Mass transport events and their tsunami hazard

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Abstract

Mass transport events, such as those from submarine landslides, volcanic flank collapse at convergent margins and on oceanic islands, and subaerial failure are reviewed and found to be all potential tsunami sources. The intensity and frequency of the tsunamis resulting is dependent upon the source. Most historical records are of devastating tsunamis from volcanic collapse at convergent margins. Although the database is limited, tsunamis sourced from submarine landslides and from collapse on oceanic volcanoes have a climate influence and may not be as hazardous as their frequency suggests. Conversely, tsunamis sourced from submarine landslides at convergent margins may be more frequent historically than previously recognized and more hazardous.

Keywords Tsunami • submarine landslide • volcano • hazard

1. Introduction

Destructive tsunamis are mainly generated by earthquakes. However, they can also be sourced by failure of sediment and rock both on land and at the seabed. Most of these sediment/rock failures are submarine or from volcanoes, fewer are subaerial. Despite records that, in some places (e.g., Japan), go back thousands of years, there are few reliable historical accounts of tsunamis from submarine and subaerial failure but there are significantly more from volcanoes. The oldest historical records of tsunamis generated by mass failures are of volcanic lateral collapse in Japan and date back to the 18th century e.g., Oshima-Oshma in 1741 (e.g. Satake 2007). Historic records of devastating tsunamis resulting from subaerial landslides, are few, e.g., Scilla, Calabria in 1783 (Graziani et al. 2006) and Vaiont, Italy in 1963 (Hendron and Patten 1985).

Although submarine landslides, including slumps, debris flows and turbidites, have been researched for decades, until recently these were rarely indentified as a tsunami

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source. In fact they were discounted as a cause of destructive tsunamis (e.g. Jiang and LeBlond 1994; LeBlond and Jones 1995). This, despite tsunamis such as the Grand Banks in 1929 (e.g. Heezen et al. 1954; Piper and Asku 1987) and those associated with the Good Friday 1964 earthquake in Alaska, at Seward and Valdez, (e.g. Lee et al. 2003). These events might have flagged the hazard from submarine landslides but they did not and, it was not until 1998, when a submarine slump caused the devastating tsunami in Papua New Guinea, in which 2,200 people died, that the threat from submarine landslides was fully realized (Tappin et al. 2008a; Tappin et al. 2001). It is thus the intention of this paper to provide a broad overview of the tsunami hazard from mass transport events. The review mainly addresses tsunamis generated from submarine landslides and volcanoes, but subaerial failures are briefly considered. The objective is to review submarine mass transport processes relevant to tsunami formation and identify where these may be a tsunami hazard.

2. Mass transport events

Mass transport events take place in many different environments. Hampton et al. (1996) introduced the term "landslide territory" for those areas where they are more common than elsewhere; with locations identified from unique combinations of sedimentology and physiography. The environments recognized include the open continental shelf, submarine canyon/fan systems, fjords, active river deltas and volcanic islands. In addition, Lee (2005) identified convergent margins as an important environment where submarine landslides also take place. Consideration of these landslide environments indicates several dominant controls on slope stability, that have been elucidated by Lee (in press) as: i) sediment delivery to the continental margins; its rate, volume and type, ii) sediment thickness, iii) changes in seafloor conditions, which can influence hydrate stability and the possible generation of free gas, iv) variations in seismicity and, v) changes in groundwater flow. However in many respects these controls may be secondary to the main driving force, namely global climate change which, over the past hundreds of thousands of years, has resulted in alternating glacial and interglacial environments. The major impact of these climate changes has been on eustatic sea level. During glacial/interglacial cycles changing sea level has controlled the delivery of sediment to the oceans, as well as influencing seismicity along the continental margins, mainly through sea water loading and glacioisostacy. With regard to controls on volcanic mass failure there is an added contribution from magmatism that is driven by deep earth processes and regional structural controls on intrusion. However, climate change may affect volcanic collapse through both changes in sea level that affects slope stability (Quidelleur et al. 2008) and in rates of volcanic activity that also has an influence on flank collapse (McGuire et al. 1997).

