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Late Quaternary evolution of channel and lobe complexes of Monterey Fan

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Abstract

The modern Monterey submarine fan, one of the largest deep-water deposits off the western US, is composed of two major turbidite systems: the Neogene Lower Turbidite System (LTS) and the late Quaternary Upper Turbidite System (UTS). The areally extensive LTS is a distal deposit with low-relief, poorly defined channels, overbank, and lower-fan elements. The younger UTS comprises almost half of the total fan volume and was initiated in the late Pleistocene from canyons in the Monterey Bay area. Rapidly prograding high-relief, channel-levee complexes dominated deposition early in the UTS with periodic avulsion events. In the last few 100 ka, much of the sediment bypassed the northern fan as a result of allocyclic controls, and deposition is simultaneously occurring on a sandy lobe with low-relief channels and on an adjacent detached muddier lobe built from reconfinement of overbank flow from the northern high-relief channels. During the relatively short-lived UTS deposition, at least seven different channel types and two lobe types were formed. This study provides a significant reinterpretation of the depositional history of Monterey Fan by incorporating all available unpublished geophysical data.

Keywords: submarine fan; deep-water turbidites; channel–levee complex; detached lobe; depositional processes

1. Introduction

The Monterey Fan lies offshore central California between Monterey Bay and the Murray Fracture Zone (Fig. 1). Even though Menard (1955) and Wilde (1965a,b) recognized that the fan radius was more than 300 km, much of the subsequent published research prior to the last decade has been confined to the northeastern quadrant of the system. Of the 90 sediment cores collected from the fan area prior to the studies of the southern lobe area (Gardner et al., 1991, 1996), only about 20 have been discussed in openly available literature (Hess and Normark, 1976; Brunner and Normark, 1985; Normark et al., 1985; Normark and Gutmacher, 1988). Similarly, the only comprehensive review of available seismic-reflection profiles is provided in two unpublished theses in Italian (Fildani, 1993; Livoti, 1993). Therefore, to understand

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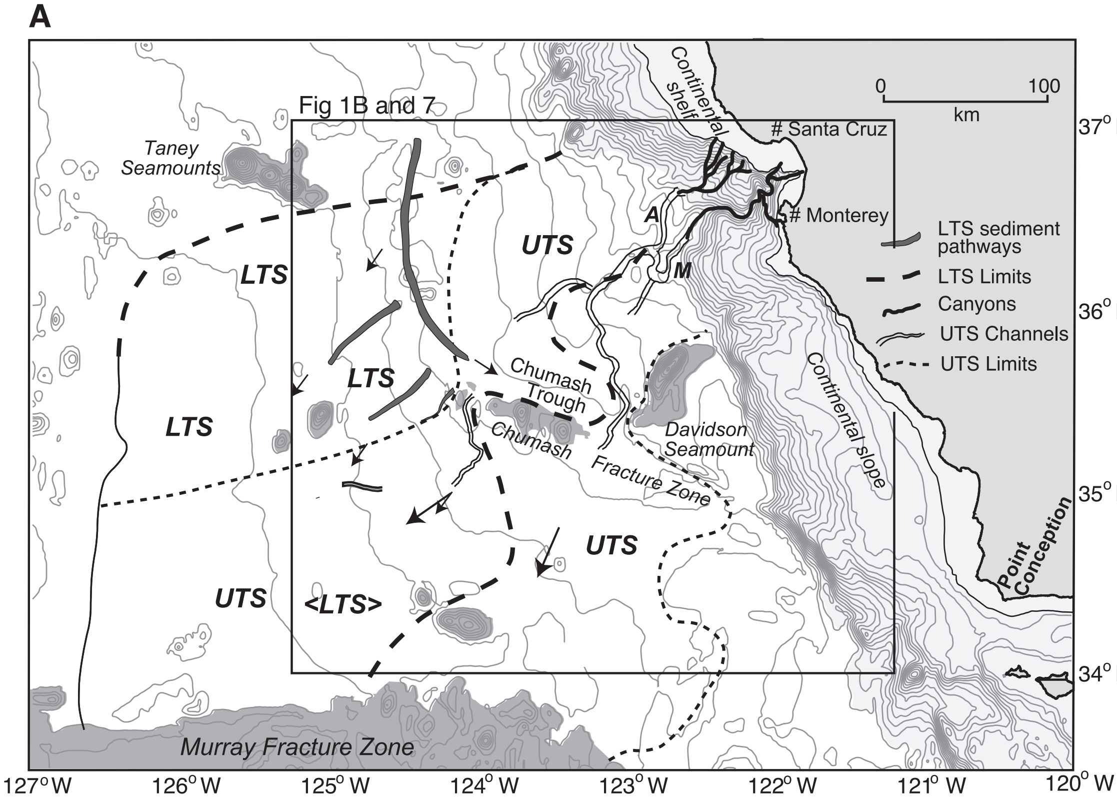
A
Fig 1B and 7
Taney Seamounts
Continental shelf
Santa Cruz
Monterey
0 100 km
LTS sediment pathways
LTS Limits
Canyons
UTS Channels
UTS Limits
UTS
LTS
A
M
Chumash Trough
Chumash
Davidson Seamount
Fracture Zone
Continental slope
Point Conception
<LTS>
Murray Fracture Zone
37° N
36° N
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125° W
124° W
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122° W
121° W
120° W

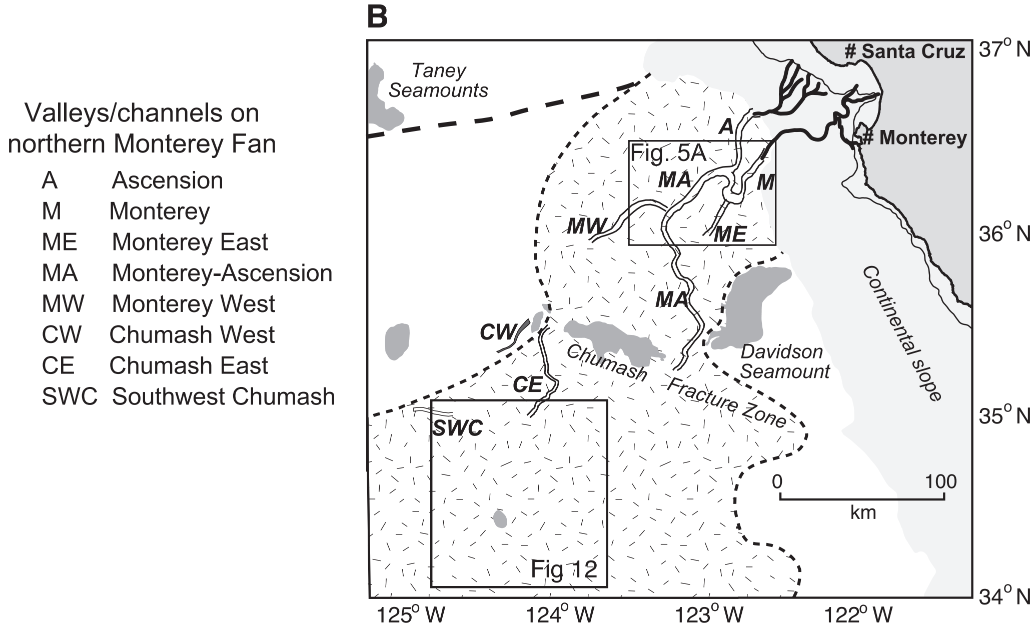
B
Valleys/channels on northern Monterey Fan
A Ascension
M Monterey
ME Monterey East
MA Monterey-Ascension
MW Monterey West
CW Chumash West
CE Chumash East
SWC Southwest Chumash
Taney Seamounts
Santa Cruz
Monterey
Fig. 5A
MA
MW
ME
CW
CE
SWC
Chumash
Fracture Zone
Davidson Seamount
Continental slope
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Fig 12
37° N
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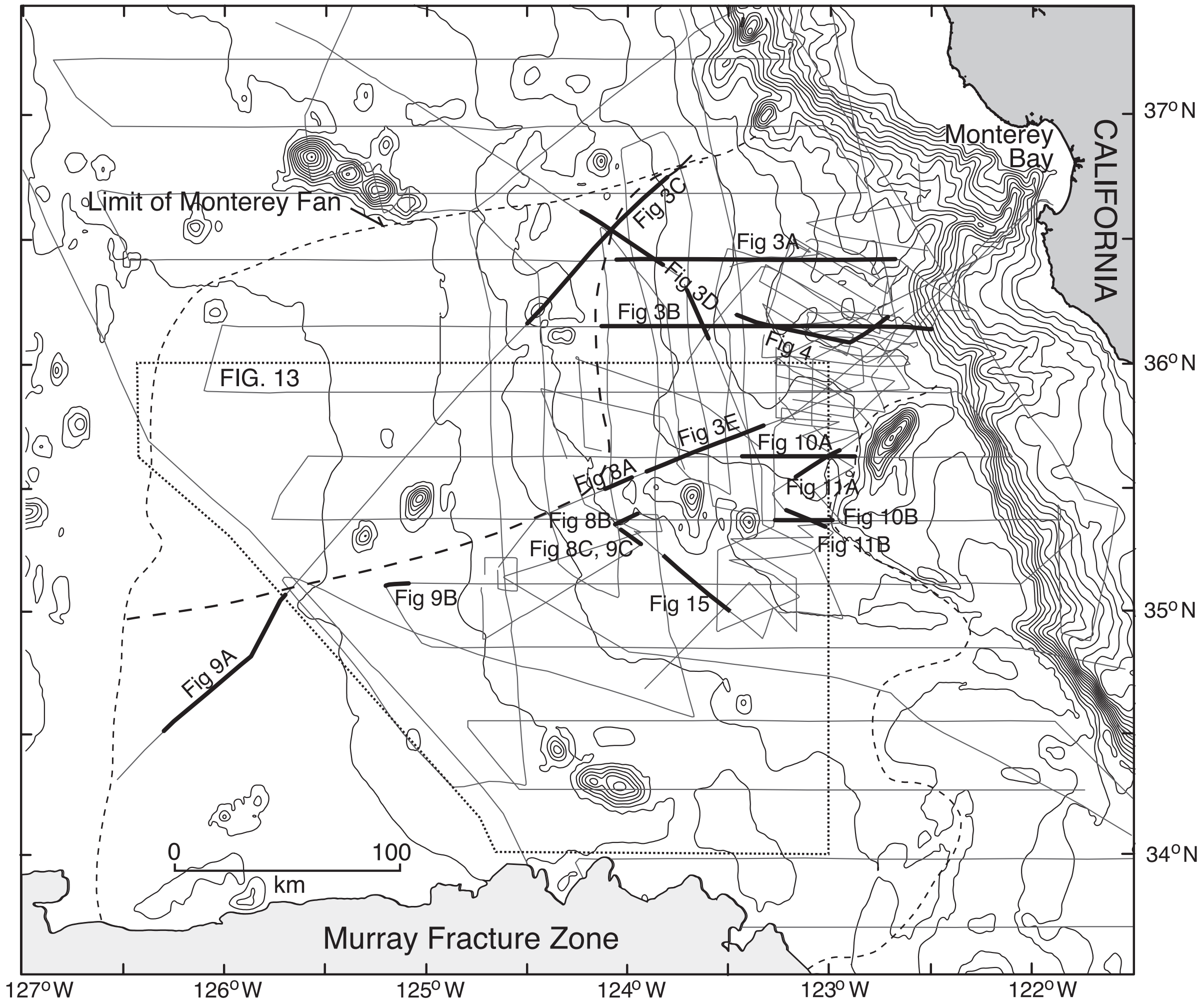

Fig. 2. Trackline coverage of single-channel and high-resolution (e.g., 3.5 kHz) seismic-reflection data available for the study. Limit of area generally understood as the Monterey Fan is also shown as thin dashed line. Approximate northwestern limit of UTS shown in thicker dashed line. Location of profiles in (Figs. 3, 4, 8, 10, 11, and 15) are shown along area of Fig. 13. Bathymetric contour interval is 100 m.

the evolution of the channel systems on Monterey Fan, we provide a brief review of the stratigraphic development of the fan that utilizes unpublished theses and technical reports in addition to published papers. Fig. 2 and Table 1 summarize the data available.

1.1. Regional setting and fan stratigraphy

The Monterey Fan area with its prominent channel features occupies two distinct geographical and depositional areas north and south of the Chumash Fracture Zone (CFZ; some recent papers have used the term

Fig. 1. (A) Schematic map of Monterey Fan showing limits of Lower Turbidite System (LTS) with heavy dashed line and Upper Turbidite System (UTS) shown with light dashed line. Boxes show areas of Figs. 1B and 7. UTS overlies LTS in the eastern half of the fan. Major channels (UTS) and sediment pathways for LTS are shown. Limit of area generally understood as the Monterey Fan extends from northern LTS boundary to Murray Fracture Zone to eastern limit of UTS. (B) Schematic map showing UTS area (stipple pattern) and details of channels on northern Monterey Fan. Boxes show areas of Figs. 5A and 12.

