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Submarine Mass Failures as tsunami sources – their climate control

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Recent research on Submarine Mass Failures (SMFs) shows that they are a source of hazardous tsunamis, with the tsunami magnitude mainly dependent on water depth of failure, SMF volume and failure mechanism; cohesive slump or fragmental landslide. A major control on the mechanism of SMF is the sediment type, together with its post-depositional alteration. The type of sediment, fine- or coarse-grained, its rate of deposition together with post-depositional processes may all be influenced by climate. Post-depositional processes, termed sediment 'preconditioning' is known to promote instability and failure. Climate may also control the triggering of SMFs, for example through earthquake loading or cyclic loading from storm waves or tides. Instantaneous triggering by other mechanisms such as fluid overpressuring and hydrate instability is controversial, but is here considered unlikely. However, these mechanisms are known to promote sediment instability. SMFs occur in numerous environments, including the open continental shelf, submarine canyon/fan systems, fjords, active river deltas and convergent margins. In all these environments there is a latitudinal variation in the scale of SMF. The database is limited, but the greatest climate influence appears to be in high latitudes where glacial/interglacial cyclicity has considerable control on sedimentation, preconditioning and triggering. Consideration of the different types of SMF in the context of their climate controls provides additional insight into their potential hazard in sourcing tsunamis. For example, in the Atlantic, where SMFs are common, the tsunami hazard under present day climate may not be as great as their common occurrence suggests.

Keywords Tsunami • submarine mass failure • hazard • climate

1 Introduction

Tsunamis, especially destructive ones, are mainly (~70-80%) caused 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 in submarine sediments or from volcanic lateral collapse. Historical records of destructive tsunamis caused by lateral collapse include 18th century examples from Japan, such as Oshima-Oshima in 1741 (Satake and Kato, 2001; Satake, 2007) and Unzen in 1792 (Siebert et al., 1987) as well as the 1888 AD collapse of Ritter Island in Papua New Guinea (Johnson, 1987; Ward and Day, 2003). Such historical ocean-entering landslides are recognized from eyewitness accounts. In contrast, prehistorical lateral collapses, such as those in Hawaii and the Canary Islands, are identified from geological evidence (e.g. Moore et al., 1994; Urgeles et al., 1997). This difference in identification is significant in terms of hazard recognition. Submarine seabed failures, termed here Submarine Mass Failures (SMFs), are less easily recognised than those onland, and there are few historical accounts of these events. Thus SMFs may have been underestimated as a tsunami source. In fact, until recently, they were discounted as a cause of destructive tsunamis (e.g. Jiang and LeBlond, 1994; LeBlond and Jones, 1995). 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) might have flagged the hazard but they did not. It was not until 1998, when a submarine slump caused the devastating tsunami at Sissano Lagoon in Papua New Guinea, in which 2,200 people died, that the threat from submarine landslides was fully realized (Tappin et al., 1999; Tappin et al., 2001; Tappin et al., 2008).

Since 1998 there have been major advances in understanding SMFs as sources of tsunamis. Applying new mapping methodologies, such as multibeam bathymetry, the numerous architectures of SMFs have been identified. Additionally, there has been an improved understanding of the mechanisms of SMF, including their formation and triggering. Based on the new knowledge, advanced parametric mathematical models of SMF have been developed that form the basis of more realistic tsunami wave propagation and runup (Tappin et al., 2008). Thus SMFs and their potential to generate hazardous tsunamis are now much better understood. An aspect of this improved understanding is the influence of climate on both their formation and triggering. It is, therefore, the objective of this paper to present an overview of the tsunami hazard from SMFs in the context of their climate control(s). Specifically to, i) consider the temporal evidence on how climate change may relate to SMF, ii) how climate change may influence the stability of submarine sediments leading to mass failure, iii) whether climate can control the triggering of SMFs and iv) how climate, and associated sea level change may influence the preservation potential of tsunami sediments derived from SMFs and thereby our potential to recognise in the geological record SMFs as tsunami sources. The focus of the paper is on non-volcanic SMFs, although it is recognised that volcanic mass failure may also pose a significant tsunami hazard.

2 Submarine Mass Failures

SMFs range from cohesive slumps to translational landslides (Hampton et al., 1996). Study of SMFs has advanced our understanding of, i) their role in the transport of sediment from the land to the ocean, ii) their potential as deep-water hydrocarbon reservoirs and iii) their hazard to seabed infrastructure, particularly in relation to the hydrocarbon industry. The recent realisation that SMFs may cause hazardous, if not devastating, tsunamis has also led to new research in this context. Controls on SMF are many and varied and include their sediment properties resulting from initial deposition and post-depositional alteration, termed 'preconditioning', together with 'triggers' that are instantaneous events causing sediment failure. Deposition and post-depositional alterations are the result of uplift and erosion and basin subsidence.

