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Origins of large crescent-shaped bedforms within the axial channel of Monterey Canyon, offshore California

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ABSTRACT

Crescent-shaped bedforms with wavelengths from 20 to 80 m, amplitudes to 2.5 m, and concave down-canyon crests occur in the axial channel of Monterey Canyon (offshore California, USA) in water depths from 11 to more than 350 m. The existence of these features may be an important new clue as to how sediment moves through submarine canyons. Three complementary studies were initiated in 2007 to understand the origin and evolution of these bedforms. (1) Vibracoring. Three transects of closely spaced remotely operated vehicle–collected vibracores were obtained across these bedforms. The seafloor underneath these features is composed of gravity-flow deposits. (2) Acoustic array. Three boulder-sized concrete monuments containing acoustic beacons were buried just below the surface of the canyon floor in ~290 m water depth and their locations were redetermined on 17 subsequent occasions. Although the beacons became more deeply buried >0.6 m below the seafloor, they still could be tracked acoustically. Over a 26-month period the position of 1 or more of the beacons moved down-canyon during at least 6 discrete transport events for a total displacement of 994–1676 m. The movement and burial of the monuments suggest that the seabed was mobilized to >1 m depth during gravity-flow events. (3) Autonomous underwater vehicle (AUV) repeat mapping. AUV-acquired high-resolution multibeam mapping, and CHIRP (compressed high-intensity radar pulse) subbottom profiling surveys of the seafloor in the active channel were repeated four times in the first half of 2007. In addition, the movement of large instrument frames deployed in 2001–2003 within the axis of Monterey Canyon in the area now known to be associated with the crescent-shaped bedforms is documented.

The fate of the frames has helped elucidate the frequency, transport potential, and processes occurring within the axis of Monterey Canyon associated with these bedforms. The crescent-shaped bedforms appear to be produced during brief gravity-flow events that occur multiple times each year, commonly coincident with times of large significant wave heights. Whether the bedforms are generated by erosion associated with cyclic steps in turbidity flows or internal deformation associated with slumping during gravity-flow events remains unclear.

INTRODUCTION

Processes that occur within and shape submarine canyons are among the oldest problems considered in the field of marine geology (Shepard, 1981). While submarine canyons are frequently carved into competent strata and act as major conduits for cross-margin sediment transport, progress in understanding the processes involved has been hampered by the difficulties of access within these remote and topographically complicated seafloor environments. Analogies between submarine canyons and rivers are common, yet the types of basic measurements that led to an understanding of the dynamics of rivers (e.g., detailed sampling, repeat mapping, and monitoring) have only recently become possible in submarine canyons. The development of remotely operated vehicles (ROV), autonomous underwater vehicles (AUV), high-resolution navigation, and sophisticated multibeam mapping tools have enabled measurements in submarine canyon channels to be made at high spatial resolutions comparable to those in terrestrial river channels.

Within the past decade the understanding of physical processes within submarine canyons in general, and specifically in Monterey Canyon (offshore Monterey Bay, California, USA; Fig. 1), has expanded enormously and has

included several surprises. The first major step was the use of a hull-mounted 30 kHz multibeam system for the acquisition of a regional bathymetric grid (5 m resolution; Greene et al., 2002) that delineated the axial channel in Monterey Canyon. Sediment cores collected using an ROV-mounted vibracoring system have revealed that the axial channel of upper Monterey Canyon contains coarse-grained sediment clasts that represent all the major lithologies that crop out in the Salinas and Pajaro Valleys (Paull et al., 2003, 2005). Monitoring activities have revealed the occurrence of numerous subannual sediment transport events (Paull et al., 2003; Xu et al., 2004). The discovery that the recurrence frequency of significant sediment transport events is subannual was unanticipated.

Higher-resolution multibeam data (~1 m resolution) have been collected near the head of Monterey Canyon to a water depth of ~250 m by the California State University Monterey Bay Seafloor Mapping Laboratory using a Reson 8101 200 kHz multibeam system carried on a dedicated launch. These multibeam bathymetric data revealed for the first time large crescent-shaped bedforms on the seafloor within the axial channel of Monterey Canyon (Smith et al., 2005, 2007). These features have wavelengths to 80 m, amplitudes to 2.5 m, and distinct arcuate, asymmetric crests oriented roughly perpendicular to the channel and facing concave down-canyon. We now know that similar crescent-shaped bedforms occur within Monterey Canyon to a depth of at least 1900 m, and also within Santa Monica, Mugu, Redondo, Carmel, and La Jolla Canyons (Paull et al., 2008). These bedforms appear to be common features on the floor of active submarine canyons.

Perhaps the greatest surprise came from the comparison of repeated multibeam mapping surveys conducted since 2004 near the head of Monterey Canyon, which detected active movement of crescent-shaped bedforms between successive surveys (Smith et al., 2005, 2007). While it is

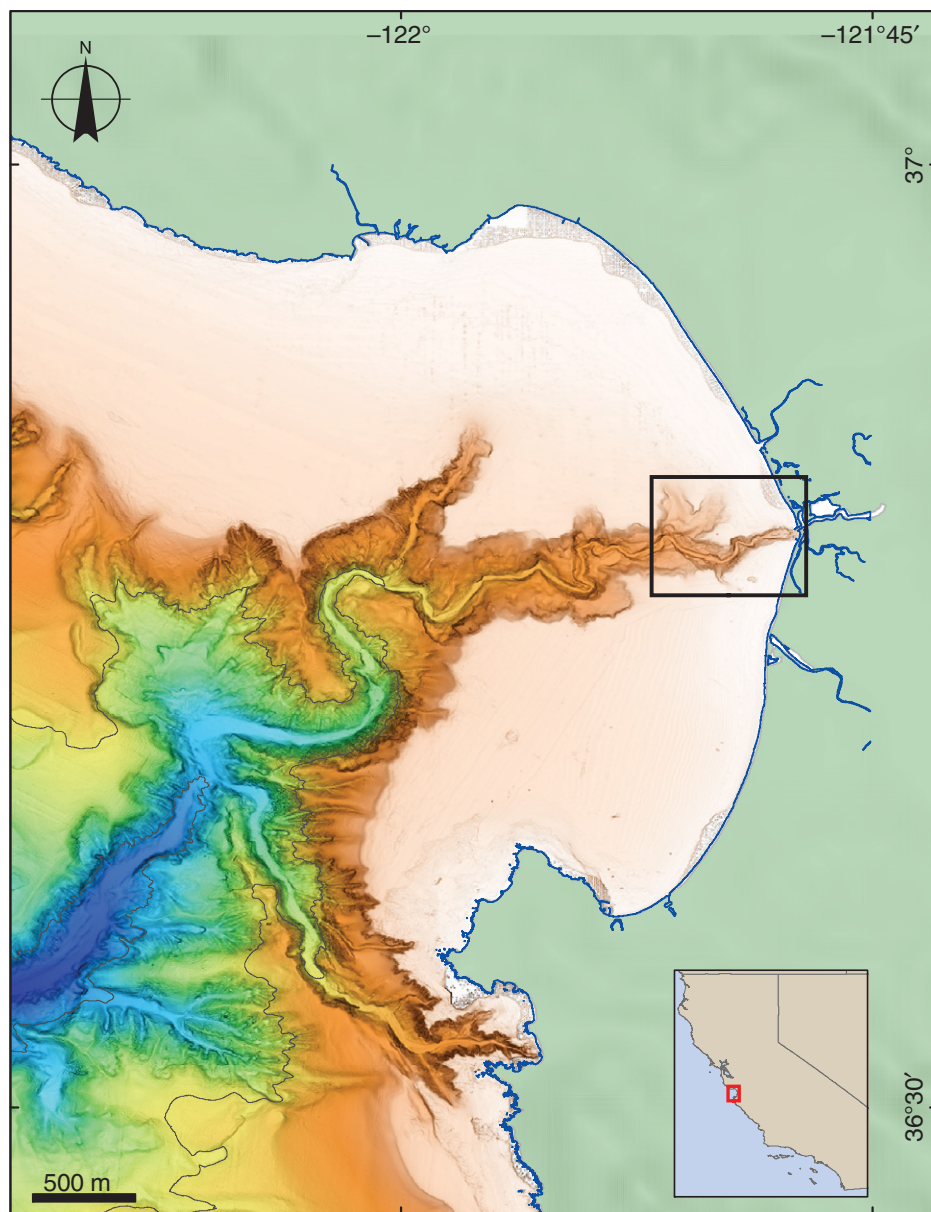


Figure 1. Map showing bathymetry of Monterey Bay and Monterey Canyon out to 2300 m water depth based on regional EM-300 multibeam survey (Greene et al., 2002). Inset map shows location of Monterey Bay with respect to California. Box outlines area of AUV surveys shown in more detail in Figure 2.

clear that the position of these bedforms changed between surveys conducted only months apart, the direction of bedform movement has not been resolved. Smith et al. (2007) argued that these bedforms migrate up-canyon, while Xu et al. (2008) questioned whether this observation reflected a sampling artifact, and proposed that the bedforms migrate down-canyon. Xu et al. (2008) also reviewed the existing knowledge of currents within Monterey Canyon. Bedform migration for both of these models depends on sediment movement driven by tidal currents.

The common occurrence of tractive currents sufficiently energetic to both form these crescent-shaped bedforms and cause their migration in relatively shallow water (11 m to >1900 m water depth; Paull et al., 2008) is uncertain.

Formation of Large Crescent-Shaped Bedforms

Large seafloor bedforms commonly called sand waves are known to form where turbulent flows driven by strong currents and mobile sandy

beds occur (Wynn and Stow, 2002; Hulscher and Dohmen-Janseen, 2005). Sand waves can range in size to 25 m high, have wavelengths as large as 300 m, and can be as long as 5 km. Such features are common on tidally influenced shelves (Field et al., 1981; Passchier and Kleinhans, 2005), open continental shelves (Duffy and Hughes-Clarke, 2005), within constricted straits (Lonsdale and Malfait, 1974; Mosher and Thomson, 2000, 2002; Barnard et al., 2006; Fenster et al., 2006), and along sections of continental slopes exposed to strong currents (Mienis et al., 2006). Sand waves are usually found on relatively flat seafloor ($<0.5^\circ$), and migrate due to tractive forces. The internal stratigraphy of sand waves (e.g., cross-stratification and reactivation surfaces) reflects their formation mechanism.

Similar waved-shaped features have been observed in the axes of submarine channels and canyons (e.g., Prior et al., 1986; Piper et al., 1985; Wynn et al., 2002; Green and Uken, 2008). These bedforms have a predictable internal layering and are usually interpreted as being produced by the combination of erosion and deposition caused by tractive forces. Submarine canyons are commonly viewed as the conduits through which turbidity currents flow, feeding the submarine fans below (Bouma, 2000; Ito and Saito, 2006).

Repetitive crescent-shaped bedforms in a variety of environments have been interpreted as being formed by cyclic steps in turbidity currents and other vigorous flows (Kostic and Parker, 2006a, 2006b). Cyclic steps are related to the development of hydraulic jumps in the flow, i.e., a short zone over which the flow makes a rapid transition from shallow, swift supercritical flow (Froude number > 1) to thick, tranquil subcritical flow (Froude number < 1). Theory and models indicate that cyclic steps in overriding flows (Koyama and Ikeda, 1998; Parker and Izumi, 2000; Sun and Parker, 2005; Taki and Parker, 2005) can create repetitive trains of scarps on the bottom through a combination of erosion and deposition. These trains of scarps will migrate with the hydraulic jumps in the flow above them. The sizes of these features range from <1 m in stream beds to giants as long as 6 km (Fildani et al., 2006; Lamb et al., 2008), spanning the size range of the crescent-shaped scarps in Monterey Canyon.

Hsu (1989) suggested that crescent-shaped bedforms on the floors of submarine canyons might be generated by slumping. Slumps are masses of material that move downslope, usually along a concave-up glide plane (Dingle, 1977). The surfaces of slumps in cohesive materials commonly contain repetitive trains of en echelon secondary scarps with similar concave-shaped crests facing down-canyon that are more or

less parallel with the headwall scarp (Lee et al., 1993; Hampton et al., 1996; Canals et al., 2004; Martel, 2004). Slumps are formed by a series of small listric faults that rotate and back-tilt the displaced material on the surface of the slide and have strike-slip faults along their sides. The displacement on these small listric faults can be minor in comparison with the total displacement of the slide mass, which is focused primarily on master failure surfaces. The small-displacement listric faults sole out onto the master surface. These features indicate brittle behavior of the seafloor sediments. The morphologic appearance of such slump mass surfaces is similar to the crescent-shaped bedforms described herein (e.g., Gardner et al., 1999; Gazioglu et al., 2005).

Slumps and other submarine mass movements are initiated when the sediment's shear resistance is exceeded by a driving stress (Lee et al., 2007). While there are a number of factors that may contribute to submarine failures, increase in the pore pressure within seafloor sediments reduces the sediments shear resistance, and is one mechanism to stimulate bottom failures. Pore pressure increases are commonly associated with cyclic wave loading during time of large seas and by rapid sedimentation. Increased pore pressure can also cause

loss of internal cohesion within seafloor sediments that can trigger the formation of fluidized debris flows (Iverson, 1997). Agitation within the fluidized sediment flows creates the characteristically poorly sorted gravity-flow deposits. Transient brittle behavior during emplacement and dewatering may be responsible for formation of small displacement faults superimposed on the newly deposited sediments.

