Geoheritage (2019) 11:577–596
https://doi.org/10.1007/s12371-018-0306-z

ORIGINAL ARTICLE

Volcanic Geoheritage of Landslides and Rockfalls on a Tropical Ocean Island (Western Samoa, SW Pacific)

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Received: 20 October 2017 / Accepted: 14 May 2018 / Published online: 2 June 2018

Abstract

Landslides and rockfalls on volcanic islands in tropical climate are characteristic landscape shaping features. Their common formation poses potential hazard for island communities; hence, understanding their formation and recognition on modern landscapes are vital element of educating local communities and providing mitigation strategies for future events. As landslides and rockfalls are continuously shaping tropical islands' landscapes, they contribute significantly to the volcanic geoheritage of those islands. Rockfall and landslide hazards are commonly associated with the Fagaloa Formation and Salani Formations of Western Samoa in the SW Pacific. Four case studies (Mauga-o-Fao, Mauga-o-Vaea, Fagaloa Bay, and Leagi'agi Hill) are reported here, based on highly populated areas which are predicted to be vulnerable in generating rockfalls and landslides in the future. Field observations and interpretation of aerial photographs and satellite images were used to identify landslide and rockfall hazards in the region. The lack of records and previous studies related to rockfalls and landslides in the region is the major challenge for this investigation. Commonly, rockfall and landslide scenarios in Western Samoa are associated with the presence of high angle faults, highly weathered, extensively jointed, and fractured rocks. Surface and groundwater could expand the size of the joints, and existing fault scarps trigger the rock face to become more unstable by losing its support. There are two networks of jointing patterns commonly occurring in both old (3 Ma to 800 ka) and young (200 ka to 3 ka) volcanic rock formations: parallel and perpendicular with lava flow axis. These joint networks would increase the instability of tabular lava flows especially nearby to fault scarps and thick columnar jointed lavas. It is suggested that the major faults on the main islands almost running perpendicular to the central volcanic rift (elongated north east to south west) could be other main drivers of the rockfall and landslide hazards in the region.

Keywords Basalt · Weathering · Scoria · Columnar joint · Fissure · Erosion

Introduction and Background

Volcanic islands under tropical climates are commonly quickly reshaped after volcanic eruptive phases producing characteristic tropical erosion features define the appearance of such volcanic islands. Mass movements are generated by slow and rapid processes together providing a typical landscape of volcanic islands. In such landscapes, erosion scars of landslides and rockfalls are commonly overlooked from their geoheritage and geoeducation values. The abundance of such erosion features on the modern landscapes can provide a perfect educational avenue along local communities to learn the geological background of landslides and rockfalls. The increased scientific research on volcanic regions is commonly associated with development of ideas to form volcanic geoparks in various scales (e.g., Moufti and Németh 2013). Such educational aspects can then contribute significantly to the natural geohazard awareness of local populations. In addition, landslides and rockfalls can produce spectacular landforms that could be utilized in geotourism.

The Samoan island chain is located in the southern part of the Pacific Ocean to the northeast of New Zealand between latitudes 13° and 15° S and longitudes 186° and 191° W

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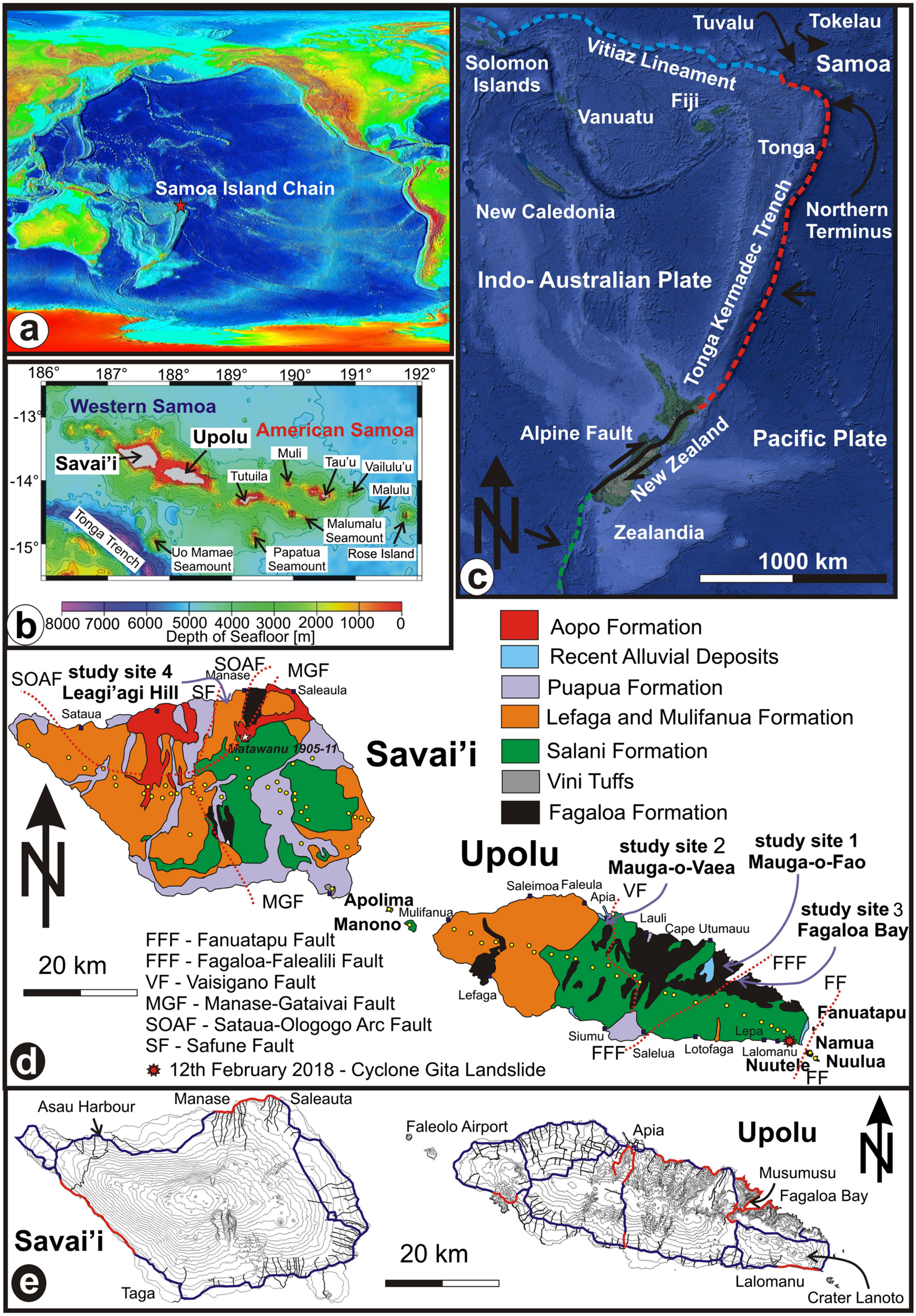
a
Samoa Island Chain
b
186°
187°
188°
189°
190°
191°
192°
-13°
-14°
-15°
Western Samoa
American Samoa
Upolu
Savai'i
Muli
Tutuila
Tau'u
Vailulu'u
Malulu
Malumalu Seamount
Tonga Trench
Uo Mamae Seamount
Papatua Seamount
Rose Island
8000 7000 6000 5000 4000 3000 2000 1000 0
Depth of Seafloor [m]
c
Tuvalu
Tokelau
Samoa
Solomon Islands
Vitiaz Lineament
Fiji
Vanuatu
Tonga
New Caledonia
Northern Terminus
Indo- Australian Plate
Tonga Kermadec Trench
Alpine Fault
New Zealand
Pacific Plate
Zealandia
N
1000 km
d
SOAF
study site 4
Leagi'agi Hill
SF
SOAF
Manase
MGF
Saleaula
Sataua
Matawanu 1905-11
Savai'i
N
20 km
MGF
Apolima
Mulifanua
Manono
FFF - Fanuatapu Fault
FFF - Fagaloa-Falealili Fault
VF - Vaisigano Fault
MGF - Manase-Gataivai Fault
SOAF - Sataua-Ologogo Arc Fault
SF - Safune Fault
12th February 2018 - Cyclone Gita Landslide
Aopo Formation
Recent Alluvial Deposits
Puapua Formation
Lefaga and Mulifanua Formation
Salani Formation
Vini Tuffs
Fagaloa Formation
Upolu
study site 2
Mauga-o-Vaea
study site 1
Mauga-o-Fao
Saleimoa
Faleula
Apia
VF
Lauli
Cape Utumauu
study site 3
Fagaloa Bay
FFF
FF
Fanuatapu
Lefaga
Siumu
FFF
Salelua
Lotofaga
Lepa
Lalomanu
Namua
Nuutele
Nuulua
FF
e
Asau Harbour
Manase
Saleauta
Savai'i
Taga
Faleolo Airport
Apia
Upolu
N
Musumusu
Fagaloa Bay
20 km
Lalomanu
Crater Lanoto

◀ **Fig. 1** Location maps of the Samoan island chain. **a** Samoa Island located on the southern part of the Pacific Ocean. **b** The two political parts, Western Samoa and American Samoa surrounded by deep ocean (seafloor data modified after Hart et al. 2004). **c** GoogleEarthPro (2018.02.20) image shows the island chain located to the northeast of the sharp bend part of the Tonga - Kermadec Trench (TKT) at the Northern Terminus (NT). **d** Geological map of Western Samoa shows the six formal formations associated with major and minor faults on the two main islands based on the Kear and Wood (1959) geological map (modified from Fepuleai 2016). It also shows the four study sites (three on Upolu and one on Savai'i). Volcanic cones in the axis of Savai'i Island informally refer to "Savai'i Major Fissure System" (SMFS). In Upolu, the rift zone defines the "Upolu Major Fissure System" (UMFS). The two fissure systems are inferred to be connected through the "Inter-island Fissure System" (IFS) that is parallel with the line along Manono and Apolima Islands. **e** The road network of Western Samoa mainly consists of dirt roads. Sealed roads are limited around the main islands (blue lines). On the map, the most vulnerable roads to landslide and rockfall hazards are shown by red lines

(Fig. 1a, b). The western group of the islands is the independent nation of Western Samoa while the eastern group is the US-administered American Samoa. Western Samoa has two main islands, Upolu and Savai'i, while American Samoa composed of Tutuila and Manua as its main islands. Upolu and Savai'i have landmasses spanning 1114 and 1709 km^2, respectively. Both island groups are surrounded by deep ocean basins ranging from 800 to 5000 m in depth (Fig. 1b).

The island chain has 1400 km in length with a width of up to 380 km. It aligned northwest to southeast along the northeast of the sharp bend of the Tonga-Kermadec Trench (TKT) region, known as Northern Terminus (Fig. 1c). TKT represents a boundary between the two major plates, Indo-Australian Plate and Pacific Plate. The Indo-Australian Plate moves north east at 6.6 cm/year while the Pacific Plate advantages westward at 7.1 cm/year (Hawkins 1987; Hart et al. 2004).