Tectonics undoubtedly influences sedimentation by creating depositional, 'accommodation' space with uplift of sediment source areas leading to erosion and deposition. There has been considerable debate about how the environment of sediment deposition may contribute to sediment failure by 'preconditioning' sediment physical properties (e.g. Biscontin et al., 2004; Masson et al., 2009). Earthquakes are recognised as the main SMF trigger (e.g. Bugge, 1983; Laberg et al., 2000), but other mechanisms include salt movement, storm wave loading and low tides (Prior et al., 1982a; Prior et al., 1982b; Twichell et al., 2009). Triggers, such as increases in sediment pore pressures and hydrate destabilisation, are more controversial (see discussion in Dugan and Stigall, 2009; Grozic, 2009).

Another first order control on sedimentation of SMFs is global climate change. During recent Earth history, over the past hundreds of thousands of years, global climate has fluctuated with remarkable cyclicity. A major result of these fluctuations is the variation in the expansion and contraction of continental ice sheets that have resulted in eustatic sea level changes of up to 120 m. A consequence of these glacial/interglacial cycles is a variation in the rate of sediment delivery to the ocean. The combined effects of climate and sea level change result in changes in location of SMFs along the ocean margins. For example, at high latitudes the large volumes of sediment delivered to the ocean margins during glacial periods are destabilised by earthquakes that result from glacioisostatic uplift as the ice sheets melt and contract (Bryn et al., 2005). At mid and lower latitudes the glacial influence is less evident and the database less substantial, but here also there is evidence of a climate control on SMF (e.g. Gee et al., 1999; Henrich et al., 2009).

3 Landslide Territories

SMFs take place in many different environments and Hampton *et al*. (1996) introduced the term "landslide territory" for areas where they are more common than elsewhere (Figure 1). These environments 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 environment where submarine landslides also take place. Recent research in the South Pacific on reef-front environments suggest that these too may be prove to be a location where SMF can cause hazardous tsunamis, as in the Suva, Fiji event of 1953 (Rahiman et al., 2007).

The locations of SMFs are identified by unique combinations of sedimentology and physiography, with common factors including thick sedimentary deposits, sloping seafloor and high environmental stresses. Several dominant controls on slope stability are recognised that include, i) the rate, volume and type of sediment delivery to the continental margins; 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. With regard to tsunami generation, there is a recognisable close and genetic relationship to most landslide territories. On open continental slopes and canyons, fjords and convergent margins, there is evidence that SMFs can result in hazardous, if not, devastating tsunamis. Examples include the

Grand Banks event of 1929, Alaska in 1964, PNG in 1998 and Storegga at 8,200 years BP. However, on active river deltas, there is no evidence of tsunamis sourced from SMFs. For example, submarine landslides are common on the Mississippi Delta (Prior and Coleman, 1982) yet no associated tsunami has yet been recognised.

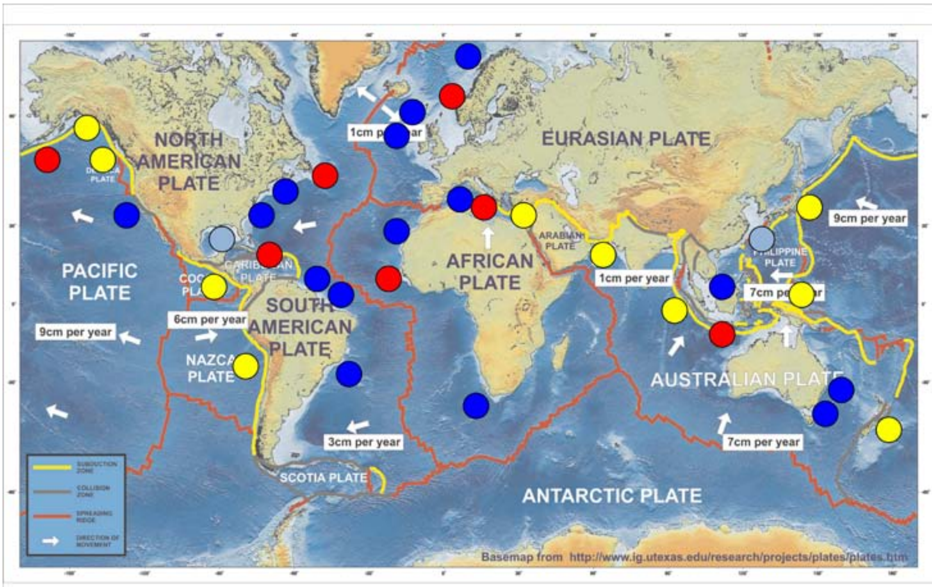

Figure 1. Global distribution of mapped SMFs. Blue dots – SMFs on continental shelves and fan systems – no identified tsunami. Yellow dots – SMFs located along convergent margins, no identified tsunami. Red dots – Locations of SMF sourced tsunamis, or where there may be a SMF contribution. Grey-blue dots - Active river systems – no tsunami identified.

