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Evidence of a turbidity current in Monterey Submarine Canyon associated with the 1989 Loma Prieta earthquake

NEWELL GARFIELD,* THOMAS A. RAGO,* KURT J. SCHNEBELE*† and CURTIS A. COLLINS*

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Abstract—Evidence of a turbidity current sweeping through the Monterey Submarine Canyon following the October 1989 Loma Prieta earthquake was documented by the movement of bottom-deployed acoustic transponders used to navigate free-falling oceanographic instrumentation. Measuring sites located along the Canyon at distances of 55, 130 and 190 km from the Canyon head off Moss Landing, CA, all showed evidence of tectonically induced sediment transport. At the site 55 km from the Canyon head, one transponder, located in the axis of the Canyon, was carried 1.9 km down the axis and was deposited among a field of rocks. The other three transponders had been deployed on the sides of the canyon and showed evidence of sediment slumping toward the Canyon axis. Circumstantial evidence from the site 130 km down the canyon suggests that sediment deposition occurred outside the channel axis. Sediment slumping or erosional cutting moved one transponder deeper at the site 190 km from the canyon head.

1. INTRODUCTION

THE Naval Postgraduate School conducted a field program from April 1988 to April 1991 to investigate the kinematics of the California Undercurrent. The free-falling acoustic dropsonde *Pegasus* (SPAIN *et al.*, 1981) was used to profile the vertical distribution of the horizontal velocity field at 10 locations off Monterey Bay and Point Sur, California (Fig. 1). The instrument is tracked by recording the round-trip acoustic travel time between *Pegasus* and an array of bottom-deployed acoustic transponders. The array can be up to six transponders replying in the frequency range 11.5–14.0 kHz (at 0.5 kHz frequency steps). Each transponder is identified by the acoustic frequency at which it replies. If the locations of the transponders in the array are precisely known, the position of *Pegasus* in the water column can then be determined by triangulation for every 16 s time interval. A minimum of two transponders plus a depth sensor are needed to determine the relative position of the instrument in the water column. The velocity profile is obtained by differentiating the *Pegasus* position with respect to time.

Three of the measurement locations (designated C-5, C-7, and C-10) are located in, or adjacent to, Monterey Submarine Canyon off the California coast (Fig. 1). C-10 is situated

*Department of Oceanography, Naval Postgraduate School, Monterey, California, U.S.A.
†Present affiliation: Allan Hancock Foundation, USC, Los Angeles , California, U.S.A.

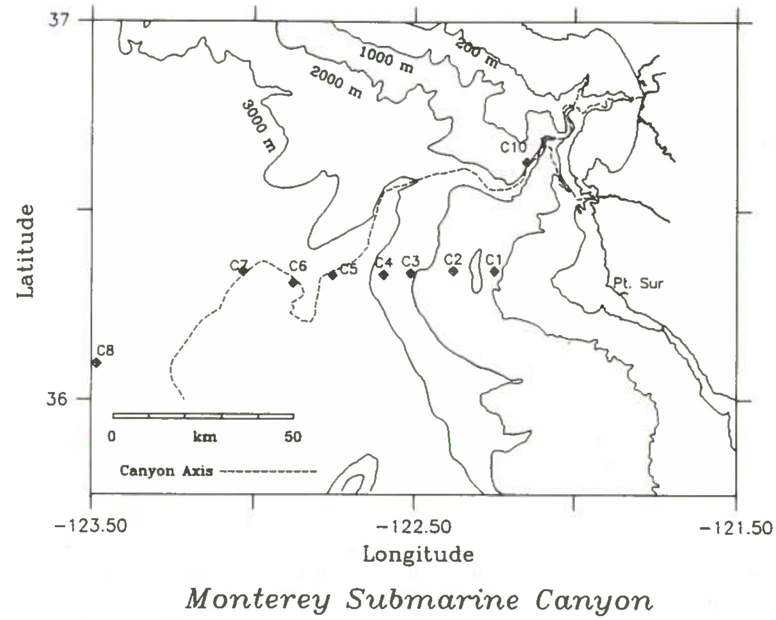

Fig. 1. Chart showing the Monterey Submarine Canyon and nine of the 10 *Pegasus* sampling sites. The dashed line is the axis of the Monterey Submarine Canyon and the major tributaries associated with the canyon. C-5, C-7 and C-10 are located in Monterey Submarine Canyon.

