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Submarine slides on volcanic islands – a source for mega-tsunamis in the Quaternary

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Abstract: Slope instability and mass movements on volcanic islands may generate large magnitude tsunamis. During the Quaternary, tsunamis originating from volcanic islands have significantly impacted the world's coastlines. However, research has only recently begun to analyse the effects of tsunamis in coastal environments. This paper overviews the distribution, magnitude, recurrence interval, and age of large submarine slides on volcanic islands and their potential for the generation of mega-tsunamis during the Quaternary.

Key words: mass movement, Quaternary, submarine slide, tsunami, volcanic islands.

I Introduction

A tsunami may be generated by different events including earth- and seaquakes resulting from tectonic movement, shock waves resulting from explosive volcanic eruptions, meteor impact, large rock falls or submarine slides. Discussions have centred on volcanic activity as the causal factor for tsunamis. The collapse of the volcanic cone on Santorini Island (Greece) formed a caldera in 1628 BC and initiated a tsunami that is believed to have extinguished the Minoan culture on Crete (Greece). However, no field evidence has been found for this event (Dominey-Howes, 1996). Other reports include the Krakatoa eruption (Indonesia) in 1883 that caused a 35-m-high tsunami claiming 36 000 lives. With the exception of initial ideas by Moore (1964), it was not until the eruption and collapse of Mount St Helens (USA) on 18 May 1980, which initiated the sliding of the northern slope of the mountain with a volume of 2.3

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km^3 (Voight *et al.*, 1981), that large landslides on volcanoes began to be discussed as a primary cause for mega-tsunamis.

This paper concentrates on the tsunami-generating potential of submarine slides on volcanic islands during the Quaternary, because (1) volcanic trembling of these islands may initiate slide activity; (2) repeated slide action may occur on the same location during short geological timespans because of the ongoing growth of volcanic islands; (3) slides and related tsunamis may be frequent and extremely large owing to height, slope instability and steepness of the islands; (4) mega-tsunamis generated by slides on young volcanic islands may have significantly affected the world's coastlines during the Quaternary. Historically, the term mega-tsunami has not been clearly defined. For this research, a 'mega-tsunami' significantly exceeds large historic tsunamis, such as Krakatoa (1983), Chile (1960) or Alaska (1964), having a wave-height potential of several metres in the deep ocean and a run-up of several decametres or more at beaches thousands of kilometres away from the source area.

New measurement techniques and the improvement of the three-dimensional display of the seafloor through side scan sonar (GLORIA; Geologic Long-Range Inclined Asdic) in 1983 (Moore *et al.*, 1989), complemented by deep-sea drilling and dating projects, allow for a clearer understanding of the ocean floor. Several studies (Moore, 1964, 1987; Duffield *et al.*, 1981; Fornari and Campbell, 1987; Lee, 1989; Holcomb and Searle, 1991; Masson *et al.*, 1998; Masson *et al.*, 1998, 2002; Carracedo, 1999) have provided evidence for extensive mass movements at the flanks of volcanic islands on the seafloor, which, based on their dimensions, may have caused tsunamis of extreme magnitudes and extent and could continue generating future tsunamis. The critical slide-generating factor is not necessarily a volcanic eruption or an earthquake, but simply the fact that volcanoes may grow rapidly and usually centrally produce large volumes of material. Therefore, they tend to build up relatively steep slopes within a short geologic timespan that does not allow sufficient time for erosion processes to reduce the relief or for stabilization through settlement. Mass movements on volcanic islands may be initiated through exceeding critical slope values. Since most volcanic islands remain volcanically active and grow, sliding on volcanic islands may occur repeatedly even in the short geologic period of the Quaternary. However, certain stages in the development of volcanic islands are particularly susceptible to large landslide generation, particularly the early shield stage (e.g., Moore, 1964, 1987).

Submarine slides have also been observed in areas without any volcanic activity (Bugge *et al.*, 1988; Dawson *et al.*, 1988; Hampton and Lee, 1996), when large amounts of sediments have accumulated on slopes. Furthermore, submarine slides are common at the front of large deltas. In addition to slope instability and earthquakes, it is assumed that gas hydrate eruptions belong to the initiators of submarine mass movements.

The speed of an individual submarine mass movement is generally unknown and the material maybe viscous due to a high water content, making it difficult to correlate the initiation of a tsunami (LeBlond and Jones, 1995). However, it can be assumed that many of the detected submarine debris avalanches caused tsunamis owing to their movement of tens of kilometres from their source areas over a relatively flat and even uphill sea floor which require great velocities (>100 km h^{-}).

This paper provides a summary of the present stage of knowledge on tsunami-generating submarine Quaternary mass movements on volcanic islands, as well as examples for the dimensions, age and recurrence intervals of these mass movements. This paper also discusses the potential of tsunamis generated by these slides, and geomorphic impacts of these tsunamis on coastal landforms.

II Volcanic islands and submarine mass movements

1 Location and age of volcanic islands on Earth

Volcanic islands that are geologically young and still active are mainly located within three geodynamic situations on Earth, listed in order of relevance (least to most):

1. Divergence zones of the ocean floor (e.g., Iceland, Tristan da Cunha, Réunion).
2. Subduction and plate collision zones (e.g., the Aleutians, Japanese Islands, Sunda Chain, Antilles). In these situations, young volcanoes are often located on larger islands and may have relatively flat foreshore areas.
3. Hot spots (e.g., Canary Islands, Marquesas, Hawaiian Islands). These islands generally lie isolated from each other in loose chains. Their age sequence ranges from older inactive volcanoes such as seamounts or atolls, to actively growing volcanic islands.

