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Deposits, flow characteristics, and landscape change resulting from the September 2009 South Pacific tsunami in the Samoan islands

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ABSTRACT

The September 29th 2009 tsunami caused widespread coastal modification within the islands of Samoa and northern Tonga in the South Pacific. Preliminary measurements indicate maximum runup values of around 17 m (Okal et al., 2010) and shore-normal inundation distances of up to ~620 m (Jaffe et al., 2010). Geological field reconnaissance studies were conducted as part of an UNESCO-IOC International Tsunami Survey Team survey within three weeks of the event in order to document the erosion, transport, and deposition of sediment by the tsunami. Data collected included: a) general morphology and geological characteristics of the coast, b) evidence of tsunami flow (inundation, flow depth and direction, wave height and runup), c) surficial and subsurface sediment samples including deposit thickness and extent, d) topographic mapping, and e) boulder size and location measurements. Four main types of sedimentary deposits were identified: a) gravel fields consisting mostly of isolated cobbles and boulders, b) sand sheets from a few to ~25 cm thick, c) piles of organic (mostly vegetation) and man-made material forming debris ramparts, and d) surface mud deposits that settled from suspension from standing water in the tsunami aftermath. Tsunami deposits within the reef system were not widespread, however, surficial changes to the reefs were observed.

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1. Introduction

On September 29, 2009, three near-simultaneous great submarine earthquakes occurred along the northern Tonga Trench region and generated a region-wide tsunami (Fig. 1) that caused nearly 200 deaths and severe damage to coastal housing and infrastructure in American Samoa, Samoa and Tonga (Dominey-Howes and Thaman, 2009). The earthquake epicenters were approximately 190 km southwest of Samoa near the north end of a 3000-km-long segment of the north–northeast trending Pacific/Australia plate boundary (http://earthquake.usgs.gov/earthquakes/recenteqsww/Quakes/us2009mdbi.php; last accessed on 01/18/2011) (Beavan et al., 2010; Lay et al., 2010). The first earthquake, which was located at 15.51°S, 172.03°W, occurred as a normal-fault rupture within the outer rise of the subducting Pacific plate followed within minutes by interplate subduction events of a similar magnitude (Lay et al., 2010). The second earthquake was composed of two sub-events (the first at 15.75°S, 172.25°W, the second at 16.0°S, 172.25°W) — their combined Moment Magnitude was equivalent to M_w 8.0. The earthquakes triggered a tsunami with maximum local runup of about 17 m (Fig. 1) (Okal et al., 2010) and shore-normal inundation distances of up to ~620 m (Jaffe et al., 2010). The tsunami arrived 15–20 min after the shaking that was strongly felt in Samoa. The tsunami was either observed or recorded on tide gages across a significant part of the Pacific.

In coastal areas at risk from tsunami inundation, and where there are limited written historical records and/or studies of prehistoric events (such as is the case for the islands of Samoa), analysis of

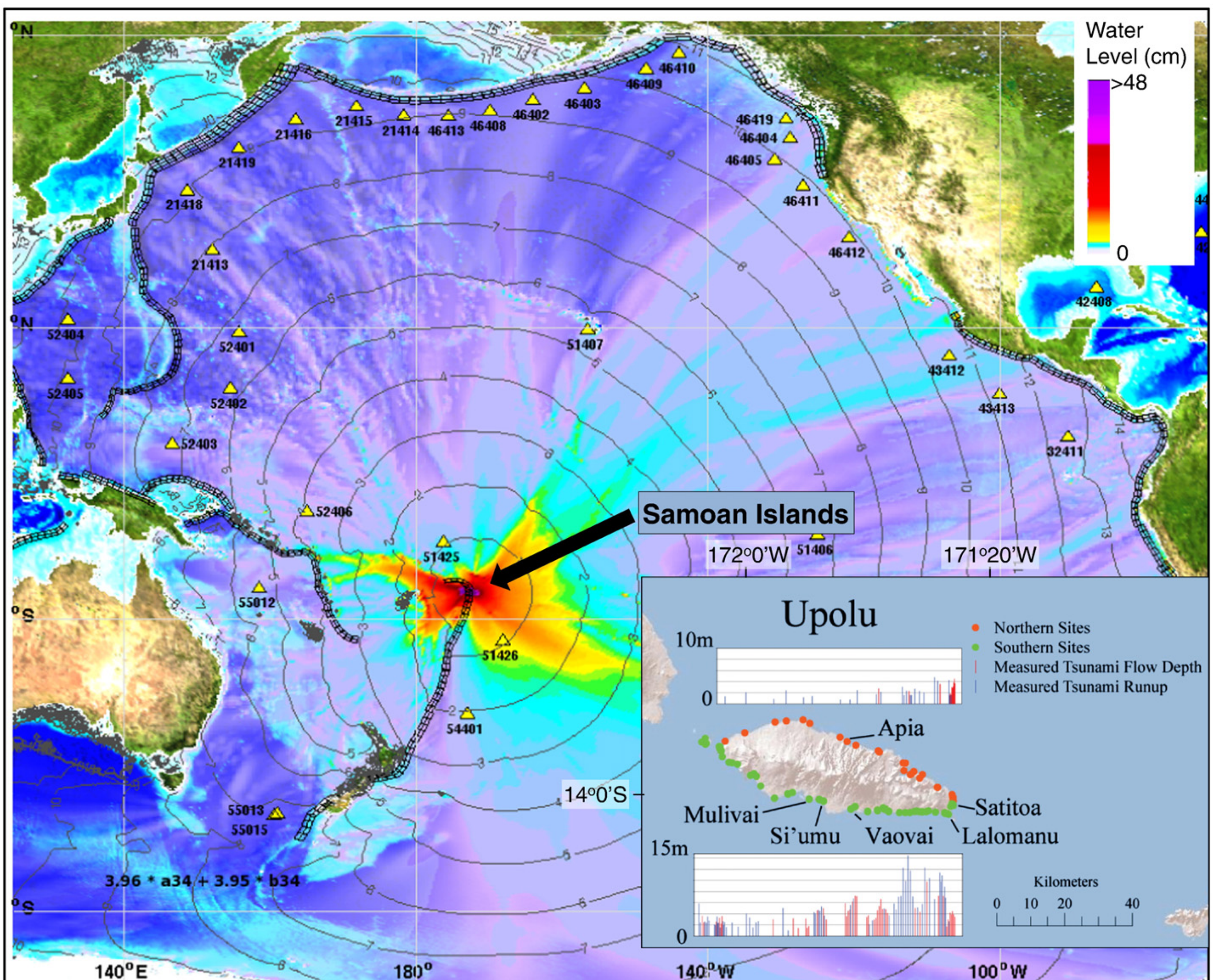

Fig. 1. Modeled (MOST) maximum deep water wave amplitude of the 29th September 2009 South Pacific Tsunami by the NOAA Pacific Marine Environmental Lab, Center for Tsunami Research. The colors relate to the deep water wave amplitude in centimeters (http://nctr.pmel.noaa.gov/samoa20090929/pagopago_20090929a_maxh.png; last accessed 02/24/11). The inset map shows measured tsunami runup values for Upolu.
Data from Okal et al. (2010); Fritz et al. (2011).

modern tsunami deposits associated with events like that of the 29th September 2009 can provide critical information on the coastal impacts including the movement of coastal sediment, relative magnitude of the event, and local vulnerability to inundation. In addition, the spatial distribution of the deposits, combined with sediment texture and composition, provides valuable criteria in the discrimination between tsunami deposits and those formed by other processes such as extreme storms or variations in sea level (Nanayama et al., 2000; Goff et al., 2004; Kortekaas and Dawson, 2007; Nanayama et al., 2007; Morton et al., 2008).

The historical record of tsunamis affecting Samoa is poorly documented, partly because the Samoans had no written language and their history was preserved through oral traditions. The NOAA National Geophysical Data Center on-line tsunami database (http://www.ngdc.noaa.gov/hazard/tsu.shtml; last accessed 01/05/11) lists 36 definite tsunamis since 1837 that have caused measured runup in the Samoan Islands. Tsunamis with a runup greater than 2 m are listed in Table 1. The largest documented event prior to the 2009 tsunami was in 1917 with a maximum reported runup of 12.2 m. This tsunami was associated with an 8.3 magnitude earthquake in the Samoa–Tonga region. The 1960 far-field tsunami associated with the 9.5 magnitude great Chile earthquake was the most recent significant event to affect Samoa prior to the 2009 event and resulted in maximum runups of 4.9 m. For a more detailed review of tsunamis prior to 2009, refer to Okal et al. (2011-this issue).