Table 1
Data sources

Cruise ID	Year	Seismic source	3.5-kHz profiles	Other data
Channel	1968	160 cm^3 air gun	No	
7 TOW 10	1970	160 cm^3 air gun	Yes	Deep tow
L12 76 HW	1976	40 kJ sparker	Yes	
L2 77 NC	1977	8200 cm^3 air gun array	Yes	cores
S3 78 NC	1978	40 kJ sparker	Yes	cores
S15 79 NC	1979	40 kJ sparker	Yes	cores
L12 80 WF	1980	160 cm^3 air gun	Yes	
F2 84 NC	1984	320 cm^3 air gun	Yes	GLORIA
F4 84 WO	1984	320 cm^3 air gun	Yes	GLORIA

Morro Fracture Zone, e.g., Gardner et al., 1996). The CFZ is a ridge of seamounts that extends west–northwest from the North American continental margin to 124°W longitude (Chase et al., 1975). Seamounts and ridges, including CFZ, Davidson Seamount, and Taney Seamounts have influenced sedimentation in the area, acting as diversion dams to flows heading southward since the early stages of deposition (Fig. 1; Menard, 1955). Not only were flows unable to pass this CFZ seamount barrier, but the presence of a large depression (CFZ Trough) on the northern side of the ridge trapped more than 1000 m of sediment (Fig. 4 in Normark et al., 1985). Beyond the western termination of CFZ, the fan extends uninterrupted at least 150 km further west (Normark and Gutmacher, 1989).

Normark (1999) recognized that the prominent leveed valleys of the upper fan were confined to a late Pleistocene unit, which was designated the Upper Turbidite System (UTS). The UTS rests unconformably or disconformably on older deposits (Fig. 3). Working independently, Fildani (1993) and Livoti (1993) divided the fan stratigraphy into four units; their uppermost Unit D roughly corresponds to the UTS of Normark (1999). Subsequently, Fildani et al. (1999) introduced the term Lower Turbidite System (LTS) for all turbidite units older than the UTS. The LTS and UTS are recognized north and south of the CFZ but are different in both source area and morphologic characteristics. The morphology of the UTS constitutes the deposit identified as the modern Monterey Fan in earlier studies (e.g., Normark et al., 1985), and it laps out to the west and the southwest (Fig. 3) covering only two-thirds of the area generally recognized as Monterey Fan (Fig. 1).

The UTS, which comprises half of the fan thickness (~ 500 m) near the base of the continental slope, rapidly thins to the west and is limited to the area east of 124°W longitude on the north side of the CFZ (Fig. 1), where it is only half of the width of the previously defined Monterey Fan (Fig. 1). The northern UTS basically coincides with the recognizable morphology of the prominent channels on the Monterey Fan and it reaches its maximum thickness where the channel/overbank complexes are best-developed (Figs. 3 and 4). From west to east there are three main channel features: the Monterey West (MW), the Monterey–Ascension fan valley (MA), and the Monterey East channel (ME) (Fig. 4).

The stratigraphic expression of the UTS is markedly different south of the CFZ, where the UTS is more areally extensive and was deposited as a series of lobes after the CFZ barrier was breached. Lobe deposits crossed by multiple channels characterize the southern UTS; large leveed channel complexes are absent. The currently active channel south of the CFZ has been the object of the most recent detailed ground-truth studies (Gardner et al., 1996; Masson et al., 1995).

The LTS, which underlies an area comparable in size to the UTS, is characterized by distinctly less prominent and recognizable channel morphology, in part because of compaction effects. Southerly flowing turbidity currents that deposited the LTS generally were constrained by the north–south oriented abyssal-hill fabric of the oceanic crust. Because the channels are not well defined, only the 'preferred sediment pathways' of the LTS are identified in Fig. 1A.

Leveed channels were identified only in the middle and upper units of the LTS west of the main UTS wedge. No clear feeder systems (canyons) related to a source terrane have been identified for the LTS. The sediment pathways are not observed to connect with existing canyons farther north on the California margin. Deposition of the LTS could have started as early as Miocene (age of the oceanic crust), and plate motion reconstruction suggests that the paleolatitude of the source area would have to be south of Point Conception (Fig. 1; Atwater, 1989; Atwater and Severinghaus, 1989).

The CFZ ridge, flanked to the north by a deep trough, was very effective in controlling LTS deposition (Fig. 3; see also structural contour map of Fig. 4 in Normark et al., 1985). A large amount of the

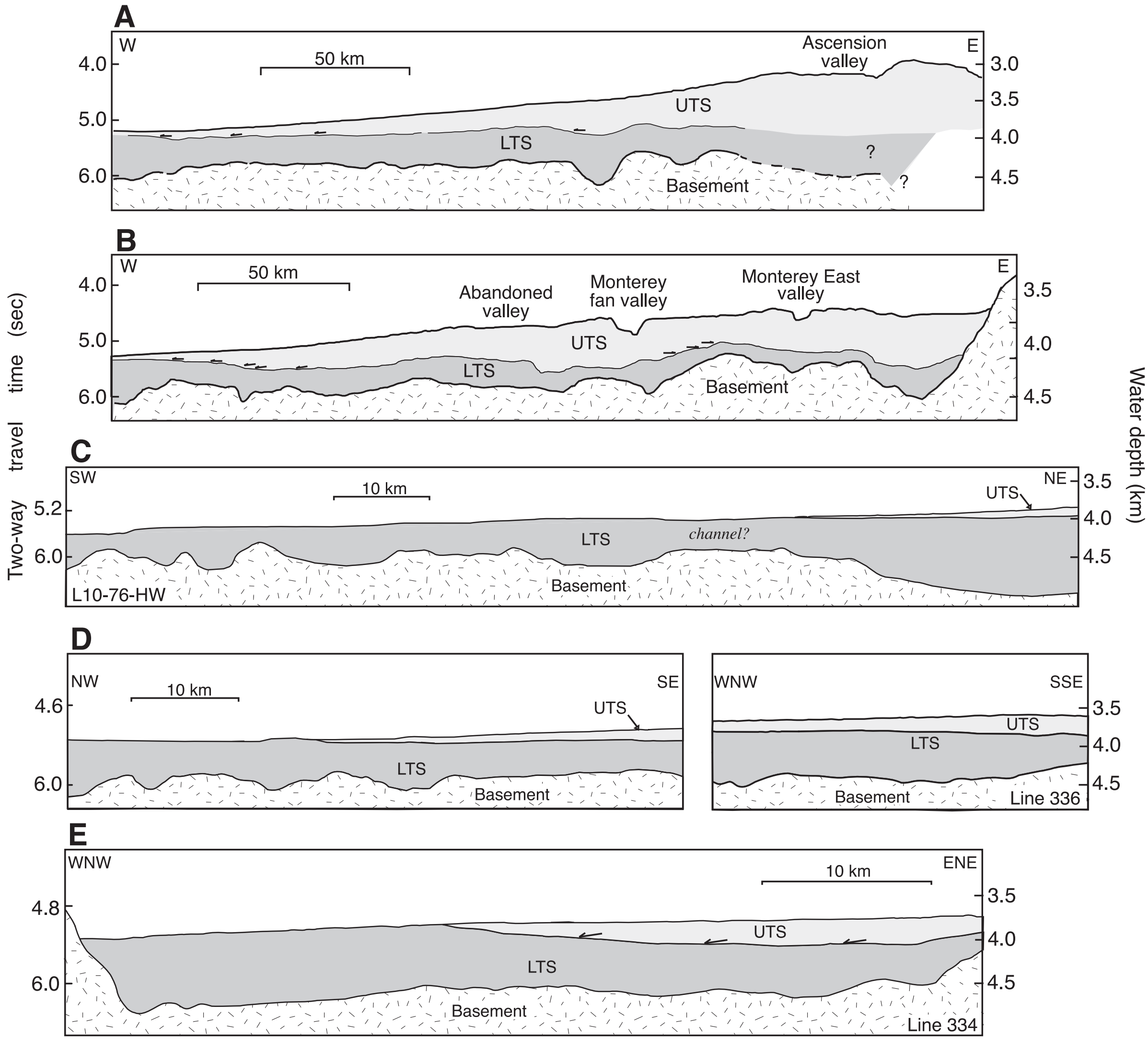

Fig. 3. Simplified line drawings, based on seismic-reflection profiles, showing the wedging and westerly downlapping of the UTS and its relationship with the LTS. Locations of figures noted in trackline map (Fig. 2).

sediment coming from the north was captured in this depression. Only when this elongate basin-like feature was nearly filled were the flows able to pass through and around the CFZ ridge; the first flows that breached the CFZ were near the western termination of the ridge (Fig. 1).

1.2. Previous work on Monterey Fan channel systems

Early work on Monterey Fan was focused on the prominent fan channel extending from Monterey Canyon, which was recognized even then as one of the larger submarine canyons in the world oceans (Dill et al., 1954; Menard, 1955; Shepard, 1966, 1973). With the availability of seismic-reflection profiling, the stratigraphy of the modern Monterey Fan was found to result from two main feeding canyon systems, Monterey and Ascension (Fig. 1). Much of the prominent depositional relief (levee/overbank) of the upper fan was related to the Ascension Canyon system (Normark, 1970). The channel extending from Monterey Canyon is now

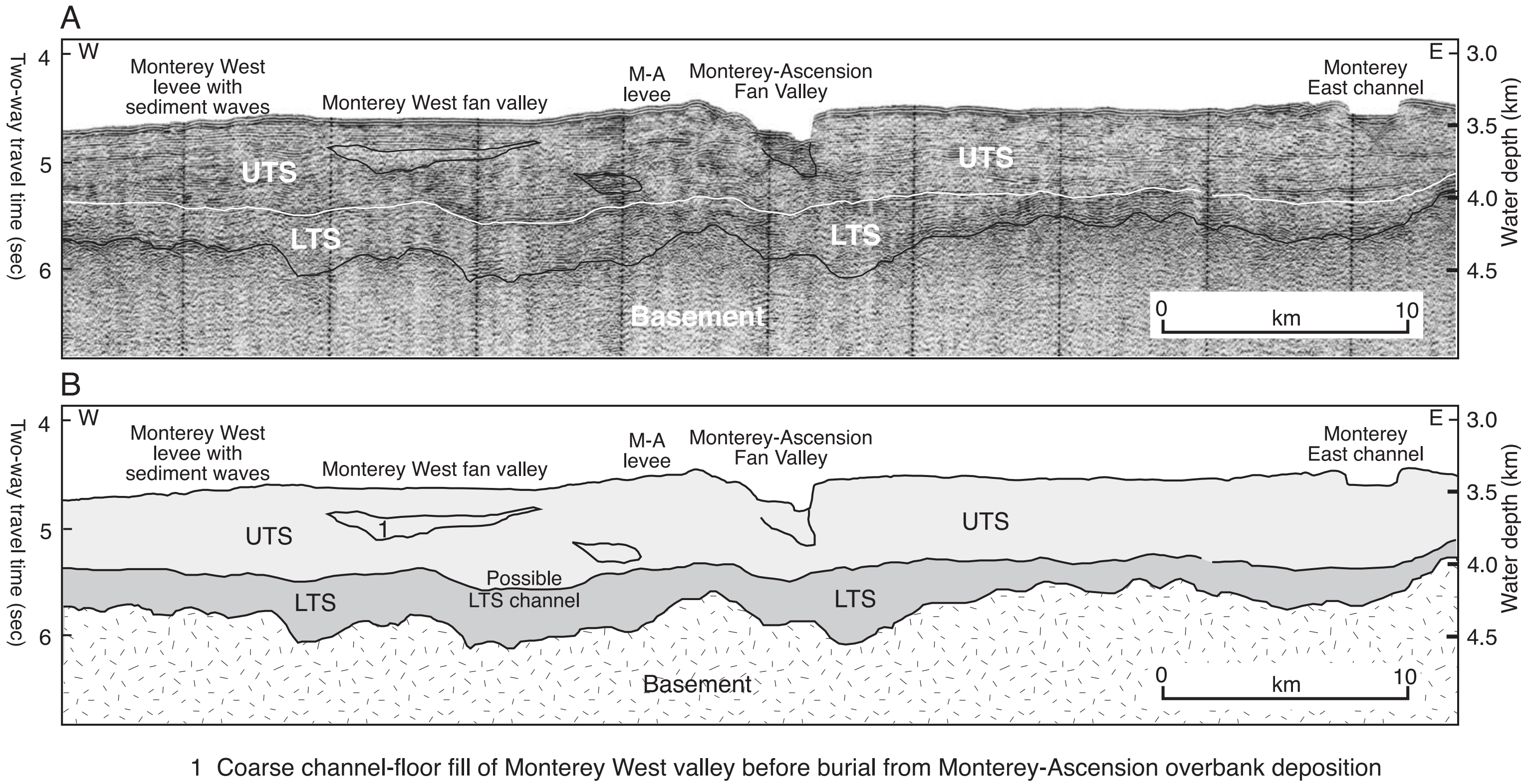

Fig. 4. (A) Seismic-reflection profile and (B) line drawing showing the stratigraphic relation between LTS and UTS and the Monterey West fan valley, the Monterey–Ascension fan valley, and Monterey East channel (modified from Reid et al., 1999). Channel-fill acoustic character is outlined. Locations shown in Fig. 2.

contiguous with the lower part of the Ascension fan.