The world map in Figure 1 illustrates the present dispersion of these volcanic islands on Earth. Over time, the weight of the volcanic island exerts pressure on the ocean floor with an overall sinking effect on the island. For example, the Hawaiian Islands have

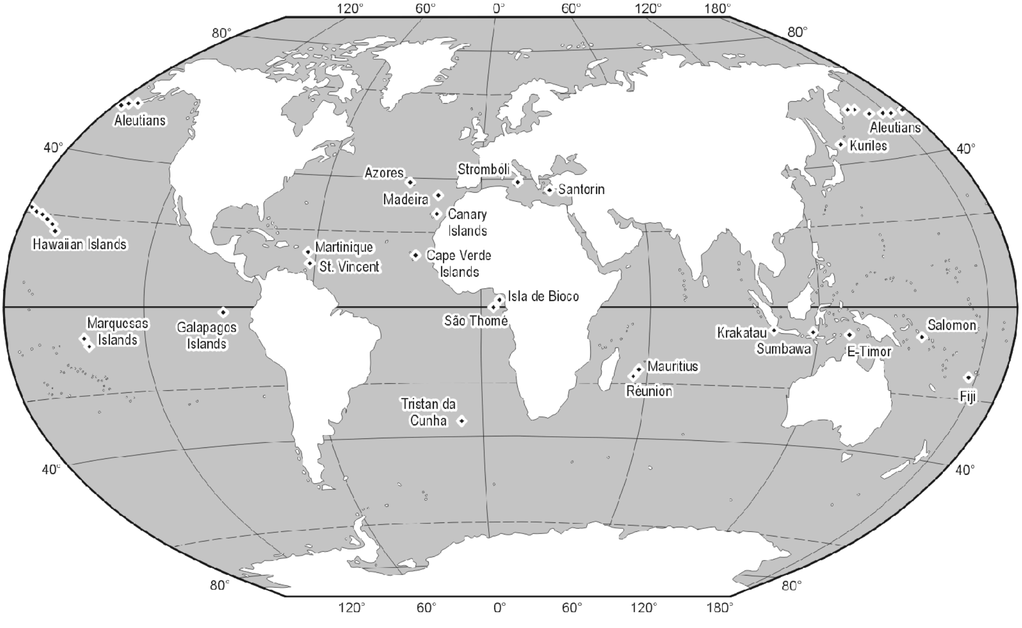

Figure 1 Location of young volcanic islands in the deep oceans of the world

been sinking at a rate of approximately 2.6–2.7 mm year^{-1} during the last 475 000 years (Szabo and Moore, 1986; Ludwig *et al.*, 1991). Despite the sinking, the active islands continually grow both in their heights above sea level and their diameters.

Lava flows above sea level tend to create relatively flat slopes (often far below 10°), while submarine lava flows tend to build steep slopes (more than 20°) owing to rapid cooling processes. In tropical and subtropical regions, coral reef terraces serve as deposition areas for volcanic material and build steep outside slopes that may exceed 20° (Moore and Clague, 1992). Because of rapid island growth, terrestrial erosion processes cannot significantly reduce these build ups that become increasingly unstable with time. It is important to understand that the largest of these young volcanic islands (including the Hawaiian Islands) have reached elevations exceeding 4000 m asl and total heights of approximately 10 000 m. These large islands reached their current diameters of several 100 km over a time period of a half to one million years. When the growth process is close to attaining a shield stage, the slope stability threshold is usually significantly exceeded and cracks and slides occur. Cracks along deep crevasses or along spreads with dike formation can weaken the volcano and may initiate volcanic eruptions. The addition of water may increase the explosiveness.

The ages of islands experiencing volcanic growth and destruction processes range from several thousand years for new islands on hot spots or along rift zones to 28 million years for the oldest island remnants on the Emperor Chain northwest of the Hawaiian Ridge, or for Fuerteventura, the oldest of the Canary Islands. Island age may be derived from the velocity of plate tectonic movements. For example, the distance from Niihau and Kauai, the two main northwestern Hawaiian Islands, to the Kilauea-region on the Island of Hawaii is approximately 700 km. Based on an estimated plate movement of approximately 12 cm year^{-1} on the hot spot, their age difference is approximately 5.8 million years (Moore and Clague, 1992).

2 Processes of mass movements: causes, processes, destructive and constructive effects

Submarine mass movements on volcanic islands may be classified into three groups, including slumps, debris avalanches and turbidity currents, as described by Lipman *et al.* (1988) and by Moore *et al.* (1989, 1994b). Turbidity currents neither generate tsunamis nor new formations on the sea floor. They may be sourced directly from debris avalanches, as suggested by Masson *et al.* (2002) for the El Golfo landslide on El Hierro (Canary Islands). Suspension currents usually thinly spread the sediment (a few decimeters to a few meters) over a large area. In contrast, slumps and debris avalanches may cause great vibrations or shaking initiating mega-tsunamis. Most slumps are rock masses that slide stepwise and reach depths up to 10 km along an island's flanks (Smith *et al.*, 1999, see also Figure 2). The rock mass loses its connectivity during its movement along crevasses or fractures or during the rotational sliding process of individual sections. One example of a slump of extremely large dimension is the Hilina slump located to the east of Kilauea on the Island of Hawaii (Figure 3). This slump is mostly submarine and reaches several thousand metres to the deep ocean floor (Smith *et al.*, 1999). The Hilina slump has a volume of more than 10 000 km^3, fifty times the volume of a typical large debris avalanche.

