Part II
Submarine Landslide Deposits in Current Active and Passive Margins

12

Modern Submarine Landslide Complexes: A Short Review

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ABSTRACT

Submarine landslides have been identified in almost all ocean basins worldwide. The largest submarine landslides occur on very shallow slopes and can be far larger than any terrestrial landslide. Submarine landslides can produce tsunami whose far-reaching effects can rival those produced by earthquake-tsunamis and threaten increasingly populated coastlines. Even small landslides can damage very expensive and critically important offshore infrastructure, such as pipelines used for oil and gas recovery, and telecommunication cables that now carry over 95% of digital data traffic. A better understanding of submarine landslide processes, including triggering mechanisms, preconditioning factors, timing, and frequency as well as dynamics of submarine landslide, and their consequences are of clear societal and economic importance. Despite their importance, many fundamental submarine landslide processes are still poorly understood. We currently have many studies that have mapped and sampled submarine landslide deposits; however, in order to fill outstanding but key knowledge gaps, future studies may have to go beyond this in order to unravel processes governing submarine landslides with even more interdisciplinary approaches. This chapter provides a very short review about submarine landslide studies, with emphasis on the emerging needs in future landslide research.

12.1. GENERAL CHARACTERISTICS AND PECULIARITIES

Submarine landslides occur on virtually all ocean slopes worldwide. They cover a wide range of settings, from passive to active continental margins, river-fed pro-deltas, and submarine fans, on the flanks of volcanic islands as well as glaciated and sediment-starved margins (e.g., Hampton et al., 1996; Hühnerbach et al., 2004; Masson et al., 2006; Twichell et al., 2009; among many others; e.g., Figure 12.1a). It is apparent that submarine landslide deposits form a significant proportion of the sedimentary succession of all continental margins, both active and passive (Hampton et al., 1996; Boyd et al., 2010; Giles et al., 2010). For example, the surface expression of mass-wasting deposits covers a large percentage of the Mediterranean Sea (18%) and of the Gulf of Mexico (27%) (McAdoo et al., 2000; Urgeles & Camerlenghi, 2013).

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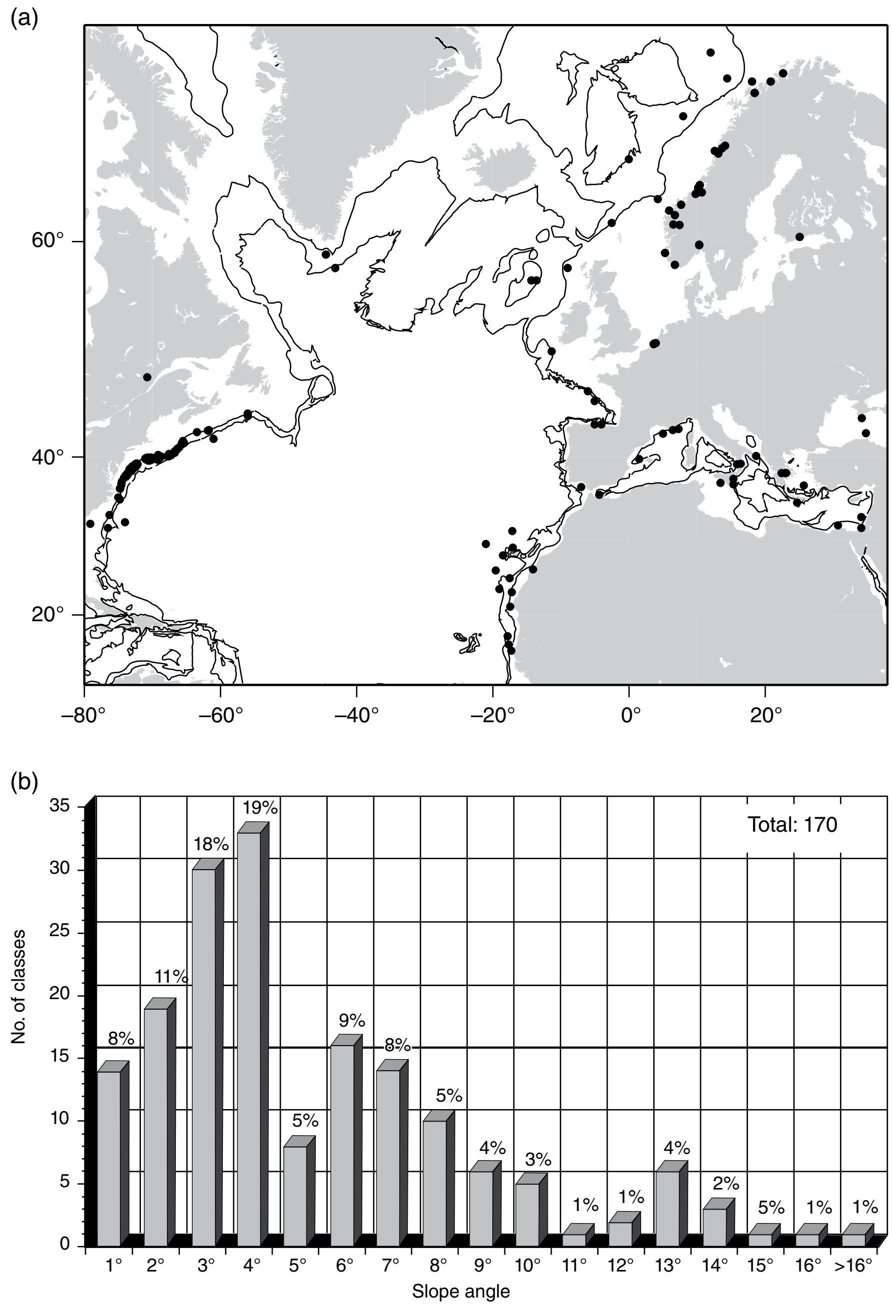

Figure 12.1 (a) Exemplarily mapped slope failures in the western and eastern North Atlantic including adjacent seas (Mediterranean Sea, Black Sea, Baltic Sea), fjords of Norway and eastern Canada, and failures in other limited/confined areas. Each point represents a single failure or slope failure complex. Source: From Hühnerbach et al. (2004). (b) Frequency distribution of empirical compiled data from modern examples of submarine landslides with increasing slope angle along the U.S. Atlantic continental slope. Source: After Shanmugam (2015).

