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USING TSUNAMI DEPOSITS TO IMPROVE ASSESSMENT OF TSUNAMI RISK

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Abstract: In many places in the world the written record of tsunamis is too short to accurately assess the risk of tsunamis. Sedimentary deposits left by tsunamis can be used to extend the record of tsunamis to improve risk assessment. The two primary factors in tsunami risk, tsunami frequency and magnitude, can be addressed through field and modeling studies of tsunami deposits. Recent advances in identification of tsunami deposits and in tsunami sedimentation modeling increase the utility of using tsunami deposits to improve assessment of tsunami risk.

WHY STUDY TSUNAMI DEPOSITS?

Makers of public policy require a better understanding of where future destructive tsunamis might occur and what the possible magnitude, frequency, and history of occurrence of such events might be. Such information would help guide coastal development, location of emergency facilities, and tsunami evacuation planning (Geist et al. 2000). In many places in the world, the written record of tsunamis is too short to accurately assess the risk of tsunamis. Sedimentary deposits left by tsunamis can be used to extend the record of tsunamis to improve risk assessment.

When sediment is deposited by a tsunami and preserved, a geologic record of that tsunami is created. By looking at the sedimentary record in an area, geologists may be able to identify such deposits and infer the occurrence of past tsunamis. The recognition of deposits from past tsunamis allows geologists to extend the relatively short or non-existent historical record of tsunamis in an area. Because scientists cannot yet predict when a tsunami will occur, obtaining a geologic record of past events may be one of the only means to assess future risk.

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This paper explores how recent developments in tsunami sediment transport modeling and refinements in identification of tsunami deposits can be used to improve tsunami risk assessment. After addressing tsunami risk assessment, we discuss identification and interpretation of tsunami deposits. Examples focus on deposits from paleotsunamis in Cascadia (the region from northern California to Vancouver Island, British Columbia) and deposits from a modern event, the 1998 Papua New Guinea tsunami. We conclude with a discussion of limitations and potential of using tsunami deposits for improving tsunami risk assessment.

TSUNAMI RISK ASSESSMENT

Many factors contribute to tsunami risk, but the two primary ones are tsunami frequency and magnitude. These two factors are analogous to earthquake frequency and magnitude that have been used for many years to assess earthquake risk. The record of earthquakes is large enough in many regions of the world to develop a reasonable estimate of risk. This is the case not only because of the size of the earthquake record, but also because the record, since the invention of the seismograph, includes all earthquakes above a low detection threshold. The range of magnitudes and the use of a distribution function allow extending the earthquake record. The tsunami record is not as complete as the earthquake record. The longest written record of tsunamis is in Japan where monks have kept records on causes of death, including tsunami, since approximately 600 A.D (Iida 1984). The 1400 year tsunami record is biased towards large tsunamis (the ones that caused death) and therefore is not as rich as the earthquake record. The longest continuous tsunami record outside of Japan in the Pacific is on the order of several hundred years (Lockridge and Dunbar, 1996). An additional difference between earthquake and tsunami risk assessments is that destruction decreases, in general, with distance from the epicenter while a tsunami can be more destructive thousands of kilometers from its generation region than near it because of focusing and modification by bathymetry. An example of this is the high risk of destructive tsunamis in the Hawaiian Islands from transoceanic tsunamis generated around the perimeter of the Pacific. Locally generated tsunamis, although they pose a risk, impact the Hawaiian Islands less frequently (and are usually smaller, with the exception of those generated by infrequent large submarine landslides that occur on the order of every ten or hundred thousand years, Moore 2000) than those generated across the Pacific. Because of the multiple tsunami generation sources, each with a unique magnitude and frequency distribution, assessing tsunami risk in the Hawaiian Islands is challenging. This degree of complexity requires a longer record to capture the true frequency and magnitude distributions. Although most regions are not as complex as the Hawaiian Islands, there is a worldwide need (with the possible exception of Japan) to extend the record of tsunamis to improve our understanding of their risk. This can be done using tsunami deposits.