There is a close and genetic relationship between most landslide territories and tsunami but, whereas there may be similar controls on sediment deposition and landslide triggering, in some territories, such as active river deltas, there is no evidence that mass movements have resulted in tsunamis. For example, submarine landslides are common in the Mississippi Delta. In 1969, when Hurricane Camille struck the Gulf coast, three offshore drilling platforms collapsed as a result of seabed sediment failure that resulted in a change of seabed relief of up to 12 m (e.g. Bea et al. 1983). However, there was no associated tsunami. The lack of evidence may, however, be more apparent than real. In other territories, such as open continental slopes and canyons, fjords, convergent margins and volcanoes, there is significant evidence that mass movement can result in hazardous, if not, devastating tsunamis; such as at Mt Unzen in 1792 (Siebert et al. 1987), PNG in 1998 and Storegga at 8,200 years BP (Bondevik et al. 2005).

3. Submarine mass failures

3.1 Open Continental slope and rise

Continental margin environments are regions where sediment transfer from land to sea takes place. During changes in sea level sediment in these regions has the potential to become unstable, in the process triggering tsunami. One of the best studied regions for submarine landslides on the open continental slope and rise is the North Atlantic (Hühnerbach et al. 2004; Lee in press; McAdoo et al. 2000). Numerous focused initiatives, such as ENAMII (Mienert 2002) and the high scientific interest from surrounding nations have resulted in an extensive database of submarine landslides, their depositional character, age, and triggering mechanisms. In addition, the discovery off of Norway of the second largest gas field in Europe beneath the largest submarine landslide in the North Atlantic, resulted in one of the most intensive investigations into offshore slope stability ever undertaken (Solheim et al. 2005).

There are numerous submarine landslides of all scales along the Atlantic continental margins. Mechanisms of failure are numerous and include, debris flows, landslides and slumps. Submarine landslides are generally more abundant in the western North Atlantic (off Canada and the US) than in the eastern North Atlantic (off Europe). Landslides in the west are generally smaller than those in the east. On both sides of the Atlantic, most slides originate in water depths between 1000 and 1300 m. Three geographic regions are recognized: a glaciated margin north of 56° N (southern tip of Norway), a "glacially-influenced" margin from 26° N to 56° N, and a non-glaciated margin south of 26° N (Weaver et al. 2000).

Four giant submarine landslides border the Norwegian margin, Andøya Traenadjupet, Finneidfjord, and Storegga, with the latter the largest at 3,500 km^3. Farther south, off Britain and Ireland, there are further submarine landslides including Peach and Rockall off of Scotland. The Storegga slide generated a tsunami that hit the west coast of Norway with runups of up to 20 m (Bondevik et al. 2003). The evolution of the slide is probably representative of similar slides along the Norwegian margin. Failure took place at the end of the last glaciation or soon after deglaciation. The slide was translational with failure planes related to strain softening behavior of marine clay layers. Destabilization prior to failure is related to rapid loading from glacial deposits with generation of excess pore pressure and reduction of the effective shear strength in the underlying clays. The slide failed towards the base in a retrogressive manner. Climatic processes led to a preconditioning of the sediment mass, subsequently failing through earthquake shock, the result of isostatic uplift driven by ice retreat. Although hydrate destabilization may contribute locally, this is not regarded as a primary driver of mass failure (Bryn et al. 2005).

Off the US margin 48 landslides have been mapped (Chaytor et al. 2007), the largest of which, the Cape Fear Slide, has a volume of 200 km^3 (Lee in press). Landslides on the slope are generally larger than on the rise, thus having a higher potential to generate damaging tsunamis. Off of Canada, 24 submarine landslides have been identified (Piper and McCall 2003). The best known is the 1929 Grand Banks event. 41 people lost their lives in the ensuing tsunami. The tsunami was the result of a debris flow released from the Canadian shelf by earthquake shock. Recent mapping of the landslide indicates that it was relatively thin (20 m average) and probably retrogressive (Mosher and Piper 2007). Off of North Africa there are five or six large submarine landslides, including the giant Saharan debris flow. In the south Atlantic, submarine landslides lie off the Amazon Delta, with volumes of 2,500 km^3 (Maslin et al. 1998); off of southern Africa is the Agulhas Slump with a proposed volume of $20,000^3$ km (Dingle 1977) although this figure is based on pre-swath bathymetry data. Yet, of all these landslides on the margins of the Atlantic, that must be several hundred in number, the only direct evidence of any tsunamis associated with their failure, is from Storrega where there sedimentary deposits (Bondevik et al. 2005)and the Grand Banks, where there are survivors accounts an sediments (e.g. Tuttle et al. 2004). In the case of Storegga, the sediments have been preserved for 8,200 years.