Results of later surveys showed that the fan extends as much as 400 km southwest from the mouth of the canyon (Fig. 1A; Normark et al., 1985). GLORIA long-range sidescan sonar images (EEZ-SCAN 84 Scientific Staff, 1986) together with ground-truth studies using sediment cores and deep-towed geophysical systems confirmed that the most recently active channel systems on the fan bring sediment as far south as the Murray Fracture Zone over a width exceeding 200 km (Fig. 1A; see also Gardner et al., 1991). Other deep-tow studies of the channel system of the upper fan focussed on overbank deposits and their bedforms and on channel processes (Hess and Normark, 1976; McHugh et al., 1992; McHugh and Ryan, 2000). Samples collected using the ALVIN submersible from the deeply eroded MA valley provide the only age control for UTS deposition (Normark, 1999).

Understanding of the size and history of Monterey Fan continues to evolve since it was first described as a fan delta by Dill et al. (1954). This evolution has been controlled by the development of new mapping and imaging techniques ranging from deep-tow geophysical surveys of small areas to fan-wide long-range sidescan imagery and multibeam bathymetry. Technological advances in data types and increasing area of coverage of successive surveys have seen a proliferation of interpretations of Monterey Fan history. This paper focuses on the varied morphologic channel forms for the UTS, the history of channel development, and the relation of the evolving channel system to the multiple lobes on the southern part of the fan, only one of which has been studied in detail by others (Masson et al., 1995; Gardner et al., 1996). No study to date, however, has integrated all available data to document the stratigraphic development of the fan and its feeding systems, and as a result, none of the existing depositional models for Monterey Fan history are accurate.

1.3. Data sources

The data available for this study includes: seismic-reflection profiles (single-channel and 3.5 kHz), GLORIA side-looking sonar images, multibeam bathymetric data, deep-tow sidescan images, and stratigraphic control provided by piston cores and outcrop samples obtained by manned submersible (Table 1). Except for the multibeam-echo-sounding data, which are limited to the northeastern part of the fan and were collected by the National Oceanic and Atmospheric Administration (NOAA), most of the data used in this study were collected by the United States Geological Survey (USGS) over the last three decades (1977–present). Fig. 2 shows the trackline coverage for all geophysical data collected on the fan. Because of the difficulty in integrating the interpretation of seismic-reflection data from more than 10 cruises that used different sound-sources and acquisition systems (most data are available in analog format only), the resolution of channels and their acoustic character differ among profiling systems. Nevertheless, the integration of the multiple data sets improves our understanding of the depositional evolution of one of the largest deep-water clastic systems offshore western North America.

2. Channels and lobes of the Monterey Fan

Since the latest Pleistocene, most sediment moving through the Monterey–Ascension (MA) channel (Fig 1B) has bypassed the UTS area north of the CFZ, and is deposited south of the CFZ (Gardner et al., 1996; Fildani et al., 1999; Normark, 1999). Although the timing of its channel evolution is poorly resolved because of limited age control, the sequence of changes in growth pattern on the Monterey Fan can be inferred from seismic-reflection and sidescan sonar data. In turn, the evolution of the channel systems provides clues for understanding the stratigraphic development of the fan both north and south of the CFZ.

2.1. Channels of the UTS north of CFZ

The modern Monterey–Ascension (MA) channel system is the most prominent channel-leveed feature within the study area and together with the abandoned MW channel system forms the bulk of the UTS (Figs. 1 and 4). The MA channel system is fed by both the Ascension fan valley, which in turn is fed by multiple tributary submarine canyons that head on the outer shelf, and the Monterey Fan valley, which is fed by the large Monterey Canyon system. The MA channel has been the focus of many studies because of its deep incision, high and broad levees, prominent sediment wave fields, and the development of the tight 'Shepard' meander on the tributary Monterey channel (Fig. 5A; Shepard, 1966; Normark, 1970, 1999; McHugh et al., 1992; McHugh and Ryan, 2000). In this section, we present new information on the other two prominent and less known channel features of the northern UTS, the Monterey West (MW) and Monterey East (ME) channels.

The Monterey West (MW) fan valley is a sinuous, broad elevated channel with wide levees and associated sediment wave field (Fig. 5B). Reflection profiles show it is nearly completely buried by the western levee of the MA valley. It can be traced to the northern edge of the Chumash Trough north of the CFZ (Fig. 1). MW was probably the main channel during an early phase of UTS deposition, and it was filled by a series of smaller aggradational (thalweg) channels during its mature stage (Fig. 4). MW was abandoned when the MA fan valley became the main sediment conduit toward the south. Crests of the levees of the MW channel are still positive relief features even near the crest of the MA levee (Figs. 4 and 5B).

The Monterey East (ME) channel system is a unique feature on the UTS that was originally thought to be a leveed channel extending from the Shepard meander as a hanging distributary (Normark, 1970). Multibeam bathymetry shows that the ME feature

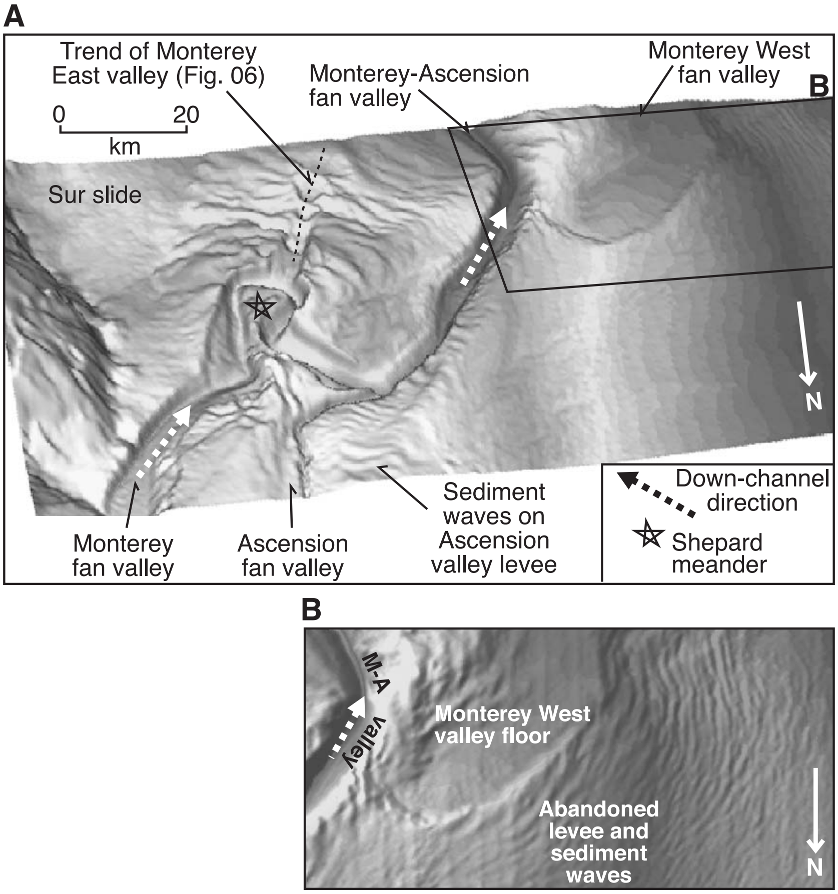

Fig. 5. (A) Multibeam shaded-relief oblique view from the north of channels on the proximal Monterey Fan showing common occurrence of sediment wave fields associated with both active and abandoned leveed channels. Location in Fig. 1B. (B) Multibeam shaded-relief shows enhanced view of Monterey West levee with sediment waves (location in Fig. 5A). Bathymetric data from NOAA.

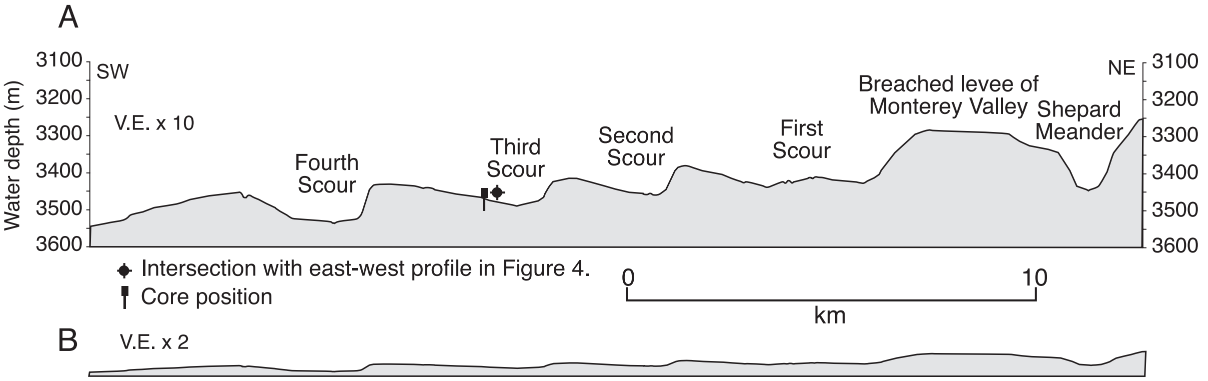

Fig. 6. (A, B) Longitudinal profile of the Monterey East channel showing scours at two different vertical exaggerations (modified from Reid et al., 1999). Location shown in Fig. 5A.

dissects an area characterized by large, arcuate sediment waves (Fig. 5A). The sediment waves extend over a radius of ca. 30 km and are concentric about the Shepard Meander, which has a radius of curvature of about 4 km. The proximal ME channel feature lies more than 200 m above the floor of the modern erosional Monterey channel at the Shepard Meander (Figs. 5 and 6). The ME is bordered to the west by the deeply eroded modern MA fan valley; to the east and south, and the ME-related deposits are buried by the

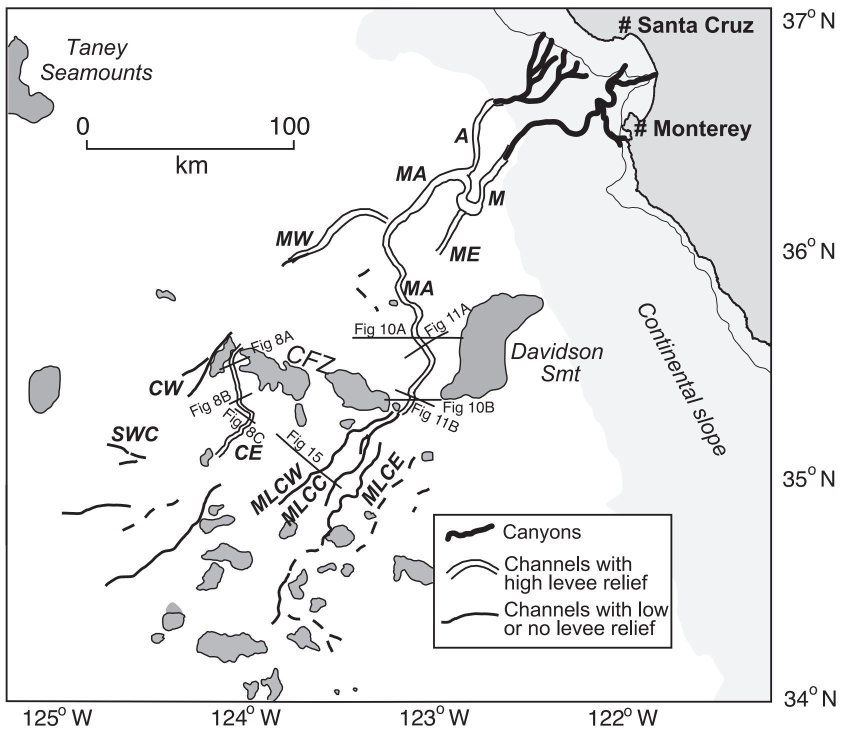

Fig. 7. Simplified map of channels mapped on the modern seafloor using 3.5-kHz, single-channel seismic-reflection lines and GLORIA sidescan sonar backscatter images (track coverage in Fig. 2). Location given in Fig. 1A. Channel names are given in Fig. 1B except for modern Lobe Channels West, Central and East (MLCW, MLCC, and MLCE, respectively). Dark gray shading indicates basement relief.

Sur submarine slide of probable Holocene age (Fig. 5A; Normark and Gutmacher, 1988).

