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IDENTIFICATION AND INTERPRETATION OF TSUNAMI DEPOSITS FROM THE JUNE 23, 2001 PERÚ TSUNAMI

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Abstract: On June 23, 2001 a strong earthquake of moment magnitude 8.4 generated a deadly tsunami that hit the southern coast of Perú. A team of 16 scientists from Perú and the United States conducted a field investigation from September 6-15, 2001 to determine the presence, distribution, and style of sedimentary deposits left by the 2001 tsunami. Tsunami deposits were found at all 6 sites studied along a 45-km stretch of coast in the Camaná Province. Tsunami deposits were positively identified in three different coastal settings: (1) muddy, (2) fluvial, and (3) sandy open-coast. Tsunami deposits had sand layers, which in general fined upward and often contained a heavy mineral layer at their base. Deposits typically had an erosional contact at their base. Mud rip-up clasts were found in deposits in muddy settings. A mud cap, which was sometimes a clay powder, was also used as an indicator of the possible presence of tsunami deposits. Deposits were found up to 490 m inland. Thickness of the deposits varied from site to site and with distance from the ocean, thinning out within 15 m of the limit of inundation. Deposit thickness ranged from 0.5 to 28 cm. Features of tsunami deposits (thickness, multiple sand layers, grain size, flow indicators) were interpreted to provide qualitative information about the 2001 Perú tsunami. The location and elevation of the furthest inland tsunami deposit in open-coast settings was found to give reasonable estimates of runup and inundation.

INTRODUCTION

On June 23, 2001 a deadly tsunami hit the southern coast of Perú, triggered by a massive earthquake of moment magnitude 8.4, the largest earthquake recorded worldwide in 35 years. The tsunami was observed in many coastal areas of the Pacific including Perú, Chile, Hawaii, and Japan. Hardest hit was the region around Camaná in southern Perú, where the tsunami killed 25 people

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(with an additional 62 missing) and destroyed more than 3000 structures (Dengler et al. in press). The tsunami inundated more than 1 km inland in some locations in Perú and, based on runup measurements by the 1st International Tsunami Survey Team (1st ITST) (Okal et al. 2002; Borrero 2002; Dengler et al. in press), had the potential to leave sedimentary deposits along many miles of coast. A team of 16 scientists from Perú and the United States conducted a field investigation in Perú from September 6-15, 2001 to look for tsunami deposits. The team included scientists from the US Geological Survey, la Dirección de Hidrografía y Navegación de la Marina de Guerra del Perú (DHN-PERÚ), Instituto Geofísico del Perú (IGP), Instituto Geologico, Minero y Metalurgico (INGEMMET), University of California, Santa Cruz, University of Southern California, and University of San Agustin, Perú. This team is referred to here as the 2nd International Tsunami Survey Team (2nd ITST).

A goal of the 2nd ITST was to answer two fundamental questions; (1) Did the 2001 Perú tsunami leave deposits?, and (2) If the tsunami left deposits, what can be learned about the tsunami from its deposits? This paper presents field observations and discusses tsunami sedimentation for the 2001 Perú Tsunami. This research builds on previous studies of deposits from recent tsunamis (Gelfenbaum et al. in press; Bourgeois et al. 1999; Nishimura and Miyaji 1995; Sato et al. 1995; Shi et al. 1995; Dawson 1994) and paleotsunamis (Atwater 1987; Bourgeois and Minoura 1997; Goff et al. 2001). We focus on a subset of the data we collected to answer these questions for three different coastal settings in the Camaná region.

METHODS

The 2nd ITST investigated tsunami sedimentation along shore-normal transects at 6 locations along a 45-km stretch of coast centered on Camaná, the hardest hit area (Fig. 1). Transect locations were chosen during a 2-day long field reconnaissance guided by inundation and runup data collected in July, 2001 by the 1st ITST (Okal et al. 2002; Borrero 2002; Dengler et al. in press).

At each transect, deposits were trenched, measured, described, photographed, and sampled. Short (< 1-m long) trenches were dug at approximately 25 m intervals and were augmented by additional trenches where it was necessary to trace layers. Along some transects, it was necessary to dig trenches more than 100 meters long. Different techniques were used for trenching wet and dry sediment. For trenches with wet sediment, a vertical exposure was created using a shovel and trowel. Transects with dry sediment were carefully wetted by percolating water through a cloth placed on the surface prior to trenching. This minimized disturbance of deposits. Trench descriptions included sediment grain size and color, layering, presence or absence of sedimentary structures, and nature of contacts. Layer thickness was also measured. A total of 123 sediment samples were taken for laboratory analysis.