The largest submarine landslides can affect more than 10,000 km^2 of the seafloor and involve >1000 km^3 of sediments. Some well-known, extremely large examples include the Storegga Slide (e.g., Bryn et al., 2003; Haflidason et al., 2004), the Trænadjupet Slide (e.g., Laberg & Vorren, 2000), the Hinlopen Slide (e.g., Vanneste et al., 2006; Winkelmann et al., 2008), and the Sahara Slide Complex (e.g., Embley, 1980; Georgiopoulou et al., 2010). These failed materials can move downslope for hundreds of kilometers (e.g., Masson, 1994). Landslides transforming into turbidity currents can flow even longer distances, and their deposits are capable to cover large parts of ocean basins (e.g., Masson, 1994; Talling et al., 2007; Hsu et al., 2008). Thus, submarine landslides can be several orders of magnitudes larger than their terrestrial counterparts. Perhaps even more remarkably, submarine landslides can occur on exceptionally low gradient slopes (<1°; Figure 12.1b), which are almost always stable on land (Field et al., 1982).

As summarized by Urgeles and Camerlenghi (2013), submarine landslides have unique peculiarities compared to their much better studied onshore equivalents: (a) specific sediment types, which allow (i) failure to occur on very low slope gradient (Figure 12.1b) and potentially (ii) exhibit a high degree of remolding (e.g., Tanaka & Locat, 1999; Volpi et al., 2003; Løvholt et al., 2017); (b) the common presence of fully saturated sediments, which may be charged with dissolved gas and thus might cause hazardous effects in case of unloading (Tréhu et al., 2004; Vanoudheusden et al., 2004; Sultan et al., 2008); and (c) the ambient seawater, which might cause long failure runout due to hydroplaning at their flow front (Mohrig et al., 1998; Harbitz et al., 2003; De Blasio et al., 2006). Furthermore, the environmental stresses imposed on the seafloor (e.g., water hydrostatic pressure and currents resulting from tides, waves, and internal waves) create additional unique conditions for submarine landslides. Therefore, although the physical behavior of submarine landslides builds on understanding of terrestrial soils (e.g., Lambe & Whitman, 1969), boundary conditions for the material involved in submarine landslides are significantly different, and similarities between the morphologies of emerged and submerged slope failures may belie totally different processes.

The continental margin architecture and slope stratigraphy, in particular the stacking of layers with different physical properties or permeabilities, play an important role where failure surfaces are localized in the sediment stratigraphy. The concept of mechanically weaker layers of lower shear strength, which serve as preferred failure and glide planes of submarine landslides, is today widely accepted (e.g., Masson et al., 2010; Locat et al., 2014; see below for details in Section 12.3). Nevertheless, the interplays between a variety of physical processes and parameters (e.g., sediment composition and texture, grain interlocking, grain breakage, transient pore pressure fluctuations) are still not fully understood and have therefore become the focus of numerous recent research projects. In addition to so-called preconditioning factors, there are a number of short-term triggers that may reduce submarine slope stability (e.g., Masson et al., 2006; Locat & Lee, 2009). Among the processes, most crucial to slope stability are (i) seismic loading (i.e., earthquakes), (ii) storm wave loading, (iii) rapid sedimentation (in deltas, through mass wasting, etc.), (iv) gas hydrate dissociation, (v) deep-seated fluid generation and upward migration and seepage, (vi) oversteepening, (vii) cyclic loading by tides, (viii) gas charging, (ix) groundwater charging, and (x) base-of-slope erosion. Both long-term preconditioning factors and short-term triggers are discussed more detail in Section 12.3.

Due to their size, long runout distances, and high transport velocities (up to 20 m/s; Hsu et al., 2008), submarine landslides can be very hazardous because of their potential to generate harmful tsunamis at an ocean-wide scale (ten Brink et al., 2009; Løvholt et al., 2015; Urgeles et al., 2018) as well as their potential to damage critical offshore infrastructure. For instance, underwater telecommunication cables, which transport more than 95% of all digital data traffic, are vulnerable to damage by submarine landslides and their runout (Carter et al., 2009; Cattaneo et al., 2012; Pope et al., 2017). A first well-documented example for cable breaks was the earthquake-triggered Grand Banks landslide and turbidity currents, which occurred offshore Newfoundland in 1929 (Piper & Aksu, 1987). More recently, 11 telecommunication cable breaks were caused by the earthquake-triggered submarine landslides and turbidity currents in the Kaoping Canyon offshore SW Taiwan (Hsu et al., 2008). Thus, a deeper understanding of the timing and frequency of submarine landslides is important and timely.