Documenting the sedimentary characteristics of recent tsunami deposits is an important tool used for the identification of paleotsunami in the geologic record (Goff et al., 2004; Peters and Jaffe, 2010; Chagué-Goff et al., 2011). The primary goal of this study is to identify and characterize the September 2009 tsunami deposits and to further the development of geologic criteria for identifying historical deposits in the geologic record. Identifying and interpreting tsunami deposits can improve our understanding of tsunami hazards both in Samoa and globally. Recent studies of the sedimentary record left by tsunamis have contributed substantially to our knowledge of tsunamigenic processes including: refinement and evaluation of models for coseismic subsidence using peat–mud couplets (Shennan et al., 1996), multiple tsunami sources (Williams et al., 2005), and anomalous sand sheets (Atwater, 1987) in the U.S. Pacific northwest; distinguishing between extreme storm and tsunami deposits in Japan (Nanayama et al., 2000; Goto et al., 2010), the US Atlantic coast (Tuttle et al., 2004), Caribbean (Morton et al., 2008), Portugal (Kortekaas and Dawson, 2007), Australia (Switzer and Jones, 2008), and New Zealand (Goff et al., 2004); extending the record of Holocene tsunamis for thousands of years in Kamchatka, Russia (Pinegina et al., 2003), Chile (Cisternas et al., 2005), Japan (Fujiwara et al., 2000; Nanayama et al., 2007), Washington (Atwater and Hemphill-Haley, 1997), and New Zealand (Goff et al., 2010a; 2010b); and calculating tsunami flow speed from the deposit thickness and grain size (Jaffe and Gelfenbaum, 2007).

Worked summarized in this paper was done as part of an interdisciplinary United Nations Education, Scientific and Cultural Organization (UNESCO) Intergovernmental Oceanographic Commission (IOC) International Tsunami Survey Team (ITST) survey, officially referred to as the UNESCO-IOC ITST Samoa (see Goff and Dominey-Howes, Editorial, this issue). We report initial findings regarding deposits from the 2009 South Pacific Tsunami, measurements of flow characteristics from physical evidence left behind by the tsunami, and changes to the coastal landscape.

1.1. Physical setting

The Samoan archipelago consists of three main and several smaller islands (Fig. 2) that are the subaerial expression of an ~1000 km long volcanic chain produced by the Pacific Tectonic Plate overriding a stationary mantle plume hotspot (Koppers et al., 2008). Westward Pacific plate motion at about 7.1 cm yr^{-1} results in volcanic edifices becoming younger towards the east with the current hotspot located beneath the Vailulu`u Seamount to the east of Tutuila. Young volcanic rocks (0.39 Ma and younger) exposed at the surface on Savai`i are the result of post-erosional volcanism (Koppers et al., 2008).

The main islands of Samoa represent the summits of high volcanoes with heavily embayed and irregular coastlines. Three general coastal types are identified based on coastal landforms and adjacent reef characteristics. These are: a) steep, commonly cliffed with little or no reef development, b) fringing reef fronting a narrow coastal plain with beaches, barrier spits, and coastal wetlands associated with streams, and c) wide fringing reef transitional to a shallow barrier reef (Richmond, 1992; 1995). Fringing reefs are the most common type of reef in Samoa. For example, on Tutuila about 90% of surveyed reefs are less than 217 m wide with an average width of 116 m (Gelfenbaum et al., 2011-this issue). The major coastal sedimentary deposits occur in back-reef settings, on the coastal plains, that are typically narrow, and at stream mouths. In general, the volume of coastal deposits is relatively low and the coastal system is sediment limited (Apotsos et al., 2011-this issue), when compared to continental systems. The more spatially extensive and thicker coastal deposits in Samoa occur on the east coasts of both Tutuila and Upolu and the south coast of Upolu as a result of exposure to consistent onshore SE tradewinds, relatively high wave energy, and well-developed reef complexes that provide much of the sediment (Kear and Wood, 1959; Richmond, 1991, 1992, 1995).

A rapid response International Survey Team (ITST) began collecting tsunami water level data six days after the event (Okal et al., 2010). Following discussions with the team led by Okal and with members of the UNESCO-IOC ITST Samoa, we decided to focus the majority of our detailed studies in the Aleipata District, east Upolu (Fig. 2), where inundation was extensive and sediment supply was high resulting in considerable onshore deposition of sediment. Tracts of undeveloped land that were left relatively untouched in this area during the initial clean-up effort, allowed for observation and sampling of the unmodified deposit. Other sites where we collected data on Upolu included Lalomanu, Vaovai, Si`umu, and Mulivai (Fig. 2). In addition to the sites where we spent at least a half day collecting data, we drove most of the Upolu coastal road and made brief site visits that included photographs and observational notes at numerous sites. The locations of our primary study sites are shown in Fig. 2 and listed in Table 2.

Table 1
Historical Samoan tsunamis since 1837 with a measured runup greater than 2 m (data from NOAA National Geophysical Data Center on-line database).

Year	Location of observation	Max water height (m)	Max inundation distance (m)	Tsunami source
1868	Apia, Upolu	3.0		Earthquake (8.5)
1907	Savai`i Island	3.6	110	Volcano
1917	South Coast, Samoa	12.2		Earthquake (8.3)
1960	Apia, Upolu	4.9		Earthquake (9.5)
2009	Samoa	14.5	440	Earthquake (8.0)

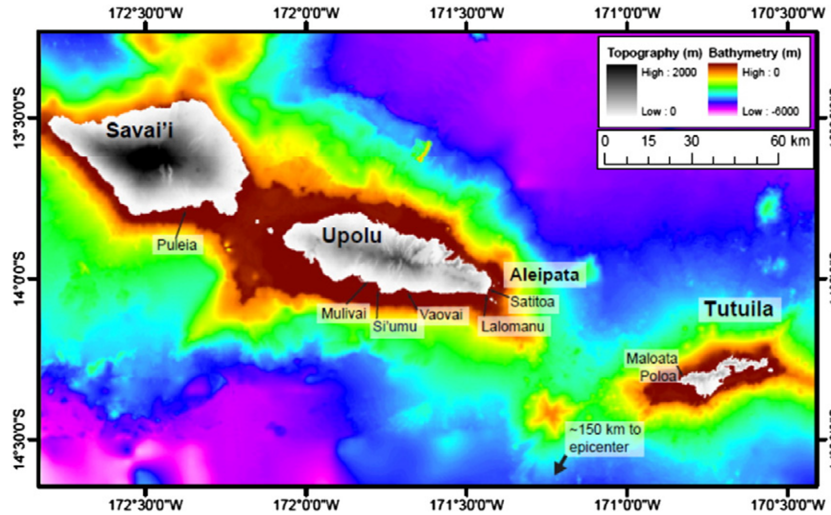

Fig. 2. Location map showing the main islands of Samoa and general topography and bathymetry. Bathymetric and topographic data are from the EarthRef.org *Seamount Catalog*, http://earthref.org/cgi-bin/sc.cgi?id=SMNT-137S-1725W (Last accessed 6/2010). The earthquake epicenter was just over 150 km to the south.

2. Survey methods and data collection

A combination of handheld GPS, laser rangefinder and real-time kinematic (RTK) GPS were used for surveying and marking sample locations. The RTK-GPS was used for obtaining micro-topographic profiles, with horizontal and vertical accuracy between points less than 0.02 m. The elevation accuracy relative to mean tidal level varied depending upon the quality of the available elevation points for calibration. Geodetic benchmarks with elevations known relative to mean tidal level were used for calibration wherever possible. This calibration was undertaken along the eastern coastline of Upolu where the surveys could be tied into a geodetic benchmark at Lalomanu. For surveys at the other sites visited where geodetic benchmarks were not available, natural tide markers such as the debris line at the high water mark and tide levels at various times of the day (compared to Apia tide tables) were used to calibrate the data to mean tidal level. For RTK-GPS measurements we estimate the uncertainty relative to mean sea level to be ± 0.2 m to account for the variability in calibration method. Handheld GPS units were used for spot location determination and had an accuracy of about +/−5 m. A laser rangefinder was used to measure elevations (flow depths) with an accuracy of about +/−0.1 m over the relatively short distances used in this type of survey. The topographic surveys extended from the nearshore (inner reef flat) landward to beyond the limit of inundation as identified by field inspection. Survey transects were collected in shore-parallel, shore-normal, and flow-parallel lines. Line-spacing density was a function of the size of the study area and time spent at the site. The offshore distance of nearshore surveys were limited to wading depths and therefore partially controlled by tide stage at the time of survey, with lower tides allowing a greater distance to be traversed.

