Characterising diagnostic proxies for identifying palaeotsunamis in a tropical climatic regime, Samoan Islands

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Abstract— **The September 2009 South Pacific Tsunami (2009 SPT) in the Samoa Islands resulted in local public and national calls to improve understanding of the medium- to long-term risks of tsunamis in these islands in order to further mitigate their impacts. This research addresses some of these calls through an interdisciplinary palaeotsunami investigation. Historical data beginning in 1837 indicate that the Samoan Islands have been impacted by tsunamis from all the major tsunamigenic zones within the Pacific Rim of Fire, making it an ideal location for starting to understand tsunami frequency and distribution within this region. Furthermore, the region has an historical record of extreme tropical cyclones.**

The overarching concept of this study is that tsunamis, like cyclones, leave a distinct geological deposit within coastal landscapes they impact. The origin of a high-energy geological deposit, be it storm or tsunami, can be determined by using a suite of diagnostic criteria. However, the origin of a deposit can still be ambiguous, because some of the diagnostic criteria (e.g. grain size, microfossil assemblages and characteristics) can be extremely similar for both processes. Moreover, local factors can also influence the characteristics of deposits.

This project aims to elucidate this enigma by establishing a suite of diagnostic criteria (e.g., stratigraphy, lithology, macro- and micro-palaeontology, geomorphology, grain size characteristics, geochemistry, anthropology, archaeology, numerical modelling) to distinguish between tsunamis and cyclones in this tropical climatic regime. Preliminary studies show that a geological record of historical /palaeotsunamis and storms/palaeostorms is preserved on the south and south east coast of Upolu, west and northeast coast of Savai'i (Independent State of Samoa), and northwest coast of Ta'u in the Manu'a Group (American Samoa). We present preliminary X-ray fluorescence spectroscopy (XRF) and geochronological results (C-14 radiocarbon dates) conducted on samples (sands and paleosols) collected from various sites on Upolu, Savaii, and Ta'u islands.

These serve as a starting point for developing a suite of diagnostic proxies for identifying and distinguishing tsunami from storm deposits in the Samoan Islands, and establishing the geochronology of identified events. Numerical modelling of wave resonance around these islands, as well as identified palaotsunamis will form an additional proxy for interpreting the palaeotsunami data. Further, it forms a basis for starting to understand the likely sources of these events, forming a basis for

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refining the frequency and (likely) magnitude distributions associated with these events.

Planned Pb-210, Cs-137 and C-14 dating will enable a detailed interpretation of the chronology of specific events identified in the geologic record. Furthermore, they will enable a correlation of deposits with known historical events, providing a control on distinguishing recent tsunami from storm deposits (subsequent to 1837 AD), and enabling palaeo-events to be identified. This will form a basis for identifying similar events within the geologic record in similar environmental regimes. Ultimately, this work will significantly improve understanding of the nature and risks of coastal hazards in Samoa, thereby improving local capability to mitigate their medium- to long-term impacts. It will also contribute to tsunami hazard mitigation efforts within the broader SW Pacific through a strengthened tsunami database in the region.

Keywords-palaeotsunamis; diagnostic proxies; Samoan Islands

I. INTRODUCTION

Investigating tsunami deposits has become a key component in tsunami hazard assessments worldwide, and is recognized as essential in efforts to mitigate tsunami risk to communities [1], [2]. Recent studies of modern tsunami deposits during immediate post-tsunami surveys have provided the opportunity to characterise, establish, and refine diagnostic criteria associated with the deposits [2], [3]. Much of these studies were enabled through recent tsunamis such as the December 26, 2004, Indian Ocean tsunami [4], [5], the September 29, 2009, South Pacific tsunami (2009 SPT) [6], the February 27, 2010, Chile tsunami [7], and the March 11, 2011, Japan tsunami [8]. Understanding the characteristics of historical (or modern) tsunami deposits enables the identification of palaeotsunamis within the geologic record that have similar deposit characteristics [9]. This improves understanding of the long-term risk of tsunamis to communities and underpins efforts to mitigate their impacts, including loss of life and property.

While much has been written and debated about the diagnostic proxies of tsunamis [1], [3], [11], [12], [13], [14], [15], [16], [17], [18], [19], much work still remains to be done in the context of detailed deposit and geomorphological analyses [2].

In the Samoa Islands, tsunami research prior to the 2009 SPT was extremely limited and focussed entirely on establishing a record of historical tsunami events [20], reviewing early warning systems [21], and limited modelling for coastal hazard planning purposes [22], [23]. While inundation modelling and hazard mapping remain a key focus for current research, significant emphasis has been made on characterising the 2009 SPT deposits as a proxy for identifying palaeotsunami deposits in the geologic record [2], [19], [24].

The results and interpretations we present in this paper are preliminary, and form part of an ongoing project to characterise and establish tsunami deposit criteria specific to the Samoan Islands in the context of hazard assessment. Major emphasis is made on identifying palaeotsunami deposits using the established criteria or proxies, and establishing their age constraints through datable material either within the deposits or within adjacent sediment horizons.

