Eos®

Submarine Avalanche Deposits Hold Clues to Past Earthquakes

Scientists are making progress on illuminating how undersea sedimentary deposits called turbidites form and on reconstructing the complex histories they record. But it's not an easy task.

By **Valerie Sahakian**, **Debi Kilb**, **Joan Gomberg**, **Nora Nieminski,** and **Jake Covault**

18 March 2024

These turbidite beds in Cornwall, England, formed long ago when an underwater avalanche sent sediments tumbling downhill. Credit: Kevin Walsh/Flickr, CC BY 2.0

Earthquakes and other natural events sometimes shake the seafloor near coastlines severely enough to cause underwater avalanches that rush down steep slopes, scouring the seabed and carrying sediment to greater depths. These fast-moving sediment-laden flows, called **turbidity currents**, have at times damaged underwater infrastructure like pipelines and communications cables, as they did, for example, in **snapping transatlantic cables** off the coast of Newfoundland after the 1929 Grand Banks earthquake.

Apart from their destructive tendencies, turbidity currents pique scientists' interest for other reasons too. When they slow and reach their new resting places on the seafloor, sand and other coarse materials in the currents settle first, followed by mud and silt and, eventually, the finest-grained particulate matter. This gravity-driven sorting produces distinctly layered deposits known as turbidites, which preserve records of the currents that formed them.

The accuracy of modern earthquake hazard assessments depends on correctly **characterizing past earthquakes** by estimating their size, location, frequency of occurrence, and associated uncertainties, and researchers often use turbidites to define these quantities. Doing so requires integrating knowledge of diverse physical processes from seismology, sedimentology, geotechnical and mechanical engineering, physical oceanography, and geochronology.

At a **2023 workshop** ("Advancing the Use of Turbidite Observations in Understanding Offshore Tectonic Processes and Seismic Hazards"), scientists from many disciplines came together to discuss the state of knowledge on how to use turbidites to constrain possible sources of ancient earthquakes.

The Promise and Problems of Turbidites

Paleoseismologists study the geologic record for evidence of past earthquakes by observing evidence of their occurrence directly from fault offsets or indirectly from the surface effects of the shaking and deformation they caused. Turbidites, for example, can offer indirect evidence of earthquake shaking that sends sediments flowing downslope (Figure 1).

> *Distinguishing nonseismogenic from seismogenic triggers using geologic samples of turbidites is challenging—and sometimes not possible.*

Groups of turbidites found within areas consistent with the spatial footprints of shaking from large earthquakes have been used to help define past earthquake locations and estimate earthquake magnitudes. The idea is that if a large earthquake violently shakes an offshore region, it can synchronously mobilize sediment and produce turbidity currents in different locations throughout that region. These currents form similar turbidites that scientists may be able to correlate within and surrounding the rupture zone.

However, various factors complicate such efforts. In particular, earthquakes **aren't the only events** that produce turbidites. Floods, storms, submarine volcanic explosions, ocean currents, and **internal tides** can also cause turbidity currents. As a result, distinguishing nonseismogenic from seismogenic triggers using geologic samples of turbidites is challenging—and sometimes not possible.