12.2. DISTRIBUTION AND CLASSIFICATION

Numerous studies of the modern seafloor have revealed that large landslides occur preferentially along passive margins, whereas small-scale but more frequent events occur along active margins. For example, only ~7 and 3% of the tectonically active California and Oregon margin seafloors, respectively, are occupied by mass-wasting deposits (McAdoo et al., 2000) in comparison to the 27% at passive margins mentioned above. At first glance, this may contradict observations that (i) the majority of ancient landslides are associated with seismically active zones (e.g., Pini, 1999; Camerlenghi & Pini, 2009) and (ii) earthquakes are identified in many studies as the most common trigger mechanisms of submarine landslides (e.g., Locat, 2001; Sultan et al., 2004a; Haeussler et al., 2014). However, the low occurrence of landslides on active margins has been explained by (i) a lack of available sediments (Tappin et al., 2007) and/or (ii) an increase of sediment shear strength caused by earthquake shaking (Lee et al., 2004; Strozyk et al., 2010; ten Brink et al., 2016). At sites of low sedimentation rate and with frequent earthquakes, the excess pore pressures generated by sedimentation may have time to dissipate, such that normal consolidation prevails, or the sediment may become over-consolidated (Sawyer & DeVore, 2015; ten Brink et al., 2016). In addition, there is still a lack of completeness of marine surveys. As most landslide morphologies tend to be draped and preserved, the number of small to midsized landslides may even increase in line with the increasing high and ultrahigh resolution of geophysical mapping cruises (Lee, 2005; Casas et al., 2016).

Extensive statistical studies investigating magnitudes of modern terrestrial landslides, in terms of both area and volume, showed that landslides exhibit a power law scaling behavior distribution (Stark & Hovius, 2001 and references herein; Figure 12.2a). This observation has been confirmed using numerous submarine landslide complexes within different tectonic settings (e.g., Chaytor et al., 2009; Moernaut & De Batist, 2011; Urgeles & Camerlenghi, 2013). The rollover points observed in power law scaling of submarine landslides point to incomplete catalogues for the smaller failure sizes (<1 km^3). The number of such events will increase with improvement of offshore technology and higher-resolution mapping of the *sub*-seafloor, including the ability to identify not only buried landslide deposits but also buried landslide scars (Posamentier et al., 2007). Several studies have already shown that there are 3.5 times more landslides of 1 km^3 than landslides of 10 km^3 and ~12 times more than landslides of 100 km^3 (Urgeles & Camerlenghi, 2013; Figure 12.2b). Data from the Mediterranean Sea suggest that this ocean basin experiences ~1.5 times slope failures >10^{-3} km^3 every year and one slope failure in excess of 10 km^3 every ~1000 years (Urgeles & Camerlenghi, 2013).

It is challenging to conduct robust statistical and/or comparative analyses of landslide distributions (size, volume, etc.) as the term "slide" is not always consistently used; rather many authors use "submarine landslides" as superordinate term for all types of deposits resulting from gravity-driven sediment transport. The definition and measurement of morphometric parameters are not always performed in a consistent manner between studies or disciplines (e.g., Clare et al., 2018). However, submarine landslides are typically distinguished from other mass-wasting events (e.g., debris flows) as a coherent translational block on a planar glide plane (shear surface), without internal deformation (e.g., Nardin et al., 1979; Mulder & Cochonat, 1996; Moscardelli & Wood, 2008; Figure 12.3). After initial slope destabilization, a slide may transformed into a slump, which represents a coherent rotational mass transport. Upon addition of fluid during downslope motion, slumped material may transform into a debris flow (Shanmugam, 2015). These flows can then grow dramatically in size and pick up speed, entraining material from the substrate and margin, but the mechanism of its growth is still unclear (Iverson et al., 2011). Even if a landslide shows a well-developed seafloor expression, it cannot be identified with a single event; rather it is a sequence or composite of events.

Mass-transport complexes (MTCs) are the sedimentary expression of stacked or adjacent mass-transport deposits (MTD) with internal facies variably consisting of rotated, translated blocks or thrusted blocks, as well as