TSUNAMI DEPOSITS AND TSUNAMI RISK ASSESSMENT

Tsunami Frequency

The frequency of tsunamis may be developed through dating a series of past or paleotsunami deposits. This has been done in several places around the world. For example, in Cascadia Darienzo and Peterson (1995) dated a series of tsunami deposits and determined the recurrence interval for subduction zone earthquakes and associated tsunamis is from 200 to 600 years. For this technique to give accurate recurrence intervals, the dating methods must be robust, there must be positive identification of the deposit as a tsunami deposit, and the record must be long enough to encompass many tsunamis. Although an important aspect of tsunami risk assessment, this paper does not focus on developing tsunami frequency, but rather addresses identification and interpretation of tsunami deposits.

Identification of Tsunami Deposits

The identification of tsunami deposits has improved markedly over the past decade. Much of this improvement is the result of more researchers approaching the topic. For example, in Cascadia there have been 48 researchers who have written 34 papers on tsunami deposits (Peters et al. 2001). There have also been several field investigations of recent tsunamis that have included studies of tsunami deposition (Gelfenbaum et al. 2001, Jaffe et al. 1999, Jaffe et al. 1998, Minoura et al. 1997, Jaffe et al. 1996, Moore et al. 1996, Sato et al. 1995, Shi et al. 1995).

A tsunami deposit is usually identified by sedimentary context (e.g. deposited on soil associated with coseismic subsidence), larger grain size than surrounding sediments indicating higher-energy depositional conditions, spatial distribution of the deposit, and by ruling out other high energy depositional modes (e.g. storm surges or floods). For Cascadia, paleotsunami deposits are identified as being anomalous sand layers in low energy marsh or lacustrine environments (Peters et al. 2001, Atwater 1987, Clague et al. 2000). Additional information that indicates a seaward source of sediments, such as microfossils (Hemphil-Haley 1995) or geochemical signature (Schlichting 2000), are also useful for determining that a deposit was formed by a tsunami. Although at times identification is difficult, deposits believed to be from paleotsunamis have been identified at 53 locations in Cascadia (Fig. 1) (Peters et al. 2001).

Studies of modern tsunamis, where eyewitnesses can verify deposition by tsunami and deposits are not significantly altered by post-tsunami processes, are invaluable for building a catalog of tsunami deposit characteristics. For example, two international teams conducted field studies after the 1998 Papua New Guinea tsunami, a devastating tsunami that killed over 2,000 people and had water levels greater than 15m (Kawata et al. 1999, Gelfenbaum et al. 2000). Identification of deposits in Papua New Guinea used the "anomolous sand layer" criteria used in Cascadia (Gelfenbaum et al. 2001, Jaffe et al. 1999, Jaffe et al. 1998). The other criteria used were the thickness and spatial distribution of the sand layer (as thick as 16 cm), mud rip-up clasts mixed with the sand, an erosive base, upward fining, shells in the