Lee (in press) reviewed the depositional environments and known ages of submarine landslides on the margins of the Atlantic Ocean. He found that, over the past 20,000 years, there is a relatively even distribution of large landslides with the period between the last glacial maximum until about five thousand years ago. The database is limited, however, because few slides have been dated. Notwithstanding, he found that most failures took place during glacial periods or just after. He attributed the distribution of ages to the accumulation of thick sedimentary deposits on the upper continental slope during glacial periods and their failure due to increased seismicity (caused by isostatic readjustment) during and following deglaciation.

From areas outside of the Atlantic, there are numerous submarine landslides. In the Mediterranean, probably the largest is the ‘BIG’95 debris flow off of Spain with an area of 2000 m^2 (Lastras et al. 2004). In the other areas, landslides have been identified off France and in the eastern Mediterranean off of Egypt and Israel. Again, there is little evidence for associated tsunami. Two major studies have been carried on landslides off California on the US west coast. The Goleta Slide, in the Santa Barbara Channel, is a compound failure that contains both surfical slump blocks and mud flows, forming a total volume of 1.75 km^3. The slide is interpreted as Holocene in age (Fisher et al. 2005; Greene et al. 2005) . There are three main lobes one of which, upon failing, has been modeled to source a tsunami wave with a runup of ~10 m. Although historical records suggest that tsunamis struck the area in the 19^{th} century, they appear to be sourced from earthquakes rather than from submarine landslides. The Palos Verdes debris avalanche, located in a submarine canyon offshore of Long Beach (Bohannon and Gardner 2004), is the largest late Quaternary SMF in the inner California Borderland basins, dated at 7,500 years BP (Normark et al. 2004) and with a volume of 0.34km ^{3}. Modeling indicates that it was large enough to generate a significant tsunami that would inundate the adjacent coastline (Locat et al. 2004). However, as of yet, there is no evidence of the tsunami on the adjacent coast.

3.2 Fjords

Submarine landslides are common in fjords. In glacial environments rapid sedimentation results in deposits that are susceptible to failure. Decay of organic matter deposited from rivers produces methane gas that may lead to elevated pore water pressure and further reduce sediment strength. Fjord head deltas can fail under cyclic loading (e.g. Prior et al. 1986) as at Kitimat Fjord in British Columbia in 1975. Triggered by a low tide, a landslide in the fjord created a tsunami of up to 8.2 m (Lee 1989; Prior et al. 1982). Although there was significant damage, no lives were lost. Weak sediments can also fail through earthquake shock as happened during the great Alaska earthquake of 1964. The resulting tsunamis were enormously destructive, with loss of lives and infrastructure (Hampton et al. 1993; Lee 1989; Plafker et al. 1969). At Seward a 1 km section of the waterfront failed as a result of submarine failure, creating a 10 m high tsunami (Lemke 1967). The destruction was compounded by a subsequent earthquake-generated tsunami, also 10 m high, arriving 30 minutes later. Most of the 13 people who died were inundated by the tsunami. At Valdez, an initial landslide volume of 0.4 km^3 increased to 1 km^3 as it incorporated sediment from the seabed (Coulter and Migliaccio 1966). The resulting tsunami attained heights locally of 52 m. 32 people died in the event.

3.3 Convergent margins

Convergent margins, like passive open continental slopes and rises, are regions of important sediment flux between the land and the sea. Their characterization into those margins where the sediment flux is significant (sediment rich) and those where it is not (sediment starved) has implications for landslide generation, although the relationships are complex. It is not always those margins where sediment flux is large that produce the most hazardous tsunami. For example, the PNG event took place along the New Guinea trench which is sediment starved (Tappin et al. 2001). Landslides along the Sunda margin, where there is a much larger accretionary prism than in New Guinea. are small-scale and less of a hazard in sourcing destructive events (Tappin et al. 2007). Submarine landslides have been mapped on many convergent margins (McAdoo et al., 2004). Their size varies from ‘super-scale’ in Cascadia (Goldfinger et al. 2000) to ‘small’ along the Sunda margin in the Indian Ocean (Tappin et al. 2007). Along the Nankai accretionary prism, highly eroded lower slopes show little evidence of large, well-preserved submarine landslides (McAdoo et al. 2004). The Makran and Kodiak accretionary margins evidence mass wasting on the upper slopes, with the lower slopes lacking large landslides. In contrast, the sediment-starved Sanriku, Nicaragua, and Aleutian margins have large landslides.