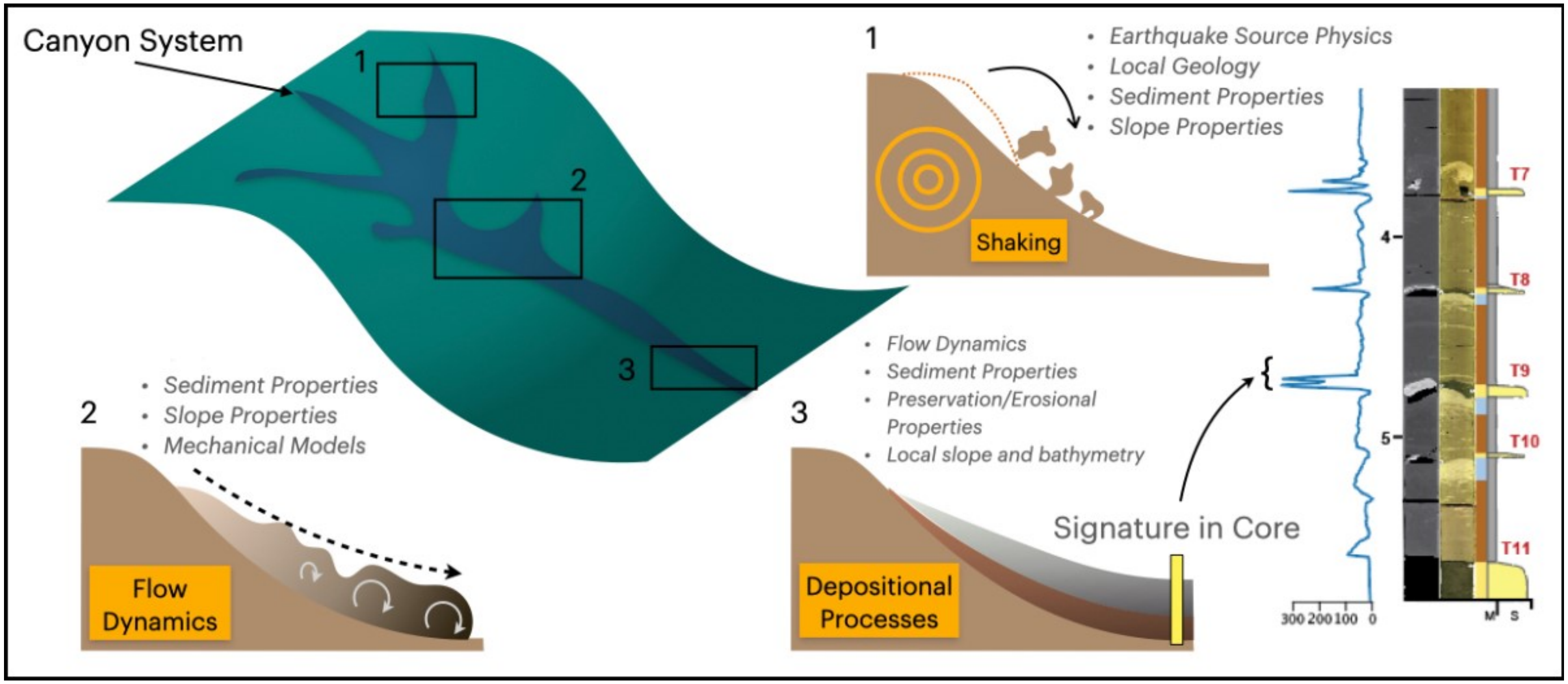

Fig. 1. If an underwater canyon system on a continental margin (top left; numbered boxes correspond to the other diagrams) is subjected to violent shaking during an earthquake (top right), sediment can be mobilized. If a sediment-laden turbidity current forms (bottom left), it will cascade downslope, creating complex fluid dynamics governed by sedimentologic properties and seafloor structure. These dynamics affect the ultimate settling and deposition of sediments down canyon (bottom right), as well as the subsequent character of an individual turbidite as identified in a core sample. An example core is shown at right, with magnetic susceptibility data (the turbidite "signature") plotted in blue, a computed tomography (CT) scan and image of the core, and a core description indicating grain size and content. Each "T#" corresponds to an individual turbidite.

In addition, the complex and varied characteristics of large to great earthquakes, combined with variability in how shaking may be modified by local geology, can produce vastly different shaking characteristics at different sites within the shaken area. Moreover, spatial variability in sediment supply, sediment strength properties, and slope stability can produce turbidites with different characteristics or spatial extents, even for the same level of shaking. And not only can conditions that mobilize sediment vary greatly, but also, once mobilized, turbidity currents can undergo downstream changes related to their grain size and concentration, thickness, and velocity.

In short, for a given level of shaking, sediment can mobilize and travel in drastically different ways, and earthquakes in the same region and of the same magnitude can leave behind vastly different turbidite signatures [*Atwater et al.*, 2014]. Thus, interdisciplinary work is crucial to determine whether turbidites were likely caused by earthquakes and to use turbidites to estimate past earthquake locations and sizes.

Additional Uncertainties Complicate Correlation

Inferring that numerous turbidites came from a single past earthquake to help constrain an earthquake's characteristics requires demonstrating that they formed at the same time in the same event. This is often accomplished by correlating turbidite signatures (e.g., depth variabilities in grain sizes and characteristics, which are like barcodes for the deposition process) from multiple locations in both time and space.

Radiocarbon dating of microfossils sampled in the sediments just above and below turbidites provides estimates of when a turbidity current occurred and is a critical tool for establishing temporal correlations, but this work can be fraught with challenges.

The shells of single-celled foraminifera, which incorporate radiocarbon and sink to the seafloor after the organisms die, are common targets for such dating. But this dating is complicated by the fact that variations in ocean mixing lead to differences in the amount of radiocarbon (and thus fossil dates) in different ocean environments, depths, and time periods in which foraminifera have lived.

In addition, because foraminifera are sampled above and below turbidites, corrections for the time that elapsed between when the organisms and the corresponding turbidite were deposited on the seafloor require hard-to-come-by independent estimates of local sedimentation and erosion rates. As such, turbidite dates from radiocarbon often come with uncertainties ranging from tens to hundreds of years, making it nearly impossible to establish from these dates alone whether multiple turbidites were deposited at the same time.