This study was initiated to investigate whether tractive forces generated by regular tidal currents cause changes in the position of crescent-shaped bedforms in Monterey Canyon. Some observations about the movement of large instrument frames deployed within the canyon floor are also described here. Together the data show that the crescent-shaped bedforms are produced during discrete, high-energy gravity flow events, but the detailed mechanism of their formation remains unclear.

METHODS

AUV Surveys

High-resolution surveys of seafloor bathymetry were conducted using an AUV developed specifically for seafloor mapping (Kirkwood, 2007; Caress et al., 2008) by the Monterey Bay

Aquarium Research Institute. This AUV carries a Reson 7100, 200 kHz multibeam sonar and an Edgetech 2–16 kHz CHIRP (compressed high-intensity radar pulse) subbottom profiler. The AUV obtains high-resolution multibeam bathymetry (vertical resolution of 0.15 m and a horizontal footprint of 0.7 m at 50 m survey altitude) and CHIRP seismic-reflection profiles (vertical resolution of 0.11 m). Initial navigation fixes are obtained from a global positioning system (GPS) when the AUV is at the sea surface. AUV position is subsequently updated using a Kearfott inertial navigation system and a Doppler velocity log (DVL). These surveys were conducted at 3 knots with the AUV programmed to fly 50 m above the seafloor.

Four AUV multibeam mapping, subbottom CHIRP surveys were conducted within the axis of upper Monterey Canyon on 31 January, 1 February, 27 February, and 18 June 2007 using the same mission strategy (Figs. 2, 3, and 4). To provide continuous DVL bottom tracking, the AUV was launched from the R/V *Zephyr* on the continental shelf north of the head of Monterey Canyon in ~40 m water depth. The AUV was pre-programmed to proceed to 145 waypoints within the canyon. The programmed waypoints took the vehicle down through the sinuous canyon to

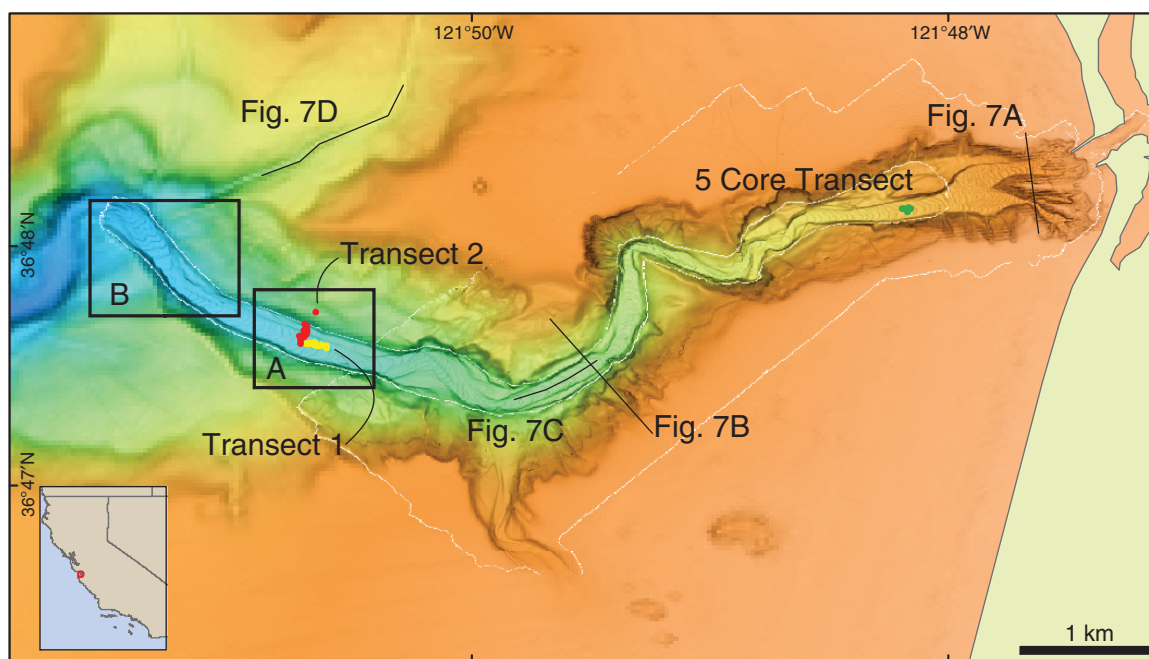


Figure 2. Bathymetric map of uppermost Monterey Canyon out to 380 m water depth including EM-300 multibeam data (Greene et al., 2002), California State University Monterey Bay data (Smith et al., 2005, 2007), and 18 June 2007 autonomous underwater vehicle (AUV) survey data. Location indicated in Figure 1. Box A outlines area shown in more detail in Figure 3. Locations of an 18 core transect (transect 1) collected along the canyon axis (yellow dots), a 19 core transect (transect 2) collected perpendicular to the canyon axis (red dots), and a 5 core transect (transect 3) along the canyon axis in upper Monterey Canyon (green dots) are shown. Area of detailed images showing changes between repeated AUV surveys in Figure 4 is indicated by box B. Locations of CHIRP (compressed high-intensity radar pulse) profiles shown in Figure 7 are indicated with lines.

a water depth of 340 m, turned it around to fly back up to the canyon head, and turned it back down the canyon again to obtain three overlapping swaths. Upon completion, the AUV passed up a gully on the north flank of the canyon and was recovered on the shelf. A total of 25.6 km of seafloor survey data was collected during each mapping survey. Data processing was accomplished using MB-System, an interactive multi-beam software package (Caress and Chayes, 1996; Caress et al., 2008). Difference maps were made by subtraction of the subsequent from the previous survey. Full bathymetric and difference maps associated with these surveys are provided in the Supplemental Figures 1¹ and 2².

ROV Coring and Observations

On 26, 27, and 28 June 2007 the ROV *Ventana* collected 18 vibracores along a 130-m-long transect (transect 1) within and parallel to the axis of Monterey Canyon between 284 and 290 m water depth (Figs. 2 and 3; Table 1). Transect 1 crossed the crests and flanks of three crescent-shaped bedforms. An additional transect of 19 vibracores (transect 2) was collected on 15, 16, 18, 19 October 2007. Transect 2 was oriented perpendicular to the axial channel and extended 181 m from the center of the channel (292 m water depth) to the north-northeast, onto a bench on the canyon side, and up the lower slope of the canyon wall to 279 m water depth (Figs. 2 and 3). On 22 October 2007 an additional five vibracores were taken along an 80-m-long transect (transect 3) across the crest

and flank of one crescent-shaped bedform near the canyon head in 117–119 m water depth.

The ROV *Ventana* vibracoring system is capable of collecting cores as much as 4 m long using 7.65 cm internal diameter (I.D.) aluminum core tubes (Paull et al., 2001). Vibracores from the crescent-shaped bedform area are 49–200 cm in length and those from the lower slope of the canyon wall are as much as 391 cm in length (Table 1). These cores were logged with a GEOTEK (<http://www.geotek.co.uk>) multisensor core logger, split, scanned with a GEOTEK digital line-scanning camera, and archived at the U.S. Geological Survey in Menlo Park, California.

The position of the ROV was determined using a Sonardyne International Ltd. ([http://](http://www.sonardyne.co.uk)

www.sonardyne.co.uk) ultra short baseline system (USBL) between transducers mounted on the ROV and on a pole that extends below the hull of the R/V *Point Lobos*, the support vessel for the ROV *Ventana*. Position of the *Ventana* was calculated in real time relative to the ship GPS location. Previous experience indicated that ROV positions based on individual fixes are accurate to ~15 m. Because this level of error exceeded the desired spacing between cores along transects, a portable acoustic transponder beacon (Sonardyne Homer Pro) was used to help refine the relative positions of vibracores collected along transects. The transponder beacon was deployed by the ROV on a syntactic foam float anchored with a lead ball, so that the beacon was 1 m off the seafloor at the first

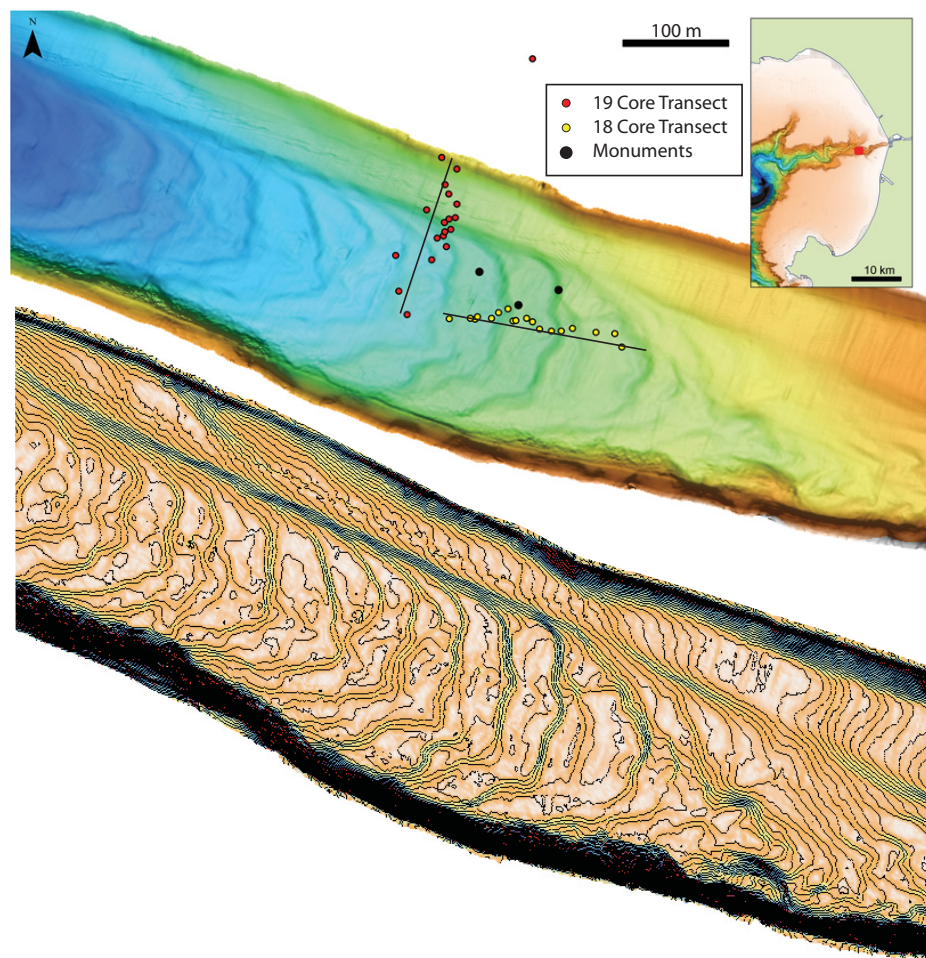


Figure 3. Image showing details of autonomous underwater vehicle–collected bathymetry associated with one small section (box A in Fig. 2) of the floor of Monterey Canyon. Upper panel is bathymetry (ranging in water depth from 260 to 300 m) and lower panel contains a slope map of the same area with 50 cm contours. Darker shades indicate steeper slopes. Locations of cores in transects 1 and 2 illustrated in Figures 8 and 9 are shown with yellow and red dots, respectively. Black dots indicate the initial position of the three poured-concrete monuments.

¹Supplemental Figure 1. PDF file of images that show bathymetric coverage from each of the four repeated autonomous underwater vehicle–flown bathymetric surveys of the axis of upper Monterey Canyon. The initial survey was conducted on 31 January 2007, and repeated on 1 February 2007, 27 February 2007, and 18 June 2007. These are color-coded over a depth range of 100 m (orange) to 360 (blue). Map above shows location of repeated surveys (outlined with box) with respect to the regional bathymetry. If you are viewing the PDF of this paper or reading it offline, please visit <http://dx.doi.org/10.1130/GES00527.S1> or the full-text article on www.gsapubs.org to view Supplemental Figure 1.

²Supplemental Figure 2. PDF file of images that show bathymetric coverage from 18 June 2007 [color-coded over a depth range of 100 m (orange) to 360 (blue)] and difference maps between the four repeated autonomous underwater vehicle–flown bathymetric surveys of the axis of upper Monterey Canyon (e.g., 31 January to 1 February 2007; 1 February to 27 February 2007; and 27 February to 18 June 2007; color-coded with a depth range from –3 to +3 m). Map shows location of repeated surveys (outlined with box) with respect to the regional bathymetry. If you are viewing the PDF of this paper or reading it offline, please visit <http://dx.doi.org/10.1130/GES00527.S2> or the full-text article on www.gsapubs.org to view Supplemental Figure 2.