Within the Monterey East feature there is no continuous channel axis. Rather, a 20- to 40-m-deep breach in the Shepard Meander levee that is 3 km wide connects to a series of deep scour-shaped holes that shallow and broaden down fan (Figs. 5 and 6). These scours are flute-shaped, 2.5–3.5 km wide, 2–5 km long, and as much as 110 m deep (Fig. 6A and B). High scarps form the northern, eastern and western margins of these scours, with gentle, lower-relief slopes along their southern (down-slope) margins. Deep-tow side-looking sonar images, 3.5-kHz reflection profiles supplemented by multibeam bathymetry, and sediment core samples indicate that the area containing and surrounding the scours has experienced recent activity, including erosive action, sand deposition, and/or sediment reworking. Available core samples are short compared to the depth of the scours, but they show evidence of fine-grained turbidite beds. These turbidite deposits may represent the upper part of the turbidity currents flowing through the Monterey Fan valley that have been flow-stripped (sensu Piper and Normark, 1983) at the Shepard meander. A recent (unpublished) radiocarbon date from 4.2 m depth in a core obtained from the third scour (Fig. 6) gives a

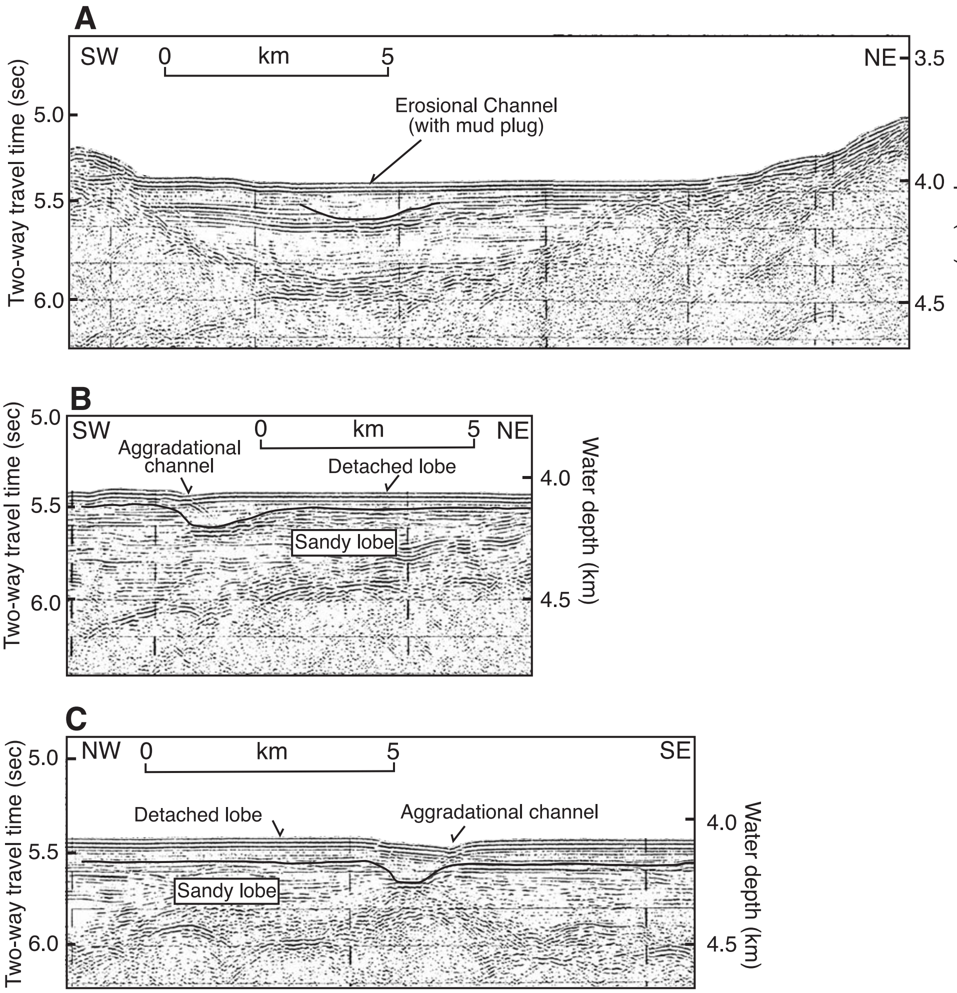

Fig. 8. Seismic-reflection profiles (A–C) from the south side of Chumash Fracture Zone showing successive crossings from north to south of the Chumash East channel, which is probably transitional between LTS and UTS deposition (see text). Locations in Figs. 2 and 7.

Holocene sediment accumulation rate of 122 cm/ka. This rate is more than five times those measured for a piston core from the MA overbank area at almost the same latitude (McGann and Brunner, 1988).

2.2. Channels of UTS south of CFZ

Near the western end of the CFZ seamount ridge, two channel systems, Chumash West (CW) and Chumash East (CE), might have formed near the end of LTS deposition. These channels have since been reoccupied with the capture of distal overbank flows from UTS channels (Figs. 1, 7, and 8). After LTS deposition nearly filled the CFZ Trough, distal flows from the MW and probably also overbank flow from the MA of the UTS rejuvenated the CE channel. Deposition extended to the present southwestern limit of the fan (Fig. 9A). Positive low-relief levees resulted

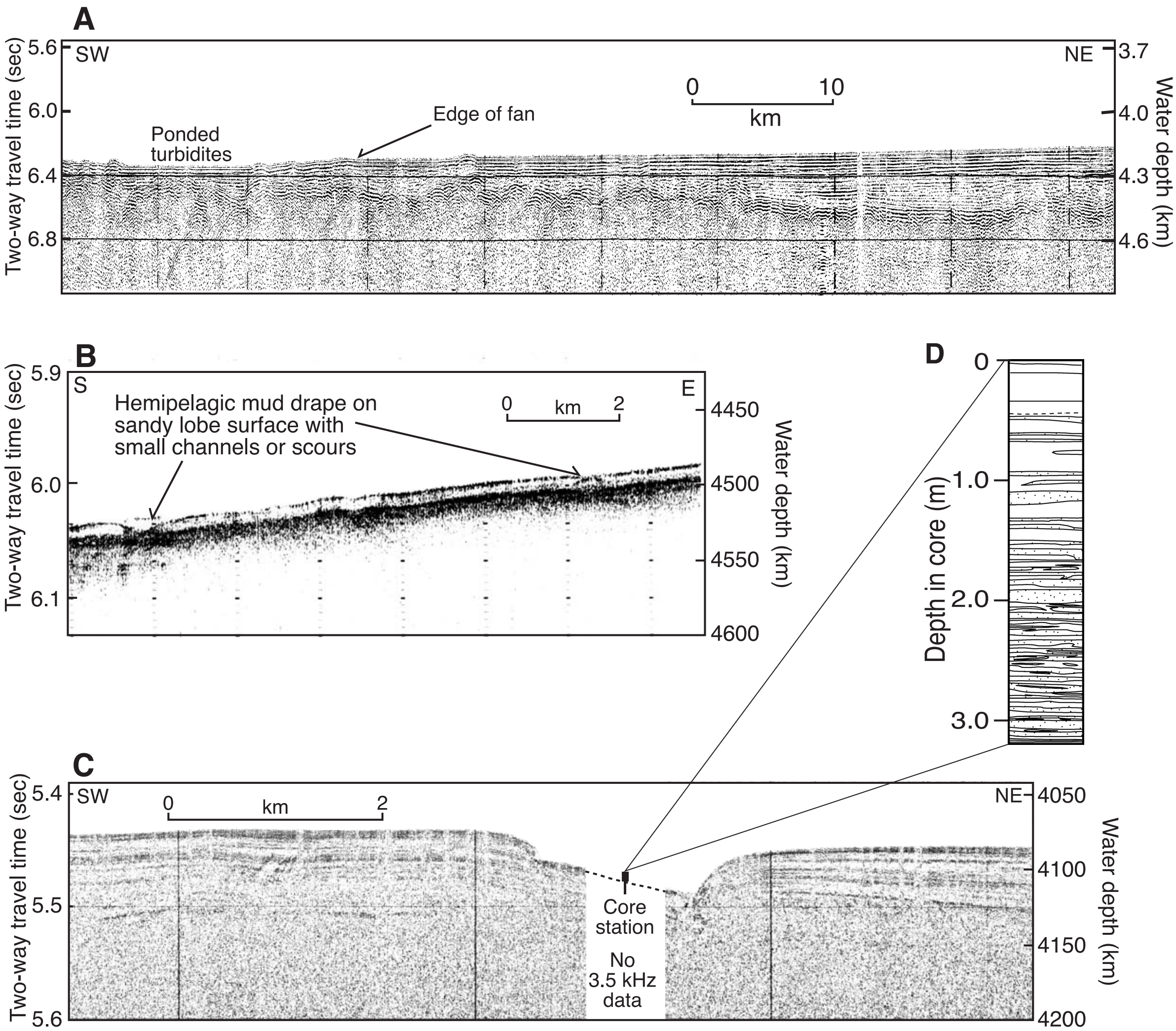

Fig. 9. (A) Seismic-reflection profile of southwestern edge of Monterey Fan showing turbidite ponding on lower fan. (B) 3.5-kHz profile from abandoned western lobe showing 11-m-thick blanket of acoustically transparent sediment overlying sandy deposits characterized by high-amplitude, discontinuous reflectors. (C) 3.5-kHz profile of channel south of Chumash East channel showing thin-bedded aggradational filling. The core (see 9D) located in the thalweg shows a thin-bedded fine-grained turbidites getting muddier toward the top. (D) Core 9P from channel of Fig. 9C. Locations in Fig. 2.

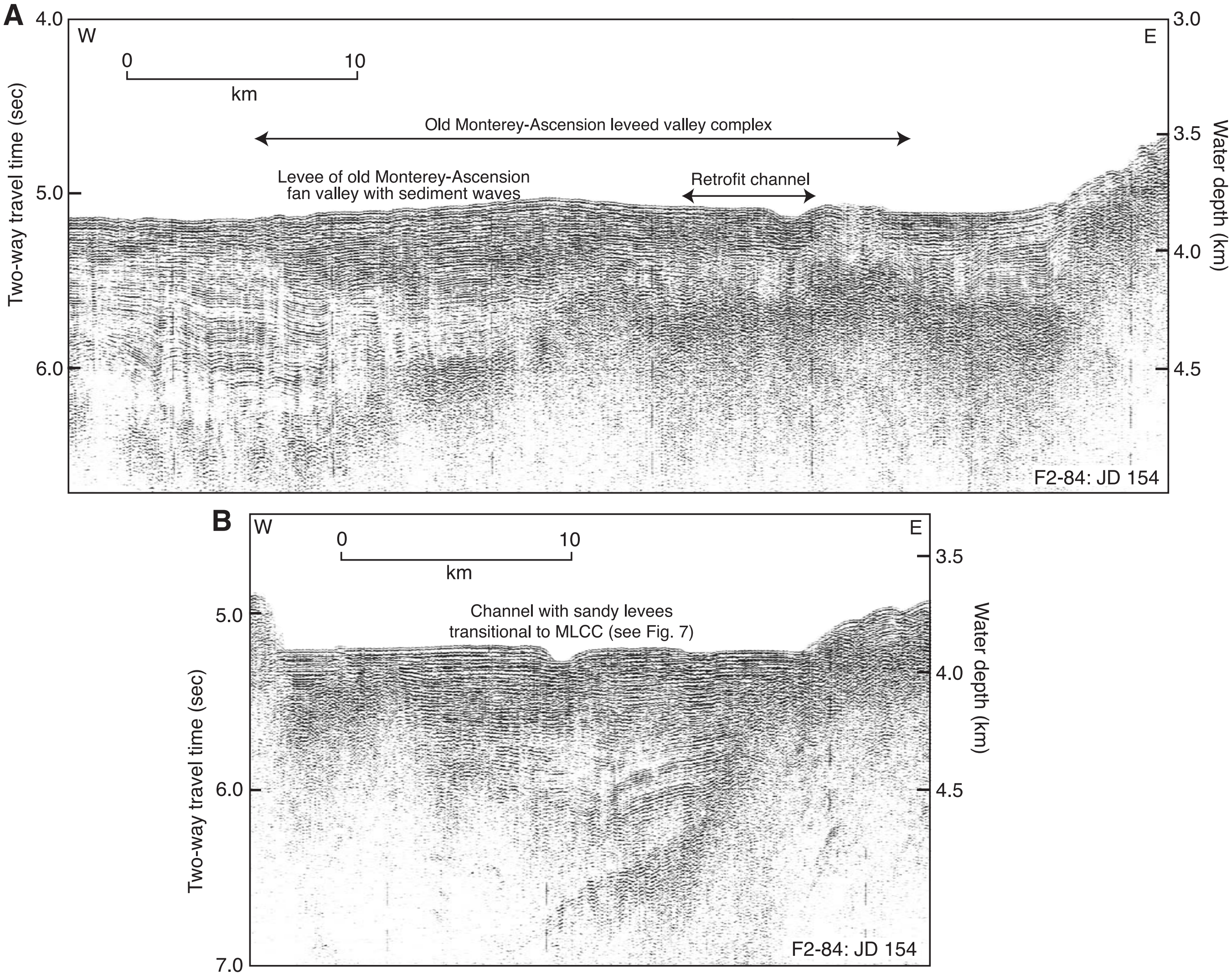

Fig. 10. Seismic-reflection airgun profiles showing transitional channel form between the deeply eroded large leveed old Monterey–Ascension fan valley with retrofit channel (A) to smaller sandy channel form with sandy overbank deposits (B) where the modern channel approaches the southern lobe area. Profile locations in Figs. 2 and 7.

