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GEOLOGICAL INVESTIGATION OF PALAEOTSUNAMIS IN THE SAMOAN ISLANDS: INTERIM REPORT AND RESEARCH DIRECTIONS

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ABSTRACT

The September 29, 2009 Samoa Tsunami provided the opportunity to sample the sediments deposited in the Samoan Islands landscape by the tsunami. Analysing the characteristics of the sediment deposits using an established suite of diagnostic criteria, and assessing how they differ from cyclone deposits enables the identification and dating of similar events in the geologic record. This helps to better understand the long-term frequency and likely magnitude of these events. Here we report on a pilot palaeotsunami field-sampling investigation carried out in 2010 at selected sites on Upolu and Savaii Islands in the Independent State of Samoa, and on Ta'u Island in American Samoa. We present empirical stratigraphic data for the investigated sites, and we demonstrate the existence of high energy marine inundation deposits at some of these sites which were laid down by past tsunamis and/or cyclones. We review and discuss the analytical outcomes, as well as summarise the overarching directions of this research. We propose that there is a need for this study to continue and for such studies to be carried out in other islands in the Pacific. By doing this, we can build on the sparse palaeotsunami database in the region, thereby helping to improve our understanding of the long-term frequency, impact distribution, and likely magnitude of these events. Further, we can start assessing their likely sources and the long-term risk these hazards pose to coastal cities and communities in the Pacific.

1. INTRODUCTION

Following the September 29th 2009 tsunami in the Samoan Islands, public and national calls were made to improve our understanding of the medium- to long-term risks of tsunamis in the archipelago in order to mitigate their impacts. The historical database of tsunamis in Samoa, which extends back to 1837, indicates that these islands have been impacted from all the major source regions within the Pacific Rim of Fire (PARARAS-CARAYANNIS AND DONG, 1980: WILLIAMS AND LEAVASA, 2006). Given that there is virtually no specific reference to tsunamis in Samoa's prehistory (i.e. the approximate 3000 years prior to the arrival of the first official missionaries in 1830), it is difficult to ascertain the long-term frequency and subsequent risk of these hazards to the people of Samoa (WILLIAMS 2009; WILLIAMS ET AL., 2012).

This study aims to improve our long-term understanding of the frequency and magnitude distributions of tsunamis within the Samoan Islands through an interdisciplinary palaeotsunami investigation. Future modelling of potential sources attributed to the identified palaeotsunamis will improve our understanding of the frequency and potential magnitude distributions associated with individual source regions. This information can then be used to re-evaluate the medium- to long-term risk of tsunamis in Samoa.

This work builds on the recommendation made in the United Nations Educational, Scientific and Cultural Organization – Intergovernmental Oceanographic Commission International Tsunami Survey Team (UNESCO-IOC ITST) Interim Field Report of October 2009 for a national palaeotsunami study (DOMINEY-HOWES AND THAMAN, 2009). Preliminary discussions with the Assistant Chief Executive Officer - Meteorology Division of the Ministry of Natural Resources and Environment in February 2010 resulted in the implementation of this collaborative field investigation.

A summary of the provisional observations, local interviews, current analytical outcomes and deductions to date as well as directions for future work is presented.

2. FIELD OBJECTIVES AND METHODS

The overarching concept behind this study is that tsunamis, like cyclones, leave distinct sedimentary evidence in the coastal landscapes they impact (GOFF ET AL, 2001; GOFF ET AL, 2009). Many of these deposits are preserved in wetland environments, although they are not limited to these environment types.

Tsunami and cyclone deposits are generally known as catastrophic saltwater inundation (CSI) events, and distinguishing the two in the field remains a challenge. Recent characteristic and analytical advancements within the global tsunami community have proven successful in distinguishing these events based upon detailed laboratory analysis (e.g. CHAGUÉ-GOFF ET AL., 2011).

This field study involved geological investigations at targeted sites in Upolu, Savaii and Ta'u Islands in order to identify CSIs. These sites are listed in Table 1 and shown in Figure 1. Trenches were dug at the sites shown in order to record the subsurface sediment stratigraphy and to identify CSI deposits. Sampling of sediment within the trenches was conducted for detailed laboratory analysis of their physical and geochemical characteristics. Core samples were also obtained from the sites shown, which were subsequently logged at the University of Canterbury in New Zealand.

Table 1: Summary of investigated sites.

Site	Coordinate Location	Distance inland from high tide mark (m)	Approximate elevation (m)	Stratigraphic depths (m)
Fagalii	$13^0$50.628' S; $171^0$44.131' W	150	< 10	3
Falealupo	$13^0$29.663' S; $172^0$46.523' W	165	< 10	0.5
Fale o le Fee	$13^0$55.134' S; $171^0$44.285' W	7.5	475	0.6
Lano	$13^0$37.176' S; $172^0$11.938' W	150	< 10	1.5
Ma'asina	$13^0$56.607' S; $171^0$33.585' W	40	< 10	0.7
Manono	$13^0$52.120' S; $172^0$04.263' W	75	< 5	2.5
Mulivai	$14^0$00.505' S; $171^0$47.651' W	25	< 5	1.02
Satitoa	$14^0$01.363' S; $171^0$25.754' W	280	<15	0.84
Satupaitea	$13^0$45.576' S; $172^0$19.209' W	75	< 10	1
Tau	$14^0$13.542' S; $169^0$30.921' W	140	< 5	0.67
Vaovai	$14^0$02.140' S; $171^0$40.832' W	20	< 5	0.72
Vaiula	$14^0$02.361' S; $171^0$39.631' W	100	< 10	0.7

Personal interviews were also conducted at Salimu (Fagaloa) and Vaovai on Upolu, and Lano and Falealupo-tai on Savaii.

Fault scarp sampling of the SE Upolu, Fagaloa and SW Savaii faults was conducted with the long-term objective of cosmogenically dating past landslide activity. These data would help establish an understanding of the timing of catastrophic coastal landslides (and subsequent tsunamis) which resulted in the exposed escarpments. The assumption for such events occurring in these islands is based on the Ta'u catastrophic landslide scenario presented in Williams et al (2012). Reconnaissance of the Ologogo fault in NW Savaii, the largest fault in Samoa, was also conducted, although sampling was not undertaken due to the lack of accessible scarp outcrops.