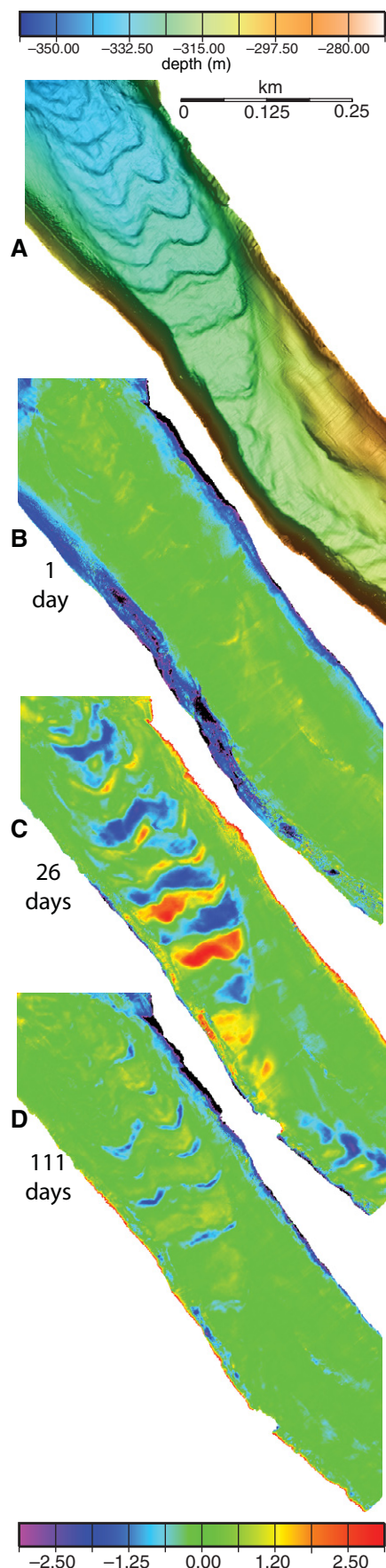
Origins of large crescent-shaped bedforms within the axial channel of Monterey Canyon

Figure 4. Images resulting from the autonomous underwater vehicle multibeam surveys in upper Monterey Canyon within area outlined by box B in Figure 2. (A) Detailed bathymetric data collected during the 18 June 2007 survey. (B, C, D) Difference maps showing the changes that occur between the surveys. Color scale at the top applies to A and color scale at the bottom applies to difference maps in B, C, and D. Depth units are in meters. Negative changes in depth correspond with removal of sediment.

TABLE 1. LOCATIONS AND LENGTHS OF CORES FROM THREE REMOTELY OPERATED VEHICLE-COLLECTED VIBRACORING TRANSECTS WITHIN THE AXIS OF UPPER MONTEREY CANYON

Dive and core	Depth (m)	Latitude	Longitude	Length (cm)
Transect 1 (18 core canyon axis transect)				
V3029 VC-A	286.2	36.79306	-121.84380	97
V3030 VC-B	285.9	36.79303	-121.84398	66
V3031 VC-C	287.3	36.79305	-121.84408	73
V3032 VC-D	287.3	36.79311	-121.84414	161
V3033 VC-E	287.0	36.79312	-121.84431	176
V3034 VC-F	286.9	36.79314	-121.84419	111
V3035 VC-G	289.6	36.79322	-121.84435	95
V3036 VC-H	289.4	36.79319	-121.84443	150
V3037 VC-I	289.3	36.79314	-121.84449	138
V3038 VC-J	289.1	36.79313	-121.84463	49
V3039 VC-K	289.0	36.79315	-121.84461	101
V3040 VC-L	289.4	36.79314	-121.84467	99
V3041 VC-M	287.2	36.79312	-121.84428	150
V3042 VC-N	285.3	36.79302	-121.84360	110
V3043 VC-O	284.8	36.79301	-121.84344	157
V3044 VC-P	285.1	36.79290	-121.84338	200
V3045 VC-Q	291.0	36.79314	-121.84485	64
V3046 VC-R	285.9	36.79303	-121.84390	61
Transect 2 (19 core canyon flank transect)				
V3096 VC-120	290.2	36.79384	-121.84490	147
V3097 VC-121	292.1	36.79368	-121.84531	86
V3098 VC-122	289.6	36.79396	-121.84489	146
V3099 VC-123	289.9	36.79407	-121.84504	170
V3100 VC-124	285.5	36.79411	-121.84479	313
V3101 VC-125	280.4	36.79441	-121.84479	339
V3102 VC-126	289.0	36.79390	-121.84484	172
V3103 VC-127	284.7	36.79400	-121.84480	297
V3104 VC-128	279.1	36.79451	-121.84491	391
V3105 VC-129	284.2	36.79428	-121.84489	192
V3106 VC-130	280.6	36.79535	-121.84414	345
V3107 VC-131	288.8	36.79382	-121.84495	126
V3108 VC-132	289.2	36.79375	-121.84488	138
V3109 VC-133	289.8	36.79364	-121.84500	84
V3110 VC-134	290.0	36.79317	-121.84521	61
V3111 VC-135	288.9	36.79337	-121.84528	117
V3112 VC-136	283.6	36.79420	-121.84485	297
V3113 VC-137	285.1	36.79399	-121.84485	230
V3114 VC-138	287.5	36.79388	-121.84489	130
Transect 3 (5 core canyon head transect)				
V3117 VC-141	118.1	36.80234	-121.80279	199
V3118 VC-142	117.7	36.80267	-121.80271	142
V3119 VC-143	117.4	36.80264	-121.80256	202
V3120 VC-144	119.5	36.80260	-121.80301	161
V3121 VC-145	119.4	36.80264	-121.80316	157

coring site. The range to the beacon was then measured at each subsequent coring site. For cores taken within 50 m of the transponder beacon, an ROV camera was used to visually locate the beacon, and the ROV then headed off on a set course for a coring transect. The beacon provided a range to the ROV that is accurate to ~1%. Although visual navigation was typically impaired by low visibility in the turbid bottom waters of the upper canyon, some bottom observations were possible.

Acoustic Array to Track Sediment Movement

A small acoustic array was deployed within the axis of Monterey Canyon in 2007. This array was designed to assess whether sediment within the canyon floor moves either in episodic events or more or less continuously down-canyon. The array used six Sonardyne Coastal Homer beacons, which are like the Homer Pro beacons but have a more restricted depth range (<600 m).

A Coastal Homer beacon was cast within each of three boulder-sized, poured-concrete truncated square pyramids, referred to as monuments (Fig. 5). These monuments (~45 kg, ~50 cm in height) were buried in the seafloor at water depths between 285 and 288 m using a sediment suction pump on *Ventana* so that the beacons protruded ≤ 10 cm above the sediment surface. They were arranged in a line parallel to the canyon axis, about ~30 m south-southwest from the northern edge of the axial channel (Fig. 3).

Each of the remaining 3 Coastal Homer beacons was attached to 60 kg frames consisting of a 1.5-m-tall steel mast mounted on a 1 m square angle iron base. These steel frames were designed to remain upright in currents as high as 2 m/s. This current rating is 2.5 times the maximum observed speed (80 cm/s; Xu et al., 2008) of daily tidal currents that sweep through the axis of the canyon. These frames were deployed using the ROV *Ventana* along an ~75 m line parallel with the canyon axis on the edge of a bench on the canyon's northern flank just ~2 m above the active channel (Figs. 2 and 3) in water depths between 283 and 285 m. This array of beacons had a clear line-of-sight path onto the canyon floor to the monuments buried in the axial channel.

The initial plan was to track the relative positions of the concrete monuments and steel frames by periodically locating each beacon with *Ventana* by sitting on the seafloor and triangulating to adjacent beacons. If the monuments

became buried by the migration of the crescent-shaped bedforms, the thickness of the sediment cover could also be determined by finding the minimum distance to the beacon when *Ventana* was sitting on the seafloor directly over the beacon. Previous (albeit inadvertent) experience with locating buried Homer Pro beacons indicates that they can be detected when they are buried by 1 m of sand (Paull et al., 2003). Signals from the Homer Pro beacons are attenuated nominally by a sand cover on the canyon floor.

Simultaneous with these deployments was an effort to improve the navigation system that allowed the Homer Pro beacon positions to be determined using the USBL system on the R/V *Point Lobos*. Homer Pro beacon positions were determined by slowly driving the R/V *Point Lobos* over the sites in a figure-8 pattern while collecting individual fixes every 2 s. When a large number of individual fixes are averaged (>200), the composite error in the position can be reduced to <1 m.

Movements of Large Instrument Frames

Four large steel instrument frames were deployed in the axis of Monterey Canyon between 289 m and 520 m water depths during 2002 as part of an engineering test to connect them together with ROV-laid fiber-optic and power cables. A description of what happened to these frames is included in this paper. The unanticipated entrainment of these frames

in gravity-flow events helped to elucidate the processes and triggering mechanism for transport events occurring within the canyon axis.

Each frame consisted of a 2-m-square, thick steel base, with a mast sticking up from its center (Fig. 6A). The tops of the masts were made to hold instrument packages that could be deployed and swapped out using an ROV. Two frames also had trawl-resistant sidings, which were designed to hold instruments packages and weighed ~1360 kg with 3-m-high masts (Fig. 6A). The other frames weighed 227 kg and resembled an overturned thumbtack in shape with a 2-m-high mast coming up from the center of a thick steel base.

The frames were lowered from a surface ship on a wire and released when ~2 m above the seafloor. Their position within the axial channel was confirmed with ROV observations before the frames were instrumented. The instrument packages included a Nobska MAV-3 current meter equipped with conductivity, temperature, pressure, and turbidity sensors and a Homer Pro beacon (as in Paull et al., 2003). Each of these deployments was followed by 3–10 inspections with the ROV *Ventana* over a 10-month period during which the instrument packages could be swapped out, their position redetermined, and their condition observed. In all cases ROV visits continued until the frames were abandoned after being damaged or repeated ROV searches failed to relocate them.

RESULTS

AUV Surveys—Multibeam Results

AUV surveys were focused on the axial channel in upper Monterey Canyon between 100 and 350 m water depth, an area that is dominated by the previously described crescent-shaped bedforms (Smith et al., 2005, 2007; Xu et al., 2008). Compared to previously published data, the 50-cm-resolution AUV-acquired multibeam data provide increased detail (Figs. 3 and 4; Supplemental Figs. 1 and 2 [see footnotes 1 and 2]). These bedforms have concave down-canyon crescent-shaped crests with wavelengths between 20 and 80 m. Their crests are asymmetric with a longer surface facing up-canyon that is nearly horizontal or dipping slightly up-canyon, while the down-canyon face is more steeply dipping ($\sim 20^\circ$ or greater) with relief typically between 1 and 2.5 m.

The quality of the multibeam data in water depths shallower than ~150 m in the uppermost canyon was diminished by numerous mid-water (false bottom) returns. These mid-water returns were associated with schools of sardines, which were plentiful in this area during the surveys.

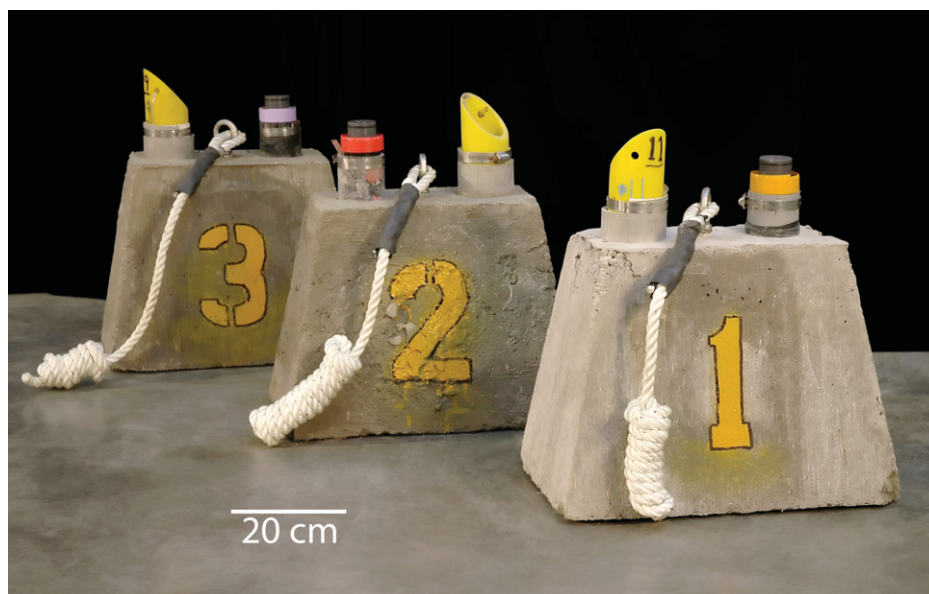


Figure 5. Photograph showing concrete monuments containing acoustic beacons (yellow shroud) that were buried within the floor of Monterey Canyon. The movements of the beacons are shown in Figure 10 and Table 2. The second beacon encased in the monument was not used for tracking.

