The importance of geologists and geology in tsunami science and tsunami hazard

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Abstract: Up until the late 1980s geology contributed very little to the study of tsunamis because most were generated by earthquakes which were mainly the domain of seismologists. In 1987–88 however, sediments deposited as tsunamis flooded land were discovered. Subsequently they began to be widely used to identify prehistorical tsunami events, providing a longer-term record than previously available from historical accounts. The sediments offered an opportunity to better define tsunami frequency that could underpin improved risk assessment. When over 2200 people died from a catastrophic tsunami in Papua New Guinea (PNG) in 1998, and a submarine landslide was controversially proven to be the mechanism, marine geologists provided the leadership that led to the identification of this previously unrecognized danger. The catastrophic tsunami in the Indian Ocean in 2004 confirmed the critical importance of sedimentological research in understanding tsunamis. In 2011, the Japan earthquake and tsunami further confirmed the importance of both sediments in tsunami hazard mitigation and the dangers from seabed sediment failures in tsunami generation. Here we recount the history of geological involvement in tsunami science and its importance in advancing understanding of the extent, magnitude and nature of the hazard from tsunamis.

Until the late 1980s tsunami science was mostly the province of seismologists, numerical modellers, geophysicists and historians; tsunamis received little attention from geologists (e.g. Bailey & Weir 1933; Coleman 1968, 1978). Earthquakes were considered the main, if not the only, mechanism that could generate elevated tsunami waves that were very destructive at the coast. Other tsunami-generation mechanisms, such as submarine landslides, were not considered a major hazard despite evidence to the contrary such as from the Grand Banks event of 1929 (Bardet *et al.* 2003). Numerical tsunami modelling of submarine landslides was in large part theoretical (Jiang & LeBlond 1992, 1994). The slow landslide failure velocities were perceived as inhibiting tsunami generation, in contrast to earthquake-generated tsunamis where rupture velocities of kilometres per second were regarded as instantaneous in the context of the relatively slow (metres per second) velocity of tsunami wave generation (Geist 2000; Ward 2001). Historians provided evidence on older tsunamis, hopefully for use in estimating tsunami frequency–magnitude relationships for future tsunami risk, although the limitations of historical data were recognized (Ambraseys & Jackson 1990). When a paper (rarely) considered the geology of tsunamis, it was on the sediments deposited from inundation and authored by seismologists (e.g. Wright & Mella 1963).

The involvement of geologists in tsunami research began in the early 1980s, with the first papers on deep-sea deposits in the Aegean Sea. Here, unusual seabed sediments, termed homogenites, were proposed as deposited from a tsunami generated by the Late Bronze Age eruption of Santorini (Kastens & Cita 1981; Cita *et al.* 1984). In the Hawaiian Islands, boulders and coarse-grained gravels preserved at high elevations (hundreds of metres) were considered to result from tsunamis generated by large-scale volcanic collapse (Moore & Moore 1984). The early results from the Mediterranean and Pacific were controversial due to the uncertainty over whether there were tsunamis generated at these locations. In addition, this approach of using sediments to identify tsunamis from their sedimentary record had not been attempted before. The tsunami from the Late Bronze Age (LBA) eruption of Santorini had been a major controversy for decades (Marinatos 1939). Sand had been found in Minoan buildings on the coast and used as evidence for tsunami inundation; its origin was however disputed as it was located at sea level and the sand could have been deposited from storms or was present for religious purposes. Subsequent validation has been impossible because the sand deposits were destroyed during subsequent excavations. The Aegean Sea homogenites provided the first geological evidence in support of the tsunami hypothesis but, even today, the origin of the

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homogenites remains controversial (see Pareschi *et al.* 2006; Shanmugam 2006; Weiss 2008; Polonia *et al.* 2013). The suggestion that the Hawaiian deposits were from tsunamis was groundbreaking because of their use in identifying tsunamis from volcanic collapse. Previously, the deposits were interpreted as laid down during sea-level highstands (Stearns 1978). Their origin is also still disputed (Stearns 1978; Rubin *et al.* 2000; McMurtry *et al.* 2004*a*).

In 1987 and 1988, two groundbreaking papers published on tsunami sediments demonstrated their potential in evaluating tsunami hazard. The first (Atwater 1987) was on prehistoric sediments in Cascadia, which identified a sequence of earthquakes and their associated tsunamis that extended back in time to over 10 ka before present (BP). The second paper (Dawson *et al.* 1988) on sedimentary deposits in Scotland identified a major prehistoric tsunami from a massive submarine landslide (Storegga) located off Norway (Bugge 1983; Bugge *et al*. 1988). These sediments motivated the first attempt at numerical modelling of a tsunami from a submarine landslide mechanism (Harbitz 1992). In 1998, a devastating tsunami struck the north coast of Papua New Guinea (PNG) killing over 2200 people (Kawata *et al.* 1999). The associated M_w 7 magnitude earthquake was too small to generate all of the elevated local run-ups of 15 m. Amid confusion and controversy (e.g. Geist 2000), marine surveys organized in response to the disaster acquired hydroacoustic and sample data offshore of the impacted area. These surveys identified an offshore slump, which preliminary numerical simulations demonstrated to be the local tsunami mechanism (Tappin *et al.* 1999). The PNG event was seminal in identifying the major hazard from submarine landslides in tsunami generation. It was the first tsunami to be studied from responsive marine surveys led by geologists. Submarine landslides were well researched previously, but rarely in the context of tsunami generation and not by collaboration between geologists and numerical modellers (e.g. Grand Banks in 1929).

The 1987–88 research on tsunami sediments in the USA and Europe, together with the landslide-generated PNG tsunami, resulted in the major involvement of geologists in tsunami science and the recognition of the contribution which geology could make to an improved understanding of tsunamis and their hazard. Demonstrating the mechanism of the PNG tsunami was seminal in confirming the tsunami hazard from submarine landslides. It was based on marine surveys carried out by geologists, with the geological interpretations underpinning the numerical tsunami models. Much later, the PNG tsunami was the first attempt to use inverse and forward modelling of tsunami sediments to determine tsunami characteristics (Jaffe *et al.* **EDQ1** 2007). More recent, devastating, events in the Indian Ocean (2004) and Japan (2011) have expanded this geological involvement in tsunami sediment characterization (e.g. Paris *et al.* 2007), in inverse modelling of tsunami-generation mechanisms (Spiske *et al.* 2010; Sugawara *et al.* 2014) and in research on submarine landslides in tsunami generation (Tappin *et al.* 2007, 2014). Storegga, PNG and most recently Japan have led to an increased realization of the tsunami hazard from submarine landslides.

Here it is recounted how over the past *c.* 30 years geologists became increasingly involved in tsunami science and how they have contributed to an improved understanding of tsunami mechanisms and their hazard. Although there were earlier, isolated precursors to the main ‘catalyst’ events identified above, it was during the 1980s that ‘geology’ became significant in advancing tsunami science; this advancement was initially from the application of tsunami sediments, followed by an improved understanding of tsunami frequency, hazard and risk, and more recently, with the Japan tsunami, from the use of sediments as a basis for inverse numerical models of tsunami-generation mechanisms (e.g. Sugawara *et al.* 2014). The motivations for this paper were the two meetings held in Japan and the United Kingdom in 2014 and 2015 on the theme of ‘Tsunami Hazards and Risks: Using the Geological Record’. The focus of the Japan meeting was the use of tsunami sediments in the mitigation of tsunami hazard. The aim of the UK meeting was to bring together geologists and hazard and risk modellers. In this paper the use of the geological record in contributing to tsunami hazard is extended by the addition of how the identification of submarine landslides have led to their recognition as a major hazard in tsunami generation, a hazard previously overlooked (Bardet *et al.* 2003; Løvholt *et al.* 2015). To underpin realistic modelling of tsunamis generated from submarine landslides requires their architectures to be determined from hydroacoustic data, including multibeam echosounders (MBES) and seismics. Mapping of seabed failures has led to the transition from theoretical numerical models, which suggested that landslides were ineffective in tsunami generation (LeBlond & Jones 1995), to realistic, event-based models that prove otherwise (Harbitz 1992; Tappin *et al.* 1999). The use of the term ‘geology’ is interpretative in the sense that sub-seabed structure can be determined from remote data such as multibeam echosoundings and seismics. It is also recognized that the characterization of tsunami sediments and their discrimination from other depositional mechanisms is still undergoing review (see Shanmugam 2012), so here the focus is on well-studied examples from well-established mechanisms.

Tsunami sediments

Sediments deposited from tsunamis are mainly recognized on land. Those described from the seabed are rare and their identification and application in tsunami hazard assessment are more controversial (see Shanmugam 2006; Dawson & Stewart 2007), but they are covered here briefly for completeness (Fig. 1). Seabed tsunami sediments are found in deeper, oceanic water depths, include the homogenites in the eastern Mediterranean noted above. There are also shallow-water shelf deposits resulting from tsunami backwash (or backflow). Turbidites in the deep ocean have been well studied (e.g. Heezen & Ewing 1954; Kuenen 1957; Piper *et al.* 1988). Triggered by earthquakes, and in combination with onshore sediments, turbidites can be proxies for large-scale prehistoric earthquake events. Cascadia, on the west coast of the USA, is the best-studied area (Goldfinger *et al.* 2012). Here, turbidites along the oceanic margin were first researched in the 1970s (Griggs & Kulm 1970), with the first attempt to use these to date earthquake cycles in 1990 (Adams 1990) and subsequent research developed by Goldfinger *et al.* (2012). As the distal parts of submarine landslides, turbidites can be used in dating these (e.g. Normark *et al.* 2004). High-resolution age dating of submarine landslides is important in establishing relationships to climate change, which is a major control on sediment failure (Maslin *et al.* 2004) although still poorly understood (Urlaub *et al.* 2013). Backwash flow follows the maximum inundation of tsunami waves, after which the water recedes seawards. Backwash deposits on land are well described (Dawson 1994; Paris *et al.* 2007); however, in the ocean they are poorly researched. Interpretations are speculative because there are no reliable measurements of this process and few recent examples (Fig. 1; Dawson & Stewart 2007; Ikehara *et al.* 2014). The best evidence for backwash flow is from video footage of sediment plumes moving offshore from the Indian Ocean and Japan events (see Tappin *et al.* 2012). The backwash sediment flushed seawards has rarely been studied, but from the few case histories published on shelf deposits its long-term preservation potential is probably low because of reworking by longshore currents (Tappin *et al.* 2012) and storms (Noda *et al.* 2007; Sakuna *et al.* 2012; Feldens *et al.* 2012). Reworking compromises discrimination between tsunamis and storm deposits. On the outer shelf of Japan, the preservation of backwash deposits from the 2011 tsunami is considered likely only over short timescales (Ikehara *et al.* 2014). Nearer shore, the sediment flushed seawards was soon eroded by longshore drift and redeposited on the adjacent coast, where it repaired major coastal breaches (Tappin *et al.* 2012). The use of shallow-water tsunami deposits on the continental shelf in hazard assessment at present is therefore considered too poorly understood to be considered further.

Our imperative here is therefore on coastal deposits, particularly those from recent, historical and Quaternary events. Onshore sedimentary deposits from the older (pre-Quaternary) geological record have been attributed to tsunamis (e.g. Le Roux & Vargas 2005). Where the tsunami mechanism can be established, for example Chicxulub (e.g. Goto *et al.* 2008*b*), deposit origins can be validated; where the mechanism is more uncertain, as for many of the deposits on the west coast of South America, there may ~~however~~ be considerable uncertainty (e.g. Bailey & Weir 1933; Spiske *et al.*

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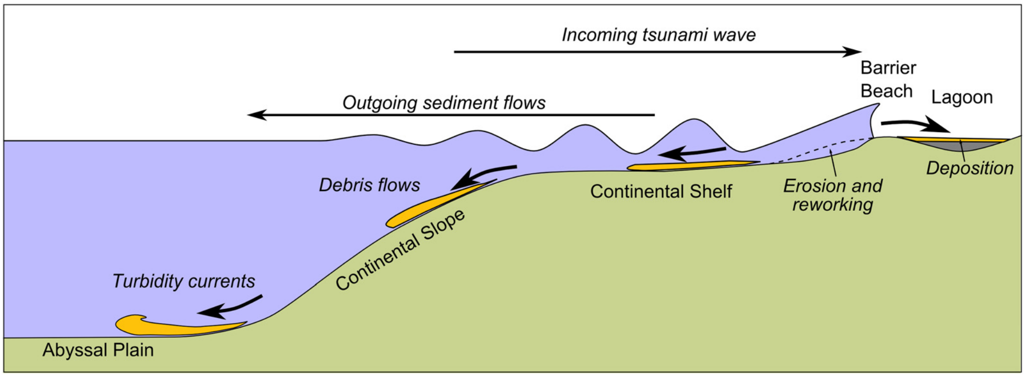

Fig. 1. Schematic illustration of principal pathways of tsunami sediment transport and deposition (Reproduced from MikeNorton; Wikipedia).

