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Chapter

Tsunami Elemental Signatures in the Samoan Islands: A Case Study

Shaun Williams

Abstract

This study uses Itrax X-ray fluorescence element data available for Samoan sediment cores, obtained from three separate locations after the 2009 tsunami in this region, to identify its elemental characteristics in the coastal landscape. Normalization of data using Al reveals a distinct elevated elemental signature for this event at sites which had experienced inundation. This provides benchmarks for identifying comparable signatures in the core profiles which likely represent past tsunamis to have inundated each site. Such information can support a better understanding of the frequency and longer-term threats posed by tsunamis in this region. The findings presented are consistent with benchmark tsunami Itrax observations at Little Pigeon Bay following the 2016 Kaikōura Tsunami in New Zealand. Furthermore, they reinforce the normalization of Itrax element data using Al to interpret tsunami episodes in sediment cores, in addition to using high resolution core scanning as an effective non-destructive tool to screen likely tsunami deposits for more targeted multi-proxy analysis.

Keywords: sediment cores, tsunami deposits, Itrax core scanner, X-ray fluorescence, element characteristics

1. Introduction

Tsunami deposit studies involve the application and use of a wide range of interdisciplinary techniques including, but not limited to, geology, stratigraphy, geochronology, geochemistry, geophysics, numerical modeling, sedimentology, micro- and macro-paleontology, geography, geomorphology, historical and ethno-historical studies, archeology, statistical and contextual studies [1]. Such studies can support an understanding of the long-term hazard frequency as well as potential magnitude, sources, and risk of tsunamis in coastal areas. These in turn can help to underpin long-term coastal resilience planning in vulnerable locations.

Identifying past tsunami deposits in sedimentary records typically requires multiple characteristic criteria to be met [2]. For example, tsunamis can deposit distinct sedimentary units which can extend up to several kilometers and fine inland and upwards within the deposit. Similarly, distinct elevations in elemental concentrations of sodium, sulfur and chlorine (which are salinity indicators) can be observed in tsunami deposits relative to underlying and overlying sediment units. Deposits are typically preserved in coastal settings such as wetlands, which absorb wave energy and enable sediment to settle out of suspension as the tsunami wanes to normal sea level. The use of trace element, principal component, radiometric and isotope analysis to help distinguish marine from terrestrially sourced sediment and determine the ages of specific sediment units can help to constrain a tsunami layer. A more detailed description of these examples, including a comprehensive list of tsunami deposit characteristics can be found in [1–8].

The use of geochemical proxies to characterize modern tsunami deposits and identify paleo-events has gained widespread use within the last few decades [3]. These include the characterization of elemental and magnetic susceptibility transitions in sedimentary sequences, isotope signatures, electrical conductivity and salinity [3]. In addition, such proxies have also been used to characterize the extent of tsunami inundation in areas which lack sedimentary transitions visible to the naked eye. For example, in [4–8].

A tool which has become more frequently used in tsunami deposit studies is the Itrax core scanner [9, 10]. The Itrax is a non-destructive, multifunction core scanning instrument which produces high-resolution X-ray fluorescence (XRF) elemental and magnetic susceptibility data, as well as optical and radiographic imagery. This enables the detection of very fine-scale elemental transitions in core sequences [9].

Raw Itrax elemental data of sediment cores from highly organic environments are subject to inherent uncertainties associated with organic dilution, matrix and instrumental effects [11–14]. However, organic dilution affects the raw datasets due to the closed-sum effect which in turn, can affect analytical interpretations if it is not adequately accounted for [11]. Normalization against Al can provide an organic-filtered dataset representative of the lithogenic faction of the sediment, which is more reliable for tsunami interpretation [8, 11]. Itrax studies of tsunami deposits prior to the results presented in [8] had not accounted for organic dilution in the datasets, often resulting in ambiguous Itrax interpretations of tsunami episodes.