In terms of the overall project, field investigations were conducted at thirteen coastal sites distributed along the islands of Upolu and Savaii in Independent State of Samoa, and Ta'u in American Samoa (Fig. 1). Trench and core samples ranging between 0.5–3.0 m were collected from sedimentary sequences containing a number of sand layers. Included in these layers were deposits from the 2009 SPT at the surface, as well as previous high-energy events at depth (storms or tsunamis), intercalated with palaeosols, on the south coast (Mulivai, Coconut Beach Resort near Maninoa, Vaovai, Vaiula) and south east coast (Satitoa) of Upolu, the west (Falealupo) and northeast (Lano) coasts of Savaii, and the northwest coast (Ta'u village) of Ta'u. These samples were collected during the 2009 UNESCO-IOC Post Tsunami Survey of the 2009 SPT and during follow up studies in August and November 2010 [25], [26].

Semi-quantitative geochemical profiles (elemental compositions) of the stratigraphic sequences were obtained using a portable X-ray fluorescence (XRF) spectrometer [24]. The results provide an initial interpretation of elemental proxies for the 2009 SPT. Moreover, they form a semi-quantitative basis for identifying deposits with similar geochemical characteristics in each sequence that may have formed from similar high-energy deposition processes for more detailed analysis, including geochronological.

Initial C-14 analysis was conducted on samples from the bases of seven priority core/trench sites in order to obtain maximum age limits for their profiles. These sites were identified using the preliminary geochemical data obtained, and included Mulivai, Vaovai, and Satitoa on the south and SE coast of Upolu, Fagalii on the north coast of Upolu, Falealupo and Lano on the west and NE coasts of Savai'i, and Ta'u village on NW Ta'u in American Samoa (Fig. 1). Geochemical results from Falealupo, Lano and Ta'u are presented here, and are discussed in the context of the initial geochronology results obtained. Ultimately, these will contribute towards forming the underpinning data required for long-term hazard mitigation in these islands.

II. PRELIMINARY GEOCHEMICAL ANALYSIS

A. *Background*

Preliminary elemental compositions were obtained for each sampled stratigraphic profile using a portable XRF spectrometer developed by Bruker Inc. The instrument determines the relative elemental chemistry composition of a sample through the emission of photons (x-rays) onto its surface, thus exciting electrons within individual elements comprising the sample causing them to fluoresce [27]. In this study, the samples tested were mainly soils, peat, and calcareous sands. Only three of the investigated sites contained the 2009 SPT deposit, each varying according to the nature of sediment being deposited, flow characteristics of the inundating tsunami, and geomorphology or landscape of the area [24]. These sites included Mulivai, Vaovai and Satitoa on the south