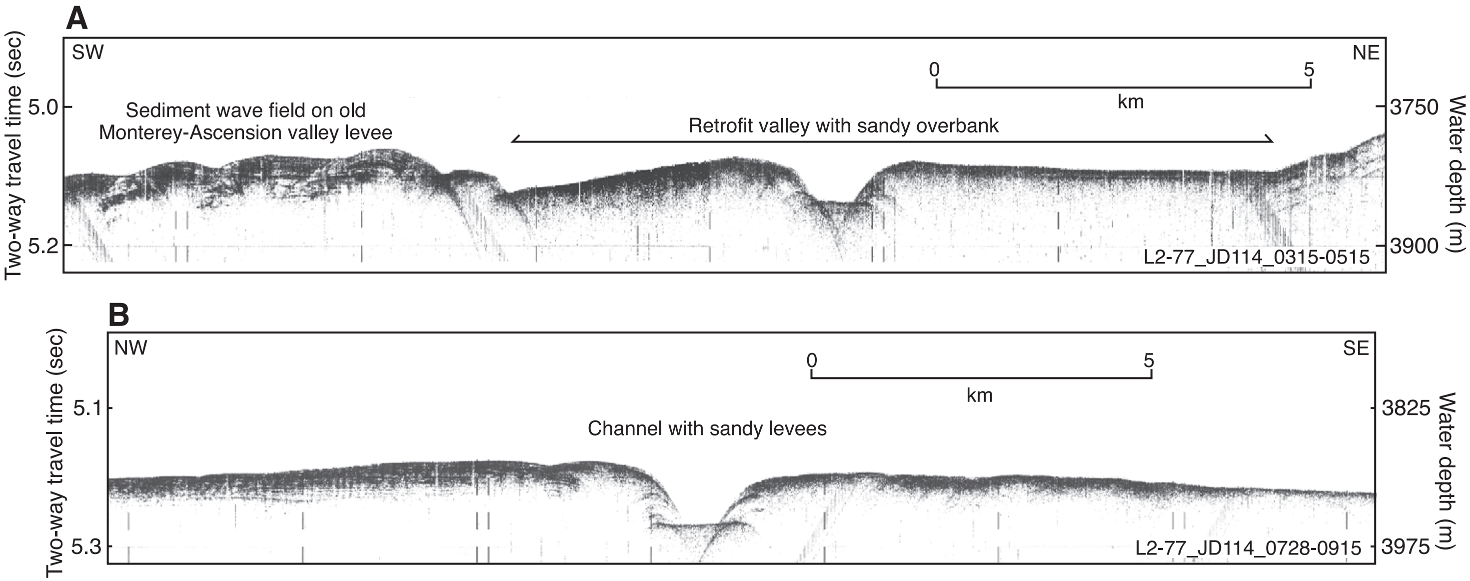

Fig. 11. High-resolution 3.5-kHz reflection profiles showing (A) retrofit small leveed channel formed within the larger old MA valley and (B) the sandy, low-relief leveed channel developing farther south. Profile locations in Figs. 2 and 7.

from aggradation of the CE channel–levee complex (Figs. 7 and 8) is still clear on recent bathymetric data. This temporarily abandoned channel has changed from a low-relief channel during LTS deposition to an aggradational channel during UTS time. The available core data to ground-truth the 3.5-kHz profiles show that the CE channel levee/overbank deposits have changed from dominantly sandy to more silt and mud (Fig. 9C and D). As a result, the channel is now partially filled by mud (Fig. 8A), as evidenced by a layer of acoustically transparent sediment comparable in thickness to that seen on the overbank areas to the southwest, e.g., Fig. 9B.

The Southwest Chumash channel (SWC) is an erosional channel-like feature without pronounced levee development (Fig. 7). This channel is related to the early growth of the westernmost fan lobe. SWC has a drape of generally acoustically transparent sediment that is 11–12 m thick (Fig. 9B). Piston cores from the channel floor and adjacent overbank

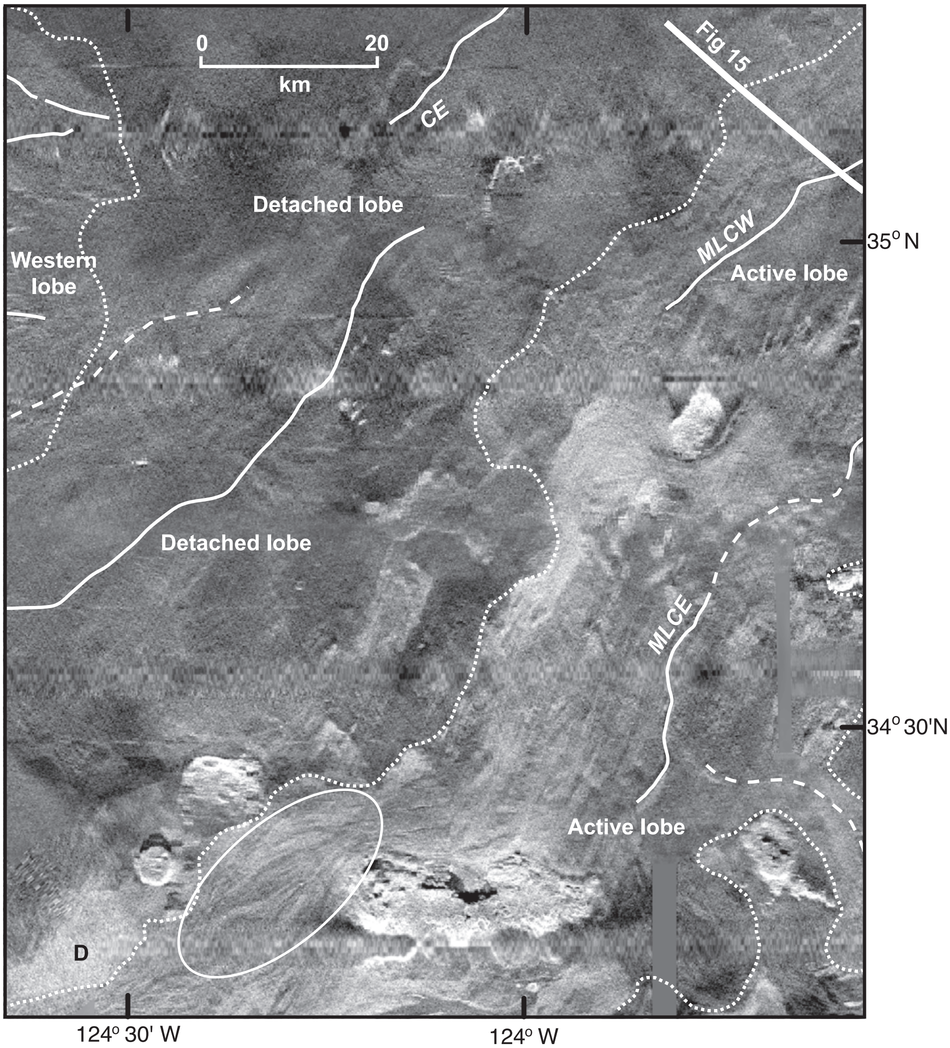

Fig. 12. GLORIA sidescan sonar backscatter image showing the detached lobe between the active lobe and the eastern edge of the Western lobe (dotted lines show lobe boundaries). Main channels are shown in thicker solid lines (dashed where uncertain). Ellipse indicates an area with braid-like channels. Bold black letter D indicates area of mud drape (identified on 3.5-kHz profiles) over sandy lobe. Locations in Figs. 1B and 13.

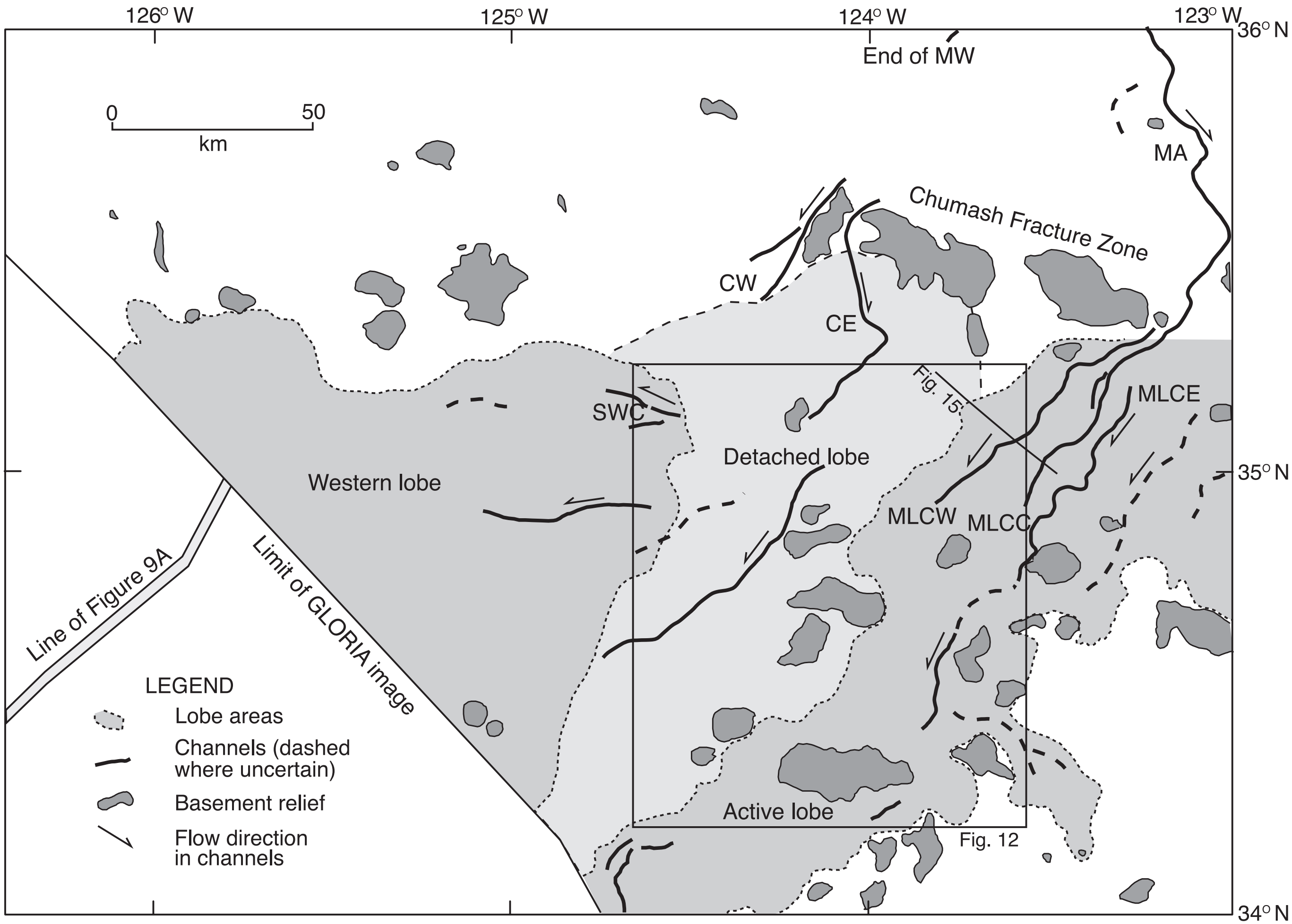

Fig. 13. GLORIA interpretation of the southern Monterey Fan area. Main lobes and channels are identified. Area of Fig. 12 shown.

area both recovered 11 m of silty mud with some thin-bedded sand near the bottom of the cores that has been radiocarbon dated at >44 ka (Normark et al., 1985).

2.3. MA channel transition to modern sandy lobes

The modern Monterey–Ascension channel–levee system dominates the fan morphology north of the CFZ and, with the MW channel–levee system, forms the bulk of the UTS deposits in this area. The currently active MA channel is a deeply eroded feature that has cut down more that 250 m into a broader aggradational channel (e.g., Figs. 4 and 5A; Normark, 1999). The present erosive character is thought to have formed when the Monterey channel was eventually able to breach the CFZ volcanic ridge and reach a lower base level. When the eastern pass on the CFZ (between the CFZ and the Davidson Seamount) was finally used by the turbidity flows, the system began feeding what is now the active lobe of the fan. West of Davidson Seamount, the erosionally deepened MA channel is now occupied by a low-sinuosity, narrow channel identifiable as a retrofit channel, i.e., the new channel with its levees occupies the larger, previously eroded Monterey–Ascension leveed valley floor (Figs. 10A and 11A). Slightly downstream, the transition to the active lobe shows an erosive channel with low-relief sandy levees characterized by erosional scours rather than sediment wave fields (Figs. 10B and 11B).

2.4. Lobes on the southern fan

The architectural elements that can be defined as lobes are found only south of the CFZ. The lobes that have been recognized have complicated channel patterns related to their growth and evolution. The oldest lobe seems to be related to the Chumash East channel system (“abandoned lobe” sensu Normark, 1985). Our interpretation now shows that this “abandoned lobe” is actually comprised of two separate lobe features: (1) a western inactive lobe and (2) a recently active detached lobe, i.e., not fed directly from a channel (Figs. 12 and 13).