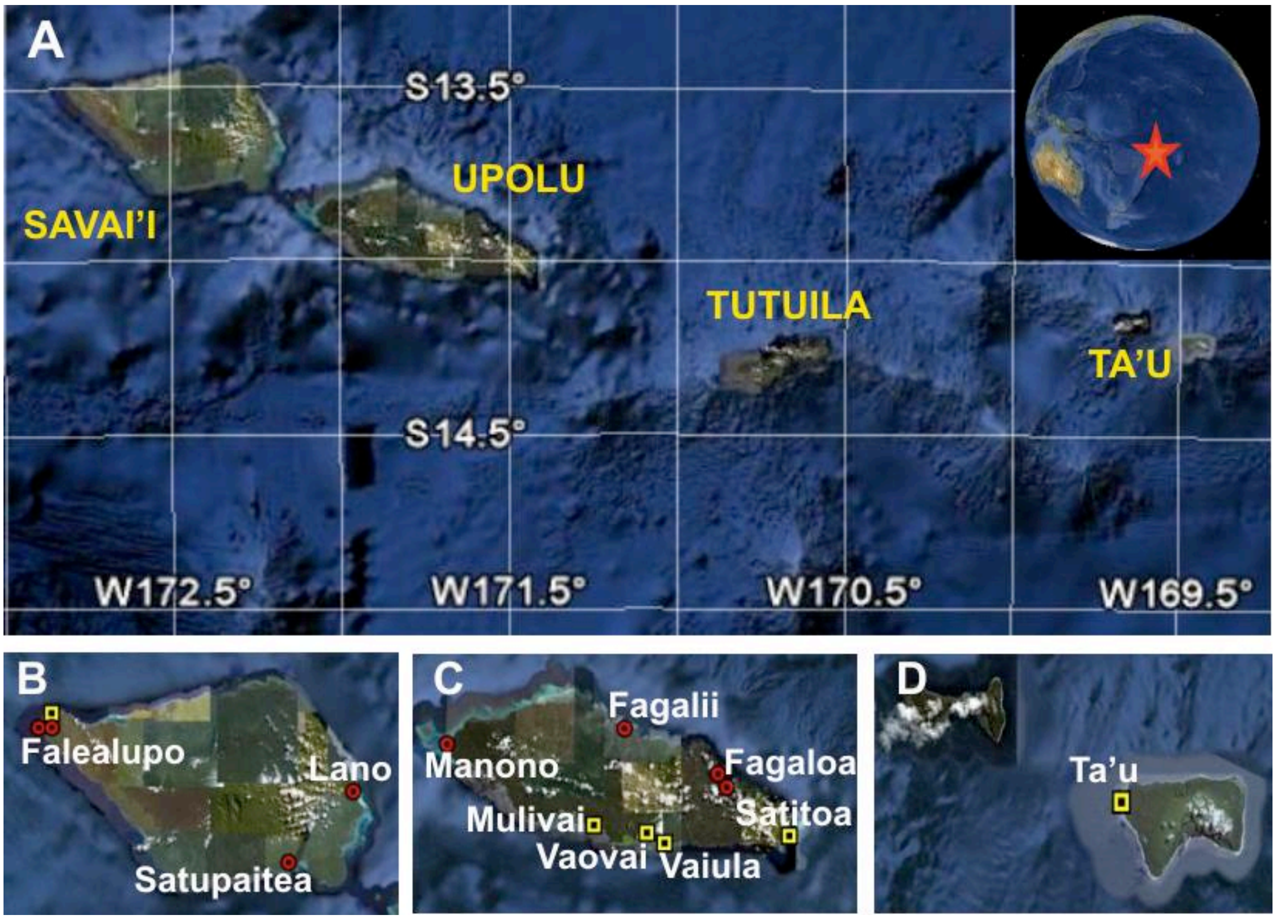

Figure 1: A) Location map of the Samoan Islands; Investigated palaeotsunami sites on B) Savai'i Island; C) Upolu Island; D) Ta'u Island. Yellow squares represent trench-sites and red circles represent core-sites (from Williams et al., 2011a). Note that Ma'asina is located at Fagaloa on NE Upolu.

2.1 Study Sites

Satellite images and field reconnaissance observations were used to select the study sites. Coastal areas with wetland or swamp depositional environments were chosen, followed by field reconnaissance to explore them in terms of their geomorphology and likelihood of preserving CSIs. Most of the areas visited had either been impacted by the 2009 tsunami, or had been impacted by an earlier event.

2.1.1 Trench and core sites

Trench studies were conducted at Mulivai near Coconuts Beach Resort, Vaiula and Vaovai, Satitoa, Falealupo, and Ta'u (Figure 1). A pit trench was also dug at Fale o le Fee to investigate possible calcareous deposits within the area. The Dwarfs Cave (Paia lava tube cave) in Savaii was also visited to investigate whether preserved sand deposits could be found.

Hand-drilled core samples were obtained from Maasina, Fagalii, and Manono-uta on Upolu. On Savaii, they were obtained from Satupaitea, Falealupo-tai, and Lano (Figure 1).

An erosional scour along the coastline at Mulivai (Safata), near the old Hideaway Resort, was also logged, although sampling at this site was not carried out. The stratigraphic log for this site is not presented in this report.

2.1.2 Fault scarps

One rock sample was obtained from the Fagaloa fault scarp on NE Upolu. Another rock sample was obtained from the SE Upolu fault scarp, as well as two rock samples from the SW fault scarp on Savaii. Attempts were made to obtain rock samples from the Ologogo fault on NW Savaii, although this was not completed due to the lack of sufficient scarp outcrops for sampling.

The faults mentioned are assumed to have undergone catastrophic ocean-island flank collapses (landsliding) in the past, with the potential to generate local tsunamis (e.g. WILLIAMS ET AL, 2012). It is planned to date these samples cosmogenically in order to constrain the likely ages of the respective collapses.

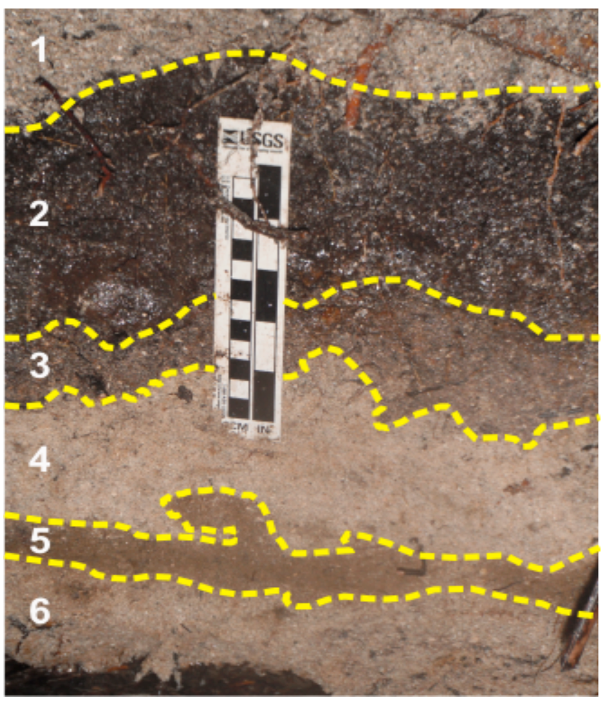

Figure 2: Stratigraphy of Mulivai trench showing six layered deposits. Layer 1 represents the 2009 tsunami deposit. Two more layers below Layer 6 are shown in Figure 3 below - not visible in this photograph due to obscuring from groundwater at Layer 6.

3. RESULTS AND OUTCOMES

Below are preliminary results associated with the investigated sites, based on field work observations. Hence, they should be treated as such. Detailed results will be reported in the future following laboratory analysis of the collected samples.

3.1 Trench logs

The subsurface stratigraphy associated with each trench was logged empirically. These serve as a benchmark for comparison with the (pending) detailed laboratory analysis of samples associated with each trench.

3.1.1 Mulivai trench (near Coconuts Beach Resort)

The trench at Mulivai was located at $14^0$00.505' S; $171^0$47.651' W, approximately 25 m inland from the high-tide water mark. A depth of 1.02m was logged (Figures 2 and 3), with bulk samples obtained from individual beds. Approximately 3 to 4 CSIs were identified empirically; the 2009 tsunami deposit at the surface, possibly the 1990 Cyclone Ofa (READY AND WOODCOCK, 1992) and the1991 Cyclone Val (ELMQVIST ET AL., 1994), and a CSI beneath the fibrous peat layer at > 1m depth.

^{14}C dating of the organic peat (sample number Wk30084) at ~1m depth (Layer 7 in Figure 3), yielded an upper-radiocarbon age limit of 528 ± 91 BP for the identified CSI at the base of the log (WILLIAMS ET AL., 2011A).

3.1.2 Vaiula trench

The trench at Vaiula was located at $14^0$02.361' S; $171^0$39.631' W, approximately 100 m inland from the high-tide water mark. A depth of 0.7 m was logged (Figures 3 and 4), with bulk sampling obtained from individual beds.