Convergent margins are the most recent addition to landslide territory environments (Lee 2005), mainly because of the 1998 tsunami in PNG. With the gradual, but not universal, acceptance that the PNG tsunami was the result of a submarine slump there is now an expanding field of research into convergent margin events from landslides. Some of this research is based on newly acquired multibeam data, e.g., Puerto Rico, 1918 (Lopez-Venegas et al. 2008), while new research is on re-evaluating anomalous tsunamis with runups that, to some degree, are too large in relation to their proposed earthquake source. The Alaska 1946 tsunami has always been enigmatic. An earthquake of M_S =7.1 produced a disproportionately large local tsunami (Mt =9.3) which claimed 167 lives (Fryer et al. 2004). A large landslide on GLORIA data indicated that this might be a more likely source but, this was not resolved on recently acquired multibeam data (Rathburn et al. 2009) so the source of the tsunami is still enigmatic. The earthquake source of the Puerto Rico tsunami of 1918 has also been re-evaluated, with a landslide identified as an alternative (Hornbach et al. 2008; López-Venegas et al. 2008). The Messina tsunami and earthquake of 1908 claimed 60,000 lives, many in the tsunami. The earthquake magnitude (M_S =7.1) is incompatible with both the height distribution and southward extent of local tsunami runups (Billi et al. 2008). A submarine landslide has been identified on multibeam data that may explain the inconsistency. Alternatively, the tsunami may have resulted from both the earthquake and a landslide (Tappin et al. 2008b). The Indian Ocean tsunami of 1945 was previously believed to the result of an earthquake located along the Makran margin. However, there are inconsistencies between the timing of tsunami runups and the earthquake, thus a landslide source has been proposed (Rajendran et al. 2008). Other events where there is a suspicion of a landslide contribution include the Sanriku tsunami of 1896 in which over 22,000 people perished, Flores tsunami of 1982 (Imamura et al. 1995) in which over 2,000 people died, and Java, 2006, where focused runups hint at an SMF source.

4. Volcanoes

Catastrophic volcanic flank collapse has been reported from numerous convergent margin and intra-plate locations. Mount St Helens in 1980 (Lipmann et al. 1988) is the best studied recent collapse event. Although on land, it has led to an improved understanding of the processes of flank failure that has been extended into the marine domain. At coastal locations, flank collapse has the potential to create devastating tsunamis (e.g. McMurtry et al. 2003; Satake 2007). Volcanic collapse along oceanic and convergent margin volcanoes has been subject to extensive research. Study of the giant submarine landslides (GSLs) on Hawaii was seminal in identifying the potential tsunami hazard from this source. Along convergent margins collapses are smaller in scale by orders of magnitude from oceanic island failures. Historical records however, show that these pose a serious hazard because of their higher frequency and because of their proximity to population centers. Tsunamis may be generated directly by volcanic eruption as exemplified by Santorini in 3,500 BC (McCoy and Heiken, 2000). Thus, to address the different tsunami sources this section provides an introduction the processes of collapse and then considers each of the main environments where collapse may result in tsunamis

Numerous volcanic edifices have large open amphitheatre-shaped structures that have been created either by caldera or flank collapse that results in debris avalanches (e.g. Siebert 1984). These amphitheatres are at all scales. The debris avalanches of Hawaii are the largest on Earth, with the Nuuanu giant submarine landslide (GSL) covering 5,000 km^2. The largest failed block, the Tuscaloosa Seamount, stands 2 km above the surrounding sea bed. The formation of volcanic avalanche amphitheatres is well known. It involves gravity sliding of large sectors of volcanoes along glide planes that steepen sharply upslope, forming near-vertical, crater-like walls at their upper ends, and that flatten down slope leaving an open breach between the low-lying tips of the amphitheatre escarpment. Slippage initially takes place as rockslides, but these disintegrate catastrophically into rock avalanches. Longer travel distances generally produce smaller blocks in the avalanche deposits. In the marine domain these features are well imaged at many volcanic locations. For example recent mapping off Ritter Island northeast of New Guinea revealed a debris avalanche that extends up to 75 km from its source (Silver et al. 2005). The deposit has three components: i) large blocks, up to 2 km across, occur adjacent to the collapse scar, ii) smaller (10 to 100 m) blocks, that form a series of discrete debris avalanche lobes or hummocks, are traced up to 35 km from the volcano, and iii) landslide deposits that form a broad, thin sheet 20 km wide.

