Submarine landslide tsunamis: How extreme and how likely?

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ORIGINAL PAPER

Submarine landslide tsunamis: how extreme and how likely?

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Abstract A number of examples are presented to substantiate that submarine landslides have occurred along most continental margins and along several volcano flanks. Their properties of importance for tsunami generation (i.e. physical dimensions, acceleration, maximum velocity, mass discharge, and travel distance) can all gain extreme values compared to their subaerial counterparts. Hence, landslide tsunamis may also be extreme and have regional impact. Landslide tsunami characteristics are discussed explaining how they may exceed tsunamis induced by megathrust earthquakes, hence representing a significant risk even though they occur more infrequently. In fact, submarine landslides may cause potentially extreme tsunami run-up heights, which may have consequences for the design of critical infrastructure often based on unjustifiably long return periods. Giant submarine landslides are rare and related to climate changes or glacial cycles, indicating that giant submarine landslide tsunami hazard is in most regions negligible compared to earthquake tsunami hazard. Large-scale debris flows surrounding active volcanoes or submarine landslides in river deltas may be more frequent. Giant volcano flank collapses at the Canary and Hawaii Islands developed in the early stages of the history of the volcanoes, and the tsunamigenic potential of these collapses is disputed. Estimations of recurrence intervals, hazard, and uncertainties with today's methods are discussed. It is concluded that insufficient sampling and changing conditions for landslide release are major obstacles in transporting a Probabilistic Tsunami Hazard Assessment (PTHA) approach from earthquake to landslide tsunamis and that the more robust Scenario-Based Tsunami Hazard Assessment (SBTHA) approach will still be most efficient to use. Finally, the needs for data acquisition and analyses, laboratory experiments, and more sophisticated

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numerical modelling for improved understanding and hazard assessment of landslide tsunamis are elaborated.

Keywords Landslide · Tsunami · Database · Probability · Recurrence · Scenario · Probabilistic · Hazard · Risk

1 Introduction

Submarine earthquakes constitute the primary tsunami source, but the importance of submarine landslides as a major contributor to tsunami generation has been more recognized over the last 20–30 years (Hampton et al. 1996; Locat and Lee 2002; Masson et al. 2006; ten Brink 2009; Vanneste et al. 2011a). This is among other factors due to the studies of the tsunami induced by the 8150-year BP Storegga Slide (Bondevik et al. 2005; Harbitz 1992) and the 1998 Papua New Guinea tsunami (e.g. Bardet et al. 2003; Tappin et al. 2008). At the same time, offshore industry explorations and geomarine surveys such as the Ormen Lange study (Solheim et al. 2005a) have provided better understanding of the evolution of submarine landslides. This has increased the attention on possible submarine landslide tsunamis caused also by industrial activities where liability on third party comes into play. Earlier studies of the 1929 Grand Banks event (Fine et al. 2005; Heezen and Ewing 1952; Piper et al. 1999) should also be mentioned in this context.

Tsunamis induced by landslides display a great variety. Most landslides that cause tsunamis result in more local effects than comparable earthquake-induced tsunamis, due to different source characteristics (Harbitz et al. 2006; Okal and Synolakis 2004). Examples of submarine landslides or slumps that have caused large run-up heights locally comprise the 1899 Ceram event (12 m, Yudichara pers. comm. 2008, NGDC 2013), the 1929 Grand Banks event (13 m, Fine et al. 2005), the 1992 Flores event (26 m or 19.6 m averaged from four nearby measurements, Yeh et al. 1993), the 1998 Papua New Guinea event (>15 m, Tappin et al. 2008), and the 1979 Nice event (3 m, Assier-Rzadkiewicz et al. 2000).

However, enormous submarine landslides exhibiting volumes of several thousands of km^3 may cause tsunamis with more widespread effects (Løvholt et al. 2005; Masson et al. 2006; Vanneste et al. 2011b). Numerical simulations reveal run-up heights up to 8.8 m for the 25–50 ka BP Currituck (165 km^3) landslide tsunami (Geist et al. 2009), and >9 m near-shore and 25 m offshore surface elevations for the 11,500-year BP BIG′95 (26 km^3) landslide tsunami (Iglesias et al. 2012; Løvholt et al. 2013). Numerical simulations and tsunami deposits from the 8150-year BP Storegga Slide (2,400 km^3) reveal regional shoreline water levels of 10–20 m (Bondevik et al. 2005, Harbitz 1992). Similarly, simulations of the 1,200 km^3 Brunei landslide reveal offshore wave heights exceeding 5 m (Okal et al. 2011). Ward (2001) simulated a series of possible tsunamis revisiting historical events, providing near-shore amplitudes of 40–60 m for the 5,000 km^3 Nuuanu landslide near Hawaii, 30 m for the Storegga landslide (assuming a volume of 5,500 km^3), and 4–7 m waves offshore for the Currituck landslide (labelled Norfolk Canyon landslide by Ward, 2001).

Volcanic flank collapses plunging into the water may also cause tsunamis inducing distant destruction (Abadie et al. 2012; Løvholt et al. 2008; Ward and Day 2001), although their tsunamigenic potentials are disputed (e.g. Gisler et al. 2006; Masson et al. 2006; McGuire 2006; McMurtry et al. 2004; Pararas-Carayannis 2002; Wynn and Masson 2003). Numerical simulations of the ca. 127 ka BP Alika giant submarine landslide and corresponding tsunami deposits at Lanai Island (corrected for sea island subsidence) indicate regional run-up heights exceeding 2–300 m (McMurtry et al. 2004). At Gran Canaria in the Canary Islands, tsunami deposits are observed up to 188 m above present sea level, probably following a 830 ka BP lateral collapse at neighbouring Tenerife Island (McGuire 2006). To the authors' knowledge, there are no examples of volcano collapse of lava domes, flank failures, pyroclastic flows, lahars, or debris flows that have caused severe tsunamis of regional impact in historical times (eruptive volcano tsunamis excluded here). Nevertheless, due to their potential catastrophic impact, these types of massive events have received considerable attention, albeit being rare. However, several local volcano flank collapse tsunami events with reported run-up heights up to 15 m are observed (some with significant loss of lives), for example, in the Caribbean (Harbitz et al. 2012 and references therein), 2002 Stromboli Island (Italy; Tinti et al. 2005), as well as 1640 Komaga-Take, 1741 Oshima-Oshima, and 1792 Shimabara Bay (Mount Unzen, Japan; Inoue 1999), 1871 Ruang and 1979 Iliwerung (Indonesia), and 1888 Ritter Island (Papua New Guinea; McGuire 2006 and references therein). The 1888 Ritter Island event of approximately 5 km^3 is the largest historical lateral volcano collapse.

In spite of low probabilities, submarine landslides may cause larger tsunami inundation compared to earthquake-induced tsunamis as demonstrated above. This may be important for location and design of critical infrastructure that are often based on very long return periods (thousands of years) that may be weakly justified (P. J. Lynett pers. comm. 2012).

The present paper attempts to respond to the important question on how we should prepare for the extreme. For submarine landslides this divides into three questions: (a) Why are submarine landslide tsunamis extreme? (b) How do we quantify the probabilities, that is, where do landslide tsunamis occur and with which recurrence rates? (c) How do we address the uncertainties of the extreme events? The questions are discussed in a hazard and risk context where scenarios need to be presented with some indication of likelihood in order to be of interest.

The first part of the paper is a review attempting to answer why landslide tsunamis may be extreme and where landslide sources occur. This forms a basis for the subsequent discussion on whether and how we can assess recurrence intervals, hazard, and uncertainties with present methods. Following Hampton et al. (1996) and Masson et al. (2006), the term 'landslide' is used in this paper as a generic term encompassing all forms of high-density flows, irrespective of process, such as slides, slumps, mud flows, debris flows, rock slides, and volcanic island landslides. Previous assessments of submarine landslide tsunami hazard are presented, for example, by Grilli et al. (2009) and ten Brink et al. (2009a, b) for US coastal areas, while Tappin (2010) has reviewed the tsunami hazard related to various kinds of submarine and subaerial mass failures worldwide.

2 Characteristics of damaging submarine landslide tsunamis

Whereas the actual external triggering mechanisms are not always known, seismicity is often considered as the main trigger setting off submarine landslides. However, prior to failure, a number of preconditioning factors related to the particular geological setting lead to potentially unstable conditions facilitating failure. These include, but are not limited to, high sedimentation rates (e.g. related to glacial–interglacial cycles), unfavourable soil layering, deposition of so-called weak layers in which slip planes develop, over-steepening (e.g. due to diapirism, tectonics, and erosion), artesian pressure, and fluid-flow-related phenomena (e.g. mud volcanoes, fluid escape). Also, the presence of gas and hydrate dissociation or wave activity is reported (e.g. Canals et al. 2004; Solheim et al. 2007). Most of these processes involve excess pore pressure and thus lead to less resistance to failure.

Examples of tsunami events that are likely to have involved combined earthquake/landslide sources include the 1929 Grand Banks and the 1998 Papua New Guinea events, both briefly described below. Sedimentation rate changes, forming of weak layers, and isostatic land uplift causing earthquakes may all originate from climate changes between glacial and interglacial conditions (Bryn et al. 2005; Kvalstad et al. 2005a; Lee 2009; Masson et al. 2006; Solheim et al. 2005b). Rapid sedimentation is also in itself a source of increased differential stress and thereby also of earthquakes, such as in the Lofoten and Norway Basins (Byrkjeland et al. 2000). For a recent summary of the knowledge on submarine landslides and their consequences, see Vanneste et al. (2011a).

Submarine landslide tsunamis may be extreme because of three peculiarities of the landslide itself. Firstly, submarine landslides may occur along any passive or active continental margin and at different water depths (see Sect. 3). Secondly, the landslide parameters governing the tsunami characteristics, that is, the physical dimensions and the mobility (acceleration, maximum velocity, mass discharge, and travel distance; De Blasio et al. 2006; Grilli and Watts 2005; Haugen et al. 2005; Løvholt et al. 2005), can all range over a large scale of values. Thirdly, the submarine landslides are difficult to observe and monitor in the subsea realm; hence, they are apparently ‘unpredictable’ in an unprepared society, a fact that in turn makes the tsunami consequences even more extreme.