2014). The focus here is ~~therefore~~ on those mainly recent, on-land deposits which can improve hazard assessment through: (1) better understanding of tsunami frequency and impact; (2) the validation of numerical models; and (3) as a basis for inverse modelling of tsunami inundation and tsunami-generation mechanisms, ~~although the application of these methodologies is still in its infancy~~ (Huntington *et al.* 2007). These deposits include both fine-grained sediments and coarse-grained gravel/boulder deposits.

Early history of research (pre-1980)

Written observations of tsunami sediment deposition date back to 1868 from the Arica earthquake off Chile, where the US Postal Steamer *Wateree* (Fig. 2) was carried inland 430 m by a wave 18 m high at the coast and buried under a mass of sand and water (recorded in Myles 1985). The first scientific publication to suggest that tsunamis might be responsible for sediment deposition is Bailey & Weir (1933) on sediments of Jurassic age located on the west coast of Scotland. No further studies of tsunami inundation and sedimentation from historical or recent large earthquakes were published until the 1946 Aleutian tsunami, which struck Hawaii (Shepard *et al.* 1950). The first observational evidence for tsunamis transporting sediment was a series of photographs also from Hawaii from the 1957 earthquake in the Aleutians (referred to in Bourgeois 2009). Observations were reported of sediment deposition from the Chile tsunami of 1960 (Wright & Mella 1963) and the Alaska earthquake of 1964 (Reimnitz & Marshall 1965), but no detailed interpretations made. The 1960 Chile event left a 1–2 cm veneer of sand over the coastal lowlands (Wright & Mella 1963). There are numerous descriptions from Japan (e.g. Kon'no 1961), but these publications are mostly in Japanese so less accessible (Bourgeois 2009). Descriptions of the Suva earthquake and tsunami of 1953 were perhaps some of the first of the modern era to suggest an associated submarine landslide-generated tsunami, which deposited coral boulders on the adjacent reef (Houtz 1962). Probably the first modern 'geologically' focused paper that described tsunami sedimentation was by Coleman (1968).

Seminal events of the 1980–90s

The first geological evidence for sediments deposited from prehistoric tsunamis, which identified their potential for use in mitigation, was from

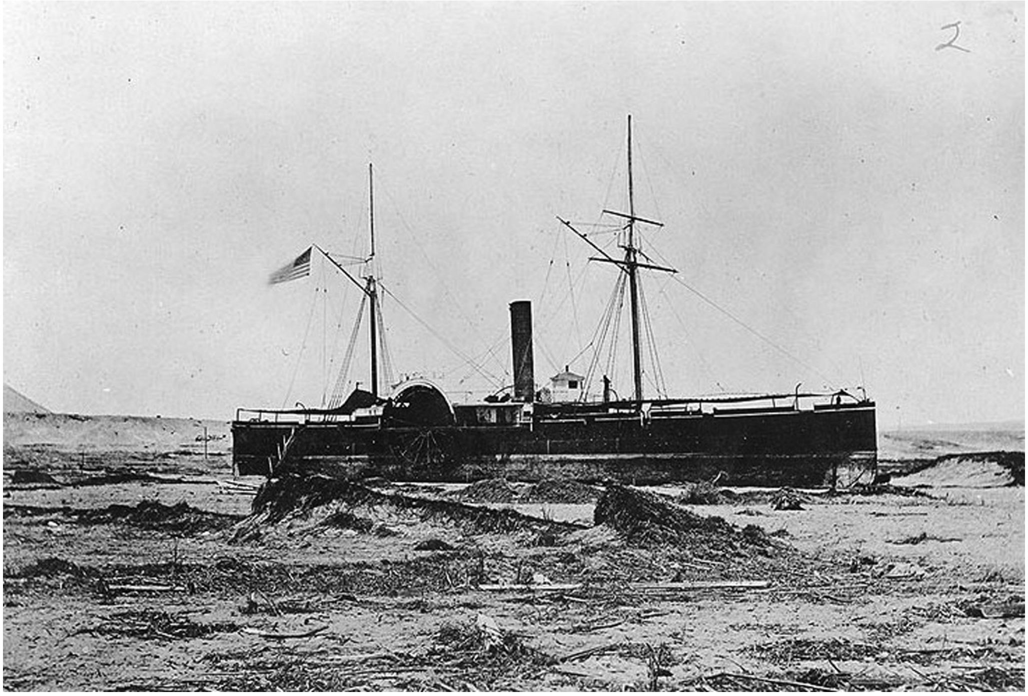

Fig. 2. USS *Wateree* (1863) beached at Arica, Chile, 430 yards above the usual high water mark, after she was deposited there by a tidal wave on 13 August 1868. Note the tsunami sand in the foreground (U.S. Navy photograph).

North America (Atwater 1987). The sediments were up to 10 ka old and preserved in sand sheets interbedded with marsh muds from the outer coast of Washington State. They were interpreted as deposited from earthquake-generated tsunamis. Recognition of the tsunami origin of the sediments led to the identification of earthquakes and tsunamis of much earlier age than that provided by historical records (up to 200 years old). A year later Dawson *et al.* (1988) described an unusual sand deposit (Fig. 3) within uplifted coastal sediment sequences in Scotland, which they attributed to a tsunami generated from the Storegga submarine landslide off the Norwegian coast (Jansen *et al.* 1987; Bondevik *et al.* 2005*a*). Deposits from Storegga had been described from the Shetland Islands by Birnie (1981), but had not been identified as originating from a tsunami. Along the Washington coast, the only explanation for the sediments was by rapid coastal subsidence from local earthquakes that generated tsunamis. In Scotland, radiocarbon dating of the sediments and Storegga landslide proved a close coeval correspondence. The identification of the deposits in Scotland motivated Harbitz (1992) to simulate a tsunami from a submarine landslide event, the first time that numerical modelling of a recorded submarine landside tsunami had been attempted.

The evidence for the origin of the sands in Cascadia and Scotland was circumstantial because their deposition from tsunamis had not been observed. For the first time the research was also by sedimentologists, unlike observations made at earlier historical events noted above which were by non-experts. Confirmatory evidence for the Cascadia research on the tsunami origin of the sands came first from a historical event in Japan. ~~In the~~ east coast of Honshu Island, sands preserved in lake sediments were also identified as laid down by a tsunami, generated from the 1983 Sea of Japan Earthquake (Minoura & Nakaya 1991). Older, underlying sands were dated as far back as 2700 years BP, confirming the association between tsunami inundation and earthquake subsidence as observed previously in Cascadia. Further confirmation of the Cascadia and Scottish interpretations of tsunami sand deposition was lacking because of an absence of post-1987 tsunami events. A devastating tsunami struck Flores Island in December 1992 killing 2190 people, over half of

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Fig. 3. Tsunami sediments (pale grey by the handle of the Nejiri-gama) from the east coast of Scotland generated by the Storegga tsunami of 8.2 ka BP. Nejiri-gama 23 cm long (Photograph, D.R. Tappin).

whom died in the tsunami. The Flores tsunami was one of the first investigated by specifically organized, responsive, field surveys (Yeh *et al.* 1993). It was the first of the modern age to include geologists in the field team (Shi *et al.* 1995). The 1991 Japanese research by Minoura and Nakaya was based solely on core samples, but at Flores field surveys reported on both the geomorphology of tsunami impact and the sediments deposited (Shi *et al.* 1995; Minoura *et al.* 1997). For the first time, there was a direct correlation between an observed tsunami and the sediments deposited. Although the Flores surveys were aimed at understanding the sedimentary processes associated with tsunami inundation, they were also planned as the first attempt to use a recent event to improve the identification and interpretation of older, palaeotsunami deposits (Shi *et al.* 1995).

Scientific objectives

Two primary objectives of sedimentological research emerged from the early tsunami studies. The first was to establish unequivocal sedimentary characteristics of tsunami deposits that would allow their discrimination from other, high-energy depositional mechanisms such as storms (e.g. Shi *et al.* 1995; Dominey-Howes *et al.* 2006). The second was to use these sedimentary characteristics to identify older, prehistoric sediments. Identification of ancient, prehistoric tsunami sediments as a record of older events, together with their reliable age dating, would allow the quantification of tsunami recurrence intervals, improving tsunami hazard and risk assessment. Initially, discrimination of fine-grained tsunami sediments was based on simple criteria such as the extent of deposits, landwards grain-size fining and deposit thinning (fine-grained tsunami sediments were normally graded and storm deposits laminated), and rip-up clasts were significant (Morton *et al.* 2007). Discrimination of coarser-grained, boulder deposits was from imbrication and boulder orientation. There were also the first attempts at mathematical modelling of boulder transport (Moore & Moore 1988; Nott 1997, 2003; Weiss 2012).

Based on the analysis of sediments from more recent events, such as PNG and the Indian Ocean, objectives that are more ambitious were identified. Detailed grain size analysis of tsunami deposits from PNG for the first time were used to model onshore flow depth and speed, from which tsunami size could be quantified (Gelfenbaum & Jaffe 2003). The results were to provide the key for long-term hazard assessments based on tsunami source mechanisms (e.g. earthquake fault slip or submarine landslides) inverted from calculated tsunami wave characteristics. After the Indian Ocean tsunami of 2004, based on the new and developing quantitative approaches developed first for PNG Huntington *et al.* (2007) identified two further key challenges: (1) closing the knowledge gap in linking modern events to their deposits with an improved understanding of tsunami sediment transport; and (2) adapting this relationship to better interpret the geologic record.

Early advances (1990s–2004)

From the early 1990s there was a steady increase in research on tsunami deposits as reflected in the number of peer-reviewed papers published (see Bourgeois 2009, fig. 3.2). The research was from responsive field surveys, which became the norm after the Nicaragua tsunami of 1992 (Satake *et al.* 1993), but also because of continued work on seminal events such as Storegga and in the Hawaiian Islands. The focus was mainly on the convergent margins of the NW Pacific and Japan, and the north Atlantic passive margin. Research in other areas where the hazard is significant, such as New Zealand, was constrained because of the challenges in proving the tsunami sediment provenance (Goff *et al.* 2001). The experience gained from the early studies on Cascadia and Storegga and more recent events (e.g. Flores in 1992) was used to research older historical events including Lisbon in 1755 (Dawson *et al.* 1995), Grand Banks in 1929 (Tuttle *et al.* 2004; Moore *et al.* 2007) and events in New Zealand (Goff *et al.* 2001). In Cascadia, further research identified six major earthquakes over the past 7 ka, three of which at least were associated with tsunamis. During the past 3.5 ka, there were seven extensive tsunamis (Atwater & Hemphill-Haley 1997; Peters *et al.* 2007). At some locations, the record extended back to 14 ka BP, with three events older than 3.5 ka (Peters *et al.* 2007). Research on the Storegga tsunami confirmed previously established relationships between the landslide and the sediments in Scotland. This was based on additional evidence from sediments preserved in elevated lakes in Norway (Bondevik *et al.* 1997*a*, 2005*a*) and in the Faeroe Islands (Grauert *et al.* 2001). At the end of the period 1990–2004, the study of tsunami sediments had expanded from a few publications based on circumstantial relationships between cause and effect (as with Cascadia and Storegga) to the reporting of recent events validated by observations of tsunami inundation. The tsunami record at some locations now extended back beyond historical reporting. Preliminary identification of simple sediment characteristics led to optimism that, with time, absolute criteria would be identified for discrimination of tsunami deposits from other high-energy mechanisms of deposition.

Considering the limited published research, there were a large number of review papers (Bourgeois 2009). New terms, such as tsunamites, were introduced to describe the sediments, although these were later subject to some controversy over their definition (Shanmugam 2006). There were several special journal issues produced (Einsele 1996; Shiki *et al.* 2000), and an edited book was in preparation (later published as Shiki *et al.* 2008). Then the most catastrophic tsunami ever generated struck in the Indian Ocean.

Catastrophic events, advances and controversy: post-2004

The Indian Ocean tsunami led to major advances in tsunami sediment science because it generated a major surge in research. Observations of the tsunami flooding the land confirmed the sedimentary evidence for the tsunami source of the coastal sediments deposited. The Indian Ocean tsunami was the largest recorded event where there was a positive association between inundation and deposition. The responsive tsunami surveys carried out since 1992 (on Nicaragua) provided the basis for the management of the Indian Ocean field surveys which, carried out over the whole region impacted, provided a comprehensive database of the tsunami impact. An even greater surprise than the Indian Ocean tsunami was the Japanese event of 2011. Japan had the most sophisticated mitigation and response strategies of any country in the world in contrast to the Indian Ocean where there was no warning system, yet 19 000 people died. The research on the Indian Ocean tsunami resulted in improved understanding of qualitative depositional mechanisms, whereas the advances from Japan were quantitative. Although the advances from these events (and other smaller events) were significant; the original objectives identified above – tsunami deposit discrimination and its use in identifying older deposits – were not quite as successful as envisaged. Sedimentary characteristics have been identified, but absolute characterization of tsunami deposits has not been achieved (Shanmugam 2012). Coarser-grained (boulder) deposits have been especially difficult to characterize (Morton *et al.* 2006).