3.1 *Open Continental Slope and Rise*

Along continental margins major sediment transfer takes place from land to sea, with slope canyons resulting from erosion and fan/delta systems from deposition. During changes in sea level, sediment in these regions has the potential to become unstable, in the process triggering tsunami. The North Atlantic is one of the best studied regions (McAdoo et al., 2000; Hühnerbach et al., 2004; Lee, 2009), and here there is an extensive database of SMFs that includes their depositional character, age, and proposed triggering mechanisms. Off of Norway, the discovery of the second largest gas field in Europe, located beneath the largest submarine landslide in the North Atlantic, resulted in one of the most intensive investigations into offshore slope stability ever undertaken (Bryn et al., 2005; Solheim et al., 2005).

SMFs at all scales are common along the Atlantic continental margins. Mechanisms of sediment mass movement include, debris flows, landslides, turbidity flows and slumps.

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Generally, they are more abundant in the western North Atlantic (off Canada and the USA) than in the eastern North Atlantic (off Europe and Africa). In the west, SMFs are smaller than those in the east. On both sides of the Atlantic, most SMFs originate in water depths between 1,000 and 1,300 m. Three climatic regions may be identified where SMFs take place: 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). However, these boundaries reflect present day climate and have fluctuated as this has changed. During glacial maximums, for example, the limit of glacial margins is located at least 10 degrees farther south than at present.

3.1.1 Glaciated margins

In the eastern Atlantic, four major SMFs border the Norwegian margin; Andøya, Trænadjupet, Finneidfjord, and Storegga. Farther south, off Britain and Ireland, large SMFs include Peach and Rockall located off of Scotland. The Storegga slide is the largest SMF in the Atlantic with a volume of 3,500 km^3. It generated a tsunami that struck the west coast of Norway with runups of up to 20 m and propagated outward striking Scotland and the Faeroes with runups of 5 to 10 m (Bondevik et al., 2005).

In high latitude, glaciated, regions there is a dynamic evolution of SMFs that is related to sea level fluctuations associated with ice sheet advance and retreat. Sedimentation rates are highest during glacial periods, with 36 to 65 m/ky for the Trænadjupet and Storegga SMFs respectively (Laberg et al., 2003; Hjelstuen et al., 2005). During interglacials sedimentation rates are much reduced, with less than one m/ky being common. These rates reflect the large volumes of sediment produced from ice sheet scouring during glacial episodes, with less sediment delivered during interglacials when ice sheets are smaller and more distant and sedimentation is mainly from slope parallel contourites. The result of these changing sedimentation regimes is complex sediment preconditioning that includes the development of high pore pressures in the fine-grained glacial sediment that results in destabilisation through earthquake loading.

The failure of Storegga is probably representative of similar SMFs along the Norwegian margin (Bryn et al., 2005). Failure took place at the end of the last glaciation or soon after deglaciation. It was translational and took place along weak layers formed in marine clays subject to strain softening. Prior to failure, destabilization was the result of rapid loading from glacial deposits, causing the generation of excess pore pressure and reduction of effective shear strength in the underlying clays. Initiation of failure was at water depths of 1,500 to 2,000 m with retrogressive failure propagating upwards from the base. Climatic processes led to a preconditioning of the sediment mass. During glacial periods, when sea level was lowered, the ice sheet advanced to the shelf break depositing large volumes of coarse-grained sediment on the slope. During interglacials, higher sea levels resulted in slope-parallel contour currents from which finer-grained sediment was deposited. These fine-grained clays formed weak layers along which failure of the sediment mass took place. Failure was triggered by earthquakes caused by isostatic uplift as the ice sheets melted. Although hydrate destabilization may contribute locally, this is not regarded as a primary driver of mass failure.

In the western Atlantic, off of Canada, 24 SMFs have been mapped (Piper and McCall, 2003). The SMFs vary in morphology from slides to retrogressive slumps. They are located in pro-delta settings, on the continental rise and in steep-sided canyons. The oldest is 125 ky, although most are younger than 50 ky. 14 failures occurred during the last glacial period. Only two are post-glacial, the best known of which is the Grand Banks event of 1929, when 41 people lost their lives in the resultant tsunami. The 1929 SMF was a debris flow and turbidite released from the Canadian shelf by an earthquake. It is relatively thin (20 m average) and probably retrogressive (Mosher and Piper, 2007). Off of Nova Scotia, there are five main episodes of mass wasting over the past 17 ky, at 5-8 ky, 12.7 ky, 13.8 ky, 17.9 ky and 14 ky. Thus SMF took place mainly during glaciation, with a glacial/interglacial ratio of failure of 3 or 4 to 1. Their broad geographic distribution suggests an earthquake trigger for all these events (Jenner et al., 2007), with earthquakes the result of post-glacial crustal rebound. This readjustment is still ongoing (e.g. Peltier, 2002).

