GEOLOGY

Understanding Sediments—Reducing Tsunami Risk

Knowledge of the processes that drive tsunami sediment erosion and deposition can help to determine and mitigate tsunami risk.

Robert Weiss and Joanne Bourgeois

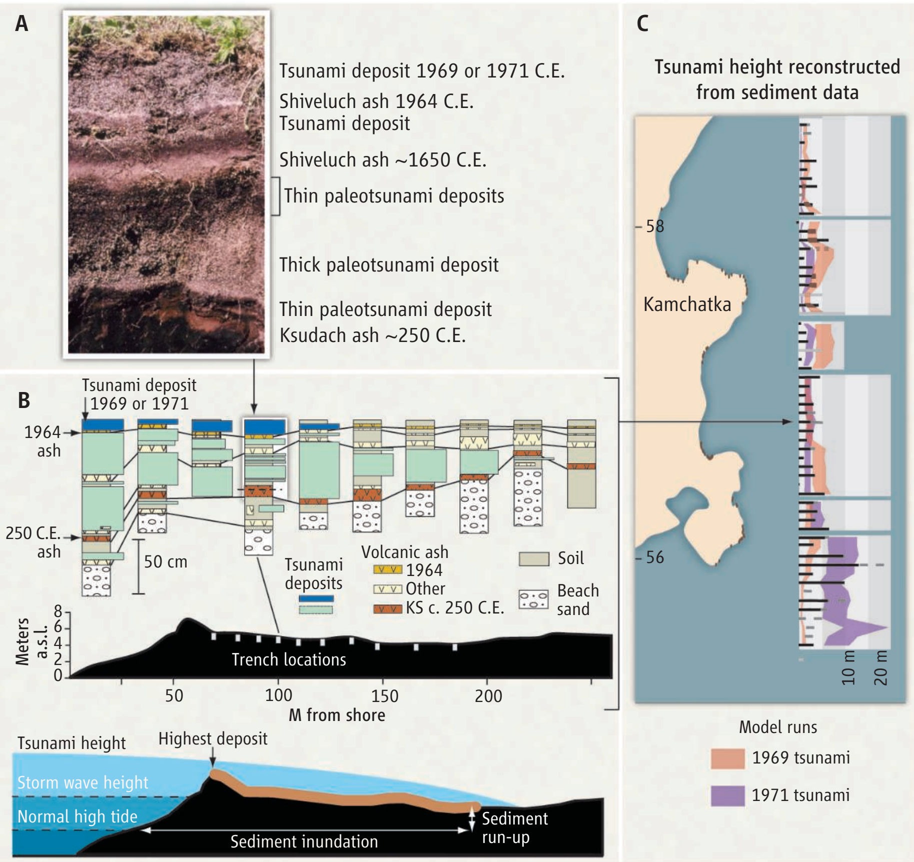
As illustrated on 11 March 2011, tsunamis can cause heavy casualties and hardship and bring about substantial economic loss and environmental change (*1*, *2*). Yet, every tsunami provides new information about the processes that govern inundation characteristics. The primary means for inferring the frequency and magnitude of past, unobserved tsunamis comes from the sediments that they leave behind (*3*, *4*). These deposits can also yield data on tsunami characteristics such as water height, inundation distance, and number of waves—information that is pivotal to forecasting the magnitude of future events.

The study of recent tsunamis has given rise to a proxy tool kit that ranges from classic sedimentary analysis to geochemical signatures of tsunamis (*4*, *5*). Numerical simulations are also a pivotal part of tsunami research. Computer models featuring two spatial dimensions (longitudinal and latitudinal directions) are commonly applied to study offshore and onshore tsunami dynamics. To explore more complex hydrodynamic processes—for example, in the tsunami wave front or during tsunami wave breaking—three-dimensional models are necessary (*6*, *7*), the detail and complexity of which can quickly exhaust computational resources available. Also, for a better understanding of complex currents created by tsunamis in harbors and ports, the incorporation of turbulent effects is pivotal (*8*). These improvements of model capability are crucial for establishing a more advanced understanding of sediment dynamics during tsunamis.

Advanced numerical simulation techniques have been successfully applied to the 11 March 2011 Tohoku-Oki tsunami to simulate turbulent flow structures near harbors (*9*) and to the 2009 Samoa tsunami to simulate sediment dynamics in a sediment-starved environment (*10*). The proxy tool kit has recently been enhanced and examined in the Tohoku-Oki case on the Sendai plain, where the tsunami outran sand deposits (*11*). However, it remains challenging to apply these techniques successfully and reliably to paleotsunami events. The challenge is no better illustrated than by Japan's Tohoku coast, where the C.E. 869 Jōgan tsunami (*12*) was known both historically and from tsunami deposits, yet the import of this knowledge was still incompletely comprehended (*13*, *14*).

A major avenue toward better understanding tsunami erosion, transport, and deposition is to bridge the gap between field-based and theoretical research. Numerical models (*15*) have generally used idealized conditions without erodible sediment or sediment-laden flows. Model development would benefit from experiments that focus on the rapidly changing flow and sediment-transport conditions, and the resulting large fluctuations in stress and pore pressure, during tsunamis. To inform theoretical and laboratory research, field surveys after a tsunami should routinely include—as some have already done—observations not only of the spatial distribution and grain-size characteristics of tsunami deposits but also of their setting (such as bed roughness and three-dimensional topography) and sediment sources.