The largest submarine landslides may involve several thousand km^3 of material, that is, two to three orders of magnitude larger than any terrestrial landslide (Hampton et al. 1996). Submarine landslides at deep water generally move with a speed lower than the wave celerity. Under this assumption, a simple analysis considering the landslide as a uniform non-deformable block reveals the following simple characteristics (following Haugen et al. 2005): the length of the landslide influences both the wavelength and the surface elevation, while the thickness and the acceleration or deceleration of the landslide as well as the wave speed (determined by the water depth) determine the surface elevation. The maximum tsunami elevation generally correlates with the product of the landslide volume and acceleration divided by the wave speed squared, while the elevated water volume correlates with the product of the landslide volume and the Froude number (the ratio of the landslide speed to the wave celerity).

However, quantification of the landslide parameters is complicated by the transformation of the landslide from a huge slab of soil to progressively smaller blocks, then to a highly viscous non-Newtonian fluid (possibly carrying clasts of different sizes) and—in many cases—to a turbidity current with fines suspended in the water by turbulence. Moreover, these stages of flow evolution are connected to different flow regimes that require different modelling approaches. Notwithstanding, indirect information on the landslide processes can be obtained from statistical analysis of their size distribution (Camerlenghi et al. 2010; Chaytor et al. 2009; De Blasio et al. 2006; Issler et al. 2005; McAdoo et al. 2000; ten Brink et al. 2006a, 2009c; Twichell et al. 2009; Vanneste et al. 2011a).

A complicating factor is that many submarine landslides develop retrogressively, that is, they are released progressively upwards from the toe. Retrogression is a fairly continuous process where the sizes of the individual landslide blocks are relatively similar (e.g. Kvalstad et al. 2005a). Based on the analysis of Haugen et al. (2005), the rate of change in mass discharge governs the height of the initial wave. Hence, a gradual increase in mass should imply a smaller tsunamigenic power for retrogressive landslides than for simultaneously released landslides. However, retrogression might increase the height of the landward propagating wave for unfavourable time lags between releases of the individual elements (Bondevik et al. 2005; Harbitz et al. 2007; Haugen et al. 2005; Løvholt et al. 2005). In some landslides, for example, the Hinlopen landslide (Vanneste et al. 2011b) and the BIG′95 landslide (Iglesias et al. 2012; Lastras et al. 2004; Løvholt et al. 2013; Urgeles et al. 2006), large intact blocks are identified within the deposits of remoulded material. These blocks may exhibit larger thicknesses than the surrounding masses and generate locally higher waves.

The extreme mobility of submarine landslides is demonstrated by the very long travel distance relative to the drop in elevation of the failed mass between the source area and the final deposit and calls for further attention. Without going into descriptions of submarine landslide mechanisms, this high mobility may be partly explained considering the large volumes involved (De Blasio et al. 2006; Edgers and Karlsrud 1982; Elverhøi et al. 2002; Locat and Lee 2002). However, subaqueous landslides appear to be more mobile even when compared to subaerial landslides of the same volume. The comparison with subaerial landslides becomes even more striking considering that the effective gravity is diminished in water due to buoyancy and that the viscous drag in water is about one thousand times larger than in air. This indicates that the explanation for the high mobility of subaqueous landslides relies on the landslide/water interaction. The mobility of cohesive debris flows can most likely be explained invoking lubrication by a thin water layer (hydroplaning; De Blasio et al. 2004; Elverhøi et al. 2005; Harbitz et al. 2003; Mohrig et al. 1999).

The energy available for the tsunami is proportional to the square of the uplift of the seabed. A submarine landslide moves less material, but might move it vertically up to 100 times as much as an earthquake resulting in a comparable amount of tsunami energy (Okal and Synolakis 2003). Typically, tsunamis induced by submarine landslides have very large run-up heights close to the landslide area (determined by the potential energy of the displaced water) and more limited far-field effects (determined by the displaced water volume) than earthquake tsunamis (Okal and Synolakis 2004). In general, initial wave heights induced by purely submarine landslide tsunamis are typically up to 10 m while initial wave heights induced by volcano flank collapses may be one order of magnitude higher. Run-up heights of landslide tsunamis may reach the order of 10–100 m.

In a simplified way, we may say that the propagation of the landslide tsunami is primarily the result of radial spreading from a local quadrupole source (a set of two dipoles). This generation mechanism differs from the lack of radial spread in the near-field of major earthquake tsunamis (propagating perpendicular to a long linear fault source), but also from smaller earthquakes that provide a dipole-like initial tsunami.

It should be noted that frequency dispersion, which is normally more pronounced for landslide tsunamis, makes the propagation more complex (Fig. 1; see also Fig. 4). The relatively short length scale of landslide thickness variations relative to the water depth is the reason for the dispersive wave characteristics (Ward 2001). Generally, the leading-order wave is reduced due to dispersion. Eventually, the trailing wave system is expected to dominate in the far field. Løvholt et al. (2008) demonstrated by using analytical expressions for a combination of one leading positive and one leading negative wave that the net displaced volume governs the propagation for impulsively generated subaerial landslides. This poses a fundamentally different property for the tsunami propagation due to subaerial landslides compared to the completely submerged ones, adding zero net volume. Frequency dispersion may be of little importance for waves generated by the large submarine landslides with moderate acceleration and deceleration where large-wavelength components dominate such as for the Storegga Slide tsunami (Bondevik et al. 2005;

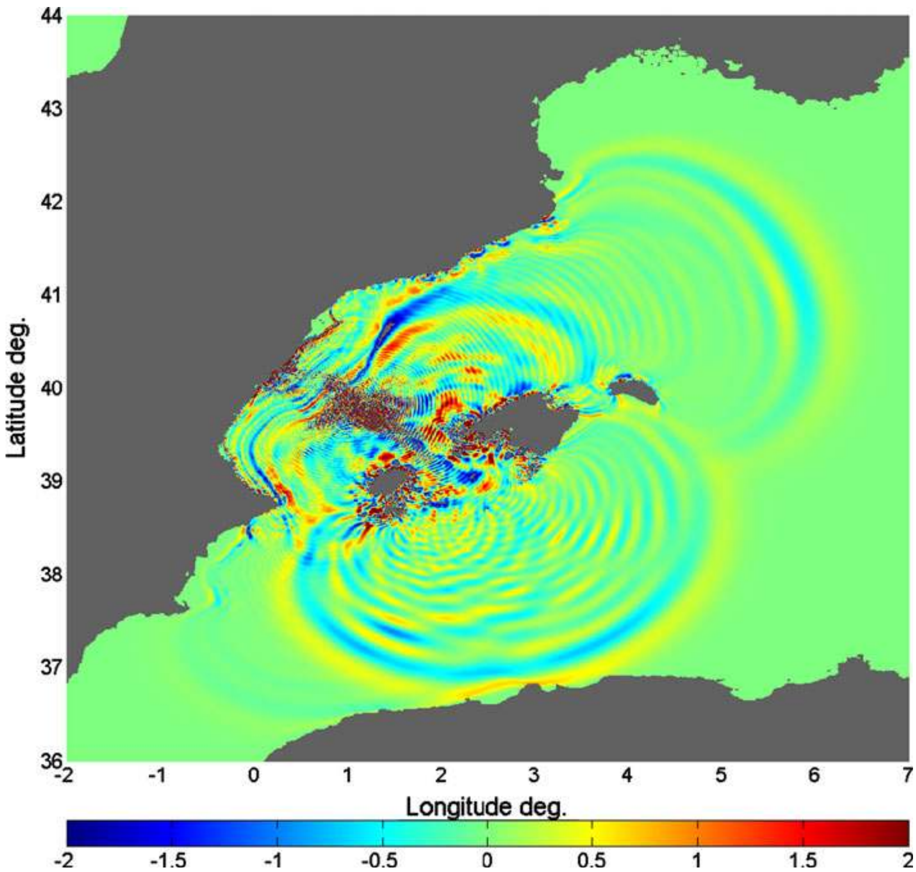

Fig. 1 Snapshots of the simulated surface elevation from the 19 km^3 (7 km^3 of slower intact blocks ignored) BIG′95 landslide in the western Mediterranean Sea after 55 min (applying the dispersive wave model GloBouss; Løvholt et al. 2008, 2010; Pedersen and Løvholt 2008). The train of shorter trailing waves, most pronounced in the southeast and northeast direction, is interpreted as frequency dispersion. A linear non-dispersive wave model gives a relative error of almost 50 % in the maximum surface elevation (this effect is typical for the points east of the source area, i.e. in deeper water and in the direction of the landslide motion). Surface elevations of more than 10 m indicate severe impact in the near-field (e.g. on the Balearic Islands and parts of eastern Spain), while elevations up to 3–5 m are produced in the far field (at cities like Barcelona and Alicante, as well as along the Algerian coastline). The tsunami has a pronounced directivity towards the southeast and the northwest, giving a narrower distribution of maximum surface elevation near the shoreline than typical for earthquake generated tsunamis (cf. Okal and Synolakis 2004)

Harbitz 1992; Harbitz et al. 2006). The influence of dispersion on tsunamis is summarized by Glimsdal et al. (2013).

Tsunamis are in general extreme not only because they are high and not anticipated. In fact, they do not need to be particularly high to cause considerable damage as for instance seen from current-induced damages in harbours following the 2004 Indian Ocean tsunami (Okal et al. 2006a). Owing to the very long wavelength of tsunamis, the propagation mimics that of a tidal wave or a storm surge around islands or shallows, through narrow straits or bends, and into harbours. In this way they inundate otherwise sheltered areas without being reduced by energy dissipation caused by wave breaking, reflection, etc., to the same extent as wind waves or swells. At the same time the wave period of a tsunami is shorter than for a tidal wave and a storm surge. Hence, the tsunami will climb the land faster and cause significantly stronger currents and fluxes than these other kinds of very long waves (even of the same height). Landslide tsunamis in particular are most often shorter than earthquake tsunamis, which favour amplification.