Landslide and rockfall hazards in any geo-environment are two of the most common natural hazards that can occur at any time without warning (Audru et al. 2010; Malheiro 2006; Nocentini et al. 2015; Valadao et al. 2002). In volcanic terrains due to the chemical and mechanical weathering of volcanic rocks, slope instability can be increased especially if the region went through some post-volcanic hydrothermal activity or it is under high precipitation climatic zone such as those in the tropics. The scale of events can range greatly from small volume mass movements such as minor flank collapse and rockfalls on a volcano to the regional scale altering large segments of volcanic landforms. Such large-scale mass movement can directly be related to volcanic activity producing volcanic debris avalanches that have been commonly documented in large stratovolcanoes in various geotectonical settings both in ancient and modern volcanoes (Siebert 1984; Blong 1986; Cacho et al. 1994; Ponomareva et al. 1998; Davies et al. 2010). Many of these large-scale volcanic edifices fail catastrophically and provide large volume of mass transported in long distances from their source volcano commonly forming extensive fans traceable in the sea floor around volcanic islands (Schneider and Fisher 1998). Such volcanic edifice failures can leave behind a scalloped morphology of the original volcanic edifice and a large volcanic debris fan dominated by volcanic debris avalanche and laharic deposits.

Another spectrum of mass movement on steep tropical volcanic islands are those landslides commonly associated with intense rainfall events occurring numerous times annually. Such events involve communities along the slope or under the shadow of highly weathered volcanic hills and mountains. These hazards are generally overlooked and not addressed in remote Pacific Islands. Only limited research plans and strategies have been developed in most of the SW Pacific. In Samoa, the situation is not different. So far, no detailed research has been conducted in spite the abundance of small-volume landslide events directly affecting the life of local villagers. In addition, traditional knowledge about such events can potentially be useful resource to understand the frequency and scale of landslide events. Legends, cultural activities, and local community views are commonly associated with oral traditions that could be linked to landslides in the past especially if they are connected to some meteorological events that affected the life of the community. In this respect, small-scale modern landslides and rockfalls carry significant geoheritage values closely associated with the local communities' cultural heritage. Such information can be extracted from local communities by participatory method workshops investigating the local communities' oral and cultural traditions. In Samoa particularly, physical evidences and information from local people confirm that landslides occurred in both island groups, Western Samoa and American Samoa, in the past more frequently than common western scientific knowledge may suggest.

A combination of rockfalls and landslides killed several people on northeast Upolu Island (Western Samoa) in 1981 based on mouth to mouth information from local people of Falevao village (Fig. 1d). Skowron (1987) not fully explained this particular event; however, landslides and rockfalls had been driven by an earthquake of 7.5 magnitudes at a depth of 31 km with an epicenter of 60 km to the southwest of Samoa. Based on data from the National Geophysical Data Center/World Data Service (NGDC/WDS), there was no extensive damage in infrastructure at any other parts of Western Samoa. On 25 June 1917, an earthquake of 8.5 magnitude which lasted for 2 min generated a landslide and associated tsunami (12 m) on both main islands (Upolu and Savai'i); however, no loss of life was reported (Skowron 1987). The epicenter of this earthquake was located about 15 50° S ,173 00° W at a depth of 10 km. It is described that the ground was agitated strongly and many large segments of the land was subsided (up to 3 m^2 or more), triggering landslides that uprooted many acres of trees (Timaru Herald 1917).

Fagaloa Formation is the oldest volcanic rock exposed as inlier in several areas on the main islands of Western Samoa, Upolu and Savai'i (Fig. 1d). Fagaloa Formation dominates the northeast part where only a small portion crops out in the southwest of Upolu Island. A narrow strip of the Fagaloa Formation crops out on the south and northeastern parts of Savai'i. Fagaloa lavas are porphyritic with coarse phenocryst (0.5 mm to 2 cm in diameter) phases of olivine, plagioclase, feldspar, and pyroxene, which are set within a fine-grained micro-crystallized matrix. Thick lava flows from Upolu yielded a potassium-argon (K-Ar) age from 1.5 to 2.8 Ma (Natland and Turner 1985; McDougall 2010) while those on Savai'i produce an argon-argon ($^{40}Ar/^{39}Ar$) date that range between 0.236 and 2.05 Ma (Workman et al. 2004). These ages, however, particularly the K-Ar ages, need to be treated with care as many recent studies elsewhere showed the difficulty to obtain geologically valid results (e.g., Balogh and Németh 2005).

The deeply weathered, strongly eroded, highly jointed, and fractured older volcanic terrains are suggested to be vulnerable to collapse at any time (Fepuleai 1997, 2016). Like many other parts of the world associated with landslide and rockfall hazards, mapping and detailed study of vulnerable sites would be significant for the future development and natural hazard management (He et al. 2003; Menendez-Duarte et al. 2003; Metternicht et al. 2005; Feizizadeh et al. 2013; Griffiths et al. 2015). Such landslide vulnerability studies have not been performed yet in the Samoan archipelago. This report provides the first key information for future development of a descriptive inventory of type of mass movements in the volcanic terrains of Samoa.

This study presents valuable field observations together with interpretative analysis of satellite and aerial photographs of several areas in Western Samoa. There are four particular sites selected for this study including those of (1) Mauga-o-Fao (northeast Upolu), (2) Mauga-o-Vaea (south of Apia), (3) Fagaloa Bay (northeast Upolu), and (4) Leagi'agi Hill (north of Savai'i) (Fig. 1d). The change in land use and urbanization in Samoa provides increased area that is susceptible for landslide hazard that need to be studied and evaluated for future mitigation. Detailed field observation and documentation of landslide and other mass movement in Samoa need to be performed for effective mitigation of this type of natural hazards. Moreover, basic geological information about landslides and rockfalls can form the foundation of geosite inventory development in the future.

Two questions are addressed in this initial study: (1) "What major factors (environment and geological) trigger rockfall and landslide in the region?" and (2) "Are landslides and rockfalls more common in association with older volcanic successions?"

Landslide and Rockfall Hazards Associate with Road Infrastructure

This section highlights several significant components of how a road network on both main islands of Samoa (Upolu and Savaii) would become a major issue if landslide and rockfall hazards occur in several vulnerable road sections. Some of these road sections locate within the four study areas shown on Fig. 1d. Figure 1e shows a sealed main road network on the two main islands. Based on field observation, several portions of the sealed road network of Upolu and Savaii, predicted to be vulnerable to landslide and rockfall hazards (Fig. 1e). Taua'a (2015) revealed that a road infrastructure is significant for social-economic development of rural Samoa; hence, their damage by landslides can affect strongly not only the rural community's life but also the economic development of large areas.

Road infrastructure development in terms of upgrading and maintenance become a high demanding issue, resulting from a population growth on both main islands. Locally available road pavement materials are coralline and volcanic rocks (Road Pavement Design for the Pacific Region 2016). A lack of proper tools for excavation determined that road construction between the 60s and the 80s used a mixture of coral detritus and scoria as chiefly materials for road building in Samoa (Vines and Falconer 1980). Scoria is continuously used as building materials in nowadays for many dirt roads, while non-vesicular basalt chip is the major aggregate to build sealed roads. Basalt chips are mostly extracted from highly fractured and jointed volcanic rock formation.

There are a few bridges constructed along several rivers/streams in urban areas and to the east of Apia township, while submerged concrete bridge dominates many other parts of the main islands (Fig. 2a, b). Submerged concrete bridge (or ford) is referred as a cheaper and simple design piece of engineering; however, it generates a lot of difficulties during the wet season from October to April (Fig. 2b) (Saifaleupolu 1985, 1996, 1998). Additionally, landslides and rockfalls that devastate road infrastructure network in many parts of Samoa commonly occur during the wet season (Fig. 2c, d). Rockfalls commonly cause road blocks even after heavy rainfalls (Fig. 2e, f). One of the largest and most disruptive landslide occurred on the 12 February 2018 in the interisland ring-road at Tuialamu near the important holiday site and popular tourist destination near Lalomanu (Fig 2g, h).

Road expansion and upgrade in the last 10 years provide effective and efficient travels to communities (NISP 2010; Taua'a 2015). Despite the upgrade in road networks on the island, the increasing level of private car traffic and the rising number of trucks on Samoan roads (including container carriers) especially in urban areas, became a

Fig. 2 Wet season in Samoa can generate surface flooding, landslide, and rockfall. **a** Leone Bridge in the Apia urban area became unstable and disconnected during heavy flooding of Cyclone Evan on the 13th of December 2012 (source: AP Photo/Seti Afoa). **b** Low concrete bridges and fords are common across Samoa and they are commonly submerge during flood events causing major disruption of transportation such as it happened in 2005 in near Manase, Savai'I (photo: K. Nemeth). **c** Landslide at the foothill of Mauga-o-Vaea (Mount Vaea) at Palisi area in the southern part of Apia narrowing one of the main road during heavy rain in May 2017 (source: Samoa Observer). **d** Landslide/rockfall and uprooted of trees on the northern part of Savaii at Manase-Safotu section during Cyclone Amos in April 2016 (source: http://www.talamua.com/samoa-cleans-up-after-a-weakened-cyclone-amos/). **e** Typical rockfall on sealed road in Upolu (Photo: Fefiloi Kerstin from http://www.samoaobserver.ws/en/04_01_2018/local/28459/Landslide-scare-on-east-coast.htm). **f** Landslide at Solosolo at 11th February 2019 disrupted traffic to the east of Samoa (Photo: Land Transport Authority - http://www.samoaobserver.ws/en/12_02_2018/local/29926/Second-cyclone-reports-dismissed.htm). **g** One of the largest landslide occurred near Lalomanu at 12th February 2018 (Source: Land Transport Authority, Samoa). **h** Volcaniclastic successions exposed along the main highway near Lalomanu in 2005 in a place where recent landslide occurred in 12th February 2018. The bedrock geology is largely unstudied so far (photo: K. Nemeth)

major challenge of maintenance (NISP 2010). Damaging of the road networks by landslides and rockfalls in several parts of Upolu and Savaii is costly. For instance, a major upgrade of road links between Apia township and Faleolo International Airport (about 30 km in length) costs approximately between $50 and $120 million based on the Samoa National Infrastructure Strategies Plan (NISP 2010).

Study Area and Geological Setting

The interaction of the two major tectonic plates nearby the Samoan island chain is believed to be the main triggering mechanism of the numerous earthquakes occurred in the region (Natland 1980; Hawkins 1987; Natland and Turner 1985; Natland 2003; Fepuleai 2016). These include the two recent earthquakes with magnitudes of 8.0 and 7.9 which generated the 29 September 2009 tsunami that killed 189 people. This tragic event has triggered new research not only on looking for traces and evidences of ancient tsunami events in Samoa but also looking at other mass movement processes influenced the landscape evolution of the Samoan islands (Richmond et al. 2011; Tonini et al. 2011; Williams et al. 2011; Mikami et al. 2013; Gonzalez-Riancho et al. 2015).

Immediately to the south of Samoa, the northern end of the TKT bends sharply to the west, to become part of the east-west aligned Vitiaz Lineament, to the north of the Fiji group (Fig. 1c). The sharp bend in the Tonga Trench is known as the Northern Terminus (NT) (Hart et al. 2004) (Fig. 1c). The Vitiaz Lineament formed as the Indo-Australian Plate continues to advance north. Its margin drags the tearing section of the Pacific Plate in a mechanism known as "down-drag subduction" (Natland 1980; Natland and Turner 1985; Hawkins 1987). In other words, the Vitiaz Lineament represents the torn lithospheric part of the Pacific Plate (Hawkins 1987; Hart et al. 2004). The highly oblique nature of the Vitiaz Lineament generates a range of transpressional phenomena from Papua New Guinea through the Solomon Islands to Samoa (Coleman 1966, 1991; Petterson et al. 1997, 1999). In Papua New Guinea and the Solomon Islands, a large number of rhombohedra-shaped basins have been produced with faults parallel to the basins forming throughout the arcs (Fepuleai 2016).