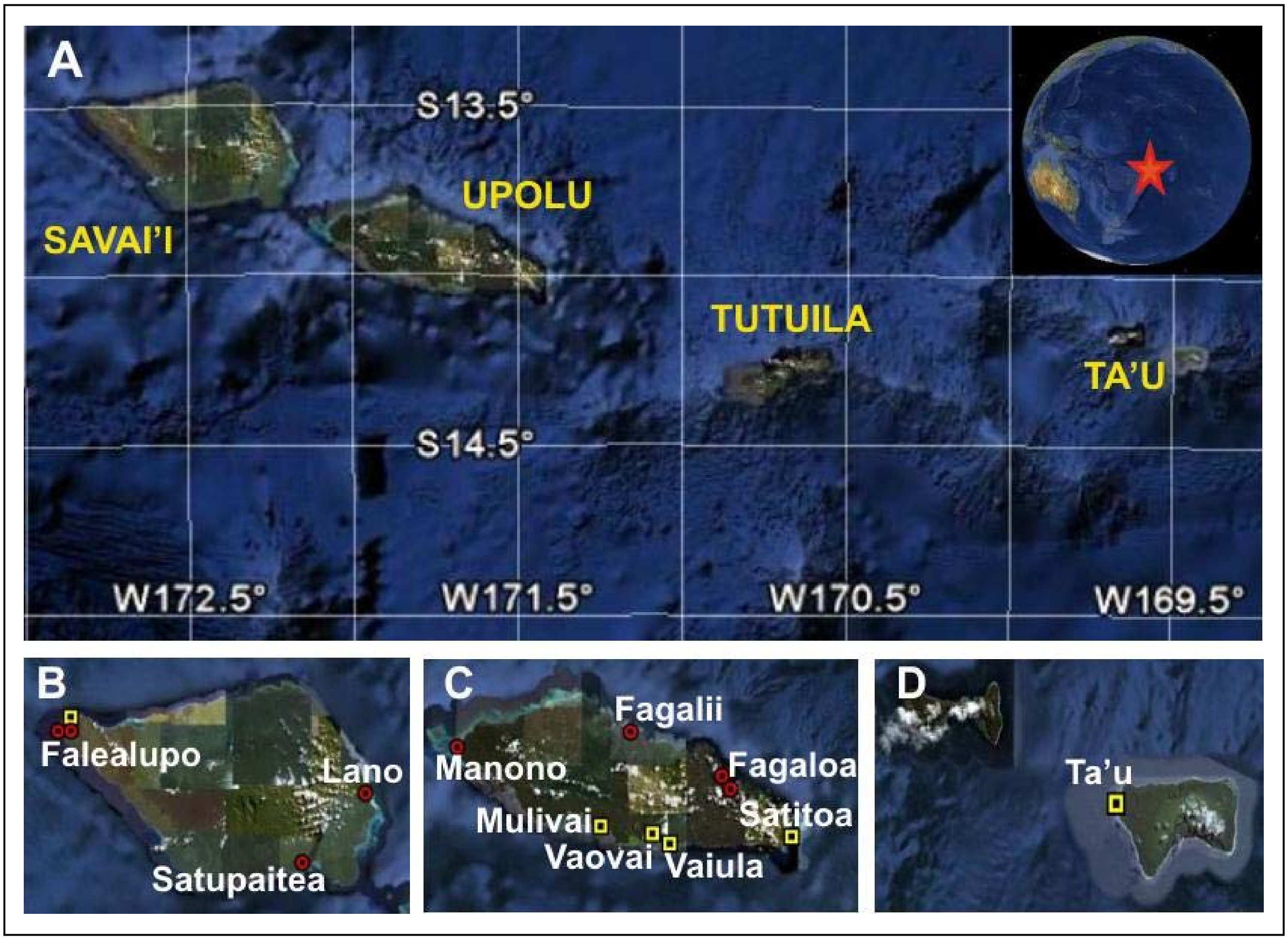

Figure 1. A) Location map of the Samoa Islands chain; B - D) Investigated sites on Savai'i (B), Upolu (C), and Ta'u (D). Investigated trench sites are depicted by the yellow squares, and core sites by the red circles. Map source: Google Earth.

and southeast coast of Upolu; a stretch of coastline hardest hit by the 2009 SPT.

These deposits provide a reference standard for identifying similar deposits formed from tsunamis that may have originated from similar sources within the geological record [10], [24]. The 2009 SPT deposit was not contained in other investigated sites (e.g. Falealupo, Lano, and Ta'u) either because they were not impacted by the event, the waves did not have sufficient energy to leave behind a deposit, or the landscape was not conducive to sediment deposition [2], [19], [24].

B. *Elemental Proxies*

A catastrophic saltwater inundation event (CSI) is a term to describe a deposit that is not known whether it is of tsunami or cyclone origin [9]. Typically they are identified empirically by distinct changes in sediment characteristics within the geologic record (e.g. marine sediments intercalated between soils, peat or palaeosols) [1]. Distinguishing between the two requires multi-proxy characterisation [2], [28], and is beyond the scope of this paper.

CSI deposits generally contain higher amounts of calcium, sulphur, magnesium, sodium, and chlorine (and other elements) relative to overlying and underlying sediment layers [2], [9], [28]. They can also contain much higher levels of heavier elements such as iron and/or titanium. Higher CSI calcium compositions occur due to the deposition of marine calcareous sediments (carbonates) on pre-existing soils.

Preliminary interpretations on the elemental characteristics of the 2009 SPT deposit at Mulivai, Vaovai and Satitoa were discussed in [24]. The results showed a relationship between the calcium-iron ratios between stratigraphic sequences at the investigated sites, and it was suggested that these observations be considered as a possible diagnostic tool for identifying catastrophic (or non-catastrophic) saltwater inundation events specific to individual sites. The analysed deposits consistently contained higher concentrations of calcium (Ca), and lower iron (Fe) and titanium (Ti) concentrations relative to underlying (pre-2009 SPT) soils at each site. The lower titanium and iron values were problematic as both elements require higher energy to transport them due to their higher density. Hence, they are typically found in CSI deposits [2], [10]. It was suggested that these heavier elements, (Ti in particular), were sourced from terrestrial sources and is therefore common in

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soils. Inundation of the 2009 SPT introduced calcareous material and some Ti and Fe, but these were relatively diluted because of the calcium in the deposit. It was assumed that Fe and Ti get transported through river channels to the coast, and are likely deposited beyond the coral reefs. This renders them relatively inaccessible to surface waves and hence there is less of them in the nearshore zone than one might expect [24].

The high Ca concentrations were explained by the deposition of marine calcareous sands high in calcium bearing minerals on top of pre-existing soils [1]. There are no reported limestone outcrops on these islands [29], [30], so high Ca found near the coast is attributed to deposition from a nearby marine source.

Other expected saltwater inundation elements such as sodium, magnesium and chlorine were not present in any of the saltwater inundation deposits investigated. It was suggested that their high mobility coupled with Samoa's tropical climatic conditions limits their retention within saltwater inundation deposits. It was also likely that the investigated sites did not necessarily undergo saltwater ponding and subsequent salt precipitation, hence their absence in the studied deposits. The element sulphur appeared to have high variability between sites, and was assumed to be the result of its mobility in tropical climatic conditions where leaching influences elemental distribution patterns between saltwater inundation deposits and adjacent soils.

These observations, while yet to be fully interpreted in the context of broader factors, form the basis for tentative elemental interpretations at Falealupo, Lano, and Ta'u discussed below.

III. Elemental results

While deposits from the 2009 SPT were not formed at Falealupo, Lano and Ta'u, the preliminary Ca-Fe ratio relationship for the 2009 SPT deposits at Mulivai, Vaovai and Satitoa form a reference standard for interpreting similar relationships at Falealupo, Lano, and Ta'u sites.

A. Falealupo Site

Fig.2 depicts the stratigraphy and Ca-Fe relationships for samples from Falealupo. The trench at Falealupo was located at 13^{0}29.663' S; 172^{0}46.523' W, approximately 165 m inland from the present high-tide water mark. A 3.5 m storm berm (resembling a sand-dune) was located at the coastline; approximately 5 m wide at its base. A depth of greater than 0.5 m was logged at the trench site, with detailed 1 cm sampling down to 20 cm depth, followed by 2 cm sampling down to the base of the trench.

