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Caught in the act: the 20 December 2001 gravity flow event in Monterey Canyon

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Abstract A sediment gravity flow descended through the axis of Monterey Canyon on 20 December 2001 at 13:35 Pacific standard time. The timing of this event is documented by a current-meter package which recorded an 11.9-dbar pressure increase in less than 10 min and was found 550 m down-canyon from its deployment site, buried completely within a >70-cm-thick gravity flow deposit. This event is believed to have started in less than 290 m of water because an instrument at this location was also lost at the same time. A 178-cm core collected after the event from the axis of the canyon at 1,297-m water depth contained fresh, greenish, chlorophyll-rich organic material at 32-cm sub-bottom depth, suggesting the event extended to this water depth. The only trigger identified for this mass movement event appears to be moderate sea and surf conditions. Thus, gravity flow events of this magnitude do not require an exceptional triggering event.

Introduction

Monterey Canyon is the dominant submarine geomorphic feature in Monterey Bay. Monterey Canyon is believed to be active because its head is currently connected to the shore. About 400,000 m^3 of sand and many times the volume of organic-rich suspended material are removed from the littoral zone and descend into the canyon each year. This estimate is based on data from Best and Griggs (1991) and the US Army Corps of Engineers (1985). Best and Griggs (1991) estimated that 200,000 to 250,000 m^3 of sand enters the canyon head each year from the northern half of Monterey Bay. A similar amount of sand may enter the canyon head from the southern side as well (US Army Corps of Engineers 1985). Thus, the canyon head would fill quickly if material did not regularly move down through the canyon.

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The geologic record leaves little question that submarine canyons are major conduits for sediment transport. The occurrence of huge volumes of material derived from the continents within deep-sea fans which emanate from the mouths of these canyons attest to the scale and persistence of sediment transport down submarine canyons (Shepard 1981). Deep-sea fans commonly include thick deposits of sands and other coarse material, which require high-energy transport events (Piper and Normark 2001). Although it is clear that submarine canyons are sediment conduits connecting terrestrial sources with deep-sea fan deposits, little is known about the frequency or intensity of sediment transport events which carry coarse material through canyon systems.

Opinions vary enormously as to how frequently canyons are active. Energy associated with normal tidal motions and internal wave pumping may be sufficient to transport large volumes of sediment down the axes of some canyon systems (e.g., Shepard et al. 1979). Alternatively, sediments accumulating in the upper portions of submarine canyons may become destabilized during high-energy storm events, forming turbid (thus dense) flows which drain down the canyon axis. Such transport events are predicted to correlate with major storms (Shepard and Emery 1941; Shepard and Dill 1966; Okey 1997). During floods, large amounts of suspended sediments in rivers may create hyperpycnal river plumes which penetrate the coastal ocean by flowing down-slope along the bottom (e.g., cf. Mulder and Syvitski 1995; Johnson et al. 2001). Conversely, major events which influence canyon evolution may be associated primarily with infrequent but catastrophic failure of canyon walls (e.g., Normark and Gutmacher 1988; Greene et al. 2002) which generate down-canyon sediment flows. The relative importance of these transport and triggering processes has enormous implications as to the sources and types of material which move through submarine canyons.

The fate of instruments located in the axis of Monterey Canyon when a high-energy event occurred on 20 December 2001 is evaluated here. We also present data from current meters and observations concerning cores collected on the canyon floor which illustrate the nature and extent of the gravity flow deposits.

Materials and methods

Four instrument packages tracked in this study had been placed in the deepest part of the axial channel of Monterey Canyon by the remotely operated vehicle (ROV) *Ventana*, which is operated by MBARI out of Moss Landing Harbor at the head of Monterey Canyon (Fig. 1). Each instrument package had an acoustic transponder beacon (homer; Sonardyne Homer Pro) which can be interrogated from the ROV for range and direction information, providing a reliable way to locate equipment or reoccupy sites on the seafloor. MBARI has made extensive use of these homers by attaching them to instrument packages or marking locations by deploying homers 1–3 m above the bottom in a syntactic foam float anchored with 7- or 11-kg lead balls.