The Western lobe is buried by an acoustically transparent layer as observed in 3.5-kHz records; this layer thins from about 12 m in the east to about 5 m in the westernmost profiles, e.g., Fig. 9B. The channel features of the lobe are still recognizable in the GLORIA backscatter data, e.g., the west edge of Fig. 12. The Western lobe was probably fed by either or both the CW and CE channels.

The detached lobe is composed of two distinctive sediment packages related to different stages of development. A lower package of coarser-grained material (based on reflection character; Fig. 8) is covered by a thin-bedded package of presumed finer sediment (Fig. 9C and D). In the late Pleistocene, the leveed channel (CE) fed a large area characterized by parallel reflections that is interpreted as a distal lobe deposit (Normark et al., 1985; Fig. 8B and C). This finer-grained lobe sedimentary package is not connected to any channel feature north of the CFZ, and is referred herein as the detached lobe (Figs. 12 and 13).

The modern channel system feeds the most recently active lobe; the channels developed when the eastern pass of the CFZ opened (Figs. 12 and 13). Acoustic-facies characters suggest that this lobe is composed of coarse sediment. A core from the main channel area had virtually no recovery except for coarse sand and parts of tree branches stuck in the catcher, suggesting a very coarse material and recent sedimentation (USGS unpublished core descriptions). A set of free-fall cores along an east–west transect all recovered sand or failed to return (suggesting they hit sand near the seafloor; unpublished data, Scripps Institution of Oceanography). The channel pattern of this youngest lobe has been studied with sidescan images and high-resolution profiles from deep-towed instruments as well as core data (Gardner et al., 1991, 1996; Masson et al., 1995; Klaucke et al., 2004).

3. Discussion

3.1. Styles of Monterey Fan channels

Monterey Fan provides one of the best opportunities among modern deep-water turbidite systems to study different constructional styles for channels.

This study recognizes seven different channel styles: (1) large leveed valley complexes, (2) erosional channels deeply cutting a leveed valley complex, (3) retrofit channels, (4) smaller sandy leveed channels, (5) erosional channels on sandy lobes, (6) braid-like channels on sandy lobes, and (7) incipient channels (Fig. 14).

(1) The large leveed valleys dominate the morphology of the modern seafloor north of the CFZ providing the most recognizable depositional relief on the fan. The Ascension fan valley north of its confluence with the Monterey (Fig. 1; see Fig. 3 in Normark, 1970) and the now mostly buried MW fan valley (Figs. 4 and 14) are the best examples of this channel type. These systems tend to aggrade with both levee and channel floor becoming elevated above the fan surface. As these large leveed channels prograde, the channel floor is characterized by stacking of smaller, aggrading channels (Fig. 14). Large leveed valleys commonly are abandoned as a result of channel avulsion (Flood et al., 1995), as may have been the case with the switch from MW to MA.
(2) A major erosional channel, the Monterey valley (M in Figs. 1B and 14), is deeply incised from its junction with the Monterey Canyon through the Shepard meander. Downstream from the Shepard meander, the Monterey valley joins the larger leveed valley system extending from Ascension Canyon (A in Fig. 1B). The two valleys converge into the largest fan valley, MA, which is an erosional feature that has as much as 400 m relief from levee crest to channel floor in the reach below the confluence. The erosional deepening of the valley floor probably accounts for more than 250 m of the existing relief (Normark, 1999).
(3) Retrofit channels develop in a later stage of channel evolution when the large erosional feature is successively filled by sediment deposited from low-sinuosity thalweg channels. Small sandy levees inside the large leveed valley (with muddy levees) develop locally (Figs. 10A, 11A, and 14). A similar retrofit channel with sandy levees has been mapped in the Hueneme fan valley off southern California (Fig. 4 in Piper and Normark, 2001).
(4) Slightly aggrading, small sandy leveed channels are formed down-fan from the retrofit channel of

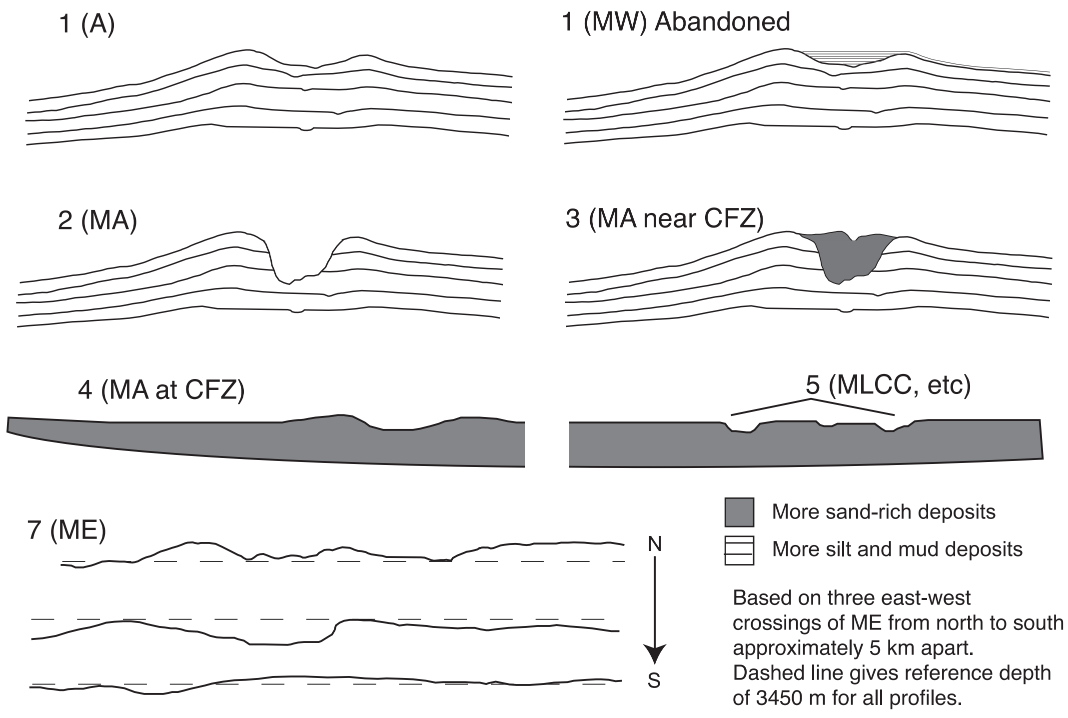

Fig. 14. Schematic representation of the channel types on Monterey Fan (see text).

the MA, such as those on the active lobe; (Figs. 11B and 15). The low relief sandy levees are more common on the northern part of the active lobe.

(5) Channels on lobe areas such as those farther south of the CFZ are typically erosive features (Figs. 14 and 15) (see Normark et al., 1985; Gardner et al., 1996; Masson et al., 1995).

(6) Braided channels are observed on backscatter sonographs from GLORIA on the distal part of the lobe (Fig. 12) This type of channel has been studied in detail with deep-tow geophysical data (Masson et al., 1995; Klaucke et al., 2004) and is not discussed in this paper.

(7) A poorly formed channel, the ME, south of the Shepard Meander does not have a continuous thalweg (Figs. 5A and 6). Seismic-reflection profiles that cross the ME all show a channel-like form but with irregularly varying depths and

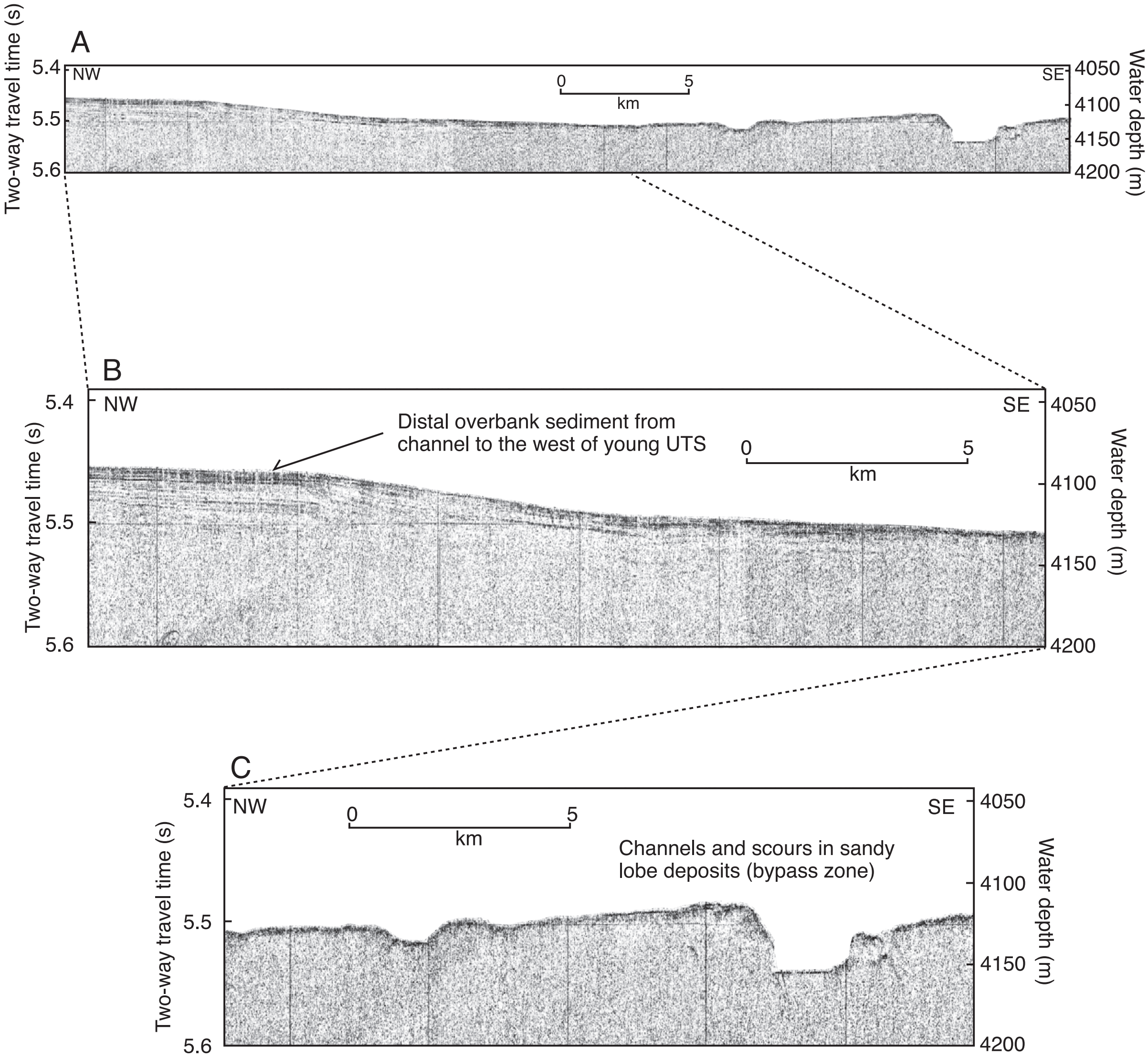

Fig. 15. (A) High-resolution 3.5-kHz profile showing transition between modern sandy lobe of UTS and the detached lobe. (B, C) Expanded view of western half of Fig. 15A; parts B and C are continuous. Well-bedded distal overbank sediment of detached lobe were deposited almost at the same time of the sandy lobe. Profile locations in Figs. 7, 12, and 13.

levee relief, i.e., on all eight crossings of ME between the reflection profile shown in Fig. 3B and 36°N latitude (see tracklines in Fig. 2 and profiles in Fig. 14). The ME might best be interpreted as reflecting an incipient stage in the development of a channel–levee system.

3.2. Channel evolution

The complicated history of channel development on the Monterey Fan is reflected in the marked change of depositional style that is associated with the growth of the UTS. The evolution of the UTS channel systems can be related to two main factors: basin morphology and sediment source.

In the southern area, the Southwest Chumash channel (SWC) is a relatively small feature that is dominantly erosional but with small levees. The SWC is located on the western lobe of the fan (Fig. 13). This channel formed probably in the late stages of LTS and it was re-used with the interception of unconfined flows during UTS deposition.

The Chumash West (CW) and Chumash East (CE) channels (Figs. 7, 12, and 13) may have developed from late LTS flows when the CFZ was no longer a barrier to flow after the Chumash Trough was mostly filled. In its early stage, CE has the form of a sandy channel with low relief levees (Fig. 8B and C). At a later stage, the CE channel shows characteristics of channel–levee complexes (Fig. 9C). This is related to a change in source material when the CE channel probably received sediment from the MW as the latter prograded into the area north of the CFZ trough. These flows were composed of finer-grained overbank material that were then reconfined through the CFZ pass, leading to an aggrading system with well-developed levees (Figs. 8B,C and 9C). A core in the thalweg of the channel shows well-bedded turbidites fining upward, a trend that is probably related to decrease in thickness of overbank flows during entrenchment of the MA channel floor (Fig. 9D).