In addition to collecting data on sedimentology, we measured the topographic profile, indicators of tsunami flow direction, inundation, and runup at each transect. Topographic profiles were measured using a scope with level, staff, and measuring tape. Elevations were referenced to the mean swash elevation at the time of the survey. These elevations have not yet been corrected for tides. Tidal range in the region is approximately one meter. Inundation, the landward limit of the tsunami, and runup, the elevation at inundation, were measured at the most landward tsunami debris. This debris appeared not to be disturbed during the two months between the tsunami and our field measurements. Whenever possible, eyewitness accounts of the tsunami were recorded to augment field data.

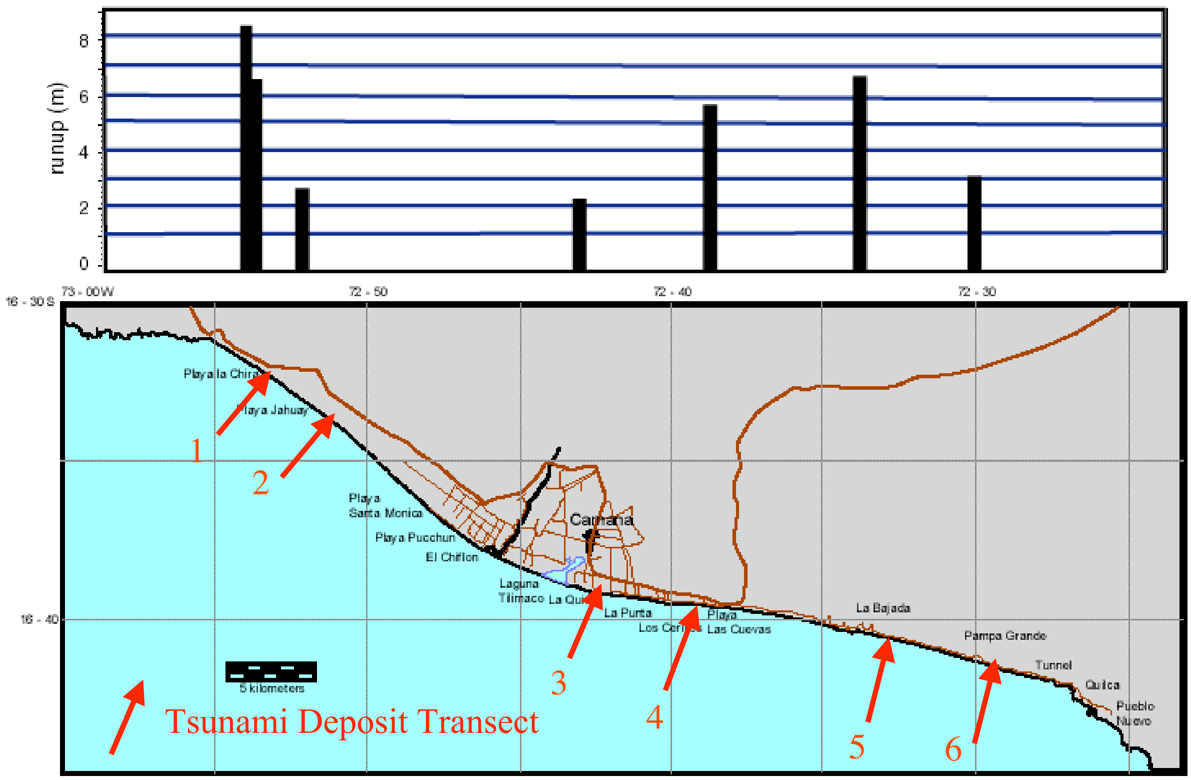

Figure 1. Location of tsunami deposit transects along the southern Peruvian coast near Camaná, approximately 700 km (435 miles) southeast of Lima, Peru. Transects were made at six sites: (1) Playa la Chira, (2) Playa Jahuay, (3) La Quinta, (4) Amecosupe, (5) La Bajada, and (6) Pampa Grande. Runup measurements, plotted on the graph above the map, were made by the 2nd ITST. Basemap courtesy of Jose Borrero, University of Southern California.

RESULTS

Tsunami deposits were found at all six transects (Jaffe et al. 2002). In this paper we focus on deposits from three transects in different coastal settings; a muddy setting at La Quinta, a fluvial setting at Playa Jahuay, and a sandy open-coast setting at Amecosupe (Fig. 1). We describe features of deposits and the tsunami for each setting.