Table 2
Summary table of sites visited. Data collected include: P — geo-located photographs, F — flow indicator measurements, S — sediment deposit measurements, T — topographic mapping. Detailed data for Satitoa and Mulivai are presented in this report.

Location	Island	Lat	Lon	~Time at site	Data collected
Maloata	Tutuila	−14.304	−170.816	1 day	P,F,S,T
Poloa	Tutuila	−14.318	−170.835	1 day	P,F,S,T
Satitoa	Upolu	−14.026	−171.428	3 days	P,F,S,T
Lalomanu	Upolu	−14.047	−171.441	<1 day	P
Vaovai	Upolu	−14.035	−171.682	1 day	P,F,S,T
Si'umu	Upolu	−14.012	−171.783	<1 day	P,F,S,T
Mulivai	Upolu	−14.010	−171.803	<1 day	P,F,S,T
Puleia	Savai'i	−13.774	−172.368	<1 day	P,F,S,T

Three physical tsunami characteristics were measured from proxy data at the sites of tsunami sediment investigation: (1) inundation distance and runup elevation, (2) flow depths, and (3) flow direction. The inundation distance is the maximum inland distance reached by the tsunami flow and was typically recognized in the field by the boundary between damaged and healthy vegetation. Debris wrack lines (cross referenced with eyewitness observations) were also used to determine inundation extent. Where possible, the runup elevation was also measured, this being the elevation at points along the maximum inundation extent. Flow depth is the height above ground level of the tsunami flow. Flow depths were estimated by reference to features such as damage to structures, gouge marks on vegetation and debris caught in tree branches. When the ground elevation at flow depth measurement points is known flow heights (flow elevation relative to mean sea level) can be calculated. Flow directions were identified from the alignment of damaged features such as the direction of bent plants, uprooted or snapped trees, or debris piles preferentially aligned in particular directions. Flow direction indicators indicate a) the strongest flow direction of the tsunami, b) the initial flow direction, or c) possibly the final flow direction (which may be return flow). The orientation of flow direction was measured by compass (either magnetic or GPS).

Sub-surface samples were collected by push coring using plastic pipe, gouge auger, Russian peat auger (D-core), or from hand-excavated trenches. Surficial samples consisted of scrapings of the upper layers of sediment from either subaerial or submarine environments. In boulder deposits, boulder size (a, b, and c axis), orientation of the long (a axis) and location were recorded.

Site surveys were either reconnaissance type lasting a few hours, or more detailed lasting at least half a day. Observations and measurements in a typical reconnaissance survey included: general morphology and physical characteristics of the coast such as orientation, exposure, landforms, and slope, the presence or absence of sedimentary deposits and erosional features, tsunami inundation and runup, flow depth and flow direction, if suitable markers were present. At detailed survey sites the above data were acquired together with more detailed topographic data and sediment sampling. Detailed surveys were carried out on Upolu at Aleipata and Vaovai and reconnaissance surveys were carried out at Lalomanu, Vaovai, Si`umu, Mulivai, and Puleia (Table 2 and Fig.2).

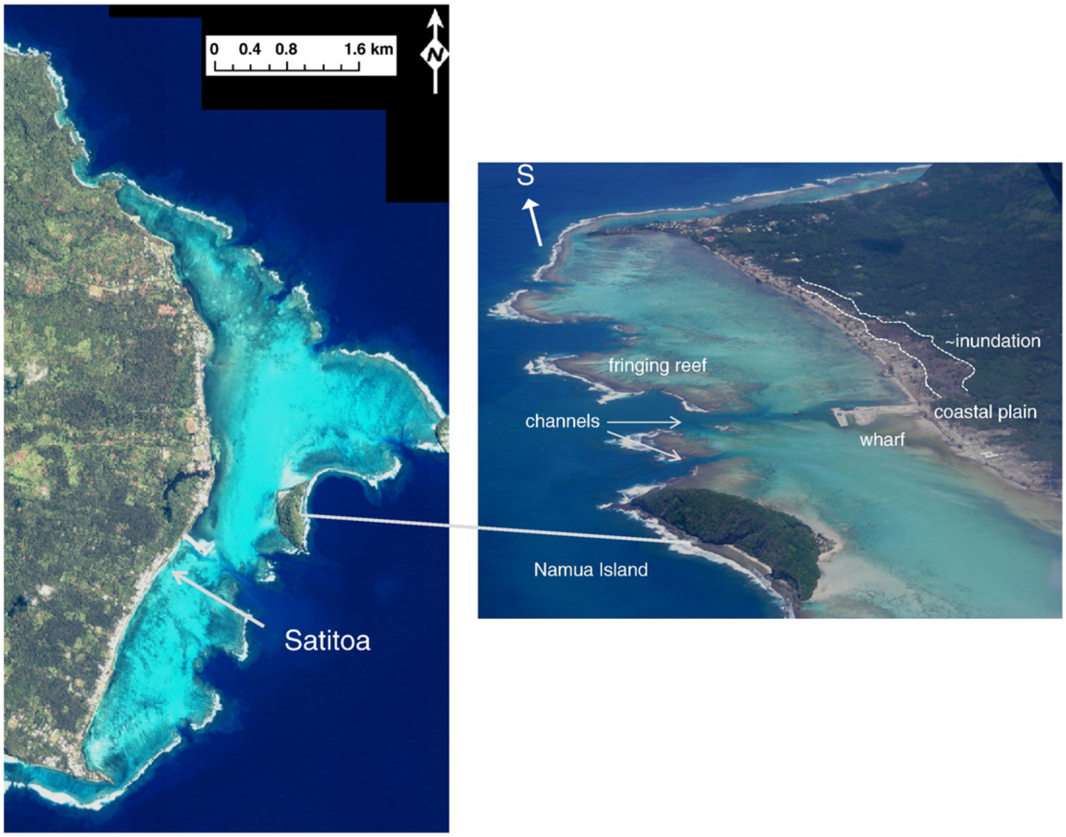

Fig. 3. Pre-tsunami Ikonos satellite image (left) and oblique aerial photograph (right) of the Aleipata District on the east coast of Upolu showing the complex reef configuration and coastal plain. Oblique photograph (view to the south) was taken a few days after the tsunami and shows the inundated coastal plain (brown zone landward of shoreline. (Photograph by Jose Borrero). The earthquake epicenter was to the south.

3. Results: detailed study sites

3.1. Aleipata study site

The Aleipata study area lies on the windward coast in an area bordered by a wide, shallow (<~5 m) fringing reef that is dissected by several deep (>~20 m) channels and two small offshore islands creating a complex coastal physiography (Fig. 3). There is a sandy coastal plain that approaches 300 m in width with the seaward margin marked by near-continuous rock revetment along the shoreline that protect the coastal road (Fig. 4). The landward margin of the coastal plain abuts against a gradually westward ascending alluvial slope commonly with low-lying wetlands along the contact with the sandy coastal plain. The coastal plain has low-relief and

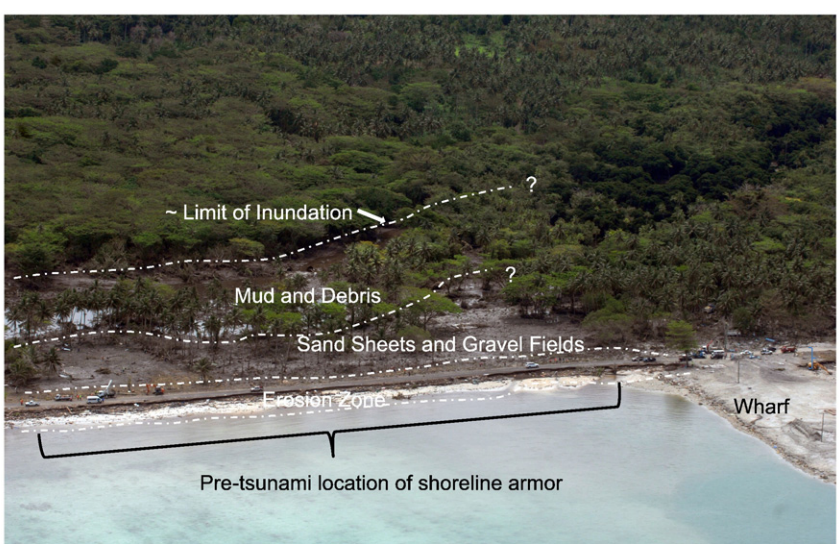

Fig. 4. Oblique aerial photograph taken between Satitoa Village and the wharf in Aleipata showing the approximate boundaries between tsunami impact zones and deposits. Photograph taken within a few days of the tsunami (photograph courtesy of the RNZAF). The coastal road was protected by a rip-rap revetment that was largely rebuilt by the time of our field work but is destroyed in this photograph.

gently undulates without well-defined beach ridges, possibly the result of gardening activities due to human occupation. Several villages and their associated gardens are located along the coastal plain.