In a hazard assessment perspective, it should be noted that also the water depth at which the tsunami sources occur influences the wave generation differently. Submarine landslides are normally (clearly) subcritical, which implies that the tsunami will run away from the wave-generating landslide, limiting the build-up of the wave. However, for a landslide occurring in shallow water, effects of critical landslide motion (Froude number = 1) give large localized waves as illustrated by Ward (2001), resulting in more hazardous waves than if the same landslide should occur in deep water. To this end, subaerial landslide and volcano collapses will always have a critical or supercritical nature which may enhance tsunami generation, causing huge waves locally (e.g. Abadie et al. 2012; Fritz et al. 2004). In contrast, tsunamis generated by earthquakes are more hazardous when the seabed displacement occurs in deeper waters, as the initial wave (which in this case depends much less on the water depth) then will become shorter and higher as a result of shoaling when propagating from deeper to shallower waters (Harbitz et al. 2006).

3 Regional characteristics of submarine landslides

Even though it is often possible to define areas prone to sliding, we are still not able to predict individual hazardous locations, not to mention the potential landslide dimensions and evolution. Depending on the triggering and rheology of the masses involved, there is a vast diversity in possible processes and dynamics including, for example, release mechanisms (comparable to the challenges in understanding nucleation processes for earthquakes, which is the main obstacle for earthquake prediction) and disintegration, mixing with water, landslide substages, retrogression, hydroplaning, etc. (Elverhøi et al. 2010).

Submarine landslides may occur on most continental margins, in a large variety of geological settings and at all water depths, even on very gentle slopes (De Blasio et al. 2006; Masson et al. 2006). Where earthquakes constitute the triggering mechanisms, the size and recurrence of failures are, to a first order, influenced by subduction rate and possibly age in active margins (a more complex picture is shown by Stein and Okal 2011), and by glacial cycles or other sedimentary deposits such as fluvial fans in passive margins. Frequent violent earthquakes might induce frequent smaller landslides rather than rare and large landslides and thus reduce the landslide tsunami hazard (Völker et al. 2011). The largest submarine landslides seem to occur on the lowest slopes, often as low as 1° (probably because of larger accumulation prior to release), or on oceanic island flanks. The greatest number of landslide headwalls occur on the mid-slope, with a peak at 1,000–1,300 m water depth, and not on the upper slope as might be expected (Masson et al. 2006).

Submarine landslides are found particularly in areas where fine-grained sediments predominate (Masson et al. 2006). Such sediments are produced by glacial action at high latitudes and by chemical weathering processes at low latitudes and form thick accumulations on the continental slope, which favour landslide formation. Submarine deltas and fans of large rivers are also subject to landsliding, especially the submarine deltas formed where rivers discharge sediment onto the steep submarine walls of fjords. Elverhøi et al. (2010) demonstrate how the dynamic processes and flow regimes of a submarine landslide depend on the primary composition of the mobilized sediment, identifying the clay-to-sand ratio as the key control parameter.

Examples of submarine landslides in various regions are given below, together with examples of landslide source likelihood and landslide tsunami hazard assessments. The intention is to present an overview useful in landslide tsunami hazard assessment (location, dimensions, likelihood, etc.) for various areas, rather than to discuss the governing geological and tectonic conditions or characteristics for comparable landslide tsunami-prone areas. Hence, a presentation simply based on geographical regions is preferred.

3.1 South and Southeast Asia

Following the 2004 Indian Ocean tsunami, the tsunami hazard in Southeast Asia has received considerable attention. Løvholt et al. (2012c) established a tsunami database covering a part of the Southeast Asia region including the Sunda Arc in the West and the Philippines and Papua in the East. Their source statistics shows that 123 of the reports are related to earthquakes, 21 to volcanoes, and 9 to landslides (Fig. 2; see 'Appendix' for further details). Furthermore, a number of landslides have been mapped following extensive seabed investigations. Brune et al. (2010a, b) found evidence for six submarine landslides in the eastern Sunda region (1–20 km^3) as well as three landslides offshore Padang, Sumatra. Four of the landslides in the Sunda region are located directly above the assumed fault plane of the tsunamigenic 1977 Sumba earthquake (M_w8.3). Tsunami simulations can neither exclude nor verify co-seismic landslide triggering and resulting tsunamis. Similarly, a major landslide has been discovered north of Borneo (the Brunei landslide, Gee et al. 2007). Recently, Schwab et al. (2012) showed evidence for submarine landslides on the western slope offshore Thailand. Based on 2D seismic data, they identified 17 landslide deposits between 0.3 and 14 km^3. Based on volume (>2 km^3) and water depth (<1,000 m) criteria, they further identified four potential tsunamigenic landslides in the sedimentary record and three possible future failures (the criteria are disputable, see e.g. Lo Iacono et al. 2012 on deep-water slope failure tsunamis). Time intervals between individual events are long (hundred ka to Ma).

Many of the historical tsunamis in South and Southeast Asia are caused by landslides or slumping. The most well-known case here is probably the 1998 Papua New Guinea tsunami (e.g. Bardet et al. 2003; Tappin et al. 2008) where the slump was located offshore. Some other examples comprise the 1992 Flores Island tsunami (Yeh et al. 1993, Imamura et al. 1995a), possibly the 1945 Makran tsunami (Ambraseys and Melville 1982; Okal and Synolakis 2008; Pararas-Carayannis 2006; Rajendran et al. 2008), as well as several older events in the Banda and Flores Seas, for example, the 1899 Ceram tsunami (Yudichara pers. comm. 2008, NGDC 2013). In addition, there are large events such as the Brunei landslide for which the temporal probability is hardly quantifiable. The 1998 Papua New Guinea, the 1992 Flores Island, and the 1899 Ceram tsunamis all caused several thousand fatalities (NGDC 2013). Beyond that, the older events are all believed to involve relatively small volumes compared to other massive events reviewed here, with parts of the volume released onshore in combination with strong earthquake activity. However, their vicinity to the coast may yet have enabled large impacts. Many of these older events are unfortunately poorly documented.

Volcano-induced tsunamis are also relatively frequent in Southeast Asia compared to other areas (Fig. 2), and this is particularly the case for eastern Indonesia and the northern Philippines. Although less frequent than earthquake tsunamis, the landslide and volcano-induced tsunamis in this region are common enough to be a source of concern.

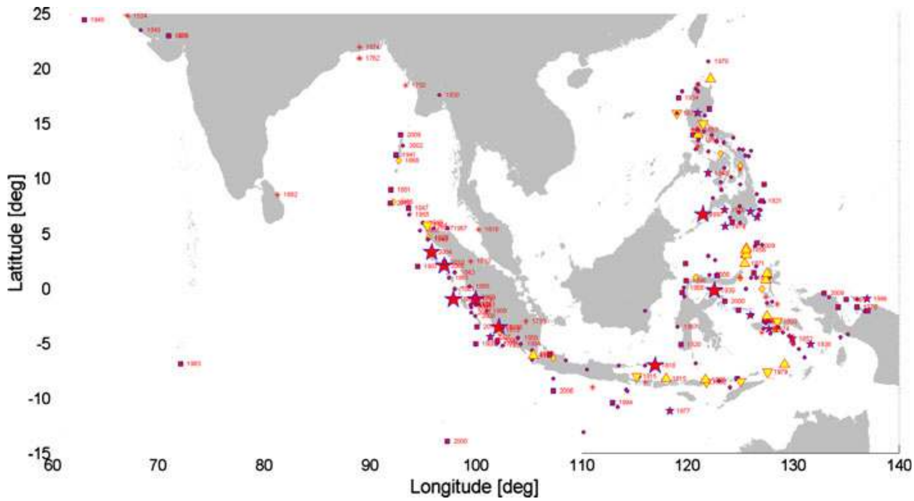

Fig. 2 Sources of historical tsunamis in South and Southeast Asia. Year of occurrence is indicated for some events. *Red markers* represent seismic sources (*large stars* display magnitudes $M \geq 8.5$, *small stars* $8.5 > M \geq 8.0$, *squares* $8.0 > M \geq 7.5$, *circles* $M < 7.5$, an *asterisk* means that no magnitude is reported), while the *yellow upward triangles* display volcanoes or combinations of volcanoes and other sources, *yellow downward triangles* display landslides or combined landslides/earthquakes, and *yellow rhomboids* display unknown sources. The figure is based on tsunami catalogues as described in the 'Appendix'

3.2 Example from West Pacific: Japan

Ikari et al. (2011) investigated slope stability along the Nankai Trough offshore Japan. Static stability evaluations from their study predict stable conditions. However, stability evaluations based on seismic loading suggested that megathrust events exceeding M_w8 lead to failure, possibly also smaller magnitude earthquakes depending on their location (e.g. a location close to a splay fault may fail for smaller magnitudes). Kitamura and Yamamoto (2012) recovered shallow sub-seafloor features of landsliding prior to subduction of the incoming oceanic plate into the Nankai Trough, suggesting that the surface of the plate is quite active. Strasser et al. (2012) described six mass transport deposits within records of about 1 Ma of submarine landsliding in the active tectonic setting of the Nankai accretionary wedge. Numerous superficial slump scars and a shallowly buried (presumably Holocene) deposit indicate that mass movements are an active process shaping the present-day seafloor. Matsumoto et al. (2012) provided evidence for a landslide induced by a $M_w6.4$ earthquake in the Suruga Bay near the Nankai Trough, responsible for displacing pipelines, etc., more than 2 km. Baba et al. (2012) concluded that the landslide contributed to the resulting tsunami.

As an example of a potential landslide in this region, the run-out of a potential landslide event at the Atsumi escarpment near the Nankai Trough is here simulated using the BING model (Imran et al. 2001). Landslide motion is dominantly west–east. The assumed length of the landslide is 4.1 km, and the width is approximately 2 km, giving a volume of 1.26 km^3. The landslide parameters represent a worst credible failure scenario based on a local static stability evaluation, yet with a low probability of failure. A Herschel–Bulkley rheology is applied with a yield strength of 14.4 kPa and a low viscosity of 0.0005 Pas. The simulated landslide profile as well as an example of the simulated hydrodynamic response at a given time step is depicted in Fig. 3. The hydrodynamic filtering effect (for a description see e.g. Glimsdal et al. 2013) is pronounced. Simulated wave propagation using the GloBouss model (Pedersen and Løvholt 2008; Løvholt et al. 2008, 2010) is shown in Fig. 4, clearly displaying a dispersive tsunami with only moderate or small offshore amplitudes.