In this study, available Itrax data for sediment cores collected from the Samoan Islands following the 2009 tsunami in this region [15, 16] (**Figure 1**), are normalized against Al and compared with tsunami Itrax observations at Little Pigeon Bay following the 2016 Kaikōura tsunami in New Zealand [8]. A distinct elevated elemental signature associated with the 2016 event was observed at Little Pigeon Bay, with comparable signatures representing characteristic types of events deeper in the sedimentary record. This provides a basis for reviewing the Samoan datasets to assess whether comparable trends are observed for the 2009 event. Distinct elevations in bromine (Br), chlorine (Cl), sulfur (S), calcium (Ca), iron (Fe), silicon (Si), titanium (Ti), rubidium (Rb) and potassium (K), are particularly targeted as these elements are known to represent marine influences [17, 18]. The findings are discussed with conclusions provided in the context of tsunami deposits and longer-term hazards in this region.

1.1 The 2009 tsunami in the Samoan Islands

The 2009 tsunami in the Samoan Islands deposited a distinct sedimentary unit in much of the coastal areas it inundated [2, 16]. The southern and eastern coastlines of Upolu Island were particularly affected [15]. In most cases, sediment deposited by the event comprised of distinct marine-derived calcareous sand units overlying dark brown and/or loamy pre-event soils. Most of these generally displayed an upwards fining within the unit from coarse sand to mud, and were commonly preserved in inundated coastal wetlands where water stagnation up to several days after the event was observed in some areas. These deposits also displayed distinct elemental elevations compared with underlying pre-event soil units as determined through coarse portable XRF (pXRF) analysis, in addition to marked changes in grain size [19].

This provides a reference for corroborating distinct elevated elemental signatures for this event in this study, and for interpreting potentially older tsunami