> ***Regionally correlated turbidites with similar signatures and overlapping radiocarbon ages have been inferred to represent deposits resulting from a single earthquake.***

In the absence of direct observations of seismically generated sediment mobilization, regionally correlated turbidites with similar signatures, or "barcodes," and overlapping radiocarbon ages have been inferred to represent deposits resulting from a single earthquake [e.g., *Goldfinger et al.*, 2012]. In addition to assuming a single causative earthquake, another implicit assumption in such cases is that the shaking from the earthquake was spatially uniform throughout a large region. However, as already noted, different earthquakes at the same location and of the same magnitude can produce very different ground motions across a region. Thus, the interpreted magnitudes and rupture limits in these past studies have not been well constrained, or they come with quantitative uncertainties.

These issues pose substantial challenges to interpreting turbidite records for seismic hazard analyses. Yet turbidites remain valuable proxies. In many regions, such as along the Cascadia subduction zone off the western U.S. coast, rich marine turbidite data sets can provide more information about long-term seismogenic behavior than onshore proxies such as coastal land level changes and dendrochronology [*Goldfinger et al.*, 2012]. Turbidite data sets become even more powerful when coupled with onshore observations.

The potential to overcome existing limitations and apply turbidites to better constrain past seismicity and inform regional seismic hazard assessments motivates scientists to continue studying them.

Making Progress Toward Key Goals

The workshop in 2023 brought together a multidisciplinary group of experts who discussed how integrating observational, instrumentational, modeling, and laboratory approaches for studying earthquake physics and shaking, sediment mobilization, turbidity current dynamics, and depositional processes can lead to a holistic understanding of turbidite-forming processes.

Workshop participants agreed that combining knowledge and contributions from seismology, sedimentology, engineering, and oceanography will drive progress toward linking turbidites to shaking events. This information will also assist in understanding mechanisms of sediment entrainment, transport, and deposition that occur between when earthquake shaking starts and when a turbidity current reaches its depositional sink. Further, it will help scientists identify new methods to correlate turbidites across long distances.

Improving seismological estimates of offshore shaking involves understanding how seafloor geology affects shaking variability

[*Gomberg*, 2018; *Miller and Gomberg*, 2023]. And quantifying relationships between shaking and underwater slope stability may further improve knowledge of what size earthquake generates which observed turbidite. Geotechnical engineering methods for quantifying and modeling slope stability in submarine environments show promise in this regard. These methods include sophisticated modeling that can predict when and where slopes may fail given a certain level of shaking, as well as how the failing mass and particles move as they begin to initiate a turbidity current [*Dickey et al.*, 2021]. From here, mechanical engineering models of turbidity current flow dynamics can be used to understand where and how sediment is transported and deposited considering its characteristics [*Zhao et al.*, 2021].

“

How can we draw connections between turbidites that are located hundreds of kilometers apart, corresponding to the distances over which large earthquakes rupture?

Process-based insights from the above methods can be integrated with sedimentologic insights into turbidite signatures (e.g., the composition and thickness of layers and fossilized biota they contain) to aid in regional correlations. Scientists collect core samples of turbidites to study such signatures and look for similarities that correlate across locales. But current research suggests that turbidites cannot be correlated with statistical significance beyond tens of meters [*Nieminski et al.*, 2023]. If this is true, then how can we draw connections between turbidites that are located hundreds of kilometers apart, corresponding to the distances over which large earthquakes rupture?

Collecting and analyzing transects of closely spaced core samples—paired with expertise in sedimentology, instrumentation, and oceanography—can reduce uncertainty in the correlation of turbidites across long distances and improve our understanding of mechanisms acting between an earthquake source and a turbidity current’s depositional sink.

More carefully considering depositional environments—that is, choosing study sites where storm- or flood-triggered turbidity currents are unlikely to occur and avoiding eroded paths where turbidites might not be preserved—can also help efforts to link turbidites to seismogenic processes more definitively. Studying other types of sedimentary deposits for clues to seismic activity also may assist in interpreting observations. For example, only very large earthquakes can produce the shaking needed to remobilize homogenites—thick, uniform units of fine-grained silt- to clay-sized particles—over large areas [*McHugh et al.*, 2020].

Finally, quantifying large uncertainties in radiocarbon dating, which present significant challenges for correlating turbidites, will improve our ability to link (or not link) turbidites to past earthquakes, thus constraining past earthquake sizes and locations for seismic hazard assessments. **Recent work** on age dating sensitivity analyses has shown that considering a broad range of variables and their likelihoods (e.g., sedimentation and erosion rates) can offer insights into how uncertainties in radiocarbon dating affect turbidite correlations and how they propagate into uncertainties in estimates of energy release during earthquakes and other seismic hazards [***Staisch***, 2024].

The Interdisciplinary Path Leads Forward

New approaches along with advances in instrumentation and data acquisition are allowing researchers to learn more about complex submarine systems, including turbidity currents and turbidites.