Sedimentary characteristics of fine-grained, tsunami sediments are now being used more effectively to estimate flow velocities from which wave magnitudes are derived. Preliminary studies (e.g. Jaffe *et al.* 2011; Sugawara *et al.* 2012; Tang & Weiss 2015) show that inverse modelling of these characteristics can be used to identify tsunami-generation mechanisms (MacInnes *et al.* 2010; Sugawara *et al.* 2012). However, palaeotsunami magnitudes and inflow characteristics derived from inverse numerical models, such as TsuSedMod (Jaffe & Gelfenbuam 2007; Spiske *et al.* 2010), are dependent on the successful discrimination of inflow from backflow deposits (Bahlburg & Spiske 2012). Most studies are of tsunami deposits from earthquakes; there are still only a few descriptions of deposits from submarine landslides (Dawson *et al.* 1988; Bondevik *et al.* 2003; Gelfenbaum & Jaffe 2003). Submarine landslide deposit research is still focused on Storegga and their sediments deposited on the coastlines of the north Atlantic (e.g. Bondevik *et al.* 2005*a*).

Intensive studies of the catastrophic Indian Ocean, 2004 and Japan, 2011 events show that previously proposed ‘simple’ discriminants described above are not necessarily unique to tsunami sediments; they may also be found in storm deposits. The assumption that tsunami sediments are only deposited from suspension settling (giving fining-upward beds) has given way to the recognition that they also result from bedload (traction) transport (giving laminated sediments), which compromises previous discrimination (Paris *et al.* 2007). Commonly deposited sediments during both the Indian Ocean and Japan events were laminated (from traction currents; Paris *et al.* 2007; Szczuciński *et al.* 2012). In addition, marine microfossils (diatoms and foraminifera), previously considered characteristic of tsunami sediments as in the Indian Ocean (Sawai *et al.* 2009), were rarely found in sediments from the Japan 2011 tsunami (Szczuciński *et al.* 2012). Without observational evidence of tsunami inundation, the identification in isolation of ‘absolute’ sedimentological criteria that allow identification of a palaeotsunami sediment does not yet seem possible.

Despite the recognition that simple discriminatory criteria are not as ‘absolute’ as previously proposed (e.g. Morton *et al.* 2007), there have been major advances in characterizing fine-grained sediments and the controls on deposition. Tsunami deposits vary because controls on sedimentation are richly variable. These controls include: (1) coastal and nearshore morphology; (2) the elevation of tsunami waves at the coast; (3) run-up (maximum inland elevation reached by the inundation); (4) the nature and amount of the sediment available for erosion; and (5) the preservation potential of the sedimentary imprint laid down during inundation. As a result, tsunami deposits are complex. There is positive news, however. Whereas there may not be absolute distinguishing sedimentological criteria that can be extrapolated between different locations, at any single location it is possible to discriminate between tsunami and storm deposits where both are present (e.g. Nanayama *et al.* 2000; Goff *et al.* 2004; Tuttle *et al.* 2004; Switzer *et al.* 2005). Research on the sediment history of tsunamis at individual locations can be used in improved understanding of event recurrence and frequency, as in Cascadia and Japan (Atwater & Hemphill-Haley 1997; Minoura *et al.* 2001; Ishimura & Miyauchi 2015). The surveys focused on the catastrophic events in the Indian Ocean and Japan yielded major advances in understanding of the (mainly) fine-grained sediments deposited, but also boulders. With the Indian Ocean tsunami, understanding was improved on characterizing the sediments and investigating their preservation and alteration over time. With Japan, the advances were in the geochemical characterization of the sediments and their use in numerical models (see 'Tsunami sediments in numerical modelling' below). In both instances, the focus was also on characterizing the deposits to provide valid diagnostic criteria to help identify palaeotsunami deposits at specific locations, from which the tsunami hazard at the location is better understood (Jankaew *et al.* 2008; Sugawara *et al.* 2012).

Analysis: new technological developments

Sedimentological analysis of deposits has advanced considerably, but new analytical techniques provide additional methodologies to support classical approaches. The use of geochemical profiling ('toolkits') of recent deposits has advanced considerably (Chagué-Goff *et al.* 2011, 2012). For example, geochemical analysis of soil profiles landwards of the limit of sand deposition now allow the maximum extent of tsunami inundation to be identified (e.g. Goto *et al.* 2011; Chagué-Goff *et al.* 2012). There are constraints with older deposits, however, where the use of geochemistry may be limited because of poor sediment preservation and post-depositional alteration (taphonomy) and reworking by rainfall, wind action, bioturbation and human activity (Szczuciński 2011, 2013). Other developing branches of study on tsunami sediments include the use of heavy minerals in their characterization, anisotropy of magnetic susceptibility (AMS) and X-ray tomography. Analysis of heavy minerals is now being used to discriminate tsunami deposits from other high-energy depositional mechanisms such as storms (e.g. Costa *et al.* 2017). AMS provides the sedimentary fabric of the tsunami deposits from which flow directions are identified. There are still too few events studied, but this technique has been used successfully on sandy deposits in northern Sumatra from the Indian Ocean tsunami (Wassmer *et al.* 2010) and pyroclastic volcanic deposits from the Krakatau eruption of 1883 (Paris *et al.* 2014). X-ray tomography is the most recent development, but has only been used on sandy deposits from the Lisbon tsunami of 1775 (Falvard & Paris 2017). It allows the characterization of grain-size distribution, structures, component analysis and sedimentary fabric of fine-grained unconsolidated tsunami deposits at resolutions down to particle scale. The results are validated by comparing to data obtained using other techniques such as laser diffraction, AMS and X-ray microfluorescence.

Numerical modelling

The study of deposits from the PNG, the Indian Ocean and Japan tsunamis has resulted in improved insights into the processes and forces acting during tsunami inundation based on the hydrodynamic characteristics of the tsunami that control sediment deposition (Jaffe & Gelfenbaum 2002; Spiske *et al.* 2008; Witter *et al.* 2012). Numerical inverse modelling, however, is still at an early stage of development and a more general physical understanding of hydrodynamic processes and their interplay with sediment is required to advance this approach (Cheng & Weiss 2013). For instance, studies of the deposits may be used to assess the tsunami flow velocity and the depth of tsunami inundations. As noted above, however, inflow and backflow deposits have to be reliably identified for the numerical models to be valid. Notwithstanding, tsunami sediments have been used to identify their earthquake source mechanisms. On the west coast of Kamchatka, alongshore distribution of tsunami sediments was used to discriminate between two earthquakes that took place in 1969 and 1971 (Martin *et al.* 2008). A study of the Kamchatka earthquake tsunami of 1952, based on the variable distribution of tsunami deposits, resulted in new models of earthquake slip (MacInnes *et al.* 2010).

The major scientific response to the Indian Ocean tsunami resulted in impacted coastlines being researched for tsunami sediments (e.g. Borrero 2005; Kench *et al.* 2006; Paris *et al.* 2007; Goto *et al.* 2008*a*; Morton *et al.* 2008). The devastating Japan tsunami of 2011 resulted in the acquisition of an extensive and comprehensive dataset of the sediments deposited. It provided another major opportunity to improve understanding of tsunami sedimentation and its use in mitigation (e.g. Goto *et al.* 2011; Szczuciński *et al.* 2012). The response to the coastal inundation was the most intensive of any previous event, with both national and international teams involved in field studies (e.g. Goto *et al.* 2011; Mori *et al.* 2011). From the Japanese field surveys, there were a number of new insights into tsunami sediment deposition: (1) tsunami inundation much greater than the depositional limit of sand; (2) geochemical analysis of muddy sediments that identify tsunami inundation beyond the limit of sand deposition; (3) a minor component of marine microfossils in tsunami sediment; (4) coarse gravel deposits thicker than sands; and (5) varied beach erosion, limited in some areas but intense in others

(Goto *et al.* 2011). These new observations formed the basis for improved understanding of older deposits preserved in the region of the 2011 inundation. One of the most devastating older historic events was the Jogan tsunami of 869. Comparison between the sediments from the two events (Minoura *et al.* 2001) showed the inland inundation of Jogan to be far greater than previously recognized. In addition, from inverse modelling of the deposits the 869 earthquake magnitude was re-evaluated and found to be much greater than previously estimated (Sugawara *et al.* 2013). The result was a major advance in understanding earthquake frequencies. The Japan, 2011 event therefore offered an important opportunity to improve: (1) how inland inundation can be identified; (2) the methodology of using inversion of sedimentary data to establish the 2011 earthquake rupture magnitude and extent; and (3) existing models of older, comparable, events in the same region (Sawai *et al.* 2012; Sugawara *et al.* 2013). The scientific advances were both qualitative (e.g. Goto *et al.* 2011) and quantitative (Sugawara & Goto 2012; Sugawara *et al.* 2014).

Boulder/gravel deposits

Tsunamis deposit individual boulder trains and boulder groups (Goto *et al.* 2007; Ramalho *et al.* 2015) as well as boulders entrained in finer-grained sediment (Paris *et al.* 2004; Yamada *et al.* 2014). The first attempts to understand the hydrodynamic mechanisms of deposition of both types of deposit were by Nott (1997); there are still uncertainties however because boulders are moved differently by storms and tsunamis, resulting in different deposit characteristics (Weiss 2012). Discrimination of tsunami boulder deposits from storm deposits is problematic (Felton 2002; Hall *et al.* 2006; Morton *et al.* 2006), but recent work suggests that tsunamis produce disorganized boulder deposits whereas, storms organize boulders along lines and clusters (Goto *et al.* 2010*b*; Weiss 2012). Individual boulders cast ashore have been used to identify tsunami impact (Goto *et al.* 2010*b*) as well as in validating tsunami-generation mechanisms and their magnitude (Moore *et al.* 1995; McMurtry *et al.* 2004*a*). As with fine-grained sediments, discrimination is possible where both storm and tsunami deposits are preserved at the same location (Goto *et al.* 2010*b*).

Boulder deposits of tsunami origin first described as far back as 1933 from eastern Scotland are coarse-grained conglomerates attributed to earthquake-triggered landslides, which were reworked by an ensuing tsunami (Bailey & Weir 1933). Subsequent research by Pickering (1984) proposed only a fault-scarp origin for the deposits, but surprisingly did not cite the earlier 1933 paper. This is unfortunate, because the opportunity to reconsider the previous interpretation of a tsunami origin in the context of improved sedimentological understanding was missed. Interpretation of other boulder deposits has also been controversial, for example discrimination between recent storm and boulder deposits on the Aruba, Bonaire and Curaçao (ABC) islands in the southern Caribbean (see Morton *et al.* 2006).

Some of the most controversial coarse-grained tsunami deposits are in the Hawaiian Islands. Here, boulders and marine gravels up to 200 m above present sea level (Fig. 4) are attributed to tsunamis from volcanic flank collapse (Moore 1964; Moore & Moore 1984, 1988; Moore *et al.* 1989). The deposits were first interpreted as marine highstands (Stearns & Macdonald 1946; Stearns 1978), then as tsunami deposits (in the Moore papers) and then again as highstands (Rubin *et al.* 2001). The best-preserved deposits are on Lanai Island, and recent interpretations attribute their origin to the last two interglacial highstands at 120 and 240 ka BP (Grigg & Jones 1997; Felton *et al.* 2000; Rubin *et al.* 2000). A problem in interpreting the origin of the deposits is the similarity between the ages of the highstands and the triggering of the landslides. The submarine landslides from volcanic collapse are probably triggered at the end of glaciations, at which time sea levels were rising rapidly (McMurtry *et al.* 1999; Quidelleur *et al.* 2008). The origin of the deposits are therefore quite complex. The importance in establishing the origin of the Hawaiian gravels is two-fold: (1) to prove (or not) the tsunami hazard from the volcanic collapses mapped offshore the islands (Fig. 5); and (2) to validate tsunami run-up elevations from the numerical models of volcanic collapse (McMurtry *et al.* 2004*b*, fig. 3). The controversy over the origin of the deposits (from highstands or tsunamis) compromises their use in identifying the tsunami-generating potential from volcanic collapse.

The basis of the controversy over the interpretation of the Hawaiian deposits is the uncertainty in the elevations of the islands when the sediments were deposited. The flank collapses (and sediments) are thousands to hundreds of thousands years old. The elevations of the Hawaiian Islands have changed since these deposits took place; some have been uplifted whereas others have subsided. Only the Big Island has a well-established vertical tectonic history, which shows subsidence for hundreds of thousands of years (Ludwig *et al.* 1991). The elevation of the sediments at their time of deposition is calculated from their age, present elevation and the known subsidence rate of the island. In the north of the Big Island at Kohala, coralliferous gravels are now at sea level. These deposits

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Fig. 4. Tsunami sediments from Lanai Island, Hawaii deposited from large-scale volcanic flank collapse. Note the two coarsening-upwards cycles. Geological hammer 40 cm (Photograph, D.R. Tappin).

are dated at 120 ka BP, the same age as the Alika 2 landslide just offshore (Fig. 5). Alika 2 is the most likely source of the tsunami which laid the deposits down (McMurtry *et al.* 2004*a*). Since deposition 120 ka ago, Hawaii has been subsiding at a rate of 3.4 mm a^{-1}. The elevation of the sediments at time of deposition was therefore ~400 m above present sea level. Numerical tsunami modelling of the failure of the Alika phase-2 giant submarine landslide results in tsunami run-ups of hundreds of metres on Hawaii and Lanai (McMurtry *et al.* 2004*b*, fig. 3). The most recent evidence from the Big Island therefore confirms that the deposits are indeed from a tsunami hundreds of metres in elevation. The fringing coastal (? tsunami) deposits on both Hawaii and Lanai are compositionally very similar. It therefore seems likely that the explanation for the gravels at both locations (The Big Island and Lanai), at least for the youngest deposits dated at 120 ka BP, is a tsunami generated during postglacial volcanic collapse.