The stratigraphy of the Monterey Canyon floor deposits described here is based on ROV observations during seafloor excavations conducted on 2–3 April 2002, using a water lift dredge, two push cores (7-cm diameter×~20-cm length) taken during ROV excavations, and six ROV-collected vibracore samples (Fig. 1; Paull et al. 2001). One of these vibracores (VC-80) was collected on 27 February 2002 as part of an ongoing study of canyon-floor facies. Five additional vibracores were collected on 5–6 June 2002 to investigate whether fresh deposits existed on the canyon floor.

Contents of chlorophyll-*a* and phaeopigments were measured in samples collected from various depths within core VC-80, after a greenish horizon was observed when the core was opened. This core came from 1,297-m water depth in the axis of the canyon. These pigment measurements were compared to 59 assessments of chlorophyll-*a* and phaeopigments in surface sediment samples from various areas throughout Monterey Bay (Barry, unpublished data). Pigment levels were measured using a Turner fluorometer, after extracting 1-cm^3 subsamples of the top 1 cm of core samples in 90% acetone for 24 h.

Results

Instrument deployment and recovery

On 11 September 2000, a small benthic mooring, equipped with an InterOcean S-4 current meter, a Seabird CTD (conductivity, temperature and tidal-precision pressure)

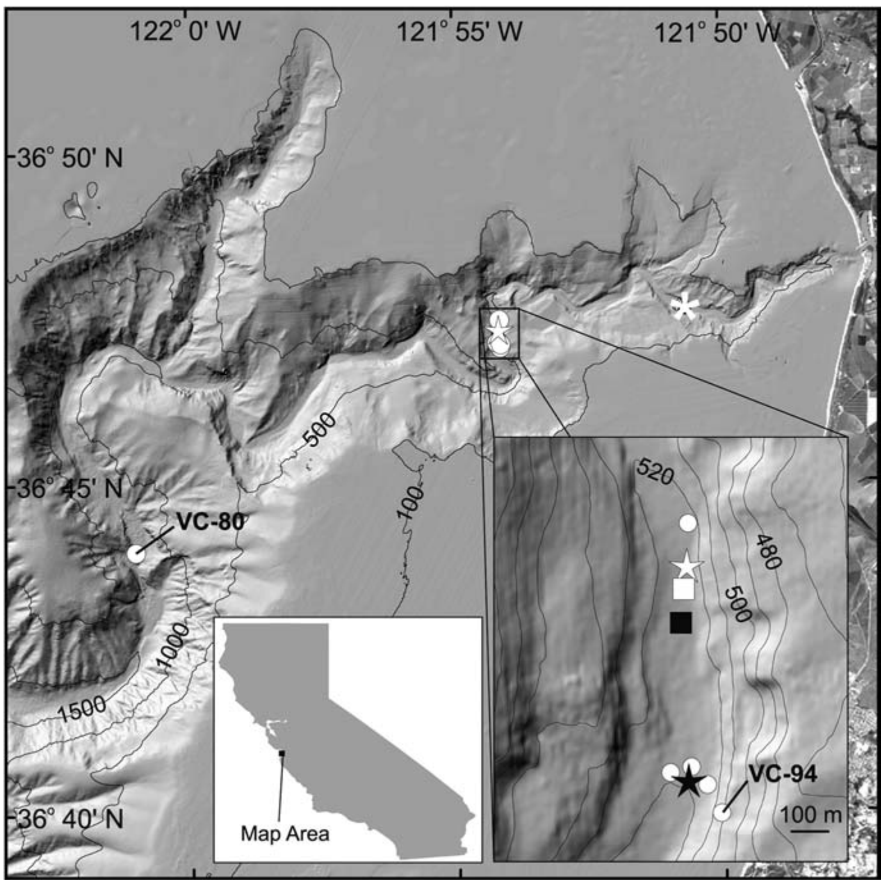

Fig. 1 Shaded relief map showing upper Monterey Canyon, based on multi-beam bathymetry (Greene et al. 2002). Locations of the instrument deployment and recovery sites are shown in the *box area* in the main map and in the enlarged *inset*. The deployment site for the S4/CTD mooring and homer #61 is shown with an *open asterisk* in the main figure. Locations of cores discussed in the text are shown with *circles*. The *inset map* shows the sites of TCM frame deployment (*open star*) and recovery (*closed star*), and of homer #60 deployment (*open square*) and recovery (*closed square*). Contours are in meters

sensor, and a homer mounted on a flotation buoy was deployed at 294 m in the axis of Monterey Canyon (Fig. 1). This instrument package was easily relocated and recovered on 17 November 2000.

