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Flank-collapse on Ta'u Island, Samoan Archipelago: Timing and hazard implications

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Abstract A discrepancy between the cartographic depiction of Ta'u Island, Samoan archipelago, in 1849 and its present geomorphology, leads to the impression that a massive collapse involving an estimated 30 km^3 occurred on the island's southern flank less than 170 years ago. It is likely that this flank-collapse, whenever it occurred, generated a tsunami with regional impacts. Here we apply exposure dating to the remnant landslide scarp using the cosmogenic nuclide ^{36}Cl, to show that the flank-collapse occurred 22.4 ± 1.8 ka during the last glacial maximum (LGM). Collapse may have been triggered due to volcanic-related processes, but it is also possible that climatic-eustatic sea-level during the LGM may have played a role in influencing failure of the flank. We confirm that the initial cartographic depiction of Ta'u in 1849 was incorrect, and that this prehistoric landslide-tsunami was not a societal hazard at the time of its occurrence. This is because the Samoan and surrounding Island Nations were only inhabited about 3 ka or so. Nevertheless, we suggest that geomorphic features similar to the Ta'u flank-collapse on analogous islands and seamounts in the Pacific likely represent signatures of landslide-tsunamis in the past. We conclude that there is a need to identify and date other such features in the Pacific, in order to further our spatial and geochronological understanding of these events. There is also a need to identify flank features that have not yet failed, and assess the likely mechanisms that could potentially trigger failure. By doing this, we can start assessing with more confidence the hazard potential of similar flank-collapses in future – a risk that is presently under-represented.

Keywords flank-collapse, ^{36}Cl, exposure dating, Samoa

Introduction and Background

Ta'u is the easternmost volcanic island in the Samoan archipelago, South Pacific, and lies within the Manu'a Group of American Samoa (Fig. 1a). It is the youngest island formed from the Samoan volcanic hotspot, which currently lies about 45 km to the East (Hart et al. 2000; Hart et al. 2004).

Geologically, it is in its shield-building stages of volcanism which commenced about 300 ka (Natland and Turner 1985; Hart et al. 2004; Koppers et al. 2008). However, the nature of the 1866 – 1867 submarine eruption of Pomasame volcanic cones reported in Turner (1889), is not well understood (Williams 2009). These cones were mapped during surveys reported in Fenner et al. (2008), and lie about 2 km NW of Ta'u along the submarine ridge connecting it to neighbouring Ofu and Olosega islands (Fig. 1b).

The southern flank of Ta'u exhibits a series of down-faulted benches which are likely remnants of a large-scale flank-collapse involving an estimated 30 km^3 (Williams 2009; Williams et al. 2012). Further, it was recognized that this flank-collapse could have occurred more recently than the year 1839 (Williams 2005 and 2009; Williams et al. 2012); although there was little tsunami evidence in the historical record to suggest it did (NGDC and ITIC 2010).

The likelihood of a recent historical collapse stemmed from the cartographic depiction of Ta'u in Wilkes (1849) and Turner (1889) (Fig. 1c, 1d). The island was depicted as having a much more symmetrical geomorphic structure that its present day planform (Williams 2009; Williams et al. 2012) (Fig. 1e, 1f). Further, the depictions were based on the initial survey data of Ta'u collected on October 8-10, 1839, and the island was described as having the form of a regular dome (Dana 1849; Wilkes 1849; Turner 1889).

Geomorphic interpretations in Williams (2009) and Williams et al. (2012), suggested that the collapse occurred after the LGM sea-level low-stand, which was assumed to have been ~18 ka. The estimated volume of material that would have collapsed based on the Ta'u depiction in Turner (1889) was about 30 km^3, and would have most likely generated a tsunami with regional impacts.