3.1.2 Glacially influenced margins

There are few large SMFs off the European margins where narrow shelves and common submarine canyons mainly funnel turbidity currents to the abyssal plain. Off the US margin, however, 55 SMFs have been identified (Chaytor et al., 2007; Twichell et al., 2009). Two types of SMFs are recognised: those originating in submarine canyons and those from the open continental slope and rise. They cover 33% of the continental slope and rise of the glacially influenced New England margin, 16% of the sea floor offshore of the fluvially-dominated Middle Atlantic margin, and 13% of the sea floor south of Cape Hatteras. Their distribution is in part controlled by the Quaternary evolution of the margin, resulting from climate controlled eustatic sea level change. The headwall scarps of open-slope SMFs are mainly located on the lower slope and upper rise; those of the canyon sourced SMFs lie mostly on the upper slope. SMFs are generally thin (mostly 20–40 m thick) and comprised primarily of Quaternary sediment. Volumes of the open-slope SMFs are generally larger (up to 392 km^3) than the canyon-sourced ones (up to 10 km^3). Largest SMFs along the southern New England margin are located seaward of shelf-edge deltas laid down during the lowered sea levels of the last glaciation. South of Cape Hatteras, SMFs are located adjacent to salt domes that breach the sea floor. The wide spatial distribution of landslides indicates a variety of triggers, although earthquakes are recognised as the most common, probably generated by glacioisostatic rebound of the glaciated margin, or by salt movement. Other triggering processes, such as fluid overpressuring, may have contributed to failure by pre-conditioning. The large-volume open-slope landslides have the greatest potential to generate hazardous tsunamis. Few of the SMFs have been dated, but most are considered to have formed during the last glaciation and early Holocene (Embley and Jacobi, 1986).

The Cape Fear Slide is the largest SMF on the US margin, with a volume of 200 km^3 (Lee 2009). It is dated at between 8 and 25 ky, forming at the transition between the end of the last glaciation and present interglacial. Salt movement, driven by sediment loading, is considered the most likely triggering mechanism, with salt diapirism causing oversteepening of the seabed slope followed by failure. The headwall lies along a major normal fault (Cashman and Popenoe, 1985; Hornbach et al., 2007). The Curritick SMF has a volume of 165 km^3 and formed on a shelf-edge delta (Prior, David B. et al., 1986). It formed between 24 and 50 ky, during glaciation (Locat et al., 2009). Very high pore pressures and/or a strong earthquake are considered the most likely triggering mechanisms. The high pore pressures are attributed to fluid seepage from coastal aquifers, sediment loading from delta construction, local sediment loading, gas hydrates and/or earthquakes. Modelling of the two slides as tsunami sources indicates that they both have the potential to be a hazard today (Hornbach et al., 2007; Geist et al., 2009). However, they formed at lower sea levels, thus making their hazard at time of deposition much greater. To date, no evidence has been found to indicate that a tsunami was generated by these SMFs (see section 4 for further discussion).

3.1.3 Non-glaciated margins

Off of North Africa there are a number of SMF complexes, although little evidence has been found (or in fact looked for) that indicates associated tsunamis. Off the Moroccan margin a complex of turbidites extends over 1700 km to seaward (Weaver et al., 2000; Wynn et al., 2002). The turbidites are up to 200-250 ky. The largest are the Bed 5 event off Morocco and, farther south off of the Western Sahara, the Saharan debris flow. Both are dated at ~50-60 ky (Gee et al., 1999; Wynn et al., 2002). Thus both were triggered when global climate was changing between glacial and interglacial conditions. Both are associated with changes in eustatic sea level, when this was either rising or falling rapidly. Farther south, off of Mauritania, turbidite complexes are also clearly climate controlled (Henrich et al., 2009). There is a high frequency of failure during deglaciation, when sea level was rising, through remobilisation of large-scale aeolian dune fields that had expanded to the shelf edge during glacial sea level lows. Pervasive, and widespread, fluid escape structures suggest high fluid pore pressures that may have initiated failure (Antobreh and Krastel, 2006). Antobreh and Krastel (2006) also propose that slide formation was pre-conditioned by uninterrupted deposition of organic-rich sediment, the result of upwelling, in an open slope environment. The result was a rapid accumulation of poorly consolidated bedded sediment (turbidites) intercalated with thin weak layers of organic rich sediment. Turbidite activity is also frequent during glacial periods; an increase that is attributed to rapid sea level rise during Heinrich events. Henrich et al. (2008) speculate that the presence in one core of a turbidite overlying a debris flow may indicate an associated tsunami. Triggers in this area are undefined, but North Africa is an earthquake prone area, as recorded in the massively destructive event that struck Agadir in 1960, thus earthquake triggers are a likely source. The synchronicity of turbidite events between the Dakar and Timiris canyons also suggests an earthquake trigger.