On 19 December 2001, two homers were deployed in the axis of the canyon (homer #61 in 290-m water depth, and homer #60 in 525-m water depth) as markers for other experiments. Although three links of steamer anchor chain (~36 kg) were used on these homers, which more than tripled the weight of a typical homer anchor, homer #60 was subsequently found 110 m down-canyon from where it was deployed, and the other was lost.

On 20 December 2001, a steel trapezoidal frame (97 cm by 83-cm base and 48 cm tall) with a Nobska MAVS-3 acoustic current meter equipped with a CTD and Sea Point optical backscatter sensor was deployed in the axis of the canyon in 525 m of water. Homer #34 was attached to the top of this frame (Fig. 2A). The weather was marginal for ROV operations that morning, and deteriorating conditions were forecast for later in the day. Because the operation would be short, we launched the ROV at 08:20 Pacific standard time (PST), deployed the mooring, recovered the ROV, and were returning to Moss Landing Harbor by 08:55 PST. At the time of deployment, homer #60 was located 38 m south of the current meter.

On 1 April 2002, *Ventana* returned to recover the trapezoidal current meter (TCM) frame. Homer #60 was easily located, but 110 m down-canyon from its deployment position. The signal from homer #34 on the TCM frame indicated that it was ~550 m down-canyon from its deployment site. The ROV tracked the homer signal to a site in the canyon axis at 537-m depth. Although acoustic returns consistently indicated that homer #34 was only ~2.6 m away, we were not able to see the homer. Because the homer receiver is mounted 2.4 m above the base of the ROV, we inferred that the homer was located directly beneath the ROV, buried by ~20 cm of sediment.

We returned to the site the following day to dig for the homer, using a suction sampler and water jet. After an hour of digging, the top of the homer was sighted (Fig. 2B) in an upright position, which suggested it was still mounted on the TCM frame. Unfortunately, the ROV suction sampler was unable to extract enough sand to expose the TCM frame. Therefore, we returned to the site for a third day, with a water-lift-dredging tool which is more effective at removing loose sand. As sand was pumped away, the homer, Nobska current meter, and top of the TCM frame were progressively exposed. A white shaft which originally held the acoustic sensors on the top of the current meter was bent parallel to the seafloor and faced downstream (Fig. 2C). As the excavation deepened, loose sand on the flanks cascaded into the hole. Rounded cobbles of coherent, stiff mud and rock accumulated in the hole, clogging the water-lift pump and slowing the operation. The diameter of the excavation cone expanded to over 3 m before ~2/3 of the TCM frame was exposed, and the mooring was finally pulled from the seabed using the ROV's mechanical arm. Upon recovery, several cobbles of cohesive clay had adhered to the base of the frame (Fig. 2D).

A crude stratigraphic profile was constructed for the upper 70 cm of the fresh sedimentary unit from which