Understanding sedimentary dynamics during modern tsunamis and their manifestation in deposits will help to quantify the



From the field to tsunami modeling. The extent of a tsunami deposit ("sediment runup") marks minimum tsunami runup and can be used to test tsunami source models. This is particularly useful in areas where few historical records exist, such as in Kamchatka, northeast Russia. (**A**) This excavation profile provides evidence of a tsunami deposit from a tsunami in 1969 or 1971. It is one excavation of 10 from one profile (**B**) of about 50 along the coast of Kamchatka (**C**). Tsunami model runs show that only the 1971 tsunami can explain the high runup in the south, whereas the runup in the north is better explained by the 1969 tsunami (C). This is a simplistic case; the future lies in three-dimensional modeling of water and sediment transport. [Figure is adapted from (*18*)]

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characteristics of causative waves in cases of buried tsunami deposits. Such analysis of repeated prehistoric events can help to project future events and their magnitude. Moreover, the combination of sedimentary and engineering analyses should yield more robust and reliable inferences of potential damage. It is important to estimate maximum flow speed and flow depth for engineering designs that can either withstand tsunami impact forces or undergo controlled failure to dissipate energy. Attempts to retrodict overland flow speed and depth show some evidence of success (*16*, *17*) but are in need of refinement.

Reconstructing past earthquakes from tsunami deposits requires comprehensive mapping and analysis. One tsunami deposit can look very much like another; a sand layer above a time marker (such as an ash layer) may represent two events closely spaced in time or geography. Such events have happened, for example, along the Nankai trough (1944 and 1946); northern Kamchatka (1969 and 1971) (*18*); Sumatra (2004 and 2005); and the central Kurils (2006 and 2007). Also, the landward limit of a sand or mud layer only represents minimum inundation; moreover, at their landward extent, deposits are thin, subtle, and easily obscured by soil processes. Coupling of deposit mapping with tsunami source modeling helps to address these problems (see the figure) (*18*–*20*).

Another avenue toward understanding tsunami flow processes and their impact lies in collaboration with the storm-science community. Storms and tsunamis have differences, but also commonalities such as onshore flooding and infrastructure damage. Recent events, such as the 2005 Katrina hurricane and the 2011 Tohoku-Oki tsunami, provide an opportunity to study deposits in built environments. Combined sedimentary and engineering analyses improve evaluation of future risk, because quantifiable damage can be linked to observed erosion and deposition.

Real-time forecasts of tsunami events are important, but more effective mitigation is achieved in combination with increased awareness and preparedness in coastal communities. The study of tsunami surface processes and deposits clearly contributes to refinement of risk and hazard assessments. There is also the potential to use the physical record of past tsunamis directly in education and in engineering design of coastal infrastructure. Not only are tsunami deposits a scientific key to past processes but also they are a concrete reminder to coastal residents that "it can happen and has happened here."

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GEOPHYSICS

A Rogue Earthquake Off Sumatra

A magnitude 8.6 strike-slip earthquake within an oceanic plate raises fundamental questions about earthquake physics.

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The magnitude (M_w) 8.6 earthquake of 11 April 2012 off the coast of Sumatra is one for the record books. It is far and away the largest strike-slip earthquake in the instrumental record. The M_w 8.2 aftershock that occurred just over 2 hours later is also among the largest such earthquakes. Furthermore, the 11 April mainshock may be the largest intraplate earthquake ever recorded, although the location (see the figure) is consistent with the notion of a wide, diffuse plate boundary that bisects the Indo-Australian Plate near the Ninetyeast Ridge (*1*). The earthquakes are the latest in a series of large (M_w 8) intraplate strike-slip earthquakes in oceanic lithosphere (*2*). What do these earthquakes reveal about earthquake physics, and how might they change earthquake hazard assessment?

The regular occurrence of M_w 8 strike-slip earthquakes, in which adjacent sides of the fault move past one another horizontally, in old oceanic lithosphere presents an interesting problem for fault mechanics. How is it possible to have such large earthquakes on faults that cut vertically through the oceanic plate? In the case of the mainshock, preliminary back-projection results (*3*) and the aftershock distribution both suggest that rupture may have occurred on multiple faults. Even so, to attain the seismic moment of 9×10^{21} N·m determined by the U.S. Geological Survey (USGS) (*4*), the product of the average slip and fault area has to be remarkably large for a strike-slip earthquake. The key to understanding this observation may lie in the depth extent of faulting.

Laboratory studies of olivine (*5*) and observed earthquake depths (*6*) had suggested that frictional failure in oceanic earthquakes is limited to temperatures below 600°C. The 11 April mainshock and aftershock had estimated centroid depths (the slip-weighted average of the depth of fault motion) of roughly 40 km and 54 km, respectively (*4*). Thus, much of the slip in the off-Sumatra earthquakes likely occurred at temperatures of 600° to 800°C, somewhat above where frictional failure is expected. The high pressure and dry conditions at these depths in oceanic lithosphere also make frictional failure unlikely.

Instead, an alternative failure mode may operate that invokes the heat generated by rapid strain in fine-grained shear zones to generate a thermal runaway feedback that results in highly localized zones of viscous failure (*7*). The thermal runaway mechanism is expected to operate only in the 600° to 800°C temperature range where slip occurred (*7*). In extreme cases of great pressure (depth) and high slip (large magnitude

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