It has so far been anticipated that the 2011 Tohoku tsunami was generated solely by the earthquake (e.g. Løvholt et al. 2012d; Romano et al. 2012). Recent analysis has suggested that time evolution of the earthquake, with large slip near the trench (e.g. Satake et al. 2013; S. Lorito pers. comm. 2013), explains both the short-wave components observed near-shore and the large run-up in the northern part of Honshu. However, other recent studies have suggested that the large run-up in the northern part of Honshu is due to a huge slump-like landslide (for a discussion see Grilli et al. 2012, Kawamura et al. 2012).

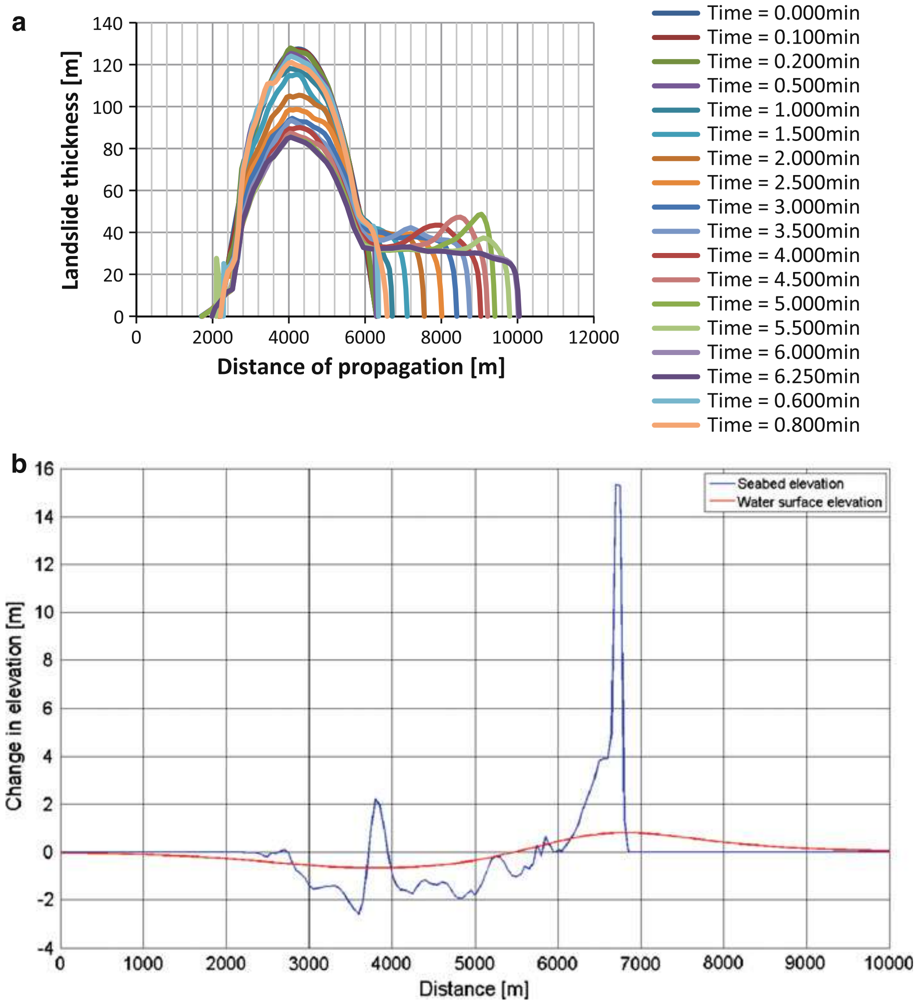

Fig. 3 **a** Simulated thickness as a function of time for a potential landslide event at the Atsumi escarpment near the Nankai Trough using the BING model; **b** comparison of the simulated change in seabed elevation due to landslide progression (*blue curve*), and the change in water surface response including hydrodynamic filtering (*red curve*) over a time interval of 6 s

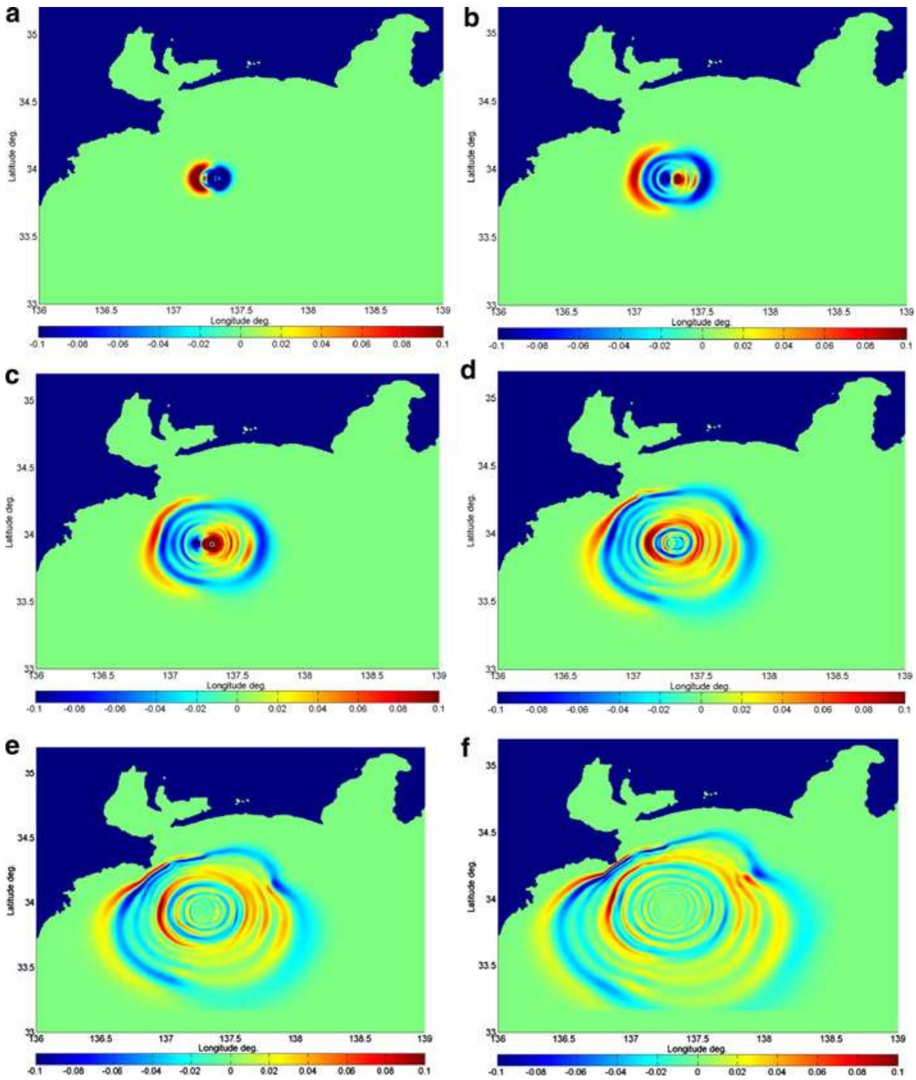

Fig. 4 Simulated water surface elevation for a potential landslide event at the Atsumi escarpment near the Nankai Trough using the optimized dispersive mode after **a** 2 min; **b** 4 min; **c** 6 min; **d** 8 min; **e** 10 min; and **f** 12 min of propagation. The waves are absorbed by a sponge layer along the southern computational domain

Evidently, more research is needed to verify to which degree a possible landslide has played a role for generating this huge tsunami. This would also have implications for tsunami early warning. Morita et al. (2012) discuss evidence for offshore slumps northwest of the 2011 rupture area based on geophysical data.

3.3 East Pacific

The east Pacific comprises the coastline from Alaska and the Aleutian forearc in the north to Chile in the south. The entire coastline has obviously not been surveyed in sufficient detail, and landslide tsunami hazard assessments are incomplete. However, some examples of submarine landslide mapping or analyses of previous tsunami events or possible tsunami scenarios are available. A review of the extent and understanding of submarine landslides in the Pacific Ocean is provided by Lee (2005).

Waythomas et al. (2009) advocate that deposits of submarine landslides and subaerial volcanic flank collapse debris flows likely exist on the trench slope south of the Aleutian Islands (though not mapped yet) and conclude that plausible mass flows can generate transoceanic tsunamis of several metres at distal locations.

Most of the losses after the 1964 Great Alaska earthquake and tsunami were caused by tsunamis probably induced by secondary local submarine landslides (Lee et al. 2006). Bathymetric surveys provide detailed information about such deposits, and the tsunamis may have been composites resulting from a number of landslide events. Murty (1979) discusses the 1975 major submarine landslide in Kitimat Inlet, British Columbia, causing at least two water waves (estimated wave height of the first wave could have been 8.2 m). Kulikov et al. (1996) showed that the 1994 Skagway, Alaska, tsunami was generated by an underwater landslide formed during the collapse of a wharf.

Goldfinger et al. (2000) describe 'super-scale' landslides in Cascadia, while McAdoo et al. (2000) present an analysis of submarine landslides on the continental slopes of Oregon and central California. Fisher et al. (2005), Greene et al. (2006), and Watts (2004) all discuss the tsunami hazard related to landslides off southern California. Watts (2004) applies a Monte Carlo approach for simulating submarine mass failures off southern California over a geological timescale. His distributions of the tsunami run-up appear to fit historical tsunamigenicity off southern California (McCulloch 1985), and the results indicate that southern California may experience fewer catastrophic tsunamis than elsewhere in the Pacific Basin.

According to Tappin (2010), the Palos Verdes debris avalanche is the largest late quaternary submarine mass flow in the inner California Borderland, dated to 7500 years BP (Bohannon and Gardner 2004; Normark et al. 2004). Numerical modelling shows that it could have caused a significant tsunami (Locat et al. 2004).

Large failures have also been mapped off Costa Rica and Nicaragua (Harders et al. 2011; Hühnerbach et al. 2005; von Huene et al. 2004) and off Peru (von Huene et al. 1989). In this area, the size and recurrence of failures are predominantly controlled by subduction rate, influenced by the topography of seamounts on the incoming plate. Hence, landslides have occurred repeatedly through time (von Huene et al. 2004). Off Guatemala mass wasting is also abundant, while off El Salvador the slope failures are less developed (Harders et al. 2011). The study by Harders et al. (2011) is the first comprehensive study of submarine mass movements at a continental slope comprising an extensive section of a convergent active erosive margin. It presents an inventory of 147 slope failure structures grouped according to changes in slope preconditioning due to variations in tectonic processes and indicates that the importance of mass wasting processes in the evolution of margins dominated by subduction erosion and its role in sediment dynamics may have been underestimated. It is suggested that the rate of sliding is considerably lower than the recurrence time of large ($>M_w6$) earthquakes.

