A History Lesson From Monterey Canyon

Submarine canyons, with their steep sides, meanders, and tributaries, dominate the geomorphology of continental margins in the same way that river valleys dominate subaerial landscapes of plateaus and high plains. Monterey Canyon, whose head lies just offshore of MBARI, is one of the largest submarine canyons on the Pacific Coast. In nearly every measure, it is as dramatic as the Grand Canyon (Figure 1).

The origin of submarine canyons is one of the oldest questions in marine geology. Francis Shepard, the first geologist to devote his life's work to marine geology, concluded in his 1963 textbook on submarine canyons that no one hypothesis could explain their origin, and that the observations were too sparse to test the competing hypotheses. He pointed out that their features are very suggestive of erosion by river-like action, but their depth is too great to be consistent with carving these canyons during periods of lower sea level. Even though many canyon heads are close to the mouths of terrestrial river systems, fresh water from the river reaching the ocean is lighter than salt water, and therefore unlikely to scour the seafloor. Debate continued from Shepard's time to the present on whether submarine canyons are active or whether they inherited their distinctive features from some catastrophic events in the distant geologic past.

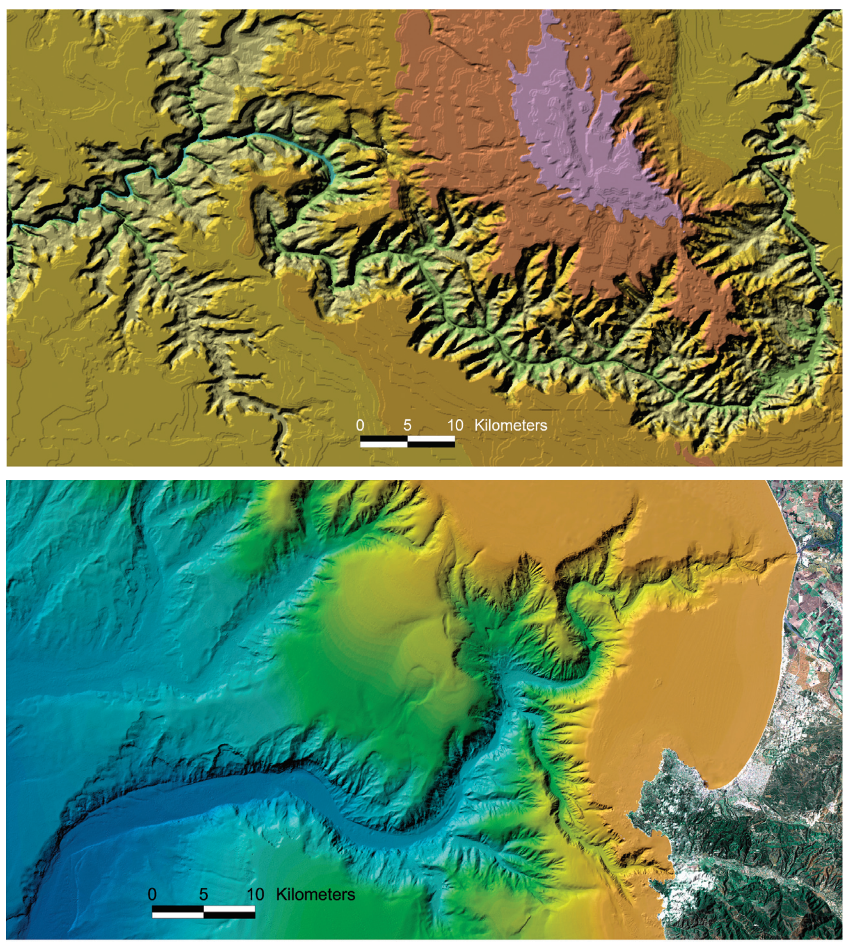
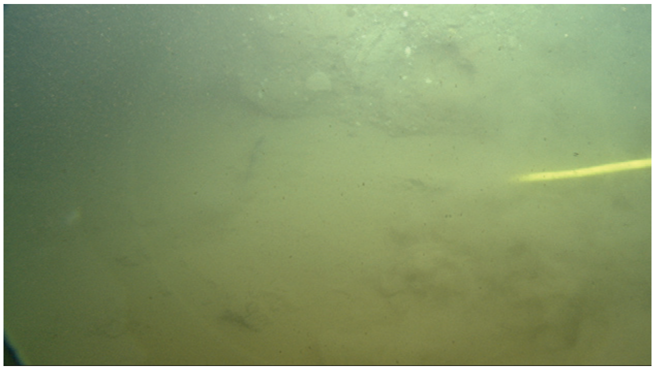


Figure 1: Images showing the morphology of the Grand Canyon of the American southwest (top) and Monterey Canyon (bottom) at the same scale demonstrate that these are analogous features in terms of their size and shape. While water flowing in the Colorado River carved the Grand Canyon, a directly analogous process is not known to occur within Monterey Canyon.

