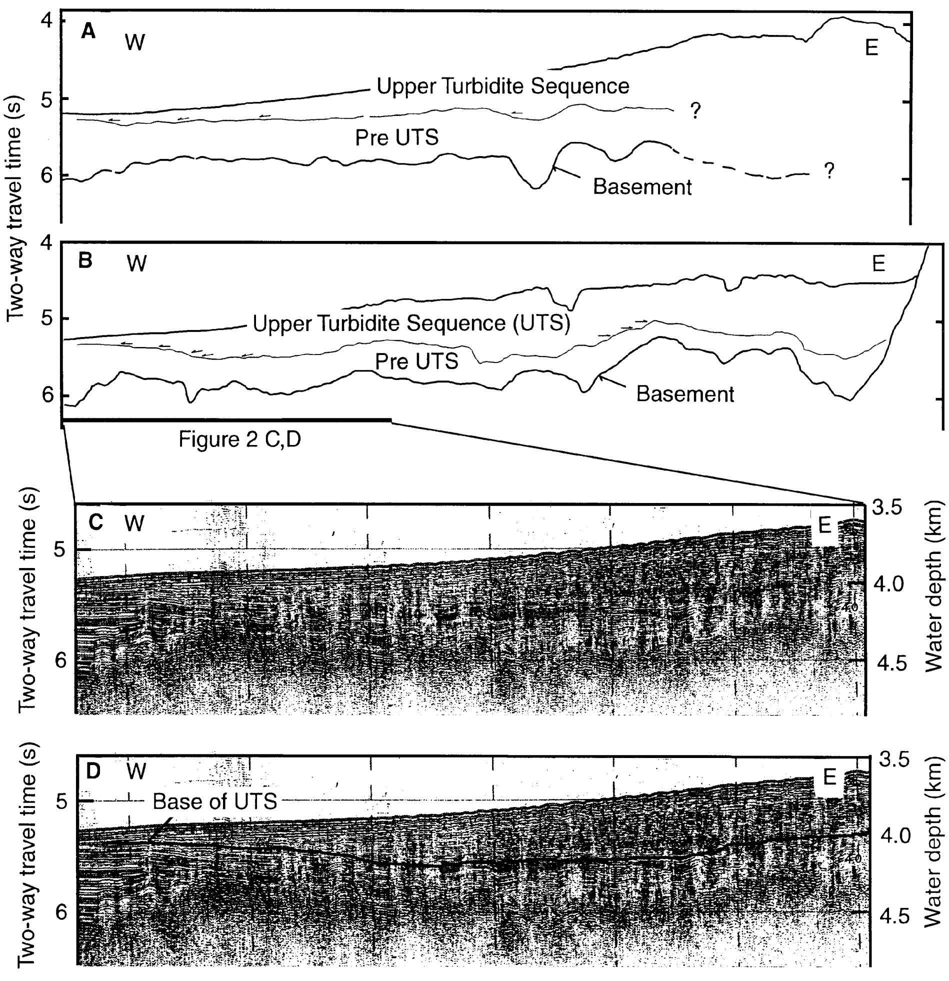

Fig. 2A, B Simplified line drawings showing sea floor, base of the Upper Turbidite Sequence (UTS), and top of the oceanic crust on east–west seismic-reflection profiles that bracket the study area and illustrate the pronounced westward-thinning wedge of UTS turbidite deposits. Profile locations shown in Fig. 1. **C** Segment of seismic-reflection profile in 2B showing difference in acoustic character between UTS wedge and the underlying sequence. **D** Profile of **C** with base of UTS denoted. **C** and **D** are adapted from EEZ-SCAN 84 Scientific Staff (1986)

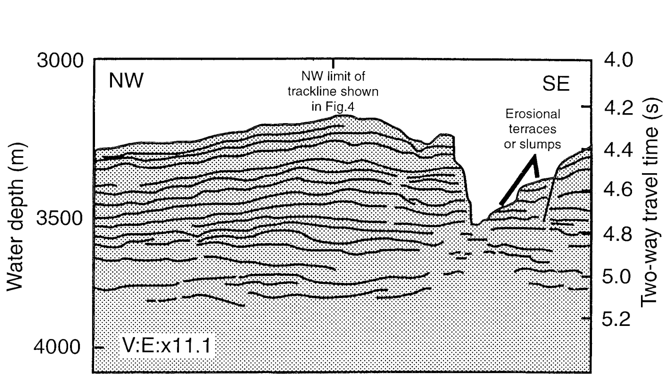

Fig. 3 Line drawing of the only seismic-reflection profile across the Monterey fan valley within the area of ALVIN dive 2124 showing the steep west wall exposing the UTS strata. The terracelike features on the eastern wall might have formed as a result of slumping of the channel–levee margin as a result of the erosional down-cutting. See Fig. 4 for location.