Geomorphic characteristics of the majority of submarine slumps are similar to those

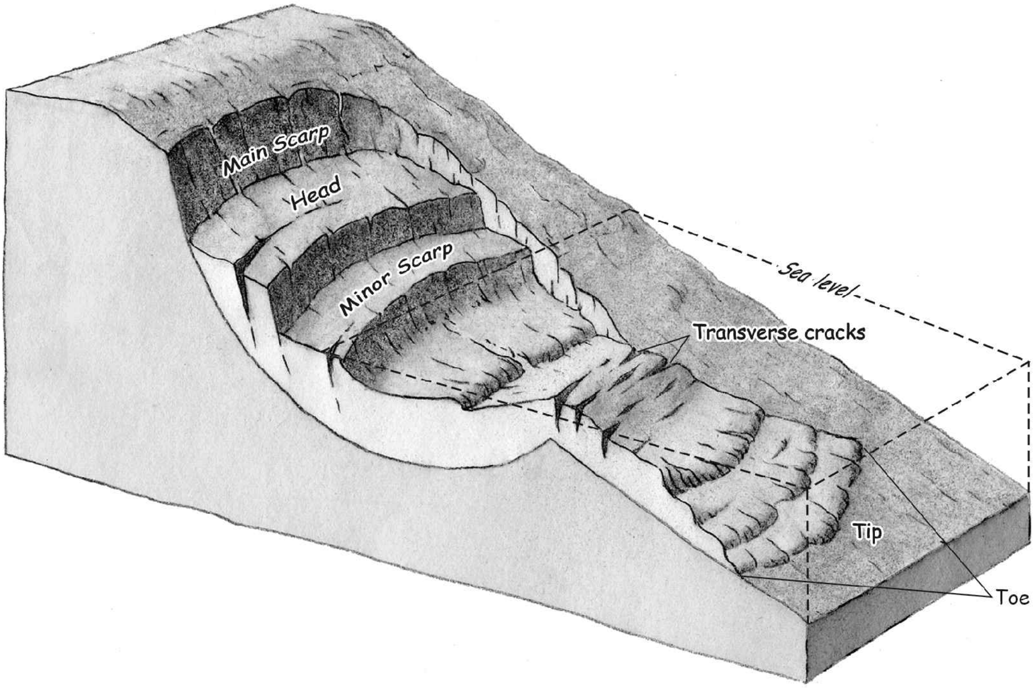

Figure 2 Major features of a typical slump

of terrestrial slumps. Most visible characteristics of slumps include steep slopes, steep toes and large transverse fissures on the mass movement. Many slumps that originate from terrestrial source areas extend into the submarine. For example, the still visible and young so-called rifts located on the southeastern slope of Kilauea are straight scarps that transverse the upper and still terrestrial area of the Hilina slump (Figure 3) and continue into the submarine section of the slump. Freshly opened cracks provide evidence for the continuing but rather slow stepwise movement of the slump. The upper part of the Hilina slump moved 8 m seaward and descended 3.5 m along a 30-km-long coastal area at the time of the 7.2 magnitude earthquake of 1975 (Moore *et al.*, 1989). The tsunami that was initiated reached Kalapana Peninsula with a run-up higher than 10 m. It is still unclear whether an earthquake mobilized the slump, or whether the movement of the slump generated the quake. Slumps are common phenomena in the entire Hawaiian Island chain.

In contrast to slumps, submarine debris avalanches occur rapidly and cover great distances. They are comparable to terrestrial rockslides, such as those caused by the eruption of Mount St Helens (USA) in 1980 (Voight *et al.*, 1981). Debris avalanches frequently have large headwall scarps, such as the 1000-m-high scarp of the El Golfo debris avalanche on the northwestern flank of El Hierro (Canary Islands). Lateral scarps of the proximal erosion area of the El Golfo debris avalanche are up to 600 m high and extend into water depths of 3000–3200 m (Masson *et al.*, 2002). Amphitheatre-like scarps often mark the heads of debris avalanches (Figures 4, 5, 6). In several cases, the head belonging to the scarp is filled through eruptions that immediately follow the mass

Figure 3 Transverse cracks (rifts) provide evidence for the movement of the Hilina slump located to the southeast of Kilauea on the Island of Hawaii

movement and occur in the deepest area of the head, where the pressure release is highest. A right and left flank borders the path of the mass movement, both slightly higher than the central groove itself. The foot appears bulging and has a steep edge along the tip. The toe is characterized by a chaotic collection of hummocks (Moore *et al.*, 1994a,b). The coherence of the mass is significantly disturbed. Sections with diameters of several kilometres and depths of several hundred metres can be preserved together within the hummocky terrain.

Based on Masson *et al.* (2002), Canarian landslides take the form of debris avalanches and have volumes ranging from 50 to 500 km^3. These debris avalanches reach lengths of up to 130 km covering several thousand kilometres of sea floor. Approximately 10% of the total volcanic structure of the small, relatively young islands of El Hierro and La Palma is accounted for by debris avalanches (Masson *et al.*, 2002).

Characteristic features of debris avalanches, including their great length that may exceed 200 km in extreme cases (Table 1) and that they frequently overcome upslope areas of several 100 m, provide evidence for extremely fast movements that have been estimated to reach more than 100 km h^{-1} (Lipman *et al.*, 1988). Debris avalanches should, therefore, have the potential to generate tsunamis of extreme magnitude.