For example, one theory for the formation of Monterey Canyon, particularly given the currently intermittent and minor flow of the Salinas River, is that the Sacramento River previously drained into Monterey Bay and carved the canyon in frequent turbidity flows. The uplift of the Coast Ranges several million years ago would have diverted that flow, making Monterey an inactive canyon today. Therefore, when MBARI Scientist Charlie Paull initiated a research program in canyon dynamics several years ago, the perceived risk at the time was that nothing would happen. Instruments placed in Monterey Canyon would need to wait years before anything significant would be recorded.

Nevertheless, the time was right to reconsider the questions first raised by Francis Shepard, as an impressive array of new technology and analytical measurements could be brought to bear on the inquiry. Paull and his collaborators have gathered the necessary high-resolution multibeam bathymetry, remotely operated vehicle (ROV)-guided obser-



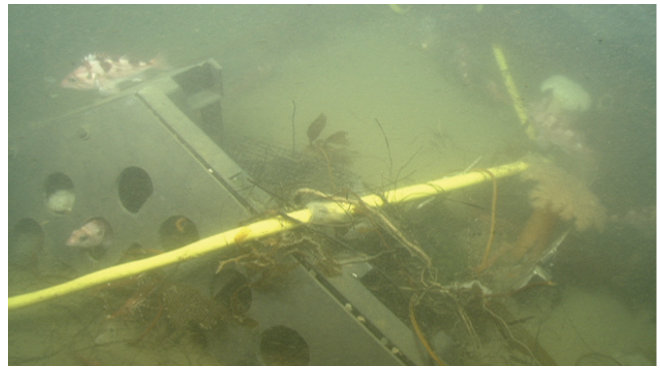


Figure 2: Right: A damaged remote instrument node (RIN) that was moved during a sediment transport event in upper Monterey Canyon. This heavy steel structure was found, using ROV *Ventana*, about 50 meters from where it was deployed. Its mast was broken off and tipped up against a ledge on the side of the canyon. Left: The yellow cable, which became buried in the sediment, connects with a cluster of instruments that *Ventana* excavated from the sediment.

vations and sampling, and data from canyon monitoring activities (measurements of near-seafloor currents, turbidity, pressure, temperature, and salinity) to "read the history" of Monterey Canyon. Some of the more intriguing scientific techniques employed by Paull and his team to provide a precise chronology of recent sedimentary events include observing the occurrences of pollen from non-native species introduced by European settlers, the pesticide DDT applied to agricultural fields between 1945 and 1969, and elevated levels of carbon-14 (^{14}C) from the detonation of nuclear weapons. Ratios of stable isotopes of carbon and nitrogen distinguish marine versus terrestrial origin of sediment inside the canyon and on its flanks.

These new observations reveal that Monterey Canyon is an extremely active feature. Gravel and coarse sand, with a composition similar to the sand found on local beaches, are captured in the canyon head as they are transported alongshore via littoral drift. Periodically the accumulations of sediment in the canyon head deposits fail, producing submarine landslides or turbidity events that are in many ways similar to avalanches on land. Instruments deployed in the axis of upper Monterey Canyon (at depths of less than two kilometers) from 2001 to 2005 recorded evidence of an unexpected number (about ten) of distinct turbidity events, ranging from mild increases in near-bottom turbidity with no detectable change in bottom currents, to major, energetic, down-canyon flows with high current speeds and turbidity, large volumes of sediment transport, and displacement of moored systems. The large events often destroyed or buried deployed instruments (Figure 2). Conditions were documented by intact instrument systems during four large turbidity events from late 2002 to mid 2005, leading the Canyon Dynamics team to reconsider what constitutes a "50-year event". Current speeds during events reached more than 200 centimeters per second near the seabed and decreased in speed with height above the bottom. Sediment transport events of this magnitude occur more than once a year in the upper canyon. Based on the known timing of these events and comparison with local earthquake, storm, and river discharge data, the most common triggers for the observed events are intense storm wave disturbance and/or random canyon wall failures. Even during the long dry season when the Salinas and Pajaro Rivers are just barely or not flowing, material moves down the canyon, lining the axis of the canyon with sand and gravel deposits.