Individual boulders without associated finer-grained sediment are common along many shorelines, and have the potential to improve tsunami hazard assessment. As with fine-grained tsunami deposits, however, there is considerable controversy over their discrimination from the other potential depositional mechanisms such as storms, especially where both storms and tsunamis affect the same coast (Hearty 1997; Noormets *et al.* 2002; Mastronuzzi & Sanso 2004; Mylroie 2008; Switzer & Burston 2010; Weiss & Diplas 2015). The elevation of the deposits is an important discriminant (Ramalho *et al.* 2015) but local tectonic history needs to be established to avoid conflict, such as in Hawaii (Rubin *et al.* 2000; McMurtry *et al.* 2004*a*). Apart from boulder elevations, there are geomorphological and sedimentological methodologies proposed that might discriminate between the different mechanisms (e.g. Morton *et al.* 2006; Spiske *et al.* 2008; Goto *et al.* 2010*a*). Unfortunately, there are still too few case studies based on a systematic sedimentological approach to deposit analysis to formulate robust criteria for distinguishing between coarse-clast storm and tsunami deposits (Morton *et al.* 2006).

Submarine landslide tsunami

The potential for submarine landslides to generate tsunamis has been known for over 100 years (Milne 1898; Montessus de Ballore 1907; Gutenberg 1939), yet most research has been on

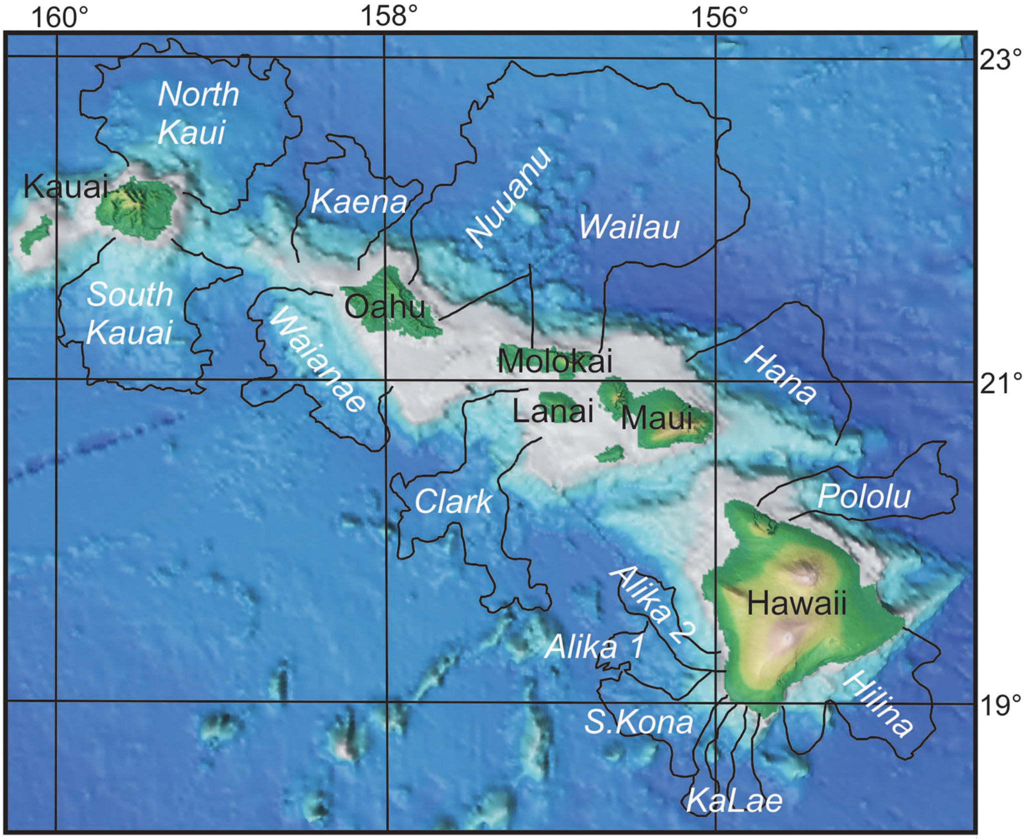

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Fig. 5. Hawaiian seabed morphology and locations and extents of the Giant Submarine Landslides as mapped by Moore *et al.* (1989) (From Tappin, 20[illegible]).

mechanisms of failure (Piper *et al.* 1987; Talling *et al.* 2007; Masson *et al.* 2009; Talling 2014) and very little published on their potential to generate tsunamis (Masson *et al.* 2006). Significant proven historical submarine landslide-generated tsunamis before 1998 include those of the Grand Banks in 1929 (Heezen & Ewing 1952), Nice in 1979 (Assier-Rzadkiewicz *et al.* 2000; Dan *et al.* 2007) and Skagway in 1994 (Kulikov *et al.* 1996; Rabinovich *et al.* 1999). Both Nice and Skagway landslides were probably triggered by human impact, although the tsunami mechanisms are controversial. Both these events came sharply into focus after the PNG tsunami (Synolakis & Bernard 2006). Other controversial events include the tsunami generated by the earthquake of 1946 in the Aleutians, where the 40 m local run-ups were most probably from a local submarine landslide triggered by the earthquake (Fryer *et al.* 2004; Okal & Herbert 2007; von Huene *et al.* 2014). The 1945 tsunami in the Indian Ocean off Pakistan is a similar event to the Aleutians in 1946 (e.g. Heidarzadeh *et al.* 2008), but no submarine landslide has been found or, indeed, even looked for. The tsunamis generated by the earthquake of 17 August 1999 at Izmit, Turkey are also probably associated with submarine landslides (Altinok *et al.* 2001).

The best-known historical submarine landslide tsunami before PNG was in 1929 on the Grand Banks, Canada but surprisingly, considering the importance of the event, most research has been on the landslide (e.g. Piper & Asku 1987) and earthquake (e.g. Hasegawa & Kanimori 1987) and not the tsunami. Only one paper is published on numerical tsunami modelling of the submarine landslide (Fine *et al.* 2005), but this is based on a theoretical mechanism. The most significant prehistorical tsunami from a submarine landslide is Storegga which, because of the discovery of the Ormen Lange Gasfield, is also the best studied. Research on tsunamis generated from volcanic collapse has identified another submarine landslide mechanism, analogous to clastic sedimentary events. However, volcanic collapse tsunamis, even those in the Hawaiian Islands, have not generated as much interest in their hazard to the same degree by which PNG raised the profile for non-volcanic submarine landslides. The exceptions are the Canary Islands landslides perhaps, which have had a consistently high media profile because of their potential to generate high-elevation, 'megatsunamis' in the far field, which could be a significant hazard to the east coast of the USA (Ward & Day 2001; Gisler *et al.* 2006; Løvholt *et al.* 2008; Hunt *et al.* 2013; Tehranirad *et al.* 2015). A point to note is that the Hawaiian collapses are submarine, whereas those in the Canary Islands are partly sub-aerial. Because of their retrogressive failure mechanisms however, which initiate on the seabed, the Canary Island collapses are included here. The Canary Island collapses are analogous to those of the Hawaiian volcanoes but smaller in volume which, together with their multistage, bottom-up collapse mechanisms proposed for the largest events such as those on Tenerife (Hunt *et al.* 2011), suggest that elevated tsunami wave heights could be more localized and concentrated near to source. Recent numerical tsunami modelling indeed suggests that, in the far field, frictional effects of propogation over the wide US coast shelf significantly reduces their onshore impact, although the volumes used in tsunami generation may be small (Tehranirad *et al.* 2015) and possibly underestimated (Simon Day, pers. comm., 2016).

The impact of Papua New Guinea, 1998

It was not until 1998 in PNG, when over 2200 people died in a tsunami now recognized as generated from an offshore seabed sediment failure (Kawata *et al.* 1999; Tappin *et al.* 1999), that the hazard from submarine landslide tsunamis was fully recognized (Bardet *et al.* 2003; Løvholt *et al.* 2015). The PNG event was the first investigated by a responsive programme of marine surveys (Fig. 6), and scepticism greeted the initial results (e.g. Geist 2000). The landslide architecture was constructed from the marine dataset, and for the first time used as the basis for realistic numerical models of tsunami generation (Tappin *et al.* 1999, 2001, 2008). Although the hazard from submarine landslides is now more generally recognized, the marine surveys required to map the submarine landslide hazard are expensive so only a few countries have so far carried these out to the degree necessary to fully identify the hazard (e.g. Grilli *et al.* 2009; ten Brink 2009; Clarke *et al.* 2014).

How submarine landslides generate tsunamis

Before PNG, simulations of tsunami generation were mainly confined to earthquake sources (Satake *et al.* 1996). Numerical earthquake tsunami-generation

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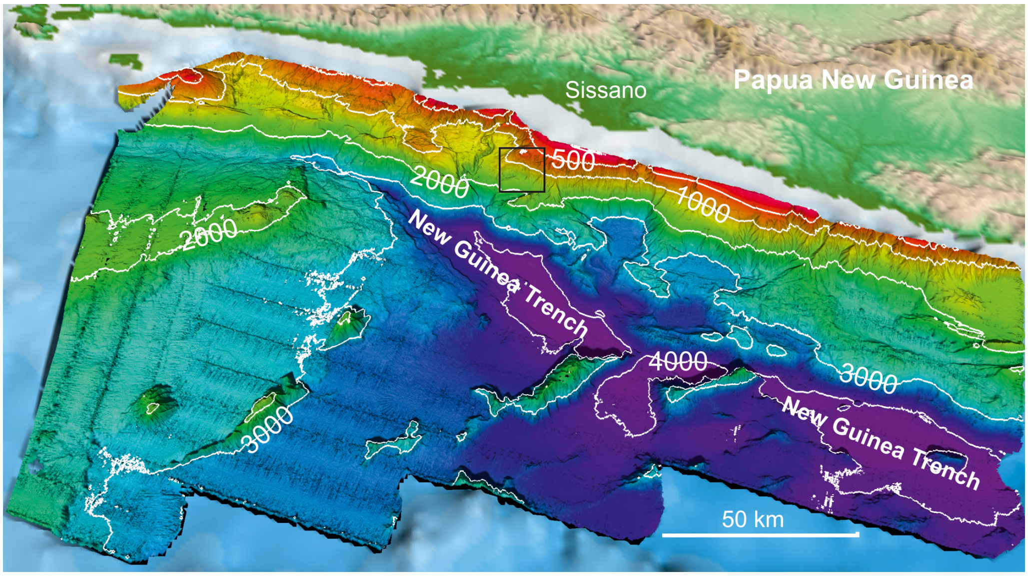

Fig. 6. Papua New Guinea regional bathymetry viewed from the north, showing the convergent margin in the foreground and the Papua land mass to the rear. Depths in metres. Black square the location of Figure 7 (From Tappin, 20

models are based on an assumption that the initial water surface deformation is instantaneous and equal to that at the seabed. For the rise time of most earthquakes, the long-wave phase velocity in the ocean is slow enough so that displacement can be considered instantaneous. There are slight modifications to the tsunami wave field for earthquakes of slow rupture duration (tsunami earthquakes). Seabed deformation is calculated from earthquake fault parameters using theoretical deformation models such as Okada (1985). Underwater landslides were considered to be ineffective at generating significant tsunamis because of their longer source-generation times, smaller areas of seabed disturbance (compared to earthquakes) and the directivity of the tsunami produced (Hammack 1973; LeBlond & Jones 1995; Geist 2000). Before the PNG event, one of the major challenges was in understanding how the relatively slow-moving submarine landslides generate tsunamis.

A further complication in understanding tsunamis generated by submarine landslides is the range of failure mechanisms which vary according to morphology, sediment type and/or kinematics (see Hampton *et al.* 1996; Turner & Schuster 1996; Keating & McGuire 2000; O'Grady *et al.* 2000). Theoretical numerical modelling of submarine landslides was visualized as a Bingham-type fluid flow, analogous to a translational mechanism, where large blocks disintegrated on travelling downslope to form turbidites (Hampton 1972; Geist 2000). Modelling of solid block landslides at the time of the PNG tsunami was in its infancy (Watts 1998). Submarine landslide failure is dependent mainly on sediment composition, which controls landslide morphology and kinematics. Numerical tsunami-generation models were initially based on depth-averaged wave equations that represented immiscible liquids or water as a Bingham plastic (e.g. Jiang & LeBlond 1992, 1994). While depth-averaging accurately applies to tsunami generation from earthquakes, it is questionable when applied to landslide tsunamis because it does not allow for vertical fluid accelerations, important during submarine landslide motion and tsunami generation (Grilli *et al.* 2002). In 1998, landslide constitutive equations used in modelling were largely untested by laboratory experiments or case studies (Tappin *et al.* 2008). Submarine landslide models were idealized, and not based on geological data. There was no established method of merging geological data with numerical landslide models. In total, there was little appreciation of the complexity of modelling tsunamis generated by the different submarine landslide mechanisms. All this was to change because of two major events: one prehistoric and thousands of years old, Storegga; and the other recent and devastating, Papua New Guinea in 1998.