The interaction of the two major plates at the sharp angle causes a portion of the Pacific Plate to be torn, suggesting that it generates rejuvenate volcanism in Samoa (Natland 1980). This tearing part of the Pacific Plate forms a down-drag subduction, as the Indo-Australian Plate advance toward north-east (Fig. 1c) (Hawkins 1987; Hart et al. 2004). Hart et al. (2004) use the term "rejuvenated" to describe post-erosional activities dominating the later (young) subaerial and submarine volcanic cone. Rejuvenated eruption is the stage where a volcano "refuels" after a long period of dormancy and erosion. It is suggested that Holocene volcanic activities of the post-erosional stage spread along the island chain of Samoa (Kear and Wood 1959; Natland 1980, 2003). The evolution of the Samoan volcanism could be very similar to that of Hawaii. Fepuleai (1997) subdivided the oldest volcanism (Pleistocene to Pliocene), Fagaloa Formation into two parts: Lower Fagaloa and Upper Fagaloa sub-formations. Cibik (1999) stated that the Lower Fagaloa sub-formation represents the pre-shield stage whereas the Upper Fagaloa sub-formation evolves from the major shield building phase. Kear and Wood (1959) suggested that major erosion occurred as the major shield activities ceased. This represents a major unconformity between older rock formations (Pliocene-early Pleistocene) and post-erosional suites exposed on the main islands. Post-erosional volcanism is generated along the major rift axis where similar new volcanoes erupted following some structural elements with unknown eruption frequency (Fepuleai 1997). A plumbing system of the volcanic ocean island like Samoa could associate with fractures along the lithosphere. These could trigger a series of lava spatter eruptions, scoria cone grows, submarine (Surtseyan-style) volcanism, and development of compound small-volume volcanoes over regions repeated magma rise occurred (Németh and Cronin 2009).

Submarine debris avalanche on the south, north, and southwest of Western Samoa inferred to correspond with those subaerial slope failures recognized on the main islands in the past (Hill and Tiffin 1993; Keating et al. 2000; Goodwin and Grossman 2003).

Fepuleai (2016) described that major and minor faults on the main islands were part of a cone-collapse event (CCE) occurred sometime at least 22.3 ka. Cone-collapse in various scales is a particular event that associates with several geomorphological features in the region such as (1) collapsed scoria cones of Fagaloa Formation of Upolu and Salani Formation of Savai'i, (2) upthrown (up to 60 m) of the Salani lava (easternmost part of Upolu and northern portion of Savai'i), (3) collapse of a Fagaloa depression informally referred to as a caldera (northeast Upolu), (4) flank collapse of Tau Island (American Samoa), (5) collapse on off-shore islands in the easternmost part of Upolu, and (6) a submarine avalanche deposit recognized to the seafloor of the north eastern part of Savai'i.

The age of the CCE was determined from rock units of the Salani Formation. Many of these mass movement-related rock units believed to be generated by activity along the main fault network such as the Fagaloa-Falealili Fault (FFF), Manase-Gataivai Fault (MGF), and Sataua-Ologogo Arc Fault (SOAF) (Fig. 1d). The cessation of the volcanic activity responsible to produce rock units of the Salani Formation was also confirmed by radiometric dating of tephra deposit from Crater Lake Lanoto, to the easternmost part of Upolu (Fepuleai 2016).

This particular event was triggered from more tension across the Pacific Plate at the sharp bend of the Kermadec Tonga Trench (KTT) known as the Northern Terminus region (Fig. 1c). The CCE suggested to correspond with the time of the waning stage of volcanic activity generated the volcanic successions of the Salani Formation and also predates the waxing stage of volcanism formed the rocks of Mulifanua Formation.

The sharp bend at the Tonga Trench (Fig. 1c) represents east-west striking normal dip-slip faults, which were more or less parallel to the main thrust which extends from the Vitiaz Lineament to the KTT. Hill and Tiffin (1993) described these faults having a vertical displacement of at least 800 m along their lengths that range between 25 and 80 km.

Radiometric dates also revealed that the landforms composed of rocks part of the Fagaloa Formation have ages ranging between 1.5 and 2.8 Ma (Natland and Turner 1985;

Workman et al. 2004; McDougall 2010). This old volcanic formation contains rocks that are fresh in physical appearance in many outcrops on Upolu and Savai'i; however, it affected by a series of jointed patterns and heavily fractured lithology.

Structural Geology of Western Samoa

Volcanic cones of Savai'i Island take the form of a chain over a broad convex plain and those in Upolu are distributed along a topographic crest known as a "rift zone." Fepuleai (2016) referred the rift zone of Savai'i as "Savai'i Major Fissure System" (SMFS). In Upolu, the rift zone was named "Upolu Major Fissure System." It also suggests that the two major fissure systems connect each other along an "Inter-island Fissure System" aligns parallel with Manono Island and Apolima Island (Fig. 1d).

Volcanism in Samoa is subdivided from stratigraphy point of view into six formal rock formations (Kear and Wood 1959) from the youngest to the oldest: Aopo Formation (1760–1911), Puapua Formation (Middle to Late Holocene), Lefaga Formation (Early Holocene), Mulifanua Formation (Late Pleistocene), Salani Formation (Middle Pleistocene), and Fagaloa Formation (Middle Pleistocene to Pliocene) (Fig. 1d). The Fagaloa Formation seems initiated as shield volcanism (Pliocene-Pleistocene) before later activities erupted as post-erosional volcanism during Salani Formation, Mulifanua Formation, Lefaga Formation, Puapua Formation, and Aopo Formation. The island chain of Samoa has been dominated by alkalic volcanic activities (Fepuleai 1997; Cibik 1999). The geochemical nature of lavas from deep submarine and subaerial volcanoes, of the Samoan island chain, reveals a combination of shield and post-erosional volcanism (Fepuleai 2016). Upolu and Savai'i are deeply dissected by series of major and minor faults (Fig. 1d). These faults are mainly normal or strike-slip. Sataua-Ologogo Arc Fault (SOAF), Safune Fault (SF), and Manase-Gataivai Fault (MGF) seem cross cutting each other to the northern part of Savai'i. Vaisigano Fault (VF), Fagaloa-Falealili Fault (FFF), and Fanuatapu Fault (FF) are more like elongated northeast southwest.

A series of basaltic dikes referred as Fagaloa Intrusion (Fepuleai 2016) intruded in the Fagaloa Formation on the northeast of Upolu range from centimeters (Fig. 3a, b) to many meters (Fig. 4a, b) in width. Dikes dip from shallow angles through to almost vertical in several locations and are commonly composed of fine chilled margin (Fig. 3). A massive dike called Lemafa Intrusion (Fig. 4a, b) extends from Falevao along Fagaloa Bay and east toward the Uafato and Ti'avea village. It has a width of 15 to 100 m and is more than 10 km in length.

Kear and Wood (1959) described the Lemafa Intrusion as a part of a deeply weathered intrusive body associated with strong erosion of Fagaloa Formation. The erosion has resulted deeply incised relief, particularly northeast Upolu. These erosional processes formed amphitheater-headed canyons, which merge to produce sharp peaks and a steep rugged terrain of narrow razor-backed ridges (Fig. 4b).

The Fagaloa Intrusion is strongly elongated from east to west and associated with columnar jointed basalts and a series of fractured coherent volcanic rocks of northeast Upolu. Like the older geological formation, younger rock formations such as the Salani, Mulifanua, Lefaga, Puapua, and Aopo are also associated with series of columnar joints in many parts of Upolu. Combination of major and minor faults associated with networks of joints and fractures in Fagaloa lava suites are the perfect candidates to host numerous slope failure (Hawkins 1975, 1987; Desktop Study Report 2015).

Methods

A basic geological mapping was the main technique used in this study to identify a nature of landslide and rockfall hazard. This including orientation of fault system, joints pattern that dominate the rocks, weathering process associated with rock formation, and rock type identification. Aerial photographs, topography maps (in scale of 1:50,000), and satellite images were also used to trace faults.

Four specific sites were targeted in this investigation in respect to identify main characteristics of landslide included: (1) Mauga-o-Fao (northeast Upolu), (2) Mauga-o-Vaea (south part of Apia town), (3) Fagaloa Bay (northeast Upolu), and (4) Leagi'agi Safune Hill (central north coast of Savai'i) (Fig. 1d). The important hazard scenario was the fact that the rocks at the four sites are vulnerable to collapse in an area where population growth and urban development are apparent in the last decade.

Landslide and Rockfall Hazards

Landslide is a nonspecific term for movement (slow to rapid) of rock, debris, or earth down a slope from low to steep angle (Montgomery 2006; Girty 2009). Landslide results from the gravitational failure of the materials which make up the hill slope and are driven by the force of gravity, or when the shear stress exceeds the shear strength of the material. Landslides are known also as landslips, slumps, or slope failure (Montgomery 2006; Girty 2009).

A rockfall refers to quantities of rock falling freely from a cliff face (Varnes 1978; Montgomery 2006; Girty 2009). A rockfall is a fragment of rock (a block) detached by sliding or toppling, that falls along a sub-vertical cliff, proceeds down slope by bouncing and flying along ballistic trajectories or by rolling on talus or debris slopes (Varnes 1978). Alternatively, a "rockfall is the natural downward motion of a detached block

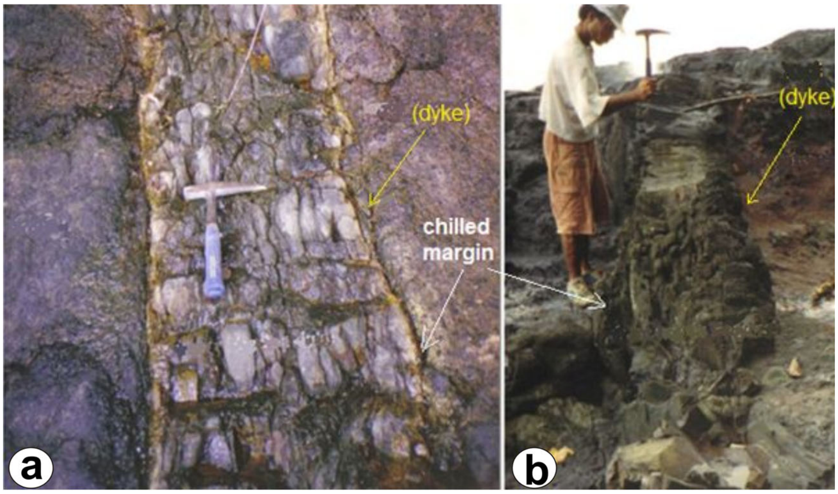

Fig. 3 Mafic magmatic intrusion swarm in northeast Upolu at Fagaloa Bay. **a** A dark green to blackhighly jointed, about 45 cm wide, fine-grained aphanitic mafic dike with chilled margin exposed in road cut. It intruded a reddish porphyritic coarse grained mafic lava of the Fagaloa Formation along the beach on the eastern part of the Fagaloa Bay. This dike shows two patterns of joints; one parallel to the orientation of the dike (parallel the hammer), and the other one that is perpendicular to the dike-parallel joints. **b** A 50-cm-wide dark green fine-grained, highly jointed dike exposed in a road cut intruding a thick porphyritic reddish coarse grained lava part of the Fagaloa Formation