One of the major constraints in assessing the tsunami hazard from volcanic collapse is the triggering mechanism(s) because they are numerous and varied (McGuire 1996). Volcanic rift zones have been recognized on many oceanic islands such as Stromboli and the Canary Islands and have been linked to edifice failures (Siebert 1984). They concentrate magma upwelling as dyke swarms, which can trigger instability by strength reduction through thermal or mechanical pressurization of pore fluids (Elsworth and Day 1999), or by the growth of an anomalously high topographic load (McGuire, 1996). Slope angle and gravitational instability favor failure, but low-angle edifices such as oceanic shield volcanoes, the Hawaiian Islands for example, are also prone to large-scale flank destabilization. Asymmetric building onto a dipping basement can direct collapses towards a preferred direction. Such structural control of preferred landslide direction has been advocated in the Lesser Antilles (Deplus et al. 2001). Instantaneous destabilization of weakened edifices can result from strong regional earthquakes, or from seismicity along listric basement faults acting as décollement surfaces. Strength-reduction basal volcanic layers by hydrothermal alteration and/or increased pore fluid pressure such as during periods of high rainfall can also favor instability. Finally, however, as McGuire (1996) points out, the main driving force of collapse is gravity.

Proposed climate controls on volcanic slope stability are intimately associated with glacial and interglacial cycles. Analysis of GRIP ice cores reveals a strong correlation over the past 110,000 years between accelerations in rates of sea level change and increased rates of explosive volcanism (Zielinski et al. 1996). These may in turn influence flank collapse (McGuire et al. 1997). Over longer time scales, large-scale flank collapse of volcanic islands may correlate with sea-level rise driven by climate change. On Hawaii, McMurtry et al. (2003) propose that large flank collapses are related to increased retention of groundwater during wet and warm climates characterizing interglacial periods.

Quidelleur et al. (2008) using a more global dataset, identify large volume (>10 km^3) collapses at glacial stage terminations.

4.1 Convergent margins - Volcanic flank collapse

The earliest recorded historical tsunamis from flank collapse are from Japan. In 1640, on Komagatake volcano, Hokkaido, collapse resulted in a large-scale debris avalanche that entering the sea, caused a tsunami in which more than 700 people died (Nishimura et al. 1999). In 1741, also in Hokkaido, catastrophic volcanic collapse on Oshima-Oshima Island created a tsunami in which there were approximately 2,000 fatalities (Satake 2007). The tsunami resulted in local runups of up to 13 m. In the far field, over 1,000 km to the southwest, on the coast of Korea there were runups of 3-4 m. In 1792 collapse on Mt Unzen led to a debris avalanche that swept through Shimabara City and into the Ariaka Sea. The tsunami resulted in the loss of over 10,000 lives (Miyachi 1992; Siebert et al. 1987). In Papua New Guinea, the Ritter Island sector collapse of 1888 created a local tsunami of 12-15 m (Johnson 1987). Run ups several hundred kilometers away were up to 8 m (Cooke 1981), scores, if not hundreds of people in local villages perished. The most recent tsunami caused by a volcanic flank failure was on the 30 December 2002, on Stromboli, in the Aeolian Islands. The local tsunami was up to 10 m above sea level and caused significant damage to buildings on the eastern coast of the island but no loss of life (Tinti et al., 2005).

4.2 Convergent Margins – Eruption tsunami

The most prominent eruption tsunamis are undoubtedly those from Krakatau in 1883 and Santorini in 3,500 BC. Other examples include the 1815 eruption of Tambora in Indonesia, generated by pyroclastic flows entering the ocean (Self and Rampino 1981) causing coastal inundation of up to 4 m (Van Padang 1971). Pyroclastic flows from the eruption of Aniakchak volcano, Alaska in 3,500 years BP resulted in a tsunami with runups as high as 15 m (Waythomas and Neal 1997). In 1883, over 36,000 people died in the Krakatau tsunami. 40 m tsunami waves were reported from Java (Simkin and Fiske 1983). The source of the tsunami is controversial, with three possible volcanic sources, i) large-scale collapse of the northern part of Krakatau Island (Self and Rampino 1981), ii) pyroclastic flows (e.g. Francis 1985)and, iii) a submarine explosion (Yokoyama 1987). A submarine explosion, one to five minutes duration best fits the observed tsunami heights and waveforms recorded at Batavia (Normanbhoy and Satake, 1995). It is possible that the smaller tsunamis were caused by pyroclastic flows (Francis 1985; Sigurdsson et al. 1991).