Seven sequences were identified empirically based on changes in sediment characteristics between adjacent sequences. Sequences 2 and 3 in Fig. 2 (A) represents the December 7 – 10, 1991, Cyclone Val, and the February 1 – 4,

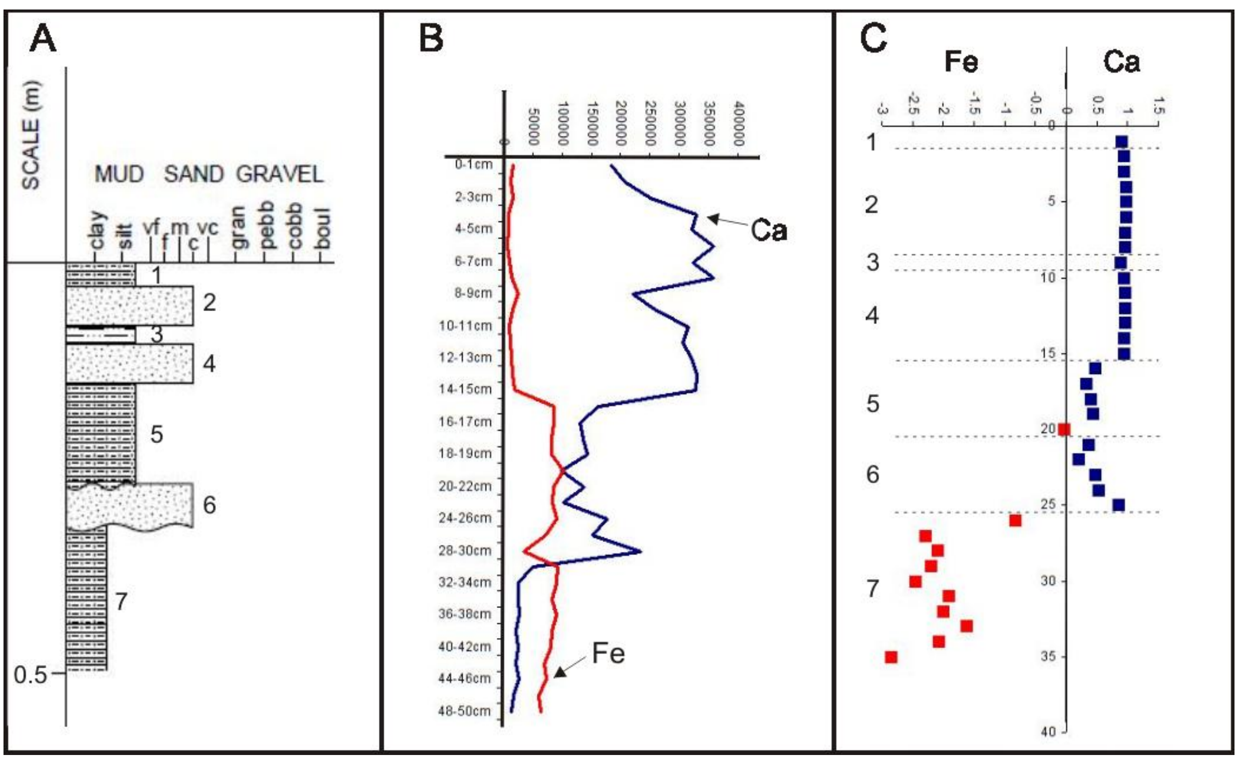

Figure 2. A) Empirical stratigraphic column at Falealupo site showing 7 stratigraphic sequences. Sequences 4 and 6 are assumed to be of tsunami origin; B) Relative calcium (blue) and iron (red) concentration curves for samples obtained from each sequence; C) Calcium-iron difference as a function of calcium [(Ca-Fe)/Ca] for each sample in (B). Positive values indicate more calcium than iron for that particular sample, and vice versa for negative values.

1990, Cyclone Ofa deposits, respectively. These deposits are empirically characterised by poorly sorted, coarse yellow calcareous sand. Cyclones Ofa and Val collectively were the worst category 5 cyclones ever recorded in Samoa within the last 100 years in terms of their socioeconomic impacts [31].

Sequence 4 shown is empirically characterised by coarse greyish-yellow sand comprising organic laminae at approximately 12.5 and 13.5 cm depths. Coral cobbles approximately 4 – 6 cm at their longest axis were also comprised within the deposit matrix. This deposit required higher wave energy to transport these coarser sediments 165 m inland, and is likely to represent the June 25, 1917 tsunami which impacted the Samoa Islands. This tsunami originated approximately 130 km northwest along the same tear-fault region that the 2009 SPT originated [7], [32], and its inundation impacts are believed to have been more geographically widespread across southern and parts of northern Upolu and Savai'i [24].

Sequence 6 represents another saltwater inundation and is empirically characterised by coarse yellow-grey sand deposited between two organic soil layers both comprising sub-angular to sub-rounded boulders 10 – 30 cm at their longest axis. It is assumed that Sequence 6 likely represents a palaeotsunami deposit based on its empirical sedimentary characteristics relative to adjacent palaeosols.