Conservative numerical modeling of the likely event in Williams et al. (2012) strengthens this landslide-tsunami hypothesis. However, it was suggested that if

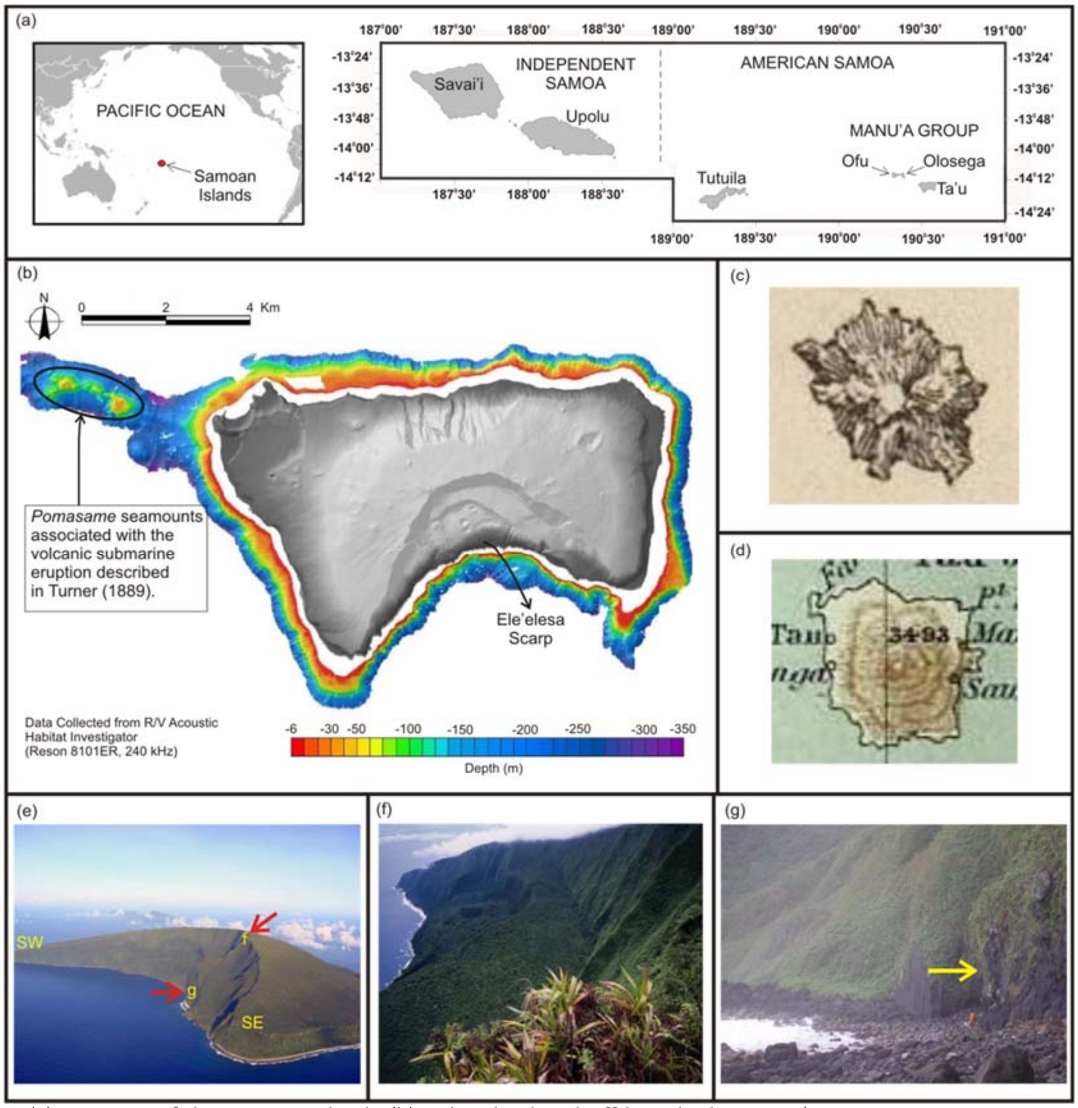

Fig. 1 (a) Location of the Samoan Islands (b) Ta'u Island and offshore bathymetry (Map source: American Samoa Department of Wildlife and Conservation) (c) Depiction of Ta'u in Wilkes (1849) based on 2 days of survey data collection in October 1839 (d) Depiction of Ta'u in Turner (1889) based on survey data of Wilkes (1849) (e) South flank of Ta'u (Photo by Michael Tenant) (f) Summit (~925 m), view looking west (Photo by Mark Rauzon) (g) Sampled outcrop in this study.