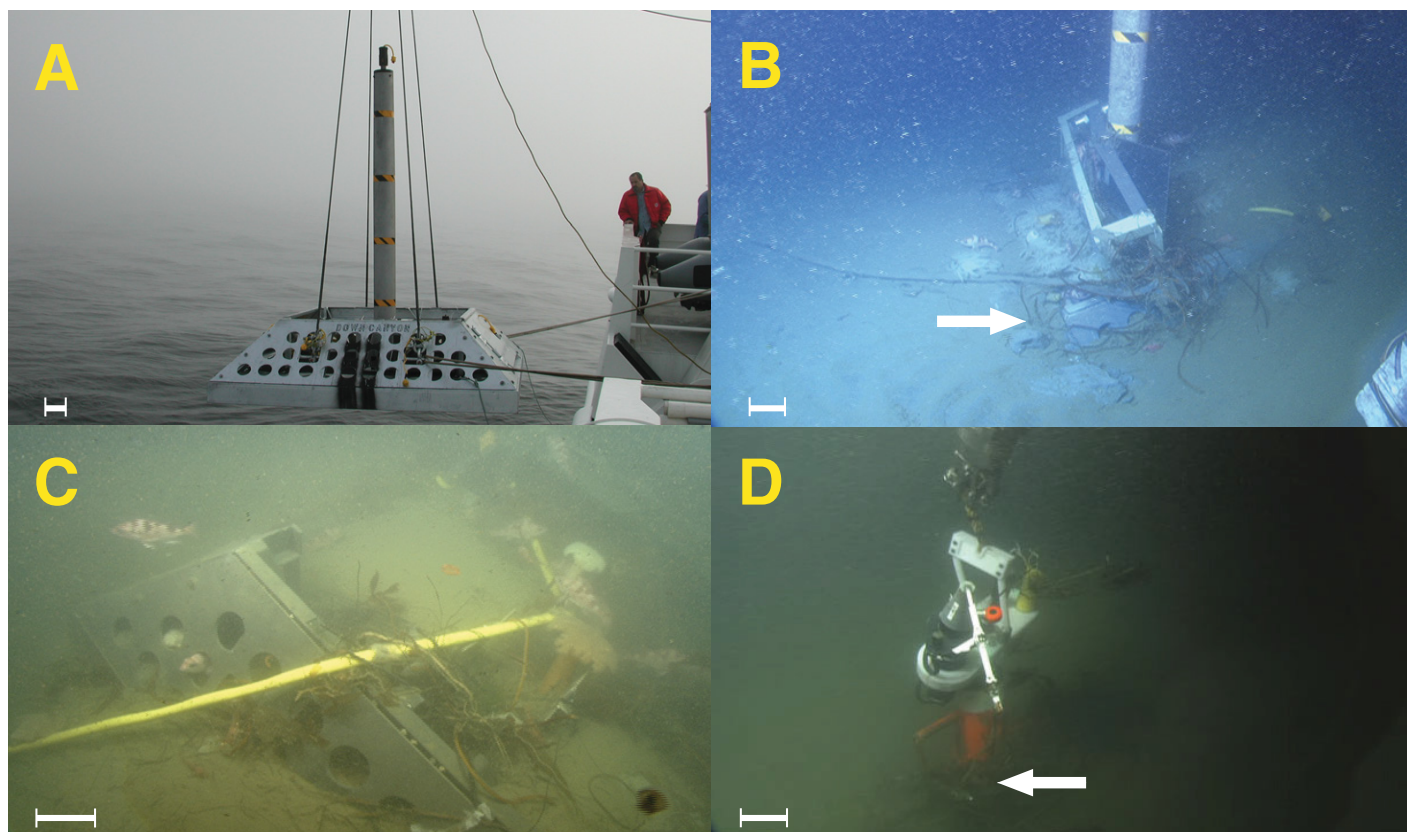


Figure 6. Images of the large instrument frames deployed within upper Monterey Canyon. (A) Photograph of a large instrument frame being deployed from R/V *Western Flyer* on 5 June 2002. (B–D) Video images collected by the ROV *Ventana* showing the appearance of the frames after transport events. (B) Frame on 2 July 2002 after a transport event moved it 170 m down-canyon. One edge of the frame is sticking out from the seafloor (indicated with arrow); the mast is still intact, but a battery case is bent around the mast. (C) Same frame on 28 February 2003, after an additional movement of 200 m. Mast has been sheared off, but is still connected to the frame via yellow cable. (D) The instrument package on 3 April 2002 still mounted on top of a mast after 70 m of movement. The sediment-water contact is indicated by the arrow. The mast's near-vertical orientation suggests frame is still upright, but its base is buried by ~1.5 m of sediment. Scale bar in each photo is approximately 15 cm.

Figure 4 illustrates differences in seafloor morphology between repeat AUV mapping surveys conducted in 2007 (31 January and 1 February; 1 February and 27 February; and 27 February and 18 June). No significant changes occurred during the 1 day period between 31 January and 1 February. Substantial changes occurred within the 26 day period between the 1 February and 27 February surveys. Relative to the 1 February survey, seafloor depths increased and decreased by as much as 2.5 m (Fig. 4). The magnitude and shape of the depth changes shown on the difference maps suggest that these depth changes are associated with the repositioning of the crests of crescent-shaped bedforms. Modest changes were observed over the 111-day period between the 27 February and 18 June surveys. Thus, the AUV-acquired multibeam data suggest that while substantial changes occur in the active channel between some surveys, the amount of change in the bottom shape is not constant with

time. These data also show that the canyon is not becoming shallower relative to features outside the active channel (e.g., benches); therefore the observed changes in seafloor morphology must not be caused by the simple addition of more sediment fill to the canyon floor.

The thalweg was traced from 104 m to 342 m water depth using the 18 June AUV data. Along this section of the canyon the average slope of the canyon floor is 1.8° and the sinuosity is 1.4, similar to previous measurements in upper Monterey Canyon (Paull et al., 2005).

AUV Surveys—CHIRP Subbottom Profiles of the Canyon Floor

High-resolution seismic reflection profiler data collected by surface ships and AUV are available for Monterey Canyon. One of the original objectives of collecting these data was to define the characteristics of the canyon floor fill.

Profiles collected from surface vessels (Figs. 7A, 7B) are dominated by side echoes and illustrate the difficulty of imaging the seafloor and near subbottom in areas of complicated bathymetry.

AUV-collected CHIRP profiles of the canyon axis consistently lack internal reflections (Fig. 7C). Characteristically, there is a dipping reflection that extends into the subsurface and is approximately continuous with the downstream face of the crescent-shaped bedforms. Whether these apparent dipping reflections are side echoes from the crescent-shaped down-canyon faces of the bedforms or the surfaces of listric normal faults is ambiguous. In contrast, AUV-collected CHIRP profiles from the flanks of the canyon resolve numerous nearly horizontal reflectors that indicate thinly bedded layers (Fig. 7D). In places higher up on the canyon walls, these thin-bedded sediments are offset by normal faults locally parallel to the canyon axis (Smith et al., 2005, 2007).

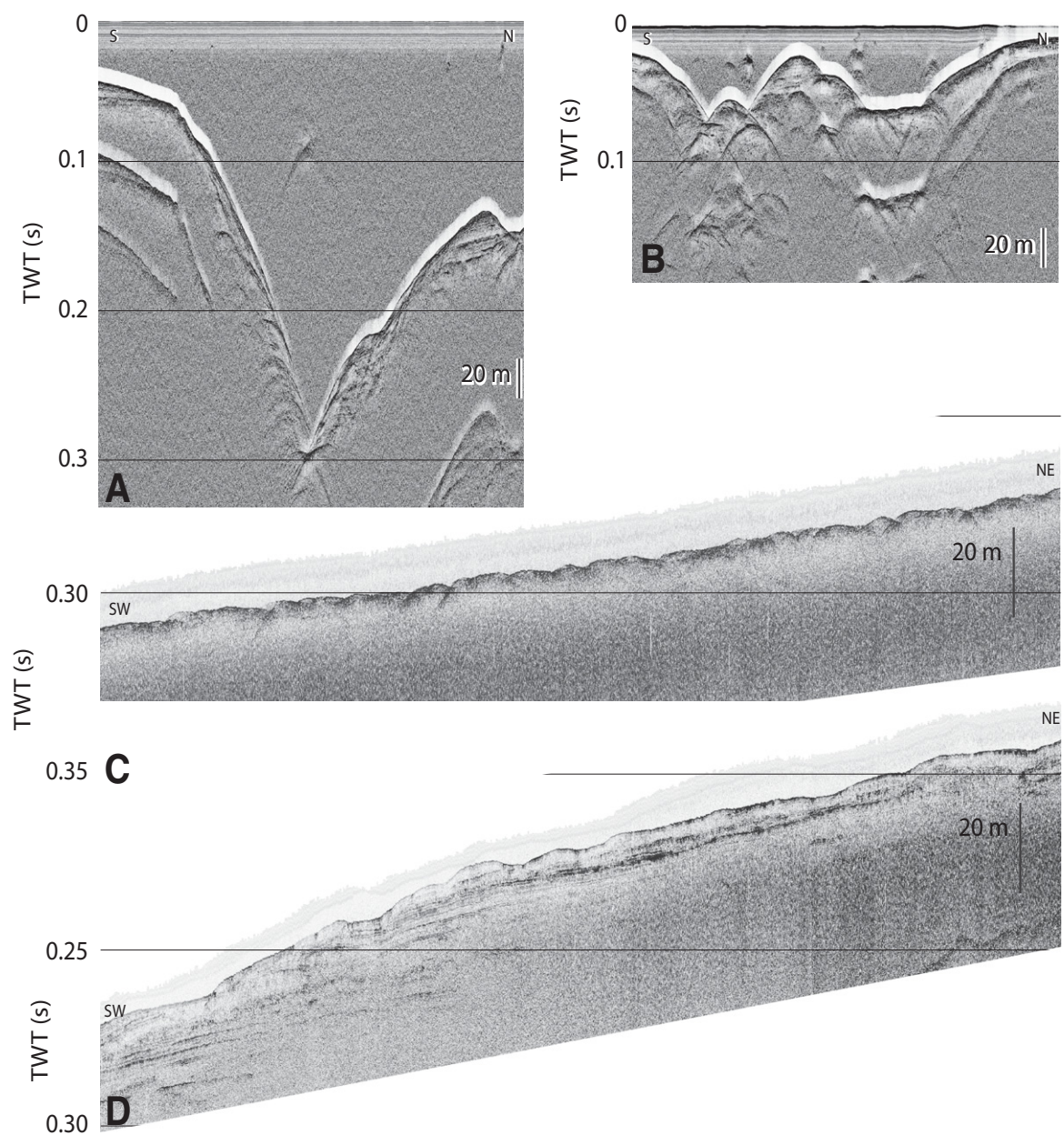


Figure 7. High-resolution seismic-reflection profiles (TWT—two-way traveltimes) collected within upper Monterey Canyon comparing surface ship and AUV (autonomous underwater vehicle)–collected CHIRP (compressed high-intensity radar pulse) profiles. Profiles A and B are high-resolution single-channel CHIRP profiles that were collected by the U.S. Geological Survey using a surface-towed seismic reflection system (Edgetech 512i, 500–7200 Hz, Line5 and 1, respectively, on cruise F-1-07-NC). Profiles C and D were collected with Monterey Bay Aquarium Research Institute's mapping AUV. This comparison illustrates the limitations of collecting subbottom data from a surface vessel. See Figure 2 for line locations.

Coring Transects

Three transects of closely spaced ROV-collected vibracores characterize the internal stratigraphy of the sediment forming the crescent-shaped bedforms within the axis of Monterey Canyon (Figs. 8, 9, and 10; Table 1; Supplemental Figs. 3³, 4⁴, and 5⁵). These core transects augment the previously available information about the canyon floor facies and sediment sources (Paull et al., 2005, 2006).

Sediments in the 18 vibracores from transect 1 parallel to the canyon axis in 284–290 m water depth are composed of fining-upward sequences that are 40 to >200 cm thick (Fig. 8; Supplemental Fig. 3 [see footnote 3]). These sequences characteristically contain poorly sorted intervals

³Supplemental Figures 3A, 3B, and 3C. PDF file of photographs of the surface of longitudinally split vibracores that are schematically illustrated in text Figure 8 showing the variation in lithologies within the 18 core transect 1 extending along the canyon axis (text Fig. 3). Cores are arranged from west to east in the same order as in text Figure 8; Part A consists of the westernmost 6 cores (V3045 VC-Q, V3040 VC-L, V3038 VC-J, V3049 VC-K, V3037 VC-I, and V3036 VC-H); Part B consists of the middle 6 cores (V3035 VC-G, V3033 VC-E, V3041 VC-M, V3034 VC-F, V3032 VC-D, and V3031 VC-C); and Part C consists of the eastern 6 cores (V3030 VC-B, V3046 VC-R, V3020 VC-A, V3042 VC-A, V3043 VC-O, and V3044 VC-P). Core liner has a 7.8 cm inside diameter. If you are viewing the PDF of this paper or reading it offline, please visit <http://dx.doi.org/10.1130/GES00527.S3> or the full-text article on www.gsapubs.org to view Supplemental Figure 3.

⁴Supplemental Figures 4A, 4B, and 4C. PDF file of photographs of the surface of longitudinally split vibracores that are schematically illustrated in text Figure 9 showing the variation in lithologies within the 19 core transect 2 extending perpendicular to the canyon axis (text Fig. 3). Cores are arranged from south to north in the same order as in text Figure 9. Part A consists of the 7 southernmost cores (V3110 VC-134, V3111 VC-135, V3097 VC-121, V3109 VC-133, V3108 VC-132, V3107 VC-131, and V3096 VC-120); Part B consists of the middle 6 cores (V3114 VC-138, V3102 VC-126, V3098 VC-122, V3099 VC-123, V3113 VC-137, and V3103 VC-127); and Part C consists of the 6 northernmost cores (V3100 VC-124, V3112 VC-136, V3105 VC-129, V3101 VC-125, V3104 VC-128, and V3106 VC-130). Core liner has a 7.8 cm inside diameter. If you are viewing the PDF of this paper or reading it offline, please visit <http://dx.doi.org/10.1130/GES00527.S4> or the full-text article on www.gsapubs.org to view Supplemental Figure 4.