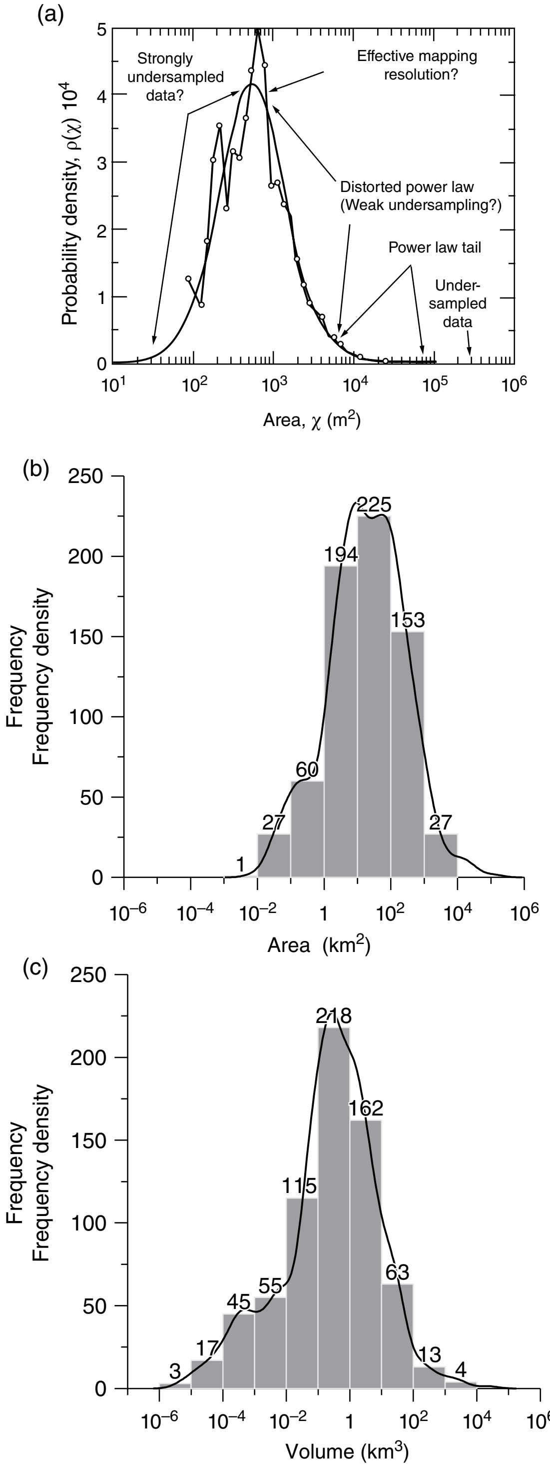

Figure 12.2 (a) An example of landslide size distribution, from the Central Range of Taiwan, plotted as a probability function. Source: From Stark and Hovius (2001). (b) and (c) Magnitude indicators of submarine landslides in the Mediterranean Sea whereby (b) shows the area (log scale) versus frequency and kernel density function and (c) the volume (log scale) versus frequency and kernel density function. Source: After Urgeles and Camerlenghi (2013).

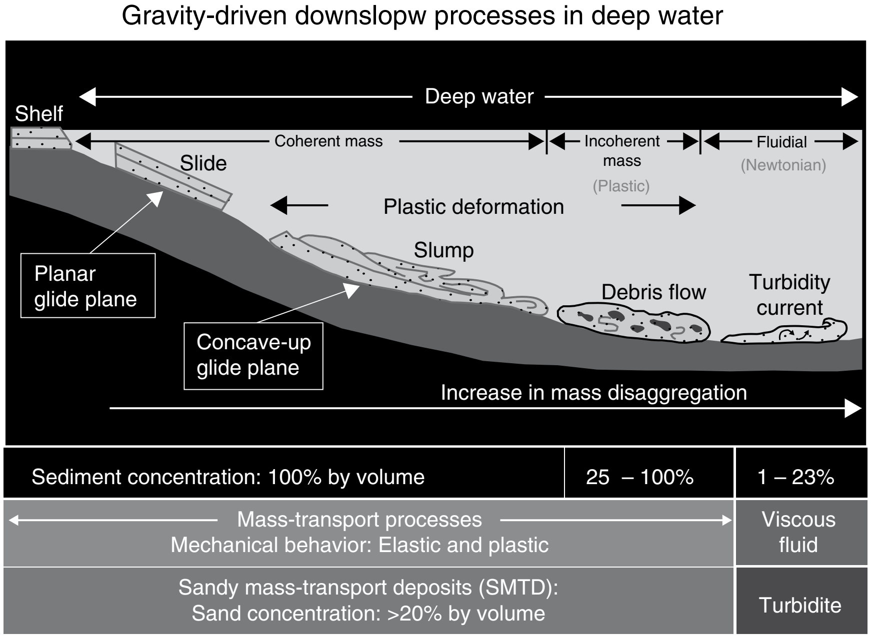

Figure 12.3 Schematic diagram showing four common types of gravity-driven downslope processes that transport sediment into deep marine environments: slides that may be transformed into a slump, which represents a coherent rotational mass transport of a block or strata on a concave-up glide plane with internal deformation. Upon addition of fluid during downslope movement, slumped material may transform into a debris flow that transports sediment as an incoherent mass in which intergranular movements predominate over shear-surface movements. As fluid content increases in debris flow, the flow may evolve into a Newtonian turbidity current. Not all turbidity currents, however, evolve from debris flows. Some turbidity currents may evolve directly from sediment failures. Turbidity currents can develop near the shelf edge, on the slope, or in distal basinal settings. Source: After Shanmugam (2015).

chaotic facies. MTCs are characterized by great lateral extent, and individual events within the MTCs have the ability to flow across gentle slopes and to transport intact blocks with dimensions of tens or even hundreds of meters (Shanmugam, 2015). MTCs have been increasingly recognized along several continental margin settings worldwide, through enhanced resolution bathymetric maps (Lastras et al., 2002, 2004; Gamberi et al., 2011; Rovere et al., 2014) and 3D seismic data (Moscardelli et al., 2006; Dalla Valle et al., 2013), and, by combining diverse data sets, across different scales and resolutions (Georgiopoulou et al., 2018).

In addition, slope failures causing submarine landslides may also progress in a staged fashion, such as retrogressive failures where the unloading from downslope failures sequentially imposes new failures upslope. The best known example of a retrogressive slope failure is the Storegga Slide (Kvalstad et al., 2005), although other large landslides, such as the Trænadjupet Slide, exhibit retrogressive failure too (Løvholt et al., 2017). In these cases, enhanced morphometric analyses contribute largely to the understanding of mass-wasting processes, provided that bathymetric data are of sufficient high resolution (Micallef et al., 2007).