The prominent channels and fan valleys of the northeast quadrant of Monterey Fan formed during UTS deposition (Fig. 1). In the UTS, the earliest recognizable channel forms are depositional, large leveed systems that prograde as both levee and channel floor aggrade. Monterey West appears to be stratigraphically the oldest channel on the northern UTS (Fig. 4) and flows from this channel added to filling the trough north of the CFZ. A probable avulsion caused the abandonment of MW and what is now the Monterey–Ascension fan valley became the main conduit of sediment from Ascension canyon to the south. Overflows from the Monterey–Ascension fan valley eventually filled the MW channel, which was already partially filled by deposition from a series of aggrading small thalweg channels within the larger valley floor (Fig. 14). Nevertheless, the levee of MW still possesses topographical relief and an impressive sediment wave field (Fig. 5B).

The dominant topographic features in the UTS are the high levees of the Ascension, Monterey, and MA fan valleys. The greatest thickness of the UTS is the western levee of the Ascension and MA fan valleys (Figs. 3A,B, 4, and 5). The age of the UTS is late Pleistocene, perhaps no more than 500–600 ka. This age is based on indurated sediment taken from the wall of the Monterey–Ascension fan valley near its point of deepest erosion as reported in Normark (1999). The only source suggested for the rapid sedimentation of the UTS is the draining of Pleistocene Lake Corcoran about 600 ka. Normark (1999) also noted that the erosional deepening of the Monterey–Ascension fan valley probably occurred over several glacial–interglacial cycles, implying that the UTS north of the CFZ was deposited in a short time interval (~ 300 ka). Deposits related to a Monterey Canyon source are much smaller in both area and thickness.

Neither the timing or processes resulting in the confluence of the Monterey and Ascension valleys are firmly established, but the result is that both canyon systems can provide sediment to the MA fan valley. The Ascension Canyon heads are near the outer shelf and are active sand conduits only during times of lowered sea level. Sand deposition on the floor of Ascension fan valley during the Pleistocene changed to silty mud during the Holocene (Hess and Normark, 1976). In contrast, the Monterey Canyon heads nearshore and can feed sediment to the fan regardless of relative sea level position. Recent work has documented sand transport in the lower Monterey Canyon (Xu, oral communication, 2004) and the existence of muddy hyperpycnal flow during the largest flood events in the nearby Salinas River (Johnson et al., 2001). During the current sea level highstand, deposition on the levees of the modern Ascension channel is limited (Brunner and Normark, 1985; McGann and Brunner, 1988).

Avulsion occurs periodically in response to both allocyclic and autocyclic controls. Early UTS channel systems (MA and MW) show aggradation, with filling of the main broader channel through smaller channels, and eventual avulsion (MW abandonment). When the MA system was able to reach a new base-level south of CFZ, headward erosion cannibalized and redeposited MA channel fill in the lobes further downfan. A more pronounced headward erosion caused the flows to became confined in the thalweg and only the finer part of the flow was stripped off and deposited on the overbank and continued flowing southwest. This is probably the stage when large sediment waves formed during later UTS deposition (Normark et al., 2002). By this time, erosion was sufficient to cause significant bypass of the coarser sediment to lobes south of CFZ. The levees were still aggrading during final downcutting and continued to receive silty overbank sediment as late as the early Holocene (Brunner and Normark, 1985; McGann and Brunner, 1988). Maturation of the systems might have resulted in a lower gradient and backstepping within the larger erosive valley that led to its partial filling by the retrofit channel (Figs. 10A and 11A).

South of 36°N latitude, the high levee of the MA fan valley rapidly decreases in relief. The valley floor also undergoes a transition related to its passage through the CFZ where the MA feeds the channel systems south of fracture zone ridge. A retrofit channel that now occupies the erosionally deepened floor of the larger leveed valley of MA in turn transforms into a channel with sandy levees (Figs. 10 and 11). The latter channel directly feeds the eastern active lobe (Fig. 13; see Gardner et al., 1991, 1996; Masson et al., 1995; Klaucke et al., 2004).

The relation between channels on the active eastern lobe is not clear from the GLORIA image alone (Fig. 12). Using all the available 3.5-kHz profiles together with the GLORIA data, three channel segments are identified that appear continuous but only one has a uniformly deepening gradient. The three channels present on the lobe (modern Lobe Channel West, MLCW; modern Lobe Channel Central, MLCC; and modern Lobe Channel East, MLCE; Figs. 7 and 13) are constructive channels with low relief sandy levees (e.g., Figs. 14 and 15); farther south they become mainly erosive features (Gardner et al., 1996). The three channels, which have reaches that locally exceed 60 m in relief, were probably active at different times. The most recently active system is the MLCC, at least in the northern area of the lobe. We cannot exclude (and it seems reasonable) that local overflow from one channel may become rechannelized in the other two, meaning that all of the channels could remain partially active in feeding the lobe.

Two of the three channels, MLCW and MLCE, appear to have discontinuous thalweg gradients that we believe are related to allocyclic factors, such as receiving overflow from the nearby active channel. Variations in gradient and local basin morphology control formation of lobe areas with channels (mainly bypass zones) and intervening ponded areas (mainly depositional zones). The southernmost area of the most recently active lobe has been surveyed only with GLORIA and associated follow-up deep-tow studies and is south of areas with USGS seismic-reflection lines (Fig. 2). These studies show that this is the most recently depositional area with sand at or close to the surface (Gardner et al., 1991; Masson et al., 1995; Klaucke et al., 2004).

Neither the evolution nor the role of the Monterey East channel as a conduit distributing sediment to the fan are well understood. The ME ‘channel’ was first interpreted as the remnant of an original channel extending from Monterey Canyon that was pirated by the Ascension fan valley (Normark, 1970). A later hypothesis suggested that it was an abandoned channel plugged by mass wasting from the slope (Greene and Hicks, 1990), but the ME is in reality a more complicated and interesting feature. Seismic-reflection profiles normal to the ME trend show channel-like characteristics in most crossings (e.g., Fig. 4) but multibeam bathymetry and deep-tow data do not support the interpretation of a continuous channel (Figs. 5 and 6). No clear channel thalweg is present and a series of ridges in the form of large-scale, arcuate sediment waves are cut by the broad, flute-shaped depressions (Fig. 6). The available seismic-reflection data show that the depressions that constitute the ME trend are not left from a partially filled channel but appear to have developed late during UTS deposition (Fig. 4). The available core data show that the highest documented sedimentation accumulation rate (122 cm/ka) on the fan north of CFZ is in the ME system (core location in Fig. 6). As a result, the Monterey East appears to be an incipient channel that might eventually become the main conduit extending from Monterey Canyon.

3.3. Sandy lobes

Modern lobes in the Monterey Fan area related to the late Pleistocene UTS depositional system lie south of the CFZ (Fig. 13). As noted above, there are two distinctive lobe types recognized on the Monterey Fan, sandy lobes and a composite (finer grained) lobe. The composite lobe is an example of a detached lobe (sensu Mutti, 1985) discussed in the following section. The western lobe and the active eastern lobe are both sandy lobes. Whereas the western lobe is now completely abandoned, the eastern lobe has been interpreted as the most recent area of coarse-grained sediment deposition on the fan (Masson et al., 1995; Klaucke et al., 2004). The active lobe is easily recognized in the GLORIA backscatter image (Fig. 12). No drape of pelagic sediment is evident in the seismic-reflection data (Fig. 15). Cores and deep-tow studies of this lobe demonstrate the sandy nature of this part of the fan (Gardner et al., 1991; Masson et al., 1995).

The western lobe is the broadest sandy lobe on the fan. It extends well west of the limit of the GLORIA survey and its western limit is seen only in the reflection profile of Fig. 9A. The GLORIA backscatter image of the Western lobe shows many features seen on the eastern lobe but with slightly less amplitude (grayer) returns (e.g., compare sheets 11 and 12 in EEZ-SCAN 84 Scientific Staff, 1986). The western lobe is blanketed by 5–12 m of acoustically transparent sediment on the 3.5-kHz records (e.g., Fig. 9B).

The thickness of drape on the Western lobe can be used to estimate the time of its abandonment. A radiocarbon date attempted from the bottom of one of the cores gave only >44 ka (Normark et al., 1985). The latitude of ODP Site 1016 is within the latitude range of the western lobe and is from a sediment section on a hill that stands above the fan surface (Yamamoto et al., 2000). The sediment accumulation rate at Site 1016, which should be similar to (or slightly higher) than that of non-turbidite accumulation on the western lobe, suggests that the end of coarse sediment deposition on the lobe was during isotope Stage 6 (see Yamamoto et al., 2000). It is likely that the lobe began to be abandoned when the erosional deepening of the Monterey–Ascension system began. Stage 6 would thus also mark the end of rapid growth of the UTS north of CFZ.

3.4. Detached lobe

The upper part of the lobe located between the Western and active lobes is a detached lobe, i.e., it has never been directly connected to a channel currently part of the system extending from Ascension and Monterey Canyons (Fig. 13). The detached lobe is fed by unconfined overbank flow (from the MA channel) that is dammed behind the CFZ before eventually flowing through a saddle in the volcanic ridge. The CE channel was formed as a result of overbank flow being reconfined through the saddle and is a feature related to the detached lobe.

The detached lobe is a composite feature in the sense that it has been involved in different stages of fan growth. Seismic-reflection profiles reveal that its lower part shows acoustic characteristics of a sandy lobe with channels similar to those on the northern part of the active lobe (Fig. 8B and C). This growth stage changed when the supply of coarse material was apparently shut off, which might have been related to the avulsion that led to the abandonment of the MW channel. The loss of supply may well be related to the opening of the modern pass through the Chumash Fracture Zone occupied by the MA. When this passage opened, the modern Monterey lobe started forming and the MA became the main conduit. At this stage, the main depositional area was directly south of MA, but finer sediment overflowing the MA western levee was still able to reach the CFZ trough area and eventually these unconfined flows were refunneled through the CFZ pass. The morphological control of the pass through the CFZ caused the overbank flows to thicken and acceleration of the flows was enhanced by the steeper gradient to the south. These rechannelized flows had sufficient energy to form an erosional channel when passing through the restricted area in the pass through the CFZ (Fig. 8A). Only the finer overbank material was able to reach the western CFZ; thus the detached lobe exhibits a reflection character in 3.5-kHz records that is typical of thin-bedded turbidites (Fig. 9C and D). The deposition of the detached lobe was essentially simultaneous with the deposition of the active Monterey sandy lobe. The thick turbidity currents were delivering coarser material to the active lobe and fine material to the detached lobe (Fig. 15).

The process of deposition for the detached lobe is only one expression of the types of allocyclic controls that result in confinement and unconfinement of turbidity current flows. These allocyclic controls in turn lead to the development of turbidite elements that appear out of place with respect to expected geometries of submarine fans (Normark, 1985). On the most recently active lobe, a series of ponded turbidite areas are connected by erosional channels (also in Masson et al., 1995). In the case of the modern eastern lobe, these ponded turbidites are composed of coarse material. Variation of gradient as a result of the local topography (presence of abyssal hills and isolated volcanic seapeaks) seems to be the main factor controlling the position of the depositional areas. Semi-confined flows deposit in low gradient areas between local hills and peaks. These areas fill rapidly and later flows are able to move farther into the basin. As soon as the unconfined flows have enough energy to reach the distal part of the local basin and bypass the topographic barrier that caused the ponding, the flows are able to accelerate, increase in competence, and form a new channel. This process generates fragmentary looking channels on lobes (Figs. 7, 12, and 13).

4. Conclusions

The modern Monterey Fan is a complex depositional system with a multistage growth history. In the Neogene, deposits of the Lower Turbidite System (LTS) appear to consist of relatively distal elements of a system that is now separated from its feeding canyons (Fig. 16A). The inferred age of the LTS suggests that it initially began to form when its apex was at the paleolatitude corresponding to the present Point Conception. The LTS is present north and south of the CFZ and is overlain by the late Pleistocene Upper Turbidite System (UTS), which reflects the initial significant contributions from canyons in the Monterey Bay area (Fig. 16B). The UTS finished filling a trough on the north side of the Chumash Fracture Zone (CFZ) resulting in overspill through different passes in the volcanic ridge. The overspill reoccupied some existing LTS channels as well as forming new channels and lobes south of the CFZ.

The Monterey Fan area shows different channel styles reflecting different steps in the evolution of the UTS. Large leveed valleys (type 1) characterize the initial UTS deposition (Fig. 16B). This channel prograded to the southwest and completed the filling of the trough along the north side of the CFZ. Initiation of the Ascension (A) channel and its confluence with the Monterey (M) channel shifted deposition to the southeast (Fig. 16C and D). Eventually, turbidity currents were able to breach an eastern pass through the CFZ (Fig. 16E) and headward erosion started in the large leveed valley (type 2). Deposition at a new base level on the south side of the CFZ resulted in forming the retrofit channel (type 3) as well as erosional channels with low relief sandy levees (type 4; Fig. 16E). Erosional channels with low or no levees (type 5) characterize the upper lobe areas and braid-like channels (type 6) on the lower lobe area (Fig. 16F). As the lobes fill local relief on the oceanic crust, turbidity currents flow farther south building new lobes and causing erosional deepening of channels on the more proximal lobe areas (Fig. 16F). Subsequently, headward erosion in the MA fan valley resulted in coarse sediment bypassing to the modern eastern lobe and abandonment of an earlier western lobe by about isotope Stage 6 ($\sim$ 150 ka). The ME channel feature (type 7) is a late development resulting from flow stripping at the Shepard Meander.