⁵Supplemental Figure 5. PDF file of photographs of the surface of longitudinally split vibracores showing the variation in lithologies within the 5 cores of transect 3 extending along the canyon axis (text Fig. 3) in 117–119 m water depth. Cores are arranged with deepest and westernmost on left (V3119 VC-143, V3118 VC-142, V3117 VC-141, V3121 VC-145, and V3120 VC-144). If you are viewing the PDF of this paper or reading it offline, please visit <http://dx.doi.org/10.1130/GES00527.S5> or the full-text article on www.gsapubs.org to view Supplemental Figure 5.

containing coarse gravel or multicolored clay clasts near their base, overlain by fining-upward sand (Fig. 8). Sand-supported rounded cobbles and angular clay chips occur floating within these sands. Some cores contain 2 or 3, >40-cm-thick fining-upward units, but most have only one. These facies are clearly gravity-flow deposits. A few water escape tubes were noted. No systematic variations were noted along the transect that suggest that these bedforms contain identifiable and predictable lateral changes in their internal stratigraphy (e.g., cross-stratification) that would result from migrating sediment waves. Moreover, no obvious erosional lags were identified.

The first 7 vibracores along transect 2, conducted perpendicular to the canyon axis starting in 290 m water depths (Fig. 9; Supplemental Fig. 4 [see footnote 4]) from the crescent-shaped bedforms in the axial channel, are lithologically indistinguishable from those in transect 1 (Fig. 8). However, a distinct lateral facies change occurs at the edge of the bench. The cores collected from the first bench on the side of the canyon (which is only ~2 m shallower than the adjacent channel) are composed of numerous thin horizons (≤10 cm) containing fining-upward medium- to fine-grained sand separated by clay-rich units. No material coarser than medium sand was encountered in the cores from this bench or higher upslope on the canyon side (Paull et al., 2005, 2006). The transition occurs over a horizontal distance of <10 m and vertical change of ~4 m.

Visual observations made while maneuvering the ROV to collect cores showed that most of the bottom is covered by at least a few centimeters of fine-grained soft sediment. While the scarps that form the down-canyon side of the crescent-shaped bedforms were too steep to core, sediments exposed on these scarps appear to be composed of fining-upward sequences. Near the base of these scarps coarse gravel and even boulder-sized clay clasts are exposed on the seafloor. The material exposed on the down-canyon-facing scarp faces of these bedforms does not appear to differ from the material sampled within the vibracores from their flanks. These thick, fining-upward gravity-flow deposits consistently blanket the axial channel floor.

A third transect (transect 3) comprising 5 vibracores was collected parallel with the canyon axis in ~120 m water depths. These cores were composed of clean, well-sorted medium-grained sand similar to beach sand of Monterey Bay. Few internal stratigraphic variations were observed in cores from this transect (Supplemental Fig. 5 [see footnote 5]).

The facies of the material forming the crescent-shaped bedforms changes down-canyon. Cores from transect 3 within the bedforms in water

depths of ~120 m show that the canyon floor at this depth is almost entirely composed of sand compositionally identical to beach sand in Monterey Bay (Paull et al., 2005). Presumably, Monterey Bay beach sand is transported to the canyon head via longshore transport, becomes trapped within the topographic low associated with the intersection of the canyon head and the shoreline, and moves downslope within the canyon axis. In contrast, the facies encountered within morphologically similar bedforms further down-canyon in ~290 m water depth is more heterogeneous and contains numerous cobble-sized clasts. The sources of this added coarse material are presumably gravel beds within the canyon floor and from sediments slumping off the canyon walls. Gravel beds have been observed to crop out on the sides of benches during ROV dives.

The thickness of the individual event layers (>70 cm) in the crescent-shaped bedforms is significantly greater than the thinner layers (typically <5 cm) deposited on the benches on the adjacent channel flanks. This pattern of deposition (e.g., substantially greater deposition in the axis than on the bench on the flanks) is not sustainable without the channel filling. Thus, successive thick gravity-flow deposits are not simply being deposited over the previous layer. Apparently, there is either significant downward erosion during a gravity-flow event or slabs of the seafloor move downslope, opening up accommodation space and maintaining a steady-state channel depth. Thin-bedded turbidites have accumulated on the benches on the side of the channel without evidence for significant erosion.

Acoustic Array

Homer Beacon Locations

The ROV *Ventana* deployed and located 3 monuments (Fig. 5) and 3 small instrument frames on 7 and 8 February 2007. A resurvey from the R/V *Point Lobos* on 12 February 2007 determined that the monuments and frames had moved between 50 and 151 m down-canyon from their initial positions. The ROV *Ventana* was immediately launched to inspect the array. The bottom water within 20 m of the canyon floor was unusually turbid, making ROV operations difficult. The signal from the beacon on what was originally the most up-canyon frame allowed it to be located. Two of the small instrument frames were found entwined and on their sides. ROV to ship positions confirmed that the small instrument frames had moved ~50 and ~75 m down-canyon from their initial deployment sites. These small instrument frames were recovered. The third small instrument frame was never located.

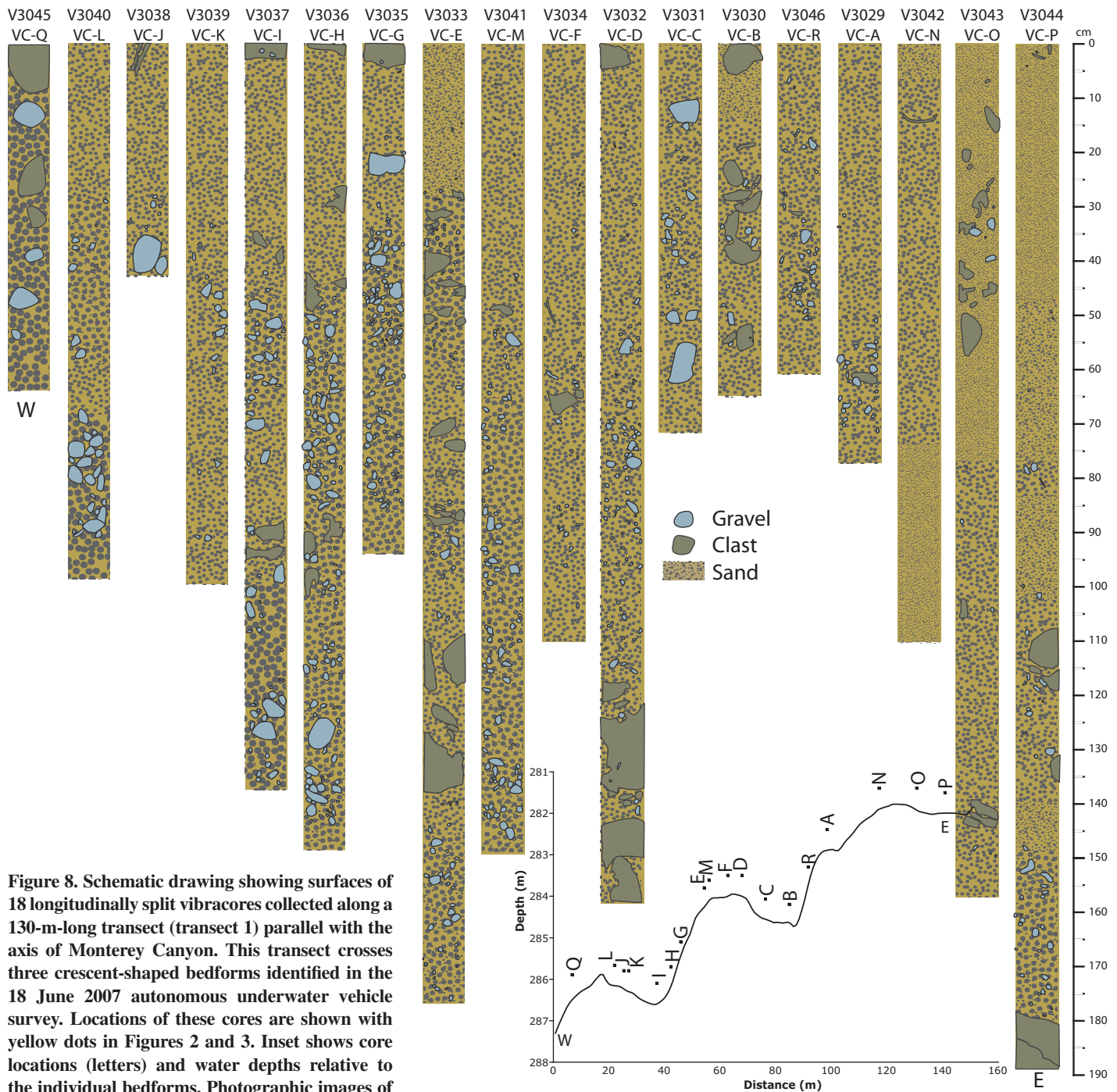
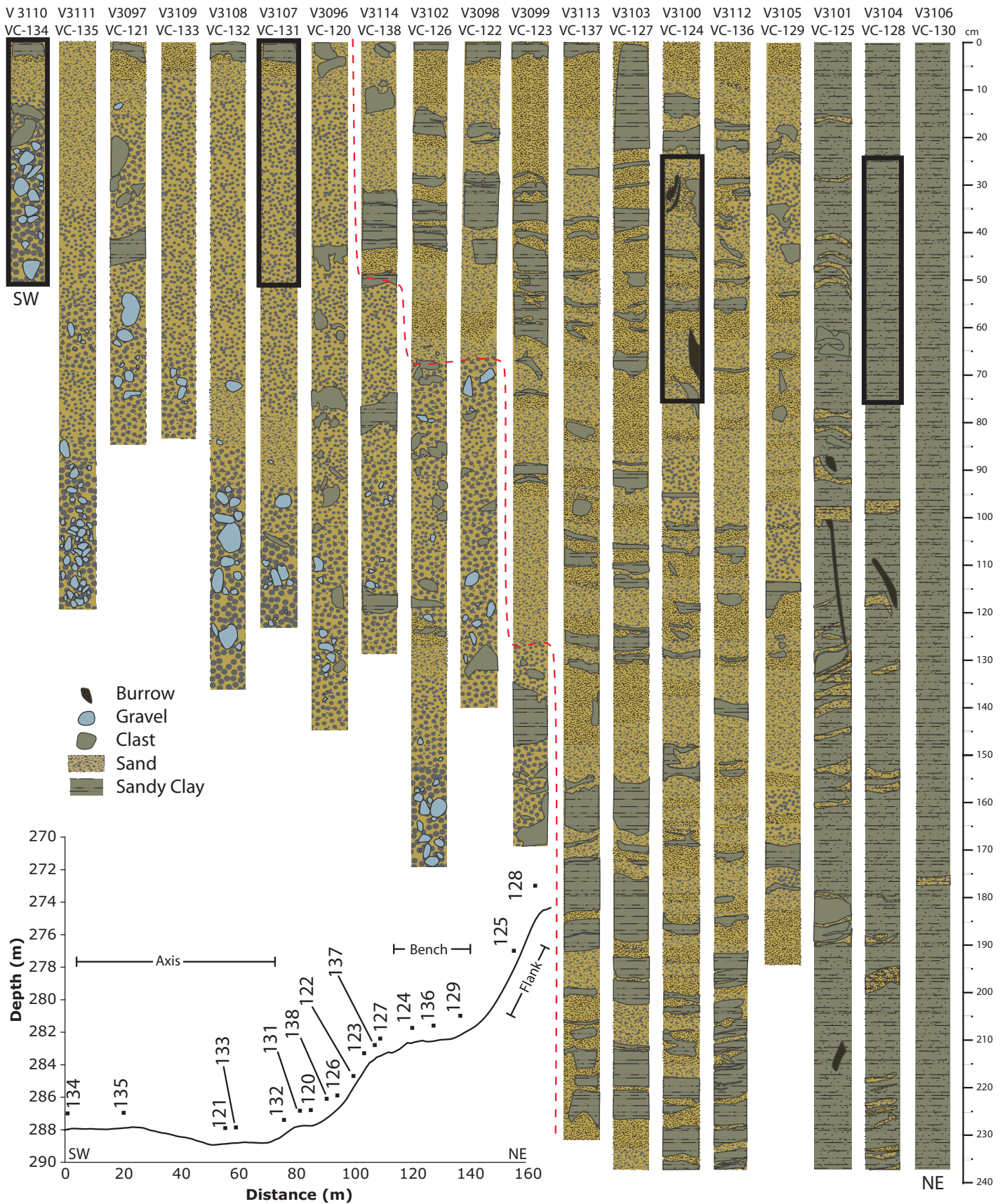


Figure 8. Schematic drawing showing surfaces of 18 longitudinally split vibracores collected along a 130-m-long transect (transect 1) parallel with the axis of Monterey Canyon. This transect crosses three crescent-shaped bedforms identified in the 18 June 2007 autonomous underwater vehicle survey. Locations of these cores are shown with yellow dots in Figures 2 and 3. Inset shows core locations (letters) and water depths relative to the individual bedforms. Photographic images of these cores are in Supplemental Figures 3A, 3B, and 3C (see footnote 3).

Figure 9. Schematic drawing showing the surfaces of 19 longitudinally split vibracores collected along a 181-m-long transect (transect 2) extending from the center of the axial channel of Monterey Canyon where crescent-shaped bedforms are common, onto a bench on the side of the canyon, and up onto the lower flank of the canyon. Locations of cores are shown with red dots in Figures 2 and 3. Photographic images of selected cores imaged in Figure 10 are outlined with boxes. Inset shows core locations and water depth relative to the canyon floor. Dashed red line highlights a distinctive facies change between coarse-grained canyon fill and finer-grained sediments on the bench and canyon flanks. Cross section in lower left shows relative location of the cores except for VC-130, which came from ~110 m further up slope. Photographic images of these cores are in Supplemental Figures 4A, 4B, and 4C (see footnote 4).