in about 2200 m of water, 55 km down the axis of the Canyon from the canyon head at Moss Landing. C-5 is in 3150 m of water, 130 km down the Canyon axis from Moss Landing, and C-7 is in 3500 m of water 190 km down the Canyon axis. Although C-5 and C-7 are only 30 km apart, the along canyon distance is 60 km because of the presence of Shepard Meander between the two sites. During the research cruise following the 17 October 1989 Loma Prieta earthquake, it was found that the transponder array at C-10 had been dramatically rearranged. Initially it was assumed that only the transponder on the canyon axis had moved a significant distance. However, a subsequent cruise specifically to resurvey the *Pegasus* sites revealed that all the transponders at C-10 had moved, in varying degrees. The one most centrally on the Canyon axis, in fact, had moved such a substantial distance that it initially could not be located. Through the work described here we determined that this transponder had shifted 1.9 km down the canyon axis, an impressive distance for an object weighing approximately 25 kg in water. The other transponders, located on the Canyon walls, all moved down the walls toward the Canyon axis. While the most dramatic results were found at C-10, sediment deposition is inferred at C-5 and slumping along the canyon wall is suggested at C-7.

The movement of the transponders suggests that an unusually strong current occurred along the bottom of the Monterey Canyon axis. A turbidity current associated with seismically induced activity seems the most likely explanation. The movement of the shallower C-10 transponders and one transponder at C-7 suggests that significant slumping or cascading occurred along the walls throughout the Canyon. This article documents the transponder movements which occurred between 30 September and 15 November 1989, our observations of bottom conditions, and our conclusions as to how the transponders were moved.

2. BACKGROUND

Turbidity currents are suggested as the major mechanism by which continental sediments are transported to the deep ocean floor (e.g. KENNETT, 1982). While the origin of these currents is not clearly understood, there is a clear association between slumps, slides and the generation of turbidite sedimentary sequences. Turbidites are graded deposits normally consisting of fining-upward sequences of gravel, sand, silt and mud material. KENNETT notes that minimum speeds of turbidity currents are about 13 cm s^{-1}, while maximum speeds can attain 870 cm s^{-1}, and that in general the currents carry up to 3 kg m^{-3} of material over distances of up to 1000 km from the source. Turbidity currents generally occur in submarine canyons, and have long been cited (beginning with DALY, 1936) as a major mechanism for subaqueous canyon formation. They also occur at other continental slope locations, the best documented example being that which was associated with an earthquake on the Grand Banks on 19 November 1929 (HEEZEN and EWING, 1952; PIPER *et al.*, 1988; SHOR *et al.*, 1990). Direct measurements of turbidity flow were obtained during the downslope movement of current meter arrays moored off Kahe Point, Oahu, Hawaii. Downslope movement of four current meter arrays (one array initially at 800 m depth was moved 2.25 km to 1030 m depth) was attributed to a series of turbidity flows initiated by storm surge associated with Hurricane Iwa in 1982 (DENGLER *et al.*, 1984). Recent reviews of turbidity flows are found in SEYMOUR (1990) and NORMARK and PIPER (1991).

Scripps and Monterey Submarine Canyons have both been studied extensively to provide insight into turbidity flows (see SEYMOUR, 1990; GARDNER *et al.*, 1991; GREENE *et al.*, 1991b; and NORMARK and PIPER, 1991 for reviews). Deposits in the channel axes of submarine canyons generally contain coarse material, usually noted by the presence of sands and pebbles, indicative of strong currents. While no direct measurements of turbidity flows are available, DILL (1964) reported on larger material, blocks of concrete, auto bodies, and current meter moorings being carried down the axis from the head of Scripps Canyon. The postulated mechanisms for moving the large objects were "partly (by) creep and slumping, but perhaps also by sand flows and turbidity currents" (SHEPARD, 1973). Sediment accumulation in the upper canyon and then removal through turbidity currents is a regular feature of the evolution of Monterey Canyon (GREENE *et al.*, 1989). Much of this material is carried to the Monterey Deep Sea Fan, 250 km from the head of the Canyon, but Greene (personal communication in SCHWING *et al.*, 1990) suggests that the coarse material may be trapped along the canyon axis by slump dams blocking the axis of the Canyon. Flows reaching the Monterey Fan must, at times, be very strong. GARDNER *et al.* (1991) reported gravel up to 2 cm diameter had been sampled from the distal end of the fan. KOMAR (1969) used a series of twelve crossings of the Monterey deep-sea fan channel to discuss the channelized flow of turbidity currents.

The Loma Prieta earthquake occurred on 17 October 1989. This magnitude 7.1 earthquake, located along the San Andreas fault zone, caused widespread damage in the central California region. The beach at Moss Landing experienced sediment liquefaction and lateral spreading which destroyed a number of buildings along this spit separating the Old Salinas River and Moro Cojo Slough from Monterey Bay. It was estimated (GREENE *et* al., 1990, 1991a) that a large area around Moss Landing (up to 8 km^2) underwent sediment liquefaction which resulted in massive downslope movement of this material offshore via Monterey Canyon. This inference is supported by the presence of fresh slump scarps along the southern rim of the Canyon in water depths of 80–100 m (GREENE et al.; SCHWING et al., 1990). These features were up to 6.3 m high and over 4 m wide.

