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The continuing underestimated tsunami hazard from submarine landslides

David R Tappin(1), **Stephan T Grilli**(2)

(1) British Geological Survey, Nottingham, NG12 5GG, United Kingdom

(2)University of Rhode Island, Narragansett, RI 02882, United States of America

Abstract

Tsunamis generated by submarine landslides are a, relatively, recently identified hazard, resulting from the Papua New Guinea event of 1998, when 2,200 people died. In the context of the PNG event, recognition of the hazard from submarine landslide has been possible because of the application of advanced technology, such as multibeam echosounders, now available to image the seabed to high resolution. In addition, the architecture of submarine landslides developed from marine mapping has been used as a basis for new numerical models of tsunami generation from seabed sediment movement. Tsunamis, post-dating PNG, where an earthquake mechanism was not realistic, have been considered in this new context, and new relationships identifed. These relationships have been particularly with strike-slip and large magnitude (great) earthquakes, as well as with small magntude events where a dual mechanism is most likely. Submarine landslide tsunamis are now recgnised from all geological environments; passive, convergent and strike-slip margin as well as volanoes. Despite these new advances in understanding, recognition of the hazard from submarine landslide tsunamis is still limited.

Keywords

Submarine landslide, tsunami, hazard, earthquake

Introduction

Over the past 20-30 years, there have been a number of catastrophic tsunamis, which resulted in over 300,000 fatalities (Tappin 2017a), and it seems, that we are living in the 'Age of Tsunamis'. Most of these tsunamis (e.g. 2004, Indian Ocean) were generated from earthquakes but, the development of sophisticated seabed mapping capabilities, together with high resolution position fixing and the manipulation of large data volumes have resulted in the identification of numerous submarine landslides (SL) offshore of most continental margins (Tappin 2017c). These landslides pose a significant potential hazard to local coastal communities in the generation of tsunami.

The wake-up call for landslide tsunamis was in July, 1998, when a small magnitude, 7.1 earthquake triggered a tsunami which devastated local coastlines on northern Papua new Guinea (PNG), causing 2,200 fatalities (Tappin et al. 2008) (Figs. 1 and 2). For the first time, an offshore marine survey programme, funded by Japan, identified a small volume (6km^3) slump as the tsunami mechanism (Tappin et al. 2001). The data acquired during the marine surveys included multibeam echosounder and seismic data, sediment cores and seabed photographs and videos (Figs. 1 and 2). Based on these data, new numerical models for tsunami generation from submarine landslides were developed.

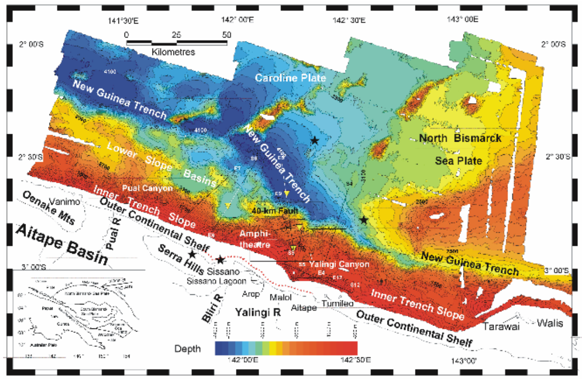

Fig 1. Bathymetry and main morphologic elements offshore of northern Papua New Guinea together with the main coastal locations and features (Box is the area of map in Figure 2). Red triangles = main area devastated by the 17th July 1998 tsunami. Reproduced from Tappin, 2007) (Location Fig. 3).

In this context, consideration of previous events, including those of the Grand Banks in 1929, and

Storegga, 8,200 years BP, resulted in a reappraisal of the previously unappreciated tsunami hazard from seabed sediment movement (Tappin 2017b).

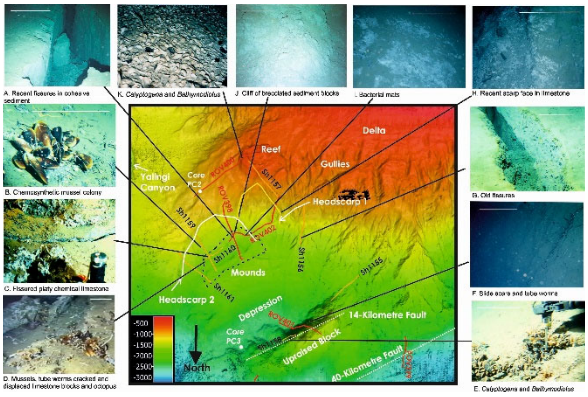

Fig 2. Amphitheater area off Sissano lagoon (for location see Figure 1) with main morphologic features labelled and photographs of significant seabed features (Scales: solid white line = 1 meter. (Reproduced from Tappin, 2019) (Location Fig. 3).