Submarine landslide numerical models

Storegga (8.5 ka BP). The first realistic attempt at numerically modelling a submarine landslide based on a slide architecture from seabed morphology was Storegga (Harbitz 1992). Validation of the tsunami generated was from run-up recorded in coastal sediments deposited on the east coast of Scotland (Fig. 3; Dawson *et al.* 1988; Long *et al.* 1989) and uplifted lake sediments in the west of Norway (Svendsen & Mangerud 1990). The landslide modelled was translational, moving at velocities of 20–35 m s^{-1} which were taken from measurements of the Grand Banks tsunami of 1929 (Heezen & Ewing 1952). Three major slide events were modelled: the first and third as partially liquefied debris flows; and the second retrogressive failing from the bottom upwards. Individual slide volumes were between 1700 and 3880 km^3. Average slide thicknesses used were between 88 and 114 m. The recorded run-up heights of 4 m on the east coast of Scotland were best reproduced by slide velocities of 35 m s^{-1}. The 1992 paper was a benchmark in tsunami numerical models as it was based on both a realistic landslide model and run-up data measured from sediments deposited on land. The numerical model was a major advance at the time, because only a few earthquake tsunamis had been simulated and the controls on tsunami generation by landslide architecture were not recognized. Submarine landslide tsunamis were only identified along two ocean margins: Storegga (Norway) and Grand Banks (Canada). In 1992, there were no numerical models of the Grand Banks tsunami.

Subsequent numerical models of Storegga post-dated the PNG event (Bondevik *et al.* 2005*a*; Hill *et al.* 2014) and made significant improvements on the 1992 results of Harbitz as they were based on a more comprehensive dataset of geophysics and coring of the landslide (Bryn *et al.* 2005). The motivation to investigate Storegga was not the 8.2 ka BP tsunami, but to ensure that exploitation of the underlying Ormen Lange gas field would not create another hazardous submarine landslide similar to the 8.2 ka BP event (Bryn *et al.* 2005). Validation of later numerical models was based on a more extensive dataset of tsunami run-up data from Norway (Bondevik *et al.* 1997*a*, *b*), Faroe Islands (Grauert *et al.* 2001), Shetland Islands (Bondevik *et al.* 2003, 2005*b*) and mainland Scotland (Smith *et al.* 2004, 2007). With the later numerical models based on improved landslide architecture, maximum tsunami run-ups on the Shetlands increased to 20 m which agreed with new studies on the elevations of tsunami sediments on the islands (Bondevik *et al.* 2003). Sea levels were much lower when the Storegga landslide took place (8.2 ka BP) than at present. The sea-level curve for the Shetlands is still uncertain, so these run-up elevations are most probably still underestimated.

The later numerical models of the Storegga tsunami also used a more comprehensive geotechnical and morphological dataset from the landslide (Forsberg 2002; Haflidason *et al.* 2005). These confirm that the Storegga failure mechanism was retrogressive, with large block failure initiated at the base of the slide at a water depth of *c.* 1000 m. The time lag between the individual block failures as the slide retreated landwards is a major control on tsunami generation (Bondevik *et al.* 2005*a*; Løvholt *et al.* 2005). Tsunami run-up elevations from sediments preserved at the different locations constrains the timing of block slide development. The shape and volume of the modelled slide used by Harbitz (1992) were adjusted until they fitted the new and much more detailed slide reconstruction. Modelling of Storegga was not just to simulate the tsunami, but also to establish the slide mechanics and triggering (Kvalstad *et al.* 2005). In the revised slide model the maximum thickness (400 m) of the slide is near the upper headwall, gradually becoming thinner towards the slide front in the offshore direction. The slide volume generating the tsunami is estimated to be 2400 km^3. The Storegga slide is probably the best studied of any tsunami from a translational-type failure mechanism.

Papua New Guinea tsunami (1998). The PNG tsunami struck during the initial development of the Ormen Lange gas field in 1998. PNG was an important precursor to the Indian Ocean tsunami of 2004 because the loss of life was greater than from any previous recent event. It resulted in a major revision in understanding of tsunami-generation mechanisms from submarine landslides; in this context it is second only in importance, although the generation mechanisms are different. Identifying the mechanism of the PNG tsunami required marine geophysical and geological data and, as with tsunami sediments, it utilized the expertise of geologists (Tappin *et al.* 1999, 2001, 2008). PNG also provided an important context to the identification of tsunamis from tsunami earthquakes (Kanamori 1972), where the associated tsunami is much larger than expected from the earthquake magnitude. It showed that although an earthquake might be small it might not be slow, and the tsunami mechanism could alternatively be from a submarine landslide. The discrimination between tsunamis generated by 'tsunami' earthquakes and submarine landslides is still uncertain, as initially suggested by Kanamori (1972) and further supported by events such as Java in 2006 (e.g. Kanamori 1972; Fritz *et al.* 2007).

The earthquake magnitude of the PNG event was small in comparison to the 10–15 m high tsunami that devastated the coast around Sissano Lagoon. It was not a 'tsunami' earthquake based on Newman & Okal's (1998*a*, *b*) discriminant of E/M0 (E/M0 is the ratio between high-frequency energy E and low-frequency seismic moment M0), because it did not have the required 'slow' source characteristics. Several other aspects of the event also suggested the earthquake was not responsible for the tsunami. The aftershock distribution indicated a shallow-dipping thrust (McCue 1998; Hurukawa *et al.* 2003) rather than a steeply dipping event necessary to generate the recorded tsunami. The peaked run-up distribution along the coast suggested a local focused source rather than the broad source usually associated with an earthquake tsunami. The 20 minute time lag between the felt earthquake and the tsunami striking the coast did not agree with an epicentre located just offshore. The tsunami in the far field was very small and undoubtedly generated from the earthquake (Kikuchi *et al.* 1999), but it seemed unlikely that the local tsunami was from this mechanism.

All evidence therefore initially converged on a submarine landslide mechanism located close offshore. This conclusion was highly controversial (e.g. Geist 2000), so marine hydroacoustic and sampling surveys were required for confirmation. For the first time after a major tsunami, responsive marine surveys funded by Japan and the USA acquired a comprehensive hydroacoustic dataset with some sediment sampling off northern PNG (Tappin *et al.* 1999, 2001; Sweet & Silver 2003). The hydroacoustic data comprised over 19 000 km^2 of multibeam bathymetry (Fig. 6), 4.2 kHz high-resolution, sub-bottom seismic lines (SBSL), and both single (SCS) and multichannel seismic (MCS) data. In the region of the landslide, four 7 m long sediment piston cores were recovered together with numerous shallow (30 cm) push cores of sediment, rock samples and marine organisms. Still and video photography of the seabed were acquired from a tethered remotely operated vehicle (ROV) and a manned submersible (MS).

Before the surveys, a translational landslide was proposed as the most likely tsunami mechanism (e.g. Geist 2000) and the first published numerical models were based on this mechanism (e.g. Heinrich *et al.* 2000). These numerical models successfully reproduced the recorded on-land tsunami elevation data, with the translational landslide treated as a fluid-like flow of a cohesionless granular material (Heinrich *et al.* 2000). From the marine surveys, however, this translational mechanism was shown to be unrealistic because seabed morphology and seismic data revealed a rotational slump (Fig. 7; Tappin *et al.* 1999). Theoretically, slumps by volume generate the largest tsunami (Tappin *et al.* 2008). At the time of the PNG tsunami, theoretical

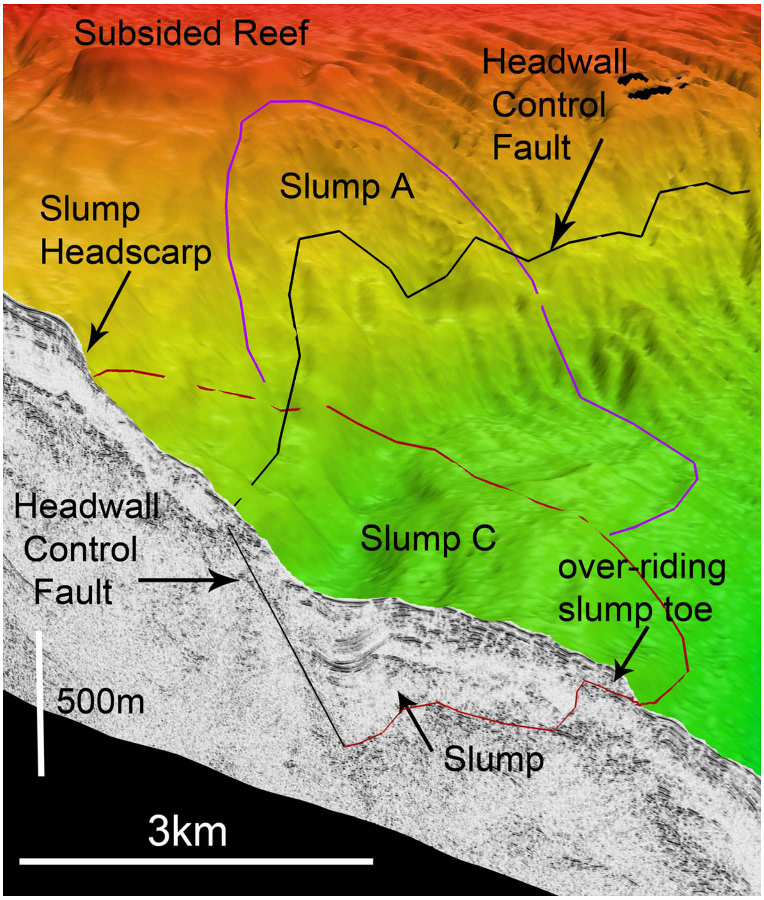

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Fig. 7. 3D cutaway image of the PNG slump C that generated the 1998 tsunami, including a seismic section, viewed from the NE. Vertical exaggeration ×3. Location shown in Figure 6 (from Tappin *et al.* 2008).

numerical models of tsunamis were based on: (1) sliding blocks (e.g. Watts 1997; Grilli & Watts 1999); (2) finite volume discretization–volume of fluids (VOF) of the Navier–Stokes equations (Heinrich 1992); or (3) deformable landslides, with the generated waves governed by the finite volume discretization (Jiang & LeBlond 1992, 1994).

To model the tsunami from the rotational slump, new numerical models were developed based on rotational failure with travel distance being limited (800 m) (Watts *et al.* 2003). The results showed that non-linear and dispersive tsunami propagation models were necessary to model submarine landslide tsunamis, with the shape and motion of a realistic submarine landslide wavemaker defined from marine survey data. This is unlike earthquake tsunamis where numerical wavemaker models are based on ground deformation from fault slip, derived from inversion of seismological, geodetic or tsunami observations (Okada 1985). To identify the landslide mechanism at PNG (see Tappin 2010a) multibeam echosounder (MBES) technology was used to map the detailed seabed morphology, the first time this had been attempted. The MBES data, combined with sub-seabed seismic, led to the construction of the submarine landslide architecture (Fig. 7) that underpinned the numerical wavemaker models. In addition, whereas earthquake rupture models are mainly defined by strike, dip and rake, the failure mechanisms of submarine landslides are many and varied as they are dependent on the nature of the sediment. As well as the differences in initial tsunami wave generation between earthquakes and submarine landslides, there are also significant differences in how their tsunamis propagate. Coseismic displacement from vertical seafloor deformation usually generates tsunamis with longer wavelengths and periods than those generated by landslides, because of their larger source area (Hammack 1973; Watts 1998, 2000). Coseismic displacement generates tsunami amplitudes that correlate with earthquake magnitude (Hammack 1973; Geist 1998) except for tsunami earthquakes; submarine landslides produce tsunamis with amplitudes limited only by the vertical extent of centre of mass motion or the water depth (Murty 1979; Watts 1998).

The first numerical simulation of the PNG slump was devised at sea during the first survey in 1999; it was rudimentary, with many assumptions not validated. Initial tsunami-generation estimates were computed by hand, based on published (or soon to be published) literature (Watts 1998, 2000; Grilli & Watts 1999). The slump architecture was provisional because it was based only on the bathymetric data acquired during the survey (Tappin *et al.* 1999). The tsunami source used was a solid block two-dimensional (2D) underwater landslide (Grilli & Watts 1999). It did not use depth-averaging; instead, it solved fully non-linear potential flow (FNPF) equations which allowed for vertical water acceleration. However, the tsunami propagation simulation used linear shallow-water wave equations. The maximum wave height of 6 m generated by the model was located offshore of the sand spit at the 10 m water depth contour. Although approximating the relative distribution of run-up along the coast, the maximum offshore water height was not of the same magnitude as run-up measured on land by the responsive surveys. Despite these shortcomings, the results were a major advance; not only was it the first time that a landslide-generated tsunami was modelled from a real event, but the modelling was based on MBES data. Comparison with the alternative earthquake-generation mechanism, which gave a maximum wave height at the shore of 2 m based on a shallow-dipping rupture mechanism, demonstrated that it was the slump rather than the earthquake that generated most of the local tsunami.