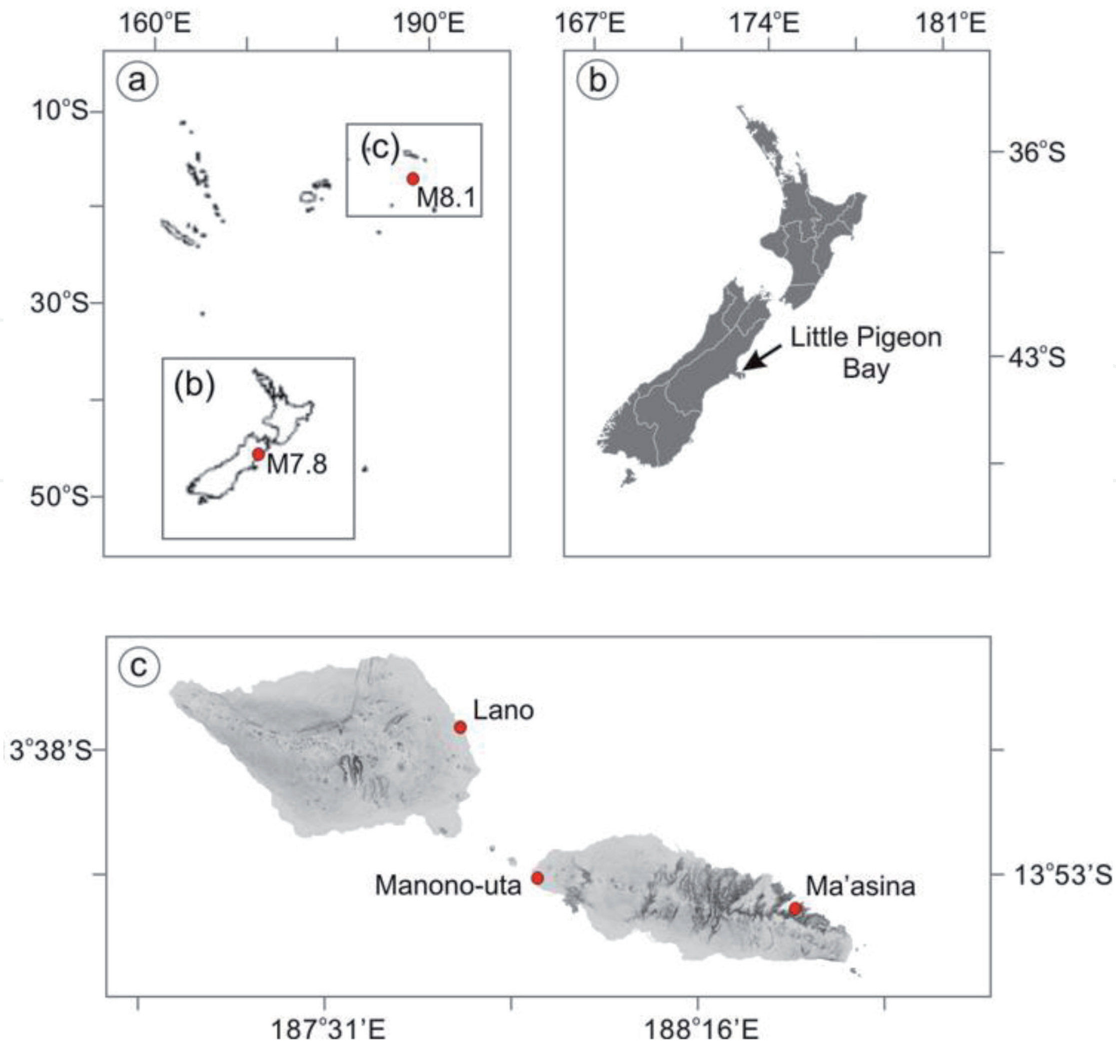

Figure 1.
(a) Location of New Zealand and Samoa in the Southwest Pacific showing the 2016 M7.8 Kaikōura earthquake and 2009 M8.1 Samoa-Tonga earthquake locations. (b) Little Pigeon Bay site, New Zealand. (c) Core site locations in the Samoan Islands. Detailed descriptions of the Little Pigeon Bay site and core profiles are provided in [8], with the Samoan sites and profiles provided in [16, 19].

episodes in the core profiles. For example, an interpreted older episode in a core profile might comprise of a distinct calcareous sand unit bound by an upper and a lower soil unit, and which displays distinct elevated elemental signals relative to the adjacent soils that are comparable to the 2009 tsunami signature.

2. Methods and materials

2.1 Study area and sampling

The data used in this study were obtained from three cores which were sampled in November 2010 using a hand-held D-Corer from three separate locations; (1) 0.7 m core extracted ~20 m inland of the shore at Ma'asina (S1); (2) 2 m core extracted ~75 m inland of the shore at Manono-uta (S2); and (3) 1.5 m core extracted ~150 m inland of the shore at Lano (S3) (**Table 1**).

The cores were sampled from coastal wetlands inland of the shore, and for the case of Manono and Ma'asina, these wetlands were exposed to inundation during the 2009 tsunami. At Ma'asina, a discernible calcareous sand deposit was observed between 0.4–0.8 m depth in the core. The embayment which this area is located has been impacted in the past by far-field tsunamis such as the 1960 Valdivia

Site	Coordinate location	Distance from shore (m)	Elevation above mean sea level (m)	Core length (m)	Sample environment (m)
Lano	13037.176′ S; 172011.938′ W	150	8	1.5	Coastal wetland
Ma'asina	13056.607′ S; 171033.585′ W	40	8	0.7	Coastal wetland
Manono-uta	13052.120′ S; 172004.263′ W	75	3	2.0	Coastal wetland

Table 1.
Core site locations and descriptions used in this study.

tsunami and 1952 tsunamis originating from the Chile/Peru region, and the 1957 tsunami originating in the Aleutian Islands. However, a distinct calcareous sand unit indicative of the 2009 event was not discernable to the naked eye at the surface of the core.

No discernible calcareous sand deposits were observed in the Manono-uta core, though distinct changes in grain size, organic content (loss on ignition) and indicative pXRF elemental compositions comparable with the characteristics of the 2009 tsunami deposits on eastern Upolu were reported in [19]. At Lano, a distinct calcareous sand deposit was observed at ~1 m depth intercalated between dark brown soil units.

2.2 Itrax data and analysis

Itrax XRF involves the excitation of a sample by X-rays using either a molybdenum (Mo) or chromium (Cr) anode X-ray tube, causing the sample to fluoresce. That is, the sample emits secondary X-rays that are distinctive of the elements which they were emitted from. The relative intensity of these fluorescent signals provides an indication of the elemental composition of the sample [9, 10]. The Mo- tube is commonly used in most applications and is more appropriate for detecting heavier elements, while the Cr- tube more adequately detects lighter elements. For example, Al and Si. Nevertheless, an X-ray exposure time of approximately 10–20 s on the sample using a Mo- tube and the Itrax Q-spec procedure is adequate for obtaining acceptable data for these light elements [10].