3. METHODS

3.1. *Transponder deployment and ship survey methods*

The dropsonde *Pegasus* is navigated through the placement of acoustic transponders on the ocean floor. The transponders used in this project, manufactured by Oceanographic Instrument Systems, are housed in aluminum cylinders, weigh 9.98 kg and displace 5035 cm^3. Two methods have been used for deployment of the transponders. Most commonly, in regions with smooth bottom topography, the method of SPAIN et al. (1981) is followed where the beacons are tossed over the side of the ship in a pattern so that the transponders are separated horizontally by a distance equal to the water depth. However, where more rugged bottom topography might cause acoustic shadowing of the transponder, the transponder is often moored above the bottom by suspending it on a cable connecting an anchor and a glass flotation sphere such that the transponder will be a predetermined height above the bottom. When mooring transponders, the ship is positioned at the desired site, and the mooring is launched anchor last.

At C-5 and C-7 arrays of three transponders were deployed directly on the sea floor. At C-10 (Fig. 2) only two of the transponders (12.0 and 12.5 kHz) were deployed directly on the bottom, while the other two (11.5 and 13.5 kHz) were suspended approximately 15 m above the bottom to increase their acoustic visibility. The net weight in water of each of these two transponder moorings was about 25 kg.

The locations of the bottom-deployed transponders must be known precisely in order to obtain absolute current profiles from *Pegasus* data. Traditionally these locations are determined by an acoustic "survey" which is conducted in two stages (SPAIN et al., 1981). The transponder arrays at C-5 and C-7 were deployed and surveyed in this manner. However, the four transponders at C-10 were not deployed at the same time; only the original two transponders (12.0 and 12.5 kHz) were deployed and surveyed in April 1988 using the Spain et al. technique. Time and equipment constraints prevented a ship survey of the later-deployed moored transponders (11.5 and 13.5 kHz) prior to the Loma Prieta earthquake. The approximate locations of these two transponders were initially taken from the Loran coordinates at the times of their launchings. This assumed that there was little lateral drift as they fell through the water column. These approximate locations, as well as the more exact positions of the original two transponders, were later verified using the least-squares survey technique described below.

3.2. *Instrument survey methods*

A determination of the initial C-10 array geometry, including the locations of the 11.5 and 13.5 kHz transponders, was accomplished using the *Pegasus* travel time and pressure data from one deployment in a least-squares navigation technique (HASKELL, 1991). With four transponders and pressure data, redundant position data is available and least-

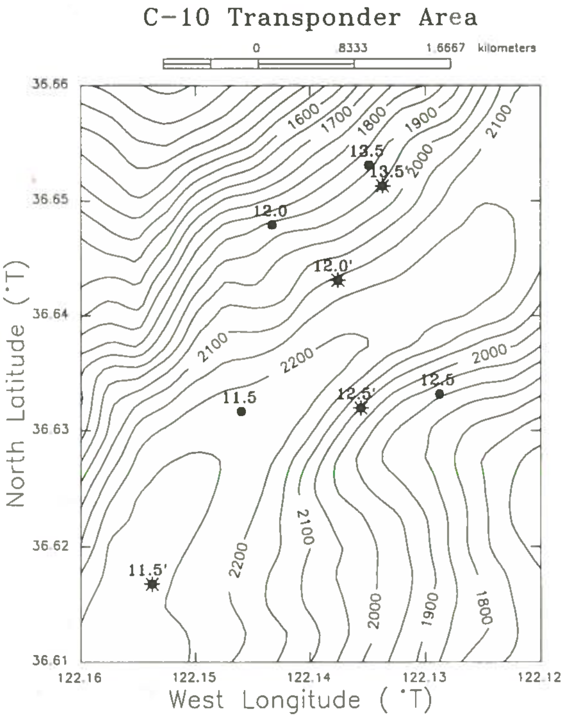

Fig. 2. Plan view of Monterey Submarine Canyon at C-10 showing the initial and final locations of the four acoustic transponders. The initial positions are designated by the circles and the post-earthquake positions are indicated by the rayed circles.