La Quinta (Transect 3)

La Quinta is a muddy setting in an agricultural area located south of the town of Camaná. Inundation was 760 m at La Quinta. Runup was 3.2 m. Much of the area had been plowed after the tsunami before the 2nd ITST arrived. However, a small field (about 50 m by 60 m) 110 m from the coast was undisturbed. We examined this field to determine if the tsunami had left a deposit. Cobbles from the beach and mud clasts ripped up from the agricultural fields were deposited on the surface (Fig. 2). The cobbles were transported 100 m from a 2.9-m high cobble berm at the beach. Crab shells were also found on the surface indicating flow from the ocean.

Figure 2. Beach cobbles and mud rip-ups on surface of agricultural field at La Quinta. The field is between 110 and 160 m inland from the ocean.

Trenching revealed deposits overlying agricultural soil (Fig. 3). Deposits included: (1) multiple sand layers, (2) an erosional base, (3) rip-up clasts near the base of sand layers, (4) a mud layer between sand layers, (5) mud cap, and (6) normal grading. Not all trenches showed the full suite of these features. These deposits were similar to tsunami deposits found in Papua New Guinea (Gelfenbaum and Jaffe in press; Gelfenbaum et al. 2002).

The total thickness and number of layers in tsunami deposits varied greatly over a distance of less than 40 m in the shore-normal direction. Total thickness of deposits ranged from 5.5 to 14.0 cm. Typical thickness was 6 to 8 cm. Most deposits had two sand layers, although some had more layers. All deposits had a mud cap that was from 0.5 to 1.0 cm thick. Mud was also found at the top of most sand layers in the deposit.

Flow indicators, which include aligned debris and imbricated cobbles, recorded oblique onshore flow. We also observed vegetation bent in the direction of flow and preserved at the base of a deposit, documenting oblique onshore flow towards the northeast during the tsunami. We did not find evidence of a return flow at La Quinta.

