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Submarine Canyons: A brief review looking forward

Andrea Fildani
Statoil Research Center, Austin, Texas 78730, USA

Submarine canyons are conduits delivering vast amounts of sediment, nutrients, and pollutants to deep-sea submarine fans, the largest accumulations of sediment in the world. Submarine canyons have attracted generations of earth scientists since their discovery in the early 20th century and recently they attracted an even broader community from marine sciences because of their complex ecosystems and intricate role in ocean life. They were described as V-shaped erosional features dissecting the continental slope (Daly, 1936), and are recognized and characterized via acoustic geophysical technologies (see improvements through the many editions of *Submarine Geology* [Shepard, 1973]).

Canyons extend across the seafloor from continental shelves into the deepest reaches of the oceans where they eventually transition into channels across the lower continental slope (Shepard and Emery, 1941). Sediment-gravity flows, together with slumps and slides, effectively ‘carve’ canyons and deliver material into deep water. They can break seafloor cables (e.g., the turbidity current event off the Grand Banks, Newfoundfland; Heezen and Ewing, 1952), and they pose a serious threat to seafloor infrastructures (e.g., Cooper et al., 2013). The flow dynamics and sedimentary processes of gravity currents are largely interpreted from depositional products observed in outcrop and core (e.g., Migliorini, 1943; Bouma, 1962; Lowe, 1982), physical models (e.g., the ‘flow ignition’ of Parker et al. [1986]), and laboratory experiments (e.g., Garcia and Parker, 1989). Although much progress has been achieved since these seminal publications, there is still a notable lack of direct observations of submarine gravity flows and their depositional processes. There have been a few ‘events’ tracked in different canyon systems around the world, as summarized in Talling et al. (2015). However, a large-scale sediment gravity flow initiating in a canyon and traversing an entire submarine fan has yet to be directly observed. Such flows are difficult to monitor because they are rare over observational time scales, and initiation mechanisms are still poorly understood and unpredictable (Piper and Normark, 2009).

Symons et al. (2017, p. 367 in this issue of *Geology*), integrate direct physical measurements of flows traversing the Monterey Canyon (a topographic feature offshore California, USA, comparable in scale to the Grand Canyon) with high-resolution maps of seafloor morphology and direct sampling via sediment traps. Their study used direct measurements from flows (in this case identified as turbidity currents) ‘caught’ by U.S. Geological Survey (USGS) sediment traps and arrays of current meters in 2004 (deployed between 2002-2003, and published by Xu et al., 2004) and ‘chased’ the deposits along transects positioned perpendicular to the flow direction at sediment trap positions. Remotely operated vehicles enabled the collection of samples from the canyon axis and walls, allowing characterization of the range of deposits at key positions in order to speculate on vertical flow structure and flow rheology. Although Symons et al. could not capture with certainty the 2004 event beds (flow measurements and samples were collected 12 years apart), their contribution presents an exciting integrated approach to understand the processes and products of submarine flows by integrating repeat monitoring and revisiting earlier observations/data.

The conclusions of Symons et al. have several implications. Firstly, the sediment-gravity flow has been reconstructed from trapped sediment and cores positioned at similar heights along canyon walls; these data constrain the flow properties from the vertical distribution of grain sizes and the time evolution of the flow. The combination of direct physical measurements and cored deposits is used to propose a three-part model of turbidity current behavior with a flow that evolved from thin and high-concentration sediment layer to a thicker and dilute one. Second, this data set presents a new way of constraining experiments (both numerical and laboratory) with direct observation and grain-size patterns.

Thus far the internal structures of deep-water sedimentary flows and their temporal evolution are derivatives of experimental and numerical results combined with outcrop and seafloor observations (see Talling et al., 2015). Direct measurements in the Squamish Delta (British Columbia, Canada) (Hughes-Clarke, 2016) and from saline gravity currents in the southwest Black Sea (Dorrell et al., 2016) are already helping our understanding of flows and their temporal evolution. There is an opportunity here, with more direct data collection, to tune synthetic models to natural observations by fully integrating oceanographic measurements and sampling with laboratory and numerical efforts.