squares adjustment procedures yield unique solutions (Uotila, 1986). Haskell applied this method to transponder positioning at C-10 using *Pegasus* data. This approach has advantages over the navigation procedures outlined above because it uses all the observational data, and it has the added benefit of providing statistical information on the quality of the derived results. Haskell found that the technique could produce convergent estimates of all four C-10 transponder positions using data from as little as one *Pegasus* drop centered within the array. The horizontal coordinates obtained are only relative, expressing the lengths and interior angles of the array baselines. Absolute coordinates and array orientation with respect to north cannot be determined by this technique. Depths, however, are tied to a sea level reference because of the depths observed by *Pegasus*. The transponder array baselines determined from this analysis agreed with the shipboard survey to within 150 m for the two baselines surveyed, and 10 m in depth for all transponders. The estimated precision was 15 m (Drms)* in relative horizontal positioning and 3 m (1 σ) in depth. This pre-earthquake configuration also was confirmed in a second analysis described below.

Attempts were made following the Loma Prieta earthquake to survey the 11.5 kHz transponder at C-10 using the standard ship survey techniques. These survey attempts

*Drms = Distance root-mean-squared: a measure of precision for two-dimensional coordinates indicating the radius of a nominal 68% confidence region.

Table 1. Pre- and post-earthquake C-10 transponder array geometry determined from least-squares regressions of Pegasus *drop data. The origin was set at the* 13.5 kHz *transponder under the assumption that this transponder moved the least. All distances are in m*

Transponder	x (east)	y (north)	z (depth)
Pre-earthquake transponder positions			
11.5	−1210.	−2100.	−2230
12.0	−850.	−520.	−1990
12.5	530.	−2030.	−1880
13.5	0.	0.	−1890
Post-earthquake transponder positions			
Transponder	x (east)	y (north)	z (depth)
11.5	−1690.	−3730.	−2270.
12.0	−320.	−990.	−2180.
12.5	100.	−2040.	−2040.
13.5	0.	0.	−1960.

were unsuccessful because the ship's transducer could not simultaneously detect both the 11.5 kHz signal and any other transponder signal while bisecting the baselines created with the 11.5 kHz transponder. This effort confirmed the suspicion that the transponder array geometry was no longer as it had been when initially deployed.

On the other hand, *Pegasus* received signals from all four transponders while falling through the water column. The program used by HASKELL (1991) was modified to use data from multiple *Pegasus* drops in order to make new estimates of the transponder positions both prior to and following the earthquake. Data from five *Pegasus* drops between July, by which time all four transponders had been deployed, and September 1989, the last cruise before the earthquake, were subsampled to form a set of 150 records of roundtrip travel times to all four transponders. Similarly, a post-earthquake data set of 184 records was taken from 14 drops made between November 1989 and April 1991. For the analyses of both sets the *a priori* estimates of transponder coordinate precision were relaxed to allow the least-squares fit the widest possible range of solutions. Normally the transponder coordinates would be constrained by the estimated precision of the ship survey results. However, following the earthquake, the only coordinate known with any confidence was the depth of the 13.5 kHz transponder, observed during a submersible dive. This depth was held relatively fixed (*a priori* $\sigma = 500$ m for horizontal and 100 m for depth). These relaxed *a priori* estimates were used for both the pre- and post-earthquake analyses to avoid biasing the results. Table 1 shows the computed pre- and post-earthquake positions and Table 2a gives the movement which occurred during the time of the Loma Prieta earthquake of the 11.5, 12.0, and 12.5 kHz transponders relative to the 13.5 kHz transponder.

The analysis of the pre-earthquake data produced coordinates agreeing with Haskell's (1991) previous values. The largest horizontal coordinate difference was 23 m, which is not significant given the 15 m precision cited previously. Depths agreed to better than 3 m for all transponders. The post-earthquake results, however, showed relatively large horizontal movements (Table 2a). Estimated precision of these horizontal coordinates is consider-

Table 2a. The relative change in position of each C-10 transponder before and after the earthquake when the position of the 13.5 kHz transponder is held fixed. Δx, Δy and Δz are the east, north and vertical displacements. Δh is the horizontal displacement determined from Δx and Δy. The slope of each transponder displacement was determined by $\tan^{-1}(\Delta z/\Delta h)$

Transponder	Δx	Δy	Δz	Δh	slope
11.5	−480.	−1630.	−40.	1700	1.3
12.0	530.	−470.	−190.	710	15.0
12.5	−430.	−10.	−160.	430	20.2
13.5	0.	0.	−70.		

Table 2b. The total change in position of each C-10 transponder before and after the earthquake when the position of the 13.5 kHz transponder is adjusted, as described in the text, to fit the bottom topography.