Itrax elemental data used in this study were initially presented in [19] and were obtained in 2012 using the Itrax core scanner at the Australian Nuclear Science and Technology Organisation (ANSTO). The scanner was fitted with a Mo- tube and a magnetic susceptibility meter, with XRF scans performed on each core at 30 kV and 55 mA using 10 s exposure time and sampled at 500 μm step size. In comparison, Itrax analysis of the Little Pigeon Bay cores were carried out using similar settings at the University of Auckland [8], with a negligible difference of 4 s exposure time between the two datasets [20].

The samples were air dried and the surfaces cleaned to minimize water content and matrix effects in the core prior to analysis. Data quality was ensured through normalization against the Al detected for each core, with profile gaps resolved through interpolation by a moving average curve. This enabled more meaningful trends to be observed in the core sequences. Identified elevated elemental signals relative to adjacent units were compared for consistency with detected changes in unit stratigraphy, grain size, loss on ignition (indicative of organic content if the changes are greater than 5%), and pXRF results for these cores, provided in [19].

2.3 Tsunami deposit identification

Normalized data was used to identify distinct elevated elemental signals in the core profiles comparable to benchmark tsunami signatures provided in [8]. Elevated signals at the surfaces of the Ma'asina and Manono cores are particularly screened for benchmark signatures indicative of the 2009 tsunami. Identified elevated elemental units are compared with descriptions of sites, core stratigraphies, and analogue tsunami deposits of the 2009 tsunami in [16, 19], to interpret distinct tsunami episodes in the core profiles.

3. Results and interpretations

The Samoan cores show comparable elemental profile trends to those observed at Little Pigeon Bay when normalized against Al (**Figure 2**). At Little Pigeon Bay, a sharp sedimentary contact denoted by distinct elevations in elemental levels