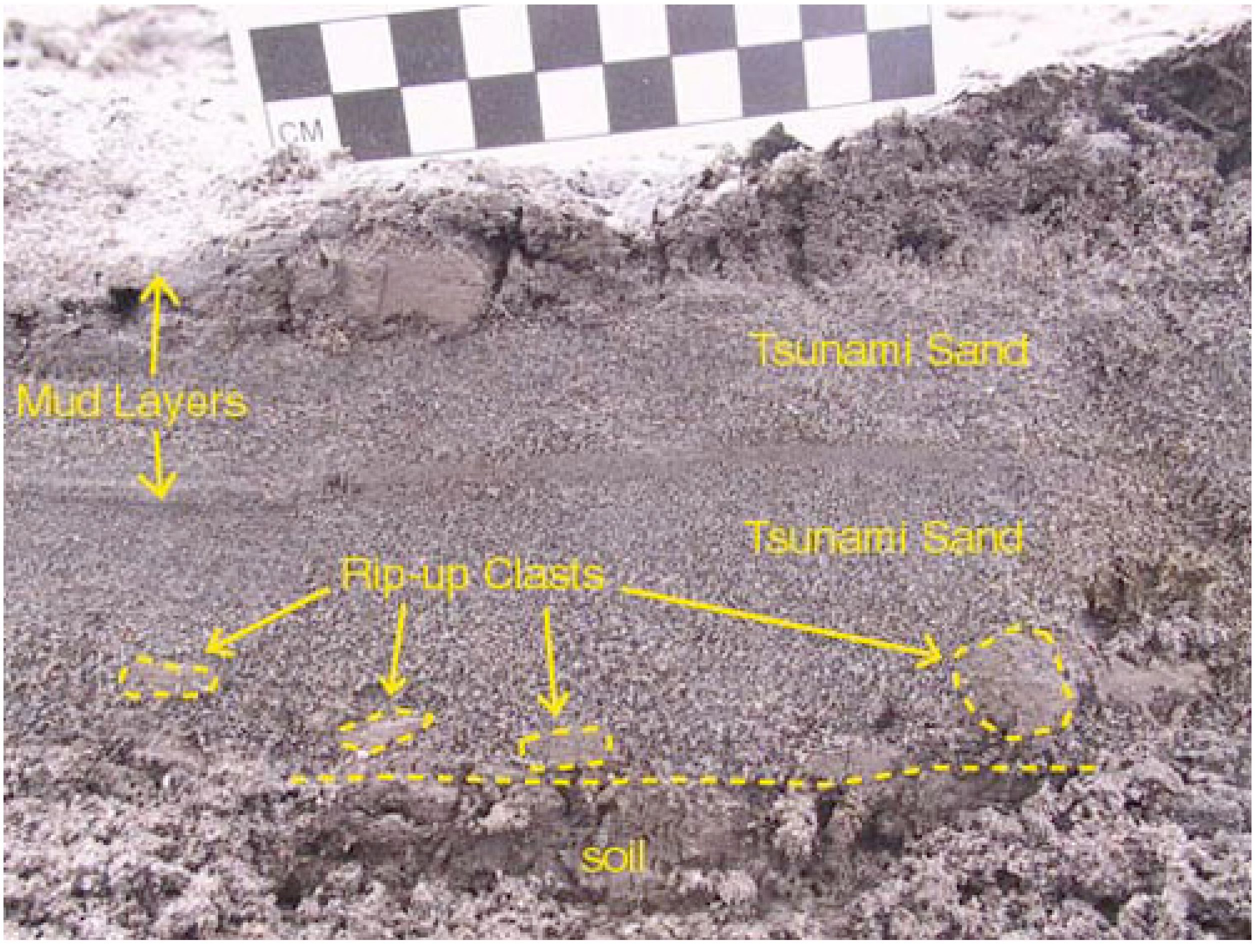

Figure 3. Tsunami deposit at La Quinta overlying agricultural soil. A thin layer of mud divides the deposit into two distinct layers. A mud cap also covers the surface of the deposit. Note mud rip-up clasts above soil in bottom layer and mud rip-up beneath mud cap in top layer. Normal grading is clearly visible in the lower layer. This deposit was approximately 130 m inland from the ocean.

Playa Jahuay (Transect 2)

Playa Jahuay, approximately 20km northwest of Camaná, includes a fluvial setting (ephemeral stream). Inundation was 360 m at Playa Jahuay. Runup was 2.4 m. At the time of the survey, the stream was dry.

Tsunami deposits found near the stream did not contain mud layers or mud rip-ups (Fig. 4) because there was little mud available for deposition. They did, however, like the La Quinta tsunami deposits, have multiple sand layers and an erosional base. In addition, tsunami deposits at Playa Jahuay often had heavy mineral lags at the base of each sand layer. Sand layers were typically normally graded, but inverse grading was also observed. Identification of tsunami deposits was aided by contrast between them and the underlying stream deposit. Sand in the tsunami deposit was coarser and a different color than the stream deposit (Fig. 4).