Völker et al. (2012) claim that 5–6 % of the convergent continental margin of southern central Chile is formed by submarine mass wasting processes. The three huge ones of 3–500 km^3 each (among the largest known landslide deposits at active margins) are located off the Arauco Peninsula and seem to be preconditioned by uplift of the marine forearc causing oversteepening. The youngest of the three events has a minimum age of 200 ka. New submarine landslides on the open slopes or fresh failures of canyon or slide walls do not seem to have formed as a direct result of the 2010 Maule earthquake (M_w8.8), perhaps because the average interval between giant earthquakes on this active margin spans less than 300 years (more than double the historical average of 128 years; Cisternas et al. 2005), thus stabilizing the ground on long timescales and favouring frequent small-scale landslides (Völker et al. 2011).

Finally, it was previously thought that the 1946 Aleutian tsunami (also striking Hawaii hard) was induced by a landslide (Fryer et al. 2004), but as the landslide was not resolved on later multibeam data (Rathburn et al. 2009), the tsunami source is now considered to be a so-called tsunami earthquake (Okal and Hebert 2007), that is, an earthquake with an unusually high slip compared to its magnitude.

3.4 Caribbean and Gulf of Mexico

One out of seven tsunamis worldwide takes place in the Caribbean Sea (O'Loughlin and Lander 2003). Both McCann (2006) and Zahibo and Pelinovsky (2001) estimate the tsunami threat in this region, including that from landslides. It should be noted that all Caribbean areas have not been similarly well surveyed, which is especially the case for potential submarine landslides along the margins of the Caribbean Sea (Teeuw et al. 2009). As part of a tsunami hazard and exposure study for the Caribbean, Harbitz et al. (2012) established a tsunami database with 85 definite, probable, or questionable events (Fig. 5; see also 'Appendix' for further details). In this database, 74 % of the tsunamis were caused by earthquakes, 14 % by volcanoes, 7 % by landslides, and only 5 % were of unknown origin. Fatalities were reported from 17 out of the 85 tsunamis, and more than 15,000 people have perished due to tsunamis since 1498, which means that the number of tsunami fatalities in recorded history in the Caribbean exceeds that of the U.S. West Coast, Hawaii, and Alaska combined (ten Brink et al. 2005). A thorough literature survey on non-seismic tsunamigenic sources in the Caribbean is presented by NGI (2009).

Using high-resolution bathymetric data, Deplus et al. (2001) mapped large-scale debris flow deposits on the seafloor surrounding several active volcanoes. The long run-out distances and large areas involved indicate that these flow deposits most likely represent catastrophic events also generating huge tsunamis. The age of the debris flows is probably less than 100–200 ka (Deplus et al. 2001). The individual return period of the smaller non-seismic events in the northern part of the arc can be estimated to be more than 1,000 years, while the individual return period of larger events in the southern part of the arc is more on the order of 10,000 years (Harbitz et al. 2012). Watt et al. (2012) use high-resolution geophysical data from off Montserrat to show how landslides around volcanic islands occur in multiple stages.

ten Brink et al. (2004) studied possible tsunami sources located in the Puerto Rico region, which may generate significant tsunamis mainly towards the coast of Puerto Rico, Virgin Islands, and Dominican Republic. From 160 landslides described in the area, only 9 are supposed to have volumes of more than 5 km^3 (ten Brink et al. 2006b), which could have caused tsunami run-up heights above 2.5 m. The conditions of the Mona Canyon (between Puerto Rico and Hispaniola) and its secondary canyons with their steep slopes may possibly generate submarine landslides. The combined landslide tsunami recurrence rate for the north coast of Puerto Rico from the entire carbonate platform is about 70–250 ka (ten Brink et al. 2006b). Finally, ten Brink et al. (2006a) established an inverse power-law volume frequency distribution for submarine slope failures (cf. Sect. 4) north of Puerto Rico.

ten Brink et al. (2009b) state that submarine landslide tsunami hazard should be considered in the Gulf of Mexico owing to observations of landslides along the continental

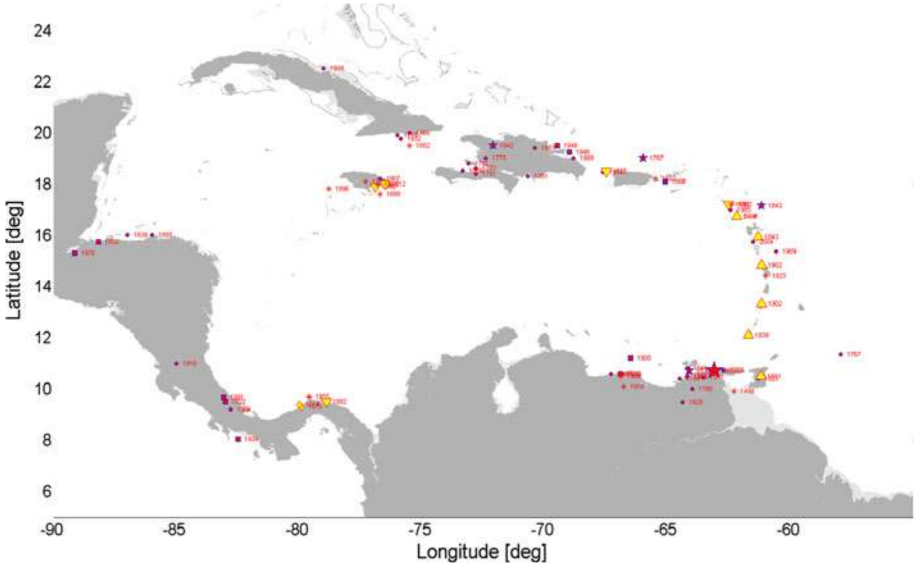

Fig. 5 Sources of tsunamis in the Caribbean with year of occurrence. *Red markers* represent seismic sources (*stars* display 8.5 > $M \geq 8.0$, *squares* 8.0 > $M \geq 7.5$, *circles* $M < 7.5$), while the *yellow upward triangles* display volcanic sources, *yellow downward triangles* display landslide sources, and *yellow rhomboids* display combined/unknown/other sources. The figure is modified from Harbitz et al. (2012) and based on tsunami catalogues as described in the 'Appendix'

margin of sufficient volume to cause destructive tsunamis. The larger landslides were probably active more than 7000 years BP, but sediment supply, especially from the Mississippi river, continuously contributes to slope steepening and increasing pore pressure in the sediments. Hurricanes or cyclic loading has also been presented as possible contributors to the initiation of submarine landslides in the Mississippi delta (Masson et al. 2006; Prior and Coleman 1982). Morphometric statistics of landslides along the US continental slopes including the Gulf of Mexico is presented by McAdoo et al. (2000) and serves as an example of how measured landslide parameter values provide insight into landslide locations, dimensions, evolution, and controlling factors such as local geology, slope, sedimentation, and erosion for various regions.

3.5 Northwest Atlantic

Submarine investigations have revealed a number of past landslides offshore the eastern US and Canadian coastlines (Chaytor et al. 2009; Hühnerbach et al. 2004; McAdoo et al. 2000; Piper and McCall 2003; Twichell et al. 2009; Urgeles et al. 2002). The most well-known event here is the 1929 Grand Banks earthquake and landslide that generated a tsunami of regional impact (Fine et al. 2005; Heezen and Ewing 1952; Piper et al. 1999). This M 7.2 earthquake is moreover important since it occurred in a so-called stable continental region. Chaytor et al. (2009) showed that the cumulative volume distribution of the failure scars along the US Atlantic margin is well described by a lognormal distribution. Modelling of the possible tsunami from one of the largest of the ancient events, the 165 km^3 Currituck landslide (Locat et al. 2009), reveals a potential for a devastating tsunami impact (Geist et al. 2009). A probabilistic tsunami hazard assessment (see below) for landslide tsunamis based on slope stability parameters by Grilli et al. (2009) suggested a potential for moderately large run-up of 3–4 m offshore New York and New Jersey for a 500-year return period. It is worth noting that many of these landslides are located in areas of relatively low seismicity. In the review of Lee (2009), the onset of major landslides on the Atlantic Ocean Margin is heavily linked to glacial cycles in a similar fashion as for the landslides offshore Norway (Solheim et al. 2005b). Glacial transport of sediments was found to be the only mechanism capable of providing sufficient volumes and sufficiently high sedimentation rates to form overpressure zones crucial for landslide release and subsequent evolution. Time effects such as consolidation and pore pressure dissipation may reduce the tsunami hazard (and timing in relation to the glacial cycle must be accounted for also here). Other geological processes like sediment deposits from rivers, etc., also contribute, but not to a similar extent.

3.6 Arctic Ocean and East Atlantic

Submarine landslides along the European and African continental margins have been extensively studied (see e.g. Canals et al. 2004; Mienert 2002), the main areas covering the Norwegian margin (e.g. BGS 2009; Bugge et al. 1988; Elverhøi et al. 2002, 2010; Laberg and Vorren 2000, Laberg et al. 2000; Laberg et al. 2003), the Mediterranean (e.g. Camerlenghi et al. 2010; Lastras et al. 2004; Urgeles et al. 2006), as well as western Africa and the Canaries (see Sect. 3.8). Evidence for large landslides is also found north of Svalbard (Vanneste et al. 2011b) and in the Canada Basin (Mosher et al. 2012). The Norwegian margin is particularly well covered due to the studies related to the Ormen Lange gas field explorations (Solheim et al. 2005a; Bryn et al. 2005; Haflidason et al. 2005). As already noted, the glacial cycle must be taken into account when assessing the hazard in such regions. As a consequence, there is currently no potential for major tsunamigenic landslides originating from the Storegga landslide escarpment (Kvalstad et al. 2005a; Nadim et al. 2005). Areas such as the glacially dominated North Sea or Bear Island fans may comprise masses prone to release of larger landslides (Elverhøi et al. 2010; Harbitz et al. 2009), but also here consolidation and pore pressure dissipation reduce the tsunami hazard.