major changes at the confluence of the channel axes of the two systems. This relationship suggests that the valley extending from Monterey Canyon now occupies the lower reaches of what was a channel-levee system extending from the Ascension Canyon (Normark 1970). The cross-channel profile of the Ascension fan valley is assumed to be unaffected by erosional downcutting because this valley enters the Monterey fan valley as a hanging tributary; the only erosional feature in the Ascension valley is a small thalweg channel that has been downcut by headward erosion from the point of confluence (Hess and Normark 1976; Embley et al. 1990). These observations on the form and internal structure of the levees, together with the depth of incision (150 m) of the Ascension fan-valley thalweg, which enters the Monterey fan-valley as a hanging tributary with 100 m of relief, suggest that a minimum of 250 m of down-cutting in the Monterey fan valley has occurred since piracy.

A series of broad terraces occurs on the eastern wall of the Monterey fan valley (Fig. 3). It is not clear whether the terraces are formed entirely as erosional remnants or might, in part, result from rotational slumps. Multibeam bathymetric mapping shows that the steep western channel wall appears to be a continuous slope in most areas with no, or only a few, narrow terraces. Reentrants above 3300-m water depth suggest the oversteepened levee has failed locally (e.g., northeast of the dive track shown in

Fig. 4). The apparent preferential erosion along the western wall suggests that the outcrops observed from the submersible probably expose overbank deposits of the combined Monterey–Ascension levee rather than channel-floor deposits.

Age of Monterey fan

The maximum age of the sea floor underlying the Monterey fan complex is about 20 Ma based on the magnetic-anomaly pattern preserved in the oceanic crust (Atwater 1989; Atwater and Severinghaus 1989). This age limits the initiation of sedimentation for the area near the fan apex to about 20 Ma for the area north of the CFZ (Chase et al. 1975). A substantial grid of seismic-reflection profiles (Fig. 1 in Normark and Gutmacher 1989 and EEZ-SCAN 84 Scientific Staff 1986) shows that the upper fan is generally less than 1 km thick except near the fan apex and in local basement depressions, e.g., a trough forming the northern limit of the CFZ. The acoustic character of sediment imaged in seismic-reflection profiles shows a pelagic interval on the oceanic basement with turbidite deposition becoming more common up-section (Normark and Gutmacher 1989; Fildani 1993). The long-term average sedimentation rate over most of the fan area includes both pelagic and turbiditic sequences and is generally less than 5 cm ka^{-1} (i.e., ≤ 1 km in 20 Ma). Assuming that pelagic sedimentation began shortly after the sea floor was formed, this long-term sedimentation rate is surprisingly low for a depositional setting along a tectonically active continental margin.

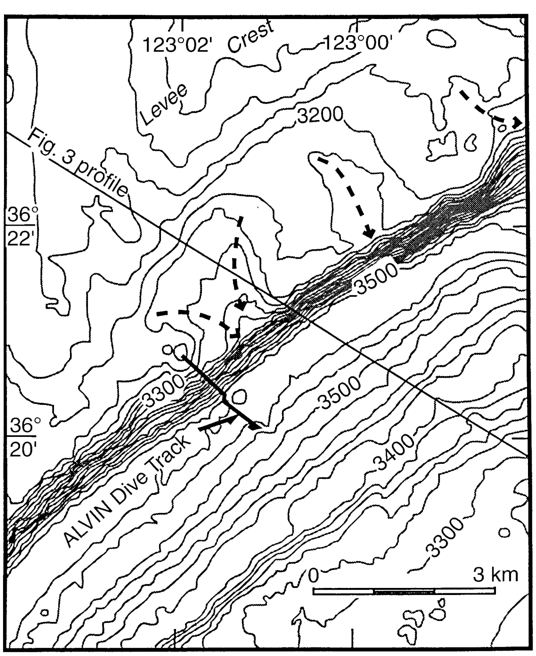

Fig. 4 Detailed bathymetry of the Monterey fan valley floor and west wall showing the trackline (bold line) for ALVIN dive 2124. Location for the seismic-reflection profile of Fig. 3 is also given. The dashed arrows denote possible mass failure scars on the upper, less consolidated section of the Monterey fan–valley levee. Bathymetry derived from multibeam sounding data from the National Oceanic and Atmospheric Administration