Measurements of sediment transport in the upper canyon near 1,300 meters depth highlight both the high volume of transport in the canyon axis and the dominance of transport during turbidity flows. Moorings with sediment traps, current meters, and optical backscatter sensors deployed in the canyon axis by MBARI Scientist Jim Barry's group revealed that sedimentation in the canyon is normally about 15 to 20 times greater than measured at the same depth on Smooth Ridge, on the continental slope outside the canyon. More importantly, rates of canyon sediment transport and deposition during events were 300 to 500 times those observed during non-event periods. Thus, a single significant event per year can result in more than 85 percent of the annual inorganic and organic carbon transport budget.

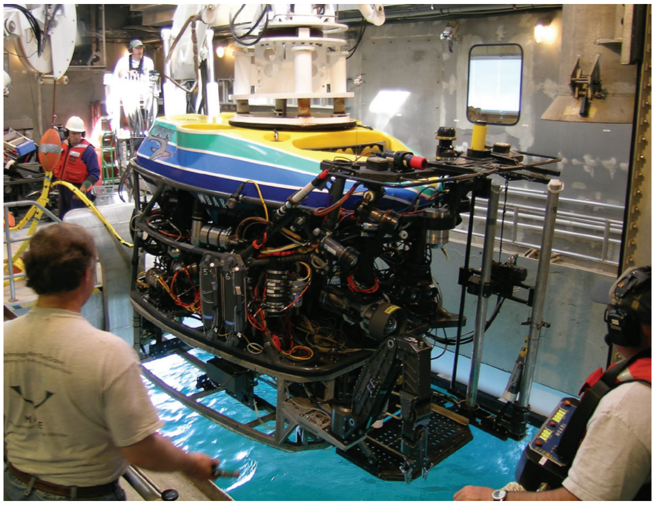


Figure 3: ROV *Tiburon* is launched with the vibracoring system mounted on the front.

The axial channel associated with Monterey Canyon extends as a distinct continuous channel to depths of more than four kilometers, where the winnowed material is ultimately deposited onto the Monterey Fan. Paull's team has extensively sampled the sediment in the submarine channel and the fan using a vibracoring system (Figure 3) mounted on MBARI's remotely operated vehicle *Tiburon*. The widespread occurrence of sediment with DDTr (the sum of DDT and its decay products) in the top five centimeters of sediment throughout the canyon and fan system indicate that significant volumes of fine grain sediments have been transported across the margin and onto the fan since 1945 (Figure 4). The canyon is apparently a major conduit for transporting a substantial amount of organic material from land and the coastal zone to the deep sea in modern times. It has long been suspected that vertical transport of carbon from the upper ocean to the deep sea away from the coastal zone is insufficient to maintain the size of the benthic community. Thus, Paull's use of DDT as a tracer for contemporary carbon transport to the deep sea suggests that canyons might be important in supplying that missing carbon to nourish the deep sea.

To test this hypothesis, in 2004 monitoring equipment was deployed in 3,450-meter water depths within the axis of the deep-sea channel—called Shepard Meander after Francis Shepard—at the down-slope end of Monterey Canyon. The Shepard Meander experiment continued throughout 2005 with the regular servicing of these instruments (Figure 5). Sediment traps and current meters deployed within the canyon axis and outside the canyon on its flanks are providing a several-year record of both vertical and lateral flow and carbon transport gradients in the vicinity of the canyon.

Curiously, while several large sediment transport events have occurred in the upper reaches of Monterey Canyon in the last 18 months, no significant sedimentological events have been recorded at the deep Shepard Meander node in the lower canyon during the same time period. However, these data have already provided a unique constraint on how frequently the deep-sea benthos is fed from land. And though the upper canyon is an active conduit for carbon transport, the high frequency of gravity flow events can disturb benthic communities. Barry's group has documented the low abundance of sessile fauna in the upper canyon and their increase in abundance with depth, presumably due to the lower frequency of disturbance events in the lower canyon. Clearly, there appear to be ecological trade-offs for the fauna in Monterey Canyon. Areas in the upper canyon with the highest food availability may also be the most hazardous to inhabit. Conversely, the lower canyon is relatively food-poor, but safer. Thus, the canyon's "carbon highway" may be an important conduit feeding the