Subsequently, numerical models improved with the definition of slump architecture (Fig. 8) (Watts *et al.* 1999; Tappin *et al.* 2001). Most recent numerical modelling (Tappin *et al.* 2008) is from a slump modified from the marine survey data that included seismics (Fig. 7). Numerical modelling used an initial condition (wavemaker) using ‘Tsunami open and progressive initial conditions system’ (TOPICS) software that provides the vertical landslide displacements as outputs, as well as a characteristic tsunami wavelength λ_0 and a characteristic tsunami period T_0. To account for the dispersive nature of landslide tsunamis, the Boussinesq propagation models GEOWAVE (Watts *et al.* 2003) and the later development FUNWAVE (Tappin *et al.* 2008) were used. The initial numerical models provided tsunami wave elevations offshore, not on-land run-ups, and the later modelling provided tsunami wave elevations at the coast. This was a significant improvement over earlier simulations using tsunami source and (non-dispersive) shallow-water, wave tsunami propagation models (see discussion in Tappin *et al.* 2008).

Raised awareness after PNG 1998 event

The great loss of life from the PNG tsunami and the demonstration of the non-earthquake mechanism from numerical models were a catalyst to an intense period of research on how submarine landslides generate tsunamis (Synolakis & Bernard 2006). Recognition of the submarine landslide hazard in tsunami generation resulted in increased awareness of these events but also that there were no comprehensive models that covered all aspects of landslide-induced tsunamis from source mechanism, through propagation to coastal inundation. Before the identification of the submarine landslide mechanism of the PNG tsunami, understanding of the mechanics of landslide tsunamis was lacking. After the PNG event, there was a re-evaluation in the USA of other possible submarine landslide events such as Palos Verdes, California (Fig. 9) where the under-prediction of the height of the leading wave led to the dismissal of the local tsunami hazard. PNG also led to the resolution of the dispute concerning the landslide trigger of the 1994 Skagway, Alaska tsunami (Synolakis & Bernard 2006). Marine geophysical data now reveal that submarine landslides are common along most continental margins (Fig. 9), especially those of California, Oregon and the east Coast of the USA. As a result, the level of hazard posed by relatively moderate earthquakes and submarine landslides was re-examined (e.g. Borrero *et al.* 2001, 2004). There was an increased recognition, by both the scientific research and tsunami forecasting communities, that earthquakes affecting oceanic margins frequently trigger submarine landslides (e.g. Geist *et al.* 2009; Grilli *et al.* 2015). Although many of these might not be tsunamigenic in the far field, they had the potential to generate significant local tsunamis, even if the earthquake magnitude was small and not of a sufficient magnitude to generate a significant coseismic event.

Once the landslide mechanism became evident, one of the first responses to the PNG tsunami was the workshop on landslide tsunamis sponsored by the National Science Foundation at the University of Southern California on 10–11 March 2000. The resulting special publication (Bardet *et al.* 2003) recognized that landslide tsunamis require multidisciplinary studies that build upon experience in engineering seismology, geotechnical engineering, marine geology, modelling of sediment deposition

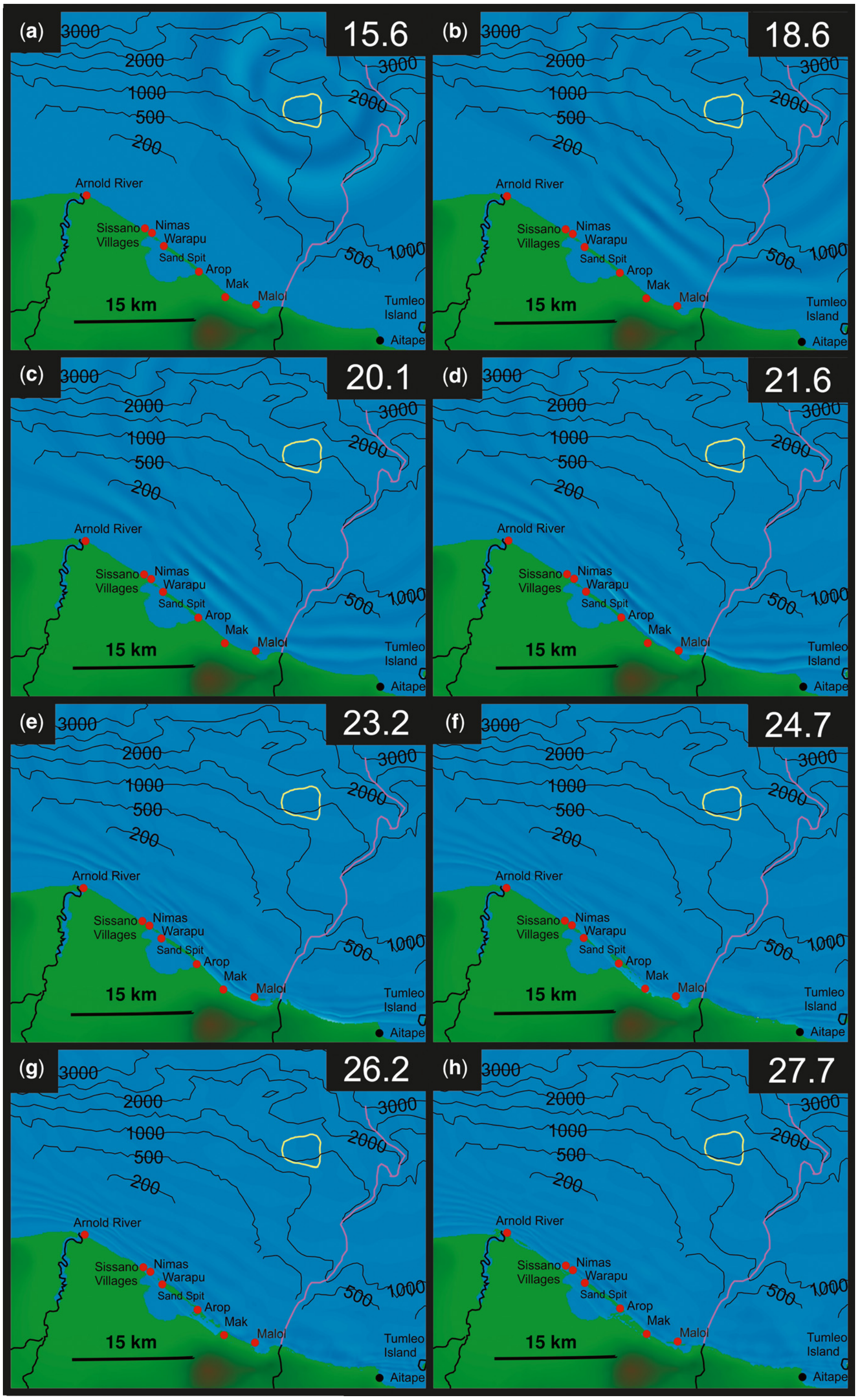

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Fig. 8. Eight snapshots of Papua New Guinea, 1998 tsunami propagation and inundation from a slump source. Light blue are elevation waves and dark blue are depression waves. Numbers in the top right of each image are the tsunami propagation times after the main earthquake shock trigger. The slump location is in yellow (from Tappin *et al.* 2008).

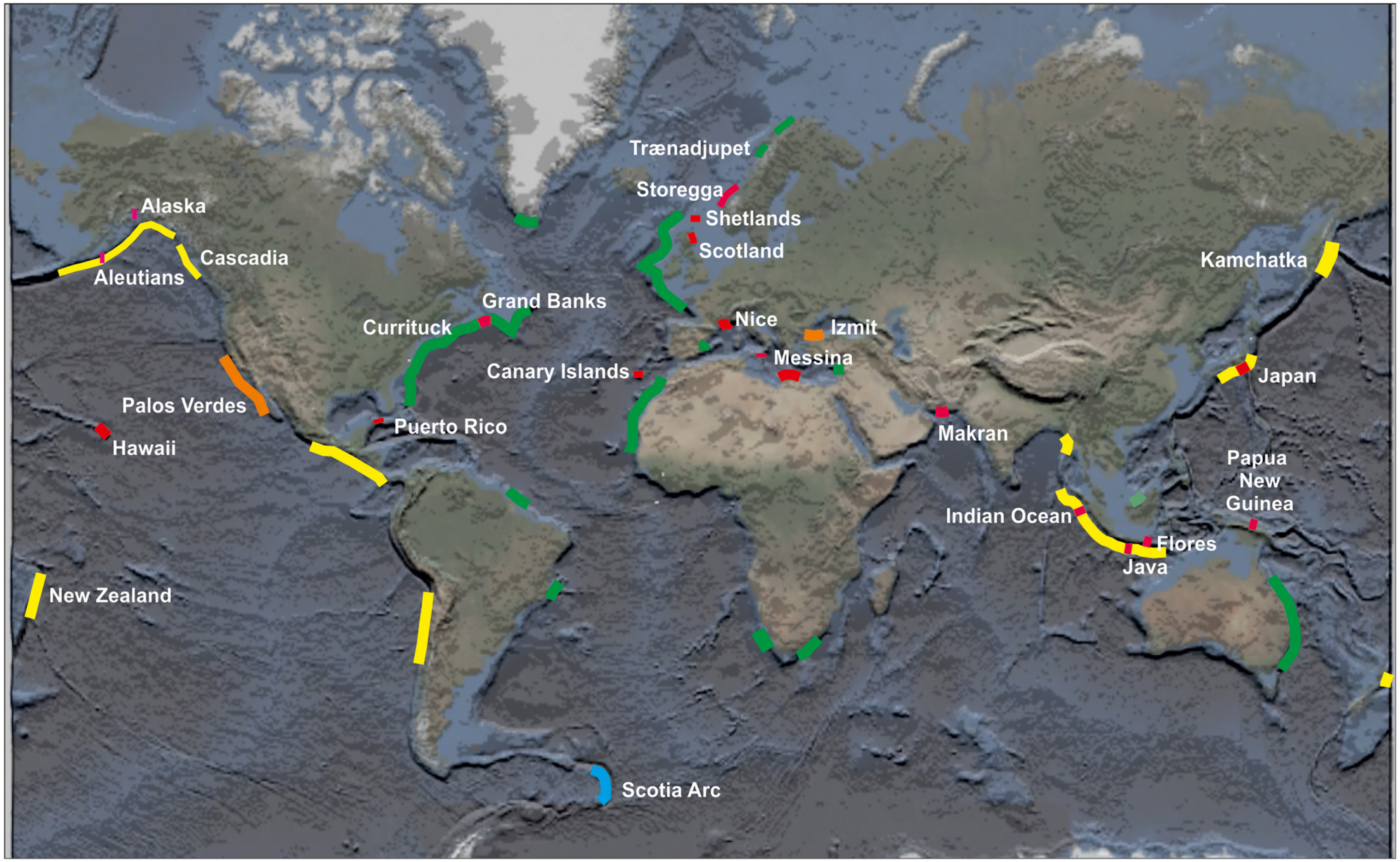

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Fig. 9. Global distribution of mapped submarine landslides. Green lines: landslides on continental shelves and fan systems. Yellow lines: landslides located along convergent margins. Red lines: locations of landslide-sourced tsunamis, or where there may be a landslide contribution. Pale blue lines: volcanoes. Orange lines: landslides along strike-slip margins. Pale yellow lines: landslides along fjord margins. Significant landslides named.

and run-off, and hydrodynamics. Another special publication (Tappin 2007) focused on tsunami sediments. In approximately 35% of all tsunami events studied, nearshore waves from landslide tsunamis could exceed those resulting solely from coseismic ground motions (Watts 2004). In the USA, submarine landslide research programmes resulted in a special issue of the journal *Marine Geology* focused on the tsunami hazard along the east coast of the US (Chaytor *et al.* 2009; Geist & Parsons 2009; Grilli *et al.* 2009; Lee 2009; ten Brink 2009; ten Brink *et al.* 2009; Twichell *et al.* 2009).