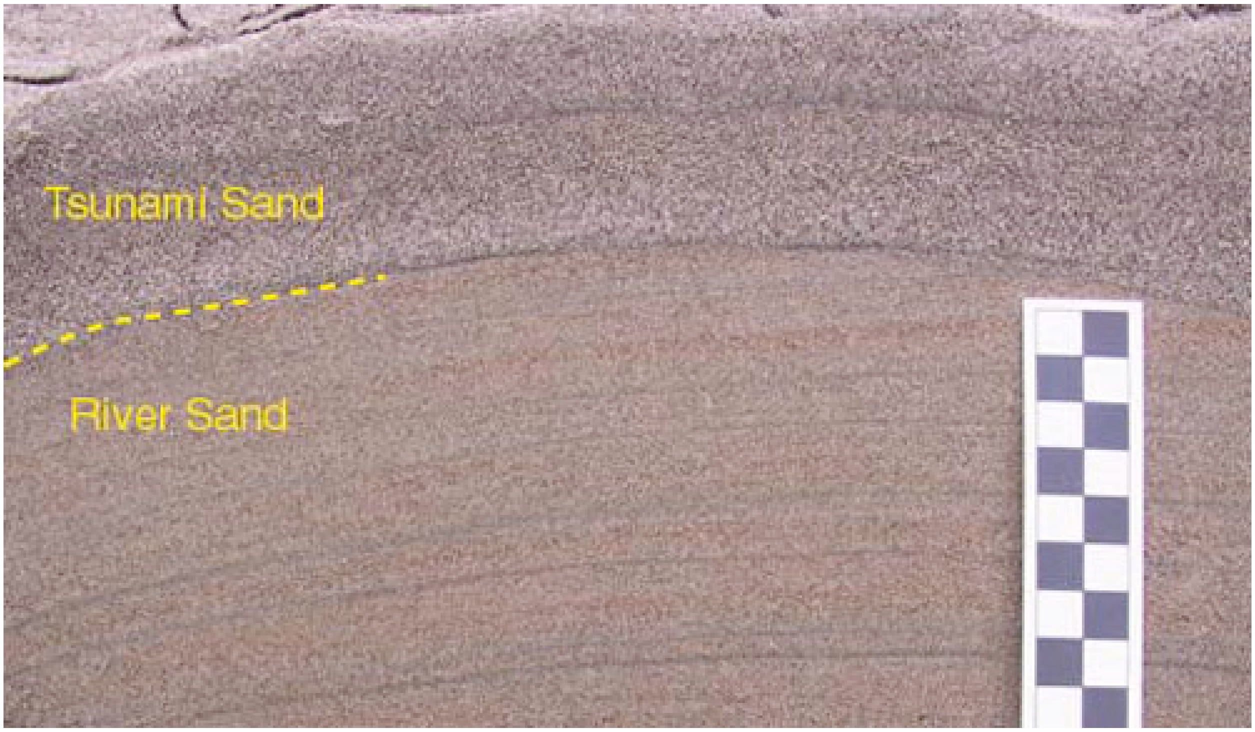

Figure 4. Tsunami deposit (grayish sand) overlying river sands (reddish sand) at Playa Jahuay. Tsunami deposit has 2 layers while river sand has multiple layers. Layering in both tsunami and river deposits may be defined by a heavy mineral lag. This deposit was approximately 230 m inland from the ocean.

Bent vegetation at Playa Jahuay documented a complex pattern of tsunami flow. The tsunami traveled both up the stream channel and over higher areas adjacent to the channel. Flow converged where the channel turned to run obliquely to the coast. Less evidence of the return flow was preserved. Return flow was recorded by grass bent towards the ocean approximately 200 m inland. It is likely that much of the return flow traveled in the topographic low of the stream channel, as occurred in the 1994 East Java tsunami (Jaffe et al. 1996).

Amecosupe (Transect 4)

Amecosupe is a sandy open-coast setting located approximately 7 km southeast of the town of Camaná. Inundation was 490 m at Amecosupe. The tsunami stopped where the slope of the coastal plain increased at the Pan American Highway (Figure 5). Runup was 5.7 m at Amecosupe.

Positive identification of tsunami deposits at Amecosupe was more difficult than at La Quinta or Playa Jahuay because there was not a strong contrast between underlying beach sand and tsunami sand. Rip-up clasts were rare because there were not significant sources for rip-ups. Deposits were identified as having formed from a tsunami by; (1) multiple sand layers, (2) erosional base, (3) heavy mineral lags at bases of layers, and (4) mud cap. Some tsunami deposits had mud layers separating sand layers. Tsunami deposits were also identified by their lack of trample structures and abundant trample structures in the underlying sediment. Trample structures form when humans or animals walk on beach or sandy coastal plain deforming existing layering or other sedimentary structures in