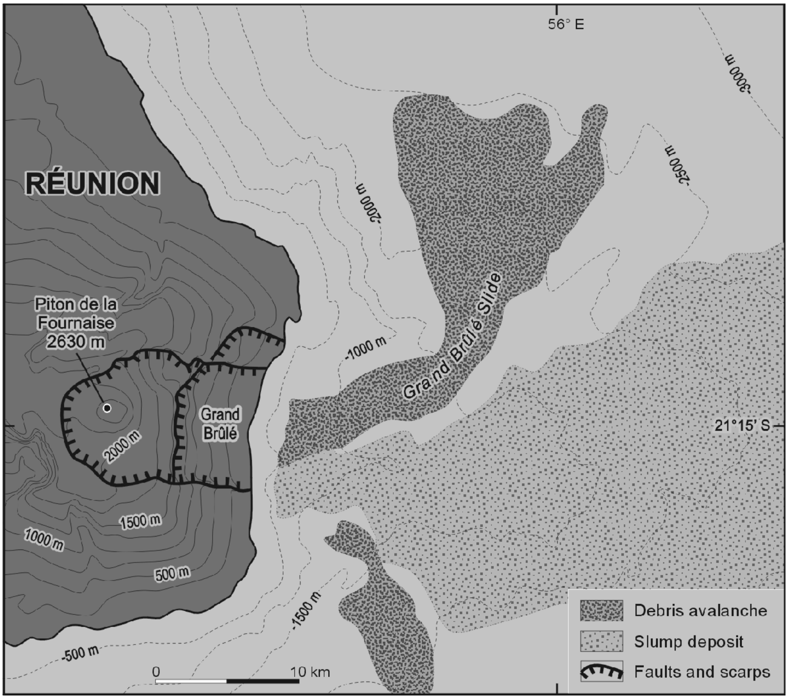

Figure 4 Island of Réunion, Indian Ocean. Note the amphitheater-headed valley appearing similar to a caldera-like opening on the eastern side of Piton de la Fournaise, a source area for large Pleistocene and Holocene slides that reach great water depths (Lénat *et al.*, 1989; Lenat and Labazuy, 1990)

Figure 5 The Napali Coast in northern Kauai (Hawaiian Islands) is the source area for the North Kauai slide that occurred more than one million years ago. Since then, fluvial erosion has deeply incised the area and caused valley formation

Figure 6 The so-called mega-cliff in the eastern Kohala Mountains, Island of Hawaii, is relatively young and hardly incised. The cliff is the head-scarp of the Pololu slide that has been dated 370 ka (Moore *et al.*, 1989)

3 Dating of submarine mass movements

A limited number of dating projects on submarine mass movements have been conducted so far. A variety of methods to determine the ages of these events are available, including the radiometric Potassium–Argon method for volcanic rocks. This method cannot directly date the mass movement event, however, it allows for the dating of volcanic products that are older or younger than the slide. Other methods include the examination of sediments accumulated on debris avalanches or slumps. Here, the thickness of the accumulated sediment in the deep sea allows for an age determination (10 cm of fine sediment may equal several thousand years). For example, only 5–10 cm of sediment have accumulated on the boulders of the Alika 2 slide off Maui that was dated approximately 100 ka (Lipman *et al.*, 1988). Methods of sediment-based age determination also include Amino Acid Racemization and 14C dating of carbon remnants (e.g., foraminifers) contained in the accumulated sediment. However, Accelerator Mass Spectrometry (AMS) and ^{14}C dating may only be applied to a time frame that does not exceed the late Pleistocene to Holocene. The rate of sedimentation is very low in deep water off islands that provide little sedimentation material because of their limited source area. Therefore, many slides with ages of several million years have quite a fresh appearance on SONAR imagery. A third dating method is applicable to submerged volcanic islands, where submarine profiles frequently represent coral reef terraces. Szabo and Moore (1986), Moore and Clague (1992) and Ludwig *et al.* (1991) described these profiles for the Island of Hawaii for depths up to 1335 m. The decrease in sea level owing to the advance of an ice age may correlate with the sinking speed of the island for a while. In contrast to most regions on Earth, this reef terrace sequence

Table 1 Dimensions of large submarine slides (debris avalanches) on young volcanic islands

Islands	Slide name	Length (km)	Width (km)	Depth (m)	Vertical distance moved (m)	Area (km^2)	Volume (km^3)	Estimated age[a] (ka)	Reference
1. Réunion	Ralé-Poussée	40	10	100	1700	200	30	4.2	Labazuy (1996)
2. Réunion	Eastern Plateau	60	60	850	3000		500	15–60	Labazuy (1996)
3. Cape Verde	Fogo	25	12		1200		100	>10	Day *et al.* (1997, 1999)
Canary Islands									
4. El Hierro	El Golfo	65	50	100	5000	1500	400	100–130 15–20	Fornari and Campbell (1987)
5. El Hierro	El Julan	60	50		4600	1800	130	>160	Carracedo (1996,
6. El Hierro	Las Playas II	50	50		4500	950	<50	145–176	1999)
7. La Palma	Cumbre Nueva	80	60		6000	780	200	125–536	Day *et al.* (1997,
8. Tenerife	Guimar	>50	90		>4000[b]	1600	120	780–840	1999)
9. Gran Canaria		30[b]	25		>2000[b]	>600[b]	~450		Lipman *et al.* (1988)
10. Fuerteventura		110[b]	65		>2000[b]	>5000[b]			Masson (1996), Masson *et al.* (2002) Moore *et al.* (1989) Lipman *et al.* (1988) Urgeles *et al.* (1999) Watts and Masson (1995)