Piston-core and long gravity-core samples along a transect across the higher (and thicker) western levee of the Monterey upper fan valley shows that the Holocene/Pleistocene boundary lies 2.5–4 m below the fan surface (Brunner and Normark 1985; Brunner and Ledbetter 1987; McGann and Brunner 1988; McGann 1990). The Holocene sedimentation rate for the upper fan western levee is thus 23–36 cm ka^{-1}, substantially higher than the average long-term rate (~ 5 cm ka^{-1}) for the entire sediment accumulation under the levee. All of the sediment sequence overlying oceanic crust could have been deposited in only 3 or 4 Ma at the Holocene rate. Thus, comparison of the Holocene rate for levee growth with the overall average rate for sedimentation on the oceanic crust underlying the upper Monterey fan area suggests that a relatively young turbidite system rests on a pelagic and/or hemipelagic sequence that is locally interbedded with turbidites.

New data

Submersible observations

In 1988, a series of ALVIN submersible dives allowed direct observation and controlled sampling of the Monterey Canyon and associated fan valleys (Eittreim et al. 1989). Cold-water seeps were commonly observed on the valley floors near the erosional channel walls (Embley et al. 1990). Deep-tow camera data and water-depth profiles provided additional geologic observations from the vicinity of the submersible dives (McHugh et al. 1992).

ALVIN dive 2124 crossed the Monterey fan valley in the area of the greatest erosional relief on the upper fan (Figs. 4 and 5). The dive transect started over the edge of the deepest terrace on the east side of the valley and trended directly across the valley floor to the base of the west wall at a depth of about 3560 m. At this locality, the lowermost 8 m of the valley wall is a vertical scarp exposing parallel bedded, dominantly silty turbidites (Fig. 6A and B). Bed thickness generally is 5–20 cm. Locally, large-scale cross bedding was observed, suggesting some coarser units (Fig. 6B). A 150-m-long transect along the basal scarp showed no major changes in scarp height or bedding characters.

Three in situ samples were recovered from the lowest meter of the channel wall, using the submersible's two manipulators and several tools. Two additional samples were taken from a mound that is interpreted to be an erosional "stack", which protrudes about 1 m above the channel floor near the base of the scarp (Table 1).

The dive transect continued up the western wall of the valley across two more vertical scarps, 13 m and 33 m in

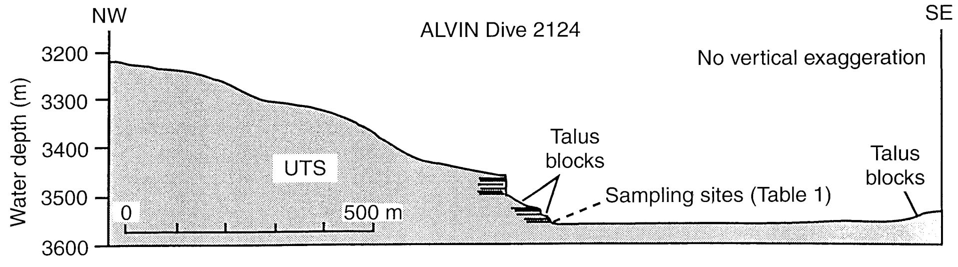

Fig. 5 Bathymetric profile along dive transect constructed from the pressure-depth record and acoustic altimeter data from the ALVIN submersible and keyed to the multibeam bathymetry in Fig. 4. The lower 100 m of relief on the west wall of the leveed valley is in indurated sediment resulting in vertical scarps separated by sloping terraces overlain with talus blocks (see Fig. 6)