Later tsunami landslide research made some significant counterintuitive discoveries. One of the most fascinating was that along the passive margins of the North Atlantic (Fig. 9) the majority of potentially tsunamigenic submarine landslides were found to occur on seabed slope angles of less than 5°, with some of the largest slides failing on slopes of less than 1° (Hühnerbach *et al.* 2004). This evidence on slope failure resulted in considerable conjecture on how submarine landslides fail (Canals *et al.* 2004; Smith *et al.* 2013; Talling *et al.* 2014). Subsequently, there has been a large amount of physical and numerical modelling work devoted to studying tsunamis generated by submarine landslides (e.g. Heinrich 1992; Grilli & Watts 1999, 2001, 2005; Watts 2000; Tinti *et al.* 2001; Ward 2001; Grilli *et al.* 2002; Lynett & Liu 2002; Enet *et al.* 2003; Watts *et al.* 2003, 2005; Locat *et al.* 2004; Enet & Grilli 2005, 2007; Fine *et al.* 2005; Haugen *et al.* 2005; Liu *et al.* 2005; Abadie *et al.* 2012; Ma *et al.* 2013, 2015; Løvholt *et al.* 2015; Smith *et al.* 2016).

Improved understanding after Japan 2011 event

Up until March 2011, PNG remained the only proven catastrophic tsunami generated by a submarine landslide. There were suspicions of a submarine landslide contribution to other events including Java, 2006 (Fritz *et al.* 2007) and the highly focused tsunami at Riangkroko, Flores Islands in 1992, where coastal (sub-aerial) landslides were the probable cause (Yeh *et al.* 1993). Without marine surveys at these locations, their proposed submarine landslide tsunami-generation mechanisms remain unresolved. It was not until the Japan tsunami of 11 March 2011 that exceptionally high (40 m) and focused run-ups along the Sanriku coast on northern Honshu Island, north of the main earthquake rupture, suggested another submarine landslide event in addition to the magnitude M_w 9 earthquake (Tappin *et al.* 2014). Two important aspects of this event suggested a second tsunami mechanism in addition to the earthquake. Firstly, the numerical tsunami simulations from earthquake mechanisms could not reproduce the elevated (40 m) wave elevations recorded along the coast between latitudes 39° 30′ and 40° 15′ N (e.g. Fujii *et al.* 2011). Secondly, even when inverting tsunami waveforms and using dispersive-wave Green's functions, the simulations could not satisfactorily reproduce the timing and high-frequency content of tsunami waveforms recorded at the nearshore GPS buoys located in this area, nor the timing and dispersive-wave train at the Deep-Ocean Assessment and Reporting of Tsunamis (DART) buoy #21418 located 600 km off the coast (Gusman *et al.* 2012; Iinuma *et al.* 2012; Løvholt *et al.* 2012; Romano *et al.* 2012; Grilli *et al.* 2013; Satake *et al.* 2013; Yamazaki *et al.* 2013). These deficiencies were identified by comparison of the tsunami mechanisms from ten earthquake source models, obtained by inverting seismic and geodetic data and tsunami waveforms (see MacInnes *et al.* 2013, fig. 4). This comparison found that none of the mechanisms satisfactorily reproduced the elevations of the recorded run-ups on the Sanriku coast north of latitude 39° 00′ N.

Marine hydroacoustic data of the type previously used to identify seabed failure elsewhere (such as PNG) were available in the region of the Japan earthquake; the area off Honshu Island had been mapped by MBES both before and after the tsunami. From these data, and a limited number of seismic lines, the presence of submarine landslides offshore of the elevated Sanriku run-ups was confirmed (Fig. 10). In addition, in the region of the earthquake there were offshore bottom sensors which recorded the frequency content of the tsunami waveforms. This was the first time that these marine seabed data were available to record a tsunami generated by a large-magnitude earthquake. Analysis of these data provided the potential to discriminate between different tsunami mechanisms, because the wave frequency content of tsunamis from earthquakes and submarine landslides are quite different. Since the wave frequency content of tsunamis from earthquakes is much lower than from submarine landslides, it could be used to identify the submarine landslide location and to validate the numerical tsunami models.

Although a submarine landslide was the most likely second tsunami mechanism, an alternative was out-of-sequence (splay) faulting. There was no evidence for the splay faulting in the published seismic profiling data for the source region (Tsuru *et al.* 2002); however, there was considerable evidence supporting a submarine landslide. Large slumps had been found on the margin of the accretionary prism off the Sanriku coast (Cadet *et al.* 1987; von Huene *et al.* 1994; Tsuru *et al.* 2002). Data from two ocean bottom pressure gauge stations

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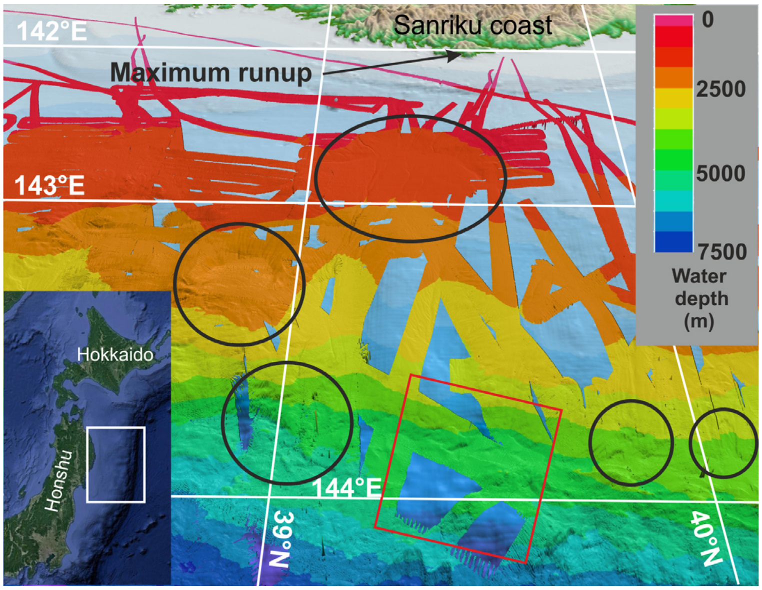

Fig. 10. Japan, 2011. Submarine landslides (black circles/ellipses) in the region off northeastern Honshu Island from bathymetry, viewed from the east. Red square: the location of the landslide triggered by the March 2011 earthquake. Highest elevation observed tsunami run-up/inundation (around 39.5° N) along the Sanriku coast is also marked. Approximate location of this figure shown in inset (From Tappin *et al*. 2014).

TM1 and TM2 off Kamaishi (latitude 39° 12′ N) indicated that at least part of the tsunami source in this region is a narrow area in the deeper part of the Japan Trench (Maeda *et al.* 2011). Seabed movement had been identified in the area of earthquake rupture from before and after bathymetry (Kawamura *et al.* 2012), but this was south of the region of elevated onshore run-ups. Backward ray tracing using the higher-frequency, leading elevation wave from the tsunami recorded by the seabed buoys located offshore of the region of high run-ups identified the most likely location of a submarine landslide that could have generated these. Within this area, north of that identified by Kawamura *et al.* (2012), a number of submarine landslides were identified from bathymetry acquired from before and after the earthquake (Tappin *et al.* 2014). There were few seismic data in this region and none at the location identified by the ray tracing as the potential additionary tsunami source, so subseabed structure was not available to confirm this interpretation. A slope stability analysis confirmed that earthquake shaking could have triggered the landslide. Numerical modelling of a dual earthquake and submarine landslide tsunami mechanism (Fig. 11) demonstrated that in combination they reproduced the waves recorded along the Honshu coast, especially in the north of the inundated area in the Sanriku region (Tappin *et al.* 2014).

Undefined hazard

Extensive mapping of continental shelves reveals the common presence of submarine landslides, although large regions remain unmapped (Fig. 9). At present however, only four significant submarine landslide tsunamis have been mapped, modelled and validated: Storegga, Grand Banks, PNG and Japan (two of which have led to a significant loss of life). For volcanoes, only the flank collapse of Alika 2 on the Big Island of Hawaii is well studied; the tsunamis from the Canary Island volcanoes remain controversial.

Regarding passive margins, the best-studied region is the North Atlantic (Fig. 9). Here, the general controls on landslide failure are related to climate-controlled influences on sedimentation during glacial and interglacial periods (e.g. Lee 2009; Talling *et al.* 2014), with earthquakes being the most likely triggering mechanism. The specific relationships between climate and landslide failure are still far from clear, however (Urlaub *et al.* 2013; Talling *et al.* 2014). Storegga is well studied in the NE Atlantic, and the associated tsunami was elevated along the surrounding coasts and geographically extensive. There is still no evidence for tsunamis from the other large-volume landslides off Norway (such as Trænadjupet; Fig. 9) located north of Storegga. Further south in the Shetlands

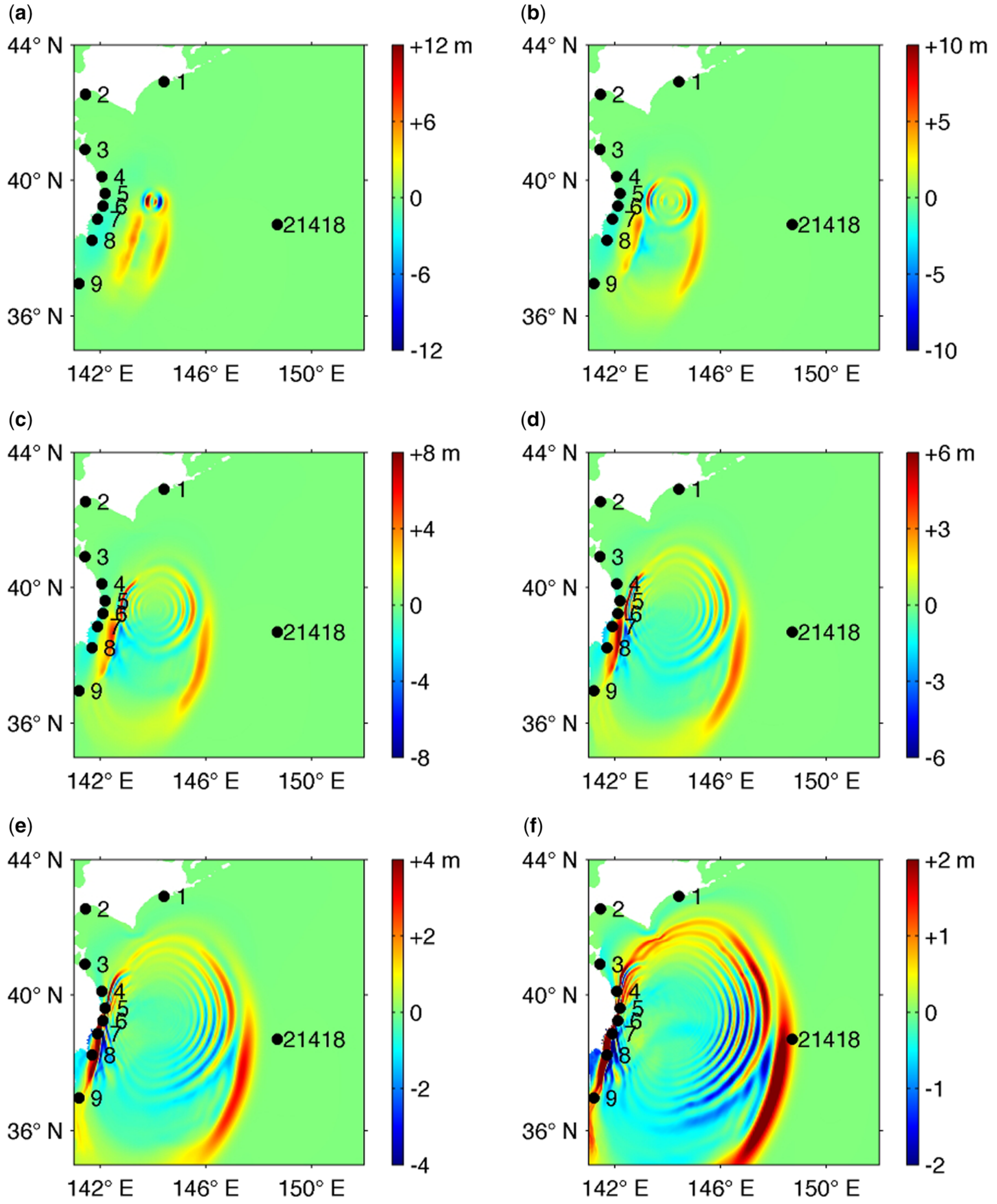

Fig. 11. Japan tsunami, 2011. Numerical simulation of the 2011 tsunami using a dual earthquake and submarine landslide source mechanism, showing instantaneous surface elevations at time (**a**) 5, (**b**) 10, (**c**) 15, (**d**) 20, (**e**) 25 and (**f**) 30 min. Labelled black dots mark the locations of GPS buoys and of DART buoy #21418. Note the highly dispersive nature of waves generated by the SMF source to the north, as compared to the longer-wavelength, long-crested, non-dispersive earthquake-generated tsunami waves to the south (From Tappin *et al.* 2014).

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(Fig. 9) there are tsunami sediments much younger than Storegga, dated at 1.5 and 5 ka BP (Bondevik *et al.* 2005*b*), but there is no obvious tsunami mechanism for these events except the possibility of submarine landslides. The most likely location for the landslides is off Norway, for example Trænadjupet where two events are recognized, but the ages of these were dated at 3–5 ka BP and 19–22 ka BP

EDQ5 (Laberg & Voren 2000), that is, different from the Shetland events. The mechanisms for the Shetland sediments therefore seem to be more local, but are yet to be found.