Table 1 Site Data.

Sample (Field Code)	Longitude (⁰W)	Latitude (⁰S)	Altitude (m)	Horizon Correction	Thickness (cm)[1]
TAVI-06	169°26'50	14°14'56	8	0.50	5.5

1. ρ = 3.0 g.cm^{-3}; Λ = 160 g.cm^{-1}

Table 2 Major element data (wt.%).

SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MgO	MnO	CaO	K_2O	Na_2O	P_2O_5
50.74 ± 0.31	13.11 ± 0.14	9.91 ± 0.09	3.69 ± 0.10	6.39 ± 0.05	0.14 ± 0.004	12.47 ± 0.12	0.78 ± 0.03	2.63 ± 0.30	0.04 ± 0.001

Table 3 Trace element data (ppm).

[B][1]	[Cl]	[Sm]	[Gd]	[Th]	[U]	cross section (10^{-3} cm^2 g^{-1})
5.0 ± 2.0	54.4 ± 1.2	7.62 ± 0.04	7.44 ± 0.07	3.23 ± 0.10	0.72 ± 0.02	7.84 ± 0.10

1. Estimated from similar rocks

Table 4 ^{36}Cl exposure ages.

Field Code	Lab Code	[^{36}Cl]$_c$ (x10^4 g^{-1})[1]	[^{36}Cl]$_r$ (x10^3 g^{-1})[2]	Exposure age (ka)
TAVI-06	ANU-225-19	5.84 ± 0.435	4.88 ± 0.19	22.4 ± 1.8

Data are normalised to the GEC standard (^{36}Cl/Cl = 444 x 10^{-15}). Carrier ^{36}Cl/Cl = <1 x 10^{-15}. ^{36}Cl decay constant 2.3 x 10^{-6} yr^{-1}.
1. C = cosmogenic component
2. R = nucleogenic component

the event was younger than 1839, the impacts of the tsunami would not have gone unnoticed by local inhabitants. The absence of any such event occurring within recorded history (both written and oral), led to the suggestion that the event was much older than 1839, and that the depiction of Ta'u in Wilkes (1849) was incorrect.

Here we investigate this hypothesis. We use ^{36}Cl cosmogenic surface exposure dating of a basalt sample obtained from the Ele'elesa scarp to infer the likely age of the collapse. We discuss the implications of the result with respect to the depiction of Ta'u in Wilkes (1849), as well as to the associated geo-climatic context of collapse occurrence. The nature and implications of the event in a regional hazard and risk context is also considered.

Methods and Results

Field sampling

A basalt sample was obtained from a massive outcrop on the Ele'elesa scarp (Tab. 1 and Fig. 1g), which is the lower expression of the collapsed block mass that formed the south flank benches.

^{36}Cl cosmogenic surface exposure dating

The extraction of ^{36}Cl was undertaken at the Exeter Cosmogenic Nuclide Laboratory at the University of Exeter. Total ^{36}Cl was measured on the whole rock because the fine-grained nature prevented effective mineral separation. The concentrations of major target elements for ^{36}Cl production were determined using X-ray fluorescence. The concentrations of trace elements with large neutron capture cross sections (Gd, and Sm) and neutron-producing elements (U and Th) were measured by inductively-coupled plasma mass spectrometry. Chlorine content was determined by isotope dilution. The isotopic ratio of ^{36}Cl/Cl was measured by accelerator mass spectrometry on the 14UD accelerator at the Australian National University (Fifield et al. 2010). Major and trace element abundances and neutron capture cross sections are listed in Tab. 2 and Tab. 3.