SMFs have been mapped in the south Atlantic, although to date there is no evidence of any associated tsunamis, although again these have not been looked for. Off the Amazon Delta, there are large-volume (up to 2,500 km^3), catastrophic failures of the continental slope. These failures are sourced from rapidly deposited, under-consolidated sediment laid down on upper-fan levees (Piper et al., 1997; Maslin et al., 1998). The dating is poor, but suggests a late glacial to early Holocene age. If correct, then the failures may correlate with climate-induced changes in sea level. Failure is attributed to either, i) rapid sea level fall, that resulted in destabilisation of gas hydrate, and/or ii) deglaciation in the Andes leading to the large-scale flushing of Amazon River sediment onto the continental slope; resulting in excessive loading of fan sediment laid down previously during glacially-induced sea level lows. Youngest failures are 14-17 ky (Maslin et al., 1998), with older events at 35 ky and 42-45 ky. Hydrate disassociation is mainly associated with the younger events.

Off Brazil, the Rebelde complex is believed to have been triggered by either an earthquake or high fluid pore pressure. Again the SMF is poorly dated (Ashabranner et al., 2009). Off of southern Africa, the Agulhas Slump has a proposed volume of 20,000 km^3, although this figure is based on single-beam, bathymetry data (Dingle, 1977).

3.1.4 Other areas
Outside of the Atlantic, there are numerous SMFs although there is little evidence of associated tsunamis with the notable exception of the Nice event of 1979 in which 12 people died (Dan et al., 2007). There has been little research on the relationship between SMF and climate. In the Mediterranean, probably the largest SMF is the 'BIG'95 debris flow off of Spain, with an area of 2,000 m^2 and dated at 11.4 ky (Lastras et al., 2004). Proposed triggering mechanisms include seismicity and oversteepening of the slope due to a volcanic structure underlying the main headwall.

SMFs have been identified off France and in the eastern Mediterranean off of Egypt and Israel. Two major SMFs lie off California. The Goleta Slide, in the Santa Barbara Channel, is a compound failure with a total volume of 1.75 km^3. It is formed of three main lobes with both surfical slump blocks and mud flows. It is interpreted as Holocene in age (Fisher et al., 2005; Greene et al., 2005). Earthquakes are a likely trigger because historically, earthquakes of magnitudes • 5 occur about every ~20 years. Modelling of one lobe of the Goleta Slide as a tsunami source produces a local runup of ~10 m (Greene et al., 2005). Records show that tsunamis struck the area in the nineteenth century, but these appear to be sourced from earthquakes rather than SMFs. The Palos Verdes debris avalanche is located in a submarine canyon offshore of Long Beach (Bohannon and Gardner, 2004). It is the largest late Quaternary SMF, with a volume of 0.34 km^3, in the inner California Borderland basins. It is dated at 7.5 ky (Normark et al., 2004). Modelling 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 that such a tsunami struck the coast.

3.2 ***Fjords***
SMFs are common in fjords (Syvitski et al., 1986; Hampton et al., 1996) with numerous records of associated tsunamis. In these glacial environments rapid sedimentation results in deposits that are susceptible to failure. Streams that drain glaciers, transport and deposit sediment formed of low plasticity rock flour that is vulnerable to earthquake loading; rapid sedimentation can lead to underconsolidation. Organic matter deposited from rivers may decay to produce methane gas that may lead to

elevated pore pressure and further reduce sediment strength. Thus there is a strong climate control both on the location of the fjords and the volume of contributed sediment.

Fjord-head deltas can fail under cyclic loading (e.g. Prior, D. B. et al., 1986). For example, at Kitimat Fjord in British Columbia in 1975, a landslide was triggered by a low tide, creating a tsunami up to 8.2 m in height (Prior et al., 1982a; Lee, 1989). Although there was significant damage, no lives were lost. Weak delta sediments can also fail through earthquake loading, as happened during the great Alaska earthquake of 1964. The resulting tsunamis were enormously destructive, with loss of lives and damage to infrastructure (Plafker et al., 1969; Lee, 1989; Hampton et al., 1993). At Seward a one km section of the waterfront collapsed 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 at Seward were killed 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 up to 52 m, and resulted in the loss of 32 lives.