Origins of large crescent-shaped bedforms within the axial channel of Monterey Canyon



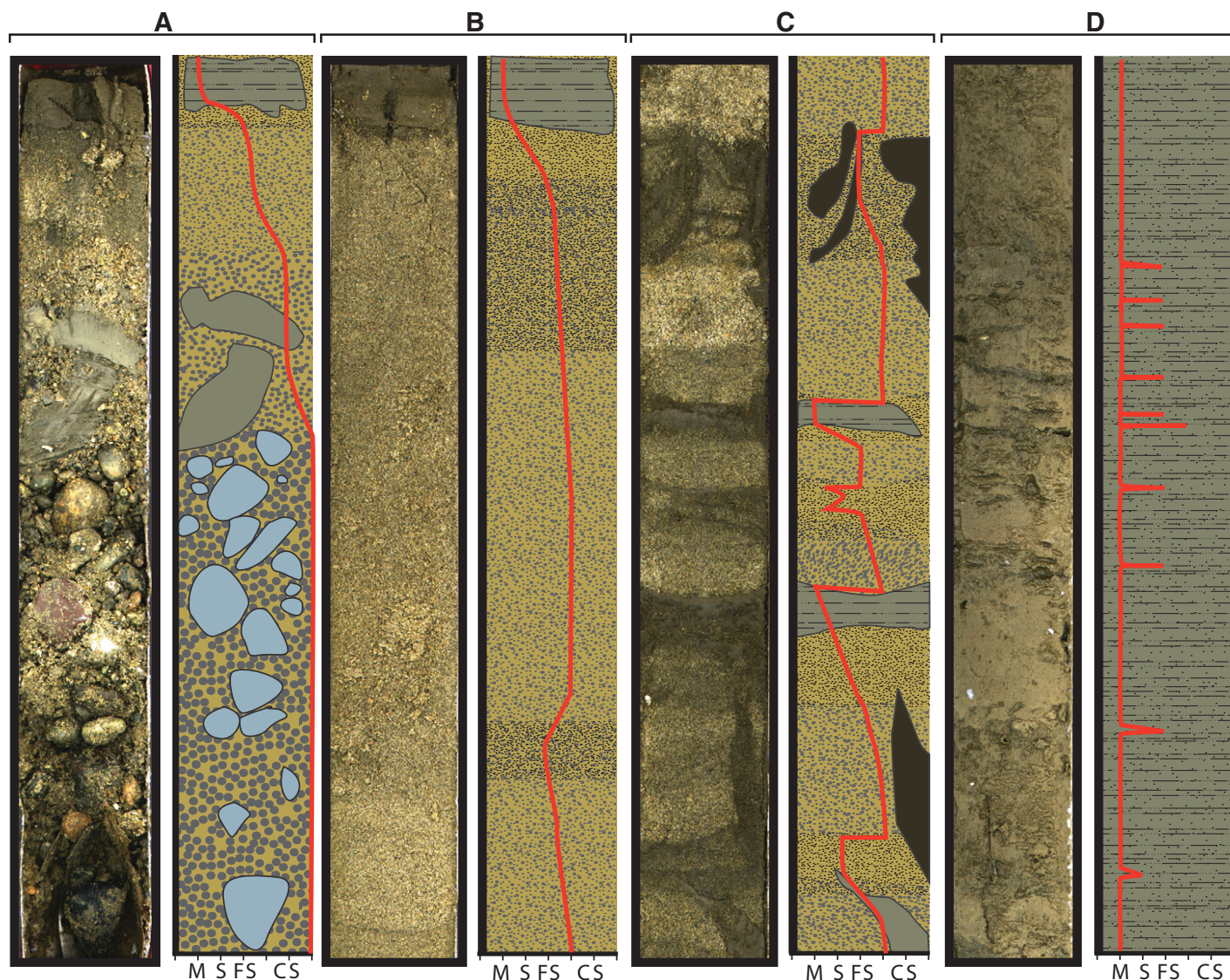


Figure 10. Photographs and interpretive drawings of the surface of four 0.5 m sections (A to D) of the longitudinally split vibracores selected to show the variation in lithologies within transect 2 extending from the canyon axis across the lower flank of the canyon (Fig. 3). Sections of cores that are illustrated here are identified in Figure 9. For each section the photo is to the left and the interpretive drawing to the right. Key for the interpretive drawing is the same as in Figures 8 and 9. Grain size profiles (red lines) inferred from the images are superimposed on the interpretive drawing with increasing sizes plotted to the right (M—mud, S—silt, FS—fine sand, CS—coarse sand).

Subsequent to 12 February 2007, positions of the three monuments were determined from the R/V *Point Lobos* 17 times over 26 months (Fig. 11; Table 2). Movements of these monuments were sporadic and unpredictable. These surveys show that positions of the monuments did not change through 12 December 2007. Surveys on 11 January 2008, and repeated on 24 January 2008, indicated that two of the monuments were still in the same location (± 0.5 m), but the third had moved another 7.5 ± 0.5 m down-canyon. No additional surveys were conducted until July 15, 2008. At this time two of the monu-

ments were found within 38 m of each other ~ 1 km downstream of their initial deployment sites. Beacon 11 (monument 1) was not located during this survey. On 5 August 2008 the positions of the two monuments located in July had not changed. A dive of the ROV *Ventana* was conducted to inspect the seafloor where these monuments were located. On this dive, a signal from the third beacon was located 400 m further down-canyon, 1.4 km downstream from its deployment location. Surveys conducted on 24 September 2008 and 28 October 2008 show that the locations of all three monuments had remained constant.

A survey on 25 November 2008 indicated that one monument moved an additional 244 m down-canyon, while the other two monuments did not shift more than 2 m. Surveys on 5 December 2008 and 6 January 2009 showed no change except that beacon 19 had moved an additional 10 m down-canyon. A survey on 7 April 2009 showed that beacon 19 had shifted another 596 m further down-canyon, while the other two beacons remained in the same location. Three additional searches were conducted (7 July 2009, 29 September 2009, and 12 October 2009); no beacons were located, and the experiment was terminated.

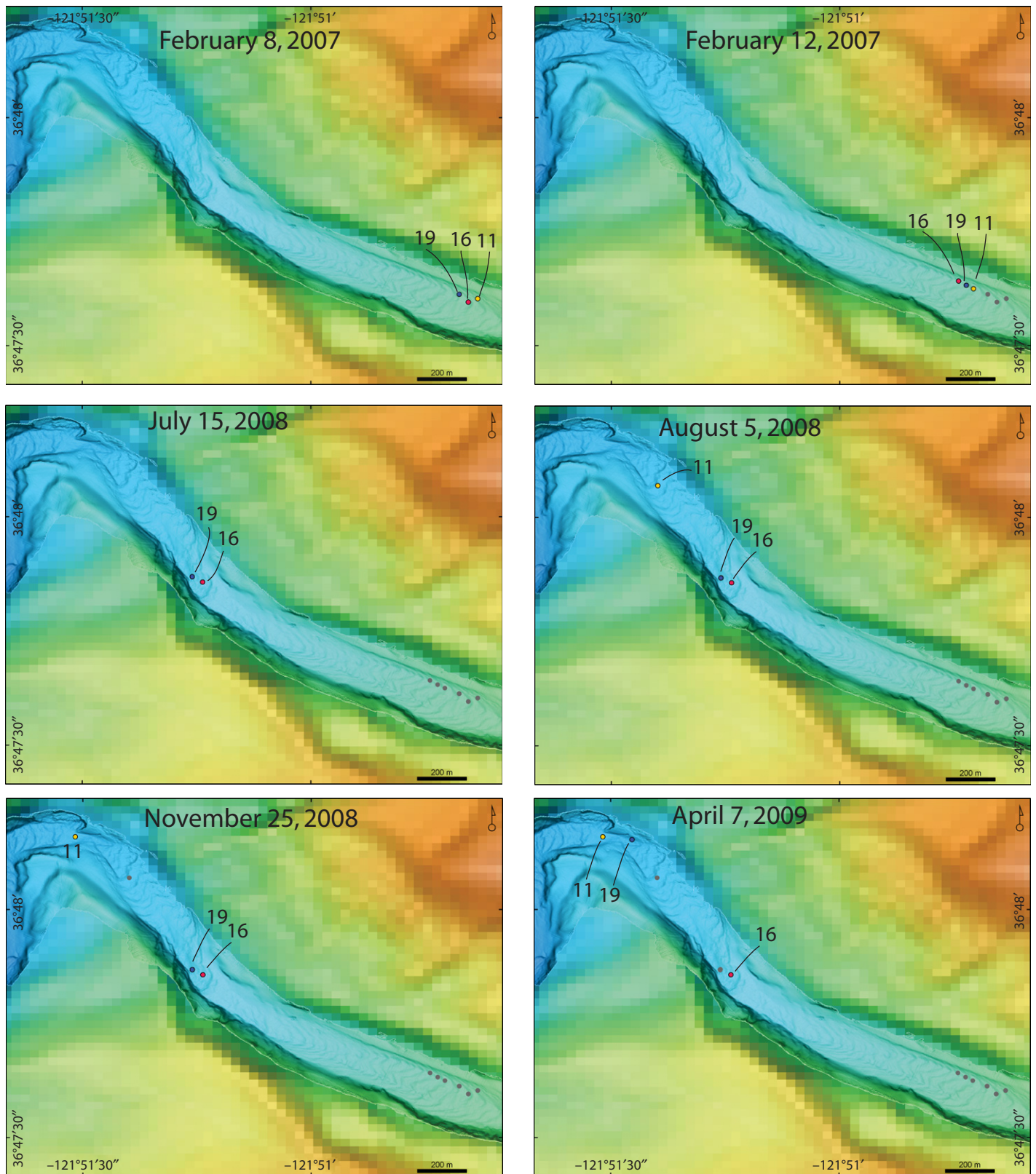


Figure 11. Maps showing how the positions of the concrete monuments (illustrated in Fig. 5) changed between selected surveys. Note change in order of the monuments between successive surveys. Data are in Table 2.

TABLE 2. DOWN-CANYON DISPLACEMENT OF CONCRETE MONUMENTS

Date of survey	Homer 11 (m)	Homer 16 (m)	Homer 19 (m)
8 February 2007	deployment	—	—
12 February 2007	114	151	79
26 April 2007	0	0	0
26 June 2007	0	0	0
12 September 2007	0	0	0
18 September 2007	0	0	0
15 October 2007	0	0	0
26 October 2007	0	0	0
12 December 2007	0	0	0
11 January 2008	7	0	0
24 January 2008	0	0	0
15 July 2008	not located	841	911
5 August 2008	1311	0	0
24 September 2008	0	0	0
28 October 2008	0	0	0
25 November 2008	244	2	2
5 December 2008	0	0	0
6 January 2009	0	0	10
7 April 2009	0	0	596
Total displacement	1676	994	1598

Homer Beacon Burial Depths

On 12 February 2007, four days after their initial deployment, the ROV *Ventana* was used to inspect the seafloor around the new positions of the monuments. Because visibility was very poor, identifying even the seafloor on the video images was difficult. The ROV landed on the seafloor numerous times but was unable to close the range between the ROV and the beacons to <4.4 m. The receiver for the homer was mounted on the ROV 2.4 m above the base of the vehicle. Previous experience with locating Homer Pro beacons suggested that the beacons were not on the seafloor, but

within the seafloor, buried by as much as 2 m of sediment.

On 5 August 2008 the burial depth of the three monuments that had already moved between 1 and 1.4 km down-canyon from their initial deployment sites was determined again. During this dive a second master Homer beacon was placed on a moveable swing arm on the side of the ROV, facing downward. Visibility on the seafloor was good, which allowed small adjustments in ROV position to minimize the range from the ROV-mounted beacon to each monument beacon, thus determining burial depth. Measurements were also made by sweeping the

swing-arm-mounted Homer beacon over the seafloor to confirm depth of burial of the monuments. By using this approach we are confident that all three of the monuments were buried 1.2–1.7 m below the seafloor. Similar surveys were conducted over all three beacons on 5 December 2008. At this time all the beacons were covered with at least 0.6 m of sediment.

Movements of Large Instrument Frames

The date of deployment, ROV observations, water depths, and comments on the conditions of the large instrument frames are given in Table 3. Two frames were deployed on 5–6 June 2002. When the *Ventana* returned to the same location to install additional frames on 2 July 2002, one frame was 170 m down-canyon, still upright, but with its base buried within 70 cm of sediment (Fig. 6B). A systematic ROV search for the other frame was conducted but it was never located.