Transponder	Δx	Δy	Δz	Δh	slope
11.5	−600.	−1810.	−40.	1900	1.1
12.0	410.	−650.	−190.	770.	13.9
12.5	−550.	−190.	−160.	580.	15.2
13.5	120.	−180.	−70.	220.	17.1

ably less (on the order of several hundred meters for horizontal coordinates) while depths were well resolved ($\sigma < 10$ m on all transponders). The degraded horizontal precision results from the lack of deep *Pegasus* observations due to the shadowing of the 11.5 kHz transponder (described below) and lack of good *a priori* transponder coordinates. The post-earthquake data set thus contained few observations below 1000 m depth compared with the pre-earthquake set. The simplest characterization is to note that the post-earthquake horizontal baselines were determined with a precision of about 11% of baseline length, or 450 m (1σ) for the longest baseline between the 11.5 kHz and 13.5 kHz transponders.

3.3. *Other observations*

In June 1990 the Navy Deep Submergence Vessel *Sea Cliff* (DSV-4) was used to search for the 11.5 and 13.5 kHz transponders at C-10. The first dive, shortened due to both deteriorating weather and technical complications, failed to locate the 11.5 kHz transponder. However, the dive did provide insight into the ruggedness of the bottom along the canyon axis. After reaching the ocean bottom (2344 m by inverted echo sounder to the surface), the submersible began an observation survey along the canyon floor going in a general up-canyon direction. The bottom in the axis area was fairly smooth with light brown mud containing numerous infaunal burrows. A short distance up-axis (about 0.25 km) the bottom became very rugged with blocks and steep rock faces. This was an area that a previous SeaBeam survey showed to be a flat, smooth bottom (Greene *et al.*, 1989). (A post-earthquake survey is planned to determine whether a rock fall occurred during the earthquake, or if the scale of the topography is less than the resolution of SeaBeam at these depths). Some of the faces were nearly vertical and greater than 6 m high. The submersible spent as much time moving vertically up and down these faces as it did traveling horizontally. The submersible rested on the top of a couple of these cliffs in order to let the sediments stirred up by the vessel clear away. The tops of these cliffs were sediment laden, and the current was estimated to be about 0.25 m s^{-1}. Bioturbation was not noted in the sediments among the rock field. The dive was terminated after 1.5 h of searching because of increasing surface sea state. The dive participants concluded that, although the 11.5 kHz transponder was elevated 15 m above the bottom and had a good acoustic reflector (a Benthos 17 inch glass sphere) 5 m above the transponder, it would still be very difficult to locate in such rugged topography. They suspected that the transponder had fallen over one of the cliffs, leaving its elevation below the top of the cliff. This observation is supported by the dropout of 11.5 kHz return signals in the *Pegasus* data whenever *Pegasus* was deeper than about 500 m.

A second dive was made to locate the 13.5 kHz transponder. This instrument was successfully found on a silty terrace or ledge area above the canyon floor in 1931 m of water. The anchor, a concrete-filled motorcycle engine block, was half sunk into the sediment. The character of the bottom topography near the 13.5 kHz transponder was significantly different from that near the 11.5 kHz transponder. No steep rock faces or cliffs were observed. Rather, a uniformly smooth, very steep (order 60°–80°) mud or silt slope was observed rising from the canyon floor at 2050 m to the ledge where the transponder was found. A relatively strong current (order of 0.12 m s^{-1}) was felt by the *Sea Cliff* throughout its ascent from the canyon floor to the ledge where the transponder was found. At one point this current necessitated burying *Sea Cliff*'s bow into the slope in order to stabilize the submersible. The gentle impact set off many mini-slides and slumps. Neither the width of the ledge where the 13.5 kHz transponder was found nor the character of the canyon wall above the ledge were determined. The smooth appearance of the sediments at the location of the transponder on the ledge gave the appearance that this instrument had not moved during the earthquake. However, the change in estimated depth after the earthquake suggests otherwise.

4. RESULTS

Table 1 presents the least-squares determined transponder array geometry at C-10 estimated from the pre- and post-earthquake *Pegasus* data set. The changes in calculated depths show that all the transponders ended up in deeper water after the earthquake

Table 2a gives the calculated relative movement of three transponders calculated by assuming that the 13.5 kHz transponder did not move. This was not accurate, as is indicated by the calculated change in depth of all the transponders. However, horizontal movement of the 13.5 kHz transponder does appear to be minimal, and we used this transponder as the origin for initial comparison of the others. Total movement of each transponder was then calculated by estimating the horizontal movement of the 13.5 kHz transponder associated with the observed 70 m depth increase. The way in which we approximated this movement was to plot the post-earthquake array geometry to the same scale as a bathymetric chart on which the pre-earthquake positions had been plotted and to then obtain a best fit visually among the four transponder depths and the depth contours from the NOAA 250 m digital bathymetric data (NOAA, 1989). The transponder array geometry was held rigid. Although the bathymetric data are from the pre-earthquake environment, a plausible visual fit was found by simply moving the 13.5 kHz transponder directly downslope. The resulting arrangement is plotted on Fig. 2 and the total movement of each transponder is given in Table 2b. Similarly acceptable results are obtained by moving the final position of the 13.5 kHz transponder southwest along the 1960 m isobath. Thus our results represent a minimum horizontal displacement of the transponders.