3.3 *Convergent Margins*

Convergent margins, like passive margin open continental slopes and rises, are important regions of 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 SMF, although the relationships are complex (Tappin, 2009). It is not always those margins where sediment flux is large that produce the most hazardous tsunami. For example, the PNG event at Sissano Lagoon in 1998 took place along the New Guinea Trench which is sediment starved (Tappin et al., 2001). Conversely, along the Sunda margin, where there is a much larger accretionary prism than in New Guinea, SMFs are small-scale and less of a hazard in sourcing destructive events (Tappin et al., 2007).

SMFs have been mapped along 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). Off Japan, there are large SMFs on the upper parts of the Nankai accretionary prism (Kawamura et al., 2009) but the highly eroded lower slopes show little evidence of large, well-preserved events (McAdoo *et al*. 2004). Along the Makran and Kodiak accretionary margins there is evidence of mass wasting on the upper slopes, with the lower slopes lacking large SMFs. By contrast, along the sediment-starved Sanriku (Japan), Nicaragua, and Aleutian margins there are large SMFs. In the Gulf of Alaska, there are a number of large SMFs located on the shelf and the continental slope. Both slumps and debris flows are present and their formation is attributed to glacial processes (Schwab and Lee, 1988; Dobson et al., 1998). During climatic cooling there is increased sediment delivery to the slope through expansion of tidewater glaciers, with resultant formation of point-sourced fans. During interglacials, as sea levels rise, sediment is delivered onto the shelf. Triggering is either by earthquake or storm wave loading.

Since the Sissano, PNG tsunami of 1998, research into convergent margin tsunamis from SMFs has increased significantly. Some studies are based on newly acquired multibeam data, e.g., Puerto Rico, 1918 (López-Venegas et al., 2008). Other studies have re-evaluated anomalous tsunamis with runups that, to some degree, are too large in relation to their proposed earthquake source, e.g. Messina, 1908 and Alaska, 1946 (Fryer et al., 2004; Billi et al., 2008). Other events, where there are inconsistencies between earthquake magnitude/location and tsunami runup, include the Makran, Indian Ocean event of 1945 (Rajendran et al., 2008), Sanriku in 1896 (Tanioka and Seno, 2001), Flores Island in 1982 (Imamura et al., 1995) and Java, 2006 (Fritz et al., 2007).

4 SMF, Tsunamis and Climate control

In most, if not all, of the landslide environments described there is evidence of strong climate control on SMF; on initial deposition, post-depositional preconditioning of sediment, as well as on triggering. The type of sediment laid down, fine- or coarse-grained, the rate of deposition and post-depositional alteration are all influenced to greater or lesser degree by climate. The location of SMFs is also climate controlled through changes in eustatic sea level. Yet there are obvious variations and differences in how climate controls SMF in the different landslide territories. There are both temporal variations over hundreds of thousands of years, associated with global, astronomically-forced, climate change together with geographic variations that are related to present-day climate and the various tectonic environments in which the landslide territories occur. Finally, in the context of tsunamis, there is the evidence on which the relationship between SMF and tsunamis is based, whether this is representative and, if not, why. These interrelations between climate, SMF and tsunami generation are, therefore, complex in temporal, geographic and tectonic frameworks.

4.1 *Temporal relationships between climate change and SMFs*

Evidence from the most intensively studied region of the Atlantic, reveals a strong climate control on the mass-wasting systems of the region that is related to the cyclical changes over the past hundreds of thousands of years that relate to glacial and interglacial periods. In the high-latitude, glacially-dominated, continental margins off Norway, the thick sedimentary deposits laid down during glacial periods and interbedded, thinner finer-grained sediments laid down during interglacials, are prone to failure, triggered from increased seismicity (caused by isostatic readjustment) during deglaciation. Farther south along the glacially-influenced margins of the USA, there is also climate control on sedimentation. During the cyclical glacial/interglacial periods changing eustatic sea level controls the location of sediment deposition, as well as the rates of sedimentation. Compared to glaciated margins, sediment delivery is much reduced, thus SMF volumes are smaller by an order of magnitude. Largest SMFs are on the margin of shelf-edge deltas, where rapid sedimentation during glacial lowered sea levels results in a potential for subsequent catastrophic failure as sea level rises.

Along the low latitude margins off West Africa, although the database is more limited, climate control is reflected in the turbidite mass failures that correlate with climate induced sea level change. Off Mauritania, turbidites are the sourced from the desert sands that advance to the shelf edge during sea level lows. Smaller SMF relate to climate controlled rates of sedimentation, in association with different types of sediment deposited between glacial and interglacials. Organic rich fine-grained sediments resulting from upwelling during sea level highs form weak layers along which failure takes place. Along convergent margins, although the evidence base is again limited, variation in sediment supply in high latitudes, such as along the Alaska margin, is related to glacial/post-glacial sediment variation (e.g. Schwab and Lee, 1988; Dobson et al., 1998).