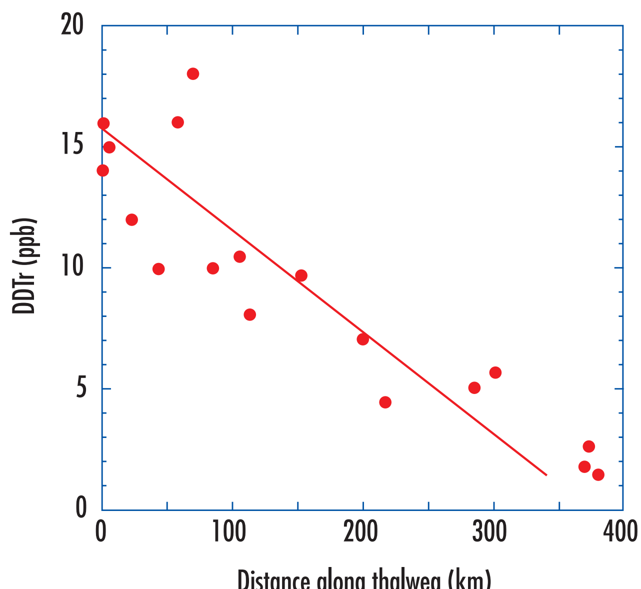


Figure 4: Plot showing the mean concentrations of the pesticide DDT and its associated residues found in seafloor sediment versus the distance along the thalweg of the channel that extends through Monterey Canyon and continues across the Monterey Fan. Detectable levels of DDTr can be found out to nearly 400 kilometers along this channel and provide a tracer for modern sediment transport.

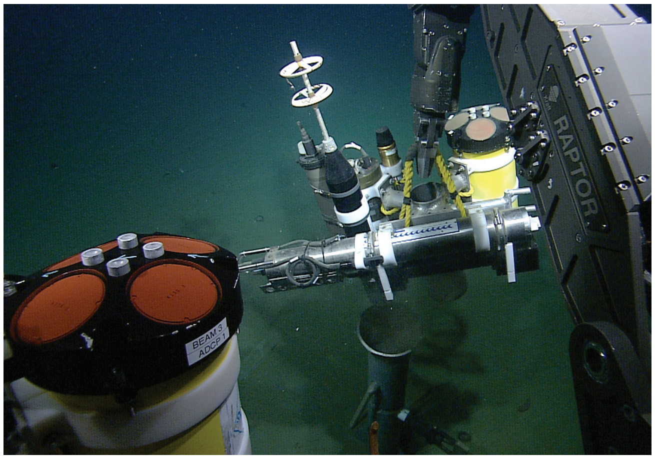


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Figure 5: ROV *Tiburon* switches instrument package on a remote instrument node in the axis of Monterey Fan Channel at Shepard Meander. Photo shows multiple instruments including two current profilers (yellow canisters with four red transponders); the one on the left will replace the one that had been deployed for six months.

deep sea, but its traffic of sediment flows may be dangerous for canyon inhabitants.

The large role of short-lived, episodic events in both the transport of materials across the continental margin and as a potentially dominant influence on the structure of benthic faunal communities increases the complexity of their study. Rather than the regular beat and tempo of oceanographic processes operating on diurnal, tidal, or seasonal periods, episodic and rare events require sensors to remain deployed and active over long periods, often sampling under higher frequencies to fully capture an event of interest. In fact, large events in the upper canyon have occasionally captured the sensors deployed to measure them, sending them down-canyon with the avalanche-like turbidity flows.

To date, the experimental apparatus at Shepard Meander has been powered by seafloor batteries, and replenishing the batteries and retrieving the data both require a visit from an ROV. In the next two years, the experiment will be upgraded to use MBARI's new Monterey Ocean Observing System (MOOS), which uses a fiber-optic cable to bring power and communications to the deep sea from solar panels, wind turbines, and satellite communications on a mooring at the sea surface. The experiences so far with deploying and servicing instruments have provided insight into how to design submarine cable-connected seafloor nodes that will connect to the MOOS mooring in the future.

The observation that little sedimentological activity happened in the lower canyon during the first 18 months of the Shepard Meander experiment is at odds with the large number of energetic events recorded from the upper canyon. Vibracore stratigraphies (see cover image) show that the seafloor within the axial channel is underlain by high-energy deposits (gravel, coarse sand, and rip-up clasts) that are at least a meter thick. Efforts to date materials in these cores indicate that the last major sediment transport event to reach the lower canyon occurred about 60 to 150 years ago, and might, speculatively, have been associated with a major disturbance such as the 1906 earthquake. The observation that coarse-sediment-carrying, high-energy events are much more common in the upper canyon than at Shepard Meander suggests that the upper canyon acts as a capacitor, accumulating sand and other coarse sediments that ultimately move down the lower canyon to the fan in much less frequent but catastrophic events.