Fig. 5 summarizes the data collected near the village of Satitoa, Aleipata and shows tsunami flow depth and direction measurements, trench locations, and topographic survey points. Topographic profiles were collected along shore-normal (2), oblique (1), and shore-parallel (2) transects and along the wharf. In addition, 28 measurements of flow depth and 23 flow directions were measured. The flow direction indicators were oriented either obliquely onshore towards the north, or roughly shore-parallel towards the northeast. Tsunami flow depth measurements decrease landward from a maximum of 5.45 m at the shoreline. Erosion, as evidenced by exposed roots, excavated soil, and minor scarps, was prominent at the shoreline, along the shore-parallel coast road, and approximately the first 25 m of the coastal plain. Deposits from the tsunami included sand sheets, gravel fields consisting of scattered and isolated boulders, mud caps, and accumulations of organic and man-made debris.

3.2. Vaovai study site

Vaovai (Fig. 2) is located on the coast in south–central Upolu in a sparsely populated low-lying coastal plain. The adjacent reef flat varies in width from about 950 m at its widest to about 300 m opposite a large channel near the main study site. Offshore there is a detached reef platform capped by a small carbonate sand and gravel island. The coastal plain is backed by a meandering fluvial channel and associated wetlands. At Vaovai (Fig. 6) one topographic profile was obtained from the intertidal zone up to the limit of inundation. Along the profile a sand sheet was sampled at trenches WS09_T20–T22 where the sand thickness ranged from a thin veneer (<1 cm) to a thick wedge about 25 cm thick. Seven flow depths and three flow directions were also obtained. A detailed topographic map from closely-spaced RTK-GPS transects was made at the Vaovai area in order to define the zone of intense shoreface erosion as evidenced by a fresh scarp and loss of coastal land.

4. Results: tsunami deposit characteristics

Where available for transport, mud, sand, and gravel size material, as well as vegetation and man-made debris, were moved by the tsunami and formed distinct sedimentary deposits. Four main sedimentary deposits were identified.

4.1. Gravel fields

The gravel-size fraction ranges from granule (2–4 mm), pebble (4–64 mm), cobble (64–256 mm) to boulder (256–4096 mm) size classes (Blair and Mcpherson, 1999). The gravel deposits we observed were

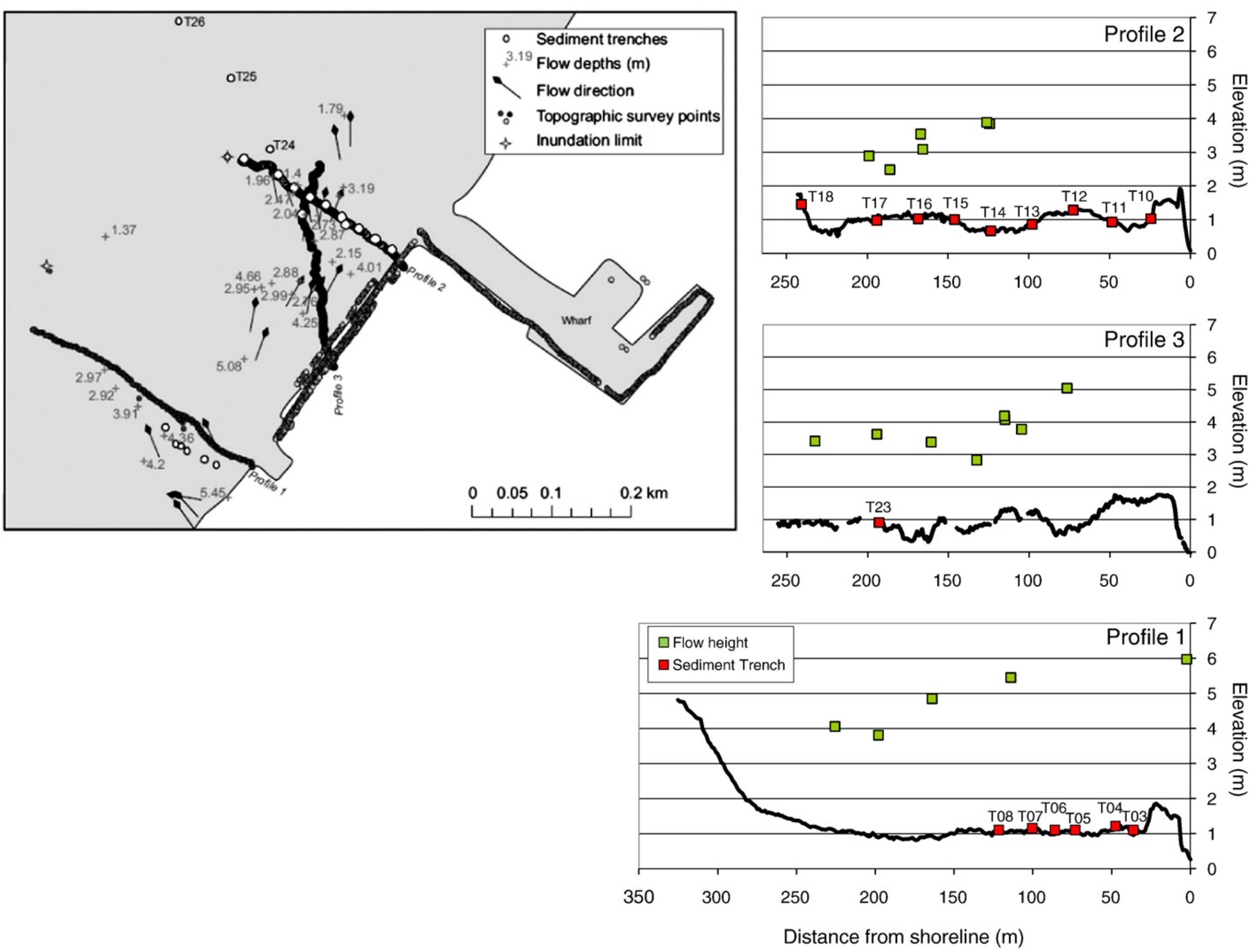

Fig. 5. Map (left) from the Aleipata District near Satitoa Village showing topographic survey points, sediment trench locations, and flow depth and direction measurements. Topographic profiles (right) show trench locations and flow height measurements.