The 2009 tsunami is represented by a thin silty-sand deposit on the surface overlying a soil. A sequence of 6 layers was noted below this soil layer, and it is difficult to ascertain at this point whether this represents a series of different CSI events, or a combination of 1 or 2, with the layers representing different wave energies associated with a single event.

3.1.3 Vaovai trench

The trench at Vaovai was located at $14^0$02.140' S; $171^0$40.832' W, approximately 20 m inland from the present-day high-tide water mark. A depth of 0.72 m was logged, with detailed 1 cm sampling down to the base of the trench.

Approximately 3 to 4 CSIs were identified empirically; the 2009 tsunami deposit at the surface. It is possible that the CSI identified in layer 5 of the stratigraphic log (Figure 3) may be associated with the 1990 and 1991 cyclones.

A local *matai* (chief), Leleimalefao Ionatana, was interviewed and reported that his grandfather had told him a story of a strong earthquake and subsequent tsunami he had experienced while a child. The wave had swept through their village at night, although minimal damaged was experienced. Leleimalefao was born in 1957, meaning it is highly likely the story his grandfather

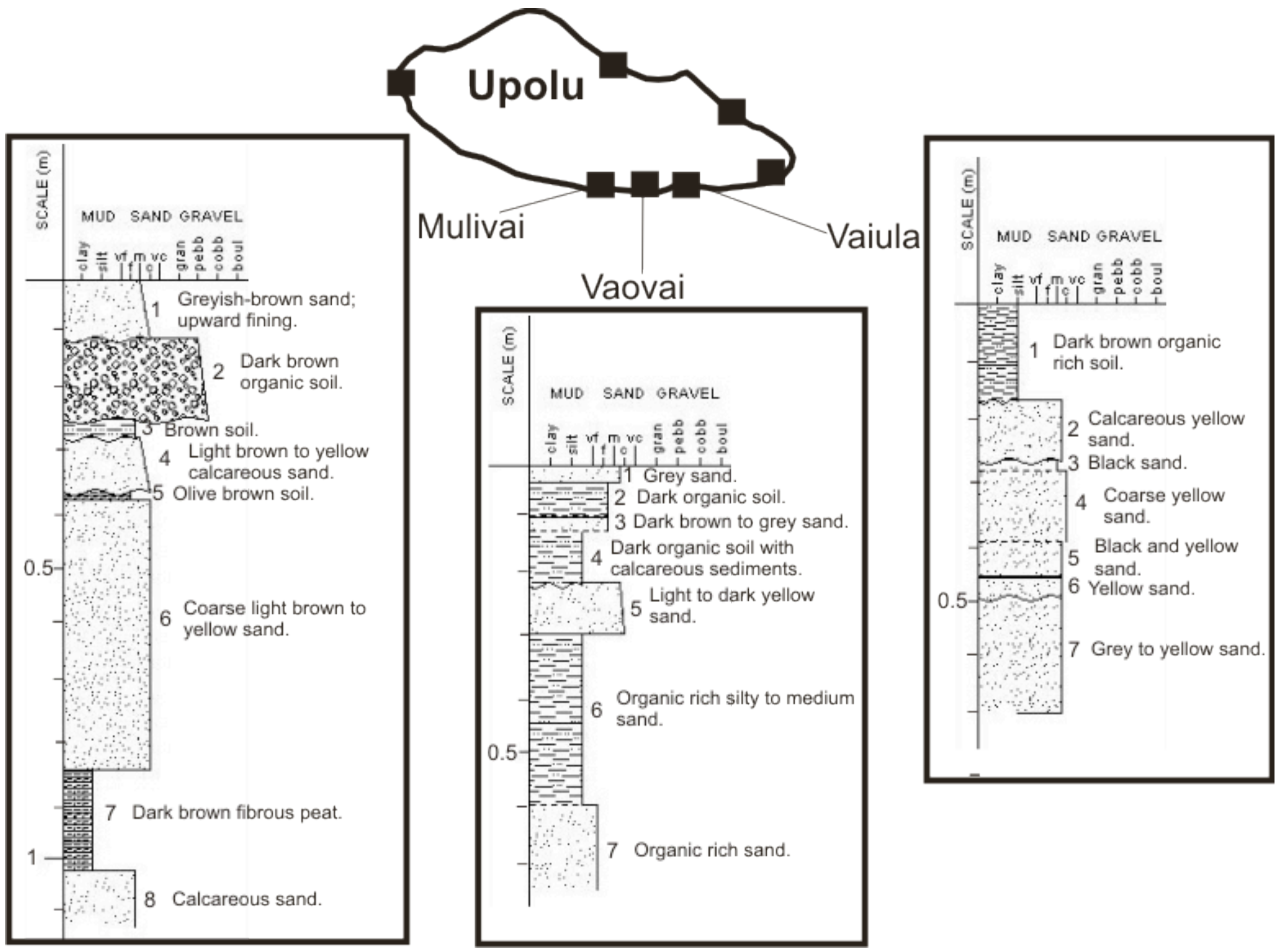

Figure 3: Empirical stratigraphic logs from Mulivai, Vaovai, and Vaiula trench sites on the south of Upolu Island. Stratigraphic depths shown are in metres. Sand particle sizes shown are; vc – very coarse; c – coarse; m – medium; f – fine; vf – very fine.

told him refers to the 1917 tsunami; assuming two generations (50 years) in the past. The 1917 tsunami originated from an M_{PAS} 8.7 earthquake at the northern Tongan Subduction bend (OKAL ET AL., 2011), about 200 km south of Falealupo and 120 km west of the 29/09 earthquake epicentre and 2009 Tsunami source. The earthquake occurred at 6:50 pm on June 25th 1917. However, there is no report in the tsunami catalogue (PARARAS-CARRAYANIS-AND DONG, 1980) of an inundation time. The fact that a strong earthquake was felt prior to the tsunami means it was local, suggesting it was most likely to be the 1917 event. Also, the fact that the wave was experienced at night further strengthens this argument since the 1917 earthquake occurred at 6:50 pm (night time) on a dry-season day. The tsunami would have inundated the Samoan islands several minutes after the earthquake; similar to the 2009 Tsunami impact time (DOMINEY-HOWES AND THAMAN, 2009; OKAL ET AL., 2011).

^{14}C-dating of an unidentified gastropod (sample number Wk30089) obtained from layer 7 in Figure 3 yielded a radiocarbon age of 576 ± 33 BP (Williams et al., 2011a). The dated gastropod is assumed to represent the age of the deposit.

Figure 4: Photograph of Vaiula L-shaped trench taken from (a) south and (b) east end of trench. (c) Northeast corner of trench which was logged (see Figure 5) and sampled.

3.1.4 Satitoa trench

The trench at Satitoa was located at 14^{0}01.363' S; 171^{0}25.754' W, approximately 280 m inland from the present-day high-tide water mark. A depth of 0.84 m was logged (Figure 5), with detailed 1 cm sampling down to 20 cm depth, followed by 2 cm sampling down to the base of the trench.

Approximately 5 to 7 CSIs were identified empirically with the 2009 tsunami deposit at the surface. There was equivocal evidence of deposits that may have been associated with the 1990 and 1991 Cyclones Ofa and Val suggesting that either these events did not impact far inland, that they did not leave any deposits, or the deposits were not preserved.

Interestingly, three pebbly layers were found within a silty-clay soil layer intermixed with calcareous sands, and two distinct calcareous sand deposits towards the base of the trench. It is likely that these are tsunami deposits; and the upper-age of the event directly below the organic layer at ~0.7 m depth can be constrained by ^{14}C-dating of the overlying organics.