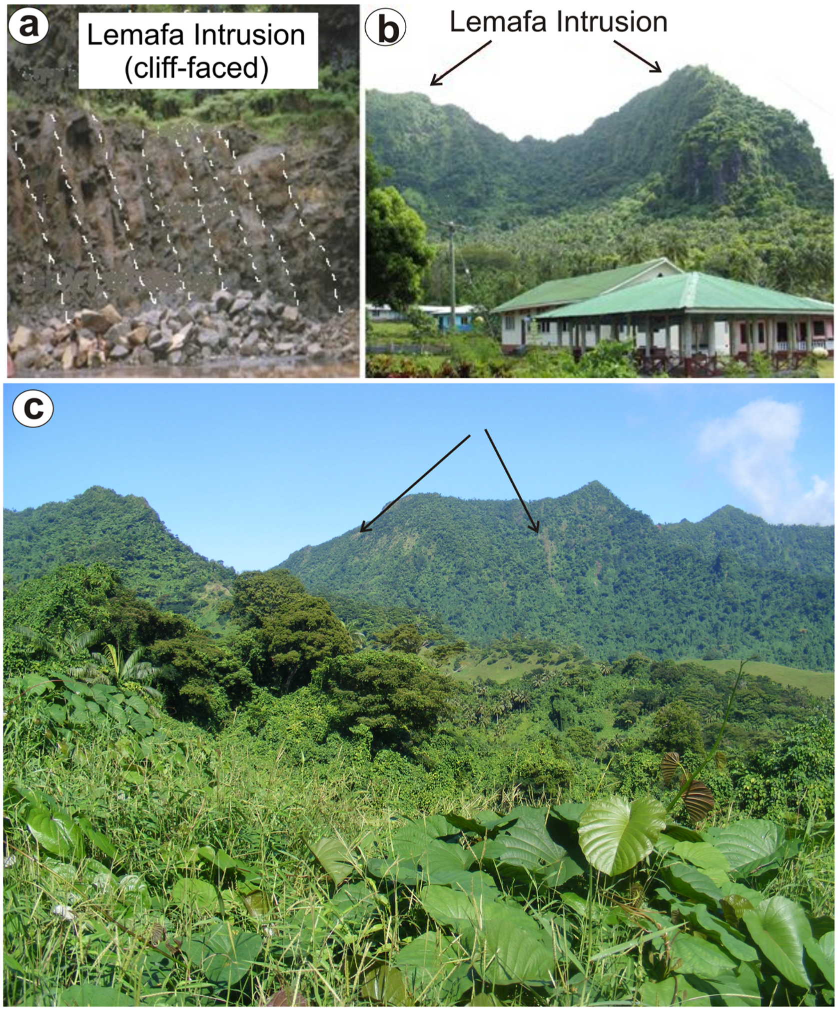

Fig. 4 Coherent mafic igneous rocks exposed as part of the Lemafa Intrusion in northeast Upolu at Fagaloa Bay. **a** Columnar jointed basalts of the Lemafa Intrusion has a near-vertical dip of 75° toward the East. **b** A section of the Lemafa Intrusion at Taelefaga on the eastern side of the Fagaloa Bay. It is a part of a long sharp peak also known as a typical razorback ridge, which “overshadows” the Fagaloa Bay. **c** Recent landslide scars on the top of the razorback ridges over Fagaloa Bay

or series of blocks with a small volume involving free falling, bouncing, rolling, and sliding."

Mechanical and chemical weathering of rock and volcanic sediment are the two most significant processes associated with many rockfalls and landslides in Samoa. The mechanical weathering involves a disintegration of rock formation through jointing and fracturing mechanism (Palomo et al. 1997; Moon and Simpson 2002; Nichol et al. 2002; Moon and Jayawardane 2004; Moon et al. 2005; Benedetti et al. 2005).

Daily cycle of temperature change that can cause cyclic thermal stress on rock cliff faces (Hall and Thorn 2014; Collins and Stock 2016; Gischig 2016; Eppes et al. 2016) is unlikely to operate under Samoa's balanced climatic conditions. Figure 5a shows rainfall records from the Apia station (data from the Samoa Meteorology Division, Apia - http://www.samet.gov.ws/) during wet season (October to April) could be a contributing factor to weather the volcanic rock by water infiltration. The temperature records (Desk Study Report, 2015) from Alafua (south west of Apia) and Nafanua (south east of Apia) station however of up to 35 °C could trigger increased expansion of exposed cliff faces further increasing the weathering of the volcanic rocks (Fig. 5b).

Hence, the combined effect of heating and rainwater infiltration through cracks attack primary minerals of the dominantly basaltic rocks of Samoa (olivine, pyroxene, plagioclase, titanaugite, ilmenite, ulvospinel, and titaniferrous magnetite) could associate with mechanical and chemical stress of these phenocrysts. This would coincide with the development of stress in rock formation outer shell and generate rockfall and landslide. Onion-skin weathering is commonly linked to hydration/dehydration cycles induced by variations in temperature and humidity (Turner et al. 2003; Jamtveit et al. 2009). Figure 6a, b shows the onion-skin structure that commonly occurs in lava of the Salani Formation. It seems the onion-skin

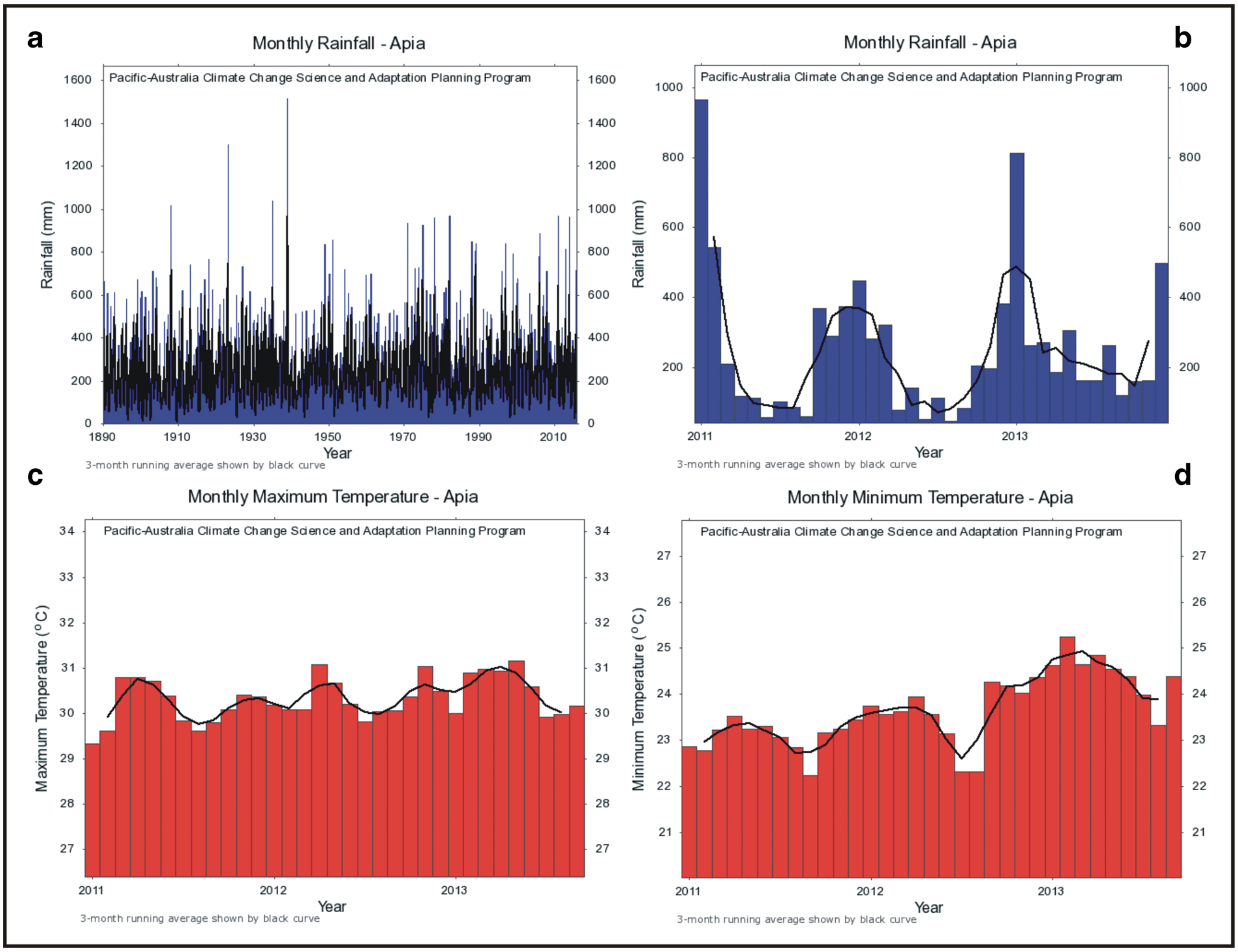

Fig. 5 Climate data provided for Samoa on the basis of the Apia Station record (data source is from the Pacific Climate Change Data Portal via http://www.bom.gov.au/climate/pccsp/). In **a**, the monthly rainfall record is shown between 1890 and 2015. In **b**, for more details, the rainfall record summarizes the data between 2011 and 2013. Maximum and minimum temperature data for the 2011 and 2011 is shown in **c** and **d**, respectively

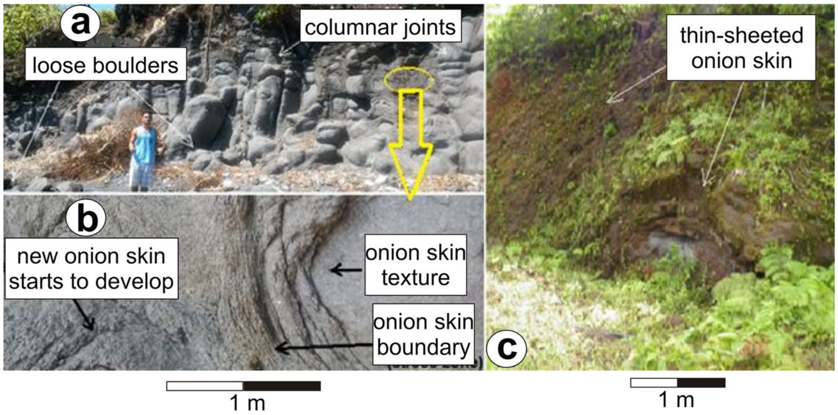

Fig. 6 Onion-skin structure of coherent basaltic rocks in the Salani Formation. **a** Onion-skin structure formed from highly weathered rocks at Sataua on the NW part of Savaii. **b** Close-up view of the onion skin texture. **c** Highly weathered thin lava sheet of the Salani Formation at Crater Lanoto (on Fig. 1e), easternmost part of Upolu (from Fepuleai 2016)

on the north of Sataua village (westernmost part of Savai'i) formed as the columnar joints outcrop collapsed (Fig. 6a, b). Chemical weathering associates with decomposition through change in chemistry of minerals in coherent volcanic rocks and volcaniclastic sediments of the six formal rock formations of Western Samoa.

