Paleotsunami Research

PAGES 205, 209

The Indian Ocean tsunami of 26 December 2004 shows poignantly that catastrophic tsunamis are too infrequent for their hazard to be characterized by historical records alone. Long-term geologic records provide opportunities to assess tsunami hazards more fully. Telltale deposits left by tsunamis help assess water depth and velocity of past inundations, estimate source locations, and aid in understanding how tsunamis affect the ecology and geomorphology of coastlines. Dated deposits allow estimates of times and recurrence intervals of past tsunamis. Such information guides mitigation efforts and may reduce losses from future tsunamis.

Paleotsunami research attracts scientists from earthquake geology, paleontology, paleoecology, geomorphology, physical oceanography, geophysics, marine geology, sedimentology, geochemistry, seismology, coastal engineering, and the social sciences, and may lead to unanticipated collaborations and advances. This article discusses the opportunities and challenges of tsunami geology, and it suggests directions for future research.

Recent Advances

Tsunami research during the past 20 years led to the discovery of long records spanning many thousands of years. For example, along the coast of Hokkaido, Japan, *Nanayama et al.* [2003] identified sand sheets, some extending kilometers inland, that show large tsunamis inundated the coast on average every 500 years, between 2000 and 7000 years ago. In a similar study of a 7000-year-long record in a coastal lake in Oregon, *Kelsey et al.* [2005] identified 12 paleotsunamis over the past 4600 years. Other long records of multiple tsunamis have been studied in Kamchatka [*Pinegina et al.,* 2003] and Chile [*Cisternas et al.,* 2005].

To identify stratigraphic records of tsunamis, geologists must be able to distinguish between tsunami and storm deposits. Comparative studies of these deposits reveal some differences in sedimentology, stratigraphy, and inland height and extent. On the basis of studies in western Europe, Indonesia, New Zealand, and Newfoundland, *Tuttle et al.* [2004] proposed several criteria to distinguish these two types of deposits that may be widely applicable.

The coincidence of tsunami deposits with tidal deposits marking sudden subsidence or uplift along subduction-zone coasts aids in distinguishing between tsunamis and storms and provides evidence that the tsunami originated nearby. Identifying coseismic tidal subsidence and/or uplift, and possibly precursory movements, requires paleoenvironmental records of relative sea level. Recent studies [e.g., *Shennan and Hamilton,* 2006] used microfossils, including diatoms, foraminifera, and pollen, to quantitatively track relative sea level change in response to the buildup and release of tectonic strain.

Tsunamis have been modeled using both geologic and historical data. *Bondevik et al.* [2005] successfully compared extensive data on the distribution and elevation of paleotsuna.1mi deposits in Norway, Scotland, and the Shetland Islands with numerical simulations of the 8000-year-old Storegga submarine slide and tsunami in the North Sea. Models fit to tsunami heights inferred from written records in Japan suggest that Cascadia's most recent large tsunami was generated in the evening of 26 January 1700 and was associated with an approximately *M*9 megathrust earthquake [*Atwater et al.,* 2005].

Finding and Dating New Records

If tsunami geology had been carefully studied around the Indian Ocean before 26 December 2004, signs of giant prehistoric tsunamis from a source between Aceh and the Andaman Islands may have been uncovered. If such a tsunami history had become widely known among coastal residents and tourists, and if this knowledge had become a basis for signage, evacuation maps, and emergency planning, lives might have been saved during the 2004 Indian Ocean tsunami. Therefore, expanded geologic efforts are needed to learn about the sources, recurrence intervals, and sizes of paleotsunamis around the world.

To date, most research on tsunami deposits has been done in tidal marshes and other coastal embayments at temperate latitudes. The Indian Ocean disaster emphasizes the need to search for paleotsunamis in tropical environments, a task that raises difficult questions: What are the best depositional environments in the tropics and semitropics for preserving a record of paleotsunamis? How well do mangrove forests preserve tsunami records? What post-burial changes occur over time in tsunami deposits that accumulated in a tropical environment?

In addition, studies of local changes in relative sea level will aid in finding and interpreting paleotsunamis in the stratigraphic record and help quantify inundation extent and height. Additional research is needed on the relationships between sea level fluctuations, evolving coastal geomorphology, and the preservation of tsunami deposits.