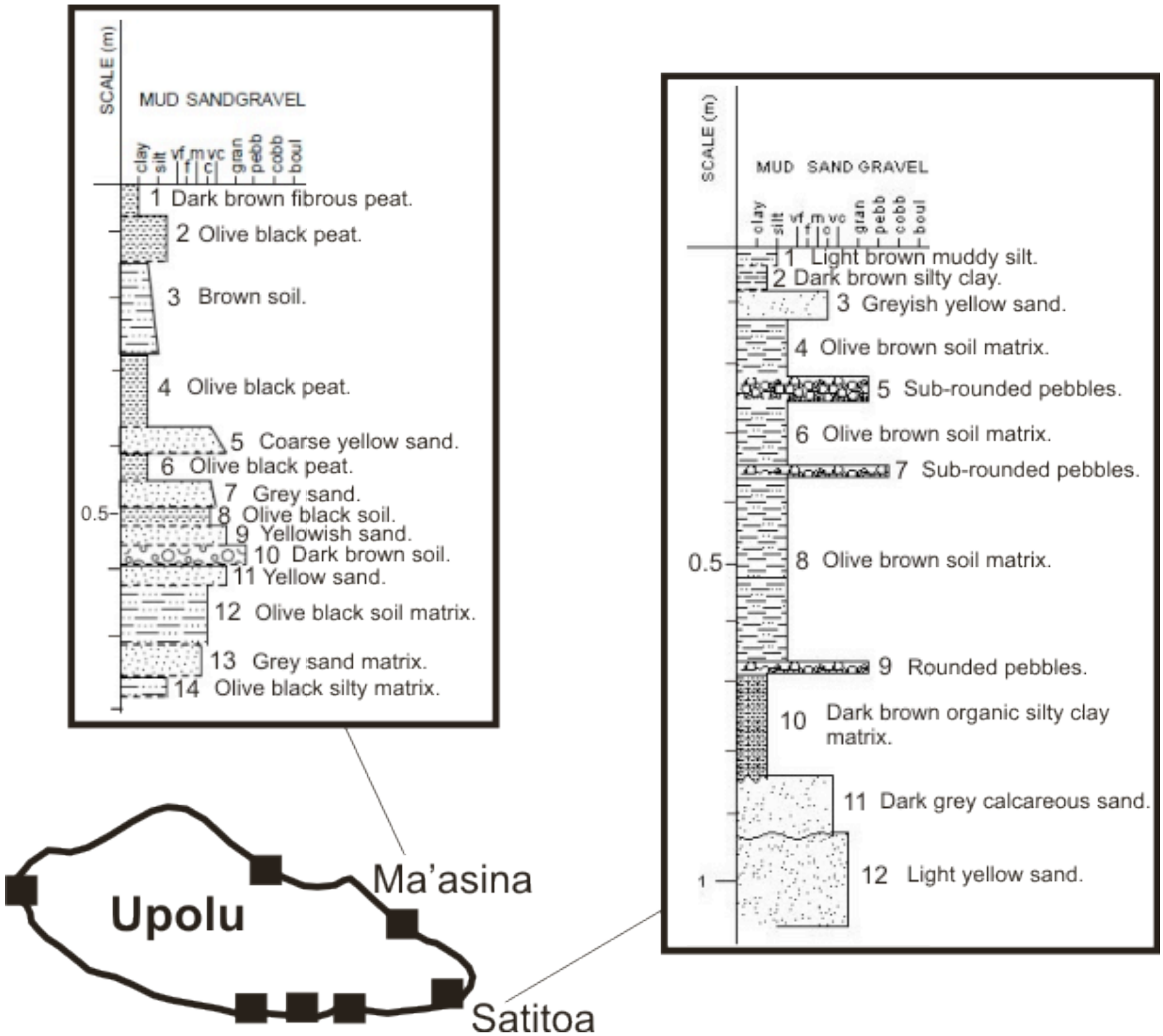

Figure 5: Empirical stratigraphic logs at Satitoa trench site on SE Upolu Island, and Ma'asina core site on NE Upolu. Stratigraphic depths shown are in metres.

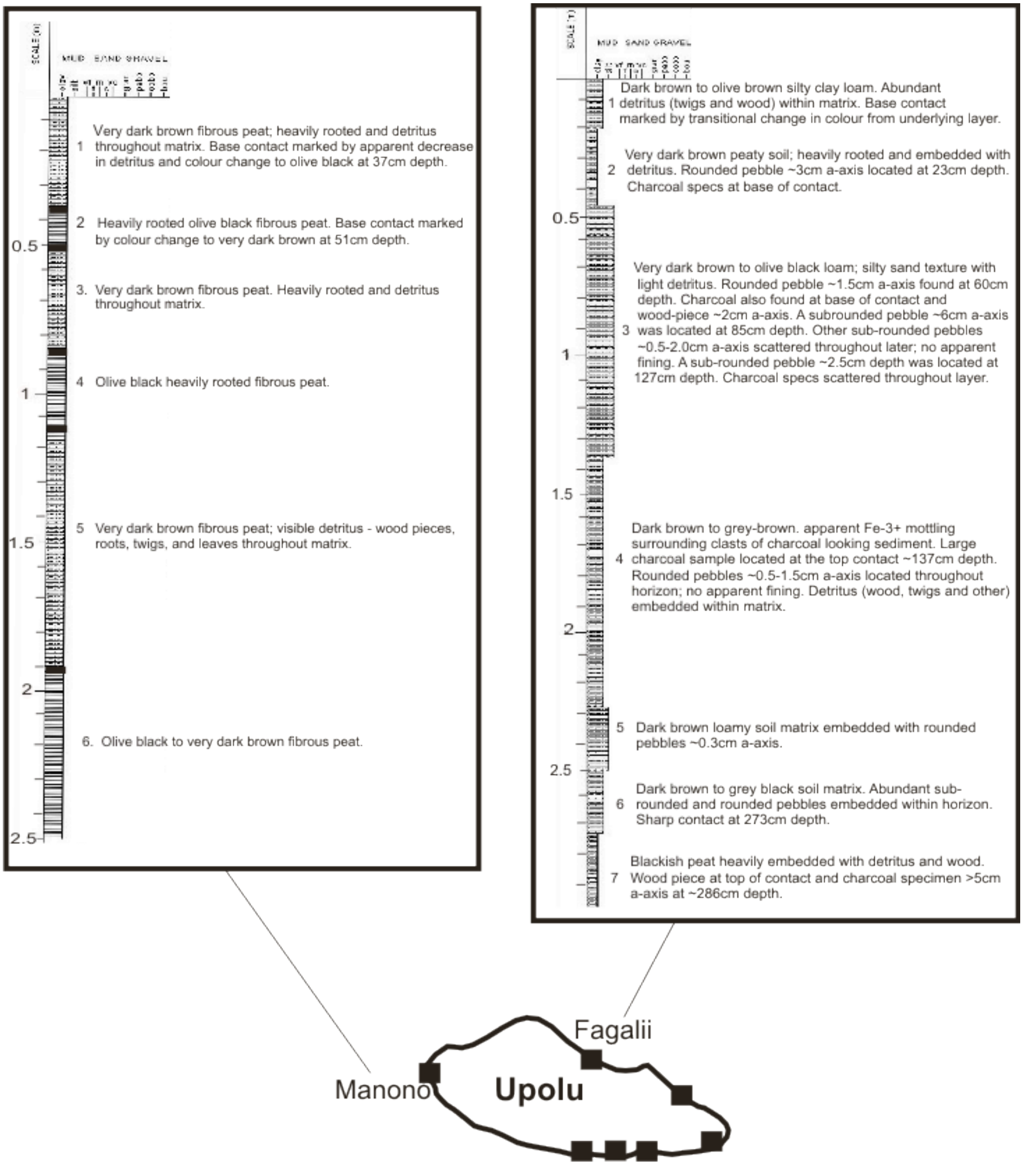

Figure 6: Empirical stratigraphic logs at Fagali'i and Manono core sites on north and west Upolu Island, respectively. Stratigraphic depths shown are in metres.