Errors in our position determination originate from a couple of sources. Instrument or systematic errors arise from timing accuracy. The resolution of the clock used to time the round trip travel time is 0.1 μs, which translates to a possible distance error of only 0.1 m. The transponders have a 12.5 ± 0.5 ms delay before transmitting the response signal. This uncertainty could translate to a distance error of 0.75 m. The *Pegasus* instrument cluster includes SeaBird conductivity and temperature sensors and a ParoScientific pressure sensor. Data from these sensors are used to calculate *in situ* sound speeds for each drop of the instrument; therefore, the sound speed error should be minimal.

Another error source is the sound ray path. The calculations done here assume no ray bending. Over the short distances involved, this assumption might lead to a 1–2 m positioning error. The error could be much larger if the direct path were blocked. Signals from the 11.5 kHz transponder are only received by *Pegasus* in the upper 500 m. Below that depth the signals appear to be blocked. It is conceivable that the signals received by *Pegasus* are from secondary paths, not the direct path. However, this is not likely since it is usually possible to detect secondary pathways by the time rate of change of the travel time data.

Errors from the ship survey techniques are more difficult to assess. Through the repeated crossings over the transponders and along the bisectors we estimate that the transponder depth error is on the order of 0.5 to 1% (<23 m) of the water depth, and on the order of 100–150 m for the baseline length. Baseline orientation error is estimated to be ±2°. These errors are not enough to explain any of the estimated transponder displacements.

The same shipboard and instrument survey techniques were used to navigate the transponders deployed at C-5 and C-7. At both locations the topography is sufficiently gentle that it was not deemed necessary to elevate the transponders above the ocean floor. The pre- and post-earthquake instrument surveys at C-5 agreed with the original ship survey results within the estimated precision of the least-squares solution. We conclude that no measurable movement occurred at this site. The deepest transponder (12.0 kHz) was at a depth of 3164 m by acoustic determination and 3270 m by the least-squares technique. The chart depth along the axis of the canyon at this location is 3320 m. The transponders all appear to be located to the southeast of the channel axis. Following the earthquake, the signal reception recorded by *Pegasus* for the 12.0 kHz transponder was much degraded compared to the reception prior to the earthquake. This transponder was the closest to the channel, and the percentage of good signals dropped from an average of 96 ± 1% good returns prior to the earthquake to 42 ± 13% for drops following the earthquake. This reduction does not appear to be due to transponder battery depletion; there is a rough inverse correlation between the distance between *Pegasus* and the transponder and the percentage of good transmissions. The percentage of good returns also dropped at the 11.5 kHz transponder from 73 ± 27% to 44 ± 27%, again with the same inverse correlation. Reception at the 12.5 kHz transponder remained high at 97% and 95% prior to and after the earthquake. A plausible explanation for this is that the 11.5 and 12.0 kHz transponders underwent significant burial from sediments carried past this site by a turbidity current. This would indicate that when the channel leaves the canyon environment and moves onto the continental rise, sediments escape from the turbidity current by lateral spreading over the relatively low channel walls and then settle out of the water column.

At C-7 the least-squares solution did not determine significant horizontal translation of any transponder between the pre- and post-earthquake instrument and the ship survey positions. However, the 12.5 kHz transponder underwent an apparent vertical shift. The ship survey depth of this transponder was 3410 m and the estimated position from the pre-earthquake least-squares fit was 3420 m. The post-earthquake least-squares depth was 3480 m. This depth change is statistically significant, suggesting that the transponder was indeed moved to deeper water. The channel axis runs through the C-7 array, and it appears that the 12.5 kHz transponder was initially positioned on the slope marking the northwest side of the channel. This bank, relatively steep on the chart, starts at a depth of 3300 m, and descends to 3540 m. The channel axis is at 3560 m. Our conclusion is that the transponder must have fallen down the slope toward the channel axis, but we cannot determine whether or not it was carried down the channel. We are therefore unable to determine whether slumping of the channel wall or the passage of a turbidity current was responsible for the movement. However, it does appear that this area was also affected by tectonic events associated with the Loma Prieta earthquake.