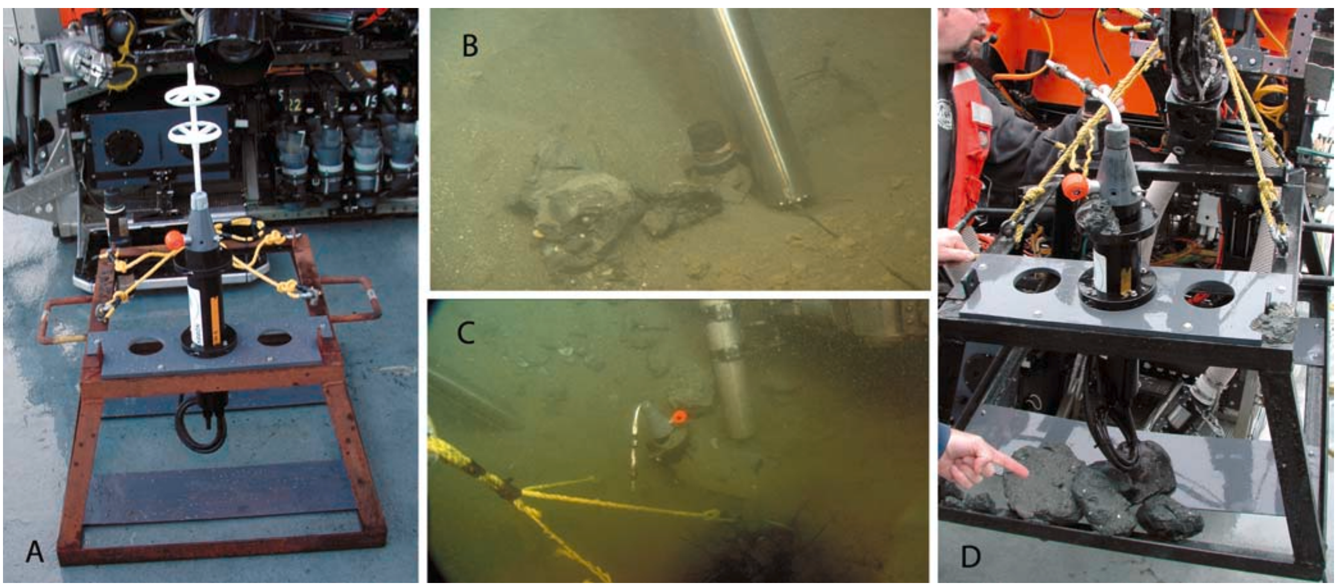

Fig. 2 **A** Photograph of the TCM frame, showing the Nobska MAVS-3 current meter (the two white rings on the shaft form the velocity sensor array) and homer (*left rear* portion of frame). **B** A ROV-manipulated sand-lifter is being used to exhume the TCM frame. The exposed top of the homer appears in the *center* of the photograph. **C** The upper portion of the Nobska current meter has been exposed. The white velocity sensor shaft is bent 90° and points down-canyon. The orange circle is the conductivity sensor. **D** A photograph of the TCM frame on the deck of the R/V *Pt. Lobos* after recovery. Note the cohesive clay clasts on the bottom shelf of the frame. The velocity sensor array has been stripped off the instrument, and the shaft has been bent 90°

the TCM frame was extracted. Except for some wood debris on the very top of the push cores, the upper 30 cm of the sedimentary unit consisted of well-sorted fine sand. The next 40 cm contained rounded and angular clasts up to 20 cm in the long dimension (Fig. 2D). Most clasts were composed of stiff, cohesive clay similar to material found commonly on the walls of Monterey Canyon. These clasts appear to have been supported by a matrix of fine sand. These observations suggest that the TCM frame was swept down-canyon within a gravity flow.

Even though its anchor chain was buried completely, making it difficult to extract from the sediment, homer #60 was also recovered on 3 April 2002. Upon recovery, the void spaces between the syntactic foam blocks which enclose the homer were found to contain sand and numerous thin, rounded pebbles. Such sediment fouling had never been observed during dozens of earlier homer deployments. The syntactic blocks usually float the beacon ~3 m above the bottom, minimizing its exposure to suspended sediment. Such fouling by sand and pebbles would therefore have required a high-energy event.

Instrument data

Data from the 11 September 2000 deployment of the current meter 1 m off the bottom, and of the CTD 2 m off the bottom at the 290-m site were combined on a common time base. A representative portion of this record (Fig. 3) shows a clear tidal signal which was evident throughout the deployment period. The strongest currents (up to 55 cm s^{-1} or ~1 knot) are associated with flows to the southeast, which is up-canyon (Fig. 1).