On September 28th, 2018, an earthquake, together with subaerial and coastal landslides generated a tsunami in Palu Bay, Sulawesi, Indonesia (Arikawa et al. 2018; Gusman et al. 2019). There were 4,100 fatalities associated with these events. Perhaps over 1,000 perished in the tsunami. But as yet, the tsunami mechanism is still uncertain (Gusman et al. 2019; Jamelot et al. 2019). Three months after the Palu event, an eruption of Anak Krakatau, in the Sunda Strait, resulted in a flank collapse, which generated a tsunami onto the adjacent coasts of Java and Sumatra that resulted in 437 fatalities (Grilli et al. 2019). Here we consider present state of knowledge on submarine landslide tsunamis, their potential hazard, their impact and mitigation.

Evidence for submarine landslides

Mapping the seabed to the resolution we have available today resulted from three main technological developments: the multibeam echosounder (MBES), satellite global positioning systems and computers able to store and manipulate large (enormous) data volumes. All of these technologies have become readily and increasingly available over the past 30-40 years; MBES since 1990, GPS since the mid-1990s (Theberge and Cherkis 2013), and computing power over the past several decades. One of major advances resulting from these developments have been the acquisition seabed bathymetry over large area of the ocean seabed (Fig. 3), and the identification along many, if not most, continental and island margins, of submarine landslides, and the recognition of their common occurrence. Not all margins are mapped (Fig.1), with major gaps off Africa, but good coverage along the margins of the Pacific and North Atlantic oceans. The seabed coverage together with the history of historical tsunami events, allows us to present a new review of the hazard from submarine landslides (Fig. 2).

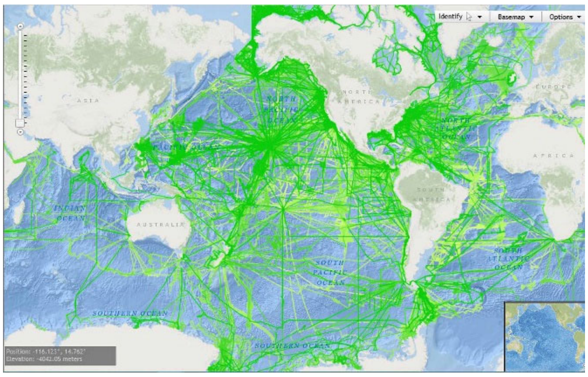

Fig 3. World ocan multibeam echosounder coverage (https://maps.ngdc.noaa.gov/viewers/bathymetry/

Passive Margins

Submarine landslides are now mapped along many passive margins, although few are associated with identified tsunamis (Figs. 3 and 4). This may seem surprising, until it is realised that the identification of tsunamis, especially prehistoric events, is mainly from sediments deposited as the tsunamis flood the land. The preservation potential of these sediments is very low because of intense erosion in these environments.

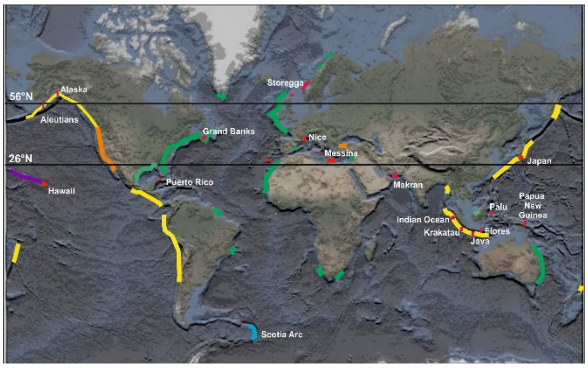

Fig 4. Global distribution of mapped submarine landslides (SLs). Green lines: SLs on passive margins. Yellow lines: SLs located along convergent margins (Reproduced from Tappin, 2017).

Although few landslides are dated, many failed during glacial periods when sea levels were much lower and continental shelves more exposed, so sediments laid down are now below sea level and probably eroded during post-glacial marine transgression.

The best studied passive margins area those of the North Atlantic along the coasts of Europe and North America, where there is an extensive database of submarine landslides, their depositional character, age and triggering mechanisms (Figs. 3 and 4) (Tappin 2013). From these studies, it is apparent that there is a strong climate control on submarine landslides, which is both geographical and temporal ((Bryn et al. 2005). In the Atlantic, continental margins may be defined by latitudinal variations that may geographically be classified as 'glaciated' north of 56° N (southern tip of Norway), 'glacially-influenced' between 26° N to 56° N, and non-glaciated south of 26° N (Fig. 2). In these areas, the only major tsunamis recorded are from the prehistoric landslide event of Storegga off Norway dated at 8,200 years BP and Grand Banks, 1929 off Canada (Bryn et al. 2005; Heezen and Drake 1964; Ruffman 1997). Both of these are located in the 'glaciated or glacially influenced' regions and reflect the strong temporal climate control from the changing sedimentation regimes during the glacial and interglacial periods operating over the past 400,000 years. Although there is a general recognition of the climate control on submarine landslide failure the relationships are complex, and as yet have to be established in detail, especially landslide triggering. The main constraint is the age dating of the landslides. Whereas there is now high-resolution age dating of climate change over the late Quaternary and Holocene, few landslides, especially in the Atlantic are dated to high resolution.