Innovative experimental approaches offer exciting leaps forward [*Sahakian et al.*, 2023; ***Clare et al.***, 2020]. For example, researchers are attempting to monitor in situ examples of shaking that leads to sediment remobilization, as well as continuing to make advances in modeling and laboratory capabilities (e.g., geotechnical and mechanical engineering models of failure and flow dynamics). Other advances include leveraging new findings in the big data and machine learning communities, such as using offshore data gathered via **distributed acoustic sensing** to observe turbidity currents. Collecting additional high-resolution **multibeam bathymetry** is another crucial need that will help advance knowledge of seafloor and flow processes and help with the siting of seafloor instrumentation and core sampling for oceanographic field studies.

“

New approaches along with advances in instrumentation and data acquisition are allowing researchers to learn more about complex submarine systems, including turbidity currents and turbidites.

Together with these innovations, interdisciplinary work among seismologists, sedimentologists, oceanographers, engineers, and specialists in predictive modeling will support advancement in the use of turbidites to understand past earthquakes and in improved application of turbidite studies to inform seismic hazard estimates. Collectively, we can create more detailed reconstructions of the incidence and aftereffects of past earthquakes, which will improve capabilities to prepare for and respond to earthquakes yet to come.

Acknowledgments

We thank the Seismological Society of America for providing the funding for this workshop. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

References

Atwater, B. F., et al. (2014), Rethinking turbidite paleoseismology along the Cascadia subduction zone, *Geology*, *42*(9), 827–830, **https://doi.org/10.1130/G35902.1**.

Clare, M., et al. (2020), Lessons learned from the monitoring of turbidity currents and guidance for future platform designs, *Geol. Soc. Spec. Publ.*, *500*(1), 605–634, **https://doi.org/10.1144/sp500-2019-173**.

Dickey, L. C., et al. (2021), Slope stability of streambanks at saturated riparian buffer sites, *J. Environ. Qual.*, *50*(6), 1,430–1,439, **https://doi.org/10.1002/jeq2.20281**.

Goldfinger, C., et al. (2012), Turbidite event history—Methods and implications for Holocene paleoseismicity of the Cascadia subduction zone, *U.S. Geol. Surv. Prof. Pap.*, *1661-F*, 170 pp., **https://doi.org/10.3133/pp1661F**.

Gomberg, J. (2018), Cascadia onshore-offshore site response, submarine sediment mobilization, and earthquake recurrence, *J. Geophys. Res. Solid Earth*, *123*(2), 1,381–1,404, **https://doi.org/10.1002/2017JB014985**.

McHugh, C. M., et al. (2020), Isotopic and sedimentary signature of megathrust ruptures along the Japan subduction margin, *Mar. Geol.*, *428*, 106283, **https://doi.org/10.1016/j.margeo.2020.106283**.

Miller, N., and J. Gomberg (2023), Variations in shaking across the Cascadia submarine forearc from OBS recordings of Gorda plate earthquakes, poster presented at Advancing the Use of Turbidite Observations in Understanding Offshore Tectonic Processes and Seismic Hazards, Seismol. Soc. of Am., Seattle, Wash., 9 Jan.

Nieminski, N., et al. (2023), Evaluating turbidite correlations for paleoseismology, *Seismol. Res. Lett.*, *94*(2B), 1,092.

Sahakian, V. J., et al. (2023), Searching for empirical links between shaking and turbidity current generation in the Cascadia subduction zone, paper presented at Seismological Society of America Annual Meeting, San Juan, Puerto Rico, 21 Apr.

Staisch, L. M. (2024), Sensitivity testing of marine turbidite age estimates along the Cascadia subduction zone, *Bull. Seismol. Soc. Am*., **https://doi.org/10.1785/0120230252**.

Zhao, K., et al. (2021), Flocculation of suspended cohesive particles in homogeneous isotropic turbulence, *J. Fluid Mech.*, *921*, A17, **https://doi.org/10.1017/jfm.2021.487**.

Author Information

Valerie Sahakian (**vjs@uoregon.edu**), University of Oregon, Eugene; Debi Kilb, Scripps Institution of Oceanography, University of California, San Diego, La Jolla; Joan Gomberg, Earthquake Science Center, U.S. Geological Survey, Seattle; Nora Nieminski, Pacific Coastal and Marine Science Center, U.S. Geological Survey, Santa Cruz, Calif.; now at Alaska Division of Geological and Geophysical Surveys, Anchorage; and Jake Covault, Bureau of Economic Geology, University of Texas at Austin

Citation: Sahakian, V., D. Kilb, J. Gomberg, N. Nieminski, and J. Covault (2024), Submarine avalanche deposits hold clues to past earthquakes, *Eos, 105,* https://doi.org/10.1029/2024EO240122. Published on 18 March 2024.