Although the Nobska MAVS-3 current meter recovered on 3 April 2002 was damaged during its trip down-canyon, data from its sensors were not lost. The CTD recorded a down-canyon transport event soon after 13:35 PST on 20 December 2001, ~5 h after the instrument was deployed (Fig. 4). This down-canyon movement is defined by an 11.9-dbar increase in pressure which occurred in less than 10 min (Fig. 4). This pressure increase is consistent with the bathymetric change caused by movements of the instrument 550 m down-canyon to its recovery site. The Nobska current meter recorded moderate up-canyon flow just prior to the event, but the current meter failed as the instrument moved down-canyon. The optical backscatter sensor recorded no signal return after the event, consistent with its burial. Pressure measurements continued for the following 28 days, and a distinct tidal signal was recorded, apparently from within the canyon-floor sediments.

Sediment core data

When one 178-cm-long vibracore (VC-80) from 1,297-m depth was split open for examination and sampling, a particularly interesting observation was made. The core consisted of ~40 cm of mud overlying a sand- and gravel-bearing layer which presumably reflected

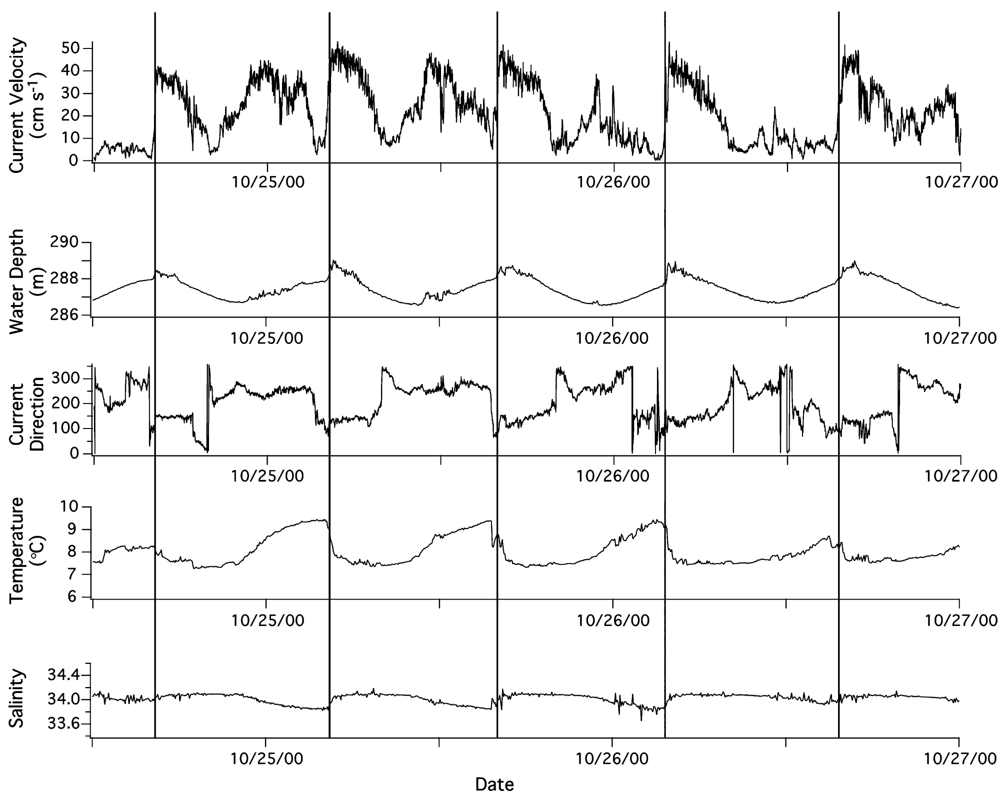

Fig. 3 Time-series records for a selected 2.5-day period of current velocity, water depth, current direction (compass orientation), temperature, and salinity from the 11 September to 17 November 2000, S4/CTD deployment at 290 m. An abrupt, up-canyon shift in current direction occurs just prior to high tide. Maximum velocities are recorded in the up-canyon direction (approximately 155°), and bring cooler and more saline water up-canyon