The ^{36}Cl exposure age was calculated as detailed in (Barrows et al. 2013) (Tab. 4). The production rate was scaled using the scheme of Stone (2000). All analytical errors are fully propagated, and the age in the text is reported at one standard deviation (68% prob.).

Discussion and Interpretations

Timing of collapse

The ^{36}Cl exposure age was calculated at 22.4 ± 1.8 ka and is interpreted to be indicative of the timing at which the scarp was first exposed to cosmic rays after flank collapse. This assumption is based on the location of the sample relative to the implied collapsed-mass deduced from Wilkes (1849) (Fig. 2). If the collapse was younger than 1839, then the scarp which the sample was obtained would have only recently been exposed to cosmic rays. That is, it is likely to have been less than a few hundred years old or so.

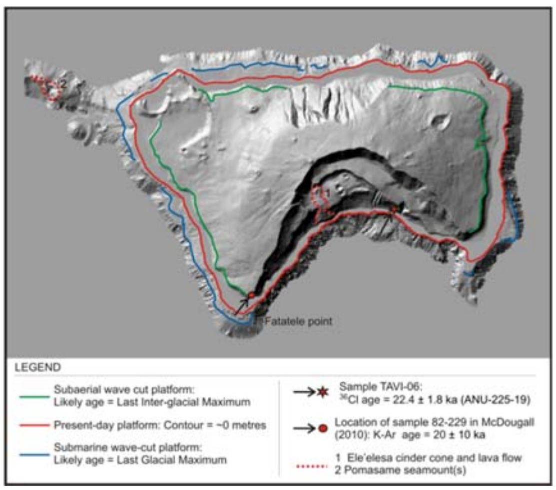

Fig. 2 Digital elevation model of Ta'u showing locations of reported ages and geomorphic features (DEM data obtained from the National Park of American Samoa).

The calculated exposure age of 22.4 ± 1.8 ka is unambiguously much older than 1839. This implies that there is a 68% probability that collapse occurred between 24.2 – 20.6 ka [this is obvious from the maths]. Nevertheless, this corroborates the suggestion in Williams et al. (2012) that the initial depiction of Ta'u in Wilkes (1849) could have been incorrect.

The proposed maximum relative collapse age of ~18 ka in Williams et al. (2012), was suggested based on geomorphic indicators. Subaerial and submarine wave-cut platforms assumed to represent the last interglacial and glacial sea-level high- and low- stands, respectively, are both absent on the southern flank. It was thus inferred that the collapse occurred after the formation of the more recent submarine wave-cut platform; which may have formed during the LGM-associated sea-level low-stand.

The timing of the collapse is also associated with the K-Ar age of a basalt sample (Sample Lab Code 82-229) collected from the densest part of the least weathered lava flow from the southwest coast at Fatatele point reported in McDougall (2010). An age of 20 ± 10 ka at one standard deviation was obtained for the sample. This indicates that the island was volcanically active around that time; which was interpreted to be pre-collapse in age.

Nature of collapse

The association of the collapse with the timing of the LGM is interesting. The LGM is the most recent period in Earth history characterised by global ice-sheet maximums and sea-level and temperature minimums (Lambeck et al. 2001; Clark et al. 2009).

Paradoxically, it is generally accepted that large-scale volcanic flank collapses typically occurred during (or associated with the onset of), warmer, wetter, interglacial period climates and rising sea-levels (McMurty et al. 2003; McGuire 2012).

However, McGuire (2012) cautioned that this acceptance does not dismiss the likelihood of collapses occurring during colder, drier climates and lower (or rapidly falling) sea-levels. He suggested that a sudden reduction of the buttressing effect as huge volumes of water were removed from the flanks of a volcano would favour collapse. Rapid changes between cold and dry to warm and wet climates, and vice-versa, were also suggested to have an effect on rapid sea-level changes which in turn would increase collapse potential. This process though is ambiguous, because there is little evidence to suggest a distinct association between rapid climatic-eustatic sea level changes and their influence on collapse behaviour.