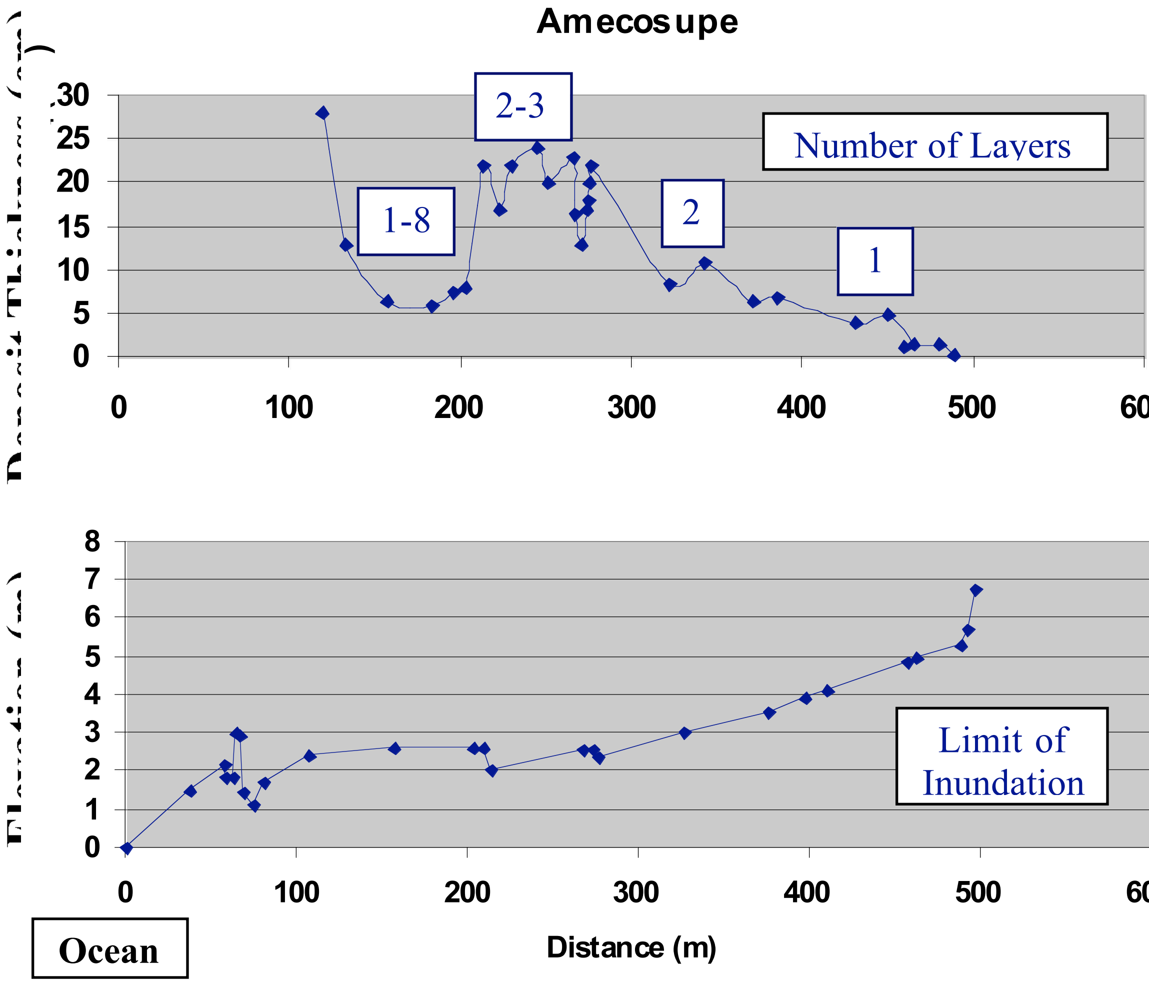

Figure 5. Tsunami deposit thickness, number of sand layers (in boxes in upper figure) and profile at Amecosupe.

an area slightly larger than the footprint. Identification of tsunami deposits also was aided by tracing sand layers towards the ocean from near the limit of inundation. Tsunami deposits were easier to identify near the limit of inundation because they were capped by mud or a fine clay powder and deposited on sand of a different color than sands more seaward.

Deposits from 120 to 200 m from the ocean had similar features to those landward, but also had a thin (<1.5 cm thick) cap of rippled sand (Fig. 6). These ripples were formed by water and could have been created by a unidirectional flow with superimposed waves. Other flow indicators (bedform orientation, aligned debris) documented shore-parallel flow towards the west in this segment of the transect. This was caused by return flow of the tsunami that was trapped and deflected alongshore by the topographic high at roadbed located approximately 60 m inland (Fig. 5).