12.3. TRIGGERS AND PRECONDITIONING FACTORS

Submarine landslides occur if the applied shear stresses, such as due to gravity, seismic shaking, and wave loading, exceed the shear strength (τ) of the slope sediments (e.g., Løseth, 1999; Sultan et al., 2004a). Applied gravity forces increase if slope angle increases as a consequence of, for example, tectonic movements referred as oversteepening. However, tectonic oversteepening is regarded more as an important precursor prior to slope failure rather than a trigger mechanism. Moreover, it is widely accepted that landslides are initiated when the shear strength of the slope material decreases in a short time (e.g., Løseth, 1999). The most efficient way to decrease the shear strength is a transient increase of pore pressure (Δu), because the effective stress is the overburden stress σ_n (primarily caused by the sediment weight) acting normal to a failure plane, minus the pore pressure (u) such that $\tau = \mu(\sigma_n - \Delta u)$ (e.g., Pestana et al., 2000; Talling et al., 2014; Figure 12.4). Here μ is the coefficient of friction. In general, the most common mechanisms that increase the pore pressure, and hence decrease the effective stress in the sediment, include rapid sedimentation

(>mm/yr) and/or tectonic loading, earthquakes, tidal variations, mineral dehydration, gas charging, and gas hydrate dissociation and dissolution processes (e.g., Hampton et al., 1996; Sultan et al., 2004b; Locat & Lee, 2009; Dugan & Sheahan, 2012; Urgeles & Camerlenghi, 2013; Hsu et al., 2018; Figure 12.4c).

Most conceptual models for slope failure based on the assumption of the presence of mechanically weak layers, which have intrinsically lower shear strength, are embedded in the slope stratigraphic architecture (e.g., Masson et al., 2010). Particularly, the sequencing of layers with different physical properties, especially permeabilities, plays an important role on where failure surfaces are localized. In many submarine landslide studies, it has been hypothesized that soft clays (e.g., Kvalstad et al., 2005; Dan et al., 2007), loose granular silts and sands (e.g., L'Heureux et al., 2012), high-porous ash layers (e.g., Kuhlmann et al., 2016), or altered volcanic deposits with high liquefaction potential (Miramontes et al., 2018) could act as weak layers, thereby serving as potential basal failure planes of submarine landslides. The physical understanding is based on the assumption that, for example, the high-porous ash-layer matrix would collapse during cyclic loading, generating transient high pore pressure (e.g., Wiemer & Kopf, 2017). A similar process is also hypothesized for diatom-ooze-rich sediments, which are susceptible to building up excess pore fluid during burial due to their high compressibility and water content (e.g., Volpi et al., 2003; Urlaub et al., 2018a). Although such layers are prone to generate transient high pore pressures, an overlaying low-permeable layer is required as a barrier to upward drainage (e.g., Dugan & Sheahan, 2012). Overpressure is most likely to be found where low-permeability ($<10^{-16}$ m^2) layers have inhibited pore fluid escape or there have been large forcing mechanisms (e.g., rapid sedimentation, tectonic stressing, heating, and volume-creating reactions; Dugan & Sheahan, 2012). The genesis and magnitude of overpressure can be controlled by physical processes (e.g., rapid sedimentation, tectonic loading, and lateral fluid transfer), as well as thermal and chemical processes