Another question to ask is, does a record of paleotsunamis exist in the near-offshore stratigraphic record? Numerous eyewitness

Fig. 1. Sediments fringing an estuary in southern Chile contain deposits of the tsunami generated by the great M9.5 *earthquake of 1960 and earlier tsunamis accompanying great earthquakes of the past millennia. Dark layers are organic-rich A horizons of soils buried by light-colored sheets of tsunami-deposited sand. The pink tape markers lie at five-meter intervals. Through study of similar stratigraphic records on the coasts of the Indian Ocean and elsewhere, the recurrence of large earthquakes and the heights, velocities, and inland extent of their destructive tsunamis can be studied.*

BY B. RHODES, M. TUTTLE, B. HORTON, L. DONER, H. KELSEY, A. NELSON, AND M. CISTERNAS

and video accounts of the December 2004 tsunami indicate seaward transport of sediment during return flow, which should have resulted in tsunami deposits offshore.

If long-term paleotsunami records are found, they then provide the opportunity to evaluate the recurrence of paleotsunamis large enough to leave lasting signatures. Determining such recurrence intervals is critical for evaluating long-term behavior of faults and assessing the probability of future events. Dating is fundamental to this analysis, but it is limited by geological and analytical uncertainties in estimated event ages that in some cases may be as large as the recurrence intervals. New analytical approaches to age data such as stratigraphic ordering of calibrated radiocarbon age distributions and summing of probability density functions of dates have helped to narrow uncertainties of event timing [*Kelsey et al.,* 2005].

As a result of tsunamis, coastal areas may experience dramatic increases in flooding, erosion, loss of wetlands, and seawater intrusion into freshwater sources. Future research should examine how coastal environments are disrupted, and how they recover in the aftermath of a tsunami. It should be possible to use the lithological, biological, and geochemical indicators described below to track these changes through time.

Potential Analytical Methods

No single analytical technique will unambiguously identify paleotsunami deposits, and local geomorphic and stratigraphic field criteria must be applied first. However, combining field observations and the analysis of geochemical, sedimentological, and paleontological signatures may enable positive identification.

The deposition of sand during tsunami inundation may cause a decrease in the total organic matter within coastal plain sediments. Conversely, analysis of the offshore sediment may include stable isotope analyses to identify terrestrial flux events for organic carbon (from carbon-nitrogen ratios). Indeed the oxygen-18 record of offshore deposits may help distinguish between tsunami and storm deposits because hurricanes are accompanied by large freshwater fluxes to the continental shelves, whereas tsunami events have no such association. Total carbonate may be influenced by the inorganic carbonate content [derived from strontium isotope ratios $(^{87}\text{Sr}/^{86}\text{Sr})$] of the tsunami deposit. Geochemical methods used to examine gradual sea level changes on coastal lakes and fjords might also find application in tsunami studies. These include identifying metal-rich deposits resulting from mixing of anoxic and geochemically speciated bottom water with oxygen-rich, relatively undifferentiated marine water [*Hamilton-Taylor and Davison,* 1995].

The sedimentology of tsunami deposits may be distinctive. They may be inversely graded, composed of multiple layers, and contain distinctive, high-flow-rate sedimentary structures. Clast texture and composition may indicate a sediment source accessible only to a tsunami. The three-dimensional distribution of a sand sheet, such as height above sea level, landward extent and taper, and regional continuity, could also support a tsunami origin.

In addition, the existence of marine fossils within a terrestrial environment may indicate transport via a tsunami [*Hemphill-Haley,* 1996]. Changes in the assemblages of ostracods, diatoms, foraminifera, pollen, and aquatic plants may reflect long-term salinity changes caused by short-lived tsunami inundation.

Interpreting Source Mechanisms

Deciphering the source mechanism of paleotsunamis has important implications for hazard assessment. During the 20th century, 498 tsunamis occurred worldwide, with 66 resulting in fatalities. The only identified source events were earthquakes (86%), volcanic activity (5%), landslides (4%), or combinations of these processes (5%). Tsunamis generated by meteorite or asteroid impacts occur much less frequently. Observations from modern and historic tsunamis are used to interpret the cause of prehistoric tsunamis. In addition, a local landslide source might produce a narrow but peaked coastal distribution of tsunami deposits; whereas a fault source might result in a broader and less peaked distribution. Other associated types of deposits, such as volcanic ash, or impact fallout can help to distinguish between earthquake-triggered slides, volcanic eruptions, and bolide impacts.

Governmental, private, national, and international funding organizations should be encouraged to support new and continuing cross-disciplinary, international paleotsunami research. Tsunami geology can improve understanding of the hazard so that societies are better prepared for the next devastating tsunami.

Acknowledgments

We thank Brian Atwater for a thorough review that greatly improved this article. We also thank the U.S. National Science Foundation for its sponsorship of the tsunami workshop where this collaboration began and some of these ideas took shape (see *Eos 86*(42) 2005).

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