Convergent Margins

There are number of submarine landslide tsunamis along convergent margins, with Papua New Guinea, 1998, perhaps the best known and researched. Other convergent margin landslide tsunamis include those of Messina (1908), Makran (1945) Aleutians (1946), Alaska (1964) Puerto Rico (1918), Flores Islands (1992) and Java (2006) (Fig. 4) (Fritz 2007; Fryer et al. 2004; Hornbach et al. 2008; Imamura et al. 1995; Parsons et al. 2014; Rastgoftar and Soltanpour 2016; Schambach et al. 2020). There were 2,200 fatalities from the PNG event, 600 people died in the Java tsunami and 1,000 at Flores. Although suspected, for most of these events the submarine landslide contribution remains uncertain, because there are no marine data to evaluate the seabed for landslides, that can be used to underpin numerical tsunami models. Hydroacoustic data has been used to evaluate the tsunami mechanisms of the Aleutians, Alaska, Messina, Puerto Rico and the Aleutians.

The great Alaska earthquake of 1964 directly generated a tsunami, but also triggered sediment failures in fjords, along the nearby coast, which also generated local tsunamis (Fig. 4) (Plafker et al. 1969). At Seward a one kilometre section of the waterfront collapsed into the sea, creating a 10 m high tsunami, with the destruction compounded by the earthquake-generated tsunami, 10 m high, which arrived 30 minutes later. Most of the 13 people who died, were drowned in the tsunamis. At Valdez, the waterfront collapsed as the seabed failed, and generated a tsunami of up to 52 m in which 32 people died.

The most devastating convergent margin tsunami after PNG was Messina, in 1908, in the Ionian Sea (Fig. 4) where 2,000 people are estimated to have drowned (Comerci et al. 2008). The earthquake magnitude (M_S =7.1) located in the Messina Strait is incompatible with both the height and extent of local tsunami runup' which extended southward along the east coast of Sicily (Schambach et al. 2020). There were seabed cable breaks in the southern Ionian Sea, so the most likely mechanism for most of the tsunami is a submarine landslide or landslides off the east coast of Sicily. There have been numerous attempts to identify its location, and the recent paper by Schambach et al. (2020) identifies a submarine block slide off of Etna (Fig. 5), which explains the tsunami elevations along the central and southern coasts of Sicily, but requires additional landslides to be present farther north. The local tsunami from the Aleutians, 1946 earthquake is now recognised as the result of a submarine landslide . There is still controversy over the tsunami from the Puerto Rico earthquake of 1918, with the landslide contribution still uncertain (Hornbach et al. 2008; López-Venegas et al. 2008).

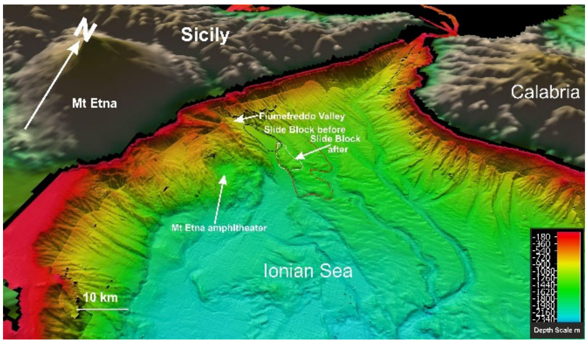

Fig 5. 3D image of the landslide block that contributed t the 1908 Messina tsunami (reproducd from Schambach et al., 2020).

The most recent devastating tsunami, which again has proved seminal, was on March 11th 2011, on the east coast of Honshu Island, Japan (Saito et al. 2011). Yet again, the mechanism is controversial. The *Mw* 9.1 earthquake, was at first was considered to be the only tsunami mechanism, however, this does cannot explain the elevated (40 m) focussed runups along the Sanriku coast of northern Honshu Island, because these are too far north of the main earthquake rupture (Grilli et al. 2013a; MacInnes et al. 2013). Numerical modelling, based only on the earthquake, cannot reproduce tsunami elevations along the Sanriku coast, so an additional submarine landslide mechanism is proposed. Numerical tsunami modelling of a dual mechanism, however, earthquake and landslide identified from multibeam bathymetry from before and after the earthquake, located off Sanriku, (Fig. 4), best reproduce the tsunami elevations from the 2011 event (Tappin et al. 2012) (Fig. 6).

