EOS

IN THIS ISSUE:

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 88 NUMBER 52 25 DECEMBER 2007

Sandy Signs of Tsunami Onshore Depth and Speed

Tsunamis rank among the most devastating and unpredictable natural hazards to affect coastal areas. Just 3 years ago, in December 2004, the Indian Ocean tsunami caused more than 225,000 deaths. Like many extreme events, however, destructive tsunamis strike rarely enough that written records span too little time to quantify tsunami hazard and risk. Tsunami deposits preserved in the geologic record have been used to extend the record of tsunami occurrence but not the magnitude of past events. To quantify tsunami hazard further, we asked the following question: Can ancient deposits also provide guidance on the expectable water depths and speeds for future tsunamis?

It has been well documented in the past 20 years that tsunami deposits, both ancient and recent, act as natural recorders of tsunami waves [*Tappin*, 2007]. With reliable dating, such deposits enable us to quantify paleotsunami recurrence intervals. But characterizing both event frequency and magnitude is critical for assessing tsunami risk. Quantifying paleotsunami size by modeling onshore flow depth and speed from tsunami deposits would provide a key for determining the deadliness and destructiveness of past events. Ideally, such a key could also inform long-term hazard assessments based on tsunami source mechanisms (e.g., fault slip or submarine landslides) inverted from calculated paleotsunami wave characteristics.

Developing quantitative tools to estimate flow depth and speed from tsunami deposits requires interdisciplinary collaboration among the coastal geomorphology, sedimentary geology, sediment transport, hydrodynamics, remote-sensing, and seismology communities. This article presents a strategy for using "sedimentology benchmarks" to enhance this collaboration. Promising preliminary work, based on a tsunami sedimentology workshop held in spring 2007 in Friday Harbor, Wash., suggests that benchmarks will lead to an improved understanding of tsunami physical processes and to advances in our ability to quantify paleotsunami magnitudes by interpreting the geologic record.

The State of the Science

Tsunamis deliver highly energetic, sustained flows that can erode everything from large blocks to fine sediment and transport them up to thousands of meters across coastal plains. The long-period waves of a tsunami approach the shore at speeds of tens of kilometers per hour, causing nearshore water surface fluctuations with amplitudes of several to tens of meters. The leading wave—commonly related to the pattern of seafloor displacement in the source region—may arrive as either a receding trough or an advancing crest. The incoming waves commonly break offshore, where they form a bore or series of bores—relatively short breaking waveforms riding on the tsunami's longer wave. For example, in many videos of the 2004 Indian Ocean tsunami, the first tsunami wave rushes onto dry land much like a surging flood. Several additional large waves, with typical periods of tens of minutes, commonly follow, and onshore flooding typically lasts for hours.

While tsunami propagation models have been around for years and have been shown to be fairly accurate at predicting basin-scale travel times and deep-water wave amplitudes, models of tsunami inundation—where waves approach shore and flood the land—are less common and have not been adequately tested against field data. Recent inundation models consider wave evolution by simulating both linear and highly nonlinear processes of various length scales and timescales [*Liu et al.*, 2007]. Model predictions are particularly sensitive to effects of local bathymetry and coastal topography that cause tsunami runup to vary significantly, even in neighboring areas.

Inverse models of flow from tsunami deposits [see *Tappin*, 2007] and forward models of deposits from flow [*Gelfenbaum et al.*, 2007] are relatively new and still under development. These models exploit the dependence of sediment transport on the relationship between grain size (grain settling velocity) and flow shear stress. Deposition occurs where sediment transport converges or when deceleration permits sediment to fall out of suspension. Empirical relationships to infer deposit characteristics from flow velocities and, conversely, flow velocities from deposits have been derived from steady channel-flow experiments.

This suggests that it should be possible to combine tsunami hydrodynamics and knowledge of the sediment available for transport to predict the structure and texture of tsunami deposits—or to reconstruct tsunami flow histories from deposit characteristics. However, fundamental questions remain regarding tsunami turbulent flow structure and the applicability of existing sediment-transport models to a tsunami's timescale and initial dry-bed conditions.

Benchmark Strategy for Collaboration

Benchmarking tsunami sedimentology models entails developing test cases that can be treated using different approaches, allowing the model results to be compared and problems to be tackled in an efficient, coherent manner. Given the limitations of existing tsunami inundation and sediment transport models, two key challenges are well suited for such an approach: (1) closing the knowledge gap in linking modern events to their deposits with an improved understanding of tsunami sediment transport, and (2) adapting that relationship to interpret the geologic record.