5. DISCUSSION

This work was undertaken to process data to be used in calculating the vertical distribution of the horizontal currents in the water column. Our efforts to determine the transponder locations were initially done for this processing. Examination of the results led to the analyses presented here. The study was not conceived as a tectonic project and, because of that, supporting evidence that would have strengthened the study was not collected. Still, the observations are impressive and should help improve our understanding of turbidity currents.

The most significant result from this work is the 1.9 km horizontal displacement down the canyon axis and 38 m vertical displacement of the C-10 11.5 kHz transponder, which is attributed to the passage of a turbidity current. Other results are the lesser, but nonetheless significant, movements of the 12.0, 12.5 and 13.5 kHz transponders at C-10. These three transponders were located higher up on the canyon walls than the 11.5 kHz transponder and underwent different displacement directions. The 12.0 and 13.5 kHz transponders were located on the northwest wall and moved primarily downslope toward the canyon axis rather than down-canyon along the canyon axis. The 12.5 kHz transponder was displaced in both downslope and down-axis directions. It came to rest about 200 m above the depth of the canyon floor. This implies that, while the 12.0, 12.5 and 13.5 kHz transponders might have "rolled" down the canyon walls (in response to either the seismic vibrations from the earthquake or something associated with the turbidity current), they remained above the core of the turbidity current which carried the 11.5 kHz transponder so far horizontally.

The estimated movement of the transponders at C-10 in Monterey Submarine Canyon following the 17 October 1989 earthquake provides further insight to strong episodic currents occurring in submarine canyons. The movement of the 11.5 kHz transponder demonstrates that large items can be moved significant distances along the ocean floor. This is known to occur in shallow water near canyon heads (DILL, 1964) and on the

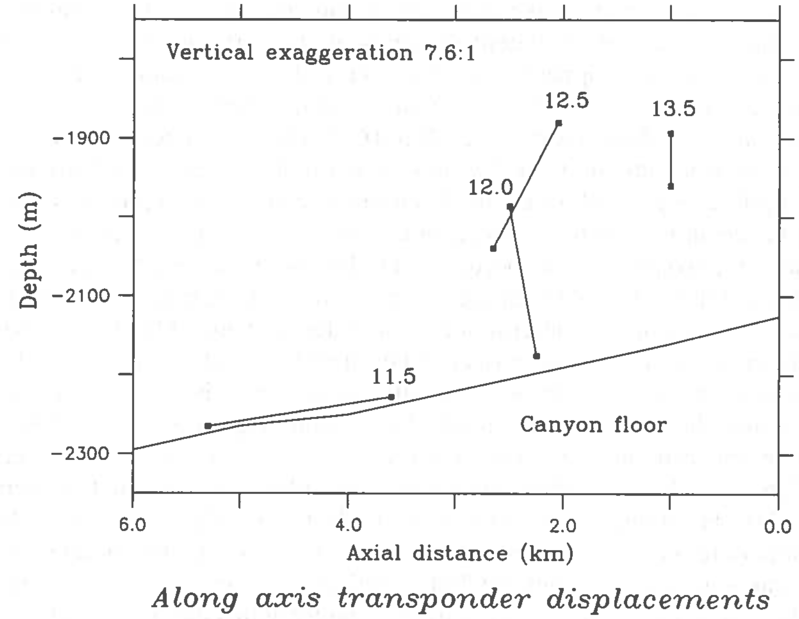

Fig. 3. Side view along the Canyon axis illustrating the along-canyon vertical and horizontal displacement of each transponder. The transponder identification is given at the initial position.

continental slope where the bottom slope was 5.8° (Dengler *et al.*, 1984). It is now documented in a Canyon axis where the average bottom slope was only 1.2° (Table 2). The 11.5 kHz transponder array weighed approximately 25 kg in water and had a glass sphere providing flotation 20 m above the bottom. The chain and hardware forming the anchor were tied together in a manner to create as much bottom drag as possible. It was estimated that a 1.5 m s^{-1} current would be required before the mooring would begin to drag along the bottom. However, this calculation assumes a compacted bottom; it does not take into account that the sediment around the anchor could have been scoured into a fluid flow. We suspect that the transponder array ultimately came to rest by falling over, and becoming sheltered behind, a large block among a rock fall similar to the ones observed from the submersible. It is interesting to speculate how far the transponder might have been carried were the Canyon floor smooth.