On 3 September 2002 an instrument package was deployed on top of the mast of the frame that had survived the previous 170 m displacement down-canyon and was now in 295 m water depth. No change was observed in the position or condition of this frame through 11 December 2002, when the instruments were exchanged. On 28 February 2003 this frame was located an additional 200 m further down-canyon in 300 m water depth. The frame was partly buried, but with one corner still sticking out of the sediment at an angle (Fig. 6C). The mast was sheared off, but a cable inside the mast was still connected to the instrument package, which was buried in

TABLE 3. CHRONOLOGY OF DEPLOYMENTS AND REMOTELY OPERATED VEHICLE (ROV) VISITATIONS OF LARGE INSTRUMENT FRAMES TO OUTLINE DATES OF MOVEMENT AND/OR DISAPPEARANCE

Object	Water Depth (m)	Net Movement (m)	Date	Comment
sRIN	203	—	10 December 2002	Frame deployed from Point Lobos
	203		11 December 2002	Instrumented frame with ROV
	?		2 February 2003	Unable to locate frame or beacon during ROV search
	?		27 February 2003	Second unsuccessful ROV search
RIN1		—	5 June 2002	Deployed from Western Flyer
	290		5 June 2002	ROV dive confirmed deployment position
	295		2 July 2002	ROV relocated frame in new position
	295		5 August 2002	ROV dive confirmed position
	294	170	3 September 2002	ROV installed instruments on mast top
	295		9 December 2003	ROV visit to swap instruments aborted dive
	295		11 December 2002	ROV swapped instruments
	?		19 December 2002	Instruments indicate position changed at 03:38 PM PST
	?	?	27 February 2003	Unsuccessful ROV search
	300		28 February 2003	ROV relocated frame in new position, mast sheared off, instrument case buried
	300	300	10 March 2003	ROV dug out and recovered buried instrument case
sRIN		—	20 December 2002	Deployed frame from Point Sur
	429		2 January 2003	ROV instrumented frame
	429		27 February 2003	ROV swapped instruments
	?		14 March 2003	Instruments indicate position changed at 01:11 AM PST
	432	70	3 April 2003	ROV found sRIN frame buried in ~1.4 m of sediment
RIN2		—	6 June 2001	Deployed from Western Flyer
	520		6 June 2001	ROV dive to confirm deployment position
	?		2 July 2001	Unable to locate frame or beacon during ROV search
	?		7 August 2001	Second unsuccessful ROV search

~20 cm of sediment further down-canyon. The time of failure of the current meter's sensor and a coincident increase in pressure indicated that the transport event had occurred 19 December 2002.

The third frame was deployed in 203 m of water on 10 December 2002 and instrumented on 11 December 2002. It was missing by 2 February 2003. We infer that this may also have moved on 19 December 2002.

The fourth frame was deployed on 20 December 2002 and instrumented on 2 January 2003. When the instruments were swapped out on 27 February 2003, no change in position or conditions of the frame was observed. However, on the next visit the instrument package was found 70 m further down-canyon. While only the top of the mast was sticking out of the sediment (Fig. 6D), its near vertical orientation suggested that it was still attached to the frame, but that the large base was buried to a depth of ~1.5 m. Although the fragile sensors on the instruments were damaged, the pressure cases were intact and were noted to be neither badly damaged nor heavily abraded.

A National Oceanic and Atmospheric Administration data buoy located offshore of Monterey Bay provides a record of significant wave heights (SWH; http://www.ndbc.noaa.gov/station_history.php?station=46042). During the entire observation interval, the mean SWH height was $2.26 \text{ m} \pm 1.00 \text{ m}$ (1σ) and the maximum, max. SWH was 9.92 m. The three events for which close time constraints exist are correlated with times when sea conditions were more than one standard deviation larger than mean seas (20 December 2001: 6.80 m max. SWH; 19 December 2002: 6.60 m max. SWH; 14 March 2003: 3.68 m max. SWH). The other time periods during which events are inferred to have occurred all contain periods with large seas (6 June to 3 July 2002: max. SWH 5.40 m; 8 to 12 February 2007: max. SWH 3.65 m; 12 December 2007 to 11 January 2008: max. SWH 9.92 m; 24 January to 15 July 2008: max. 8.21 m; 28 October to 25 November 2008: max. SWH 4.33 m; 5 December 2008 to 6 January 2009: max. SWH 5.86 m; 6 January to 7 April 2009: max. SWH 6.20 m).

During the time of the 14 March 2003 event, a new bridge was being installed across Moss Landing harbor, <200 m from the canyon head. To drive the piles associated with the bridge foundation, a huge industrial vibrating pipe driver was used. This device produced noticeable ground shaking more than 300 m away.

DISCUSSION

Four hypotheses are considered that may explain the movement of the sediments that form the crescent-shaped bedforms in the axis

of Monterey Canyon. (1) Tidal currents form crescent-shaped bedforms and cause them to migrate. (2) Erosion and deposition during turbidity current events generate crescent-shaped bedforms. (3) Slumping of canyon floor fill generates crescent-shaped bedforms. (4) Remobilization of canyon fill by fluidization generates crescent-shaped bedforms.

Tidal Currents Form Crescent-Shaped Bedforms and Cause Them to Migrate

Previous investigators have postulated that the crescent-shaped bedforms in Monterey Canyon are sand waves that migrate along the canyon floor driven by the integrated effects of tidal currents (Smith et al., 2005, 2007; Xu et al., 2008). This mechanism requires that tractive forces associated with regular tidal currents in Monterey Canyon are adequate to move sediment along the canyon floor. Progressive migration of these bedforms occurs in response to tractive forces, regardless of whether tidal flow is up-canyon or down-canyon. Depending on flow regime, bedforms formed by tractive forces may show asymmetry, indicating flow direction.

Because the monuments have moved more than one wavelength down-canyon during individual, brief sediment transport events, the identification of any particular migrating wave crest is impossible. While similarly shaped crescent-shaped bedforms reoccur in approximately the same location after successive sediment transport events, attempts to determine the direction of movement of these bedforms by comparing locations of their crests between repeat multibeam mapping surveys spaced months apart is futile.

Large seafloor sand waves are known to form and migrate in areas where the bottom undergoes strong (e.g., >100 cm/s) currents (see previous discussion, "Formation of Large Crescent-Shaped Bedforms"). While some relatively high current velocities have been measured in discrete events within the axis of Monterey Canyon, the maximum daily tidal current is ~80 cm/s (Xu et al., 2008). Such current velocities are marginal for moving coarse sand, and inadequate for moving gravel, let alone boulder-sized objects like the monuments and large instrument frames (Hjulstrom, 1935).

The observed episodic movement of the boulder-sized monuments, which have resulted in down-canyon displacement of between 994 and 1676 m in more than 2 yr, is also inconsistent with the progressive migration of these crescent-shaped bedforms by tractive forces associated with regular tidal currents. Thus, we reject tidal currents as an explanation for the formation of the crescent-shaped bedforms.

Erosion and Deposition During Turbidity Current Events Generate Crescent-Shaped Bedforms

The crescent-shaped bedforms may form by the combined effects of erosion and deposition during relatively brief, high-energy turbidity-flow events. This would require vigorous flows capable of scouring the bottom to a depth of 1 m or more, exhuming and moving boulders and large objects (e.g., the poured-concrete monuments and large instrument frames) across the seafloor presumably as part of the bedload, and finally depositing bedforms composed of poorly sorted materials further down-canyon. The coupled erosional and depositional processes would have to regenerate the distinctive recurring shape of the crescent-shaped bedforms.

Vibrocores show that sediments under the crescent-shaped bedforms are coarse grained, thick bedded, and poorly sorted, characteristics of rapid en masse deposition from discrete high-energy mass transport events. Sediments that form terraces ~2 m above the canyon floor in more than 284 m water depth (Fig. 9) contain thin, fining-upward layers that resemble thin-bedded turbidites. However, whether the observed crescent-shaped bedforms were formed during turbidity currents is less clear.

The linear trains of large crescent-shaped bedforms observed throughout upper Monterey Canyon might be attributed to erosion and deposition associated with cyclic steps in the turbidity currents and other vigorous flows within the canyon. Several observations are, however, difficult to rectify by this mechanism. The repetitive bedforms mapped within the axis of Monterey Canyon are similar throughout the canyon (Fig. 2), suggesting that the same process forms all the bedforms. While energetic flows can be envisioned to occur at the depths associated with the core transects and beacon experiments (100–350 m water depths), how adequately large turbidity currents can be generated at the canyon head in as little as 11 m water depth to produce these features is in question.

The process that forms the crescent-shaped bedforms does not appear to be purely erosional because, while the shape of the axial channel floor changes during the events, the average depth of the canyon floor does not change systematically (Fig. 4; Supplemental Figs. 1 and 2 [see footnotes 1 and 2]). If the crescent-shaped bedforms are formed during cyclic steps in an overlying flow, the buried monuments and frames would first have to be erosively exhumed from beneath ~1 m of sediment cover, carried down-canyon by the flow, then reburied in the same event that leaves the distinctive crescent-shaped bedforms. The facies generated

by the combined effects of erosion and deposition associated with cyclic steps in an overriding flow is not well known (Normark et al., 2009). However, if these repetitive crescent-shaped bedforms were in part depositional features, some organized lateral variations in the internal stratigraphy of these bedforms would be expected. Instead, the near-seafloor sediments where the crescent-shaped bedforms occur consist of a very poorly sorted heterogeneous sediment blanket indicating en masse deposition. The extreme range in object sizes (sand to 2 m, >1300 kg instrument frames) that such flow would have to alternately carry, then deposit, is difficult to rectify with a regular oscillation between erosion and deposition. Thus, the observed seabed facies underlying the crescent-shaped bedforms appear inconsistent with deposition from cyclic steps in turbidity current flows.

The potential of damaging the acoustic transponder head on the Homer beacons that protruded from the monuments by moving them ~1.6 km over the seafloor as tumbling boulders within the bed load is high. Because the beacons in all three monuments (Figs. 5 and 11) still functioned throughout the observed period, this suggests that they were not heavily abraded or subjected to high impact during their transport down-canyon. Moreover the apparent orientations of the instrument frames as they moved

down-canyon suggest that they remained more or less upright and did not tumble during transport down-canyon. This indicates that they were protected by either moving on or entombed within a coherent slab-like flow or being part of a dense sediment mixture moving as a granular flow down-canyon with minimal turbulence.

Slumping of Canyon Floor Fill Generates Crescent-Shaped Bedforms

Crescent-shaped slope failure scarps, which are similar in appearance to the crescent-shaped bedforms in Monterey Canyon, are common features on continental margins (Hampton et al., 1996) and submarine canyons (Green and Uken, 2008). Individual slump scars typically have a crescent-shaped surface expression (Martel, 2004) that connects to concave-upward subsidiary faults that sole out on a master failure surface in the subsurface. Multiple subsidiary faults commonly occur with some regular spacing. Rotational movement on the subsidiary faults causes upslope seafloor to dip up-canyon. Thus, the morphology of the crescent-shaped scarps is consistent with a slump origin.

Sediments exposed on the steep face of these repetitive crescent-shaped scarps are composed of the same lithologies and fining-upward successions as found in sediments immediately

down-canyon from the base of the scarps (Figs. 8, 9, and 10). The similarity of sampled sediments within the upper 1 m on both sides of the scarp faces is consistent with the offset being generated by small normal faults offsetting a previously continuous bed. However, individual beds in the crescent-shaped bedforms cannot be traced from core to core along either perpendicular or slope-parallel vibracoring transects.

The thick, coarse-grained sediments associated with the crescent-shaped bedforms within the canyon axis are notably different from the thin-bedded fine sands on the adjacent benches that are only ~2 m above the active channel. The abruptness of this transition provides a constraint on the thickness of the most vigorous section of the overriding flow. However, such an abrupt transition would be expected at the edge of a mass-wasting feature.

Accumulated movement along failure surfaces within the canyon fill is one way to explain how the buried equipment moved downslope without being damaged (Fig. 12). In this scenario, the monuments and instrument frames move entombed within the sediment mass. Protection by the sediments greatly diminishes the chances of the acoustic beacons being damaged, increasing the chances that their upward orientation is maintained during a sediment transport event.

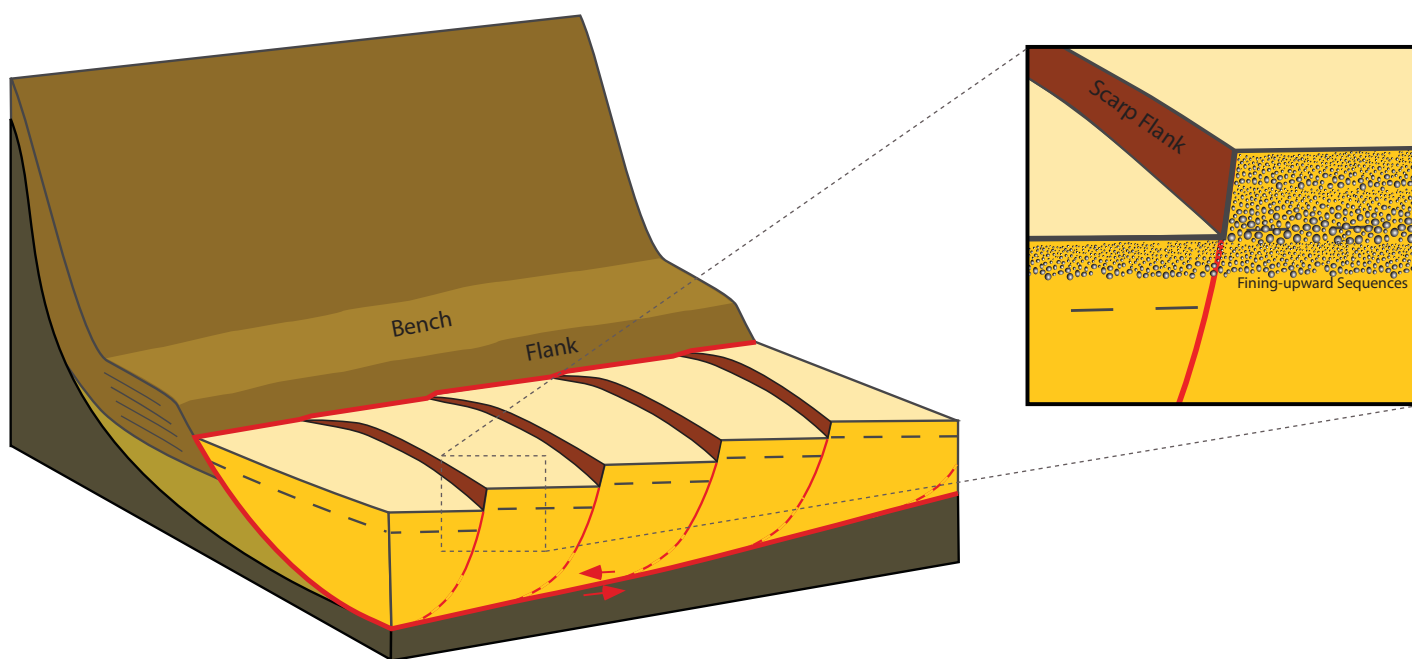


Figure 12. Conceptual diagram illustrates how small amounts of displacement along listric faults (thin red lines) could generate the observed asymmetric crescent-shaped bedforms. These are subsidiary faults that sole out onto a master failure surface (thick red line) somewhere within the canyon fill or within the still moving gravity flows (thin dashed red lines). The position of the master failure surface may change between events, but sometimes or in some places this surface may be the boundary between the preexisting country rock (dark brown) and the canyon fill. Benches on the flank will receive thin fine-grained turbidite deposits.