While the sequence deposits discussed have been tentatively identified through empirical means, the distinction between stratigraphic sequences is not so apparent using the Ca-Fe relationship technique. The assumed palaeotsunami identified in stratigraphic sequence 6 shows a very similar Ca-Fe trend to those of the 2009 SPT deposits at Mulivai, Vaovai and Satitoa [24], hence strengthening the likelihood of a tsunami origin for this deposit (Fig. 2, B and C).

The Ca-Fe trend for the deposit at stratigraphic sequence 4, which is tentatively assumed to represent the June 25, 1917 tsunami, does not show a similar trend to the reference 2009 SPT deposit trends. This makes it difficult to use the Ca-Fe relationship in this case as an indicator for the likelihood of a tsunami origin for this deposit. More multi-proxy analysis coupled with geochronological analysis will help elucidate this enigma.

B. Lano Site

Six stratigraphic sequences were identified empirically at Lano (Fig. 3). The 1.5 m core sampled from Lano was located at $13^0$37.176' S; $172^0$11.938' W, approximately 150 m inland of the present high tide water mark.

Stratigraphic sequence 1 (Fig. 3, A) represents the present soil layer, and sequences 2, 3 and 4 are likely associated with deposits from Cyclones Ofa and Val based on their empirical sedimentary characteristics, although further geochronological evidence is required to strengthen this assumption.

Stratigraphic sequences 4 and 5 (Fig. 3, C) likely represents a single deposit from a high energy wave event, and shows a very similar Ca-Fe trend to the reference 2009 SPT deposit trends at Mulivai, Vaovai and Satitoa. Sequence 4 yields a very similar Ca-Fe relationship to the surface mud layers of the reference 2009 SPT deposits [24]. Sequence 5 is assumed to be the calcareous base of the deposit overlain by a surface mud layer as the transportation mechanism lost energy; a very similar characteristic to the reference 2009 SPT deposits. It is likely that this deposit was formed from a tsunami origin, but more multi-proxy evidence is required to elucidate this.

C. Ta'u Site

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 (Fig. 4, A). A sharp contact at approximately 51 cm depth separates the overlying organic soil horizon from the underlying very coarse, grayish-yellow calcareous sand deposit. This deposit also comprised of coral cobbles (branching and brain corals), gastropod and other unidentified shells, as well as rounded basalt cobbles towards the base of the deposit matrix.

Recent category 5 cyclones which have impacted this island had insufficient wave energy to inundate 140 m inland, and hence there is no apparent deposit 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.

The Ca-Fe relationship for sequence 2 in (Fig. 4, C) also shows a very similar trend to the reference 2009 SPT deposit trends. Sequence 2a likely represents the surface mud layer similar to the reference 2009 SPT deposits formed as tsunami energy dissipated. This overlies coarser marine sediment deposited during higher energy wave inundation associated with the same deposition event. However, more multi-proxy analysis is required for a more definitive interpretation.

IV. Preliminary Geochronology Results

Standard C-14 radiocarbon analysis and anisotropy of mass spectrometry (AMS) analysis was conducted at the Waikato Radiocarbon Dating Laboratory (WRDL) on palaesols and other organic material (e.g. plant fragments, wood and coral), from the stratigraphic bases of seven investigated sites. These sites included Mulivai, Vaovai, and Satitoa on the south and SE coast of Upolu, Fagalii on the north coast of Upolu, Falealupo and Lano on the west and NE coasts of Savai'i, and Ta'u village on NW Ta'u in American Samoa. The sites were selected for initial C-14 analysis using limited funding based on the likely saltwater inundation deposits identified empirically, and through their Ca-Fe elemental relationships down their respective stratigraphies. This dating analysis was carried out in order to establish maximum age limits on the sampled profiles from these sites.

Table 1 summarizes the results from this analysis, with the resulting ages and estimated errors presented in years before present (BP). The stratigraphic profile at Satitoa yields the youngest age of 149 +/- 93 BP (i.e. 1862 AD +/- 93 years). This date was obtained from a specimen sampled from the base of an organic soil layer directly overlying an assumed palaeotsunami deposit [24].