A possible cause of increased tsunami hazard in this region is increased seismicity due to reduced ice loads and subsequent isostatic land uplift during global warming (Berndt et al. 2009). In fact, the seismicity is even at present significant along the east coast of Greenland, where there are large thicknesses of poorly consolidated sediments. Any large-scale slope failure there would generate a tsunami that could threaten the coasts of northwest Europe (BGS 2009). Excess pore pressure build-up from possible gas hydrate dissociation due to warming has also been mentioned with regard to increased tsunami hazard. However, to the authors' knowledge, a causal relationship between hydrate dissociation (causing excess pore pressure) and submarine landslides is not proven as yet, and evidence remains largely circumstantial (see e.g. Kvalstad et al. 2005b). Furthermore, no large hydrate provinces are documented in the Arctic Ocean (but this does not exclude their existence).

For a Northeast Atlantic hazard assessment, Harbitz et al. (2009) identified submarine landslides off the Norwegian continental margin as sources constituting moderate tsunami hazard. For comparison, earthquake sources off Portugal were also identified as sources constituting moderate tsunami hazard, while rock slides in the fjords of Western Norway were considered the only high-hazard tsunami source (the fjords in Greenland have not been investigated).

The clear tsunami potential for large deep-water slope failures on the northern flank of Gorringe Bank on the southwest Iberian margin is demonstrated by Lo Iacono et al. (2012).

Off North Africa there are five or six large submarine landslides (Tappin 2010), including the ~60 ka BP Saharan (600 km^3) debris flow occurring during rapid sea-level rise after a significant lowstand (Gee et al. 1999; Krastel et al. 2012). The smaller Cap Blanc Slide (<20 km^3) off Mauritania has a 25 m high headwall at ~3,575 water depth and a minimum age of 165 ka corresponding to a sea-level lowstand (Krastel et al. 2012). Further south, the headwall scarps of the Mauritania Slide (4–600 km^3) occur as a series of 25–200 m high steps from 600 to 2,000 m water depth. The uppermost debris is dated to 10.5–10.9 ka BP, that is, the end of Last Glacial Maximum sea-level rise. Seismic data show several buried units and a long history of instability. The Dakar Slide offshore Senegal shows a headwall length of at least 100 km at a water depth of 2,000–3,100 m, a minimum volume of 1,000 km^3 excluding unmapped distal deposits, and features pointing to a retrogressive failure (Meyer et al. 2012). Based on sedimentation rates, the minimum age of the landslide is 1.2 Ma. It is underlain by multiple giant mass transport deposits (reaching back to Oligocene times). The continental slope off Senegal reveals clear indications of recent failures, but the recurrence rate of large landslides is here low (>2 Ma). Likewise, the probability of future large-scale slope failures during the current highstand is generally considered to be low off northwest Africa (Krastel et al. 2012).

3.7 The Mediterranean and the Marmara Seas

The Mediterranean region is relatively complex both tectonic-wise and with respect to landslide potentials. Examples of landslide tsunamis in the Mediterranean are revealed from the historical tsunami database (Tinti et al. 2004; TRANSFER 2013). Historically, several smaller local events have occurred. In 1979, parts of Nice airport were affected by a man-made local landslide inducing a tsunami (Assier-Rzadkiewicz et al. 2000; Dan et al. 2007; Sahal and Lemahieu 2011). Another recent example is a tsunami due to the mainly submarine landslide (both preceded and followed by smaller volume subaerial landslides) off the Stromboli volcano (Chiocci et al. 2008; Tinti et al. 2005, 2006, 2008). One of the most devastating landslide tsunamis in this region is the subaerial 1783 Scilla tsunami (landslide triggered by a M_w5.8 earthquake), killing about 1,500 people (Graziani et al. 2006; Mazzanti and Bozzano 2011; Tinti and Guidoboni 1988). On a longer timescale, geological evidences account for several large landslide deposits of considerable tsunamigenic potential (Camerlenghi et al. 2010). One of the largest landslides detected in the Mediterranean is the 11,500-year BP BIG′95 landslide (Lastras et al. 2004; Urgeles et al. 2006), involving a total volume of 26 km^3. Recent tsunami simulations demonstrate that such landslide volumes may cause catastrophic tsunamis (Fig. 1; Iglesias et al. 2012; Løvholt et al. 2013). Several landslides on the Nile Fan (Garziglia et al. 2008; Loncke et al. 2009) and on the Rhône Fan (Droz et al. 2003) are much larger. The largest event in the Mediterranean is the 500 km^3 'Megaturbidite' in the Balearic Abyssal Plain (Rothwell et al. 1998). It is, however, debated whether this originates from just one event or from a series of failures. Radio-carbon dating reveals ages of about 17.6 ka BP at the top and about 20.3 ka BP at the bottom (Droz et al. 2003, 2006).

Also, the Marmara Sea has received considerable attention, much because of heavy population. Reviews of past historical events and present tsunami hazard (also including earthquake tsunamis) are presented by Hebert et al. (2005) and Yalçiner et al. (2002). The first ones describe that some of these events appeared as a series of slumps causing high local waves, strikingly similar to several of the slump tsunami events in Southeast Asia reviewed above. The submarine landslide potential of the Marmara Sea is further discussed by Gokceoglu et al. (2009). It could also be mentioned here that the catastrophic inundation of the Black Sea resulting from the collapse of the Bosporus gateway in early Holocene implies another mechanism that is not yet fully resolved (Ryan and Pitman 1999).

3.8 Major landslides originating from Hawaii and the Canaries

Ocean islands such as Hawaii and the Canary islands have the greatest relief of any topographic feature on Earth and have been subject to large subaerial and submarine landslides with volumes ranging from tens to thousands of km^3. The Nuuanu landslide, off Oahu in the Hawaiian Islands, with an estimated volume of 5,000 km^3, may be the largest known single landslide on Earth (Moore et al. 1989, 1994).

For the Canary Islands, the bulk of landslide activity is associated with the youngest and most volcanically active islands of Tenerife, La Palma, and El Hierro (Masson 1996; Masson et al. 2006; Urgeles et al. 1997). On average, one landslide has occurred somewhere in the Canary islands every 100,000 years (Masson et al. 2002), typically involving volumes of 50–200 km^3. Detailed sedimentological analyses from the Moroccan Turbidite System have revealed that their source landslides probably occurred in several retrogressive stages over a period of hours or days rather than weeks or months (Hunt et al. 2011; Wynn and Masson 2003), which is critical when assessing their tsunamigenic potential. As a consequence, transatlantic tsunamigenic potential has been disputed (Pararas-Carayannis 2002). Yet, tsunami analysis considering large volumes up to 500 km^3 released simultaneously reveals devastating consequences for a broad section of the coastlines facing the Atlantic (Løvholt et al. 2008; Ward and Day 2001). Order-of-magnitude smaller volumes would still imply catastrophic effects locally (Abadie et al. 2012), but their far-field effects are likely to be less.

Similar to the Canaries, seabed deposits off Hawaii reveal evidence for large landslides, and the largest ones greatly exceed those offshore the Canaries. The landslides are developed in the early stages of the history of the volcanoes and are divided into two separate categories, that is, slow-moving slumps with large thickness and fast-moving debris avalanches (Hunt et al. 2011; Moore et al. 1989). A landslide of the last kind is the likely cause of observed tsunami deposits on Lanai Island (Moore and Moore 1984). This has later been supported by numerical simulations of tsunamis induced by the Alika submarine landslide off Hawaii, considered from a tsunamigenic point of view as a single high-speed event causing tsunami run-up heights in agreement with the observations on Lanai Island (McMurtry et al. 2004). A smaller tsunami off the island of Kilauea is further claimed to be partly due to a slump (Day et al. 2005). However, as for the Canaries, there are conflicting viewpoints on whether tsunamis from volcanic islands, including Hawaii, pose a threat to distant communities (e.g. McGuire 2006).

4 Landslide recurrence and uncertainties—field evidence

Hazard assessment of landslide tsunamis comprises analyses of geological and geotechnical field data in combination with numerical simulations or laboratory experiments to assess previous events, slope stability, possible triggers, release mechanisms, and landslide evolution (i.e. tsunamigenic power) as well as tsunami generation, propagation, and inundation. Empirical and/or statistical relations can be applied to further determine likelihood and add information on probable landslide processes (e.g. McAdoo et al. 2000, Camerlenghi et al. 2010; ten Brink et al. 2006a, 2009c). Guzzetti et al. (2005) propose an approach for subaerial landslides based on a multi-temporal landslide inventory map (produced from interpretation of multiple sets of aerial photographs taken at different times) capturing type, size, and expected recurrence of failures. This method can probably be adapted to express submarine landslide hazard as the joint probability of landslide size, landslide occurrence in an established period of time, and landslide spatial occurrence given the local environmental setting. For a complete risk assessment, tsunami vulnerability analyses and assessment of consequences are also needed.

Basic considerations relating to recurrence intervals comprise similarities between previous landslides in the area, their age and occurrence frequencies, and whether similar events occur under present conditions. More specifically, one also needs to check whether the landslides relate to post-glacial periods, to periods of enhanced isostatic land uplift, and to earthquakes, temperature changes, consolidation, pore pressure dissipation, etc. When considering the likelihood, sea level also plays a role. During glacial maxima, sea levels were at about -120 m elevation (e.g. Fleming et al. 1998). The coastline was therefore close to the shelf break in most places, and sediments were deposited directly on the continental slope (obviously depending on the local geometry). Hence, several large-scale submarine landslides occur during sea-level lowstands. The number of landslide tsunamis at sea-level lowstands may in addition be underestimated as their tsunami deposits are not detected at subsequent higher sea level. Further, changes in sea level will disturb the equilibrium and may cause reworking of the sediments, also favouring landsliding. Higher sea level favours landsliding closer to the present shoreline. In summary, the authors believe that the landslide likelihood is higher during periods of sea-level lowstands or sea-level changes and lower at sea-level highstands, but this obviously also depends on coincidence with glacial cycles.