4.3 Oceanic volcanoes - flank collapse

Volcanic flank collapses have been mapped on numerous oceanic islands. Using a combination of onshore mapping and offshore data including multibeam bathymetry and sub-seabed geophysics, we now have access to comprehensive data sets that underpins an improved understanding of flank failure at these locations. However, only a few examples have been intensely studied in the context of their potential to create tsunami.

In Hawaii, large-scale, gravitational volcanic collapses, GSLs, have long been recognized (e.g. Moore et al. 1989). Along the Hawaii-Emperor Ridge there are over 68 major landslides over 20 km in length, some are over 200 km long, with volumes exceeding 5,000 km^3. These are the largest landslides on Earth. Two main landslide morphologies are recognized, debris avalanches and slumps, with numerous variations in-between. The slumps, fail slowly by creep, thus their potential as tsunami sources is minimal; they will not be considered further. Debris avalanches form the majority of failures and these lie on slopes <3° and are formed of fragmented volcanic rock. They are ~ 100’s m in thickness, with well defined amphitheatres at their head. They display the classic hummocky surface topography of debris avalanches. Some debris avalanches have a significant proportion of large blocks (e.g., Nuuanu and Wailau) others have smaller blocks and a greater proportion of finer material (e.g. Alika 2).

Dating of the GSLs indicates that on average failure rate is every 100,000 years. Although occurring throughout the lifetimes of the volcanoes, the largest landslides occurred when the centers were young and unstable, were close to their maximum size, and when seismic activity was at a high level. The morphology of the GSLs, together with their large lateral extent and the fact that they travelled long distances across the Hawaiian Deep upslope onto the Hawaiian Ridge, in places overtopping vertical elevations of 100s of meters, indicates that they travelled at high velocities of 100 to 200 m/s. The debris avalanches are thus almost probably catastrophic, and take place as single events.

Since their discovery the tsunami potential from the Hawaii GSLs has been the subject of controversy (McMurtry et al. 2004a; Moore and Moore 1988; Rubin et al. 2000; Stearns, 1978). However now, a combination of seabed mapping, dating of the Alika 2 GSL, modeling its’ failure as a tsunami source, and the presence of sediments at over 340 m above sea level laid down by the tsunami at the time of generation, provide strong evidence that failure of the GSL do indeed create massive tsunamis. These tsunamis locally have runups of the order of 100s of meters above sea level. In the far field, the limited modeling available from the collapse of the Nuuanu GSL indicates a real hazard; offshore heights of tens of meters may strike the coasts of southern California and the Aleutian islands (Satake et al. 2002).

The GSLs of Hawaii are not unique, most oceanic volcanoes fail catastrophically during part of their existence. In the younger and more volcanically active, western Canary Islands there at least 14 large failures on El Hierro, La Palma and Tenerife (Masson et al. 2002). The failures are smaller in volume than those in Hawaii. The debris avalanches are superficial and up to 2 km thick. They have areas of a few thousand kilometers, volumes of 50 to 200 m^3 and runouts of 50 to 100 km. Glide planes at the base of the avalanches are typically up to 10º on the upper slope and less than 5º on the lower slopes. The majority of Canary Island failures are less than 1 million years old. The youngest, on the northwest flank of El Hierro, is 15,000 thousand years BP. There is no regularity in the failures, but on average, as with Hawaii, they take place every 100,000 years. The most common failure mechanism is a catastrophic debris avalanche.