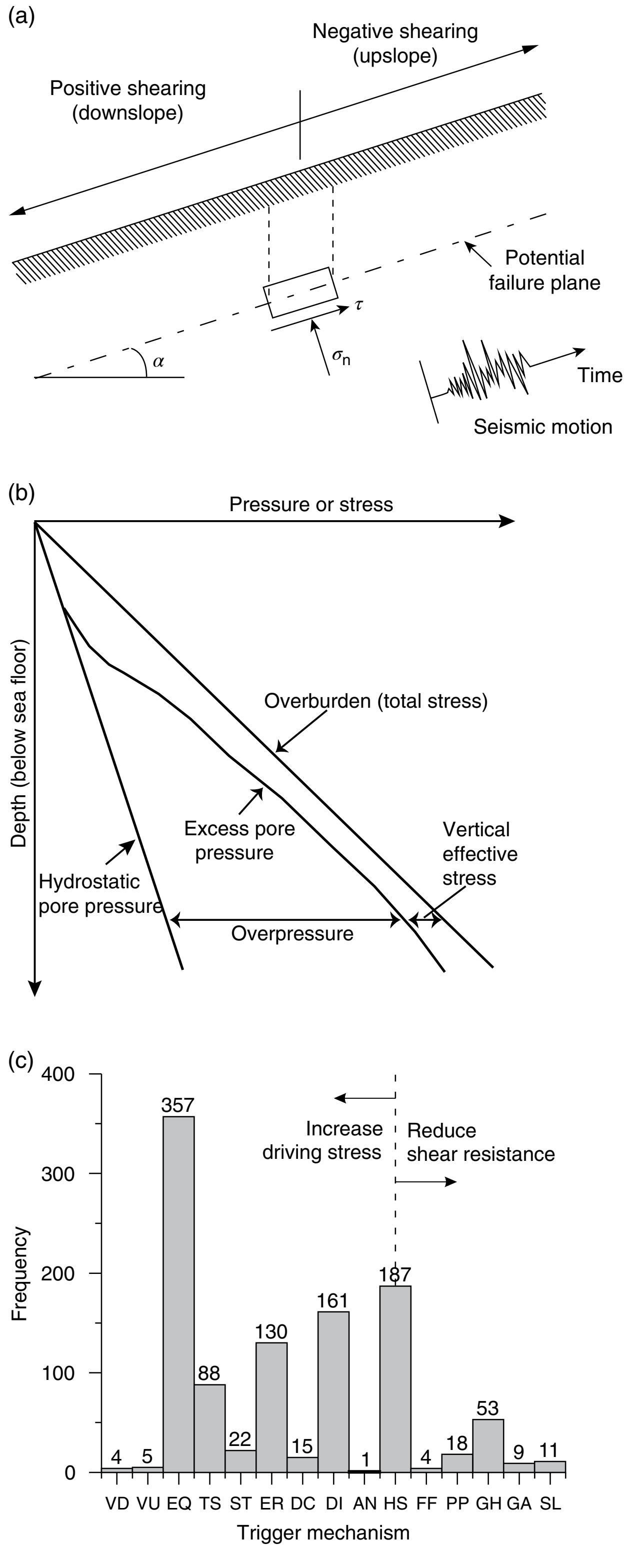

Figure 12.4 (a) Relationship between overburden (total stress; σ_n) and excess pore pressure (u) acting normal to a failure plane, and shear strength (τ) along the failure plane. Source: From Pestana et al. (2000). (b) Generalized example of change in overburden, hydrostatic pore pressure, excess pore pressure, and vertical effective stress with depth below the seafloor. Source: Modified from Talling et al. (2014). (c) Major factors cited to be involved in triggering slope failure offshore (separated according to those that increase the driving stress and those that reduce the shear strength [VD, volcano development; VU, volcano uplift; EQ, earthquake; TS, tectonic steepening; ST, steepening; ER, erosion; DC, differential compaction; DI, diapirism; AN, anthropic; HS, high sedimentation rates; FF, fluid flow; PP, pore pressure; GH, gas hydrates; GA, gas; SL, sea level]). Source: After Urgeles and Camerlenghi (2013).

(e.g., aquathermal expansion, hydrocarbon generation, mineral diagenesis, and organic maturation; Dugan & Sheahan, 2012). Thus, a stratigraphic sequence of embedded high-permeability sediments between low-permeability layers could be an essential preconditioning factor for submarine landslides, although it is still unknown where the failure plane is located: in the weak layer, in the covering layer, or along the interface (e.g., Kuhlmann et al., 2016; Urlaub et al., 2018a). Moreover, further uncertainties remain, as, for example, volcanic ash itself and diatoms exhibit high shear strength, and more importantly, shear strength even increases with increasing diatom content due to particle interlocking (e.g., Wiemer & Kopf, 2017). On the other hand, the concept of seismic strengthening also needs to be considered. Although it has been proposed that numerous submarine landslides are ultimately triggered by earthquakes (i.e., cyclic loading driven by seismic shaking; Figure 12.4c), repeated, non-failure seismic events can actually strengthen the sediment through development of excess pore pressure during earthquakes and subsequent drainage, resulting in a densification during intervening periods (ten Brink et al., 2016). This in turn is in agreement with the observation that most modern giant landslides are observed at passive margins rather than at active margins. More research is needed on the mechanics of weak layers to gain a deeper insight into the geo-mechanical behavior of submarine slope sediments. This is no trivial task, as weak layers are mostly destroyed by landslide masses, such that the sediment of which the weak layer consisted has vanished with the landslide.

Another widely debated aspect of submarine landslide initiation is the impact of climate change (see also next paragraphs). It has been repeatedly hypothesized that deepwater warming may have triggered gas hydrate dissociation in the past, thus contributing to global greenhouse gas levels and possibly to the catastrophic collapse of submarine continental slopes (Kennett et al., 2003). For example, in the last decade, deep Eastern Mediterranean water masses have undergone a temperature increase in excess of 0.5 °C (Della Vedova et al., 2003). Gas hydrates, solid “icelike” compounds of methane and water present in the pore spaces of marine sediments at continental margins, are sensitive to small changes in ambient pressure and temperature (Brewer et al., 1998). Dissociation of only a small amount of gas hydrate can substantially weaken slope sediments (Grozic, 2010). Recent studies suggested that cracking of the seafloor induced by gas hydrate dissociation might be ongoing in areas of the North Atlantic (Driscoll et al., 2000) and the Arctic Ocean (Mienert, 2009). Natural environmental changes, such as those associated with glacial/interglacial climate changes, are capable of generating free gas from hydrates, subsequent expansion of pore fluids, and pore pressure buildup, thus weakening sediment strength (Lee, 2009). Westbrook et al. (2009) and Phrampus and Hornbach (2012) report data and thermal models suggesting that changes in the Gulf Stream are rapidly destabilizing methane hydrates along the North American and Arctic continental margins. In addition, a few submarine landslides occur in areas that presently or previously contained gas hydrates (e.g., Hornbach et al., 2007; Mountjoy et al., 2014; Pecher et al., 2017; Chen et al., 2018; Kuhlmann et al., 2018). Nevertheless, the involved mechanisms, both for past and modern events, are still poorly understood, and there is no clear evidence of the interplay between gas hydrate dissociation and subsequent slope failure. Although new mechanisms for gas hydrate dissociation such as variations in pore water salinity were recently proposed (Riboulot et al., 2018), there is still a clear lack in knowledge on how gas hydrates relate to sediment stability.

Other peculiar factors that may favor mechanical weakness are sediment compaction and diagenesis (i.e., chemical changes occurring in sediments after their deposition; e.g., Volpi et al., 2003; Davies & Clark, 2006), sudden loss of strength during compaction of marine mud (destructuring), or the influence of groundwater systems on pore water distribution in nearshore marine sediments, such as in the case of the Nice margin failure in the Western Mediterranean (Dan et al., 2007). Here it has been realized that interstitial fluid flow in continental margin sediments plays a fundamental role in submarine landslide initiation (e.g., Stegmann et al., 2011; see also Figure 12.4c).