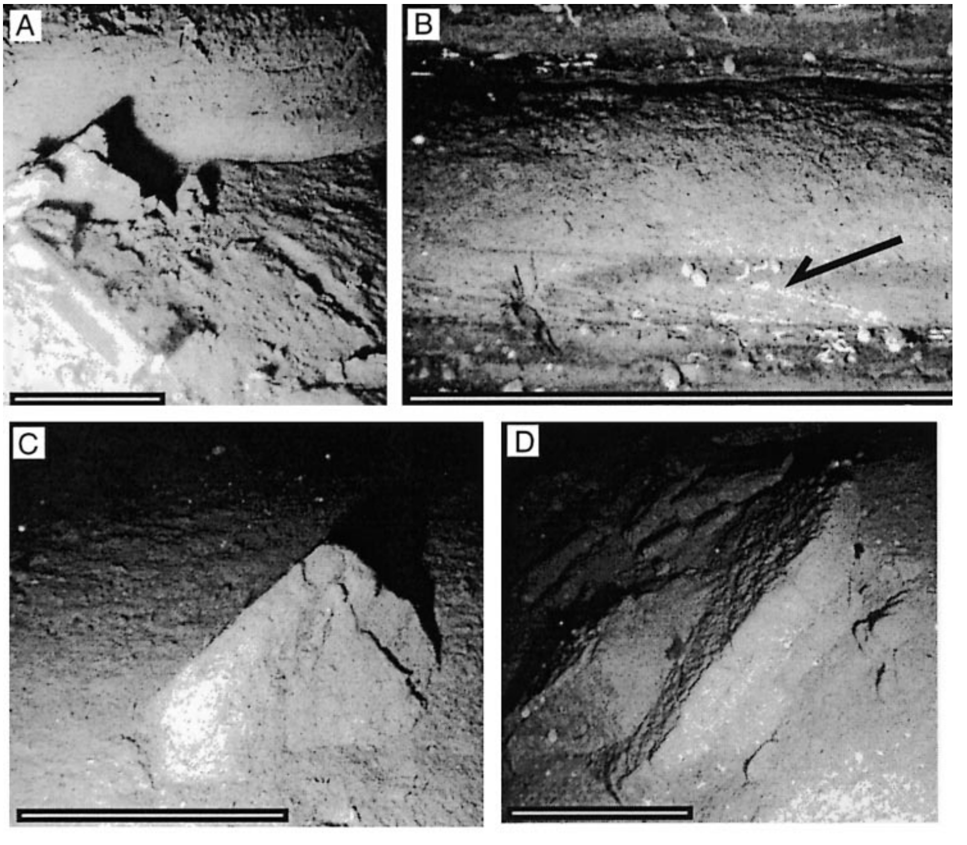

Fig. 6A–D Photographs of the western wall of the Monterey fan valley from ALVIN dive 2124. All scale bars are 50 cm. **A** Outcrop at base of vertical wall about 2 m above the floor of the valley. The reflective tube in the lower left corner is a plastic push-core barrel that was broken off during an attempt to core the channel wall sediment. **B** Close-up of a cross-bedded interval (arrow) exposed in the wall above the valley floor. **C** and **D** Talus blocks on slope between vertical scarps (see Fig. 5)

relief, respectively (Fig. 5). These higher scarps also expose horizontally bedded sediment and confirm the erosional down-cutting of at least the lower 100 m of the valley. The exposed vertical scarps are separated by steeply sloping terraces littered with angular, slablike talus blocks as much as several meters in length that are thinly covered by loose muddy sediment (Fig. 6C and D). Above the uppermost exposed vertical scarp (Fig. 5), gently sloping terraces separate two steeper areas with slopes generally between 10° and 20°. These steeper slopes clearly exceed typical levee-depositional slopes of only a few degrees and are consistent with erosional down-cutting of this depth interval as well. The bathymetric map shows that the dive terminated over a local bathymetric crest that might have formed, in part, as a result of local slope failure of the inner levee crest (Figs. 3 and 4).

Samples

The outcrop samples from dive 2124 are from a stratigraphic interval that correlates generally with the middle or lower half of the UTS. We used ALVIN's manipulators with various tools to collect cores, "rock" fragments, and small blocks from the base of the west wall of the main channel (Table 1). The larger samples were pried from the wall and caught with a scoop net or picked up from the channel floor. Thin (1–2 cm), silty fine sand, sandy silt, and graded silt beds are interbedded with thicker (to 7 cm) silty clay beds (mudstones). The samples were generally firm and friable, which explains the difficulty in recovering either cores or large pieces, although some of the silty claystone samples resembled very stiff modeling clay. Samples 2R and 3 C were from the erosional stack that is

Table 1 Samples from ALVIN dive 2124 showing sample type, size, lithology, and age limits based on biostratigraphic control

ALVIN sample ID	Type of sample	Size and lithology	Age limits
2124-2R	Piece broken from a 1-m-high mound adjacent to base of channel wall	Small, nearly tabular block (10 × 4.5 × 3 cm thick) of mudstone (silty claystone) with silty blebs; one sandy clast (4 × 8 × 20 mm)	(Not submitted for micro-paleontologic examination)
2124-3C	Push core from the 1-m-high mound adjacent to base of channel wall	5-cm-long friable sandy-silt with 1-cm-thick silty sand; core axis was approximately normal to bed contact	Late Pleistocene[a]
2124-4N	Push core into channel wall failed but broke off small fragments	Small piece (~10 × 5 × 5 cm) of silty, very fine sand	(Not submitted for micro-paleontologic examination)
2124-5N	Scoop net used to catch blocks pried from wall with ALVIN manipulater	Two blocks both about 20 × 10 × 10 cm consisting primarily of silty claystone (mudstone) with common mica flakes	Latest Quaternary, less than 300 ka[b]
2124-6R	Block of sediment that was fresh talus created by multiple attempts to sample the channel wall	Beding within block (18 × 8 × 9 cm) is perpendicular to the 9-cm-long edge of block and shows a 7-cm-thick mudstone unit with irregular silty/fine-sand blebs that overlies (?) a 2-cm-thick graded silt bed	Late Pleistocene[a] latest Quaternary, less than 300 ka[b]