Traditionally, benchmarks rely on analytical solutions or controlled experiments of known initial conditions with which to test and compare models or laboratory equipment. Our working definition of a benchmark is somewhat different for several reasons. First, there is no adequate analytical solution available for "tsunami sediment" problems, even for a case with simplified boundary conditions (e.g., planar beach topography) and homogeneous sediment. Second, while initial conditions of laboratory experiments can be specified in detail, comparing these small-scale experiments with nature is limited by scaling difficulties. Most important, while conventional benchmarks are used to rank models in well-established fields of study, tsunami sedimentology is at such an early stage that benchmarking serves instead to enhance collaboration in exploring physical processes and making improved model predictions. Such collaboration has already resulted from benchmark exercises designed to investigate the hydrodynamics on which tsunami runup models are based [*Yeh et al.*, 1996].

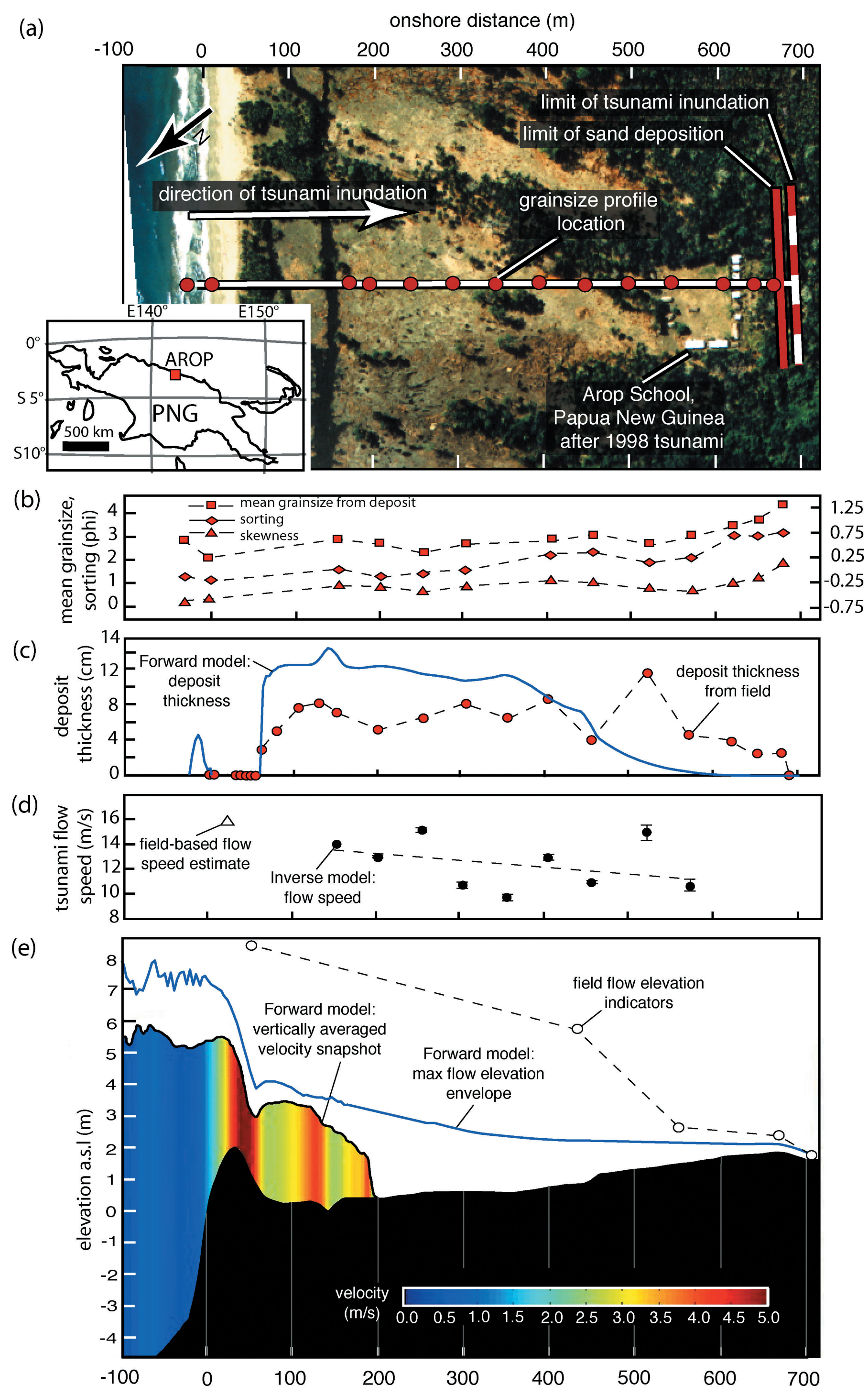

*Fig. 1. Flow depth and speed estimates for the 1998 Papua New Guinea tsunami. (a) Location and sample sites [*Gelfenbaum and Jaffe*, 2003]. (b–e) Data collected from tsunami deposit (red symbols), field-based estimates of tsunami flow elevation (sum of flow depth and land elevation, white circles) and speed (white triangle), predictions using hydrodynamic model of* Lynett *[2007] with incorporated transport model following* Rakha et al. *[1997] (bold blue lines), and inverse model predictions of* Jaffe and Gelfenbaum *[2007] (black symbols).*