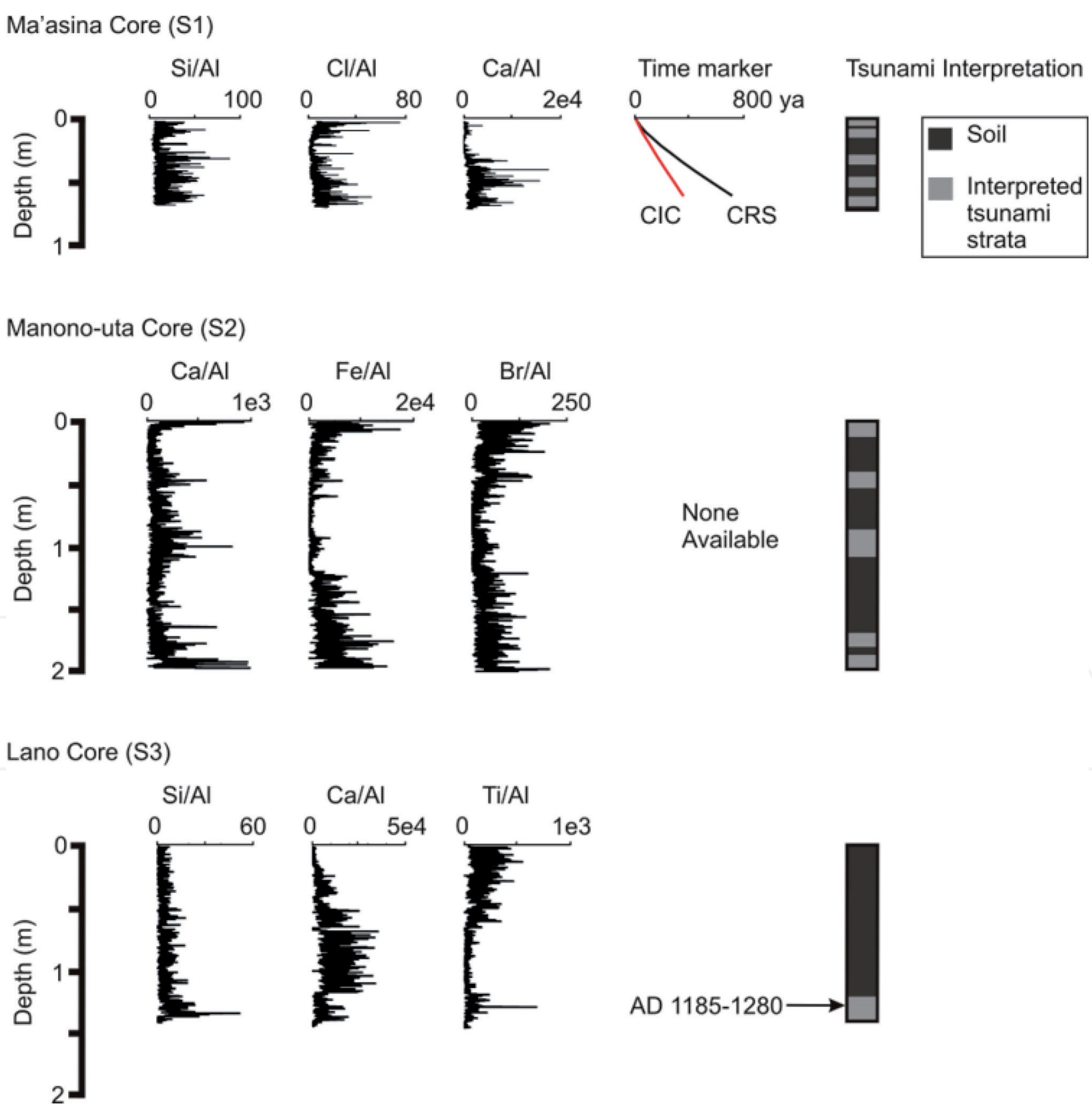

Figure 2.
Selected Itrax data (normalized over Al) for profiles S1 (Ma'asina), S2 (Manono-uta) and S3 (Lano). Time markers shown at Ma'asina are based on ^{210}Pb constant initial concentration (CIC) and constant rate of supply (CRS) ages up to 11 cm profile depth provided in [19] and are forecast using a power function curve. Calibrated ^{14}C age shown at Lano was sourced from [19]. All time markers presented are indicative only and provide tentative benchmarks for interpretation.

associated with the 2016 event directly overlies the pre-inundated sediment surface. This provided a benchmark tsunami signature at this site, with similar characteristic signals observed deeper in the cores [8].

However, significant data gaps are observed in the Samoan profiles, especially the Lano and Manono-uta cores. These gaps are associated with the Al counts approaching detection limit and/or non-detection. In contrast, the non-detection of Al in the Ma'asina core accounted for only 7% of the total dataset compared with 61 and 63% for the Lano and Manono-uta cores, respectively.

At Manono-uta, distinct elevated signals are observed at ~0.06 m depth for most of the detected elements except Si. The Si trend exhibits a relatively low and stable background elemental signal with no discernable changes in the profile, indicating that offshore and terrestrial sources for Si are not abundant at this site. Manono-uta was inundated by the 2009 tsunami with flow depths up to 2 m in some areas, including the core site in this study, with the elevated signals at the core surface likely representing the elemental signature of this event. Characteristic signals deeper in the profile which appear lower in magnitude than the 2009 signature are likely representing: (1) smaller events; (2) other types of coastal processes (e.g., storm surge or rainfall-related flooding); and/or (3) artifacts associated with interpolation and matrix effects.

Comparable trends are observed at Ma'asina where a distinct elevated signal occurs at ~0.05 m. This site was also inundated during the 2009 tsunami which suggests that the elevated signal is representing this event. ^{210}Pb ages available for this core in [19] suggests that similar signals observed at depth could be representing historical tsunamis such as the 1960 Valdivia tsunami, or storm surges which are known to have impacts this area (such as the 1991 Tropical Cyclone Val).