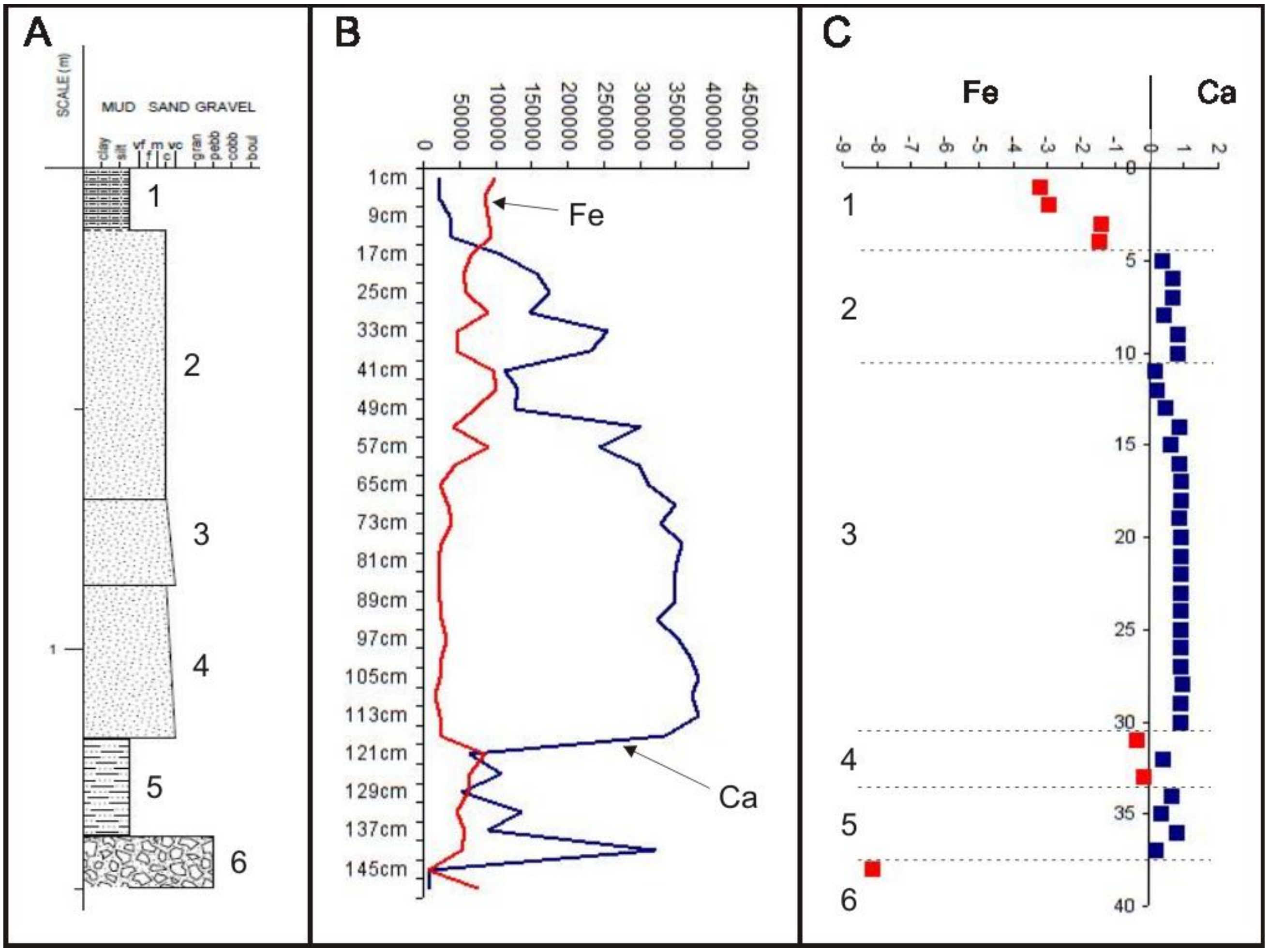

Figure 3. A) Empirical stratigraphic column at Lano site showing 6 stratigraphic sequences. Sequence 5 shown is assumed to be of a tsunami origin; B) Relative calcium (blue) and iron (red) concentration curves for samples obtained from each sequence; C) Calcium-iron difference as a function of calcium [(Ca-Fe)/Ca] for each sample in (B). Positive values indicate more calcium than iron for that particular sample, and vice versa for negative values.

The site at Satitoa was located approximately 280 m inland of the present high tide water mark. Hence, a tsunami origin was assumed the most likely cause for this deposit as cyclone waves do not have sufficient energy to inundate that far inland.

Due to the high uncertainties in the estimated age from this site, it is difficult to narrow down an association with a known tsunami origin. It is likely that this deposit may have formed from the June 25, 1917 Samoa tsunami discussed earlier. The geographical extent of inundation on Upolu and Savaii from this tsunami is believed to have been more widespread than the 2009 SPT. Other likely documented tsunami sources include the August 14, 1868, great Peru earthquake and tsunami which apparently destroyed settlements in Apia, north Upolu. Details on the extent of damage on other parts of the islands were not documented.

Similarly, the May 10, 1877, great Chile earthquake and tsunami may also be a likely source. This tsunami caused devastating damages across the Pacific, although details on the extent of impacts in the Samoa Islands were not recorded.

The standard C-14 age results given for Falealupo in Table 1 were yielded from the base of a 1.0 m core sampled from a swamp approximately 1.2 km southwest of the trench site which the Ca-Fe elemental results discussed earlier were obtained from. This site was located approximately 220 m inland of the present high tide water mark. The AMS results obtained for Falealupo were yielded from the base of the organic soil layer depicted by sequence 7 in Fig. 2. Further C-14 dating will help elucidate the age limits of the assumed palaeotsunami deposit depicted by sequence 6 in Fig. 2. Pb-210 and Cs-137 dating on the assumed 1990 and 1991 Cyclones Ofa and Val deposits, respectively, will aid in elucidating whether those deposits were indeed formed by those events. The standard C-14 age result yielded for Lano was obtained from an unidentified wood specimen located at the base of stratigraphic sequence 6 in Fig. 3.