Table 1 shows common characteristics of the six volcanic formations (grain size, texture, weathering, and their distribution) that could contribute to the chemical and physical weathering process. Change from primary to secondary (hematite, halloysite, gibbsite, goethite, and iddingsite) and late secondary mineral (magnetite and maghemite) are all associated with the reduction in rock and sediment strength (Fantong et al. 2015; Banerjee et al. 2016; Fepuleai 2016).

Post-Fagaloa Formations (Salani, Mulifanua, and Puapua) are comprised of several significant features such as columnar joint network in basaltic lava flows, fault network, fracture, and onion-skin feature, associated with rockfall and landslide scenario in Samoa. Additionally, the Fagaloa Formation also has similar features commonly occur on both main islands. Figure 7 shows columnar joints of the lava of the Puapua Formation exposed at Asau Harbor, northwest of Savaii (Fig. 1d). Columnar joint network is one of the most common features in the six rock formations of Samoa and they follow similar trends of jointing patterns of the other basaltic rocks like elsewhere (e.g., Spry 1962; Kantha 1981; Budkewitsch and Robin 1994; Goehring and Morris 2008; Mattsson et al. 2011; Hetenyi et al. 2012; Goehring 2013).

A thick outcrop of Fagaloa Formation shows two zones of the columnar joints, colonnade and entablature. The Lemafa Intrusion (Fig. 4a) in northeast Upolu shows an upper entablature zone with joints orientate in various directions or even

Table 1 Show grain size, texture, weathering, and distribution of the six volcanic formations of Samoa

Formation	Grain size	Texture	Weathering and distribution
Aopo Formation	Very fine to fine grained	Porphyritic texture with fine to medium olivine phenocryst (rare pyroxene and plagioclase). Opaque phenocryst also present (ilmenite, spinel and magnetite)	Fresh or slightly weathered formation, very thin soil, lava flow fill up older valleys and spill out over the coasts, lagoons and cover barrier reefs and only crop out to the north of Savai'i.
Puapua Formation	Fine grained	Porphyritic texture with fine to coarse olivine phenocryst (rare pyroxene and plagioclase). Opaque phenocryst also present (ilmenite, spinel and magnetite)	Slightly weathered formation with thin soil, lava flow crop out offshore and form rocky (ironbound) coasts. The unit dominates Savai'i but only small portion on the mid-west and mid-north and mid-south of Upolu
Lefaga Formation	Fine grained	Porphyritic texture with fine to coarse olivine phenocryst and pyroxene (rare plagioclase). Opaque phenocryst also present (ilmenite, spinel and magnetite)	Intermediated weathered formation with thin soil. The unit only crops out to the western part of Upolu
Mulifanua Formation	Fine grained	Porphyritic texture with fine to coarse olivine phenocryst and pyroxene (rare plagioclase). Opaque phenocryst also present (ilmenite, spinel and magnetite)	Intermediate weathered formation, consist of thin soil and highly jointed and vesicular unit. The unit dominates the western part of Savai'i and Upolu
Salani Formation	Fined to medium or coarse grained	Porphyritic texture with fine to coarse olivine, pyroxene and plagioclase phenocryst. Opaque phenocryst also present (ilmenite, spinel and magnetite)	Weathered and highly jointed formation, contain thick soil and onion-skin structure is commonly occurred. The unit dominates western part of Savai'i while covers more than half of Upolu
Fagaloa Formation	Fine to very coarse grained	Porphyritic texture with fine to coarse olivine phenocryst and pyroxene (rare plagioclase). Opaque phenocryst also present (ilmenite, spinel and magnetite)	Deeply weathered highly jointed formation, contain thick soil and associate with series of dikes (Fagaloa Intrusion). A small portion of crop out on the mid-north and mid-south of Savai'i while dominates the northeast Upolu

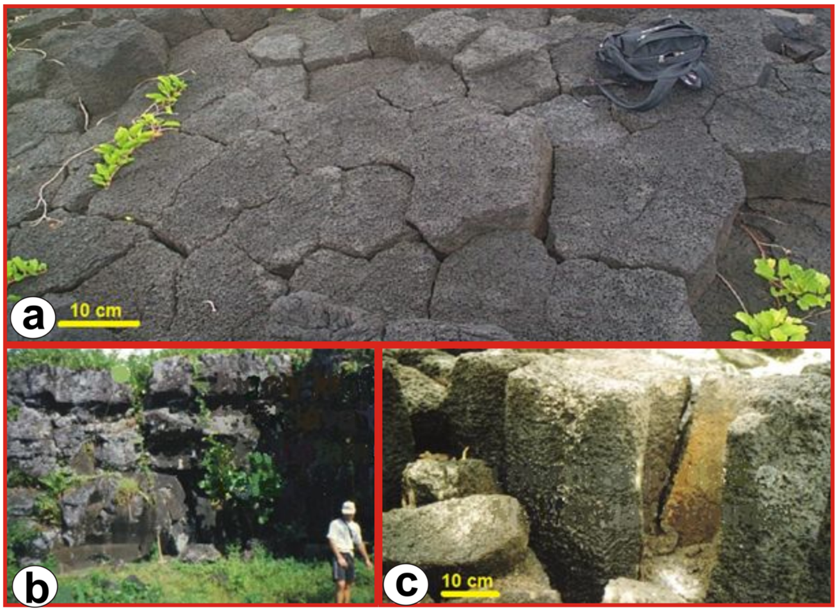

Fig. 7 Joint network of the lava rocks dated post-Fagaloa time. **a** Columnar joint (5–20 cm in diameter) of the basaltic lava flows from the Puapua Formation from Asau Harbor. **b** lava flow (1–1.8 m thick) of the Salani Formation from Taga (southern part of Savaii) shows two dominated jointing pattern (parallel and perpendicular with the flow). **c** columnar joint (20–35 cm long and 8–18 cm thick) of the lavas of the Mulifanua Formation seems have more space between vertical columnar joints

forming some sort of dome structure. Colonnade and entablature are commonly associated with some irregular zones in the jointed flows. Such textural irregularities can act as surfaces where rock can fail initiating rockfalls and landslides.

Boulders are more common on the surface of Mulifanua Formation than in the case of Salani Formation (Kear and Wood 1959). A lava flow of Salani Formation exposed at Taga village on the southern part of Savai'i (Fig. 1d) shows two dominating jointing patterns: (1) parallel or horizontal set of joints and (2) perpendicular network of joints (Fig. 7b). The two jointing pattern networks cause rock face to loosen up easier. Columnar joints of the Mulifanua Formation at Falealupo village (westernmost end of Savaii) show an increase in gaps between vertical joints. This could be associated with erosion as surface water seeps through cracks or might have occurred during the shrinking process as the lava flow cooled down (Fig. 7c).

An evolutionary landslide and rockfalls model scenario in Samoa perhaps is explained by the following two phases: *phase 1*—fault scarp formation and *phase 2*—subsequent deep dissection by the faulting (Fig. 8). Narrow razor-backed ridge and collapsed volcanic cones exposed on Upolu and Savai'i as evidence of rockfall, landslide, and slope failure. Volcanic cone collapse scenario in this study is referred to scoria cone rafting that take place during the cone growth (e.g., Németh et al. 2011) resulting an enlarged crater zone that is exposed for further erosion (e.g., Crater Olomauga, easternmost Upolu). Without doubt, these common landform features formed due to the presence of rocks with deeply weathered, highly jointed and fractured appearance that could be enhanced by series of earthquakes in the region. A series of fault scarps (Fig. 8a) can trigger razor-backer ridges for instance Mauga-o-Vaea and Mauga-o-Fao (Fig. 8a–c). As volcanic activities ceased (Fig. 8d), the volcanic cones became unstable due to weathering and surface run off providing unstable landforms that easily collapsed. These cone collapse types are defined as post-volcanic collapses, and they are clearly separated from those volcanic landforms associated with syn-eruptive cone rafting (Riggs and Duffield 2008; Németh et al. 2011).

Deeply weathered syn-eruptive failure surfaces due to weathering and erosion can act as locations where post-eruptive slope failure can take place (Fig. 8e). It is inferred that post-volcanic collapses of most of the volcanic cones of the Fagaloa Formation in northeast Upolu at Fagaloa Bay could have been triggered by rupture and displacement along the Fagaloa-Falealili Fault (Fig. 1d). Like the Fagaloa Bay, the islands to the eastern end of Upolu such as Fanuatapu, Namua, Nuutele, and Nuulua (Fig. 1d) are inferred to be the result of post-eruptive cone edifice failures however these volcanic islands had an eruptive history record with wet, phreatomagmatic phases and tuff cone formation (Németh and Cronin 2009). Tuff cones are composed of wet, sticky volcanic glass shard-rich ash and lapilli that commonly form steep sided wet volcanic cones (e.g., Németh et al. 2006). Steep cones can fail time-to-time during the growth of the cone as it has been observed on young tuff cones, generating major failure zones across the volcanic edifices (Verwoerd and Chevallier 1987; Cole et al. 2001; Sorrentino et al. 2011; Murtagh et al. 2011; Sohn et al. 2012;). While clear evidence for maar-forming eruptions in Samoa is not known, several large and broad water-filled craters along the main volcanic rifts need further research to establish their origin as explosion craters that influenced by explosive magma-water interaction