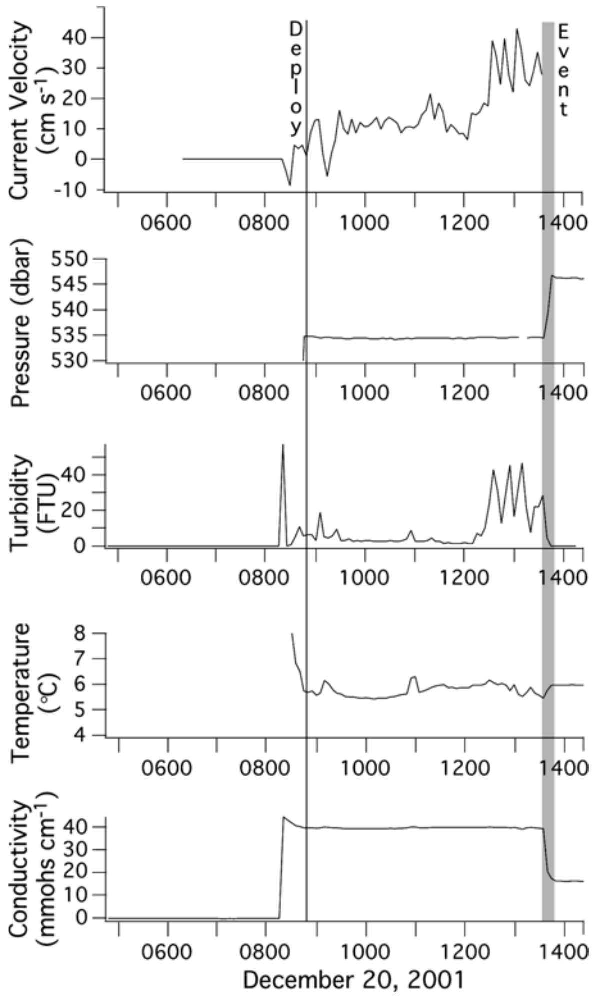

Fig. 4 Time-series data (sampled at 5-min intervals) obtained from the TCM deployment at the 525-m site on 20 December 2001. A *thin shaded line* indicates deployment at 08:45 PST, and the *thicker shaded bar* indicates the sediment gravity flow event. Current velocity measurements ceased at the beginning of the event, and pressure increased from 534.4 to 546.3 dbar in less than 10 min. Up-canyon current velocities are positive, and down-canyon velocities are negative on this time-series plot

deposition from a gravity flow event. Although such facies are encountered commonly in the axis of the canyon, an unusual, greenish organic-rich layer was observed at 32-cm depth. Samples of the greenish material, and 10 samples from the soft fine-grained sediments in this core were analyzed for chlorophyll-*a* and pheopigment contents.

Chlorophyll-*a* values in four of 12 samples (between 10- and 50-cm sub-bottom samples) from core VC-80 were anomalously high (>1.0 μg g wet wt^{-1}) from 10 to 35 cm. These values were near or exceeded levels typical of surface sediments collected within and outside Monterey Canyon (mean chlorophyll-*a* contents (μg g wet wt^{-1} ± standard error) 2.6 ± 0.41, $n=15$, and 0.9 ± 0.14, $n=44$, respectively). The chlorophyll:pheophytin (C:P) ratio was strikingly high (up to 0.30) from 30- to 35-cm depths where a bolus of relatively fresh plant material was found. The mean C:P ratio for surface sediment in Monterey Bay is 0.12 ± 0.005. Because chlorophyll degrades rapidly into pheophytins and pheophorbides, the peak C:P value at 32-cm sub-bottom depth suggests burial of fresh, surface-derived plant material within weeks (e.g., Pfannkuche et al. 2000). These high values occurred in the soft sediments overlying a >118 cm thick, poorly sorted sand, pebble and gravel layer.

We infer that the entire core sampled one gravity flow deposit, and that this fresh plant material was transported rapidly down to this site and incorporated into the mud during the waning stages of the 20 December 2001 gravity flow event. Thus, this event penetrated to at least 1,297-m water depth.