Despite the overall evidence from Hawaii that lateral volcanic collapse can result in hazardous tsunamis, there has been much debate about whether collapse of the Canary Islands volcanoes poses a similar risk (Wynn and Masson 2003). As with landslides in non-volcanic sediments, such as at Storegga, it has been proposed that the Canary volcanoes fail retrogressively, thus reducing their ability to create a large tsunami. Controversially, Ward and Day (2001) propose that a 500 km^3 collapse of Cumbre Vieja volcano on La Palma could create a tsunami that would be catastrophic in the near field and extremely dangerous to the east coast of America. Simulations of a smaller scale collapse on La Palma (e.g. 375 km^3) (Løvholt et al. 2008) indicates that local runups would indeed be devastating, but with less significant consequences in the far field. It is clear from the modeling, that the volume of the collapse, as well the particular environment, slide mobility, as well as the model used, is important in identifying and resolving whether a hazardous tsunami would be formed. Notwithstanding the controversy in the far field, sedimentary deposits at 188 m on Grand Canaria have been identified as sourced from a collapse tsunami (Pérez-Torrado et al. 2006) thereby indicating that the local event caused by a volcanic collapse may well be extremely dangerous to local communities if of sufficient volume.

5. Subaerial Failures

A number of tsunamis have been created by subaerial landslides. The most well known is at Lituya Bay in 1948 (Miller 1960). Triggered by an earthquake, a 4.3 km^3 landslide failed into the sea creating a tsunami up to 524 meters high. Two people died in the event. The most catastrophic tsunami created by a subaerial failure, was at Vaiont in Italy in 1963 (Hendron and Patten 1985). Although perhaps not strictly a tsunami, more a seiche, the collapse was created by a combination of reservoir water drawdown and heavy rains. There were warning signs. The displaced water overtopped the dam and a 250 m high wave flooded the valley below, drowning 2,000 people. In 1783, at Scilla in Calabria, a cliff collapsed into the sea causing a devastating tsunami in which 1,500 perished (Graziani et al. 2006). The fatalities were particular heavy because survivors from the previous day's earthquake were taking shelter on the open beach at Scilla located about 1 km east of the collapse. The waves reached up to 200 m inland and up to 8.3 m run-up within the town.

6. Tsunami Hazard

Review of mass transport events in the different environments described demonstrates that they all have potential to create hazardous if not devastating tsunamis. Assessment of the hazard and risk from tsunami however, is at an early stage and although understanding of processes has advanced significantly over the past decade the database of well studied events is still small. On the North Atlantic passive continental margins, there is a good preliminary understanding of the process of deposition and landslide failure. Yet there is still a paucity of data to confirm or refute recent hypotheses on how these failures relate to tsunami generation. There are still too few case studies of actual events, particularly parametric modeling of tsunami generation based on the architecture of known failures. More dates of landslide failure are required to test hypotheses on climate control of mass failure processes. At first sight, the large number of landslides suggests high risk. However, the likelihood of future tsunami from slide failure may not be as great as the numerous landslides suggest. The work of Lee (in press) indicates that most landslides fail during glacial periods or just after, thus the risk of tsunamis today may not be as great as at previous periods over the past 10,000 years. But more research is required, especially in dating more landslide events.

Apart from the major climate controls on slope stability, there are others that are effective now. On the Scotian margin, as demonstrated by the Grand Banks tsunami, there is a risk of submarine landslides triggered by earthquakes during interglacials. As noted by Piper et al. (2003) there have been three >M7 events since 1800 and these have the potential to trigger landslides (Piper et al. (1985). Progressive creep failure may also be a trigger (Piper et al. 2003). With regard to tsunami magnitude, the Grand Banks landslide was in quite deep water, yet generated an event that resulted in much destruction and loss of life.

Along the US Atlantic margin the earthquake trigger risk may not be as great as off Canada (ten Brink et al. in press). However, salt movement may be an added threat (Hornbach et al. 2007). The lack of evidence of tsunami from onshore (or in fact offshore cored sediments) is intriguing. The preservation potential of tsunami deposits is undoubtedly low. Subsidence increases the likelihood of preservation, such along the Cascadia margin where tsunami deposits over thousands of years have been laid down. Subsidence may not be taking place along passive margins, especially those previously subject to post glacial uplift, although there are advantages here as demonstrated by the Storegga deposits. Alternatively, tsunami sediments may not have been discriminated from other depositional sources, such as storms. Also, given that many submarine landslides took place at lowered sea levels, the lack of deposits may be because of the width of the US continental shelf, that in places up to 200 km wide.