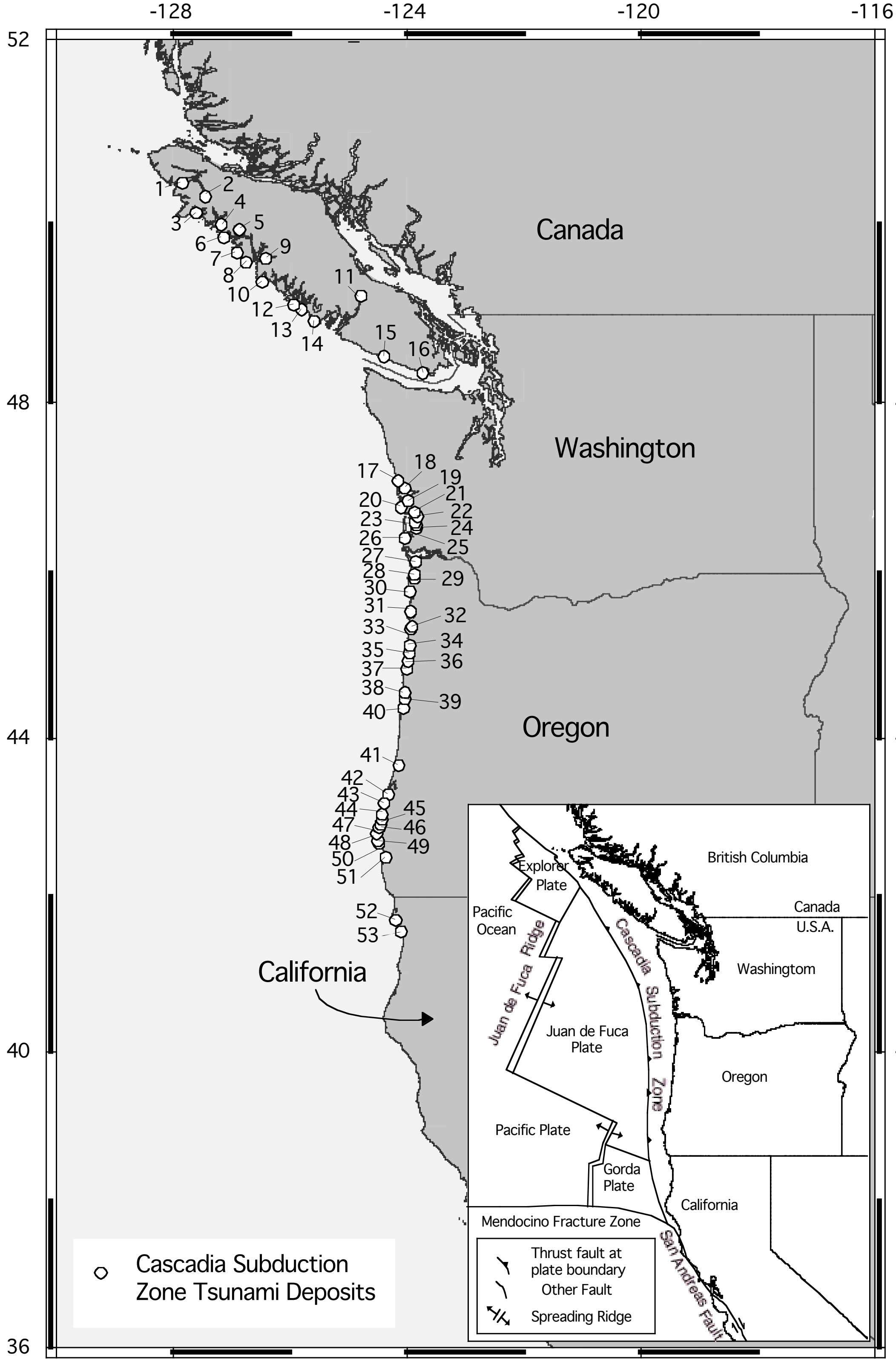

Fig. 1. Location of paleotsunami deposits along the Cascadia Margin. Numbers correspond to locations in Table 1 of Peters et al. 2001. Inset shows regional tectonic setting. Figure from Peters et al. 2001.