[a]J. C. Ingle, Jr., written communication, 21 December 1988.
[b]J. A. Barron, written communication, 22 December 1988.

adjacent to the channel wall; its relation to the in situ wall rock is uncertain, but the thickness and attitude of the bedding and the lithologic and age characteristics are similar to the adjacent wall samples (Table 1).

Three of the larger and muddier samples obtained from the base of the valley wall were selected for biostratigraphic analysis. The three samples were washed and scraped to remove any possible contamination from younger sediment that might have fallen from higher up the wall. Diatom assemblages from two of the samples indicate an age of less than 300 ka and deposition during a cold-water period; the third sample contained poorly preserved diatoms that provided no age control (J. Barron, written communication 1988). This age constraint indicates that the sediment could be no older than the low sea-level interval of isotopic stage 8, or about 250–280 ka (Chappel and Shackleton 1986; Martinson et al. 1987). The foraminifer assemblage indicates a late Middle Pleistocene age based on the exclusively sinistral population of *N. pachyderma* together with the lack of radiolarian tests (J. C. Ingle, Jr., written communication 1988). The remaining sample splits were examined by C. A. Brunner (oral communication 1988), who confirmed a late Middle Pleistocene age for the material.

The presence of shallow-water benthic foraminifers, fragments of molluscan shells, and rare glauconite pellets document resedimentation of detritus from shelf and upper bathyal depths (J. C. Ingle, Jr., written communication 1988). Preservation of the calcareous tests further indicates rapid burial at the present sample depth, which is near the carbonate compensation limit. These characteristics are consistent with the presumed rapid turbidite deposition of the UTS levee sequence.

Implications for channel–levee development

Neither thick, coarse sand beds nor gravel were observed or sampled anywhere along the outcrops traversed during the dive, as would be expected if the valley wall was cut into channel-fill material. The outcrop observations are consistent both with the truncation of an overbank sequence as interpreted from the seismic-reflection profiles and with morphologic considerations that suggest that erosional down-cutting in the dive area was at least 250 m and might be as much as 300 m.

Rates of sediment accumulation and timing of erosional down-cutting

The UTS is a large channel–levee complex than includes at least three major channel features and covers 10^4 km^2 of the upper Monterey fan (Fig. 7). It is difficult to estimate how much of the sediment supplied to the fan during UTS time might have bypassed the upper fan, but more than half might be south of the CFZ (Fildani 1993). The amount of UTS time-equivalent sediment cannot be unequivocally estimated because (1) the base of the UTS is less distinct east of the Monterey and Ascension fan–valley axes (Fig. 2), and (2) the sandier sediment south of the CFZ does not give similar acoustic signatures on seismic-reflection profiles, so that correlation of seismic stratigraphy on the lower fan with the UTS levee wedge on the upper fan is difficult (Hess and Normark 1976; Normark et al. 1985; Normark and Gutmacher 1989; Fildani 1993).