While Symons et al. indicate a way forward for deep-sea research, many questions are still open and will surely guide research for a long time. The flows ’captured’ in the study were deposited fully within the upper canyon, up-dip from a large bend in Monterey Canyon called Shepard Meander (Fig. 1). The flows did not reach the meander as the recently deployed Monterey Bay Aquarium Research Institute (MBARI, www.mbari.org) instruments recorded a “quiet” environment. The Monterey Canyon feeds the Monterey Fan, one of the largest deep-sea fans in the world, with a thickness of more than 1000 m north of Chumash Fracture Zone and extending more than 400 km beyond the canyon head (Fildani and Normark, 2004). Questions regarding the recurrence of flows, as well as their intensity, magnitude, competence, and size are still topics for debate, because monitored flows have all stopped in the upper reaches of the canyon. Fildani et al. (2006) reported that flows are common throughout the Holocene as they overspill at the Shepard Meander and initiated the Monterey East channel (Fig. 1). The differences in time scales between the input of sand into the canyon head and the ultimate output of sand to the deep-sea fan suggests that canyons may act as capacitors that accumulate detritus and nutrients over 10^3 to 10^5 yr time scales, releasing it during relatively rare, large discharge events (Paull et al., 2005). The differences between flows reported here and the ones traversing the Shepard Meander are still an unknown.

The Symons et al. manuscript is the “tip” of a large, international effort led by MBARI and built on decades of collaboration with the USGS. The activity of the upper Monterey Canyon has been monitored for more than a decade by MBARI, the USGS, and local institutions (Paull et al., 2003, 2005; Xu et al., 2004; Smith et al., 2005). The upper Monterey Canyon is an active submarine system closely coupled with sand transport along the shoreline (Paull et al., 2005). The sand has been ‘followed’ moving varying distances into the canyon on a semi-regular basis during gravity-flow events (Paull et al., 2003, 2005), and has been characterized and described in detail by MBARI in recent years. This contribution also heralds what we hope to be a period of major advancement in understanding submarine canyons with the ongoing, multi-institution

GEOLOGY, April 2017; v. 45; no. 4; p. 383–384 | doi:10.1130/focus042017.1

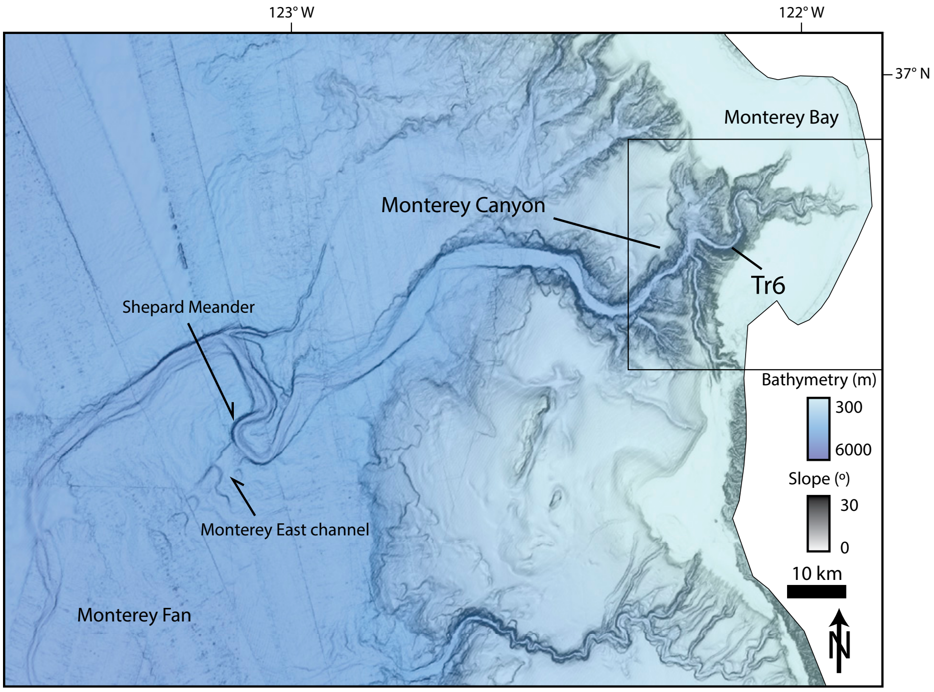

Figure 1. Map view of co-rendered bathymetry of the central California (USA) continental margin and slope showing Monterey Canyon, Monterey East channel, and Shepard Meander (bathymetric data from National Oceanic and Atmospheric Administration [NOAA] National Centers for Environmental Information; modified from Covault et al., 2017). Figure 1 of Symons et al. (2017) is highlighted by a box including the uppermost canyon and Tr6, the location of deepest sediment trap.

Coordinated Canyon Experiment led by MBARI (CCE; www.mbari.org/cce-instruments/).

Considering that the ocean covers more than 70% of the planet and ultimately supports all living organisms, exploring the deep sea and its complexities (physical, geological, and biological) is of fundamental importance for the humans.

ACKNOWLEDGMENTS

Angela M. Hessler, Jacob A. Covault, and editor Brendan Murphy commented on an early version of this contribution. Fildani would like to apologize to all the colleagues and scientists whose work could not be included here. The scientific community has been making much progress in integrated marine sciences and many have contributed tremendously to the efforts described above.

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Printed in USA