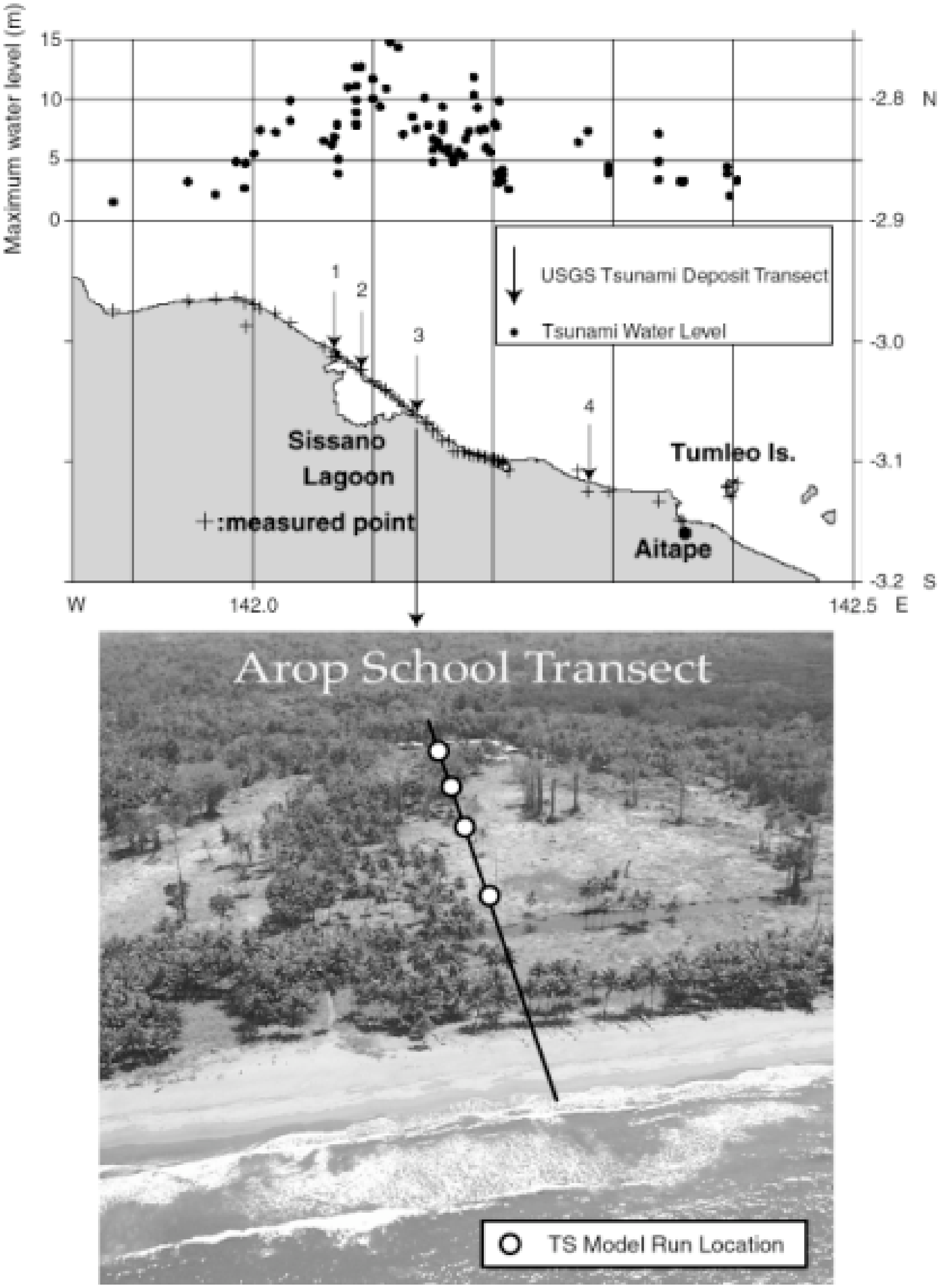

Fig. 2. Water levels from 1998 Papua New Guinea tsunami measure by International Tsunami Survey Team. Based on Figure from M. Matsuyama (CRIEPI). Oblique aerial view (bottom) of Arop School transect (transect 3) showing locations where Tsunami Sedimentation model was applied.