However, due to in-built age uncertainties associated with unidentified wood samples [33], [34], it is likely that the result obtained is not a true depiction of the age of the stratigraphic profile at this site. This assumption is supported by the AMS

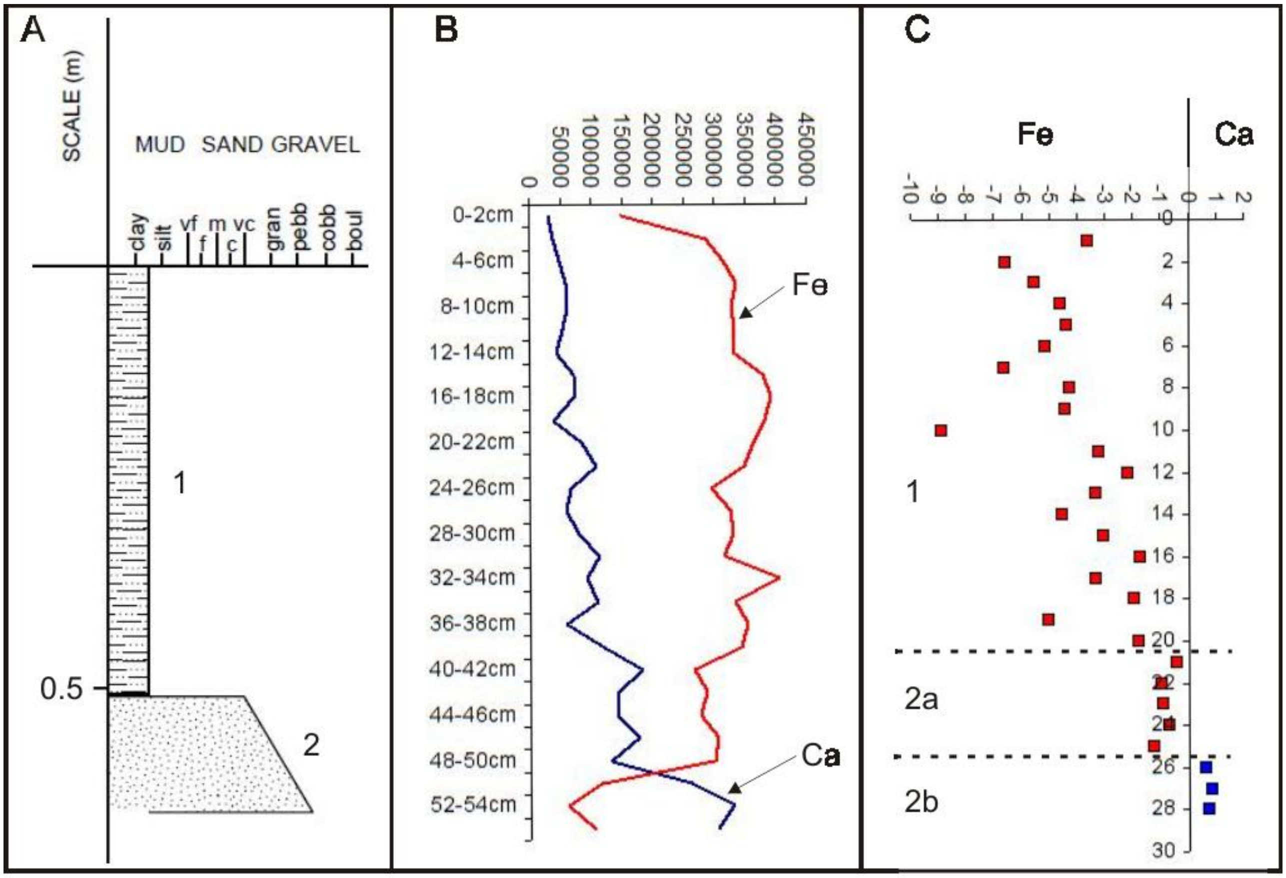

Figure 4. A) Empirical stratigraphic column at Ta'u site showing 2 stratigraphic sequences. Sequence 2 shown is assumed to be a palaeotsunami deposit, and has a higher calcium content relative to iron than the overlying sequence 1; B) Relative calcium (blue) and iron (red) concentration curves for samples obtained from each sequence; C) Calcium-iron difference as a function of calcium [(Ca-Fe)/Ca] for each sample in (B). Positive values indicate more calcium than iron for that particular sample, and vice versa for negative values.

TABLE I. PRELIMINARY RESULTS FOR THE STANDARD C-14 AND AMS RADIOCARBON ANALYSIS

	Site	Location	Sample Material	Sample depth (m)	Result
Standard C-14					
	Satitoa	Coastal marsh	Soil, organics	0.81	149 +/- 93 BP
	Falealupo (core)	Swamp	Peat	0.99	3953 +/- 104 BP
	Lano	Marsh	Unidentified Wood	1.49	1895 +/- 43 BP
	Mulivai	Marsh	Peat	0.92	528 +/- 91 BP
	Ta'u	Marsh	Unidentified Coral	0.65	3661 +/- 41 BP
	Fagalii	Back-swamp	Charcoal	2.86	3112 +/- 51 BP
	Fale o le Fee	Fluvial valley	Charcoal	0.30	398 +/- 73 BP
	Vaovai	Swamp	Unidentified Gastropod	0.67	576 +/- 33 BP
AMS					
	Falealupo (trench)	Marshy swamp	Peat	0.49	829 +/- 28 BP
	Lano	Marsh	Plant fragments	1.39	798 +/- 28 BP

age result yielded from plant fragments sampled from within the assumed palaeotsunami deposit depicted by sequences 4 and 5 (Fig. 3, C), and is held to represent the lower age limit of the deposit. As seen in Table 1, there is an approximate 1000 year age difference between the dated samples from the adjacent stratigraphic sequences 6 and 7 in (Fig. 2, A). This further strengthens the likelihood of in-built age uncertainties associated with the standard C-14 result yielded from the unidentified wood specimen.