A major constraint on identifying temporal control is undoubtedly the relatively poor accuracy of landslide dating and the limited number of reliable ages. Thus climate induced controls, such as on relatively brief periods of sea level fall, remains uncertain. Notwithstanding, the dates available indicate that over the last 20,000 years, there is a relatively even distribution of large landslides in the period between the last glacial maximum until about 4,000 years ago. These failures are in sediments deposited during lowered sea levels, interbedded with weak layers that form during interglacials, and prone to destabilisation during warming and deglaciation. Evidence of two relatively recent tsunamis from SMF (Storegga, 8,200 BP and Grand Banks in 1929) in these glacially dominated, northern regions suggests that the present-day hazard here may be high. However, where triggering of failure is mainly through glacioisostatic rebound, the decline in seismicity may well result in the hazard today not being as great as perceived, (as proposed by Bryn et al. 2005).

4.2 *Does climate influence preconditioning of submarine sediment sequences to mass failure?*

Climate preconditioning of sediment failure is recognised in many regions of the Atlantic. Off of Norway, the change in sedimentation between glacial and interglacials results in loading of fine-grained sediments thereby creating high pore pressures, and resulting in sediment susceptible to failure from earthquake loading. In fjords, rapid deposition of organic rich sediment on fjord head deltas also leads to high pore pressures and gas rich sediment, resulting in sediment that is sensitive to cyclic loading from storms and earthquake shock. Recent studies from the Gulf of Mexico (Dugan and Stigall, 2009) and Storegga (Kvalstad et al., 2005) show that high pore pressures resulting from rapid sedimentation, can precondition SMF, but an external instantaneous trigger, such as an glacioisostatic earthquake, or salt movement is still required. Thus the sediment preconditioning is climate related, although triggering may be mainly from another source.

4.3 *Climate change as a trigger mechanism for SMFs*

There has been much discussion about the instantaneous triggers of SMF. Earthquakes are undoubtedly the most common triggers. Others include storms, tides and salt movement. More controversial is triggering resulting from instantaneous hydrate destabilisation and pore fluid overpressuring. There is much circumstantial evidence on the association between hydrates and SMF, for example, the relationship between the headwall scarps of SMF with the intersection of the hydrate stability zone at the seabed. Hydrate dissociation was considered as a trigger of the Storegga slide, but this has been discounted as a major factor (Bryn *et al*. 2005). Suggestions that rapid methane increase during past interglacials is from SMF has now been disproved from isotopic ice core evidence (Sowers, 2006).

Thus, although hydrate disassociation and sediment fluid overpressures may precondition sediment for subsequent failure, under present climates an external force, such as from earthquake loading, is still required to actually initiate failure (Bryn et al., 2005; Dugan and Stigall, 2009). Elevated pore pressure is undoubtedly a significant factor in reducing sediment shear strength, but geotechnical analyses have failed to confirm that these can cause instantaneous failure. Most SMFs dated by Lee (2009) from the last 20,000 years, were emplaced during stable or rising sea level, a period when hydrate disassociation would be least expected. In the future, however, if predictions of rapid global warming are correct, then hydrate stability in shallow ocean waters may be affected. In polar regions, where present models suggest warming will be most rapid this may result in an increased potential for hydrate destabilisation (Betts and McGuire, 2010; Maslin et al., 2010). In high latitudes, SMF triggering by earthquakes during late- to post-glacial periods is well established, with the earthquakes resulting from glacioisostatic readjustment as ice sheets melt and retreat. In both Canada and northern Europe, rebound seismicity, although still occurring, is much less than in the early Holocene because the isostatic readjustment is in an asymptotic decline. Triggers, such as cyclic loading by storm waves are also climatically controlled. Continuing earthquake activity associated with glacioisostatic readjustment along the Scotia margin suggests that there is on ongoing hazard here.

4.4 *Climate and sea level change, and the preservation potential of tsunamis sediments from SMFs.*

The identification of so few tsunamis sourced from SMF is enigmatic. The magnitude of tsunamis from SMFs is determined mainly by the type of failure (cohesive slump or fragmental landslide), SMF volume and the water depth (Tappin et al., 2008). Slumps per unit volume are most hazardous, although fragmental failures are more voluminous and, therefore, potentially as hazardous. However, any SMF of sufficient volume and in appropriate water depths has the potential to create a hazardous tsunami. That SMF sourced tsunamis have only been identified along continental and convergent margins and fjords is thus considered unlikely to be representative, and it is the evidence base that is inadequate to fully identify the hazard.