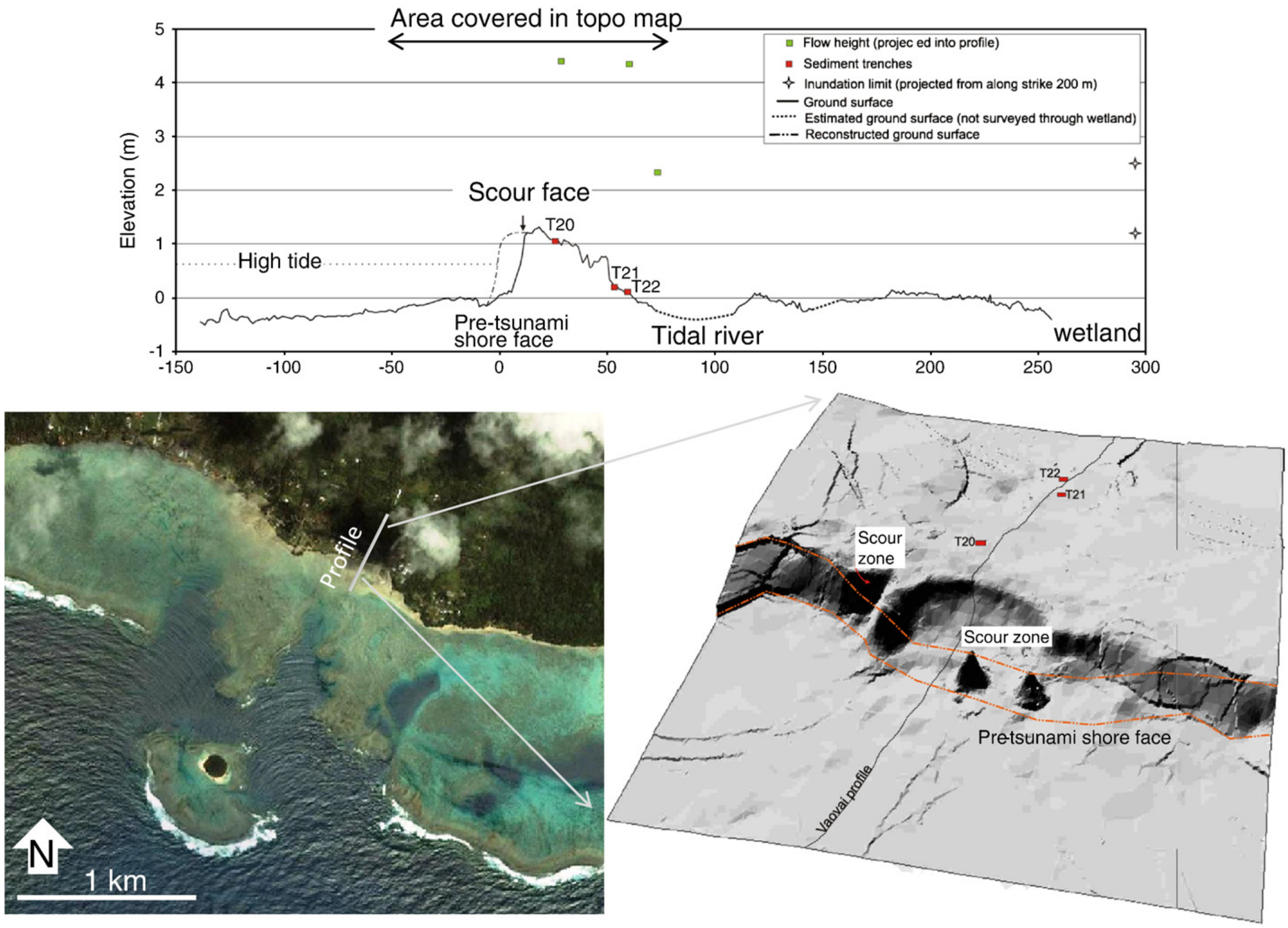

Fig. 6. Topographic profile (top), Google Earth image of the area (bottom left), and shaded relief map (bottom right) from Vaovai, south–central Upolu. The profile shows flow height measurements, trench locations, ground surface, and tide levels and distance from the shoreface (0) in meters. The map is constructed from the RTK-GPS surveys and shows the approximate pre-tsunami shoreface.

usually in the cobble to medium-boulder size classes and typically only the boulder-size material was routinely measured in the field. Gravel deposits typically occurred as either isolated coral boulders derived from the adjacent reef system and deposited on the lower beach face, or as fields of basalt boulders derived from coastal engineering structures and deposited inland on the coastal plain. In both cases the boulders were found either on the surface or partially buried by sand. Fig. 7 illustrates characteristics of a number of typical boulder deposits from the islands of Samoa including: a) coral heads and microatolls (*Porites* sp?) that have been transported from the reef flat onto the lower beach face. Living microatolls at this site presently extend from just beyond the toe of the beach to about 70 m from the shore. Many of the coral clasts have been overturned and/or broken during transport. Although runup was near 12 m at the Poloa site (west coast Tutuila), there were very few coral clasts observed to be deposited beyond the beach; b) isolated large boulders moved landward on the coastal plain from shoreline protection structures at the shoreline. In this case an ~1 m boulder has moved approximately 60 m and is associated with a patchy veneer of dark basalt-rich sand; c) dispersed gravel field of mostly boulders transported from locally constructed seawall and groin structures along the adjacent beach. The gravel is deposited on an eroded soil surface that was a flourishing garden at the time of the tsunami. There was very little sand deposited with the gravel because the adjacent beach is composed mostly of pebble to cobble sized material; and d) mixed gravel deposits near the shoreline consisting of rounded perched beach basalt clasts, angular basalt clasts, and coral debris. The angular basalt clasts are most likely derived from the underlying basalt platform and could be the result of hydraulic excavation during the tsunami. At the Puleia site (Fig. 7d), fresh coral pieces were not observed and most coral fragments were rounded, suggesting they were deposited prior to the tsunami and most likely from storms. Although it was clear the tsunami had sufficient capacity to transport boulders, we observed a number of small gravel beaches on Upolu and Savai`i where there appeared to be little landward transport of the coarse material from the beach face as a result of the tsunami. It is not clear if this is because the gravel beaches already form a wave-resistant structure that naturally dissipates wave energy, or, if local physiography or orientation limited tsunami impact.

A well-developed boulder field (Fig. 8) deposited by the tsunami was investigated near the village of Satitoa (Fig. 2). Boulder a, b, and c-axis dimensions, orientation, and a GPS waypoint were recorded for each measured boulder. Field measurements of flow directions in this area ranged from directly onshore to obliquely onshore towards the north (340° to 010°). A damaged seawall along the coastal road (Fig. 4) appears to be the source for most of the basalt clasts of the boulder field. A few small rounded boulders were encountered, but they appear to have been derived locally from pre-existing housing structures or landscaping features. Overall, 160 boulders were measured in this location. Most of the boulder deposition occurred between 25 and 175 m from the shoreline, the first 25 m being primarily an area of strong erosion. There is no strong trend in the

Fig. 7. a) Photograph of a large (a-axis 1.6 m), overturned and partially buried, coral microatoll (*Porites* sp?) in the foreground and several other coral clasts scattered along the foreshore. The coral boulders are covered with recently deceased encrusting marine fauna (with associated strong odor) indicating recent deposition which is consistent with eyewitness accounts that the coral heads on the beach were not present prior to the tsunami. View towards the west from Paloa on the west coast of Tutuila. b) Photograph showing a large basalt boulder from a shoreline engineering structure and displaced about 60 m inland. The tape measure is extended to 95 cm in length. Photograph taken at Si'umu in south–central Upolu where the tsunami flow depth reached 4.35 m. c) Photograph from Maloata on the northwest coast of Tutuila showing a gravel field deposited on an eroded soil surface. The source of most of the boulders was a low retaining wall and groin near the shoreline about 100 m away. d) Photograph of a mixed gravel deposit from a small coastal embayment east of the village of Puleia, south Savai`i. The gravel contains rounded basalt clasts from a perched beach on the basalt platform, angular basalt clasts of possible tsunami origin and derived from the underlying platform, and coral fragments from the adjacent reef system.

boulder size distribution, however most of the boulders are aligned with their a-axis perpendicular to the dominant flow direction. The Satitoa boulder deposits are further discussed by Etienne et al., 2011-this issue.

4.2. Sand sheets

In locations bordered by well-developed beaches and/or reef sand bodies, we often observed sand-rich tsunami deposits that ranged from very thin veneers (<1 cm) to broad sand sheets up to 10's of centimeters thick and 100 m inland. Well-developed sand sheets were typically thicker in topographic lows and thinner on topographic highs (Figs. 9 and 10). Physical structures, such as walls or stairs, often had thick (10–20 cm) shadow sand deposits in the lee of the structure. However, in general, the sand sheets in Samoa were thin and patchy because of the relative lack of an extensive sand supply.

Sand sheet characteristics are illustrated in Fig. 9. These include: a) thin (<5 cm) sand sheets of limited extent composed of sediment from the adjacent beach and reef flat as evidenced by the appearance of well-sorted, rounded, medium sand, similar to the sand on adjacent beaches, and fresh coral and *Halimeda* fragments that could only come from the adjacent reef. We observed both heavily eroded beaches with prominent scarps and those that appeared natural with very little evidence of recent erosion, such as the beach adjacent to the deposit in Fig. 9a, which appeared undisturbed with no strong erosional indicators); b and c) the tsunami sand basal contact is often sharp, especially where the contact is erosional and the sand overlies a material of contrasting composition and/or color. Internal layering can be complex with multiple laminations and variations in sediment size, although generally the laminations are planar. In general, the overall vertical sequence within the sand sheets appeared to be normally graded, and the upper surface was occasionally capped by a fine-grained deposit; d) man-made and natural obstacles can obstruct flow resulting in deposition of sediment in the lee of the structure.