Hawaiian Islands									
11. Kauai	N Kauai	140	100		>4000[b]	14000			Carracedo (1996, 1999)
12. Kauai	S Kauai	100	50		>4000[b]	6800		>13	
13. Oahu NE	Kaena	80	45		>4000[b]	3900			Garcia (1996)
14. Oahu NE	Nuuanu	235	35	2000	5000	23000	5000		Hampton and Lee (1996)
15. Molokai N	Wailan	195	40		>4000[b]	13000			
16. Lanai SW	Clark	150	30		>4000[b]	6100			Lipman *et al.* (1988)
17. Hawaii N	Pololu	130	20		>4000[b]	3500		370	Moore *et al.* (1989)
18. Hawaii WSW	Alika 1–3	95	15	>50	4800	4000	2000	247	Smith *et al.* (1999)
	Alika 2						200	105–127	
19. Hawaii S	Ka Lae W	85	10		5200	850			
20. Hawaii S	Ka Lae E	75	10		5200	950			
21. Hawaii	Hilina slump					2100	10–12000		

Notes:

[a] Ages originated from K/Ar dating of volcanic rocks or Th/U, ESR and ^{14}C dating of coral.

[b] Length, width and area coverage data originated from maps and graphs included in the references.

consists of build-up phases correlating to regression phases (ice ages). Some build-up phases persist for tens of thousands of years and provide an accumulation surface for volcanic material. Accumulation processes contribute to the width of the coral reef terraces and to their later preservation (Moore and Clague, 1992). Carbonate samples from these reefs may be dated using Thorium/Uranium, $^{234}U/^{238}U$ or Electron Spin Resonance (ESR), if originating from time periods ranging over several 100 000 years. The relative dating of landslides using reef formations is based upon the principle that slides are older than a reef that grew on top of them or younger than a reef they partly destroyed during the sliding process.

4 Evidence for tsunamis accompanying mass movements: extent and effects of tsunamis

Submarine mass movements belong to the largest formations on Earth that may be generated within a geologic moment. They may have dimensions greater than 200 km in length and 50 km in width, with depths ranging from several metres to 2 km (for debris avalanches) or up to 10 km (for slumps). Submarine slides may cover surfaces of several thousand square kilometres and range in volume from 20 km^3 to more than 1000 km^3 (Table 1 and Figures 7, 8, 9). On the Canary Islands, large slides removed approximately 25% of the volume of these islands. Sometimes, the structures left appear like a Mercedes star (Figure 10). The frequency of recurrence of large submarine slides is, on average, once in 100 000 years over the whole Canary Island chain, and once every 300 000 years for each individual island (Masson *et al.*, 2002). Masson *et al.* (2002)

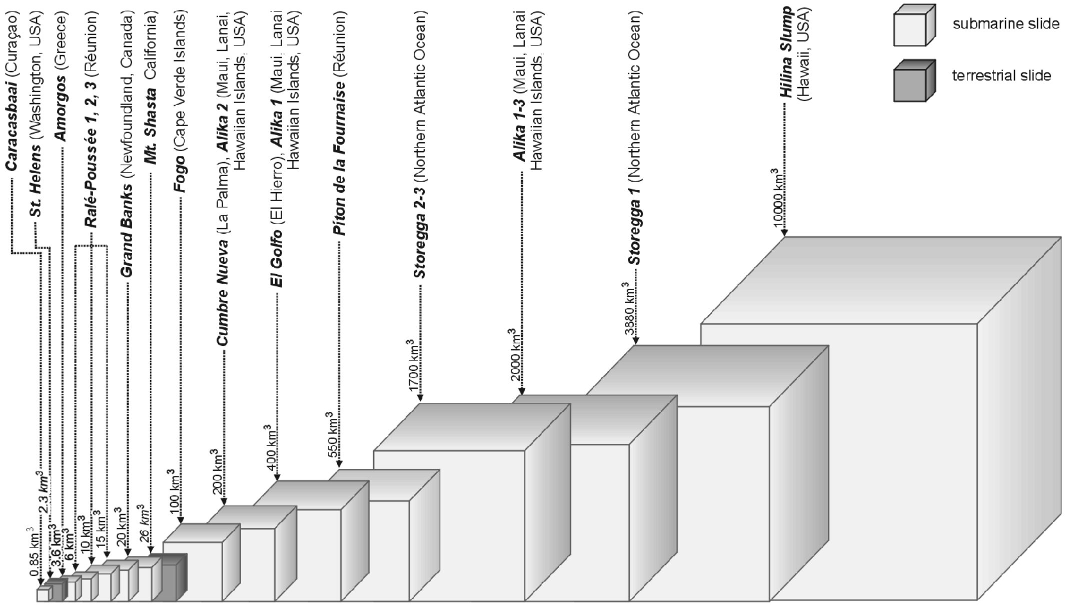

Figure 7 Illustration of volumes of submarine slides. Volumes are displayed as cubes for a simplified comparison