The downslope movement of the other three transponders at C-10 reveals other characteristics of the flow (Fig. 3). First, their movement gives some indication of the dimensions of the flow. The second deepest transponder (12.0 kHz) ended up about 50 m shallower than the initial depth of the 11.5 kHz transponder. Its movement was primarily downslope, suggesting that the height of the bottom current was less than 50 m on the western side of the Canyon. The horizontal displacement of the 12.5 kHz transponder, located on the southeastern side of the canyon, was both toward and down the canyon axis. This transponder started at the same depth as the 13.5 kHz transponder, located on the north side of the channel, and its down Canyon movement suggests that the turbidity current was stronger along the east side of the Canyon and had a height of at least 200 m. The cross-channel asymmetry in the flow because of the curvature of the canyon is similar to that inferred by Komar (1969) for the channel on the fan. Second, considerable slumping of sediments must have occurred at this location, and presumably at other locations along the canyon. Sediment slumping by the earthquake was not restricted to shallow water areas and appears to have occurred at significant distances from the earthquake epicenter, as supported by the submersible observations and the displacement of the transponders to deeper water at C-10 and C-7. The occurrence of sediment slumping along the canyon means the turbidity flows generated by tectonic activity have a huge sediment supply along the whole channel that can be involved in "ignitive processes". The same is not necessarily true for flows generated by processes at the ocean surface.

It appears that two phenomena occurred at C-10: the movement of the transponders on the walls toward the axis, and the along-axis movement of the transponder located on the canyon axis. What cannot be determined is the order of events. One hypothesis might be that the slumping and down-slope movement occurred during the earthquake, followed by a turbidity current sweeping through the site. However, it is also conceivable that the slumping along the canyon walls might have been triggered by a turbidity current undercutting the canyon wall. The difference in along-axis movement between the transponders on each side of the canyon leads the authors to favor the first scenario. The 13.5 and 12.0 kHz transponders moved primarily toward the canyon axis. Both these transponders were on the northwest canyon wall. The 12.5 kHz transponder, sited on the southeast canyon wall, experienced both vertical and horizontal displacement. This transponder was on the outer side of a canyon meander at this site. It is possible that a large volume of material was loosened from the canyon walls and fell to the canyon axis. The subsequent turbidity current would have tended to be along the southeast side at this site thus accounting for the movement of the 12.5 kHz transponder and other material some distance. This transponder came to rest almost 200 m above the canyon floor, so it probably never experienced the full strength of the current. Further evidence of side wall slumping followed by a turbidity flow is seen from the boulders and cliffs encountered along the canyon axis during the submersible dive. Greene (personal communication) found similar boulder fields further up and down the canyon axis. He speculated that the presence of the boulders and cliffs was due to a slide of metamorphic rocks from the eastern side of the canyon which may have been triggered by the Loma Prieta earthquake. If this were true, the sediments covering these features suggest that either the turbidity flow occurred after the rock slide or that there has been subsequent sediment transport unrelated to the earthquake. All of this is speculation since an accurate survey of the post-earthquake bottom topography is not available.

The possibility of sediment burial of the 12.5 kHz transponder at C-5 suggests a turbidity current swept past this site and provided sediments for deposition outside of the channel on the continental rise. Our site is very near where Komar (1969) reported the canyon axis to be about 220 m deeper than the southern rim. This suggests that the height of the current was greater than that.

6. CONCLUSION

Significant geological activity in the Monterey Submarine Canyon appears to have accompanied the October 1989 Loma Prieta Earthquake. Evidence collected at C-10 indicates that a possible rock fall, significant sediment slumping from both sides of the canyon, and a turbidity current all occurred at this subaqueous site 50 km from the earthquake epicenter. Evidence of both downslope and along canyon sediment movement suggests that tectonically generated turbidity flows have a large reservoir of sediments from all parts of the canyon and, therefore, have the potential to transport huge volumes of sediments through the canyon and out to the deep ocean.

The least-squares technique developed to navigate the transponder arrays provides an accurate determination of the array geometry and an independent estimate of the accuracy of our ship survey techniques. The improved array geometry and the accompanying improvement in navigating *Pegasus* will lead to better estimates of the ocean velocity field. Acoustic transponders could provide an excellent tool for obtaining measurements of episodic sediment transport in submarine canyons. A recent instrument deployment in 150 m at the head of Monterey Submarine Canyon (Crabtree and Ostwald, personal communication) further supports this suggestion. During a short deployment in the Canyon axis, a bottom mounted, upward-looking acoustic doppler current profiler (ADCP) underwent two downslope excursions. At this point it is not known if these events were due to natural or man-made phenomena, but it demonstrates that it should be possible to monitor such events. These observations and those by Dengler *et al.* (1984) and Syvitski and Hein (1991) suggest that a transponder network and properly ballasted instrument packages could provide an inexpensive, yet accurate, technique for monitoring turbidity current and sediment movement in a canyon environment.

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