In addition to well-developed coarse-clast deposits, the Aleipata District was the site of detailed surveys of sand sheet deposits that extended up to ~250 m from the shoreline. Fig. 10 shows a topographic profile across the coastal plain near Satitoa Village, trench locations (see Jaffe et al., 2011-this issue for detailed discussion), deposit thickness and three characteristic stratigraphic sections. Localized thick sand accumulations were common in the lee of structures, such as low walls, and in topographic depressions. The tsunami sand deposit consisted of a poorly-sorted light yellow medium sand fining upwards to a moderately-sorted medium-fine sand, overlain by a moderately well-sorted gray fine sand. The contact between the yellow and gray sands was sharp, but did not appear erosional. The yellow and gray sand sequence thinned and fined landward to a poorly sorted light yellow medium to muddy sand. Most deposits were characterized by a sharp basal erosional contact with the underlying orange-brown volcanic soil. Whilst the tsunami sand was exposed at the surface near the coast, it was overlain by a thin (1–3 mm) discontinuous, gray mud cap further inland. The mud cap became thicker and finer inland, reaching a maximum of 6–8 cm in shallow, topographic lows. A thick layer of organic debris (up to 12 cm in topographic lows) was observed overlying the thinning sand layer close to the forest edge (see Chagué-Goff et al., 2011 for further

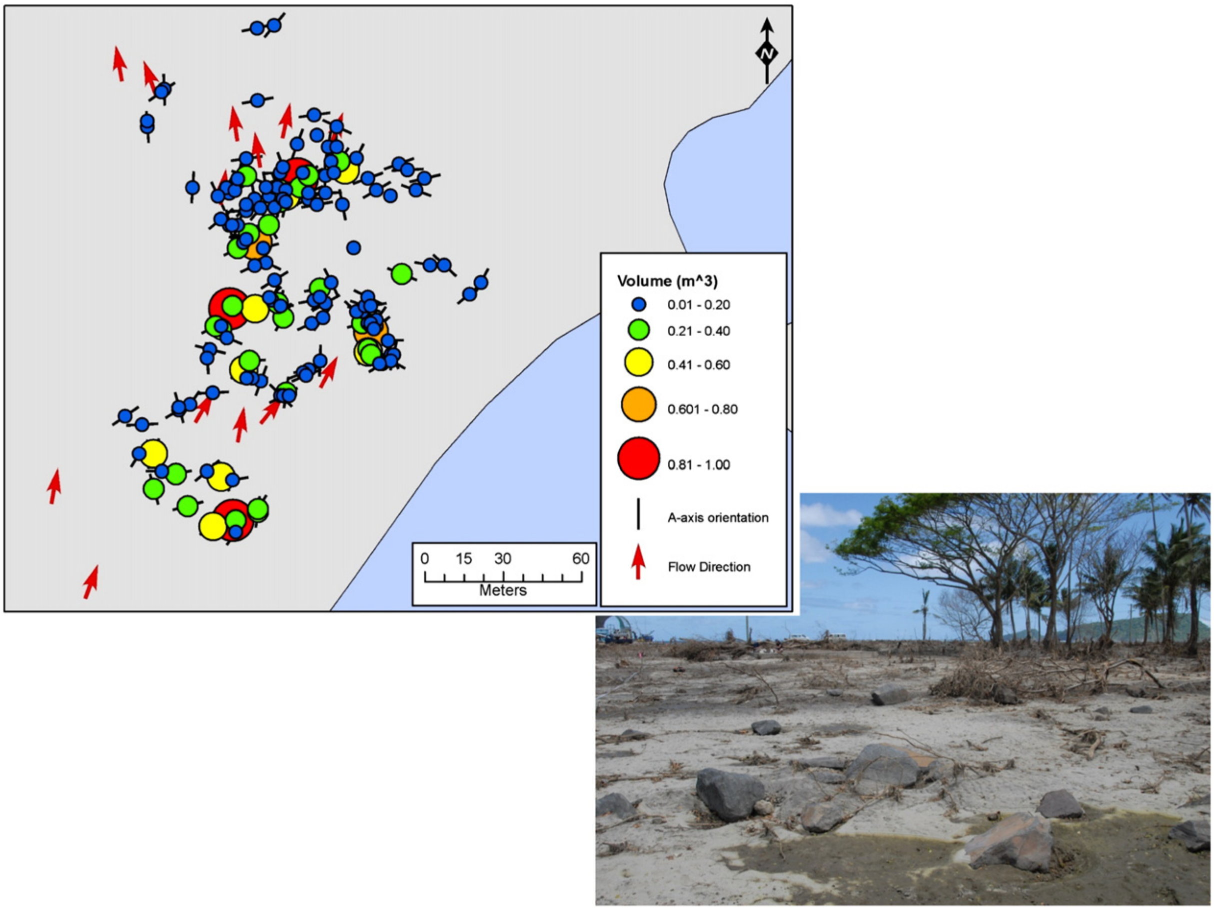

Fig. 8. Map (left) showing major flow directions (red arrows), boulder volume (circles) and a-axis orientations (black lines) of boulders within the gravel field at Satitoa. Photograph (right) shows basalt boulders from the pre-tsunami coastal seawall that have been transported landward and incorporated into the sand sheet. Dark surface in lower right is a thin mud cap overlying sand.

details). The thicker sand deposits had multiple laminations with varying degrees of particle segregation. Internal sedimentary structure of the tsunami sand deposits was often complex, showing a wide variation of grain size, composition, and number and type of laminations. Internal structure varied with distance from the shoreline and is thought to have recorded complex interactions between wave forces, microtopography, and local sediment supply. In some localities clusters of the green alga *Halimeda* were incorporated in sand deposits. The sand appeared to be derived from a combination of areas including the reef flats (fresh *Halimeda* fragments), beaches (well-sorted abraded sand), and in some cases erosion of the land surface (brownish sandy soil).

4.3. Organic and man-made debris ramparts

Debris wrack lines, formed by a variety of floating material, were common near the limit of inundation. The post-tsunami debris line is usually very conspicuous in the field and is best mapped prior to clean-up and debris removal activities. The inundation limit can usually be identified by deposits of floating debris such as vegetation, marine or man-made debris, and the limit of salt-burned vegetation. Stranding of debris often occurs when the tsunami loses its capacity to move debris in a landward direction, or when the tsunami encounters a topographic high that retards the flow.

In coastal areas that were very heavily vegetated, in addition to inundation wrack lines thick piles of vegetation debris (vegetation ramparts) occurred seaward of the inundation limit where landward transport of the thick debris no longer occurred. The vegetation ramparts represent a zone where coastal vegetation significantly retards the ability of tsunami to transport debris (Fig. 11). The vegetation ramparts commonly accumulated around existing obstructions such as tree stumps, buildings, or land surface inclines.

4.4. Surface mud deposits

Mud drapes on the upper surface of tsunami deposits were common and represent fine-sediment deposition during the final stages of tsunami inundation. The largest source of fine-grained sediment is most-likely from soil erosion of the land surface with additional input from either marine or coastal wetland environments. Surface mud deposits varied from thin mud drapes (<1 cm thick) to multi-layered, thick (4+ cm) mud caps that showed pronounced desiccation cracks two weeks after the tsunami (Fig. 11 inset). In Aleipata, thick mud drapes appear to be the result of fine-grained sediment settling out from ponded water and the drapes were thin and patchy near the coast where erosion was high and thicker inland where ponded water remained for a period of time after tsunami inundation.