3.1.5 Falealupo trench

The trench at Falealupo was located at $13^0 29.663'$ S; $172^0 46.523'$ W, approximately 165 m inland from the present-day high-tide water mark. A 3.5 m high and 5 m wide storm berm (resembling a sand-dune) was present at the coastline. A depth of 0.5 m was logged at the trench site (Figure 7), with sampling in 1 cm intervals down to 20 cm depth, followed by 2 cm sampling down to the base of the trench.

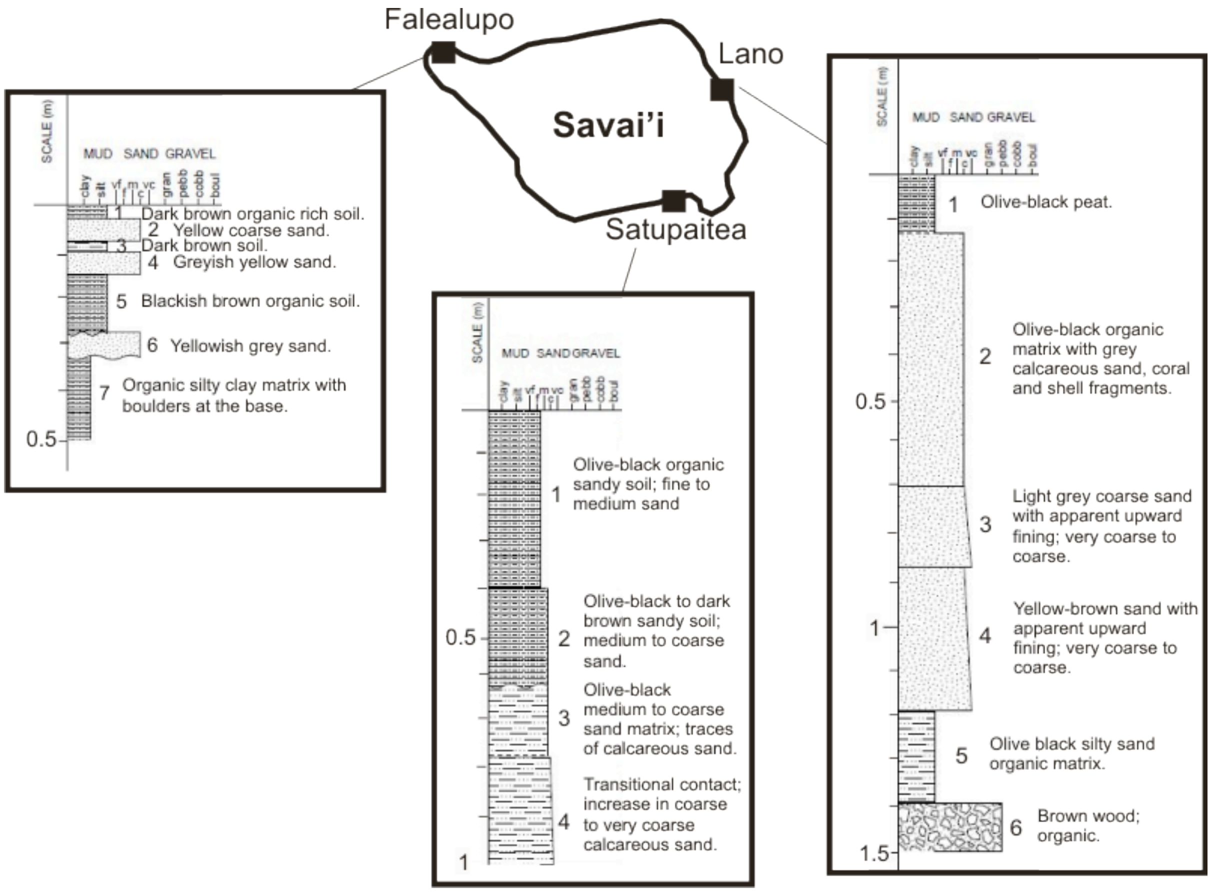

Figure 7: Empirical stratigraphic logs at Falealupo trench site on west Savai'i Island, and Lano and Satupaitea core sites on NE and SE Savai'i, respectively. Stratigraphic depths shown are in metres.

This site presents an interesting case as the primary goal was to investigate the 1990 and 1991 cyclones Ofa and Val deposits, which would serve as a baseline for distinguishing cyclone from tsunami deposits within this area. These events are most likely represented by the fine sand deposit directly beneath the surface soil layer.

The third sequence shown in Figure 8 likely represents the pre-1990 soil, while the coarse sand layer beneath that may have been deposited by an historical tsunami, possibly the 1917 tsunami. A local Falealupo resident, Mrs. Siuli Togia, reported that her father, born in 1886, told her a story of a large wave which swept through their village when he was a child. Apparently, he was returning to the coast from their inland plantation when he saw a large wave sweep through their property, taking with it his parents. Fortunately he was able to swim out and rescue them using a log as a raft to haul them back to shore. It is very likely that this narrative is an account of the 1917 tsunami which impacted the Samoan islands.

The yellowish coarse sand deposit sandwiched between the two organic layers possibly represents an earlier tsunami. The 1990 Ofa and 1991 Val Cyclones are assumed to have laid down very-fine to fine sand deposits (layer 2 and 4, respectively, in Figure 7).

In this instance, a coarser sand deposit most likely indicates higher wave energy penetrating into the coastal environment. Also, boulders up to 30 cm a-axis were noted within the organic silty layers which sandwich the lower calcareous sand deposit, indicating that they were deposited by high wave energy events.

3.1.6 Ta'u trench

The 0.67 m trench at Ta'u was located at $14^0$13.542' S; $169^0$30.921' W, approximately 140 m inland of the present high tide water mark. Only two distinct sequences were observed in the stratigraphy (Figure 8). A sharp contact at approximately 51 cm depth separates the overlying organic soil horizon from the underlying very coarse, greying yellow calcareous sand deposit. This deposit also comprised coral cobbles (branching and brain corals), gastropod and other unidentified shells, as well as rounded basalt cobbles towards the base of the deposit matrix (WILLIAMS ET AL., 2011A).

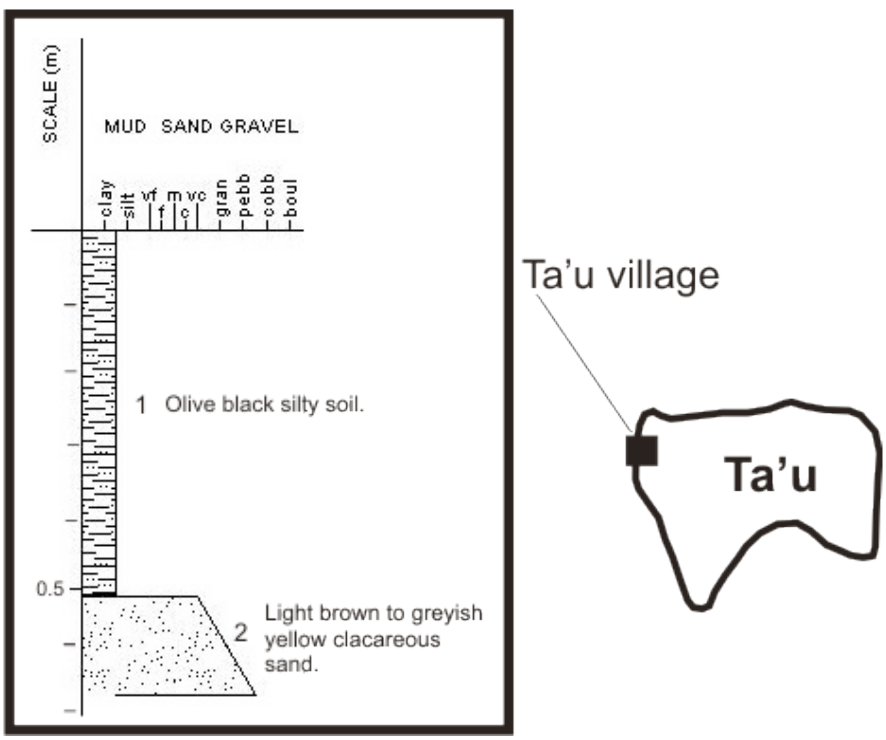

Figure 8: Empirical stratigraphic log at Ta'u trench site on NW Ta'u Island. Stratigraphic depth shown is in metres.