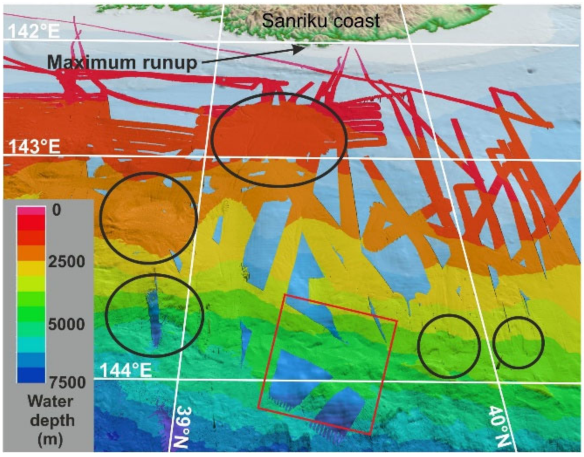

Fig. 6 Multibeam bathymetry off the east coast of Japan, showing submarine landslides (SLs). Black ellipses/circle are SLs: Red square is the location of the SMF triggered by the March 2011 earthquake. (Reproduced from Tappin et al., 2014).

Strike-slip Margins

Tsunamis from submarine landslides associated with strike slip earthquakes are more common, than might be realised. Events include those in the Gulf of Izmit (1999) and Haiti (2010) (Hornbach et al. 2010; Tinti et al. 2006). The tsunami from the Kaikoura event in New Zealand, in 2016 has been proposed as from a submarine landslide (Heidarzadeh and Satake 2017), and the earthquake that triggered the Grand Banks landslide in 1929, was strike slip (Hasegawa and Kanamori 1987). Most recently, the tsunami generated in September, 2018 at Palu on Sulawesi, Indonesia, is likely a combination of coastal landsides, and the triggering strike slip earthquake (Jamelot et al. 2019).

Submarine landslide tsunami – the hazard remains undefined

The 1998 PNG tsunami was transformative in identifying the hazard from submarine landslides. The initial basis of the identification was the small earthquake and the field surveys, which identified the tsunami elevations, but it was the marine surveys, especially the MBES data, that proved the presence of the submarine landslide. Notwithstanding, it took many years for this to be accepted, and the reasons for this have been addressed in Tappin (2017b).

Extensive mapping of continental margins now shows the common presence of submarine landslides (Figure 2). Along passive margins, there is a strong climate control on sediment failure, and research in the north Atlantic suggests that failure is related to sedimentation regimes controlled in part by the 120,000-year interglacial/glacial cycles, with triggering mainly from earthquakes (Bryn et al. 2005). The dominant controls on landslides along convergent margins are not as well established, but are more likely to be local sedimentation regimes, and triggering from earthquakes, although earthquake shaking is also shown to weaken and strengthen sediment (Tappin 2009).

Only three major submarine landslide tsunamis have been identified, researched and validated; Storegga, Grand Banks, Papua New Guinea and with two others, Messina and Japan there is strong evidence for a dual mechanism (Schambach et al. 2020; Tappin et al. 2014). Two of these, PNG and Japan, resulted in significant loss of life. Dual source, earthquake/landslide tsunamis are more common than previously recognised, with the earthquake mechanisms, either thrust or strike slip faults. Events such as Messina (1908), Makran (1945) Aleutians (1946), Alaska (1964) Puerto Rico (1918), Flores Islands (1992) and Java (2006), confirm the potential hazard from these dual mechanisms, some of which still require further research to understand their specifics.

Over the past year, large volume submarine landslides have been identified in the Scotia Arc in the south Atlantic, and although millions of years old, generated significant tsunamis (Nicholson et al. 2020). Recent submarine landslide events have also been recognised in Indonesia in the Makassar Straight, between Sulawesi and Kalimantan (Brackenridge et al. 2020). A submarine landslide, tsunami hazard that has received little attention is that associated with strike slip faults. The earliest historical example was the Grand Banks tsunami of 1929, but more recent events include the 1999, Gulf of Izmit event, 2010, Haiti and, in late 2018, Palu, Sulawesi, Indonesia. It is likely that as more areas of seabed are mapped with hydroacoustics, more landslides (and possibly tsunamis) will be identified. For example, an unusual association of low angle, normal faulting triggering submarine landslides in the Banda Sea, west Indonesia has recently been identified as the cause of a major tsunami in 1852 (Cummins et al. 2020).

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