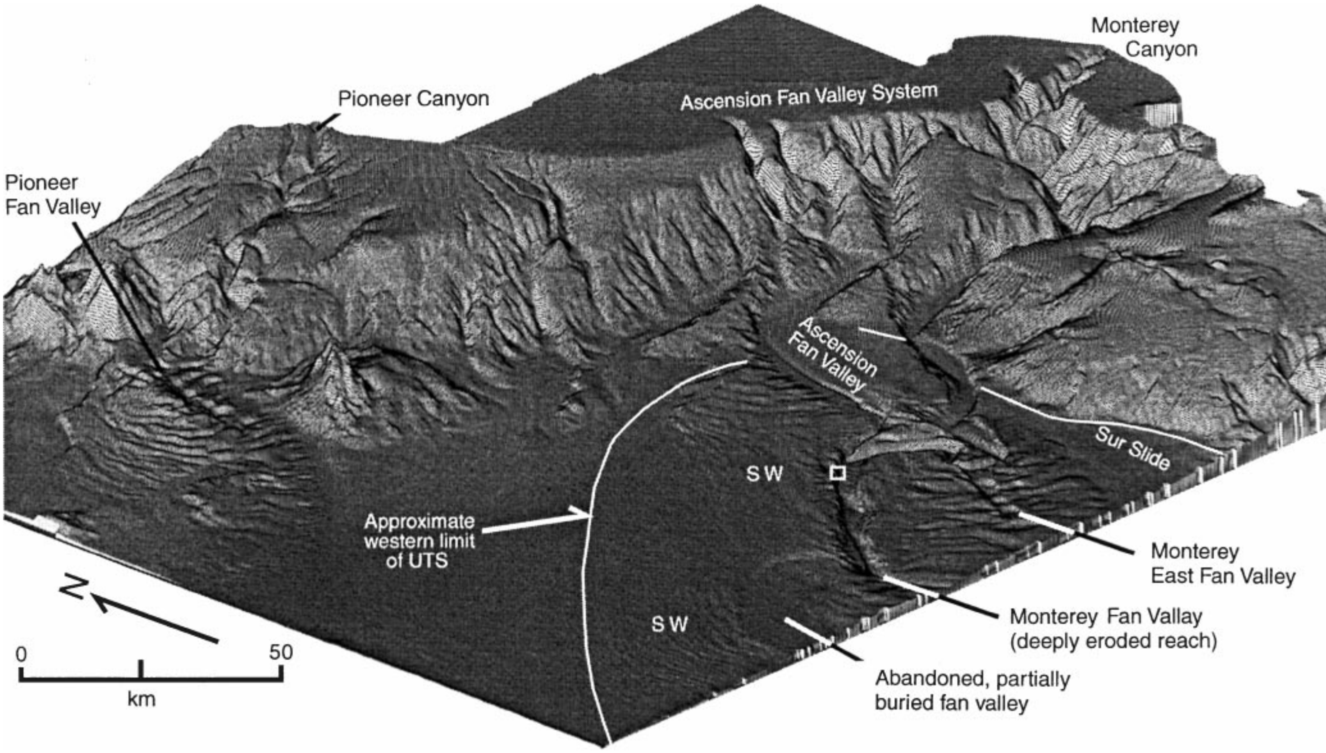

Fig. 7 Perspective view of the California continental margin offshore Monterey Bay showing the canyon systems along the central California margin; view is to the northeast (based on multibeam sounding data from the National Oceanic and Atmospheric Administration; modified from Greene and Hicks 1990). The approximate western limit of the UTS is shown by the solid curving line (segmented along the base of the slope). Small box shows the study area for the ALVIN dive. SW = sediment-wave field. The Pioneer channel–levee system is very similar in appearance to the upper Monterey fan, perhaps indicating that the Pioneer fan also went through an episode of rapid growth. The head of Pioneer Canyon most likely would have been able to intercept the same source of sediment moving south in the littoral system, at least during intervals of lower sea level

The paleontologic age estimates for the outcrop samples indicate that they were deposited during a cold-water interval no older than isotopic stage 8, about 250–280 ka (Martinson et al. 1987). Based on this, the average sediment accumulation rate for the levee sequence stratigraphically above the sampled outcrop approaches 1 m ka^{-1} (250 m in 250–280 ka). If the lower part of the UTS was deposited at rates comparable to that of the average rate for sediment above the sampled outcrops (and assuming the outcrop samples are from isotopic stage 8), then the entire UTS ($\sim$500 m maximum thickness) could have been deposited in about 500 ka. If the outcrop samples are from a cold-water interval younger than isotopic stage 8, then the accumulation rate is even higher, e.g., if the outcrops are of stage 6 (125–180 ka), then the accumulation rate is 2.8–4 m ka^{-1} and the entire UTS could be as young as 250 ka.

The relative youth of the UTS implies very low long-term sedimentation rates for the underlying sediment on the upper Monterey fan. Using the oldest possible age for the base of the UTS (isotopic stage 8), the sediment underlying the UTS was deposited at long-term rates generally < 0.03 m ka^{-1}, i.e., ± 500 m of sediment was deposited in about 20 Ma. The sediment deposited on the oceanic crust that underlies the UTS exhibits acoustic signatures indicative of pelagic sediment interbedded locally with turbiditic intervals (Fildani 1993). Without direct dating, the average long-term rate is assumed to overestimate the pelagic accumulation rate and is much lower than the rate for the presumed turbidite intervals. Nevertheless, the rapid development of the UTS turbidite system of the Monterey fan suggests that major changes in the source area(s), transport path(s), and/or climatic effects (including those of sea-level changes) along the central California margin occurred about 500 ka BP.