To address the submarine landslide hazard in the North Atlantic a major UK initiative was funded by the Natural Environment Research Council, with the focus on high-latitude ocean warming and its potential consequences on seabed slope stability. A marine programme acquiring hydroacoustic and sediment core data on the landslides off of Norway reappraised slope failure mechanisms and their ages, addressing some of the deficiencies identified by Urlaub *et al.* (2013) in the relationships between slope failures and their climate controls. Based on new data and numerical models, a further result of the project is a new numerical tsunami model of Storegga by Hill *et al.* (2014) which is the first to address the palaeobathymetric effects of lowered sea level at time of failure.

In the USA, scientific programmes to determine the tsunami hazard from submarine landslides focus on the passive margin of the east coast and Gulf of Mexico where there are large population centres and nuclear power plants (see special issue in *Marine Geology*, eight articles of which present new research; ten Brink 2009; ten Brink *et al.* 2009). Numerous submarine landslides have been mapped off the east coast of the USA (Fig. 9), but few have been well studied (Lee 2009). One of the best-researched and largest slide is Currituck, dated at 25–50 ka although it could be much younger (J. Chaytor pers. comm., 2017), which has been numerically modelled for tsunami generation (Grilli *et al.* 2015). Based on a slide volume of 134 km^3 and a rigid block failure, failure of Currituck would generate a local tsunami up to 5–6 m high, highlighting the hazard along this coast. It is likely that many of the passive margin landslides mapped on Figure 9 generated tsunamis, but there is no historical or geological evidence preserved that records their impact. Even without this evidence, the presence and distribution of such a large number of submarine landslides, some of significant volume, identifies a potential risk from their associated tsunamis (although statistical analysis suggests the risk is small; Grilli *et al.* 2009). Further research is required because the coast is densely populated and nuclear power plants are present (ten Brink *et al.* 2014). The tsunami hazard is mainly from submarine landslides rather than earthquakes (ten Brink 2009; ten Brink *et al.* 2014).

The only other country where there has been a concerted marine programme on a passive margin is Australia where, off the east coast, MBES mapping reveals a large number of landslide scars offshore of significant concentrations of population (Fig. 9) (Clarke *et al.* 2014). Numerical modelling suggests that the hazard here may be limited, however (Webster *et al.* 2016).

Along convergent margins, the hazard from submarine landslide tsunamis may be much greater than along passive margins. PNG is the best-known and most comprehensively researched submarine landslide tsunami along a convergent margin. Japan follows as a close second, although further confirmation is required to locate the exact position of the submarine landslide. Other convergent margin tsunamis where there is a possible landslide component include those of Messina (1908), Makran (1945), Aleutians (1946), Alaska (1964), Puerto Rico (1918), Flores Islands (1992) and Java (2006) (Fig. 9). One of the most devastating historical, convergent-margin tsunamis was Messina, 1908 (Fig. 9). A total of 50 000 people died in the earthquake from collapsed buildings in Messina and Calabria with a large, but uncertain, number drowned in the ensuing tsunami. Over 600 people died in the Java tsunami and 1000 at Flores, where the highly focused tsunami flooded up to 25 m above sea level. There is a hazard programme off NW USA similar to that on the east coast, established for dual earthquake and submarine landslide-generated tsunami along convergent margins. This programme recently re-evaluated the Aleutian tsunami of 1946 because of the controversy over the submarine landslide mechanism of the local 40 m high tsunami (Fryer *et al.* 2004; López & Okal 2006; Locat *et al.* 2009). Re-evaluation based on MBES and seismic data (von Huene *et al.* 2014) now identifies the landslide location previously proposed by Fryer *et al.* (2004), but this has yet to be numerically modelled. For most of the convergent-margin tsunamis identified above, the submarine landslide contribution remains uncertain because not all have marine survey data on which to evaluate the seabed for landslides that can underpin numerical tsunami models. Hydroacoustic data have been used to identify submarine landslides for the Aleutians, Alaska, Messina and Puerto Rico events (Fig. 9) and re-evaluate their tsunami hazard.

Discussion

The numerous tsunamis experienced since 1992 suggest that we are living in a period where these events may be more frequent than previously. Recognition of this (apparent) high frequency and concomitant hazard has resulted in a greater awareness of the tsunami impact, which requires better understanding so the hazard and risk can be fully addressed on a sound scientific basis. An improved understanding of the hazard and risk will necessarily require a continued geological input. A major requirement in hazard mitigation is for longer-term records so that the frequency of tsunami events can be better understood. This longer-term record can only be gained from the sediments laid down as tsunamis flood the coast. Geologists, as the arbiters of this record, can contribute based on major advances resulting from the recent catastrophic events of PNG (1998), the Indian Ocean (2004) and Japan (2011). Tsunami sediments provide a longer-term record for tsunami impact. Together with improved understanding of inundation limits from new methodologies (such as geochemistry), the impacts of older historical and prehistorical tsunamis and their generation mechanisms can be revised as in Japan with the Jogan (869) event. Based on recent events, where tsunami hydrodynamics are recorded and the origin of the sediments established, tsunami sediment can again be used through novel inverse modelling methodologies of tsunami flow speeds and depths to better understand older events at the same locations. This methodology also has potential in regions where there are no observed recent events, but where there is a historical or prehistorical record. Inverse modelling of tsunami sediment inundation provides new insight into generation mechanisms and magnitudes.

Although earthquakes are undoubtedly the most frequent mechanism of tsunami generation, two events (PNG and Storegga) indicate that submarine landslides are a secondary but important hazard. These latter events were recognized and researched over a similar period of time in the late 1990s to early 2000s; one (Storegga) was prehistoric so had little human impact, and the other (PNG) was very recent, killing over 2200 people. The recognition of the Storegga tsunami was from a coeval relationship between the tsunami sediments discovered in Scotland and a submarine landslide off the Norwegian coast, with the identification of the sediments motivating the first numerical modelling. The discovery of the Ormen Lange Gas field in 1997 led to a major investigation into slope stability and tsunami generation. When the PNG tsunami struck in 1998 and the landslide mechanism was identified, the Storegga gas field developers recognized its importance. Storegga and PNG remain the best-studied and validated examples of landslide-generated tsunamis. The reasons for their study are entirely different. At Ormen Lange, the imperative was to prove that exploitation of the gas field would not trigger another tsunami. With PNG, the scale of the loss of life and initial uncertainty in the generation mechanism dictated that the cause of the tsunami had to be understood. Unlike Storegga, where oil money was available to fund a comprehensive investigation of the landslide, with PNG there was no obvious donor to fund the marine surveys which were organized on humanitarian grounds. In both instances, geologists made major contributions both to understanding tsunami generation and validation of numerical models. PNG was the first recent event where there was a focused post-event marine survey organized and managed by geologists. For Storegga, the numerical models were based on marine data and validated by sediments deposited by the tsunami on adjacent coastlines. For PNG, although the tsunami sediments were analysed and in fact used as a basis for the first inverse modelling, the numerical models were validated from tsunami run-up elevations acquired during post-event surveys.

Although only four (five with Alika 2) significant tsunamis are positively identified as generated by submarine landslides, seabed mapping of continental shelves reveals their ubiquity (Fig. 9). Too few landslides are yet dated, and even fewer studied to a degree necessary to understand the controls on their generation. These controls on sediment failure and landslide frequency are therefore poorly understood, so the hazard from submarine landslides remains undefined. Recent studies suggest that submarine landslide failure is random (e.g. Urlaub *et al.* 2013), but there are still too few events studied in sufficient detail or accurately dated to be certain of this. Urlaub *et al.* (2013) analysed 68 events, 50% of which they were unable to date to sufficient resolution to relate to potential landslide controlling factors. Because the controls on failure are complex (Tappin 2009, 201[illegible]; Talling 2014) more events require researching before reliable conclusions can be drawn on the most important failure mechanisms. Recent overviews (ten Brink *et al.* 2016) suggest that as more events are studied, improved understanding of landslide failure and triggering mechanisms, particularly in specific tectonic environments, will result. Although earthquakes are still the most likely landslide triggers, these may not only be ‘tectonic’ in the context of convergent margin environments. There are also strong climate controls on earthquake rupture, for example in high latitudes due to glacioisostatic processes, such as established from research on Storegga (e.g. Bungum *et al.* 2005). In addition, new research suggests there may be triggering relationships between earthquakes and continental shelf loading from sea-level rise not previously recognized (Brothers *et al.* 2013; Smith *et al.* 2013). Regarding tsunami generation, most submarine landslides have the potential to generate hazardous events if of sufficient volume. The preservation potential of tsunami sediment is low; so, even though evidence for tsunamis associated with the landslides may be absent, this may not necessarily discount tsunami generation.

The Japanese tsunami of March 2011 led to the confirmation that tsunami sediments were critical in identifying inundation limits. It revealed that submarine landslides are an additional, yet unforeseen, major hazard even where a large-magnitude earthquake generates a devastating tsunami. It also demonstrated the importance of new technologies, such as seabed pressure sensors and improved geological (geochemical) methodologies, in the identification and discrimination between tsunami mechanisms and their coastal impact.

Challenges remain in improving our understanding of tsunamis and their hazard, to which geologists can contribute. The disintegration of translational landslides, and how this controls tsunami generation, has yet to be fully addressed by numerical models, which need to be more complex to be realistic. Geologists can contribute in developing more realistic landslide models from marine data and in their validation from sediment data. A major challenge is in determining the hazard from tsunamis generated from volcanic eruption, which is hardly researched. There have been some theoretical studies (e.g. Pareschi *et al.* 2006; Novikova *et al.* 2011), but these have not been validated. Even validated studies leave uncertainties over mechanisms (e.g. Ulvrova *et al.* 2016), however. There are numerical models of small-scale events, such as from Montserrat (Pelinovsky 2004), but their relevance to large-scale eruptions is uncertain. It is almost certain that, as with recent events such as the Indian Ocean, Japan and PNG where the seminal research has resulted from a catastrophe, the challenge of eruption tsunami mechanisms will be met only in response to a future major event with significant loss of life and/or major economic impact. The most recent (and only) catastrophic eruption tsunami in 1883 was when Krakatau in the Java Strait exploded, devastating surrounding coastlines and killing 36 000 people. To understand the eruption tsunami mechanism demands validated numerical models and, fortunately, Krakatau was subject to the first post-event tsunami survey ever carried out (Verbeek 1885). Although there was an immediate response to the tsunami impact, and the volcanic eruption has been well studied (e.g. Self & Rampino 1981), there is still uncertainty over the final cataclysmic explosion during which the devastating tsunami was generated. Alternative possible tsunami mechanisms include pyroclastic flows, caldera collapse or both as a dual mechanism (Francis 1985). There is only one comprehensive numerical modelling study, and this supports the entry of pyroclastic flows into the sea (Maeno & Imamura 2011). The results are however questionable because of the validation used. Globally, there are 42 volcanoes similar to Krakatau which could erupt with similar consequences. The uncertainty over the tsunami mechanisms of eruption therefore remains an important issue that needs addressing if appropriate mitigation and response strategies for eruption tsunamis are to be developed, similar to those for earthquakes and submarine landslides.

Conclusions

Over the past 30 years, there have been major advances in understanding the mechanisms of tsunami generation and tsunami impact. Improvements in technology, documentation of events and ability to model them have largely been because of devastating events. For the past 20 of these 30 years many of the advances have been by contributions from geology and by geologists. Most now-accepted ideas, such as that tsunamis lay down sediment when they flood the land and that submarine landslides generate hazardous tsunamis, were at first controversial and considered unlikely. Now, post-event surveys acquire geological data as a matter of course. Earthquakes are undoubtedly the primary tsunami mechanism, but improved understanding of earthquake mechanisms, magnitudes and frequencies in tsunami generation result from research on their associated tsunami deposits. Studies of prehistoric tsunami sediments have resulted in timescales now extended back in time for thousands of years, beyond historical records. These extended records have improved the understanding of the frequencies of these events that together allow improved mitigation and response strategies. Comparison of sediments from recent tsunamis with those preserved in geological records at the same locations offers the opportunity to better understand past events. Recent major advances in inverse modelling of earthquake tsunami magnitudes from sediments indicate their potential in this field.

Understanding tsunami generation from landslides, especially submarine events, is underpinned by geological research in mapping the locations and architectures to identify failure mechanisms and then using these mechanisms for realistic numerical simulations. Whereas the hazard from submarine landslide tsunamis is now recognized, the extent and risk from these events is still uncertain. Submarine landslides are present along the margins of most continents; many of these margins remain largely unmapped however, so their hazard is not known.

Eruption-generated tsunamis remain poorly researched, and their mechanisms are not well understood. Their global extent requires more focused programmes of research to address their hazard and risk. Based on the most recent history of scientific advance for earthquake and landslide tsunami, it may well be that advances in understanding eruption events await the next catastrophic event. Nevertheless, continued research on tsunami sediments, submarine landslides and volcanic eruptions promises to better define the global tsunami hazard from all generation mechanisms. Geology and geologists will continue to make essential contributions to this better understanding.

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