Recent Category 5 cyclones (eg. Cyclones Ofa in 1990 and Val in 1991 and Cyclone Heta in 2004 (MARRA ET AL., 2008) which have impacted this island had insufficient wave energy to inundate 140 m inland, and hence there is no evidence of deposits associated with recent cyclone activity at the site. Sequence 2 likely represents a high wave energy deposition source sufficient to transport the denser coral and basalt cobbles observed within the matrix. It is empirically assumed that this deposit is likely associated with a tsunami origin (WILLIAMS ET AL., 2011A), although further research is required to ascertain this.

3.1.7 Fale o le Fe'e reconnaissance pit-trench

Reconnaissance to Fale o le Fe'e was conducted in order to investigate the local belief that calcareous coastal deposits are present at the site. The site is ~7.5 km inland (south) of Apia and 475 m in elevation. The site is culturally significant in that it is the residence of the ancient war God of A'ana, the God Fe'e. It was visited to investigate whether coastal deposits are found this far inland, and what processes might have been involved in their deposition.

Reverend J.B Stair visited the site in 1845 and concluded that the (believed) limestone pillars and house remnants were basalts mined from a nearby outcrop (STAIR, 1894). He also concluded that (believed) corals on the nearby stream bed were actually stalagmites and calcareous spar which formed on the surface of outcrops, in association with the nearby stream.

Field observations made during this reconnaissance confirmed the former. Dense olivine basalt outcrops associated with the Salani volcanics (KEAR AND WOOD, 1959), appear to have been where the house pillars and associated building (rock) material were mined. The basalts appear to have a calcitic skin on their surface giving it a light grey colour, which likely formed as a result of secondary mineralisation of Mg/Fe olivines as they interact with CO_2 in air and water. The basalts also fracture prismatically and appear to resemble limestone at first glance. However, upon examining a few samples, visible olivine crystals ~1-3 mm along their a-axis can be seen embedded within a mafic matrix.

The (assumed) coral deposits further upstream of the site were not observed. A small calcitic pillar, including small stalactites and stalagmites were observed (during this study) in the Dwarf's lava-tube cave at Paia on Savaii; also located on olivine basalts. It is highly likely that Stair's conclusions of the calcitic like material he observed at Fale o le Fe'e formed in a similar way to that observed in the Dwarf's cave, and that they are not coastal calcareous deposits.

Calcite ($CaCO_3$) minerals formed at the coast are mainly derived from the fossils of calcareous marine organisms (Morse et al., 2007), whereas calcite formed within basalts is due to secondary mineralisation (a weathering process) involving CO_2-water-rock interactions (MATTER AND TAKAHASHI, 2007).

A pit-trench was also dug in order to rule out the possibility of a distinct sand deposit at depth (Figure 8). Interestingly, a well-preserved charcoal layer was observed at ~0.35 m depth, and is assumed to be anthropogenic. C^{14} dating of a sample (sample number Wk30088) of this charcoal presented in Williams (2011a) showed this deposit to have a radiocarbon age of 398 ± 73 BP; provisionally suggesting that likely worshipers of Fe'e occupied or used the site around this time.

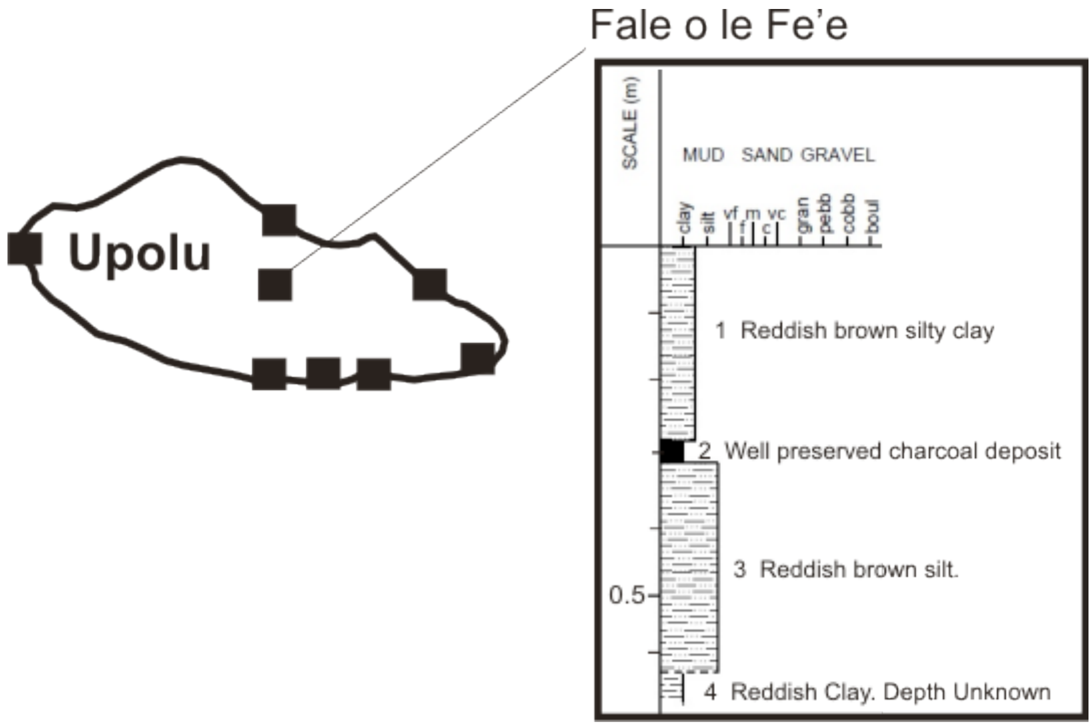

Figure 9: Empirical stratigraphic log at Fale o le Fe'e trench site on Upolu Island. Stratigraphic depth shown is in metres.

3.2 Core samples:

Core samples were obtained from the locations shown in Figure 1. The cores were not logged in the field due to time constraints. Logging and detailed laboratory analysis of the samples will be conducted in due course.

3.1.8 Ma'asina core sample

A 0.7 m core was obtained from Ma'asina village (Fagaloa Bay) in a small coastal marsh ~40 m inland of the high-tide mark A sand deposit was observed at approximately 0.4 – 0.8 m depth (Figure 8).

The historical database indicates that Fagaloa Bay has been impacted by tsunamis causing destructive damages in 1952, 1957, and 1960. The 1952 (1.8 m wave) and 1960 (2.4 m wave) tsunamis originated from major earthquakes in the Chile/Peru region. The 1957 (1.5 m wave) tsunami originated from an 8.5 magnitude earthquake in the Aleutian Islands (PARARAS-CARAYANNIS AND DONG, 1980).

3.1.9 Fagalii core sample

A 3 m core was obtained from a swamp at Fagalii village located at 13^{0}50.628' S; 171^{0}44.131' W, within the 8 km radius of Apia Township. The site was located ~150 m inland of the high-tide water mark, and directly behind the current Minister of Communication and Information Technology's residence.