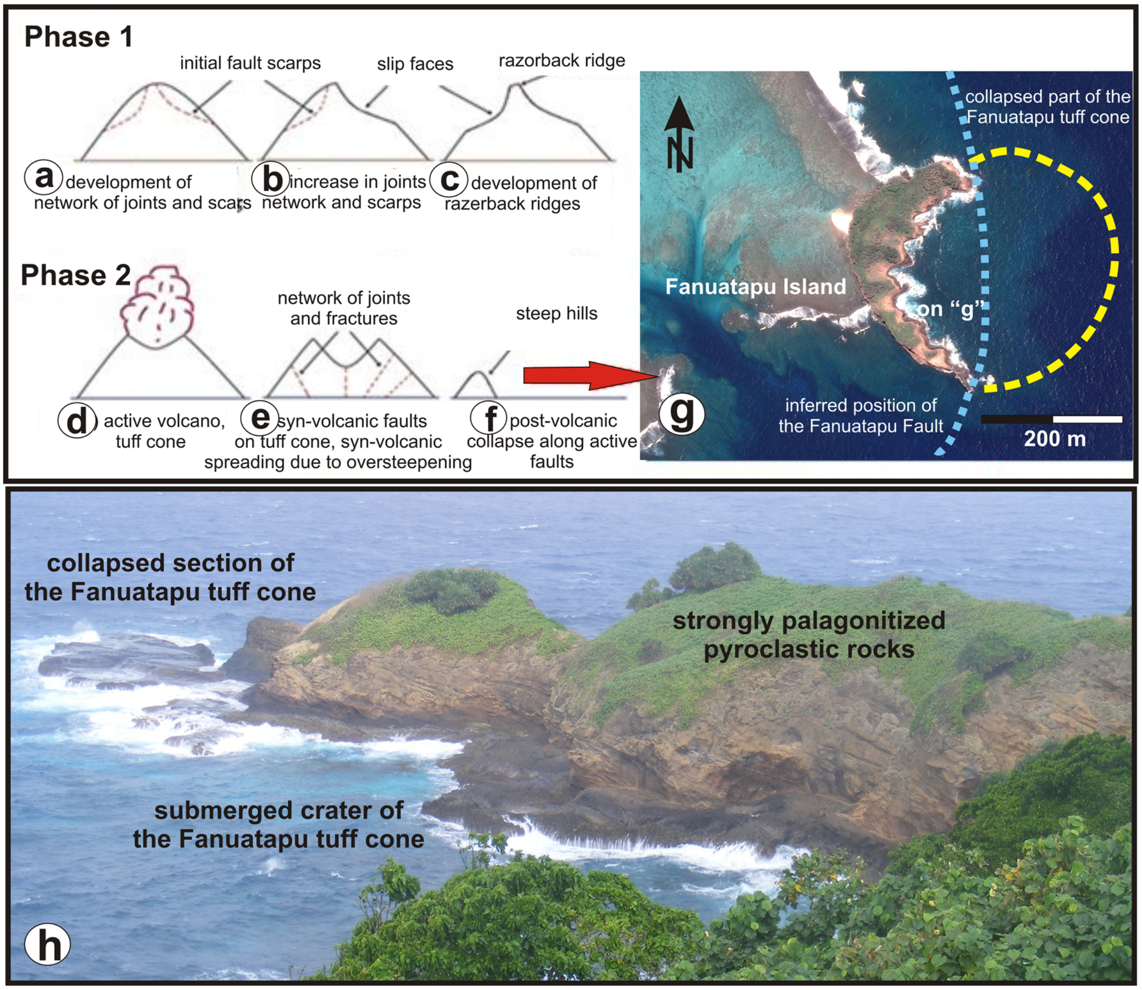

Fig. 8 An evolutionary feature of Samoan landslide and rockfall scenario of volcanic cones and hills indicate an initial (phase 1) and subsequent phases (phase 2): **a** initial stage of joint and fault scarp development; **b** increase in jointing and surface area of fault scars in hilly sites; **c** formation of razorback ridge; **d** as volcanic activity ceased, the volcanic cone become vulnerable to collapse; **e** volcanic cone associated with network of joints and faults (**f**). **g** Map view of a tuff cone at Fanuatapu Island that is located nearby to an active fault that is inferred to dissected and collapsed the seaward site of the tuff cone forming a half-moon shaped island. **h** Fanuatapu is a tuff cone as it is composed of strongly palagonitized pyroclastic rocks indicating magma-water interaction controlled eruption styles

are common along fissures on volcanic islands (e.g., Miyakejima, Japan; Geshi et al. 2011). Fine phreatomagmatic ash in other hand could affect large areas erosional response including mass movement initiation. However, to recognize such ash sheets is difficult (e.g., Pardo et al. 2014), especially under tropical conditions.

The off-shore islands of SE Upolu are dissected by the Fanuatapu Fault. The down-thrown side of the faults formed half-moon shaped morphology of the Fanuatapu Island (Fig. 8f). This suggests that the fault movement likely provides progressive collapse of the volcanic edifices when the rupture took place but also could indicate that the presence of the fault acted as main path way of magma to the surface to form volcanic edifices that likely had been affected by the fault already during the eruptions and cone growth (Norini and Lagmay 2005; Zanon et al. 2009; Vitale and Isaia 2014).

The two evolutionary phases of landslide and rockfall documented in the four case studies are presented below (Mauga-o-Fao, Mauga-o-Vaea, Fagaloa Bay, and Leagi’agi Hill).

Case Study 1: Mauga-o-Fao (Mount Fao)

Mauga-o-Fao has an elevation of 820 m above sea level. Despite a series of earthquakes (1917, 8.3; 1975, 7.2; 1981, 7.5; 2009, 7.8 and 8.0 magnitudes) dominated the islands in the past, there were no detailed studies of landslide or rockfall in the region (Skowron 1987). As previously mentioned, landside and rockfall event occurred at Falevao village, north-east Upolu (Fig. 1d) in 1981 cost the life of several people who lived under the foothill of Mauga-o-Fao (Fig. 9a). There was no published report available for this study in regarded to this particular event. However, physical evidence and local

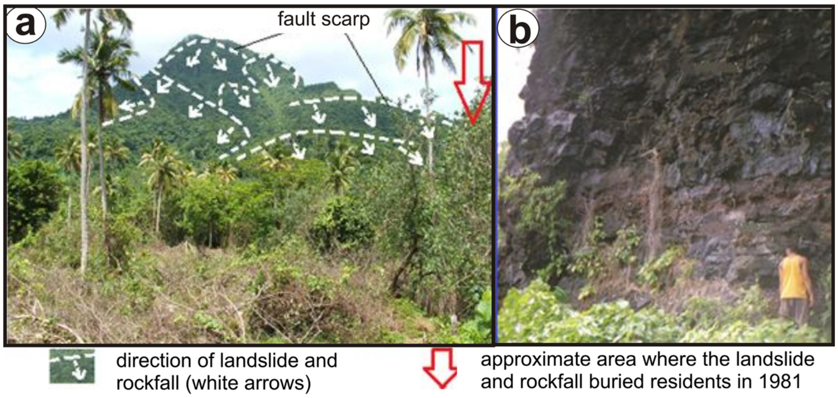

Fig. 9 **a** Looking toward northeast showing Maunga-o-Fao's (Mount Fao) peak. Dashed lines represent fault scarps where slips seem to be moved in direction of white arrows. Thick red arrow indicates the approximate area where landslide and rockfall activity buried residents in 1981. **b** Highly fractured and jointed outcrop of up to 18 m height to the north of Mount Fao exposes a lower entablature zone of the basaltic rocks of the Lemafa Intrusion along the Musumusu coastal area

people explanation were enough to classify that this event was a combination of rockfall and landslide.

Figure 9a shows the southern part of Mauga-o-Fao where it is deeply dissected by series of fault scarp and network of joints. Mauga-o-Fao seems to produce series of rockfall and landslide in the past (Fig. 9a). The mountain has a potassium-argon age of 1.5 Ma (Natland and Turner 1985) and is classified as a part of Lemafa Intrusion of the Fagaloa Formation (Fepuleai 1997, 2016). Lemafa Intrusion represents a massive dike intruded the 2.85 Ma lava of the Fagaloa Formation on the northeast of Upolu (Fepuleai 2016). The massive dike extends about several kilometers from Mauga-o-Fao to the west of Tiavea (Fig. 1d). The Lemafa Intrusion is dominated by columnar joint ranges from centimeters to many meters in length and it dips 75° west (Fig. 4a). At the top of this outcrop (note in the photo on Fig. 4a), columnar joints dip in different direction and form a thickened flow best described as a basaltic lava dome as previously explained as upper entablature zone. Mauga-o-Fao has a similar joint pattern. Rocks at the base of Mauga-o-Fao expose along the Musumusu coastal area are highly fractured and jointed lava flow and are part of a lower entablature zone of the Lemafa Intrusion (Fig. 9b). This lower entablature zone seems to generate a series of rockfall and landslide in the past, indicated with a pile of boulders at the base of cliffs along the coastal area to the north of Mauga-o-Fao. Commonly, there are two joint networks pattern associated with columnar joints of the Fagaloa Formation: (1) joint network that runs parallel with the columnar joint and (2) joint network that perpendicular dissects the columnar joint. The combination of the two joint networks associate with surface and groundwater makes easier for the Fagaloa rock to break and detach from a rock face (Fig. 4a).

The onion-skin like sheeting is commonly occurred in the Mount Fao area. This indicates that lava of the Fagaloa Formation at this part of Upolu could be associated with unloading of overburden by either erosion or landslide.

Case Study 2: Mauga-o-Vaea (Mount Vaea)

Residents live close to the foot of Mauga-o-Vaea are vulnerable to landslide and rockfall hazards (Fig. 10). Mauga-o-Vaea has an elevation of about 350 m above sea level. GoogleEarth image (2017) shows white/brownish dots (fine to coarse in size) surrounding the mountain represents populated area (Fig. 10). The current morphology of Mauga-o-Vaea indicates that the mountain had been associated with a several landslips in the past but unfortunately there was no report of any loss of life in the past. However, field observation and aerial photograph interpretation indicates that the mountain is getting close to produce a massive slip that could devastate nearby villages. This prediction is based on the presence of an intensively weathered rock assemblages that are also highly fractured.

Based on the United Nationals Retrieving Data (www.worldometers.info), it is estimated that the current population (5 June 2017) of Samoa is 195,653. About 18.8% (36,871) of the population live in urban areas. Areas that surround the foot of Mauga-o-Vaea (from Avele to Moamoa) (Fig. 10) estimated to be the most populated urban zone in Samoa which host about 18,000 residents (about half of the total urban population). These particular areas have the most developed infrastructures on the island (main road, main power line, main water line, and main communication facilities), and it also hosts Samoa's main hospital (National Hospital of Samoa). Hence, these sites are located in a hazardous area and a proper hazard analysis is essential in the future to develop a plan to mitigate mass failure hazards.

Mauga-o-Vaea has a potassium-argon age of 2.55 Ma (McDougall 2010). A rockfall hazard zone of Mauga-o-Vaea is estimated to be up to 500 m radius shown by light blue dotted line on Fig. 10. The rockfall hazard zone could be extended further on the basis of the slope angle values of the hills toward the mountaineous regions. It is inferred that