In recent years, it has also been proposed that the intrinsic sedimentary characteristics of contourites (sediments deposited under the action of oceanic bottom currents) may favor seafloor instability and failure (Laberg & Camerlenghi, 2008; Verdicchio & Trincardi, 2008; Miramontes et al., 2016). Hence, also continental margin stratigraphic architecture may control localization of excess pore pressures that build up at depth and determine a decrease in sediment shear strength that can lead to slope failure (Dugan & Flemings, 2000).

At this point, it has to be mentioned that a deeper insight into the key role of preconditioning factors or individual trigger mechanisms, for example, specific earthquake events, requires solid age dating, which is shown being one of the big challenges in recent submarine landslide studies.

12.4. AGE DATING: CAPABILITIES AND LIMITATIONS

Precise age dating of the timing of slope failure is still a very challenging task (Vizcaino et al., 2006; Gràcia et al., 2010; Urlaub et al., 2013; Clare et al., 2014). In a recent study based on 68 large and well-studied landslides worldwide, Urlaub et al. (2013) stated that uncertainties in ages are significant for a large part of the database and dating is often of poor quality. Various uncertainties still exist regarding an accurate age dating of the landslide event, which typically rise from both the availability of samples and the used method. The most used method is radiocarbon dating. However, this dating is problematic for marine sediments because of the freshwater reservoir effect (Philippsen, 2013) which always falsifies an accurate age determination. In addition, radiocarbon dating is limited to date sediments younger than 45,000 years. However, submarine landslides are in many cases much older, and such age dating is needed to accurately estimate frequencies and recurrence rates of submarine landslides over long periods or to link these to specific triggers, for example, sea level variations. In order to enable this, other methodical approaches are used, such as correlation of oxygen isotope curves and/or tephrochronology, but these techniques enable rather rough estimation than an accurate dating. Therefore, in most studies, the reliability of the individual age data is given for each deposit. Maslin et al. (2004) established a qualitative age reliability index for ages of MTD. They stressed that this is not an attempt to grade the research, but rather that it is a measure of the difficulties encountered when dating each individual deposit. The age reliability index is ranked as "excellent" (1) if reliable and reproducible radiocarbon dates at least above and below the deposit and in some cases within the deposit are available. In contrast, a "poor" (5) qualification indicates that either no radiocarbon dates are available and that ages were inferred by correlation to adjacent dated sediment cores or that there has been significant erosion of sediments overlying the MTD.

12.5. CLIMATE CONTROL AND INTERPLAY

Numerous studies have hypothesized that climate conditions, particularly their impact on sea level fluctuations and sedimentation rate, may control timing and frequency of submarine landslides (Maslin et al., 2004; Lebreiro et al., 2009; Lee, 2009). This may be supported by the view that most landslides occur in areas of highest sediment accumulation rates and/or during periods of rapid sedimentation. An example is given by Hanebuth and Henrich (2009) for the Cap Timiris Canyon offshore NW Africa, where turbidites were frequently triggered by large dust influx events. In addition, stratigraphic analysis of marine sequences in high-latitude continental margins and hydrogeological modeling efforts suggest that ice loading of continental shelves during glacial maxima had a major role in focusing of fluids, pore pressure development, and onset of slope failure producing climatically controlled deposition of submarine landslides (Llopart et al., 2015, 2019). Furthermore, it is well known that significant seismicity develops during deglaciation of these margins due to isostatic rebound, which aids in producing the stresses needed to trigger slope failure in high-latitude continental margins (Hampel et al., 2009; Brothers et al., 2013). Finally, Berndt et al. (2009) propose that global warming followed by increased seismicity around the edge of the present-day ice sheets (in particular Greenland) may trigger slope instability. Increased global temperatures may also influence slope stability from changes to the seasonality, frequency, and intensity of extreme weather events (storminess and rainfall) and from rises in global sea level (BGS, 2009).

However, other recent studies, which tried to integrate as many data sets as possible from the various regions worldwide, could not substantiate the concept that climate conditions, particularly that changes in sea level and sedimentation rate, may control timing and frequency of submarine landslides on a global scale (e.g., Korup et al., 2012; Urgeles & Camerlenghi, 2013; Urlaub et al., 2013; Pope et al., 2015; Figure 12.5). An alternative hypothesis is therefore that submarine landslides are near to random in time (Clare et al., 2014; Pope et al., 2017). Moreover, some statistical analyses have shown that there is no evidence for an immediate influence of rapid sedimentation on slope stability as failures tend to occur several thousand years after periods of high sedimentation rates (Urlaub et al., 2013; Figure 12.5). Such delays, perhaps of variable duration, will also act to decouple landslide timing from driving climate forces. At the same time, however, the various studies have also shown that the role of different controlling factors may vary between different geological settings, for example, river deltas and fans clearly respond to rapid sedimentation by multiple slope collapses, and their role might get lost in global data set, or the uncertainties are too great to identify an underlying correlation. Perhaps most importantly, the statistical analysis shows that we need to date a larger number of landslides, more precisely, to be able to determine whether landslides are random or nonrandom in time (Pope et al., 2017). So the proposed hypothesis that future climatic change may increase the frequency of submarine landslides cannot be fully answered nor neglected. Rather, this hypothesis is still to be tested rigorously.