The accumulation rates determined above for the UTS, however, would be too low if the channel erosion occurred as a separate phase of activity after deposition of the UTS had generally stopped or greatly slowed because of the length of time required to down-cut approximately 250 m after deposition of the levee section. For example, if the down-cutting of the valley occurred predominantly during intervals of lower sea level since isotopic stage 5, then the UTS section above the sampled outcrop was deposited in only 175–205 ka (the time between the oldest possible initiation of deposition of the sample horizon was during isotopic stage 8 and onset of erosion after stage 5) for an accumulation rate ≤ 1.4 m ka^{-1}.

The arguments above indicate that a reasonable accumulation rate for the UTS is about 1 m ka^{-1} and that the entire UTS sequence is on the order of half a million years old. Unfortunately, there are insufficient data to determine how much levee aggradation occurred during erosional deepening of the valley floor. The current levee-crest/channel-floor relief of 390 m is the result of both erosional down-cutting as well as continuing deposition on the levee. Larger turbidity currents are still capable of depositing thin sand and silt beds on the levee crest despite the great channel relief; e.g., Holocene deposition (2.5–4 m of sediment that includes turbidite beds) alone accounts for some of the syn- or posterosional relief difference between the valley floor and levee crest (Brunner and Normark 1985).

Lacking direct information on the initiation of large-scale erosion within the Monterey fan–valley systems, the following discussion assumes that erosion commenced not necessarily because of a change in the rate or composition of the sediment supply but because of a change to a lower base level resulting in headward erosion within the existing channels. Sediment that initially accumulated in the large channel–levee complexes of the UTS now generally bypasses the upper fan to reach the lower fan area south of the CFZ and is deposited in the lobe area described by Gardner et al. (1991, 1996). Because Holocene turbidity currents have been able to deposit sandy sediment nearly 400 m above the channel floor on the western levee (Brunner and Normark 1985), it is almost certain that turbidity currents in the latest Quaternary have been aggrading the overbank/levee areas while erosion of the channel floor continues.

UTS growth: causes for changes in sediment accumulation

As noted earlier, the recent and rapid development of the UTS represents the development of the modern Monterey fan during the last $\sim$500 ka. Possible factors that would result in such a marked change in sedimentation include new source area(s), new transport path(s), and/or climatic effects, including sea-level changes and/or increased erosion and runoff, along the central California margin. The Ascension Canyon and, to a lesser extent, the Monterey Canyon systems are the conduits for sediment transported to the UTS. Ascension Canyon is a complex of coalescing small canyons forming a line source on the upper continental slope and shelf edge (Figs. 1 and 7), and at least one of its tributary heads was eroded in Late Miocene and Pliocene time (Nagel et al. 1986). The multiple heads of Ascension Canyon, which extend more than 30 km along the upper slope and outer shelf (Fig. 1), probably formed as the distal portions of the Monterey Canyon and were moved progressively to the northwest as a result of strike-slip fault displacement (Nagel et al. 1986). Using their rates of displacement, the Ascension Canyon has moved northwest only about 5 km since UTS deposition began. Thus, the modern transport paths for sediment moving to the UTS existed long before the UTS began to form.

Second, it is difficult to see how changes in sea level alone could account for such a sudden change in the rate of sediment supply to the upper Monterey fan area. The late Pleistocene was characterized by fluctuations of eustatic sea level of similar magnitude both during and prior to the UTS deposition. Furthermore, Normark and Hess (1980) suggested that the main effect of sea-level change on sediment supply to the Monterey fan is in switching sediment input between Monterey and Ascension canyons. At low sea level, sediment transported southward in littoral drift can move into Ascension Canyon, which heads on the upper slope and outer shelf; during high stands of sea level, this sediment supply would bypass the Ascension Canyon and move southward to be intercepted by the Monterey Canyon, which (with its tributary canyons) cuts across the shelf to near the surf zone (Figs. 1 and 7).

At present, the volume of sediment entering the central California coastal region is not sufficient to account for the rate at which the UTS accumulated. Comprehensive quantitative estimates for the volume of sediment annually transported in the littoral drift cells of central California have not been determined, but Dingler et al. (1985) suggest $0.5 \times 10^6\ m^3\ yr^{-1}$ for sand-only transport in littoral drift at the head of Monterey Canyon. The dimensions given earlier for the more morphologically prominent part of the UTS component of the western levee of the combined Ascension and Monterey fan valleys yield a volume of $1.02 \times 10^{12}\ m^3$. Even assuming that all of the sediment moving past the head of Monterey Canyon found its way to the UTS, it would still take 4 Ma to deposit just the western levee component (which is probably less than half of the sediment deposited during UTS time). For comparison, this rate is equivalent to the measured Holocene accumulation on the Monterey levee noted above.