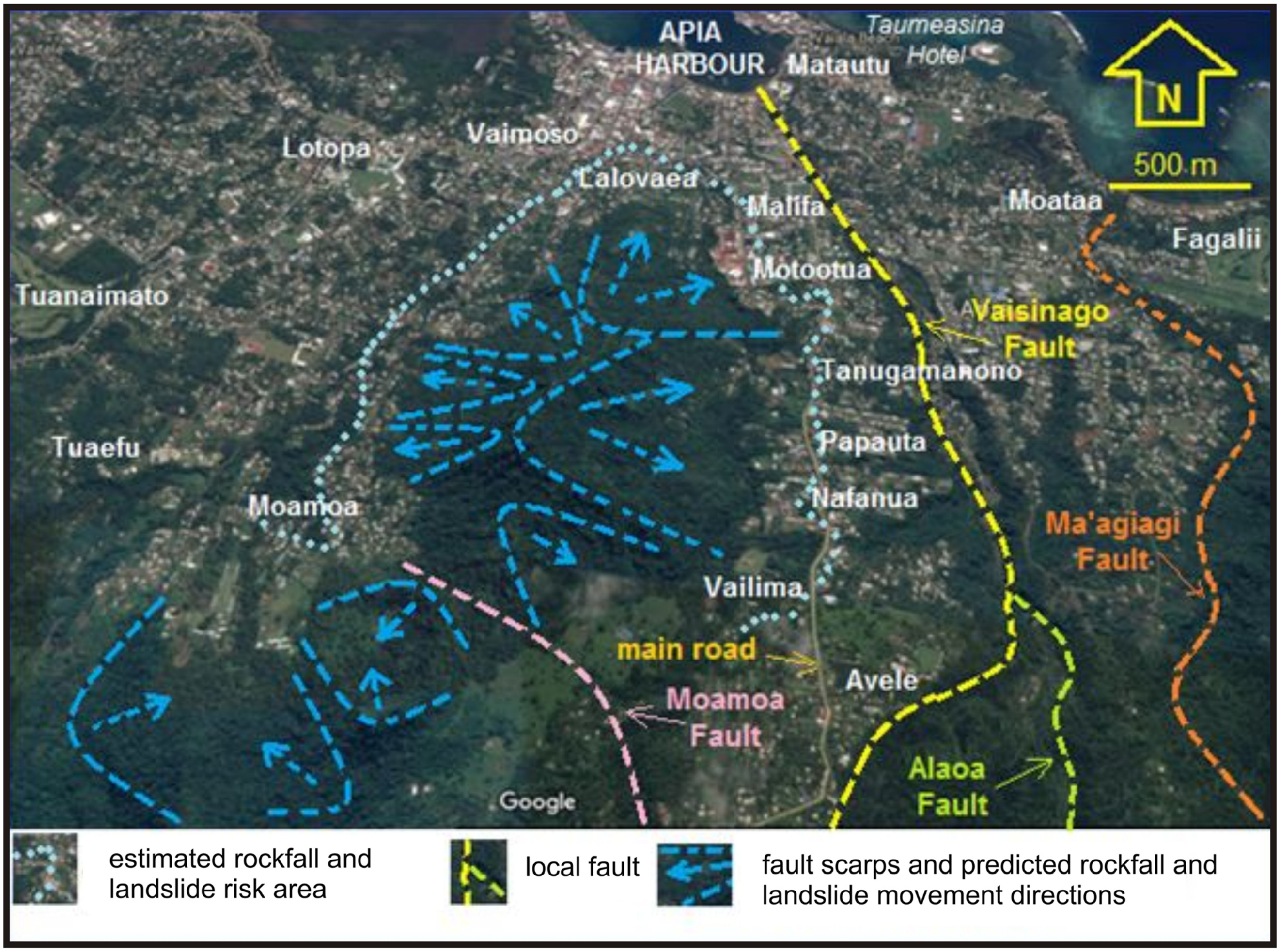

Fig. 10 GoogleEarth image (2017) of the Mauga-o-Vaea (Mount Vaea) area, which is vulnerable to landslides and rockfalls. Dashed lines with blue arrows indicate major slips. Orange dotted line indicates the approximate rockfall hazard zone. Movement along several faults (Moamoa Fault, Vaisinago Fault, Alaoa Fault and Ma'agiagi Fault) is inferred to be responsible to trigger more landslides and rockfalls in the near future

potential future landslides and rockfalls could appear in residential areas of Malifa to Vailima. Areas of Lalovaea, Alamagoto, Sinamoga, and Moamoa could also be more exposed to landslide hazards in the future. Landslide and rockfall activity occurring in these mentioned areas in the near future could destroy residential areas, main roads, power line, water supply, communication facilities, and health facilities including the National Hospital. Mass movement along several fault lines (Moamoa Fault, Vaisinago Fault, Alaoa Fault, and Ma'agiagi Fault) that are elongated north to south could generate major landslides and rockfalls. There are physical evidences of the presence of ancient debris fans at the foothills of the mountainous regions; however, they are commonly covered by dense tropical vegetation as those along the Alaoa Fault and the Vaisigano Fault (east of Vailima).

Based on field observation it seems that a network of joints parallel to the slope of the mountain, associated with various deep fault scarps could have generated several major landslides in the past and has a potential to generate more in the future (Fig. 11a). Tropical weathering and erosion induced by intense rainfall events facilitate the expansion of joints to generate failure zones landslides can be initiated (Fig. 11b) (Williamson and Bell 1994; Piccarreta et al. 2006). There is no sign of exposed dikes in the Mauga-o-Vaea area; however, it is inferred that the mountain could be associated with a network of arrested dike (Fepuleai 2016). In the eastern part of Mauga-o-Vaea toward Vailima area, however (Fig. 10), a creek incises deeply the foothill of the mountain exposing a series of dikes up to 3 m in width known as “Loimata-o-Apapula” (Fig. 11c). Arrested dikes are those terminated at depth (Sheth and Canon-Tapia 2014). This could be due to a smaller volume of injection magma or the fact that there is no continuity in the crack networks at certain depths. The arrested dike could act as groundwater aquifer barrier in the mountain site and accountable for rapid weathering and erosion in the area (Smith et al. 2015; Raiber et al. 2015). Successive evolution of the volcanic cones via distinct eruptive phases forms edifices that are hydrogeologically different (due to eruption

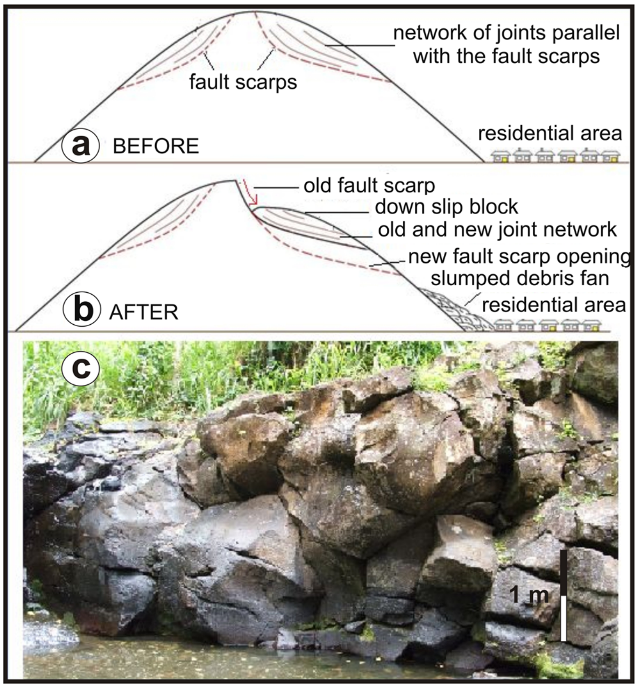

Fig. 11 Sketch of the Mauga-o-Vaea (Mount Vaea) before and after rockfall and landslide formation. **a** The sketch shows a network of joints parallel to the fault scarp and slope that are the significant factors to contribute to develop major slips of the mountain. **b** Looking west, it shows the current situation where more fault scarp generation is expected. **c** Looking along the elongated 3 m wide columnar jointed tabular lava body at the foothill of Mauga-o-Vaea (Mount Vaea). The columnar jointed coherent lava strikes NW-SE with shallow dip angle (8°). Toward the SW, the lava is subhorizontal

style changes). Such inhomogeneity of the volcanic edifices can create numerous zones where weathering and erosion can be more intensive creating zones that can fail easier (Vittecoq et al. 2014; Bolos et al. 2015; Pedrazzi et al. 2016).

Olivine is the most common phenocryst in lava and volcanic sediment of Samoa, and it commonly alters to soft fine reddish yellow iron mineral known as iddingsite. Reddish yellow or brown soil expose at several sections of the mountain indicate a domination of iddingsite. This denotes that a highly weathered soil could be another contribute factor for more landslips of the Mount Vaea in the near future.

Fault scarp system on Mauga-o-Vaea seems to be developed through a continuous process where the new fault scarp starts to develop at the base of a down-slip scarp block (Fig. 11b). Down-slip scarp block which rest along the slope, could also associate with a development of new joints pattern parallel with those of the old joints. Intensive weathering at several portions of the mountain associate with deep fault scarps triggers the block on the eastern side to slip (Fig. 11). This corresponds with an increase in joint network of the slip-block and also develops a new fault scarp at the base of the slip-block. Mauga-o-Vaea is also associated with series of columnar joints (from centimeter to many meters in length) that facilitates mass failure in various directions along the main jointing pattern (Fig. 11c).

Case Study 3: Fagaloa Bay, Northeast Upolu

Fagaloa Bay is located on the east of the Mauga-o-Fao (Mount Fao). Villages at the Fagaloa Bay from Samemea on the east toward the west of Taelefaga seem to be in a potential failure zone where future landslides and rockfalls are predicted (Fig. 12). Based on the 2006 census (www.tripmondo.com/samoa), at least 800 people are estimated to reside in the Fagaloa Bay which number will likely increase in the future. Most people in the area live on subsistence agriculture and fishing while a small portion of the population works or lives in nearby urban regions including Apia. The main road links to Fagaloa Bay is surrounded by deep valleys and steep cliffs of the Fagaloa Formation's rock units commonly failed in recent past.

Movement along the Fagaloa-Falealili Fault (Figs. 1d and 12) and few minor faults in the area at any time could generate landslide and rockfall affecting the access road to the bay and its local communities. The Fagaloa-Falealili Fault has an average movement of 50 mm per year (Gudge and Hawkins 1991). Fagaloa Bay is dominated by highly weathered, eroded, strongly jointed, and fractured lava rocks of the Fagaloa Formation with a series of faults scarps running parallel the coast. Looking northeast above around 250 m above sea level, rockfall risk is high and it is likely to affect villages sitting on the base of the steep cliffs (Fig. 12). Highly jointed narrow razor back ridge of the Lemafa Intrusion is exposed at the central part of Mauga-o-Fao on the west forming a steep morphology toward the northeast. A nature and style of ancient landslides and rockfalls in the Fagaloa Bay are very similar to those identified at the Mauga-o-Fao and Mauga-o-Vaea.

Case Study 4: Leagi'agi Hill, Northern Coast of Savai'i

Leagi'agi Hill is located in the northeast of Savai'i (Fig. 1d). The area has had no threat or experienced recent rockfalls or landslides; however, the presence of highly jointed and weathered rocks associated with steep slope of fault scarp along the Safune Fault should be considered as a potential mass failure zone. Kear and Wood (1959) described the relatively thin lava (30 to 3 m) of the Mulifanua Formation over spilled along the thick (up to 25 m) Salani Formation at this part of Savai'i. The Leagi'agi Hill is part of an exposed cliff-face of the Safune Fault, which link to the Sataua-Ologogo Arc Fault and the Manase-Gataivai Fault to the south (Fig. 13). The three faults (Safune Fault, Manase-Gataivai Fault, and Sataua-Ologogo Fault) seem to form a step-like faulting known as graben fault at this part of Savai'i, where large blocks are down-thrown to the west. The Safune Fault is down-thrown to the west about 20 to 80 m and perhaps extends to the north and could also be a part of the submarine

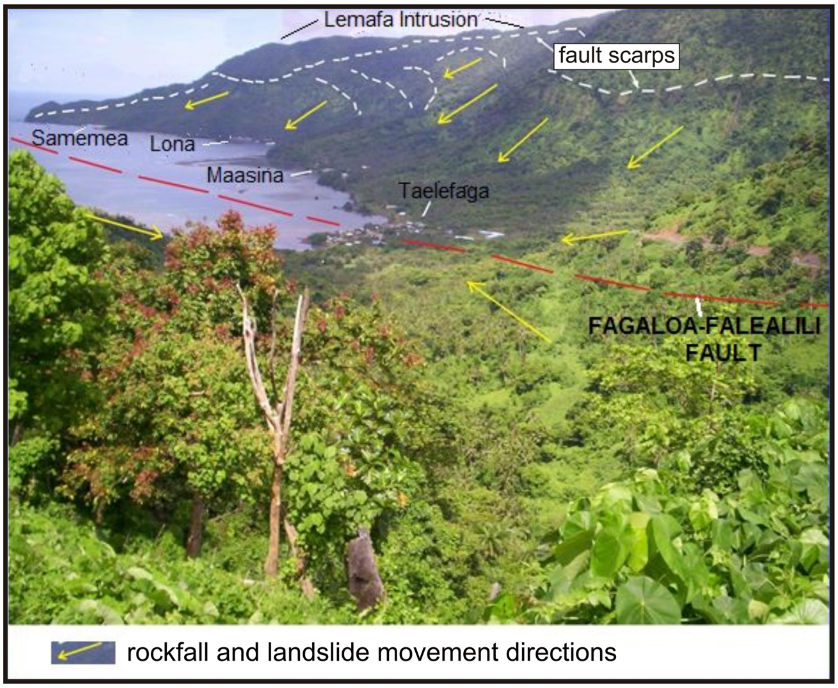

Fig. 12 Looking toward northeast of the Fagaloa Bay where small villages could be devastated from rockfalls and landslides. White dashed lines indicate the series of fault scarps and yellow arrows show the approximate direction of mass movements by rockfalls and landslides. Red dashed lines indicate the actual position of the Fagaloa-Falealili Fault trace following a north to south trending (Fig. 3). The Lemafa Intrusion exposed along the ridge toward the eastern side of the region

debris avalanche on the north east of Savai'i (Hill and Tiffin 1993). Young lava flows (Puapua and Mulifanua Formation) spilled over the fault scarps making difficult to trace the faults on the northern part of Savai'i.