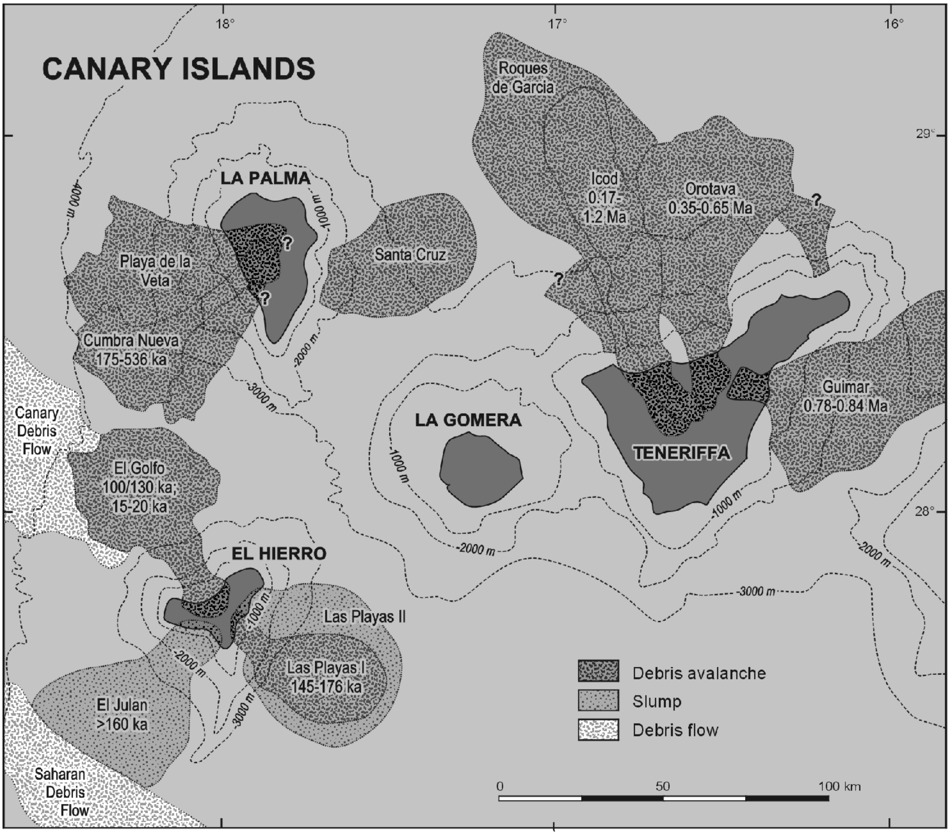

Figure 8 Large submarine slides on the Canary Islands (modified after Carracedo, 1999; Masson *et al.*, 2002)

reported that the majority of 14 large landslides on the Canary Islands occurred during the last 1 million years. The majority of the 68 large submarine mass movements that have been observed in the younger Hawaiian Archipelago (Moore *et al.*, 1989) occurred during the last 2 million years. Therefore, at least 100 large submarine slides (>20 km^3) must have occurred worldwide during the Quaternary. All rapidly occurring mass movement processes are likely to have caused a tsunami of great magnitude, wave height and run-up.

Geomorphic evidence for submarine mass movement processes should be observable in many coastal regions. Owing to their extreme energy, evidence of mega-tsunamis generated by submarine mass movements should be distinguishable from those generated by continuous littoral processes. Since these slides and their tsunamis have rarely been considered in literature on coastal geomorphology so far, this may be one of the great unsolved questions in coastal research.

The giant slides off the Hawaiian Islands (Figure 9) are considered to be among the largest on the planet (Moore *et al.*, 1994a; Lockridge, 1998; Kanamatsu *et al.*, 1998). A total of 68 major submarine slides with lengths greater than 20 km were identified along