The above arguments suggest that the UTS is from a source significantly larger in volume than presently observed coastal sources. The initiation of UTS deposition primarily reflects a change in source area(s) rather than either changes in sediment pathways to the fan or the effects of sea-level fluctuations. Sarna-Wojcicki et al. (1985) use dated ash beds to establish the sedimentation history of the Great Valley of California, which is the most probable source for large volumes of sediment entering the littoral drift system that reaches Monterey Bay. Their study indicates that the Great Valley became emergent about 2 Ma BP and that a southerly outlet to the ocean was cut off shortly thereafter. At about 600 ka BP, a northerly drainage from the Great Valley to the ocean was established in the vicinity San Francisco Bay. In a more detailed study of the Pleistocene deposits of the Great Valley of California, Davis and Coplen (1989) argue that the through-flowing drainage was established at 615 ka when the 13,000 km^2 area of Lake Corcoran was drained. Shlemon and Begg (1975) show that in the Late Quaternary, subsidence of the Sacramento–San Joaquin delta in the Great Valley, probably along a fault along the western margin of the delta, has resulted in trapping more of the sediment in the Great Valley itself. The modern volume of sediment in the littoral drift system is probably much less than when the Great Valley connection through San Francisco Bay first opened and Lake Corcoran drained. It is possible, therefore, that much of the UTS formed during a relatively short interval in the Late Pleistocene when the new pathway for sediment from the Great Valley was "fully open". Erosional down-cutting leading to significant sediment bypassing on the upper fan and a decrease in sediment supplied from Great Valley sources characterize the latest Pleistocene and Holocene.

Monterey fan growth pattern

The morphologic expression of three large channel–levee systems – Monterey, Ascension, and Monterey East – of the UTS dominates the upper Monterey fan except where the Monterey East fan valley has been buried by the Sur submarine slide (Fig. 7). Only the modern Monterey fan valley forms an uninterrupted transport pathway with a continuous channel gradient without major slope inflections. An older, almost buried, fan valley extends from the westernmost bend of the modern Monterey fan valley near Lat. 36°15′N; overbank deposition from the incised Monterey fan valley has basically isolated this feature. All of these channel–levee systems, including the nearly completely buried channel, show well-developed sediment waves in the levee areas (Fig. 7) (Normark and Gutmacher 1989; Normark et al. 1980).

All four of these large-scale leveed valleys are within the UTS. Although several of these fan valleys might have evolved from earlier channels, the thick overbank deposits that characterize these channel–levee features comprise the UTS. Such large channel–levee features are not observed in the sequence below the UTS. The older channel features are generally smaller in width and relief and lack pronounced levee and overbank deposits (Fildani 1993).

The development of large channel–levee systems, especially with extensive levees tens of kilometers in width, is common to submarine turbidite systems fed by major rivers, e.g., those fed by the Amazon and Mississippi rivers (Bouma et al. 1986; Damuth et al. 1983, 1988; Flood et al. 1995); these fans are dominantly fed by muddy turbidity currents. The broad asymmetric levee of the combined Ascension and Monterey fan valleys is more typical of fans that are fed primarily by large mixed-sediment flows such as those described on the Laurentian and Var fans in the North Atlantic and Mediterranean Sea, respectively (Piper et al. 1985, 1988; Normark and Piper 1991; Piper and Savoye 1993). Normark and Piper (1991) observed, however, that where submarine fans are fed by mixed flows ", . . . there is generally the opportunity for both pure muddy and pure sandy flows . . . . " Well-developed sediment waves on levees are most commonly associated with muddy flows. Although the Monterey fan is presently supplied sediment from small rivers and littoral drift, the UTS represents a brief interval in the overall fan development during which sedimentation rates approached those on fans fed by major rivers, and the sediment supplied was probably more muddy than the modern sediment input.

Conclusions

The most prominent morphologic expression of the Monterey submarine fan is the pronounced relief of the channel–levee complex on the upper fan (Fig. 7). This complex, which is termed the Upper Turbidite Sequence and represents approximately 500 ka of turbidite activity, includes roughly half of the sediment volume of the upper fan deposited at a rate of $\geq 1\ \mathrm{m\,ka^{-1}}$. Thus, the UTS represents only a small fraction (5%) of the time (20 Ma) during which sedimentation has occurred in this area, and the pre-UTS sequence was deposited at a much slower rate ($\leq 0.03\ \mathrm{m\,ka^{-1}}$). The growth pattern of the modern Monterey fan, therefore, has some similarities with turbidite systems fed by major rivers, but it is not representative of earlier turbidite systems that underlie the UTS.

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