Pure translation, however, would not explain the >70-cm-thick fining-upward sequences containing large clasts found within the canyon floor or the change in the composition from pure sand near the canyon head to deposits containing sand matrix-supported cobble-sized clasts and clay clasts at greater water depth. The downstream narrowing of the crescent-shaped scarps and lack of easily identified toes to the slump masses make it difficult to reconstruct a balanced section that would be required for pure translation along fault surfaces. Thus, this mechanism alone does not fully explain all the observed features either.

Remobilization of Canyon Fill by Fluidization Generates Crescent-Shaped Bedforms

Loss of the internal cohesion within the sediments will cause some portions of the canyon floor to flow down-canyon. Fluidized remobilization (i.e., debris flows) is commonly associated with slumps and other slope failure events (Hampton et al., 1996). The facies of the cores from the canyon axis (Figs. 8, 9, and 10) are structureless and contain floating clasts and thus appear to be associated with en masse deposition from what has been termed sandy debris flows (Shanmugam, 1996, 1997; Bouma et al., 1997; Lowe, 1997; Shanmugam and Moiola, 1997; Slatt et al., 1997; Amy et al., 2005) or debrites (Talling et al., 2004). Fluid movement within incoherent sediment mass, rather than simple translation of a coherent slump mass, eliminates the need to balance profiles on a local scale, or to identify a distinct downstream toe of the failed mass. Fluidized movement of sediment during a transport event and en masse deposition would explain why the width of the central channel increases or decreases with water depth (Supplemental Fig. 1). Mixing of the originally pure sands at the canyon head with coarser material as they move through the canyon during gravity-flow transport can explain the observed change in the canyon fill facies that occurs between ~120 and >284 m water depth. While the movements of the buried monuments appear to be consistent with en masse deposition following debris-flow-like movement, formation of the crescent-shaped scarps is not necessarily caused by debris-flow events.

Nature of the Sediment Transport Events

The combined data for Monterey Canyon suggest that the crescent-shaped bedforms are associated with high-energy gravity-driven sediment transport events (Figs. 8, 9, and 10); we therefore reject tidal currents as an explanation

of these features. However, none of the other hypotheses alone explains all existing observations. Individual events may involve combinations of suspended sediment transport over the seafloor (e.g., turbidity currents), translations within the seafloor (e.g., slumping), and remobilization of the incoherent canyon fill sediments.

In Monterey Canyon crescent-shaped bedforms occur in as little as 11 m water depth. The existence of downwelling flows that are sufficiently energetic to produce these features in shallow water near the canyon head seems implausible. However, the formation of scarps in shallow waters near the canyon head via slumping requires no special argument. The canyon head is believed to be trapping sands moving within the longshore transport cell, progressively oversteepening the floor of the uppermost canyon. To maintain the longitudinal profile seen in Monterey Canyon, sand must regularly move down-canyon, otherwise the canyon head would fill (Paull et al., 2005). The similarity of the observed crescent-shaped features throughout the canyon axis suggests that they were formed by a similar process throughout the canyon, independent of water depth.

The size and mass of some of the instrument frames that moved within the canyon show the capability of these mass transport events to move objects larger than naturally found in the canyon fill. If they moved simply as bedload over the bottom, the velocity of the bottom currents would be the controlling factor. However, if they were entrained within a sediment failure within the canyon fill, the velocity of the bottom currents would be less important.

A down-canyon facies change occurs from essentially pure sand in shallow water to coarser material including cobbles and clasts floating in a coarse sand matrix below 284 m water depth. This implies that the integrity of the sediment mass has been lost and the sediment has remixed, presumably during gravity-flow events. The layered deposits on the benches on the side of the canyon appear to be thin-bedded turbidites. This observation suggests that at least modest turbidity currents are associated with the events. However, neither modification of the bottom during turbidity flows nor gravity flows explains the formation of the crescent-shaped bedforms.

The average slope of the upper portion of the axial channel of Monterey Canyon between 100 and 350 m water depths is 1.8°. While this slope is gentle with respect to the much steeper sides of the canyon (averaging 28°; Greene et al., 2002), this is considerably steeper than many continental margin slope failures (Booth et al., 1993). This observation may indicate a rheological control on slope angles within the

canyon floor deposits in which these bedforms occur. Thus, 1.8° may represent the angle at which the canyon floor restabilizes after high-energy sediment transport events.

Pore pressure variations are inferred to induce slope failures. Slope failures commonly start with slumping, but the moving material can quickly lose cohesion and convert into other types of gravity flows. The sediments within the axial channel of the canyon covering the underlying country rocks are positioned at a focused hydrologic boundary where pore pressure transients are likely to be greatest (Paull et al., 1990).

During some gravity-flow events, elevated pore pressure may enable intragranular movement. However, at some point within a gravity-flow event the pore pressures dissipate and intragranular movement ceases or halts abruptly (freezes), thereby preserving the local facies. If the entire gravity-flow mass does not freeze simultaneously, other brittle-like forms of compensation would be required to accommodate the motions of still-moving sections of the canyon floor that are undergoing intragranular flow from those that are not. The last sections to stop intergranular flow may be within the canyon fill. We suggest that crescent-shaped scarps may be formed by brittle, slump-like movements (Fig. 12) that occur as pore pressures dissipate, intragranular movement within gravity flows ceases, the sediments become resolidified, and the canyon floor restabilizes at a slope of 1.8°.

Frequency and Timing of Events

The instrument frames and monuments deployed within the axis of Monterey Canyon provide some constraints on the timing of the mass transport events, the carrying capacity of the events, the displacements that occur during these events, and the process by which the frames moved. Episodic down-canyon displacement of the large frames (to 170 m) and monuments (to 1311 m) are documented here (Tables 2 and 3). In a previous experiment, a small instrument frame moved 650 m down the axis of Monterey Canyon and was buried in 2 m of sediment on 21 December 2001 (Paull et al., 2003).

While the record is incomplete, four transport events that moved large instrument frames occurred in a 16-month period in 2001–2002: on 21 December 2001 at 01:35 p.m. PST, between 6 June and 2 July 2002, 19 December 2002 at 03:38 p.m. PST, and 14 March 2002 at 01:11 a.m. PST (Table 3). In addition, the movement of the monuments indicates that 6 mass transport events occurred during a 26-month period in 2007–2009 (Table 2).

During the periods when instrument frames or monuments were deployed and tracked within the canyon axis (e.g., December 2001 to April 2003, and February 2007 to April 2009), there were no significant earthquakes or flooding events. Periods of large seas occurred during all these time periods. Disturbance associated with the pile driver used for bridge construction could explain one event. However, the coincidence of these sediment transport events with large seas suggests that wave loading may have triggered many of the observed sediment transport events.

Role of Subsurface Movement Within Canyon Sediment Fill in Carving of Submarine Canyons

Understanding the processes that carve submarine canyons has been a long-term research goal (Shepard, 1981). While we now know that sediment transport processes are very active on the floor of Monterey Canyon, it is still unclear whether active, present-day processes are playing a role in the continued carving of the canyon, because this requires eroding the underlying host strata. However, the canyon floor is covered with fill, and little or no older strata crop out within the axis of upper Monterey Canyon (Greene et al., 2002; Paull et al., 2005, 2006). Thus, if the observed mass transport processes only involve the thin surface veneer of the canyon fill, they probably will not contribute to canyon enlargement.

Surface ship reflection seismic profiles and even the AUV CHIRP subbottom profiles have not successfully imaged the canyon axis fill and identified the contact between the canyon fill and the preexisting country rock into which the canyon is carved (Fig. 7). However, the thickness of the canyon fill, which would separate the unconsolidated sediments of the canyon from the preexisting country rock, can be estimated by projecting the canyon walls downward into the subsurface. Projections of the sidewall slope make it unlikely that the fill is much more than 30 m thick (Paull et al., 2005).

If sediment transport events in Monterey Canyon are true turbidity currents, flow velocities are highest downslope in the water column and decrease to zero at the seafloor. However, down-canyon movement of the monuments during these events suggests that the velocity profile may change at the seafloor, but remain nonzero for some undetermined distance within the sediments to a master detachment surface (Fig. 13). Whether the observed movements within the bottom are caused by shear stress associated with the turbidity currents moving the uppermost layer, or movements involving most of the canyon fill, is unclear.

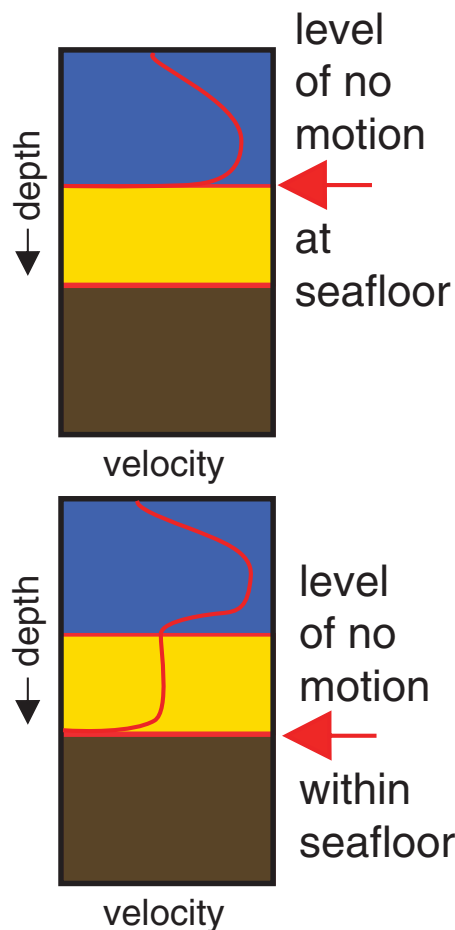


Figure 13. Two possible velocity profiles generated during gravity-flow events. On the left is a profile for a simple turbidity current, which has the level of no motion at the seafloor. The profile on the right has a level of no motion below the seafloor, which could occur during a gravity-flow or slumping event.

If the entire mass of unconsolidated canyon fill is moving downslope, it may be a significant erosional mechanism for continued carving of the canyon. Movement of the unconsolidated sediment filling the canyon may be analogous with alpine glaciers, where substantial amounts of erosion occurs at the contact between the underlying country rock and the overriding glacier (Flint, 1957). The location of the hypothesized master failure surface below the canyon floor is unknown and its depth may vary between events. However, a likely location of this failure surface is the contact between the canyon fill and the underlying country rock. Movement along this interface would inevitably cause erosion of the underlying strata. Thus, canyon incision may be occurring without having to remove the canyon fill and expose the underlying strata.

CONCLUSIONS

The existence of large crescent-shaped bedforms within the axial channel of Monterey Canyon provides new insight into the processes that move material through submarine canyons. Substantial changes in seafloor morphology associated with these features are observed between some, but not all, repeat mapping surveys in the axial channel of Monterey Canyon. The initial interpretation for the origin of these features was that they are sand waves that migrate progressively as a result of the tractive forces associated with tidal currents within the canyon axis. The facies of the sediments collected from these bedforms are composed of fining-upward sequences containing coarse-sand-supported gravel and clasts that can be as large as the diameter of the cores. Such deposits are inconsistent with their formation through tractive forces associated with tidal currents (80 cm/s).

Boulder-sized concrete monuments embedded within sediments of the canyon seafloor have moved as much as 1.6 km down-canyon in at least 6 discrete events that occurred over a 26-month period. Since their initial deployment, Homer beacons cast within the monuments have remained intact and functional for 26 months. Changes in the position of instrument frames deployed within the canyon axis also indicate that 4 discrete transport events occurred within a different 16-month period. The coincidence of these bottom movements with times of large waves suggests that seafloor pressure changes may have increased pore pressure in near seafloor sediments, triggering these events. Lithologic data obtained from the vibracoring transects indicate that the sediments beneath the crescent-shaped bedforms consist of gravity-flow deposits emplaced during brief sediment transport events, rather than through progressive waveform migration. These deposits move episodically down-canyon. This movement confirms that the seafloor associated with crescent-shaped bedforms within the axial channel of Monterey Canyon is active today. We hypothesize that as sediments resolidify at the end of gravity-flow events, slumping plays a major role in the generation of the crescent-shaped bedforms. If the movements extend to the base of the entire canyon fill, this may be a process of considerable importance for continued incision of the canyon into underlying strata.

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