4.5. Reef impacts

At several sites along the southern coast of Upolu near Si`umu and Mulivai we were able to observe impacts to the fringing reef at low tide as well as the deposition of reef-derived material in the onshore tsunami deposits. In general, living coral colonies appeared to have suffered only a small amount of damage from the tsunami, especially in areas that are subjected to frequent high waves such as south-facing coasts (Fig. 12). Corals from more protected reef environments

Fig. 9. a) Photograph at the coast near Mulivai Village in south–central Upolu showing a thin sand sheet that extends less than 10 m from the beach berm (inundation in this area was over 100 m). In addition to beach sand there are scattered coral fragments on the surface of the deposit, some of which appear rather fresh. The red and white scale is 2 m in length. b) Photograph of a shallow trench near Satitoa, east Upolu, showing a sharp basal contact between tsunami sand (light color) and underlying soil (dark material). The deposit is capped by a light gray silty fine sand. The trench face is cut at a low-angle to enhance the internal stratigraphic characteristics. c) Photograph of a wedge-shaped sand deposit that thickens landward towards a coastal tidal stream. The sand deposit was thickest (~25 cm) at about 50 m from the shoreline. View to the south. The location is near Vaovai, south–central Upolu. d) Photograph of a thin sand deposited on a concrete floor in the lee of a man-made structure (Satitoa Village, Upolu).

that were subjected to strong tsunami influence appeared to suffer greater damage (Dominey-Howes and Thaman, 2009; McAdoo et al., 2011-this issue). Accumulations of reef debris within the reef system appeared to have undergone some reorganization by the tsunami (Dominey-Howes and Thaman, 2009) but it is very difficult to quantify what underwater material was moved by the tsunami. At Si`umu and Poloa we observed the visible impact to corals caused by man-made debris that was deposited on the reef during tsunami return-flow conditions. For example, at Poloa the tsunami uprush and return flow passed through a school building and deposited furniture, building materials, and school supplies on the adjacent reef. However, overall the lack of extensive damage to the reefs of Samoa is consistent with the results from studies in the aftermath of the 2004 Indian Ocean tsunami (e.g. Stoddart, 2007) where specific studies determined less than half the reefs sustained some form of damage and only 15% had a high level of damage (Hagan et al., 2007).

Reef flat boulder accumulations that are widespread in Samoa, are often partially cemented, and for the most part do not appear to move during the tsunami (Fig. 12). The initial mechanism that deposited these clasts could either be a tsunami or more likely a large storm. For example, Cyclone Ofa in 1990 created large reef flat rubble banks on the north coast of Upolu, of which many remnants are still present (Rearic, 1990; Richmond and Morton, 2007). We investigated the reef flat deposits (Fig. 12) near Si'umu (Fig. 1), Upolu and saw little evidence of coarse clast erosion, transport, or deposition from the tsunami. Patchy accumulations of staghorn corals (*Acropora* sp?) and other detritus occurred along some shorelines and in many cases appeared to be re-deposited reef debris as evidenced by complete algal encrustation.

The most common type of visible evidence of reef-derived material being deposited on land was bleached and connected clusters of *Halimeda* (Fig. 12). *Halimeda* clusters are fragile and break down relatively quickly when exposed on land. They occur in a wide variety of reef settings.

5. Discussion

The September 29, 2009 South Pacific Tsunami provided an opportunity to examine sedimentary deposits in a variety of tropical coastal settings in the Samoan Islands. Complex and highly variable local physiography caused spatially variable tsunami characteristics (Okal et al., 2010) at the local level that combined with variable sediment supply that resulted in a non-uniform distribution of sedimentary deposits. In general, sediment availability for redistribution at the coast was limited and resulted in thin and patchy tsunami sediment deposits over much of the coast. In areas where sediment supply was abundant, well-developed deposits occurred, such as in the Aleipata District. Although the shallow lagoons and reef passages are sites of abundant reef-derived sediment accumulations, it is not clear that they supplied much sediment to the coast.

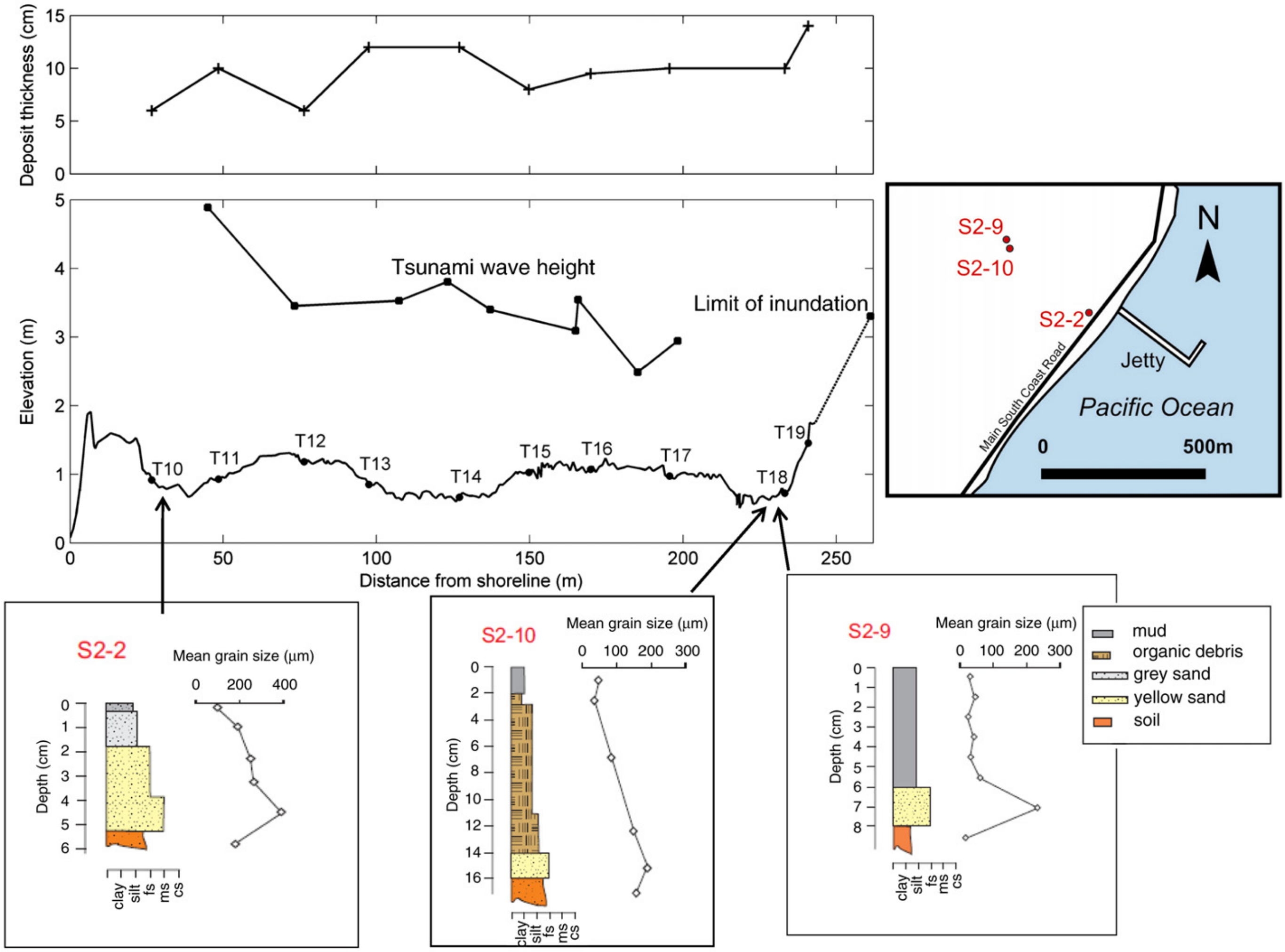

Fig. 10. Illustration showing a topographic profile and tsunami sediment thickness along a shore-normal profile near Satitoa (see Fig. 2 for location). The inserts show characteristic stratigraphic profiles for 3 locations along the profile (the stratigraphic sections were not done exactly along the profile and their locations are approximate).

5.1. Potential for preservation of paleotsunami deposits in Samoa

Trench observations during reconnaissance work for paleotsunami deposits indicate that there are numerous sand and soil couplets preserved in the sedimentary record. It seems likely that in areas subjected to minimal bioturbation, there is the opportunity for deposit preservation. The preservation of microfossils in sediments underlying the 2009 South Pacific tsunami is unknown, although it was noted that soils beneath the event had poorly preserved *foraminifera* tests and only rare diatom frustules (Chagué-Goff et al., 2011). These microfossil assemblages were only studied from the underlying soil and we are unable to determine the likely preservation of microfossils in any possible, rapidly deposited paleotsunami sediments. However, in a similar tropical setting on Futuna Is., Wallis and Futuna, Goff et al. (in press) found good microfossil preservation in paleotsunami deposits up to 2000 years old.

Visual inspection during a comprehensive sampling regime of sand and mud couplets (Fig. 13) underlying the 2009 South Pacific tsunami at Mulivai revealed distinct variations in grain size with a fining upward trend in several predominantly sand units. Chagué-Goff et al. (2011) however, suggested that there could be a distinct down-washing of fine-grained sediment over time, leading to a general coarsening of the sandy deposit (Szczuciński et al., 2007). This would reduce the preservation of chemical signatures and microfossils alike in older deposits. Szczuciński (2010, in press) reported that after 5 years, c. 50% of the deposits left in Thailand following the 2004 Indian Ocean Tsunami were still identifiable, and that the main changes included erosion, redeposition, removal of find particulates from the upper part of the mainly sandy deposits, and a decrease in

Fig. 11. Photograph along the landward margin of the coastal plain near Satitoa showing a vegetation rampart in the background and a thick (4 cm) mud cap in the foreground. The inset shows a close-up of the mud cap that exhibits a general fining upward trend and a higher amount of vegetative material in the lower section.