The tsunamigenic submarine landslides are rare on a human timescale, so the statistics are sparse. Nevertheless, estimates of recurrence rates may still be addressed. Firstly, these may be obtained from tsunami records that extend over a relatively short timescale (e.g. Burroughs and Tebbens 2005). Basic statistics from the database of the NOAA National Geophysical Data Center (NGDC 2013) reveals that 81 % of the historical tsunami events are induced by earthquakes, 7 % by landslides or combined landslide–earthquake or landslide–volcano sources, and 5 % by volcanoes or combinations of volcanoes and earthquake sources. In addition, 5 % of the sources are termed unknown (Fig. 6). As landslides were previously often not considered as plausible sources, a significant portion of the sources termed as unknown may also have been caused by landslides. In the database query, tsunamis categorized as erroneous or very doubtful and tsunamis induced by unknown sources are here ignored.

Secondly, on land paleotsunami deposits have been used to determine return periods, even though it is normally challenging to relate the deposits to specific sources. Thirdly, the use of offshore tsunami deposits is an emerging field. Marine deposits with their good preservation offer significant opportunities for stratigraphic correlation, which in turn can be used to examine recurrence models because of the longer time intervals available (Goldfinger 2009, 2011). On the other hand, in shallow marine settings tsunami deposits are difficult to distinguish from storm deposits, etc., and may well get reworked and erased by storms and other oceanographic processes over longer timescales, while in deep marine settings tsunamis are perhaps not commonly recorded by deposits (P. Talling pers. comm. 2013). Estimation of likelihood based on tsunami deposits must be done with caution as a large tsunami event may be detected in several places or small deposits suffer erosion and may disappear. Fourthly, landslide recurrence may be obtained from geomarine field investigations. Geomorphological analyses can reveal submarine landslide deposits on the seabed and be used to quantify the likelihood of submarine landslides within similar

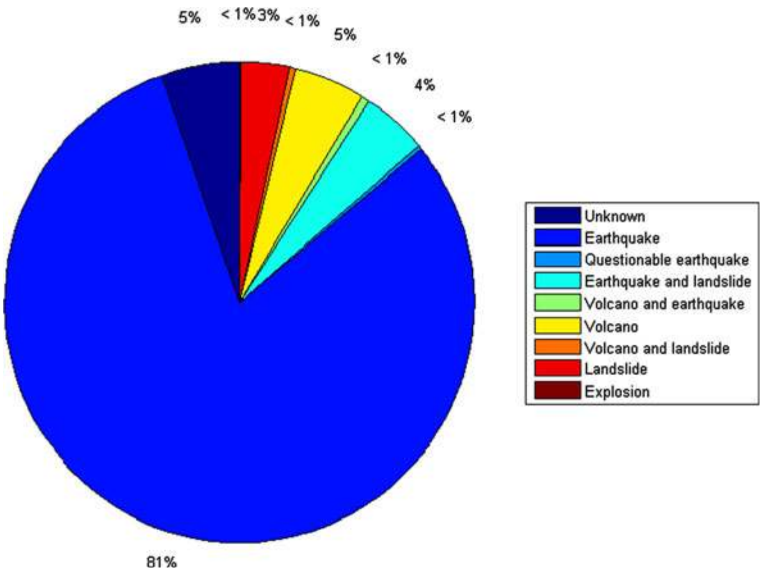

Fig. 6 Relative occurrence of various historical tsunami sources based on the NOAA/NGDC tsunami database (NGDC 2013)

geologic domains (ergodicity). However, the record from submarine geomorphology is biased towards Holocene events (Camerlenghi et al. 2010).

Furthermore, seismic profiles and stratigraphic investigations of the seabed combined with dating techniques can tell about the recurrence rate in a specific location (Geist and Parsons 2010) and have in some cases enabled coupling of tsunami deposits to submarine landslide sources with a high degree of certainty (e.g. Bondevik et al. 1997; Young and Bryant 1992). ten Brink et al. (2009a) estimate tsunami probabilities by linking landslides along the US east coast with adjacent earthquake ground motions (suggesting that a M_w7.5 earthquake must be located offshore within 100 km of the continental slope to induce a catastrophic slope failure). By combining the likelihood of occurrence with statistics of, for example, number of events as a function of volume and finally statistics of travel distance as a function of volume, it is possible to estimate roughly the likelihood of a future scenario (see also Sects. 2 and 3.4). Again, special attention must be paid to regional and geological conditions as well as climatic premises and changes.

Tsunami hazard analysis ideally goes one step further to address the temporal probability of a tsunami metric at a certain location or for a region (or even globally). Most tsunami hazard assessments have been scenario-based and focused on earthquake tsunamis (e.g. Grilli et al. 2010; Lorito et al. 2008; Løvholt et al. 2006, 2012a, c; McCloskey et al. 2008; Okal and Synolakis 2008; Okal et al. 2006b; Okal et al. 2011; Parsons and Geist 2009; Tang et al. 2009; Tinti and Armigliato 2003). In all these studies the scenarios are defined as events that could occur in the future or as credible worst-case scenarios, often weakly related to probabilities or return periods. More recently, however, a Probabilistic Tsunami Hazard Assessment (PTHA, largely inherited from Probabilistic Seismic Hazard Assessment) approach has been developed (Anita et al. 2010; Annaka et al. 2007; Geist and Parsons 2006; González et al. 2009; Sørensen et al. 2012; Thio et al. 2010).

When conveying PTHA to landslide tsunamis, challenges and limitations quickly arise, firstly because landslide data usually do not provide equally good statistics as earthquake data do (for estimation of annual probability of earthquake-induced submarine slope instability by integrating geotechnical evaluations and dating of previous landslide events, see Nadim 2012).

Secondly, landslide tsunamis are more local than earthquake tsunamis, in the sense that the hazard is more sensitive to source location and mechanisms for landslides than for earthquakes. Whereas the mechanics of the seabed deformation due to subduction zone dip-slip earthquakes follow well-established models, the landslide dimensions, the trigger and release mechanisms, as well as the dynamics are far more diverse and depend to a larger degree on the location (i.e. slope, stratification, channelling, and sediment properties). Hence, local geological and geotechnical settings are crucial and so are appropriate models for the landslide release and evolution.

The added value of current probabilistic models can be questioned when available data are limited and the risk assessment therefore is thus crucially dependent on engineering judgement. Still, landslide parameters exhibit uncertainties (sometimes also introduced from judgement) that should be accounted for. For the earthquake tsunamis, variation in co-seismic slip implies a significant uncertainty in tsunami run-up heights (McCloskey et al. 2008; Løvholt et al. 2012b). Quantifying this uncertainty implies a stochastic distribution of source elements representing the rupture, with scaling relations governing the distribution of source elements (e.g. Mai and Beroza, 2002). Similar scaling laws are lacking for landslides, implying that this uncertainty is likely even greater for landslide tsunamis. This calls for other and perhaps more general random source distributions and stochastic approaches. Recently, a limited number of studies have addressed distributed sources for landslides (e.g. Brune et al. 2010a; Anita et al. 2012). Due to the need for computing many scenarios, largely simplifying assumptions related to landslide evolution, wave generation, propagation, and amplification were taken, many of analytical nature and likely too limited for general use.

In addition to the problems that arise in determining the probabilities and the evolution of the landslides when the statistics are sparse, it is also expected that the tsunami risk is dominated by large return periods on the order of hundreds or thousands of years, generally carrying the largest uncertainties (e.g. Nadim and Glade 2006; Løvholt et al. 2012a). Furthermore, it is expected that for tsunamis there is a threshold for the tsunami metric (i.e. flow depth) where the vulnerability (e.g. mortality as a function of flow depth) changes rapidly, indicating a strong nonlinearity in the relation between the metric and the consequence. Landslide tsunami risk is therefore difficult to predict based on empirical data that cover only a few hundred years, even though field evidence of landslides and paleotsunamis may provide supplementary data. Moreover, today’s tsunami vulnerability models are few and premature; hence, landslide tsunami risk estimates are anyhow uncertain.

5 Discussion

5.1 Are extreme values part of a distribution?

It is well established that the number of subaerial landslides (large numbers available) versus volume is lognormally distributed, which is the dominating statistical distribution for most observations in Nature. This means in turn that they display self-similar (scaling invariant) characteristics. For earthquake ground motions, which are distributed in the same way, it was thought for a long time that the earthquake ground motions had truncated distributions and that these limits tended to occur already at 2–3 standard deviations. However, a significantly increased body of high-quality observations has shown (Strasser and Bommer 2009) that the observations follow the lognormal distribution at least up to four standard deviations (this requires about 10,000 observations to cover). A similar adherence to the distribution should be expected also for subaerial landslides, even if the sampling here is more difficult than for earthquake ground motions. This means, in turn, that if the distribution is truncated at the upper end, it is only because greater volumes are not physically possible. We do not know whether we have a similar situation with submarine landslides. However, the mere existence of mega landslides like Storegga or Nuuanu is a strong indication that also this distribution is quite wide and thus would allow for extreme events also in the future. However, there are two potential problems that should be taken into account in this respect.

Firstly, we have a problem with sample size, or 'the law of small numbers' (e.g. Kahneman 2012), which implies that extreme values are much more likely to (apparently) occur from small samples than from large samples. This implies in turn that the extremity of the observations is more easily overrated when we do not have a sufficiently wide body of observations to judge from.

Secondly, as mentioned already in this paper, it is a problem that we are working with observations quite unevenly spaced in time. As an example, the extreme 8150-year BP Storegga Slide occurred immediately after the last glaciation, at a time of much higher seismicity in the recently glaciated areas than at present (Bungum et al. 2005), and moreover at a time ($\sim$8.5 to 8.1 years BP) when a cluster of potentially abrupt catastrophic events in the North Atlantic-Mediterranean region seemed to occur. Hence, if the older events in the database belong to a different distribution, they cannot be included statistically with the recent observations.

Another possible statistical approach for delineating this would be to use extreme-value statistics, such as the Gumbel distribution, but this is also likely to fail in the present case since the extreme values are also poorly sampled (this approach requires normally extreme values within consecutive time windows of equal length).

Our conclusion here is that it will be difficult, due to insufficient sampling, to establish a reliable distribution for the available submarine landslide observations, which as noted above is also a major obstacle for a PTHA approach. It seems like we have to revert to a more simple and data-driven approach where we extract information from observations without the benefit from the underlying statistical distributions.