At Lano, elevated elemental signals are not apparent at the surface of the core. Compared with the sites at Manono-uta and Ma'asina, this site was not inundated during the 2009 tsunami [15], thus a signal for this event would not be expected. Interestingly, a strongly elevated signal is observed at 1.4 m which is consistent with a distinct calcareous sand unit described in [19]. An available calibrated ^{14}C age of AD 1185–1280 at 1.39 m obtained from plant fragments within this unit [19], indicates that a potentially significant inundation event might have occurred during, or after, this period.

4. Discussion

Normalization of data against Al in the Samoan cores reveals similar characteristic profile trends analogous to the findings in the Little Pigeon Bay study. This includes the identification of a distinct elemental signal of the 2009 tsunami event at Manono and Ma'asina. While data gaps associated with detection limits and low Al count rates are present in each of the profiles, the interpolated plots provide an adequate means to identify distinct elemental signals that are indicative of sudden and/or distinct influences in the coastal landscape.

The 2009 tsunami benchmark signals identified at Manono-uta and Ma'asina are unique in that they were not clearly detected during initial analysis of these cores in [19]. The characteristic signals deeper in the core at Ma'asina probably represent historical tsunamis that are known to, or may have, inundated this site. Potential candidates include the far-field 1960 Valdivia Tsunami, 1957 Aleutian Tsunami, and possibly the local 1917 Samoa-Tonga and far-field 1868 Arica Tsunamis [19] (**Figure 3**).

The lack of benchmark elemental signatures for storm surges in these Islands makes it difficult to associate any of the signals detected in this study with tropical cyclones. Furthermore, the distance of each core site from the shore makes it more likely that the signals detected deeper in the cores are representing older and/or

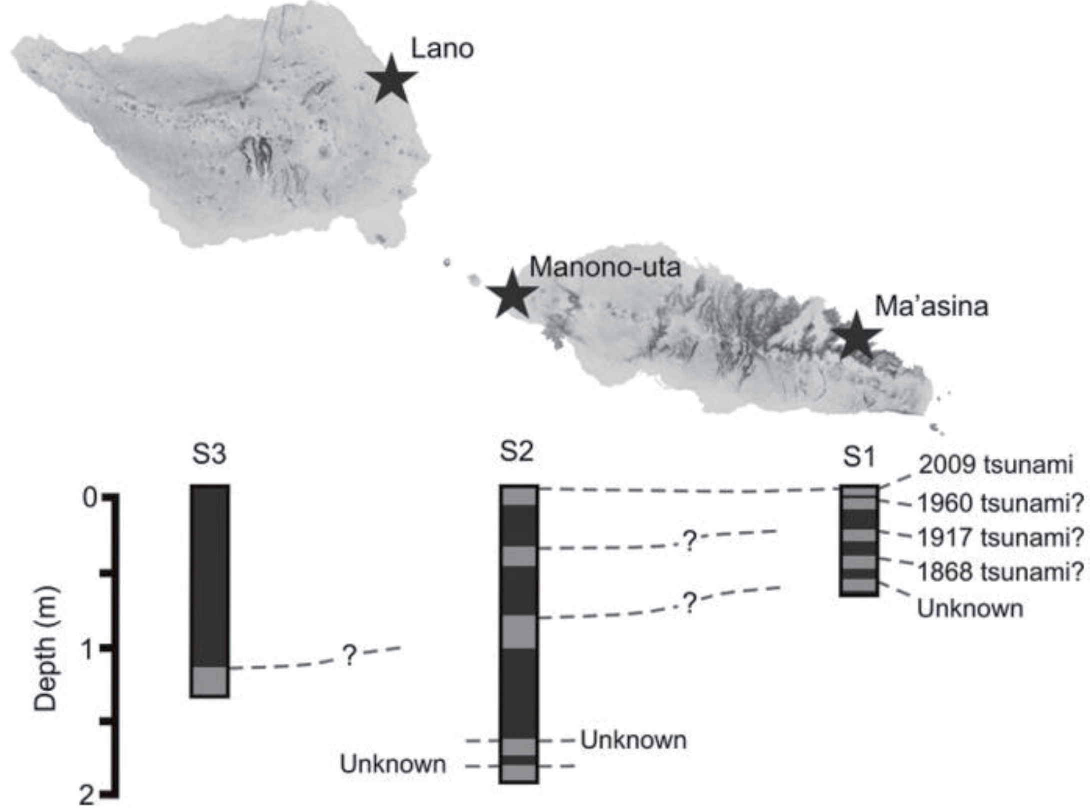

Figure 3.
Interpreted tsunami associated strata in the Samoan cores based on elemental signatures and available geochronological time markers.

unknown tsunami events. However, it is possible that smaller signals than the 2009 benchmark could be representing storm surge inundation.