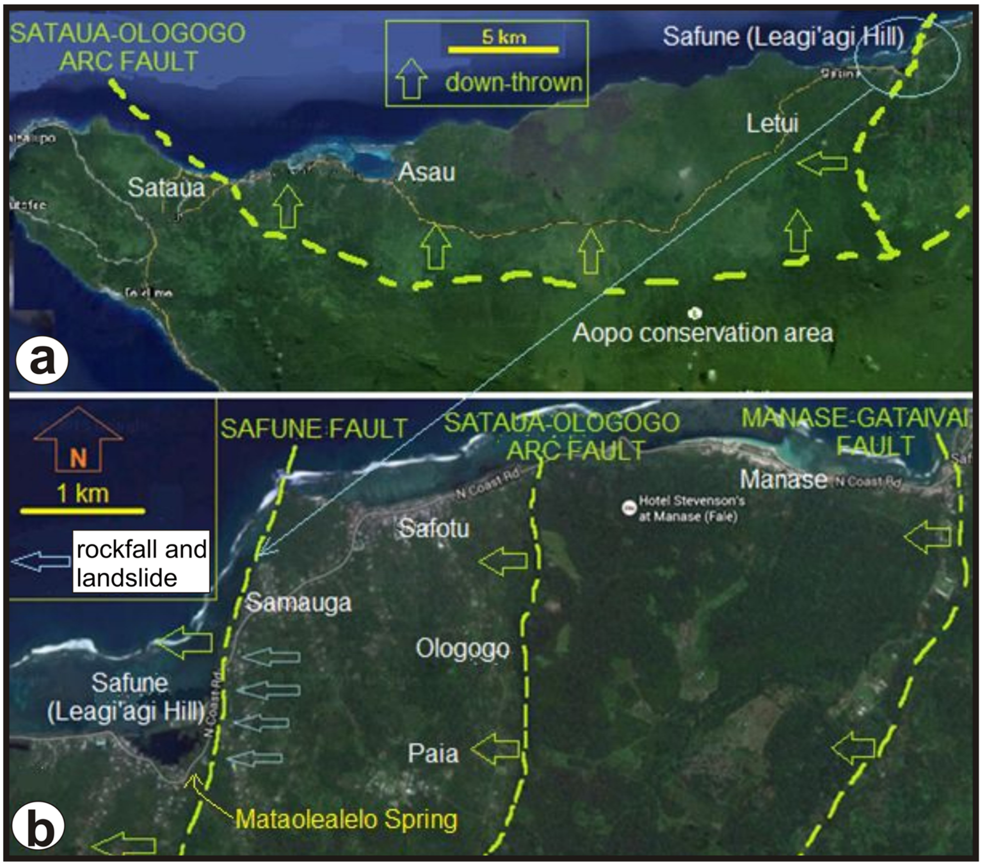

Fig. 13 Sketch map of the Leagi'agi Hill rockfall and landslide hazard. **a** The Leagi'agi Fault is the part of the Safune Fault links to the Sataua-Ologogo Arc Fault. **b** Leagi'agi Hill could be the source of series of rockfalls and landslides in the near future. The down thrown of Sataua-Ologogo Arc Fault and Manase-Gataivai Fault to the west could disturb the region along the Safune Fault

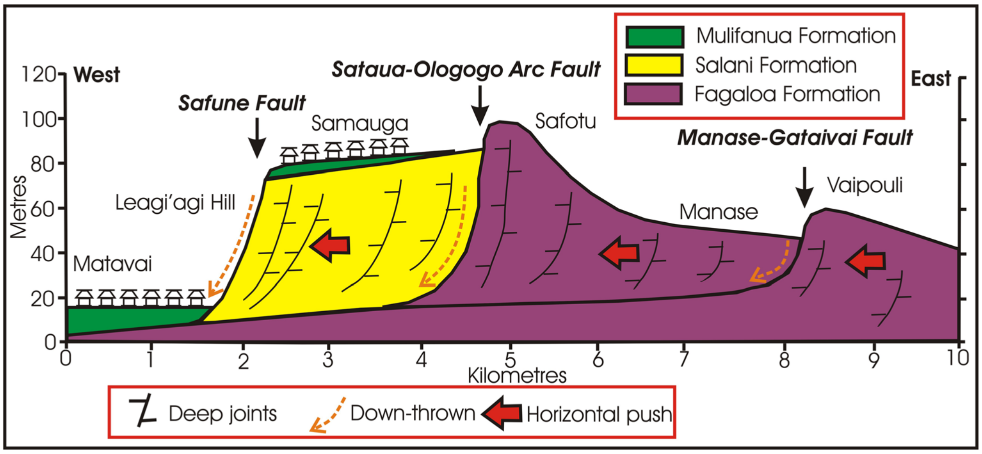

Fig. 14 Schematic cross section of the central northern part of Savai'i (from the west of Leagi'agi Hill to east of Vaipouli). Safune Fault, Sataua-Ologogo Arc Fault and Manase Fault are classified as fault scarps, where down-thrown take place toward the west. The sketch is not to scale

Safune Fault, Sataua-Ologogo Arc Fault, and the northern limb of the Manase-Gataivai Fault are down-thrown (thin green arrow) toward the west (Fig. 13a, b). Figure 14 shows a schematic cross section of the central northern part of Savai'i. The three faults are dipping at great angle. These fault scarps are located in the rock assemblages of the Salani Formation and inferred to be associated from an at least 22.3 ka volcanic cone collapse event (Fepuleai 2016). Both Salani Formation and Fagaloa Formation at this part of the island are deeply dissected by series of joints. Commonly, there are two types of joint patterns, (1) joints that are set parallel with the main fault plane and (2) joints that are set perpendicular to the main fault plane. It suggests that movement along the fault planes would generate a "horizontal-pushed force" (thick red arrow) and would trigger rockfall and landslide at the Leagi'agi Hill in the near future. In addition, surface water and groundwater seeping through these highly jointed and fractured lithologies can be responsible for mass failure in the future. Mataolealelo spring (Fig. 13b) at the base of the Leagi'agi Hill could be an indicator of the presence of arrested dike network below the surface, acting as groundwater aquifer barrier in the area. Like the other three case studies, the groundwater and surface water could extend the size of joints and generate reduction in strength of soil and rock initiating mass failure events.

Conclusion

Rockfall and landslide hazards in Samoa are needed to be treated very seriously like many other natural disasters such as tsunami, earthquake, and volcanic eruption. The four case studies presented here demonstrated well that landslide and rockfall hazard of Samoa is significant and understudied. The described four sites could also form the basis of geosites that can be used for local community geoeducation as promotion sites for landslide and rockfall hazards in Samoa The presented descriptions here could also be used as a basic scientific background to demonstrate the variety of landslides and rockfalls in Samoa. The dynamic nature of landslide and rockfall formation can alter the landscape of Samoa in a short timescale hence identification of definite geosites might be problematic. However, though the study presented here, raising the awareness of local communities and geotourists of the geohazard aspects and landscape modifying effect of such mass movement is important.

The four case studies of rockfall and landslide on Upolu and Savai'i show similarity in such geohazard scenarios in regard to their associate structure (series of joint patterns, highly fractured formation, associate with major/local faults in the area), highly weathered and eroded rock formations. Rockfall and landslide are commonly associated with the older rock units of the Salani and Fagaloa Formation son Upolu and Savai'i. However, the columnar jointed nature of lavas of the younger rocks of the Puapua and Mulifauna Formations should also be considered in future mass failure studies as such joints can act as potential failure regions where enlarged gaps between vertical columnar joints could trigger mass movement even in these younger volcanic units. Columnar joint pattern with complex join networks is also documented in Fagaloa and Salani lava flows suggesting that these joints can expand as water seeps through cracks. The increase in joint sizes could increase the surface area along unstable rock faces may fail threatening local communities.

Tropical environment (hot and wet climate) is a significant contributing factor to speed up weathering process in lava suite and volcanic sediment of Samoa. Advanced weathering triggers rock and volcanic sediment strength reduction. This includes the depletion of major elements such as SiO_2, MgO, K_2O, and Na_2O while enrichment in TiO_2, Al_2O_3, and FeO (Fepuleai 2016). Highly weathered volcanic sediment of the Crater Lake of Lanoto volcano for instance associates with surface cracks on glassy pyroclasts and various weathering halo textures as a result of palagonitization of the ash. Palagonitization of fine wet ash provides good examples of repeated wetting and drying of volcanic ash under tropical conditions. Microscopic scale mechanical weathering on the surface of individual pyroclasts or in minerals in coherent igneous rocks is inferred to contribute to the processes initiating rockfalls and landslides.

Intense weathering alters primary minerals into secondary mineral phases. Weathered primary phenocrysts of coherent lava rocks can mechanically weather out from the rock faces increasing the porosity of the rocks accelerating the saturation potential of the hard volcanic rocks. Alteration process of mafic lava rocks is commonly driven by the olivine alteration to soft, fine iddingsite formation (Fepuleai 1997, 2016). This can be seen well across Savai'i and Upolu along reddish brown stain in most road cuts. The Fagaloa-Falealili Fault, Manase-Gataivai Fault, and Sataua-Ologogo Arc Fault together linked to the termination of the volcanism formed the rock units of the Salani Formation. The three faults suggested to be triggered major, island-wide edifice collapse event occurred about 22,300 years ago (Fepuleai 2016).

Apart from the four case studies, there are other locations where rockfalls and landslides occurred recently such as the coastal road section of the southern part of Upolu and Savai'I, however these sites got less attention. Ironically, the largest known landslide occurred in 12 February 2018, along the main road connecting Apia and SE Upolu's main tourist attractions where succession of thick lava flows separated by lava flow foot and top breccias form an about 100 m high cliff right on the coast line (Fig. 2g, h). These locations are close to the central volcanic fissure and are commonly associated with rock units of the Salani and Fagaloa Formation. This recent landslide event highlights the urgent need to record and study in depth the origin and triggering mechanism of landslides in Samoa.

Further detailed mapping and seismic network study along major fault system of the four case studies would provide valuable information for future development and risk reduction on the two main islands. The four case studies are need to be geologically and geotechnically re-mapped to precisely identify highly hazardous zones for mass failure and evaluate potential hazard scenarios. Geochemical analysis of sediment at these particular sites enables to determine nature and complexes processes associate with break down rock components and internal structure of minerals.

Acknowledgements We gratefully acknowledge the School of Marine and the School of Geography, Earth Science and Environment for their unconditional support for this project. The manuscript greatly benefited by the detailed reviews of Ingomar Fritz, an anonymous reviewers and the Journal Editor, Kevin Page.

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