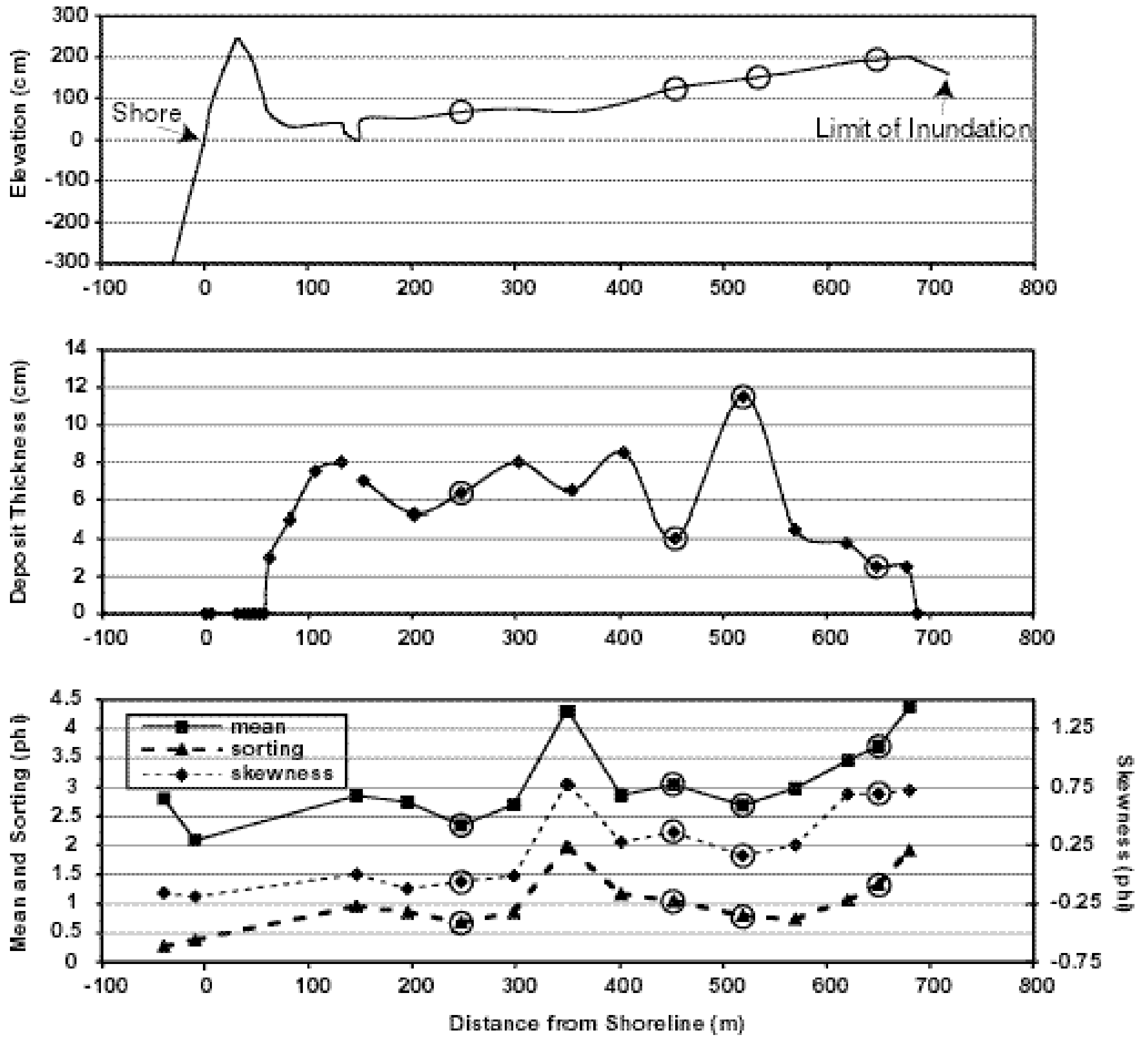

Fig. 3. Transect near the Arop School showing elevation of the coastal plain (upper panel), tsunami deposit thickness (middle panel), and tsunami deposit mean sediment size, sorting, and skewness (lower panel) plotted against distance from the shoreline. Data at seaward two locations in lower panel are from potential sand sources—they are not characteristics of the tsunami deposit. Locations where the tsunami sedimentation model was applied are identified by a circle. Modified from Gelfenbaum et al. 2001.

deposit indicating a marine source of the sediment, and a general landward fining indicating landward transport of sediment from the ocean (Figs. 2, 3). Thickness and grain size tend to decrease with distance from the ocean (Figure 3). However, in the middle of the transect there is a region where the variability is low indicating spatial gradients in transport were not significant in forming the deposit. The characteristics of the deposits reflect hydrodynamics of the tsunami that created them and can be interpreted to learn information about the tsunami magnitude.

Interpretation of Tsunami Deposits Using Sediment Transport Modeling

Tsunami magnitude can be quantified in different ways, but may include some combination of the tsunami height, flow velocity and duration, and inland extent (inundation) either at one location or averaged along a stretch of coast. These characterizations of tsunami magnitude may be learned from interpretation of tsunami deposits. For example, inundation may be estimated by the landward extent of tsunami deposits when all deposits are preserved. This is supported by field observations of the Papua New Guinea tsunami where deposition extended to within approximately 25 m of the maximum inundation (Gelfenbaum et al. 2001). For paleotsunami deposits, where preservation is likely incomplete, sediment transport modeling of tsunami sedimentation combined with field observations can better estimate inundation and flow velocity (Jaffe and Gelfenbaum in prep., Titov et al. 2001).