Fig. 12. a) Photograph from the outer reef flat of the fringing reef at Si`umu, S Upolu showing mostly undisturbed platy coral heads that appear to have survived the tsunami with little destruction. Onland runup was 3.7 m at this location (Okal et al., 2010). b) Photograph of the reef flat at Si`umu showing lightly cemented boulder clasts that did not move during the tsunami. Also note the platy coral heads in undisturbed growth position. c) Photograph from the inner reef flat at Vaovai showing dead staghorn corals that were transported from somewhere in the reef system where they had accumulated and were being encrusted by algae. Live staghorn corals that were moved by the tsunami typically appeared white because of the recent expulsion of their symbiotic zooxanthellae algae. d) Photograph of *Halimeda* clusters deposited within the erosion zone along the Aleipata coast. Note the exposed coconut palm roots that are good indicators of recent erosion.

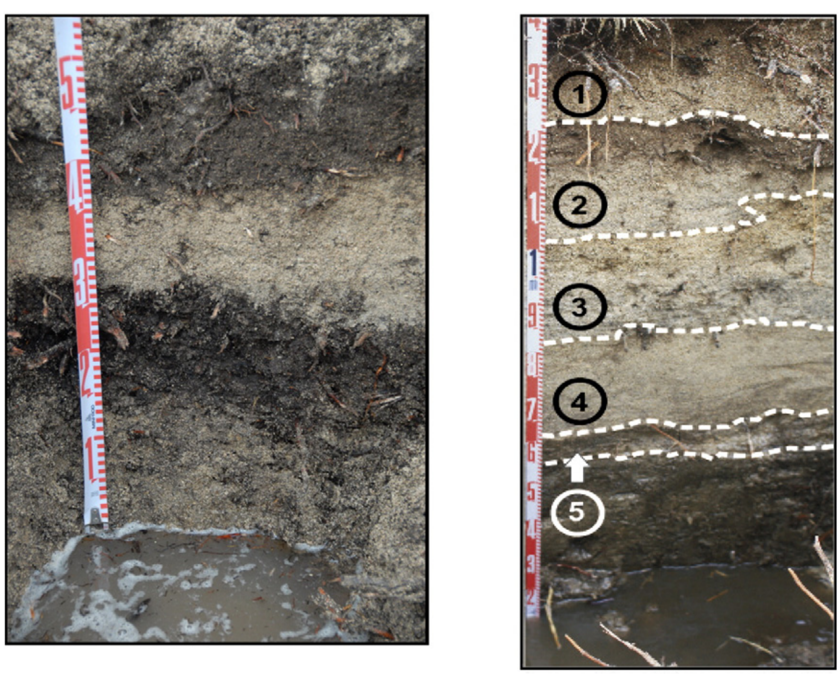

Fig. 13. Photographs from Mulivai, southern Upolu showing event stratigraphy. The right photograph shows a series of five sand and soil couplets, some with well developed soil horizons. The preservation of such deposits bodes well for paleotsunami research. Preliminary dating places the soil beneath unit 5 at about 500 years BP. The left photograph shows two well-developed soil horizons separated by a thick (~10 cm+) sand unit at Mulivai, Upolu.

salt content. It seems likely that older sediments will be preferentially preserved in areas of low bioturbation, but that a key focus of identifying them as paleotsunami deposits will be on their geographical location and the ability to compare numerous sites throughout the region in order to determine the regional extent of contemporaneously aged sediments (McFadgen and Goff, 2007).

5.2. Tsunami flow characteristics

Due to the highly irregular coastal configuration in the Samoan islands the resultant tsunami flow patterns were often very complex, as inferred from the observed tsunami flow directions and deposit characteristics. The complexity is derived primarily from the interaction between multiple tsunami waves and locally complex topography and bathymetry. For example, flow direction indicators at Satitoa show numerous directions and there were clear indications of onshore (NW) and oblique (NE) flow directions. However, because of the low-lying nature of the coastal plain and the presence of several shallow depressions that ponded water, there was very little evidence of a strong return flow. In contrast, along steep coasts such as Poloa, Tutuila, there was high runup, limited inundation and strong return flow indicators such as abundant man-made debris strewn on the adjacent reef.

In general, while moving landward across the coastal plain, tsunami waves transported organic materials (soil and coconut trees) and man-made debris (cars, boats, building walls, concrete slabs, etc.). This material aided in the incorporation of additional debris by increasing water density and opportunity for debris impact. Soils were eroded by wave turbulence and scouring under buildings caused a loss of support under the footings. Buildings and trees collapsed as the tsunami waves scoured around the foundations and roots and applied a number of forces including hydrodynamic pressures, buoyancy, uplift, and impact by debris (Ghobarah et al., 2006). The combination of forces evolved inland as the waves traversed the coastal plain: hydrodynamic pressure, uplift and buoyancy forces were greater near the coastline where flow depth and presumably flow speed were the greatest and diminished inland. As hydrodynamic forces decreased, forces exerted by carried debris increased inland as more detritus was added to the flow. This detrital charge conferred a higher power of destruction to the waves (Saatcioglu et al., 2006; Ghobarah et al., 2006). High-density debris was transported inland as bedload, whereas buoyant debris accumulated on top of the wave.

6. Conclusions

Key findings from the investigation of the tsunami deposits, flow patterns, and associated landscape changes include:

1) In areas where there was a pre-existing supply of sediment and sufficient wave forces occurred, tsunami sediment deposits were widespread, and for the most part, distinguishable from pre-tsunami sediment
   a. Areas with sufficient beach sand deposits often produced tsunami sand sheets that filled in topographic lows and thinned on topographic highs. However, not all well-developed beaches with significant flow depths and inundation distances produced extensive sand sheets, suggesting other causative factors in sand sheet generation such as local tsunami flow parameters. Physical structures, such as walls or stairs, often had thick (10–20 cm) shadow sand deposits in the lee of the structure.
   b. Mud drapes on the upper surface of tsunami deposits were common and represent fine-sediment deposition at the final stage of inundation. The largest source of fine-grained sediment is most likely from soil erosion of the land surface with additional input from either marine or coastal wetland environments.
   c. Internal sedimentary structures of the tsunami sand deposits are complex, showing a wide variation in grain size, composition, and number and type of laminations. Internal structure varied with distance from the shoreline and is thought to have recorded complex interactions between wave forces, microtopography, and sediment supply.
2) Erosion at the shoreline was widespread and resulted in the transport of sediment and debris in both landward and seaward directions. The shoreline provided sand and gravel (including revetment boulders) to the onshore sedimentary deposits. Maximum erosion of back beach areas, up to ~2 m, appeared to be driven by the offshore return flow of the tsunami in many localities as evidenced by offshore-directed flow indicators associated with major beach scarps.
3) Exploratory trenches in a number of inland sites show the existence of a number of buried sand deposits separated by paleosoils. These sand layers strongly indicate the presence of past extreme wave inundations that deserve further investigation.
4) Flow direction indicators often show numerous directions at any one locality and in some cases the relationship between the oldest (bottom) and youngest (top) gives an approximation of tsunami flow direction through time. The complexity is derived from the interaction between multiple tsunami waves and locally complex topography and bathymetry.
5) Coastal slopes exhibited a strong control on runup, inundation, and return flow characteristics. Steep coasts typically exhibit high runup, limited inundation and strong return flow indicators, whereas low-lying coasts show lower runup, greater inundation, and less pronounced return flow indicators.
6) Maximum transported clast size is often dependent upon the size of available material, and in many cases the tsunami probably had the ability to transport much larger clasts. Where coastal protection structures were constructed, mostly of basalt boulders, it was common to find boulders transported inland several tens to ~100+ m inland. Automobiles and domestic appliances appeared to be particularly susceptible to tsunami transport.
7) Wrack lines of thick vegetation debris (vegetation ramparts) are common and occur where landward transport no longer occurs. They are typically seaward of the tsunami inundation line and represent a zone where coastal vegetation significantly retards tsunami flow.

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