5.2 A robust first-order approach for landslide tsunami hazard assessment

It follows implicitly from the above review that the probability of a tsunami exceeding a certain value is often dominated by one (risk-driving) event. Hence, it may still be most efficient to use the more robust scenario-based tsunami hazard assessment (SBTHA) approach. Yet, the dilemma is that the most important risk-driving events are also generally not known. In contrast, PTHA would provide a probabilistic representation of the hazard with large epistemic (knowledge based) uncertainties related to location, release mechanisms, evolution, and return periods of the scenarios, and with much higher computational resources. There are also reasons to believe that the aleatory (random) uncertainties will tend to be underestimated.

Altogether, this would cause either underestimated PTHA results due to unrealistic assessment of uncertainties, or very high hazard levels driven essentially by large uncertainties. Hence, the simpler SBTHA approach is likely to give at least equally good results when scientific judgement is crucial for the hazard assessment.

6 Concluding remarks

6.1 Present landslide tsunami hazard assessment

Preconditioning factors and triggering mechanisms for submarine landslides are discussed in this paper together with a large number of examples substantiating that submarine landslides may occur on most continental margins. Landslide dimensions and mobility governing the tsunami characteristics can gain extreme values. Moreover, submarine landslides are hard to monitor or predict. Hence, submarine landslide tsunamis may be extreme in terms of both run-up heights and consequences.

Submarine landslide and volcano flank collapse tsunamis are most often local, but extreme landslide events are potentially catastrophic tsunami generators with regional impact that even exceed tsunamis induced by megathrust earthquakes (as seen e.g. from Abadie et al. 2012; Bondevik et al. 2005; Løvholt et al. 2008). However, it should be kept in mind that the size of a landslide is not necessarily proportional to the hazard it poses. Smaller landslides in near-shore areas may have devastating effects, while continental margin landslides that occur on very low slopes, far from land, may form relatively slowly by retrogressive processes limiting tsunamigenesis.

The overall tsunamigenic potential of the continental margins is obviously difficult to assess since important segments are not mapped in sufficient detail. There are, notably, huge unreleased sediment volumes in several places, for example, glacially dominated submarine fans in the Northeast Atlantic, in the Arctic Ocean (Harbitz et al. 2009, Mosher et al. 2012), and in the fluvially dominated Mississippi delta (ten Brink et al. 2009b). The giant submarine landslides are rare and related to climate changes and/or glacial cycles (time intervals between individual events span from hundred ka to Ma). This indicates that giant submarine landslide tsunami hazard is in most regions negligible compared to earthquake tsunami hazard. Large-scale debris flows surrounding active volcanoes or submarine landslides initiated by sediment supply in river deltas may have return periods one order of magnitude less, for example, in the Caribbean and the Gulf of Mexico.

Giant volcano flank collapses at the Canary Islands occur on average every 100 ka and are associated with the youngest and volcanically most active islands (Masson et al. 2006). Retrogressive multistage release mechanisms possibly reduce the tsunamigenic potential of these collapses. The landslide deposits off Hawaii are developed in the early stages of the history of the volcanoes (estimated ages range from tens of ka to tens of Ma; McMurtry et al. 2004), and volumes greatly exceed those offshore the Canaries.

The historical submarine landslide events have comprised more modest landslide volumes and thus caused more local tsunami impact. Among these, the 1929 Grand Banks, the 1992 Flores, and the 1998 Papua New Guinea landslides were all triggered by earthquakes. Submarine landslides triggered by the earthquakes possibly also intensified the 1908 Messina (Billi et al. 2008; Favalli et al. 2009), the 1945 Makran, the 1964 Alaska, the 2006 Java (Fritz et al. 2007), the 2009 Suruga Bay, and the 2011 Tohoku tsunamis. It should be kept in mind that frequent violent earthquakes might induce frequent smaller landslides rather than rare and large landslides, thus reducing the landslide tsunami hazard, while the larger landslides occur along passive continental margins. For the 1979 Nice, the 1994 Skagway, and perhaps the 1975 Kitimat Inlet landslide tsunamis, the trigger mechanisms were probably anthropogenic. Volcano flank collapses have also caused several local tsunamis in historical times.

Transporting probabilistic methods to landslide tsunami hazard assessment is challenging as recurrence rates and likelihood as well as the tsunamigenic seabed deformation are much more uncertain owing to limited observations, dating, and statistics, as well as to changing conditions for landslide release. Moreover, it is expected that the landslide tsunami risk is dominated by large return periods, generally carrying the largest uncertainties. It is concluded that insufficient sampling is a major obstacle for a landslide tsunami PTHA and that it will still be most efficient to use the more robust Scenario-Based Tsunami Hazard Assessment (SBTHA) approach. On the other hand, a PTHA approach will provide a probabilistic representation of the hazard with large epistemic uncertainties related to location, release mechanisms, evolution, and return periods of the scenarios. The aleatory uncertainties will probably also be underestimated.

It has been proposed that global warming followed by increased seismicity around the edge of the present-day ice sheets (in particular Greenland) will trigger slope instability, thereby influencing the landslide tsunami threat (Berndt et al. 2009). In addition, ocean warming may lead to hydrate melting and reduced slope stability. Other predictions resulting from increased global temperatures include increased storminess and changes to the seasonality of rainfall as well as rises in global sea level (BGS 2009).

6.2 Future needs, research, and prospects

In most continental margins, a more complete mapping of landslide sources would certainly improve assessment of landslide tsunamigenic potential. For the past events, mechanical analyses of the release, disintegration, and flow mechanisms will help in understanding landslide dynamics. Laboratory-scale experiments and the pertinent discussions on how they relate to corresponding natural phenomena are particularly important for submarine landslides that are difficult to observe at full scale (e.g. Breien et al. 2010; Elverhøi et al. 2010). Further, better dating would improve assessment of recurrence and relation to climatic or glacial cycles. Tsunami source statistics as shown in Fig. 6 elaborated in more detail for the various regions would also be helpful in landslide tsunami hazard assessment.

For potential sources, more sophisticated investigations are needed with respect to potential trigger mechanisms, slope stability, source locations, and source parameters with corresponding recurrence rates. Probability distributions, heterogeneities, randomness, and uncertainties should preferably be constrained by analysis of field data and used as input to both numerical tsunami propagation models and probabilistic hazard and risk assessment. For risk assessment and quantification of uncertainties, probabilistic methods that properly take into account the physics of the complex landslide evolution and tsunami generation process are desirable. Quantification of both distributions (mean values as a minimum) and uncertainties of source parameters constitutes a fundamental basis for a possible PTHA approach. However, efficient source parameterization has to be made in a way still enabling sensitivity analysis.

Monitoring of critical areas where landslides might be imminent as well as (deterministic and probabilistic) numerical modelling of landslide tsunamis for improved understanding and for hazard and risk assessment appear to be areas where advances are possible (Masson et al. 2006). Challenges related to the numerical modelling arise as submarine landslides are complex and may have huge dimensions and long run-out distances. Landslide transformation from slab to smaller blocks and further to a dense fluid, including the timing of the upslope retrogressive release, is crucial for landslide tsunami generation, albeit not much studied. Material properties, including clay rheology, are of great importance for the dynamics of most events. Mud type mass gravity flows will entrain water and produce turbulence and large vortices that cannot be conveyed properly to a depth-integrated model, while viscous drag may have a crucial influence on the shape and dynamics of the mud flow. Further, shear thinning and high-resolution grids are considered vital to model shear bands as observed in high-resolution profiles.

At present, the simplest models describe the landslide as a block or as a depth-averaged debris flow, while more elaborate approaches comprise vertical transect strain-softening models for submarine landslides accounting for retrogression, or multi-material models in three dimensions (the latter are computationally too costly for most practical applications). Such models were developed in the Ormen Lange project and helped to understand the basic principles of retrogression and its influence on tsunami generation (Gauer et al. 2005; Haugen et al. 2005; Kvalstad et al. 2005a). Combining models for the evolution of retrogressive landslides with the more sophisticated tsunami propagation models will be a huge step forward in the field of landslide tsunami research.

The prospects for the future are promising as an increased area of seafloor is being mapped at high resolution, supplemented by contributions from industry with quality data sets that are not necessarily accessible to the public or the academic community. Exploration and development in deep water has prompted industrial interest in submarine mass movements with regard to both geohazard assessment and the potential for creating hydrocarbon traps or reservoirs. Hence, it is expected that submarine mass movements and their tsunami potential will acquire a higher public profile (Mosher et al. 2010).

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Appendix

Figures 2 and 5 are mainly based on databases of the NOAA National Geophysical Data Center (NGDC 2013) and the Novosibirsk Tsunami Laboratory (NTL 2013). For many of the events the source information is corrected based on recent updates of earthquake locations, focal depths, magnitudes, and tsunami observations (BRGM 2009; Engdahl and Villaseñor 2002; Engdahl et al. 2007; E. R. Engdahl pers. comm. 2007; Villaseñor and Engdahl 2007). Using the validity index describing how likely it is that the record is a tsunami or not, tsunamis categorized as erroneous or very doubtful were removed from the queries, whereas data being categorized as questionable, probable, or definite are included. Some data have also been removed (by us) after a careful inspection of the literature sources. Parameters assigned by NOAA/NGDC for recent events were largely reliable, but discrepancies are expected to be prominent for the older events.

If sources are categorized as earthquake or probable earthquake, they are referred to as earthquakes in the visualization and the statistics. For the earthquakes, we include the magnitude, which might be of unspecified kind, or reported as the surface wave magnitude M_s or the moment magnitude M_w. Moreover, for a number of the earthquakes, particularly the oldest ones, the magnitude is not reported. Where combinations of sources are reported, sources are grouped into one of the main categories (landslides or volcanoes) to simplify the visualization. For Fig. 2 the two databases are supplemented with papers describing certain events (Imamura et al. 1995b; Natawidjaja et al. 2006; Ortiz and Bilham 2003; Satake and Atwater 2007). For Fig. 5 the two databases are in turn based on tsunami catalogues compiled by Mercado-Irizarry and Liu (2006), O'Loughlin and Lander (2003), and Shepherd et al. (1995). The results should be used with caution, as there are large uncertainties related to these data. For further information on the databases, see Harbitz et al. (2012), Løvholt et al. (2012c), and NGI (2011).

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