No apparent CSI deposits were observed (Figure 6), although detailed laboratory analysis will clarify this. Interestingly, a charcoal deposit was observed at ~2.9 m depth which is likely to be anthropogenic. If the sample is found to be anthropogenic and older than 2800 BP, this finding could represent evidence for initial human settlement in Upolu older than the currently accepted ~2800 BP (DICKINSON AND GREEN, 2008). ^{14}C-dating of this sample (sample number Wk30087) yielded a radiocarbon age of 3,112 ± 50 BP (WILLIAMS ET AL., 2011A), but further study is required to ascertain its origin.

Historically, the most destructive tsunami to have impacted the Apia region was on 14 August 1868, which originated from a major earthquake in the Peru/Chile region (PARARAS-CARAYANNIS AND DONG, 1980). It was reported that the tsunami destroyed buildings in Apia, although there were no detailed accounts on the geographic extent and magnitude of damage, nor on loss of life.

3.1.10 Manono-uta core sample

A 2.5 m core was obtained from the Manono-uta marsh located at 13^{0}52.120' S; 172^{0}04.263' W, ~75 m inland of the high-tide water mark. No apparent CSI deposits were observed (Figure 6), although detailed laboratory analysis will clarify this. The site was chosen to identify CSIs which may have impacted east Upolu.

3.1.11 Lano core sample

A 1.5 m core was obtained from a swamp at Lano village, located at 13^{0}37.176' S; 172^{0}11.938' W; ~150 m inland of the high-tide mark. A distinct CSI deposit was observed at ~1 m depth (layer 4 in Figure 7). ^{14}C-dating of plant fragments (sample number Wk30083) obtained from layer 5 at 1.4 m depth yielded a radiocarbon age of ~798 ± 28 BP (WILLIAMS ET AL., 2011A). Detailed laboratory analysis of organics above and below the deposit will help to establish its age. This site was chosen to identify events along NE Savaii.

3.1.12 Falealupo core samples

Two core samples were obtained from two separate swamps at Falealupo. Falealupo Core-1 (FC-01) was located at 13^{0}30.064' S; 172^{0}47.161' W ~220 m inland of the high-tide water mark. Falealupo Core-2 (FC-02) was located at 13^{0}29.670' S; 172^{0}46.521' W ~160 m Inland of the high tide water mark. Both cores reached 1 m in depth, and FC-02 appeared to have 2 or 3 CSIs within them. These cores were subsequently not selected for analysis as the samples obtained from Falealupo trench (see Section 3.1.5) were sufficient for the purposes of this study.

3.1.13 Satupaitea core sample

A 1 m core sample was obtained from a swamp located at 13^{0}45.576' S; 172^{0}19.209' W, ~75 m inland of the high-tide water mark. The Satupaitea coastal area comprised mainly black sandy sediments derived from inland basalts that have been transported to the coast by a network of streams and rivers, and some re-deposited by waves. Two distinct calcareous deposits were observed at 0.8 m and 0.95 m depths (Figure 7), indicating two separate CSI events. This area was chosen to identify events which may have impacted SE Savaii.

3.2 Personal Interviews

Four interviews were carried out at Salimu (Fagaloa Bay) and Vaovai on Upolu, as well as Lano and Falealupo on Savaii. One individual from each village was interviewed. Questions asked centred on any local stories related to tsunamis or unusual wave activity which were either experienced by the individuals or were told by older generations.

3.2.1 Salimu-Fagaloa interview

A 67 year old local *matai* from Salimu (Fagaloa), Limu Filifilia, stated that he had known of two unusual waves to have impacted his village while he was a teenager. The first one had slightly inundated Salimu, but had transported the local medical barge across the other side of the harbour and deposited it on the reef adjacent to Ma'asina (Fagaloa). Several years later, another wave struck which brought the barge back to its present day location (Figure 10).

Figure 10: Fagaloa harbour showing the present-day barge location relative to Salimu and Ma'asina villages. Photograph is taken facing north, and the straight-line distance from Salimu to Ma'asina is ~1.3km (standing are J. Ah Kau – left; and F. Sale – right).

The events he described are most likely the 1957 and 1960 tsunamis which impacted Fagaloa harbour. The 1957 tsunami originated from an 8.5 earthquake in the Aleutian Islands which ruptured at 3:22 am (local Samoan time) on March 9th. It had a 9 hour travel time, meaning it would have impacted Fagaloa bay at approximately 12:22 pm. 1.5 m and 1.05 m waves were reported at Taelefaga and Maasina villages, respectively (PARARAS-CARAYANNIS AND DONG, 1980).

The 1960 tsunami originated from an Mw 9.5 earthquake in the south Chile region which ruptured at 8:11am (local Samoan time) on May 22nd (PARARAS-CARAYANNIS AND DONG, 1980). The tsunami had a travel time 12.4 hours, meaning it would have impacted Fagaloa at approximately 9:00pm. 2.4 m waves reportedly inundated villages at Fagaloa, causing damage and flooding to local huts.

3.2.2 Vaovai interview

Refer to Section 3.1.3 for an account of the story told by Leleimalefao Ionatana (local matai of Vaovai village).

3.2.3 Lano interview

The late *sa'o* (head *matai*) of Lano village, afioga Vui Vaea (82 years of age in 2010), told of calcareous boulders which were deposited about 70 m inland from the core site. A local Lano story passed down to him while he was a child stated that the boulders were deposited by a large wave ages before. He viewed these coralline boulders when he was young and stated that they had average a-axes greater than 20 cm. There is no mention as to the timing of the event, and he did not indicate that it occurred during his parents or grandparents' generation. These boulders have since been removed due to recent development in the area, but it is likely they were deposited by a palaeotsunami. Further detailed geological studies in the area would be useful to clarify the nature and extent of this event.

3.2.4 Falealupo interview

Refer to Section 3.1.5 for an account of the story told by Mrs. Siuli Togia (local Falealupo-tai resident).

4. REVIEW OF PRESENT ANALYTICAL OUTCOMES

The samples collected were processed using a set of multi-proxy diagnostic criteria in relevant laboratories at the Universities of Canterbury and Waikato in New Zealand, and at the Australian Nuclear Science and Technology Organisation in Australia. The diagnostic proxy criteria used included sedimentological (stratigraphic logging, loss on ignition and grain size distributions), geochemical (elemental profiles), and geochronological (^{14}C and ^{210}Pb dating) techniques.

While the data are currently being analysed and will be communicated in due course, preliminary geochemical and geochronological aspects of the project were presented in Williams et al. (2011a and 2011b). Using elemental data collected with a portable X-Ray fluorescence spectrometer; it was found that the Ca/Fe and Ca/Ti ratio-relationships for the 2009 Samoa Tsunami deposits at investigated impact sites could be used to identify similar high energy deposits in their respective geologic records. However it was acknowledged that elemental proxies alone were insufficient in distinguishing between a tsunami and a cyclone deposit (WILLIAMS ET AL., 2011A, 2011B).

In some cases (eg. Satitoa and Ta'u), high energy deposits identified were provisionally assumed to be of a tsunami origin due to their relative locations inland from mean sea level. Moreover, we observed no evidence of any deposits at these sites which might have formed from recent cyclones over the past several decades, such as from Cyclones Ofa in 1990 and Val in 1991 (Ready and Woodcock, 1992; Elmqvist et al., 1994), and Cyclone Heta in 2004 (Marra et al., 2008).

In the case of Satitoa, a ^{14}C radiocarbon age obtained from the soil horizon (~0.81 m stratigraphic depth), overlying the assumed tsunami deposit provisionally suggests that the deposit may have been laid down by the 1917 Samoa Tsunami.