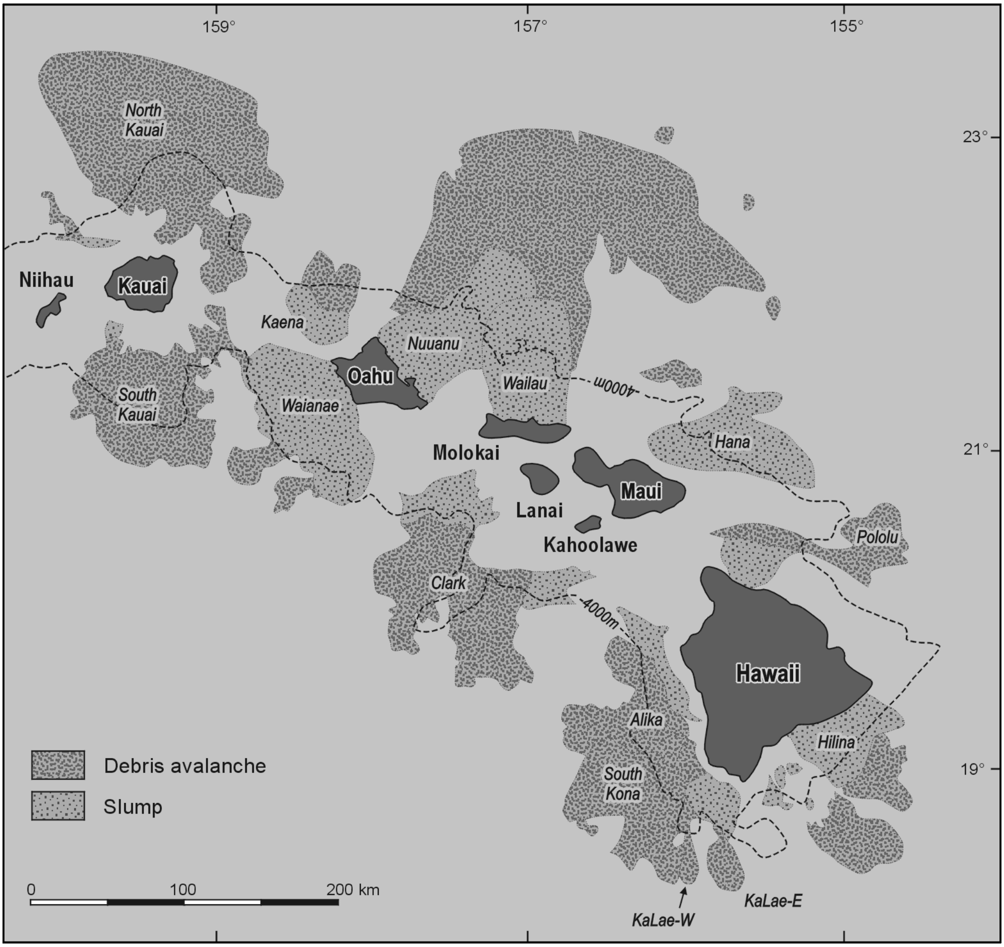

Figure 9 The Hawaiian Islands are surrounded by numerous very large submarine slides that reach into depths of more than 4000 m below sea level (modified after Moore *et al.*, 1989)

steep slopes of the islands through sidescan sonar studies conducted along the Hawaiian coastline during the 1980s. The larger Hawaiian slides are located at the seafloor and reach almost 250 km in length with deposits greater than 5000 km^3. The vast volume estimates of the prehistoric Hawaiian slides dwarf recently recorded tsunami-generating slides by factors of a hundred- to a thousand-fold. For example, the volume of the Unzen Volcano slide in 1792 (Bryant, 2001) that claimed over 15 000 lives in Shimabara, Japan, is estimated as 0.535 km^3. In comparison, a prehistoric Hawaiian slide, titled the Alika 2 slide, has an approximate volume of 200 km^3. Alika 2 occurred at the western flank of Mauna Loa Volcano (Island of Hawaii) approximately 105 000 years ago and appears to have generated a giant tsunami (Lipman *et al.*, 1988; Moore *et al.*, 1989; McMurty *et al.*, 1999). Tsunami effects include soil erosion on Kaho'olawe up to an elevation of 242 m (Lockridge, 1998). Lockridge (1998) and Moore and Moore

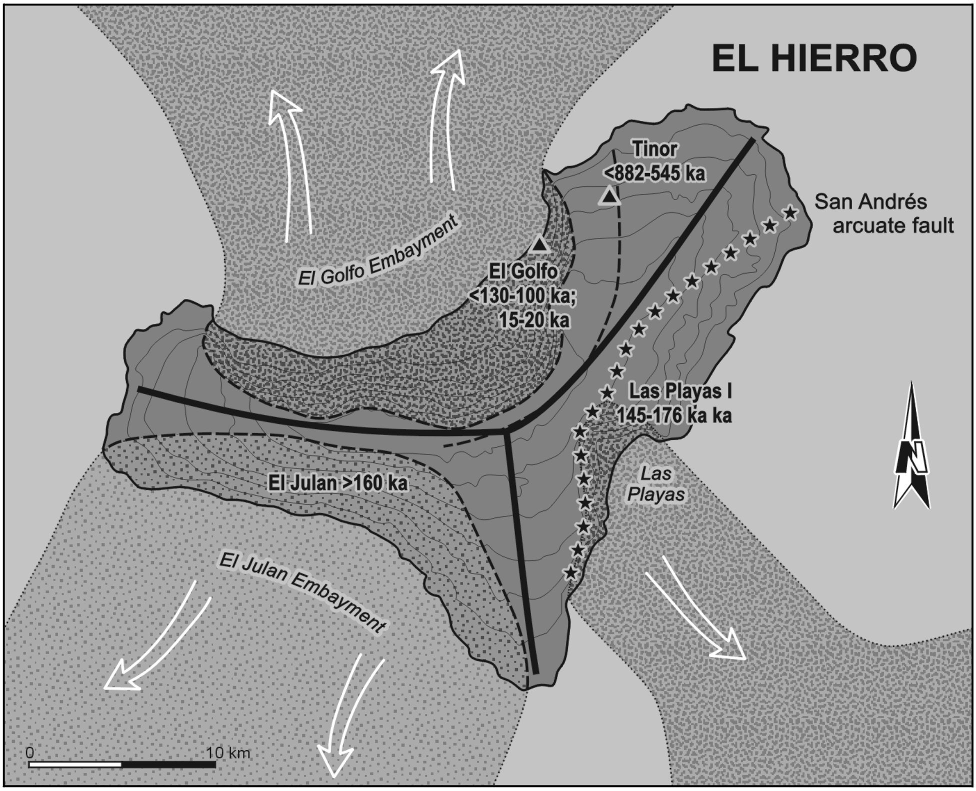

Figure 10 Scarps of three slides that moved into different directions and transformed El Hierro Island (Canary Islands, Spain) into a so-called Mercedes star structure

(1984) attribute submarine slumping as the cause of a major tsunami that left coral reef deposits known as Hulupoe Gravel at 326 m above sea level on the Island of Lanai, most probably also from the Alika 2 event (McMurtry *et al.*, 1999). A recent study by Felton *et al.* (2000) discussed the controversy of the hypothesis of the deposition of the Hulope Gravel by one single tsunami event. Keating (2000) suggested that these deposits were more likely elevated strandlines rather than tsunami deposits.

Young and Bryant (1992) and Bryant (2001) theorize that the Clark Slide, located on the Island of Lanai generated a tsunami that may have traveled 7000 km across the Pacific and eroded the New South Wales coastline. In addition, Moore (2000) observed landward-fining in onshore gravel as evidence for a late Pleistocene tsunami on the Island of Molokai. Moore's (2000) observations include coral-bearing conglomerate at up to 72 m above present sea level on the south coast of Molokai. The conglomerate was ascribed to a tsunami generated by a landslide (Moore *et al.*, 1994c).