The conceptual framework for the sedimentation model is that thickness and grain size of the deposit is the result of sediment transport during the tsunami. In general, thicker deposits with larger grain sizes indicate faster flows. A deposit is formed by spatial gradients in transport (more coming into an area than leaving it), by change in storage of sediment in suspension in the water column, or by a combination of these processes. The variation (both horizontal and vertical) in grain size in the deposit may be used to constrain the relative contributions of transport gradients and sediment storage in the water column to forming the deposit. For example, when sediment settles from suspension (change in storage in the water column) the deposit will have more particles with higher settling velocities near the bottom and more particles with lower settling velocities near the top. When density of particles is similar, larger particles have higher settling velocities. The resulting deposit will have larger particles near the bottom creating a normal grading (Jaffe and Gelfenbaum in prep., Titov et al. 2001). When deposits are formed by spatial gradients in transport, the bed may or may not be normally graded, depending on sediment source, the time history of sediment transport, and the spatial gradients in transport of each particle size.

A simple model for formation of the Papua New Guinea tsunami deposits is that the sediment deposited was in equilibrium with the maximum landward flow velocity. When the flow stopped, the turbulent eddies that suspended sediment were quickly dissipated and all of the sediment in suspension settled out of the water forming a normally graded deposit. This simple model (hereafter called the TS, short for Tsunami Sedimentation, model) is supported by normal grading observed in the Papua New Guinea tsunami deposits.

The TS model calculates flow velocity from the thickness and grain size distribution of the tsunami deposit. Model assumptions, inputs, and outputs are summarized in Figure 4. Steady uniform flow is assumed. This assumption is supported for the locations in the middle of the transect that have less variability in grain size and thickness (except for local variability related to small scale topography) than for other portions of the transect. At equilibrium, the downward settling of sediment is balance by upward mixing resulting in a steady-state concentration profile described by:

$$C(z) = Ca\ (z_o/z)^{w_s/kU_*} \tag{1}$$

where *Ca*, the reference concentration, is a function of excess shear stress and the resuspension coefficient $_o$ (Hill et al. 1988), z is the elevation above the bed, z_o is the bottom roughness parameter, w_s is the sediment settling velocity, *k* is Von Karmen's constant, 0.41, and U_* is the shear velocity.

The TS model iteratively adjusts sediment source distribution and shear velocity (a parameterization of turbulent mixing intensity) to match the observed bulk grain size distribution and thickness of the tsunami deposit. Standard formulations and values are used for coefficients of the model. The resuspension coefficient, $_{o,}$ is 1.4 x 10^{-4} (Hill et al., 1988). The bottom roughness parameter, z_o, is a combination of the Nikaradse grain roughness and a moveable bed roughness (Wiberg and Rubin, 1989). A linear eddy viscosity profile parameterizes the vertical variation in turbulent mixing. The bulk grain size distribution of the tsunami deposit is measured from field samples. The TS model used 45 size classes at 1/4 □ intervals (□=-$\log_2$ grain size in mm) to characterize the concentration profiles (45 profiles) in the water column. After determining the shear velocity needed to produce the deposit, flow velocity is calculated using the logarithmic velocity profile (law of the wall). The law of the wall:

$$U(z) = U_*/k\ ln(z/z_o) \tag{2}$$

is the simplest relationship between velocity and shear velocity, and until we know more about the actual relationship, is used in the TS model.

The TS model was used to predict maximum flow velocity (*z* = depth of the flow) at four locations along the Arop School Transect (Figs. 3, 5). As a comparison, estimates of flow velocity and water depth from the MOST model, which uses depth-averaged non-linear shallow water wave equations to simulate long wave propagation and inundation (Titov and Synolakis 1995, Titov and Synolakis 1998, Titov and Gonzalez 1998) are also shown. The TS and MOST models yield similar results at the location nearest the coast but diverge at landward locations. Titov et al. (2001) suggest that this divergence is the result of the MOST model not including friction, which results in a higher estimate of flow velocity.