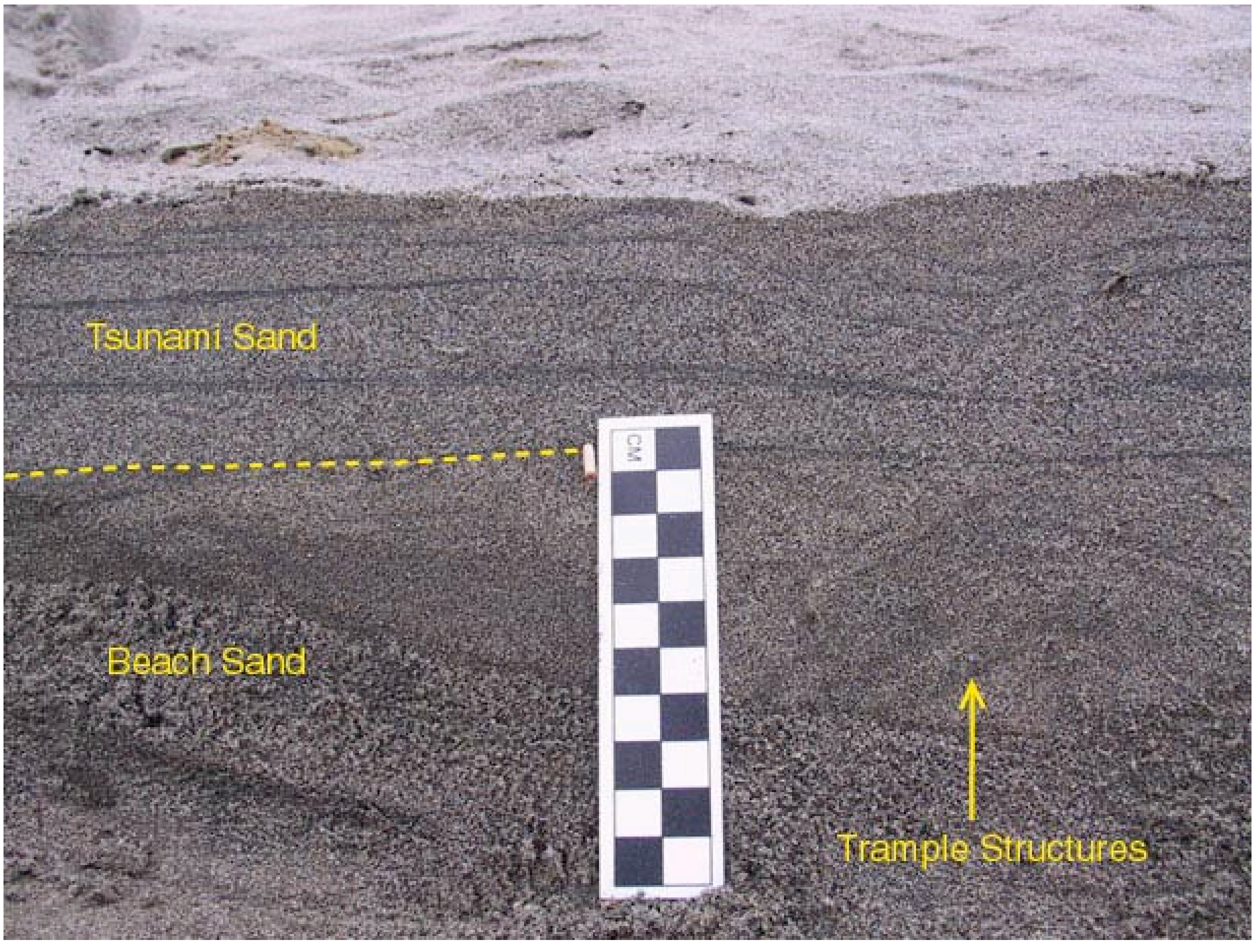

Figure 6. Tsunami deposit at Amecosupe overlying beach sand. Beach sand is identified by trample structures. Tsunami deposit has 3 distinct layers. The base of each layer has a heavy mineral lag. The upper 1.5 cm of the deposit is rippled sand. The contact between the tsunami deposit and beach sand is erosional. Note that the tsunami deposit is deformed by trample structures at the right of the photo. The deposit was 180 m inland from the ocean.

The total thickness and number of layers in tsunami deposits did not monotonically decrease landward as a simple model for tsunami sedimentation would predict (Fig. 5). No deposits were found seaward of 107 m. A zone of about 100 m adjacent to the ocean with no tsunami deposits was also observed after 1998 Papua New Guinea tsunami (Gelfenbaum and Jaffe, in press). At Amecosupe, deposits were thickest, 28 cm, at the most seaward location they were found and thinned to 6 cm at about 180 m inland. Deposits in this region have from one to eight sand layers. Deposits between 210 and 275 m inland averaged about 20 cm thick, although there is considerable variation in thickness in this region. Variation in thickness is, in large part, caused by two rock and gravel roadbeds at ~210 m and ~280m that create local highs and lows in the profile. There are two and three sand layers in tsunami deposits in this region. From about 320 to 490 m, deposits generally thin and the number of sand layers decreases from two to one. The tsunami deposited sediment within 3 m of the limit of inundation. Tsunami deposits on the three other sandy open-coast transects (Punta Chira, La Bajada, and Pampa Grande) were found within 15 m of the limit of inundation.

Flow indicators at Amecosupe documented both tsunami uprush and return flow. Indicators of uprush were found at roadbeds (greater deposition in the lee, which was landward) and in the landward portion of the profile (oriented debris). Return flow was indicated by scours around standing buildings west of the transect. There was also a large channel several hundred meters west of the transect where much of the return flow exited to the ocean. This channel was fed by a shore-parallel channel on the transect at approximately 100 m from the ocean (Fig. 5). Scour and bedforms indicate that return flow was strongest in topographic lows.

Discussion

Did the 2001 Perú Tsunami leave deposits?

It was possible to identify tsunami deposits in muddy, fluvial and sandy open-coast settings of southern Perú. Tsunami deposits were found at all 6 sites studied by the 2nd ITST. Deposits covered a large area. Assuming the tsunami deposited sediment between 100 and 200 m in the cross-shore (a low estimate) and 25 km in the alongshore (approximately half of the stretch of coast studied, a conservative estimate), the aerial extent of tsunami deposits of the 2001 Perú tsunami was between 2.5 and 5 km^2.

What can be learned about the 2001 Perú tsunami from its deposits?

At a very basic level, the presence of a tsunami deposit indicates that a tsunami impacted the area. The 2nd ITST was able, two months after the tsunami, to use deposits to learn about the extent of the 2001 Perú tsunami. This information was consistent with reports by the 1st ITST and with debris carried by the tsunami that was still present. Because tsunami deposits were found near (within 15 m at all locations) to the limit of inundation, they gave reasonable lower limits on inundation and runup for the 2001 Perú tsunami.