The relative energy for few mass movement events can be approximated. For example, the 1956 earthquake of Amorgos in the Aegean Sea, Greece (Perissoratis and Papadopoulos, 1999) with a 7.8 magnitude generated a mass movement with a volume of approximately 3.6 km^3 and a tsunami with a maximum height of 30.5 m leaving evidence for a 20-m run-up on Astipalaia Island located 40 km away. However, it is still unclear whether it was plate tectonic movement or the mass movement that generated the tsunami. In 1979, a mass movement with a volume of 150 million m^3 generated a tsunami that claimed 11 lives in the Cote d´Azur near Nice, France (Nisbet and Piper, 1998). A 7.2 magnitude earthquake initiated the 1929 mass movement near Grand Banks (Newfoundland) that had a volume of 760 km^3 and generated a severe tsunami (Prior and Coleman, 1984). A mass movement with a volume of 400 km^3 accompanied the collapse of El Golfo on El Hierro Island in the Canary Archipelago approximately 100 000 years ago. This mass movement is assumed to have transported boulders weighing more than 1000 t onto elevations of 11 m on the Bahamas located more than 3000 km away (Hearty, 1997). Alika 2 (Lipman *et al.*, 1988; Moore *et al.*, 1989; McMurty *et al.*, 1999) is a debris avalanche located between Maui and Lanai in the Hawaiian Archipelago that was dated from the last Interglacial between 105 and 127 ka. This mass movement is estimated to be 200 km^3 with a total elevation difference from the upper to lower end of the slide of more than 4000 m. The general belief that this mass movement generated a tsunami that displaced large coral boulders onto locations 365 m above sea level on the Island of Lanai is subject to current scientific debate (Keating, 2000). However, the same tsunami is also believed to have transported 50-t boulders to elevations of 30 m at the eastern coast of Australia, a location more than 7000 km away (Bryant *et al.*, 1992, 1996a,b). Several additional tsunami-generating submarine slides have been studied. These slides did not occur on young volcanic islands but may illustrate the tsunami-generating effect of large submarine slides. For example, the Storegga Slide in the northern Atlantic Ocean was last active approximately 7000 years BP and is known to have generated tsunamis affecting southern Norway, eastern Iceland and Scotland during two time periods, 30 000–50 000 BP, and around 7000 BP (Bugge *et al.*, 1988; Dawson *et al.*, 1988).

III Summary: hazard of recurrence of tsunami events initiated by submarine slides, susceptible locations, unsolved questions

At present, only approximately 3% of the potential existing tsunami-generating mass movements is known. Recent discoveries of extraordinary tsunami relicts on Cyprus Island (Kelletat and Schellmann, 2001), Aruba, Curacao, Bonaire (Scheffers, 2002), the southern Spanish Atlantic coast and on the Island of Mallorca (Spain) lead to the assumption that the majority of tsunami-related deposits and geomorphic evidence has been overlooked so far. Few reliable findings have been documented and many questions regarding tsunamis, which were initiated by submarine slides on volcanic islands in the Quaternary, remain. An increase in knowledge in this field of research may initiate the revision of several theories that are based on the slow and steady evolution of coastal landscapes extending over several millennia.

Severe tsunami hazard exists on all coastlines that face both the open sea and large and relatively young volcanic islands. Susceptible locations include the entire Pacific Ocean including Hawaii, the Greater Sunda Island Arc and the Aleutians. The central Atlantic Ocean and surrounding west and east coasts are also susceptible to tsunami activity because of the location of the Canary Islands with volcano Cumbre Vieja on La Palma, which has been unstable for 7000 years and formation of crevasses has been observed since 1949 (Carracedo *et al.*, 1999a,b; Day *et al.*, 1999). A collapse of this volcano could generate a tsunami with heights of several hundred meters. Tsunami hazard along the Atlantic coastlines is also due to the location of the Cape Verde islands with the active Fogo volcano (Elsworth and Day, 1999), which has extremely steep underwater slopes that are about three times as steep as those of the active Hilina slump on the Island of Hawaii. Severe tsunami hazard is also present in the Indian Ocean because of Píton de la Fournaise on Réunion Island. There, frequent mass movements have occurred in an eastern direction between approximately 100 ka and 4.2 ka (Labazuy, 1996).

Large submarine mass movements may occur any time without warning. Initiated tsunamis may reach heights of several tens of metres against which protective measures and warning systems are most likely ineffective. Measured by geologic time, mega-tsunamis occurred frequently. Based on studies that have been conducted on the Hawaiian Islands, tsunamis from submarine slides occur every 25 000 to 100 000 years (Lipman *et al.*, 1988). At least 100 mega-tsunamis can be estimated to have occurred worldwide during the Quaternary. During human history, however, these events were extremely rare. Smaller and more frequent slides, including those with less than 20 km^3 in volume (more than the eight-fold of the Mount St Helens slide), cannot be completely documented so far. Based on Smith and Shepard (1996), approximately 20% of all tsunamis were generated by mass movements in the vicinity of volcanoes. These slides claimed more than 20 000 lives during the last 400 years. Six large events, including a tsunami with maximum run-up heights of 15 m, occurred within the last 100 years alone. A mega-tsunami caused by a large submarine mass movement on volcanic islands may reach wave heights of several 100 m and may devastate entire coastal regions several 1000 km away.

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