The lack of detected sand-carrying events in the lower canyon is also at odds with the vibracoring data that show substantial post-1945 transport of fine sediment out to the Monterey Fan. ROV dives in the axis of the canyon frequently encounter low-visibility water conditions below the shoulders of the canyon, which are caused by suspended sediment, especially during the rainy season. MBARI Scientist Ken Johnson demonstrated that these turbid water masses are characterized by lower salinity and higher temperature than the normal ambient seawater, indicating the influence of terrestrial river flow at the floor of the canyon (Figure 6). These conditions are likely to happen when the Salinas River discharges a fine-sediment plume into the ocean as it breaks through a seasonal berm near the head of the canyon. The density of the suspended sediment is enough to offset the buoyancy of the fresh water. Observations such as these suggest that the transport of fine sediment down the canyon and onto its flanks involves different processes and is more or less decoupled from the transport of sand and other coarse fractions.

Paull's data from Monterey Canyon tell more than just the history of the canyon. The fine sediments, largely derived from erosion of the land surface, also record the history of

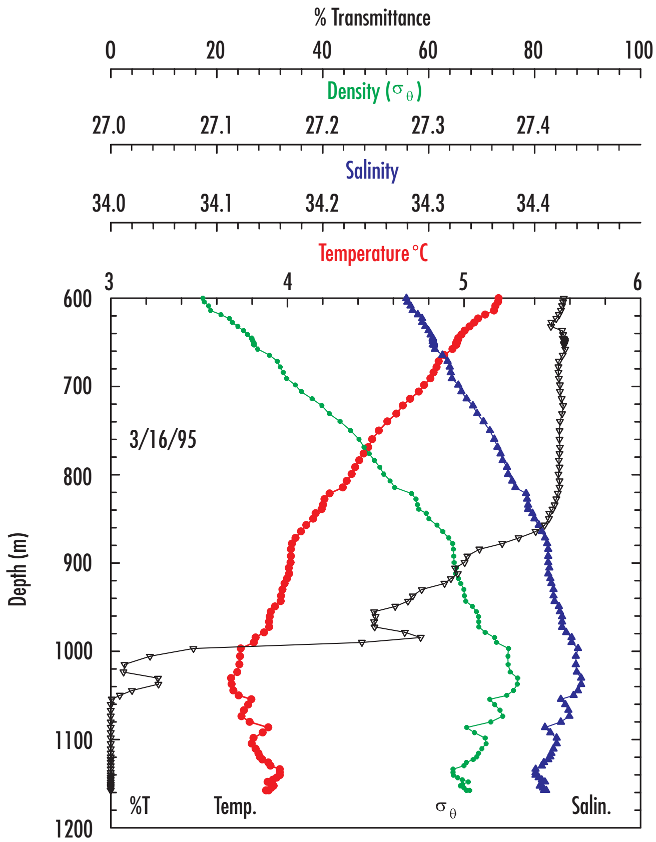

Figure 6: ROV dive into the river plume at 1200 meters shows light transmission going to zero and temperature, salinity and density signals reversing.

land-use practices in the Salinas Valley. For example, the presence of pollen grains from alien, introduced species within the fine-grained sediments indicates that more than five meters of sediment were deposited within historical times (post-1700) on the canyon flanks. The average annual sedimentation rate from 1700 to 1945 is more than double the rate for the time period since 1945, which is well determined by the presence of DDT residues in the sediment. This observation suggests that the destructive land-use practices associated with the early stages of modern development in the Salinas and Pajaro Valleys caused rapid loss of virgin soils and a subsequent increase in the proportion of older soil (as determined by its ^{14}C content) as older soil horizons were exhumed by erosion. A sharp decrease in the amount of soil being flushed off the land occurred in the mid 1900s as dams and other impoundment structures were built on the rivers.

Half a century after Francis Shepard first posed the questions concerning the dynamics of submarine canyons, we finally have some answers for Monterey Canyon that can be used as a starting model for canyons elsewhere in the world's oceans. Canyons are indeed very active, with a substantial portion of their coarse bedload coming from along-shore transport rather than direct input from a river system. Canyons are created and maintained by surges of large volumes of material down their axes triggered by storms and mass wasting of the canyon walls. The transport is discontinuous in time and space, with some sections acting as reservoirs that store the material for more catastrophic events later.

Finally, the study of submarine canyons is important to more than just marine geologists. These canyons are likely important conduits for lateral transport of material, including food, from the highly-productive coastal zone to the more impoverished deep sea. The size of the landslide events inferred from the geologic record suggests that large transport events in Monterey Canyon even have the potential to generate local tsunamis.