Qualitative aspects of the tsunami flow also may be interpreted from the deposits. For example, multiple layers in tsunami deposits indicate variation in sediment transport, which is the result of changing flow or sediment supply. A series of waves, uprush and return flow within one wave, or unsteadiness either in uprush or return flow of one wave could cause changes in sediment transport and result in multiple layers. We saw evidence for the formation of multiple layers from a series of waves and from uprush and return flow. Multiple layers caused by the uprush from a series of waves were found at the landward end (inland of 300 m from the ocean) of the Amecosupe transect. Flow indicators documented onshore flow in this segment of the transect. Only one wave reached 490 m inland while at least two waves reached 400 m inland. At 400 m inland, two layers, each formed by uprush, were found. Multiple layers, most likely caused by uprush from a series of waves, were also found at La Quinta and Playa Jahuay. Multiple layers from uprush and return flow within one wave (or possibly different waves) were found at 180 m inland at Amecosupe. The uppermost layer was formed by return flow, while the layer below it was formed by uprush.

Flow indicators preserved in deposits document the direction the tsunami traveled. These indicators were rare in Perú. At La Quinta, a tsunami deposit contained bent vegetation at their base indicating flow obliquely onshore. Asymmetry of deposit thickness over highs in the profile (e.g. Amecosupe) documented onshore flow.

Grain size of tsunami deposits is not a rich source of flow information for the 2001 Perú tsunami. We found grain size was largely controlled by sediment source. What was available for deposition limited the range of possible grain sizes in the deposit. We found cobbles deposited by the tsunami at La Quinta where there was a source on the beach. At Amecosupe and Playa Jahuay where there was not a source of cobbles, we did not find deposition of cobbles. Heavy mineral lags were found at Amecosupe and Playa Jahuay where there was a source of heavy minerals in the beach. Flow did control grain size near the limit of inundation as evidenced by landward fining. Interpreting trends in grain size can give information about tsunami flow strength for some zones.

Tsunami deposit thickness also may be interpreted to learn about the 2001 Perú tsunami. Qualitatively, tsunami sand layer thickness correlated with flow strength. Sand layers at Amecosupe were thinnest near the limit of inundation where flow strengths were low and flows were thin. Analysis of individual layers is necessary to avoid misinterpreting a single layer thick deposit with as having been formed by the same flow strength as a multiple layer deposit of the equal thickness. Grain size must also be accounted for in interpreting flow strength from layer thickness. Layers of the same thickness and different grain size result from different tsunami flow velocities.

A promising approach to determining flow velocities in the 2001 Perú tsunami is to model tsunami sediment transport from deposit grain size and thickness. This approach has been successful for the 1998 Papua New Guinea tsunami (Jaffe and Gelfenbaum 2002; Titov et al. 2001). We plan to generalize this approach to interpret the deposits of the 2001 Perú tsunami.

CONCLUSIONS

1. Sedimentary deposits from the June 23, 2001 Perú Tsunami were found at 6 transect locations spanning a 45-km stretch of coast in the Camaná Province.

2. Tsunami deposits were positively identified in three different coastal settings: (1) muddy, (2) fluvial, and (3) sandy open-coast. Deposits were identified based on their grain size, grain color, grading, thickness, contacts, fine-scale stratigraphy and geometry. Tsunami deposits had sand layers, which in general fined upward. Sand layers often had a heavy mineral layer at the base. Deposits typically had an erosional base. Mud rip-up clasts were found in deposits in muddy settings. Deposits were easiest to identify when they overlaid sediment of different grain size and

color. The most difficult deposit to identify, tsunami sand on beach sand, was usually identified by sedimentary structures (trample marks) in the underlying beach sand. Another technique for identifying tsunami deposits was to tracing easily recognizable tsunami sand layers near the limit of inundation towards the ocean. A mud cap, which was sometimes a clay powder, was used as an indicator of the possible presence of tsunami deposits.

3. Deposits were found up to approximately 490 m inland.

4. Multiple sand layers were observed in deposits. Mud layers sometimes separated sand layers.

5. Thickness of the deposits varied from site to site and with distance from the ocean, thinning out within 15 m of the limit of inundation. Deposit thickness ranged from 0.5 to 28 cm.

6. Features of tsunami deposits (thickness, multiple sand layers, grain size, flow indicators) were interpreted to provide qualitative information about the 2001 Perú tsunami. The location and elevation of the furthest inland tsunami deposit in sandy open-coast settings was found to give reasonable estimates of runup and inundation.

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