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Flow speed estimated by inverse modeling of sandy sediment deposited by the 29 September 2009 tsunami near Satitoa, east Upolu, Samoa

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A B S T R A C T

Sandy deposits from the 29 September 2009 tsunami on the east coast of Upolu, Samoa were investigated to document their characteristics and used to apply an inverse sediment transport model to estimate tsunami flow speed. Sandy deposits 6 to 15 cm thick formed from ~25 to ~250 m inland. Sedimentary layers in the deposits, that are defined by vertical grain size variation and contacts, are interpreted to have formed during onshore runup of two waves. Deposits at 3 locations (100, 170, and 240 m inland) contained two layers that are predominately normally graded (~80%), but contained massive sections (~15%) and inversely graded sections (~5%) at their bases. About 75% of the total thickness of normally graded intervals exhibits a signature of sediment falling out of suspension at their top. This type of grading, termed suspension grading here, was first recognized in turbidity current deposits and is characterized by the entire distribution shifting finer upwards in a layer as high-settling velocity, coarser material deposits first and low-settling velocity finer material deposits last. The Jaffe and Gelfenbaum (2007) inverse sediment transport model was applied to intervals within layers that exhibited suspension grading to estimate tsunami flow speed and was able to reproduce the general trends of the observed suspension grading. A key unknown input in the modeling is the bottom roughness. For a bottom roughness parameterization using a Manning's n of 0.03 (equivalent to a z_0 ~0.006 m for the observed flow depths of 2–3 m) flow speeds calculated for the 2 layers at the 3 locations were 3.8, 3.6, and 3.7 m/s (bottom layer/earlier wave) and 4.4, 4.4, and 4.1 m/s (top layer/later wave) at 100, 170, and 240 m inland, respectively. These estimates are consistent with the ~3–8 m/s tsunami flow speed from boulder transport calculations and result in Froude numbers of ~0.7–1.0 when maximum measured flow depths are used. Because the inverse model assumes the deposit was formed by sediment falling out of suspension care must be taken to model only intervals of the deposit exhibiting suspension grading. Including intervals deposited by either bedload or suspended load transport convergences result in higher, and sometimes unrealistic, tsunami flow speed estimates.

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1. Introduction

On September 29, 2009, a magnitude-8.1 submarine earthquake occurred at 6:48 a.m. Samoa Standard Time approximately 190 km (120 mi) southwest of Samoa. The initial rupture occurred near the north end of a 3000-km-long segment of the Pacific/Australia plate boundary that trends north–northeast and is marked by the Tonga trench (United States Geological Survey National Earthquake Information Center Web Site) (Fig. 1). The earthquake occurred as a normal-fault rupture within the outer rise of the subducting Pacific plate, where the plate bends downward toward the Earth's mantle (Okal et al., 2010). This earthquake triggered two major intraplate aftershocks at the northern end of the Tonga subduction zone less than 2 min after the outer-rise earthquake (Beavan et al., 2010; Lay et al., 2010). The combination of these earthquakes caused seafloor deformation that produced a tsunami that resulted in 191 deaths and widespread damage in Samoa, American Samoa, and Tonga (Federal Emergency Management Agency, 2009; United Nations Office for the Coordination of Humanitarian Affairs, 2009; National Oceanic and Atmospheric Administration National Geophysical Data Center, 2011). The vast majority of the deaths (149) occurred on the islands of Samoa.

On the island of Upolu, Samoa, the tsunami reached elevations greater than 14 m above sea level and flooded regions more than 400 m inland (Dominey-Howes and Thaman, 2009; Okal et al., 2010; Fritz et al., 2011-this issue). While this paper focuses on the relationships between tsunami characteristics (e.g., flow speed) and sediment deposit (e.g., thickness, grading, and grain size distributions), other physical and ecological impacts were also investigated by international tsunami survey teams. The combined data set is substantial and can be used to improve the understanding of tsunamis in the Pacific and elsewhere in the world.

The post-tsunami survey geology team (12 scientists from 5 countries) on Samoa worked from Oct 14 to 21, 2009 (Richmond et al., 2011-this issue) in one of the largest research efforts ever. Geologists have investigated deposits after tsunamis for nearly 50 years, with one of the earliest post-tsunami reports coming after the 1960 Chilean tsunami (Wright and Mella, 1963). In the past two decades, the participation and leadership of geologists on post-tsunami surveys have greatly increased (a partial list is: Nishimura and Miyaji, 1995; Shi et al., 1995; Dawson et al., 1996; Minoura et al., 1997; Nanayama et al., 2000; Gelfenbaum and Jaffe, 2003; Jaffe et al., 2003; Moore et al., 2006; Goff et al., 2006; Jaffe et al., 2006; Bahlburg and Weiss, 2007; Richmond et al., 2007; Higman and Bourgeois, 2008; Morton et al., 2010; Richmond et al., 2011-this issue). The objective of these geologic studies is to find diagnostic features for identifying and interpreting paleotsunami deposits (e.g., Chagué-Goff et al., 2011-this issue). Geologists, oceanographers, and mathematicians are taking the next step in understanding sandy tsunami deposits by developing and applying inverse (Jaffe and Gelfenbaum, 2007; Moore et al., 2007; Witter et al., 2008) and forward (Soulsby et al., 2007; Apotsos et al., 2009) models using data collected after recent tsunamis.

The 2009 South Pacific tsunami left a deposit near the village of Satitoa in the Aleipata District of eastern Upolu, Samoa (Fig. 1). The deposit was mainly sand, but also included mud caps, debris piles (vegetation, refuse, etc.), and gravel (pebbles, cobbles, and boulders) buried within the deposit and at the surface. This paper focuses on the sandy portion of the deposit and asks the question, “What information about the tsunami can be extracted from the deposit?” In addition to qualitative information about the tsunami (e.g., number of large waves), an inverse tsunami sediment transport model (Jaffe and Gelfenbaum, 2007; Appendix A) is applied to estimate tsunami flow speeds from the Satitoa deposits.

2. Suspension grading in tsunami deposits

Normal grading is often reported as a feature of tsunami deposits (Bourgeois, 2009 and references therein). However, normal grading is associated with other phenomena and can be created by bedload as well as suspension processes (Bridge, 2003; Bridge and Demicco, 2008). The scale (lamina, layer, sequence) and details of grading can, and should, be used to further constrain whether a deposit can be identified as forming from a tsunami, and if so, the process of formation (bedload vs. suspend load deposition).

A special case of normal grading, here termed suspension grading, is observed in the tops of layers in tsunami deposits (e.g., Jaffe and Gelfenbaum, 2007; Higman and Bourgeois, 2008) where the entire distribution shifts to finer sizes moving upward in the deposit. This shift is a signature of sediment falling out of suspension and is the predicted grading for clearing of a water column charged with suspended sediment with an exponential decrease in concentration (e.g. produced by an equilibrium between upward diffusion and downward settling of sediment). The shift of the distribution to finer sizes occurs because of the timing of when larger and smaller grains are deposited. Grains with higher settling velocities (larger particles for a given density and shape) deposit first and are absent in the water column during the later stages of deposition. The grains with lower settling velocities take longer to reach the bed and are absent from the bottom of the deposit and present in the top of it. The thickness of the