Nevertheless, the interpretation here that the Ta'u collapse occurred after sea-level reached its minimum at this site likely suggests that it occurred during the onset of warmer climes and rising sea-level; even though post-LGM sea-level rise is thought to have only commenced about 16 ka (Lambeck et al. 2001). Further investigation is needed to elucidate this enigma.

The likelihood of the collapse being triggered by an earthquake was investigated in Williams (2009). It was suggested that the potential for collapse being triggered by an earthquake with similar peak ground accelerations (0.4 g) to those in Samoa's seismic history was low. However, this interpretation did not account for the long-term effects of earthquakes experienced over geologic time. As such, further investigation is needed to understand the likely long-term seismic influence on collapse potential.

In Williams et al. (2012), it was suggested that the lava flows from the intra-caldera cinder cone which flow over the Ele'elesa scarp were possibly indicative of an association between the eruption and the collapse. Although this could be the case, it is also likely that the eruption could be much younger. In the absence of a geochronological age for this eruption, an association between the two cannot be stated definitively.

Conversely, the collapse age is associated with the timing of likely active volcanism in the area reported in McDougall (2010). His suggestion that the timing of this volcanism was pre-collapse in age is also likely; implying that volcanic-related processes may have been associated with triggering the collapse. However, the large uncertainty of ± 10 ka for the age of this volcanism limits a definite association with the ^{36}Cl collapse age reported here.

Illations and Hazard Implications

We interpret the ^{36}Cl surface exposure age of 22.4 ± 1.8 ka to be indicative of the age of the Ta'u flank collapse. Further, we surmise that the depiction of Ta'u as a complete edifice in Wilkes (1849) was incorrect. It is likely that the time spent in the field surveying the Manu'a Group in October 1839 was most likely insufficient to gather accurate data from Ta'u, leading to the inaccuracies in its depiction.

Current available geochronological and geomorphic evidence in Williams (2009), McDougall (2010), Williams et al. (2012) and this study, suggests that a volcanic-related mechanism is likely to have been responsible for triggering the collapse. Dating the upper and adjacent scarps as well as the Ele'elesa cinder cone flow would aid in elucidating this dilemma.

Whilst we recognise that climatic-eustatic conditions during the LGM may have played a role in influencing flank failure, the potential for these processes to trigger collapse is not well understood. More investigation is needed to understand, verify, or dismiss the likely associations.

The landslide-tsunami associated with the collapse modelled in Williams (2009) and Williams et al. (2012), is confirmed to not have been a hazard at the time of its occurrence. This is because the Samoan and surrounding Island Nations were first inhabited about 3 ka or so (Petchey 2001; Bedford and Sand 2007).

Nevertheless, evidence of likely active volcanism associated with the timing of the collapse (McDougall 2010; Williams et al. 2012), coupled with the recent eruption of the Pomasame submarine cones in 1866 – 1867 (Turner 1889), imply that volcanism could presently be in a temporary state of quiescence. Thus there may be a present and future eruptive hazard. Coupled with the understanding that large-scale flank-collapses typically occurred (or tend to occur) during warmer, wetter, interglacial climates comparable to present and projected conditions (McGuire 2012), the likelihood of a future collapse exists.

Further, there is a possibility that the northern flank could undergo similar large-scale collapse and generate a tsunami with likely regional impacts. More investigation is needed to understand the nature, likelihood, and hazard implications of such an event occurring in future.

To summarise, we suggest that the Ta'u flank-collapse represents similar processes in comparable volcanic settings. We propose that analogous geomorphic features on other volcanic islands and seamounts in the Pacific likely represent forensic signatures of landslide-tsunamis in the past. We conclude that there is a need to identify and date other such features, in order to further our spatial and geochronological understanding of these processes. The need to identify flank features that have not yet failed and assess the likely mechanisms that could potentially trigger failure is important. This would enable more confidence in interpreting the hazard potential of similar flank-collapses in future – a risk presently under-represented.

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