One aspect of landslides that is still controversial is the role of hydrate dissociation in the initiation of their failure (e.g. Maslin et al. 2004). As yet there are few definitive studies that show that this process has definitely caused a landslide. Most of the landslides dated by Lee (in press) from the last 20,000 yr, were emplaced during stable or rising sea level, a period when hydrate disassociation would least be expected. In addition, the relatively poor accuracy of landslide dates makes it difficult to associate failure events with relatively short periods of sea level fall (Maslin et al. 2004). Hydrate dissociation was considered as a trigger of the Storegga slide, but this has been discounted as a major factor (Bryn et al. 2005). Although there is a lot of circumstantial evidence on the association between hydrates and submarine landslides, isotopic ice core evidence now shows that methane increase during interglacials is from non-marine sources (Sowers 2006).

With regard to other passive margins, the evidence on which to assess the hazard from of submarine landslide tsunami is patchy. There are large mass failures off the Amazon Fan, but these are in deep water. Off southern Africa, there is the Aguhlas slump. In both areas there is no evidence of associated tsunami. In other landslide territories, such as fjord regions, the well researched tsunamis associated with the 1964 earthquake illustrate that these areas are may be prone, but not everywhere. Although, mass failures are known from Norway (e.g. Finneidford 1996), there is no evidence of associated tsunami. The likelihood is perhaps that the glaciers feeding the fjord head deltas in North America are of a larger scale than those in Norway. Regarding active river delta environments, the lack of tsunamis in the Gulf of Mexico, where there are numerous submarine landslides appears contradictory. Absence of tsunamis may be because the landslides are too deep, and tsunamis generated too small to notice. The storm conditions under which they are triggered may mask any associated tsunami. During a Category 5 hurricane, would a tsunami wave be identified in the storm surge?

Along convergent margins there is a tsunami hazard from both submarine landslides and volcanic flank collapse. The PNG event flagged the landslide hazard, and recent (and continuing) re-evaluation of anomalous tsunami events suggests that some anomalous earthquake tsunamis may be the result of submarine landslides. Review of tsunami processes along convergent margins also indicate that thick and rapid sedimentation regimes are not necessarily the locations of large-scale submarine failure; in regions of frequent earthquakes more frequent and smaller landslides may result, and hence a reduced tsunami hazard. More work is required to test this hypothesis. Smooth slopes along the margins seem to be the result of frequent events (McAdoo et al. 2004). However, along the Sunda margin, the slopes are heavily gullied and, mass failures frequent. More re-evaluations of anomalous tsunami events are required to assess the hazard along these margins. Small landslides, such as PNG are a real threat, but it will be very difficult to identify potential locations where these may be located. As noted by Mosher and Piper (2003) swath bathymetry doesn’t always provide definitive proof of the presence (or absence) of landslides. Large failures have been mapped along Southern and Middle American Pacific margins, for example the massive slide off Peru (von Huene et al. 1989). Large mass failures have also been mapped off of Costa Rica and Nicaragua (von Huene et al. 2004). Modeling of these events indicates that failure would result in a 50 m high tsunami wave at source. However, care has to exercised in discriminating the tsunami sources at these plate boundaries, deep water locations. Some ‘slow’ earthquakes may reproduce the same effects as a submarine landslide (e.g. Pelayo and Wiens 1990). The main discrimination between a slow earthquake and landslide tsunami is that the runups from latter would be more focused, and with a significant peak runup (Tappin et al. 2008). Additionally, there may be combined events, both earthquake and landslide as may have occurred at Messina in 1908 (Tappin et al. 2008).

Tsunamis from volcanic flank collapse into the ocean can be catastrophic, as shown by historical events from the convergent margins of Japan and Ritter Island, PNG. Thus volcanic tsunamis at these locations are a real threat, more so because at present collapse cannot yet be predicted, as at Stromboli in 2002. They may also be very near densely populated areas. On oceanic islands, such as Hawaii and the Canary Islands there has been debate on the mechanism of flank collapse – catastrophic or incremental – and whether the collapse creates hazardous tsunamis. Certainly in both locations any moderate if not small collapse could be very destructive locally. On Stromboli, a small failure created a local tsunami of 10 m. In the far field the resultant tsunami would depend on the scale of the collapse. Although a sedimentary slide on a passive margin, the evidence from Storegga shows that its' collapse created a tsunami that travelled at least as far as the Faeroes. The 2.5 km^3 collapse on Oshima-Oshma Island created a 2-3 m tsunami in Korea 1,000 km away. However, the evidence from Hawaii, and perhaps the Canary Islands, is that collapse is more likely during the early stages of volcanic evolution, thus the hazard may be small. Additionally, collapse may be more prevalent during climates not similar to those experienced at present.

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