At Mulivai (near Coconuts Beach Resort) and Vaovai sites, high energy deposits with radiocarbon ages of ~437 – 619 BP (see Sections 3.1.1 and 3.1.3) were identified at both sites, respectively. Although it was assumed the respective deposits were formed by the same event, it was uncertain whether the deposits were of a tsunami or cyclone origin.

5. SUMMARY AND DIRECTIONS FOR FUTURE WORK

While the outcomes to date provide a provisional basis for starting to understand the long-term impacts of tsunamis at the investigated sites, much work remains to be carried out in order to allow us to draw conclusive evidence to distinguish between deposits of tsunami or cyclone origin. Only coupled with a suite of multi-proxy criteria (e.g. Goff et al., 2001; 2004; 2011; 2012; Morton et al., 2007; Chagué-Goff et al., 2011; Richmond et al., 2011), and assessed in the broader regional geochronological context can we develop more robust conclusions.

Further palaeotsunami studies on other islands and nations in the Pacific are required, as they can serve as point-sources of potential palaeotsunami information. This would contribute to the existing, but sparse, palaeotsunami database for the region, and would contribute to our geochronological and spatial understanding of long-term tsunami impacts. By doing this, we can start to better understand the long-term risk of coastal communities to tsunami hazards in the Pacific.

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7. REFERENCES

CHAGUÉ-GOFF, C., SCHNEIDER, J.-L., GOFF, J.R., DOMINEY-HOWES, D. AND STROTZ, L. 2011. Expanding the proxy toolkit to help identify past events: Lessons from the 2004 Indian Ocean Tsunami and the 2009 South Pacific Tsunami. *Earth-Science Reviews*, 107, 107-122.

DICKINSON, W.R., GREEN, R.C. (1998). Geoarchaeological Context of Holocene Subsidence at the Ferry Berth Lapita Site, Mulifanua, Upolu, Samoa. *Geoarchaeology: An International Journal*, 13 (3): 239–263.

DOMINEY-HOWES, D., THAMAN, R., (2009). UNESCO-IOC International Tsunami Survey Team Samoa: Interim Report of Field Survey 14th – 21st October 2009. Australian Tsunami Research Centre Miscellaneous Report No.2, October 2009.

ELMQVIST, T., RAINEY, W.E., PIERSON, E.D., COX, P.A. (1994). Effects of tropical cyclones Ofa and Val on the structure of a Samoan lowland rain forest. *Biotropica,* 26 (4): 384-391.

GOFF, J., CHAGUÉ-GOFF, C., NICHOL, S. (2001). Palaeotsunami deposits: a New Zealand perspective. *Sedimentary Geology*, 143: 1-6.

GOFF, J., MCFADGEN, B. AND CHAGUÉ-GOFF, C., 2004. Sedimentary differences between the 2002 Easter storm and the 15th-century Okoropunga tsunami, southeastern North Island, New Zealand. *Marine Geology*, 204: 235-260.

Goff, J., Nichol, S., Kennedy, D. (2009). Development of a palaeotsunami database for New Zealand. *Natural Hazards*. DOI: 10.1007/s11069-009-9461-5.

GOFF, J., CHAGUÉ-GOFF, C., DOMINEY-HOWES, D., MCADOO, B., CRONIN, S., BONTÉ-GRAPETIN, M., NICHOL, S., HORROCKS, M., CISTERNAS, M., LAMARCHE, G., PELLETIER, B., JAFFE, B., DUDLEY, W. (2011). Palaeotsunamis in the Pacific Islands. *Earth-Science Reviews*, 107 (2011): 141–146.

GOFF, J., CHAGUÉ-GOFF, C., NICHOL, S.L., JAFFE, B. AND DOMINEY-HOWES, D. (2012). Progress in palaeotsunami research. *Sedimentary Geology,* 243-244, 70-88.

KEAR, D., WOOD, B.L., (1959). The Geology and Hydrology of Western Samoa. New Zealand Geological Survey Bulletin (No.63).

MARRA, J.J., KARI, U.S., SABBATELLI, T.A. (2008). Anatomies of historical storm events in the Pacific. *Proceedings of the Solutions to Coastal Disasters Congress,* 2008, 312: 222-228.

MATTER, J.M., TAKAHASHI, T., 2007. Experimental evaluation of in-situ CO_2-water-rock reactions during CO_2 injection in basaltic rocks: Implications for geological CO_2 sequestration. *Geochemistry Geophysics Geosystems,* 8 (2): 19 pp.

MORSE, J.W., ARVIDSON, R.S., LÜTTGE, A., (2007). Calcium Carbonate Formation and Dissolution. *Chemical Reviews,* 107: 342 – 381.

MORTON, R.A., GELFENBAUM, G. AND JAFFE, B.E., 2007. Physical criteria for distinguishing sandy tsunami and storm deposits using modern examples. *Sedimentary Geology*, 200(3-4): 184-207.

OKAL, E., BORRERO, J. AND CHAGUÉ-GOFF, C., 2011. Tsunamigenic predecessors to the 2009 Samoa earthquake. *Earth-Science Reviews*, 107: 127-140.

PARARAS-CARAYANNIS, G., DONG, B., (1980). Catalog of Tsunamis in the Samoan Islands. International Tsunami Information Center, Honolulu, 75 pp.

READY, S., WOODCOCK, F. (1992). The South Pacific and southeast Indian Ocean tropical cyclone season 1989-1990. *Australian Meteorological Magazine,* 40 (2): 111-121

RICHMOND, B.M., WATT, S., BUCKLEY, M., JAFFE, B.E., GELFENBAUM, G., MORTON, R.A. (2011). Recent storm and tsunami coarse-clast deposit characteristics, southeast Hawai'i. *Marine Geology*, 283 (1-4): 79-89.

STAIR, J.B., (1894). "O le Fale o le Fe'e": or, ruins of an old Samoan temple. *The Journal of the Polynesian Society*, 3 (4): 239-244

WILLIAMS, S.P., (2009). Ocean-island flank collapse on the south of Ta'u, Manu'a Group, Samoa Islands: Implications for risk management. MSc Thesis. Department of Geological Sciences, University of Canterbury, NZ. UC Library Repository (http://hdl.handle.net/10092/3784).

WILLIAMS, S.P., LEAVASA, A.F.M., (2006). Exploring the status of tsunami early warning systems in Samoa. In: Taulealo, T., (ed). *Proceedings of the Samoa National Environment Forum 2005*. pp. 52-58

WILLIAMS, S., GOFF, J., PRASETYA, G., CHEUNG, K.F., CHAGUÉ-GOFF, C., DAVIES, T., WILSON, T. (2011A). Characterising diagnostic proxies for identifying palaeotsunamis in a tropical climatic regime, Samoan Islands. *OCEANS'11 - MTS/IEEE Kona Conference Proceedings, 19 – 22 September 2011, Hawai'i, USA*. Program Book, art. no. 6107137. ISSN 0-933957-39-8.

WILLIAMS, S.P., GOFF, J.R., SALE, F., AH KAU, J., PRASETYA, G., DAVIES, T.R.H., CHEUNG, K.F., WILSON, T. (2011B). Sands of Time: Evidence for palaeotsunamis and/or palaeostorms in Samoa, and what this means for tsunami risk reduction. In: Malua, T.L. (ed), *Proceedings of the Samoa National Environment Forum 2010*. pp. 15-25.

WILLIAMS, S., DAVIES, T. AND COLE, J. (2012). Catastrophic flank collapse on Ta'u island and subsequent tsunami: Has this occurred during the last 170 years. *Science of Tsunami Hazards* 31(3): 178-198.