There are two distinctive lobe types recognized on the Monterey Fan: sandy lobes, one of which has been cut off from its feeding channel (the Western lobe), and silty detached lobes that are fed by unconfined overbank flows that are refocused by local morphologic features. Thus, allocyclic controls (primarily the CFZ) during deposition of the UTS has resulted in segregation of coarse and fine sediment from turbidity currents and the nearly simultaneous formation of sandy lobe elements and muddy leveed channels on the detached lobe, nearly 200 km from the mouth of Monterey Canyon.

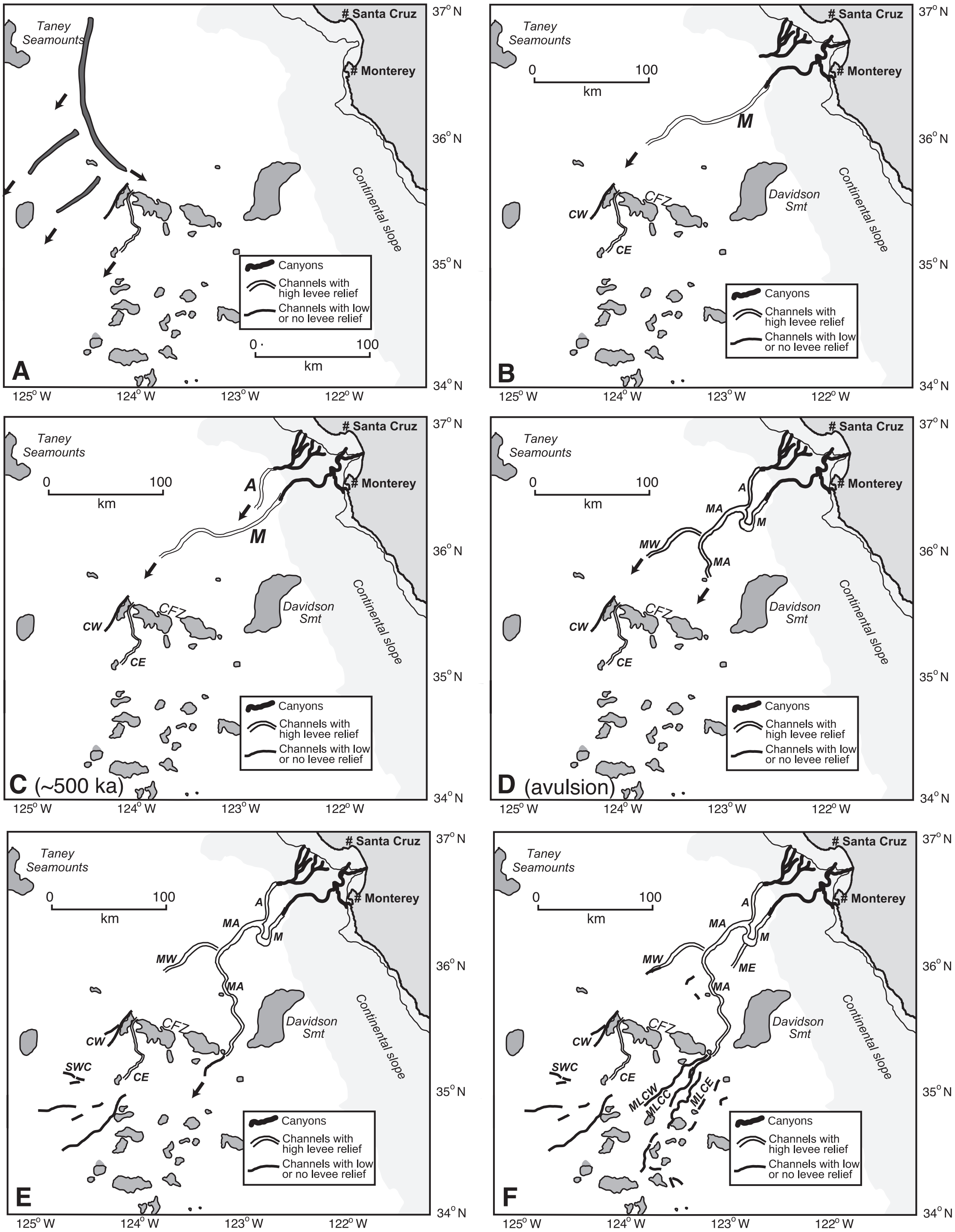

Fig. 16. Summary cartoon of channel evolution as related to fan growth (see text).

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References

Atwater, T., 1989. Plate tectonic history of the northeast Pacific and western North America. In: Winterer, E.L., Hussong, D.M., Decker, R.W. (Eds.), The Eastern Pacific Ocean and Hawaii. The Geology of North America, vol. N. Geological Society of America, Boulder, CO, pp. 21–72.

Atwater, T., Severinghaus, J., 1989. Tectonic maps of the northeast Pacific. In: Winterer, E.L., Hussong, D.M., Decker, R.W. (Eds.), The Eastern Pacific Ocean and Hawaii. The Geology of North America, vol. N. Geological Society of America, Boulder, CO, pp. 15–20.

Brunner, C.A., Normark, W.R., 1985. Biostratigraphic implications for turbidite depositional processes on the Monterey deep-sea fan, central California. J. Sediment. Petrol. 55, 495–505.

Chase, T.E., Normark, W.R., Wilde, P., 1975. Oceanographic data of the Monterey deep-sea fan. Institute of Marine Resources Tech. Report Series TR-58 (1 sheet).

Dill, R.F., Dietz, R.S., Stewart Jr., H.B., 1954. Deep-sea channels and delta of the Monterey submarine canyon. Bull. Geol. Soc. Am. 65, 191–194.

EEZ-SCAN 84 Scientific Staff, 1986. Atlas of the exclusive economic zone, western coterminous United States. U.S. Geological Survey Miscellaneous Investigations Series. I-1792, (152 pp., scale 1:500,000).

Fildani, A., 1993. Evoluzione deposizionale e significato geodinamico delle torbiditi del Monterey Fan: California Centrale (USA). Thesis. Universita degli Studi di Roma "La Sapienza".

Fildani, A., Normark, W.R., Reid, J.A., 1999. Which came first: Monterey Canyon or Fan? Elemental architecture of central California turbidite systems. Bull. Am. Assoc. Pet. Geol. 83, 687.

Flood, R.D., Piper, D.J.W., Klaus, A., et al., 1995. Proceedings ODP. Initial Reports, vol. 155, pp. 5-16.

Gardner, J., Field, M.E., Lee, H., Edwards, B.E., Masson, D.G., Kenyon, N., Kidd, R.B., 1991. Ground-truthing 6.5-kHz side scan sonographs: what are we really imaging? J. Geophys. Res. 96, 5955–5974.

Gardner, J.V., Bohannon, R.G., Field, M.E., Masson, D.G., 1996. The morphology, processes, and evolution of Monterey Fan: a revisit. In: Gardner, J.V., Field, M.E., Twichell, D.C. (Eds.), Geology of the United States' Seafloor: The view from GLORIA. Cambridge Univ. Press, New York, NY, pp. 193–220.

Greene, H.G., Hicks, K.R., 1990. Ascension–Monterey canyon system: history and development. In: Garrison, R.E., Greene, H.G., Hicks, K.R., Weber, G.E., Wright, T.L. (Eds.), Geology and Tectonics of the Central California Coast Region, San Francisco to Monterey Bay. Pacific Section, Am. Assoc. Petrol. Geol. Volume and Guidebook, vol. 67, pp. 229–249.

Hess, G.R., Normark, W.R., 1976. Holocene sedimentation history of the major fan valleys of Monterey Fan. Mar. Geol. 22, 233–251.

Johnson, K.S., Paull, C.K., Barry, J.P., Chavez, F.P., 2001. A decadal record of underflows from a coastal river into the deep sea. Geology 29, 1019–1022.

Klaucke, I., Masson, D.G., Kenyon, N.H., Gardner, J.V., 2004. Sedimentary processes of the lower Monterey Fan channel and channel-mouth lobe. Mar. Geol. 206, 181–198 doi:10.1016/j.margeo.2004.02.006.

Livoti, A., 1993. Analisi sismostratigrafica del Monterey Fan: California Centrale (U.S.A.). Thesis. Universita degli Studi di Roma "La Sapienza."

Masson, D.G., Kenyon, N.H., Gardner, J.V., Field, M.E., 1995. Monterey Fan: channel and overbank morphology. In: Pickering, K.T., Hiscott, R.N., Kenyon, N.H., Ricci Lucchi, R., Smith, R. (Eds.), An Atlas of Deep-Water Environments: Architectural Style in Turbidite Systems. Chapman & Hall, London, pp. 74–79.

McGann, M., Brunner, C.A., 1988. Quantitative microfossil (Foraminifers and pollen) and sedimentologic data on core S3-15G from Monterey Fan, central California continental margin. Open-File Report (U.S. Geological Survey), vol. 88-693. 79 pp.

McHugh, C.M.G., Ryan, W.B.F., 2000. Sedimentary features associated with channel overbank flow: examples from the Monterey Fan. Mar. Geol. 163, 199–215.

McHugh, C.M.G., Ryan, W.B.F., Hecker, B., 1992. Contemporary sedimentary processes in the Monterey Canyon-fan system. Mar. Geol. 107, 35–50.

Menard, H.W., 1955. Deep-sea channels, topography, and sedimentation. Bull. Am. Assoc. Pet. Geol. 39, 236–255.

Mutti, E., 1985. Turbidite systems and their relations to depositional sequences. In: Zuffa, G.G. (Ed.), Provenance of Arenites. NATO ASI Series. Series C: Mathematical and Physical Sciences, vol. 148. Reidel, Dordrecht, pp. 65–94.

Normark, W.R., 1970. Channel piracy on Monterey deep-sea fan. Deep-Sea Res. 17, 837–846.

Normark, W.R., 1985. Local morphologic controls and effects of basin geometry on flow processes in deep marine basins.

In: Zuffa, G.G. (Ed.), Provenance of Arenites. NATO ASI Series. Series C: Mathematical and Physical Sciences, vol. 148. Reidel, Dordrecht, pp. 47–63.

Normark, W.R., 1999. Late Pleistocene channel–levee development on Monterey submarine fan, central California. Geo Mar. Lett. 18, 179–188.

Normark, W.R., Gutmacher, C.E., 1988. Sur submarine slide, Monterey Fan, central California. Sedimentology 35, 629–647.

Normark, W.R., Gutmacher, C.E., 1989. Major submarine fans of the California continental rise. In: Winterer, E.L., Hussong, D.M., Decker, R.W. (Eds.), The Eastern Pacific Ocean and Hawaii. The Geology of North America, vol. N. Geological Society of America, Boulder, CO, pp. 373–382.

Normark, W.R., Gutmacher, C.E., Chase, T.E., Wilde, P., 1985. Monterey Fan, Pacific Ocean. In: Bouma, A.H., Normark, W.R., Barnes, N.E. (Eds.), Submarine Fans and Related Turbidite Systems. Springer-Verlag, New York, pp. 79–86.

Normark, W.R., Piper, D.J.W., Posamentier, H., Pirmez, C., Migeon, S., 2002. Variability in form and growth of sediment waves on turbidite channel levees. Mar. Geol. 192, 23–58.

Piper, D.J.W., Normark, W.R., 1983. Turbidite depositional patterns and flow characteristics. Navy submarine fan, California Borderland. Sedimentology 30, 681–694.

Piper, D.J.W., Normark, W.R., 2001. Sandy fans—from Amazon to Hueneme and beyond. Bull. Am. Assoc. Pet. Geol. 85, 1407–1438.

Reid, J.A., Fildani, A., Normark, W.R., 1999. Monterey East turbidite deposit: a proto channel/levee complex or a zone of turbulent flow stripping? EOS Trans.-Am. Geophys. Union 80, F560.

Shepard, F.P., 1966. Meander in valley crossing a deep-sea fan. Science 154, 385–386.

Shepard, F.P., 1973. Submarine Geology. Harper and Row, New York, p. 517.

Wilde, P., 1965a. Recent sediments of the Monterey deep-sea fan. Tech. Rpt # HEL-2-13, Hydraulic Engineering Laboratory, University of California, Berkeley. 153 pp.

Wilde, P., 1965b. Estimates of bottom current velocities from grain-size measurements for sediments from Monterey deep-sea fan. Mar. Technol. Soc.-Am. Litt. Soc. Proc. 2, 718–727.

Yamamoto, M., Yamamuro, M., Tada, R., 2000. Late Quaternary records of organic carbon, calcium carbonate, and biomarkers from Site 1016 off Point Conception, California margin. In: Lyle, M., Koizumi, I., Richter, C., Moore Jr., T.C. (Eds.), Proc. ODP, Sci. Results, vol. 167. Ocean Drilling Program, College Station, TX, pp. 183–194.