At Manono-uta, tsunamis to severely inundate this site and leave a signature in the landscape are more likely to be associated with events approaching from southerly directions. It is therefore probable that the characteristic, though weaker, signal observed at 0.45 m depth is representing the local 1917 event, which may have had similar impacts to the 2009 event [21]. However, a definitive correlation is difficult without chronological time-markers at this site.

The relative depth of the AD 1185–1280 (or younger) potential event, denoted by the strong signal at 1.4 m depth in the Lano core, compared with characteristic signals at 1.9 m in the Manono-uta profiles, suggests a possible event association. The depth which these signals occur implies that they are older than the deepest signal exhibited at Ma'asina. However, despite the short core length obtained from Ma'asina, extrapolating the range of available ^{210}Pb time-markers for this site in [19] suggests that the deepest signal could represent an inundation event up to several centuries ago. Furthermore, the signals detected at Ma'asina likely corroborate this embayment providing favorable conditions for preserving evidence of both local and far-field tsunamis to impact this region.

While potentially major regionally and far-field sourced transpacific paleotsunamis have been suggested in the literature [22, 23], a distinct association between such events with the signals detected in the Samoan cores is ambiguous given the limited time markers available. Nevertheless, it is probable that if a major transpacific tsunami sourced at the Tonga-Kermadec zone had impacted the Samoan Islands, it would have left a distinct elemental signal in the landscape similar to, or stronger than, the 2009 signature. The occurrence of strong elemental signals at depth in Manono-uta and Lano suggest that these sites experienced a significant inundation event at some point in the past. Whether these are representing the same event and whether they signify the extent of a major transpacific or a more localized event similar to the 2009 and 1917 tsunamis, is unclear and requires more detailed investigation.

Importantly, due to non-detection of Al and subsequent data gaps, the Lano and Manono-uta sites are only providing true representations of 39 and 37% of their total analyzed profiles, respectively, compared with 93% for the Ma'asina site. While interpolation enables more meaningful elemental profiles to be produced, it is likely that fine-scale signals at Lano and Manono-uta are diluted and not adequately represented. Consequently, the interpretations presented for these sites should be used with care.

5. Conclusion

This study set out to reassess available Itrax elemental datasets for the Samoan Islands to determine whether an elemental signature associated with the 2009 tsunami in this region is observed. After normalization of the Itrax data against Al, a distinct elemental signal for this event is identified at two of the three core sites reassessed, which provided benchmarks for identifying older potential events at each site. The dearth of evidence for tropical cyclone-related elemental benchmarks in these islands, particularly >20 m inland of the shore, limits the association of any of the detected signals with potential storm deposits. Future investigations involving isotope geochemistry and principal component analysis of likely sources would help to clarify this.

The results presented in this study are consistent with tsunami Itrax observations in the Little Pigeon Bay study, and highlights the importance of normalizing Itrax data using Al in tsunami deposit investigations. This enables a more accurate representation of tsunami elemental signatures in core profiles, and for the case presented in this study, enables an interpretive improvement of tsunami episodes compared with previous studies on these cores. The significant data gaps in the Lano and Manono-uta elemental profiles associated with low Al detection, limits their use in accurately interpreting older potential events at these sites.

Nevertheless, the findings in this study reinforce the use of high resolution Itrax elemental data as an effective tool for characterizing and identifying tsunami inundations in the coastal landscape. Furthermore, they demonstrate the potential for elemental signatures to be used as a rapid screening tool to target more detailed multi-proxy investigations of identified signals, including their potential sources and longer-term hazard implications.

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Conflict of interest

None.

Notes

Readers should also refer to citations contained within the references listed below for additional details, where relevant, on various aspects presented in this chapter.

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