Five vibracores, with an average length of 126 cm, were collected in June 2002 from the canyon's axis in water depths of 288 to 537 m. The stratigraphy of these cores showed evidence of gravity flow deposits, and none of the cores penetrated through the coarse-grained layer into earlier depositional events. Thus, 126 cm can be considered as a minimum thickness for this event. Unfortunately, none of these cores contained fine-grained sediment appropriate for chlorophyll analysis. The obviously porous sand and gravel deposits generally lacked a mud matrix and were dewatered, with the exception of one core (VC-94) which, from 60- to 227-cm sub-bottom depths, contained gravel in a still-fluid mud matrix. Apparently, the event which deposited this unit was so recent that this material had not yet dewatered. Again, we take this as an indication of a fresh deposit, presumably also associated with the 20 December event.

Discussion and conclusions

The current record from the S4/CTD instrument package deployed in the canyon from 11 September to 17 November 2000 shows that flow in the canyon is tidally modulated and strongest up-canyon. Apparently, common daily flow conditions are unimportant for coarse-sediment transport in Monterey Canyon.

Our results suggest that a sediment gravity flow occurred within the canyon at 13:35 PST on 20 December 2001, carrying one instrument package 550 m down-canyon in less than 10 min, and burying it within a >70-cm-thick sand, pebble, and cobble deposit. Two homers deployed in the canyon at this time were also impacted by this event. One (homer #60) moved 110 m down-canyon and was recovered with sand and pebbles filling voids in its flotation buoy. The other homer (#61) was not relocated, presumable because it was swept away in this event.

Dislodgement of instruments and analysis of sediment cores from the canyon axis indicate that this event impacted the canyon from at least 290- to 1,297-m water depths. The shallow end range is constrained by the loss of homer #61 which was deployed in 293 m of water, 10.5 km upstream of where the displaced homer and buried TCM frame were originally deployed. High levels of chlorophyll-*a* at 32-cm depth, within a >178 cm thick gravity flow deposit at 1,297-m water depth, suggest that a recent event occurred in this area. We infer that these observations all reflect the same gravity flow event.

Although the thickness of gravity flow deposits may vary considerably along the axial channel, these observations provide some constraints on the size of this event. A rough estimate of the volume of material involved in this mass transport event can be made by assuming that a 70-cm-thick layer of sandy sediment was deposited along the 31-km stretch of the canyon floor between 290- and 1,297-m water depths. The average channel width is over 100 m. Thus, ~2,200,000 m^3 of material could have been involved in this event. For comparison, the volume of sand estimated to enter the canyon head each year from long-shore sediment transport is ~400,000 m^3. This calculation suggests that events of this magnitude would have to occur approximately every five years to maintain the sand budget.

Knowledge of the timing of this gravity flow event allows us to assess whether an earthquake, hyperpycnal flow or storm may have triggered the event. A search of the Northern California Earthquake Data Center (NCEDC) records indicated that no seismic events greater than magnitude 2 occurred within 24 km (the distance to the San Andreas Fault) of the canyon during any of the mooring deployments. Moreover, no appreciable seismic events occurred in California near 13:35 PST on 20 December 2002. Johnson et al. (2001) indicated that hyperpycnal flows occur within Monterey Canyon when the Salinas River discharge exceeds 300 m^3 s^{-1}. Although river runoff increased in response to the winter storm on 20 December 2001, maximum flow was only 3 m^3 s^{-1} (USGS gauging station 111525000). Thus, flow conditions suitable for generating a hyperpycnal flow did not exist at that time.

Storm conditions existed in Monterey Bay on the afternoon of 20 December 2001 when the gravity flow event occurred. NOAA weather buoy #46042 records sea conditions ~100 km off shore from the head of Monterey Canyon. The gravity flow event occurred near the beginning of a 6-h interval when significant wave heights exceeded 6 m at this buoy. We suspect that these sea conditions probably triggered the 20 December 2001 gravity flow event. Although these are large swells, they are not unusually big for Monterey Bay. This weather buoy recorded similar or greater significant wave heights on eight other occasions during 2001. Thus, we conclude that sediment gravity flow events in submarine canyons do not require exceptional triggering events.

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