Benchmarking for tsunami sedimentology requires agreed-upon goals that promote interdisciplinary collaboration and development of appropriate data sets. For example, the community must identify key parameters to be estimated (e.g., wave height and speed) and set sensitivity study targets (e.g., effect of grain size on deposit thickness). These actions will ensure that the focus and scope of modeling studies are comparable. Identifying these parameters also helps to determine the minimum amount of information a benchmark data set must contain.

Proof of Concept

As a test of this approach, we performed pilot benchmark exercises on two data sets of tsunami deposits, one modern (1998 Papua New Guinea) and the other ancient (buried; Mutnaya Bay, Kamchatka, Russia). Detailed treatment of the modern case (Figure 1) was aimed at linking modern events to their deposits and improving the understanding of tsunami sediment transport. The application of the models to the ancient case allowed us to evaluate how this understanding might be adapted to interpret the geologic record.

Models were used to estimate tsunami characteristics such as flow depth, flow speed, number of waves, and where possible, tsunami source for each benchmark. The data sets included grain-size distributions, deposit thickness, topographic profiles, and bathymetry. In the case of the modern deposit, additional information (from field estimates and eyewitness accounts) on the tsunami was available [*Gelfenbaum and Jaffe*, 2003]. Paleotsunami modeling efforts were complicated by incomplete deposit preservation, lack of flow depth or inundation limit indicators, and poorly constrained pre-tsunami topography at Mutnaya Bay.

Forward modeling of tsunami inundation was based on high-resolution bathymetry and topography collected along the sam-

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ple transect for each benchmark. For the Papua New Guinea (PNG) case (Figure 1), further model constraints were provided by tsunami inundation limits and flow-depth indicators identified in the field and by the number of waves reported by eyewitnesses. Modeled and measured deposit thicknesses were comparable (Figure 1c). The modeled, vertically averaged velocity and flow depth snapshot (Figure 1e) shows flow accelerations and decelerations as the wave cascades over a topographic high, illustrating the complexity of flow-topography interactions.

Estimates of maximum flow speed from inverse modeling were based on assumptions of steady and uniform flow and on observed grain-size distributions and deposit thicknesses. The inverse model estimates for the PNG benchmark (Figure 1d) are consistent with independent field estimates of flow speed (calculated using Bernoulli's principle and water level data on buildings left standing after the tsunami). These estimates are of the same order of magnitude, but they exceed the flow speeds predicted by the forward model. Discrepancies between models may be due to missing processes (such as not accounting for momentum extracted from the flow by dense vegetation), other simplifying assumptions (such as no particle reentrainment), or poorly characterized initial conditions.

Results of the PNG case highlight the potential of using detailed data from a modern tsunami and its deposit for benchmarking inverse models. For forward models, however, a limitation of this type of benchmark is that initial conditions are poorly known for natural tsunamis. A better benchmark for forward modeling would be a detailed laboratory experiment data set with well-defined initial conditions. Whereas treating a paleotsunami deposit benchmark would be a valuable step toward interpreting the geologic record for hazard assessment, problems with preservation limit available information for ancient cases like Mutnaya Bay. Nature is not simple, but initial benchmark cases should be.

On the basis of our pilot study, we developed a preliminary list of requirements for future tsunami sedimentology benchmarks (see http://tsunami.orst.edu/sedimentology). This list is a work in progress, and we ask interested scientists to comment on it by prioritizing parameters to which their own approaches are most sensitive. For example, what are the minimum bathymetric resolution, deposit-sampling density, and grain-size detail required to test your model? Answers to these questions will vary over a broad range depending on model techniques, assumptions, and goals. Responses will help to guide data gathering, experimental design, and field campaigns and will define objectives for the next generation of tsunami sedimentology benchmark experiments.

Acknowledgments

This study was supported by the U.S. National Science Foundation (Tsunami Sedimentology Workshop, Friday Harbor, Wash., 30 April to 3 May 2007, EAR-0531497, Joanne Bourgeois, principal investigator (PI); CMS-0321889, Harry Yeh, PI; CMMI-0619083, Patrick Lynett, PI) and the U.S. Geological Survey (USGS). This article benefited from reviews by Brian Atwater (USGS at the University of Washington, Seattle), Andrew Moore (Earlham College, Richmond, Indiana), Yong Wei (NOAA Center for Tsunami Research and the University of Washington, Seattle), and two anonymous reviewers.

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