DISCUSSION OF LIMITATIONS AND POTENTIALS OF USING TSUNAMI DEPOSITS FOR TSUNAMI RISK ASSESSMENT

Tsunami deposits have great potential for improving the assessment of tsunami risk; however, they are not a panacea and are not useful in certain circumstances. The most obvious limitation for using tsunami deposits for tsunami risk assessment is deposits are not present (or preserved) in all environments. Another limitation is that it is possible to misidentify deposits that were not formed by tsunamis as tsunami deposits. This results in an overestimate of tsunami risk. Likewise, not identifying existing deposits results in an underestimate of tsunami risk. As the state of knowledge advances, misinterpretation will be less frequent as the understanding of diagnostic characteristics of tsunami deposits improves.

A very critical limitation to using tsunami deposits to assess risk is error in dating deposits. For example, in Cascadia errors for radiocarbon dating, which is typically used for determining the age of tsunami deposits, may be on the order of one-half the recurrence interval (Darienzo and Peterson 1995, Peters et al. 2001). Without improvements in either radiocarbon dating techniques, statistical interpretation of groups of dates, or different dating techniques, tsunami frequency is difficult to determine as accurately as desired. Other weaknesses in estimating tsunami magnitude from deposit are the difficulty identifying multiple waves in a deposit and the ability to filter out local variability to obtain representative deposit thickness. Even with these limitations, there is potential to extract new information from tsunamis deposits and improve tsunami risk assessment.

Tsunami Sedimentation Model

Assumptions

Deposit formed from settling of all sediment in suspension
Bottom roughness is a combination of grain and moveable bed roughness
Standard values for coefficients
Linear eddy viscosity profile
Deposits not limited by sediment supply

Inputs

Tsunami deposit thickness
Detailed sediment grain size information (45 size classes) for deposits

Output

Shear velocity (U*) necessary to create deposit
Tsunami flow velocity

Fig. 4. Key features of tsunami sedimentation model.

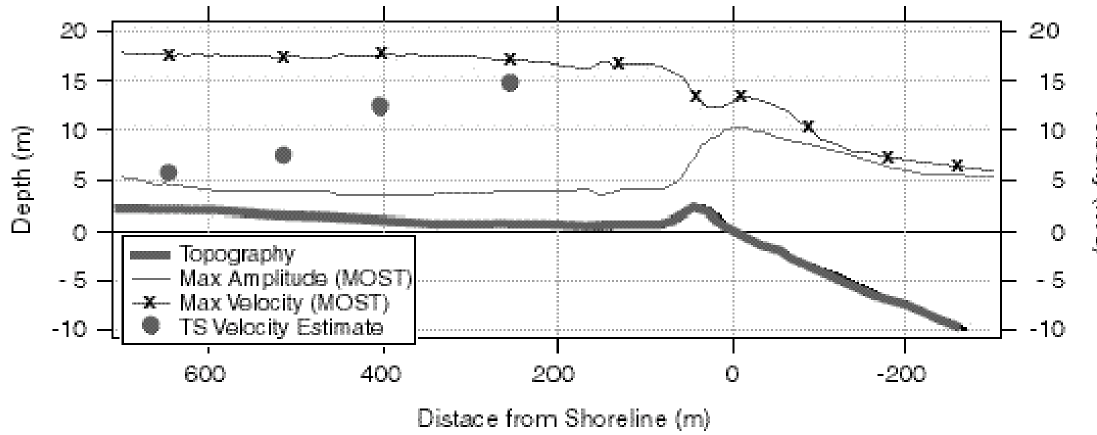

Fig. 5. Results from Tsunami Sedimentation and MOST models for Arop School Transect (Figs. 2, 3). Models yield similar results for predictions of velocity at the location nearest the coast but diverge at landward locations. Figure modified from Titov et al. 2001.

The potential for using tsunami deposits to improve tsunami risk assessment includes several aspects. An estimate of tsunami frequency can be made through identification and dating of a series of deposits. Information about the magnitude (tsunami height, flow velocity and duration, inundation, etc.) of tsunamis are reflected in the characteristics of their deposits. Unless there is a meticulous, detailed written record (or measurements) of a tsunami, this quantitative information is not obtainable using any other means. Interpretation of tsunami deposits is a new area of research with much work still to be done. Quantitative models, like the Tsunami Sedimentation model presented in this paper, are yielding valuable information about tsunamis from their deposits. Tsunami deposits will likely be key to developing improved tsunami risk assessments in the future.

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