Limitations on the identification of tsunamis may be due to the limited anecdotal evidence from survivors (for historical events) or, for prehistorically tsunamis, an absence of tsunami sediment laid down on inundation. Of recent SMF generated tsunami, such as those of the Grand Banks, 1929 and PNG, 1998 there have been positive identifications of associated sediments. The prehistorical event from Storegga, laid down sediment that extends as far afield as the Faeroe Islands. It is almost certain that tsunamis were also sourced from Andøya, Trænadjupet, Finneidfjord; the absence of associated sediments from these events is puzzling. The assumption is that any resulting deposits have not been preserved.

Modelling of the Cape Fear and Currituck SMFs indicates that at present sea levels failure would create a hazardous tsunami. As the failures took place either during the late glacial or early interglacial, at the time of failure the tsunami would have made a major impact. The lack of evidence of tsunami from onshore (or in fact offshore cored sediments) can be explained by the poor preservation potential of tsunami deposits that may lie on the seabed. Reworking during post-glacial periods may have eroded them however. The absence of deposits onland may be due to the width of the US continental shelf. Given that SMF took place at sea levels ~100 m lower than today it is unlikely that the tsunami carried completely across the width of the US continental shelf that in places is up to 200 km. Both the large-scale SMF off the Amazon and the smaller SMFs off west Africa have the potential to generate tsunamis, the absence of evidence in these areas, may be due to the timing (failure during lowered sea levels) or the lack of investigation in onshore areas to determine whether sediments resulting from these events are present.

The low preservation potential of sediments laid by tsunamis suggests that the prehistorical record maybe unrepresentative. Tsunamis during low stands may not have left a deposit on present day land, but on the present-day flooded continental shelf where, identification is compromised by difficulties in identification in cores or absence due to sediment reworking during postglacial transgression. For example, this may explain the lack of evidence of tsunamis sourced from the SMFs off of the eastern US (e.g. Carrituck and Cape Fear), despite their large volume and modelling that would suggest otherwise.

The absence of evidence for tsunamis on active river deltas is intriguing. The similarity between sedimentation mechanisms on river deltas and other landslide territories, such as continental margins and fjords, in both sediment preconditioning and triggering suggests that SMFs of sufficient volume and at appropriate depths would generate tsunami. The water depths (less than 1000 m) of known failures in the Gulf are certainly shallow enough to generate tsunamis, if the SMFs are of sufficient volume. On the Gulf Coast the most catastrophic seabed failure was in 1969, when Hurricane Camille struck. 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). Thus the SMFs are either too small or the tsunami wave was indistinguishable from the storm surge. In the instance of Katrina in 2005 the surge was between 6 and 9 m, probably of a sufficient magnitude to mask a tsunami.

5 Conclusions

The hazard and risk from SMF sourced tsunami has advanced significantly over the past decade. SMFs are generally acknowledged to source hazardous tsunamis, however, the database of well-studied events is still limited. There is a recognisable and strong climate control on SMF that impacts on their potential to source hazardous tsunamis. There are strong climate controls on the type of SMF sediment and its' rate of delivery. Climate can precondition sediment instability by introducing 'weak layers' as well as through fluid and gas overpressuring. Climate influences triggering through earthquake shock and wave loading. There is an obvious latitudinal variation in SMF architecture that suggests tsunami hazard to be greater in northern regions. During glacial periods, rates of sediment delivery are higher and sediment volumes are larger, thus forming larger SMFs that are more prone to failure. Along convergent margins, where earthquakes are more frequent, there is a climate influence in high latitudes.

Any SMF of sufficient volume in an appropriate water depth has the potential to generate a hazardous tsunami. At first sight, as in the North Atlantic, the presence of numerous SMFs suggests a present-day high risk. Consideration of the climate controls on SMF, however, indicates that these SMF took place under different environmental conditions. Their number, therefore, may not reflect present day hazard. The evidence base for the conclusions here, however, is still small. There are still too few case studies of actual events. More dates of landslide failure are required to test hypotheses on climate control of mass failure processes. The absence of tsunamis off deltas is enigmatic. The general absence of evidence for tsunamis where there are numerous SMFs may be misleading and may be attributed to limited defining evidence from anecdote, absence of preserved deposits or misinterpretation of tsunami source.

Notwithstanding, consideration of climate controls on SMF contributes significantly in improving our understanding of SMF mechanisms, allowing an improved assessment of their sources as hazardous tsunami under present climatic conditions. In the future, as climate warms, this improved understanding will underpin prediction of tsunami-sourced SMF, particularly in regions where climate change will be most rapid, such as in the Polar Regions.

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