The standard C-14 result yielded for Mulivai in Table 1 was obtained peat specimen sampled from the centre of a 16 cm peat layer towards the base of the stratigraphic profile from this site. This layer has been tentatively interpreted as a palaeosol overlying an assumed palaeotsunami deposit identified and discussed in [24]. A similar C-14 age result to that obtained from Mulivai was yielded from an unidentified gastropod sampled from a layer assumed to be associated with a palaeotsunami origin [24]. Based on the proximity of these two sites to each other on the south coast of Upolu, it is possible that their age results represent the approximate timing of a palaeotsunami that impacted them around 528 – 576 BP.

Age results for Fagalii and Fale o le Fee sites given in Table 1 are not directly associated with the objectives of this paper, and are hence not discussed any further. They are listed here for completion purposes.

The age result of 3,661 +/- 41 BP yielded for Ta'u was obtained from an unidentified coral specimen sampled from the base of the stratigraphic sequence (Fig. 4, A). It was initially assumed empirically that this deposit may have represented a relatively recent palaeo-landslide generated tsunami origin (i.e. < 500 BP), associated with the large-scale ocean-island flank collapse on Ta'u island discussed in [23]. While there is still a possibility that this deposit may be associated with the event investigated in [23], this cannot be stated definitively based on the results obtained. Dating a specimen from the base of the organic soil horizon depicted by sequence 1 (Fig. 4, A) will aid significantly in elucidating this enigma.

V. Summary and Directions for Future Work

The Ca-Fe elemental relationship technique presented in [24], for the 2009 SPT deposits at Mulivai, Vaovai and Satitoa proved useful in identifying deposits with similar Ca-Fe elemental characteristics at Falealupo, Lano, and Ta'u. More multi-proxy analytical evidence, including geochronology data, is required to state definitively that the tentatively assumed palaeotsunami deposits identified at the sites discussed in this paper are indeed of a tsunami origin. This is because the preliminary Ca-Fe elemental proxy is incapable of distinguishing between a tsunami or cyclone origin for an identified CSI deposit. Further, while the Ca-Fe elemental relationship for the 2009 SPT deposits are assumed to be a preliminary standard for similar deposits with similar origins, this assumption does not hold true for all coastal areas across the islands due to the differing nature of offshore and onshore geomorphologies. These factors, coupled with wave energy and flow characteristics, determine the nature of material deposited at a particular location. They also influence the extent of inundation inland at a particular coastal location, as well as influence whether a deposit is formed at all from a particular tsunami or cyclone event.

The Ca-Fe elemental proxy does have useful applications in the identification of likely CSI deposits. But, only coupled with a suite of diagnostic proxies can identified CSI deposits begin to be fully interpreted in the context of their origin and likely source and wave characteristics.

Samples from distinct stratigraphic units will be analysed in due course for organic matter content by loss on ignition (LOI), and grain size by laser diffraction using a particle multisizer. Selected sub samples will also be processed for pollen and micropalaeontological (diatoms and foraminifera) analysis. Planned computational modelling using the NEOWAVE numerical tsunami model [35], [36], will provide an additional proxy for interpreting the palaeotsunami data. It will also provide the opportunity for beginning to understand the likely source and wave characteristics associated with identified palaeotsunami deposits. These studies will significantly broaden the diagnostic toolkit for identifying tsunami and cyclone deposits in these islands.

The age results obtained from standard C-14 radiocarbon and AMS dating techniques form a basis for developing the geochronology of stratigraphic profiles from investigated sites. While far from complete, these initial results help provide a semi-quantitative estimation of the lower age limits of the profiles selected for dating. Further C-14 radiocarbon dating is planned for implementation in due course. This will largely complement the initial age results discussed here in that specific age controls will be established for individual tsunami/storm events identified in the investigated stratigraphic sequences.

Further, Pb-210 backup up by Cs-137 dating is also planned for implementation on deposits assumed to be of recent unknown origin (e.g. the assumed cyclone deposits at Falealupo). This will provide a good control on identifying the deposits with known historical events, thus allowing us to refine the diagnostic criteria for distinguishing cyclone and tsunami deposits in a tropical volcanic island setting.

In summary, little is known about the prehistoric record of storms and tsunamis in Samoa, although there is evidence for previous events [37]. A comprehensive study of historically documented deposits will enable us to identify their prehistoric counterparts. Correlating them with events that are recorded elsewhere in the Pacific, such as New Zealand [38], will provide an indication of their broader regional impacts, as well as the risks they pose at the regional Pacific scale. C-14 dating is thus a crucial part of this study, as it will provide the dating control allowing a correlation with known events, and the identification of unknown events. Furthermore, it will be instrumental for determining the extent of the deposits on these Islands. Pb-210 and Cs-137 dating will enable a correlation of deposits with known historical events, providing a control on distinguishing recent tsunami from storm deposits.

Ultimately, this work will significantly improve understanding of the nature and risks of coastal hazards in Samoa, thereby improving local capability to mitigate their medium- to long-term impacts. It will also contribute to tsunami hazard mitigation efforts at the broader regional scale through a strengthened tsunami database in the region.

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