12.6. GEOHAZARD POTENTIAL AND TSUNAMIS

Submarine landslides can be by far larger than any terrestrial landslide. They may produce tsunamis whose far-reaching effects can rival those produced by earthquake-tsunamis and thus threaten increasingly populated coastlines worldwide (Figure 12.6a; e.g., Camerlenghi et al., 2007; Lo Iacono et al., 2012; Harbitz et al., 2014). The most critical parameters for tsunami generation are

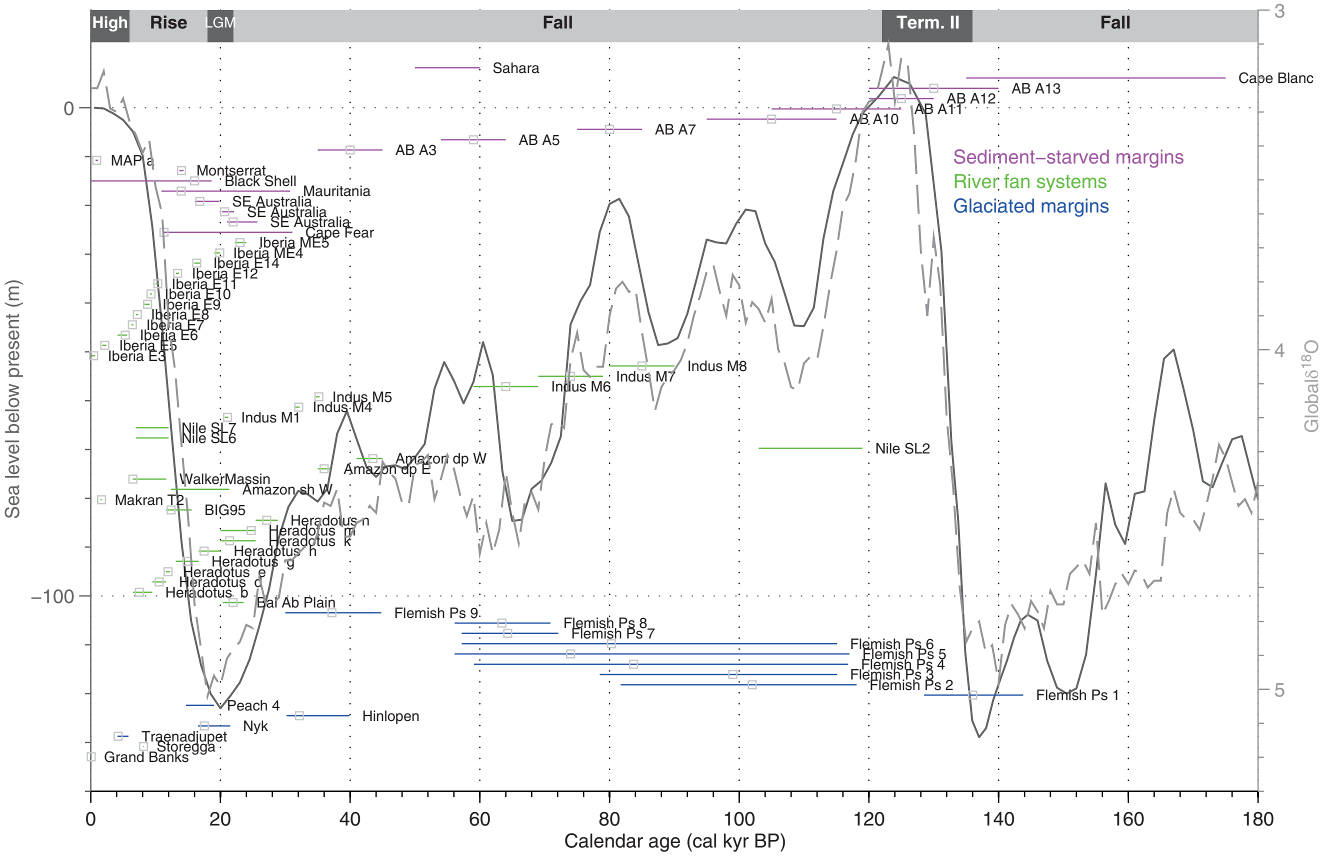

Figure 12.5 Global mean sea level (dark gray curve; Waelbroeck et al., 2002) and global stack of benthic d18O records (light gray curve; Lisiecki & Raymo, 2005) plotted with all submarine landslides including their individual uncertainty intervals. If available, the age with highest probability is shown by a gray square. The color of the uncertainty line indicates the sedimentary environment (river fan systems with high terrestrial input, glaciated margins, and sediment-starved margins). The gray timeline on the upper part of the figure indicates the sea level patterns: Sea level fall and lowstand from 180 to 136 ka BP, sea level rise and highstand during Termination II (136e122 ka BP), sea level fall (122e22 ka BP), the Last Glacial Maximum (LGM) from 22 to 18 ka BP followed by a sea level rise (18e6 ka BP), and the modern sea level highstand (6e0 ka BP). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article). Source: After Urlaub et al. (2013). (*See electronic version for color representation of this figure*)

the failed volume, the water depth, the landslide velocity, and the landslide acceleration in different tectonic settings. In addition, the location of landslide source and the release mechanism have a strong control on the scale of the tsunami. For example, the landslide tsunami generation is most efficient when slope failure occurs in relatively shallow waters because the buildup of the resulting wave is much more efficient (e.g., Harbitz et al., 2006; Løvholt et al., 2015). Furthermore, for the same unit volume, a landslide originating on the submerged flanks of a volcanic island will produce a smaller tsunami than a landslide comprising the subaerial volcanic edifice (Watt et al., 2012). In addition, tsunami magnitude is also critically dependent on whether failure occurs in one stage or in successive separate stages. Failure in a series of stages separated by a few tens of seconds or minutes can substantially reduce the resulting tsunami magnitude (e.g., Haugen et al., 2005). It has been shown that such staged failure can involve failure of more blocks at a time (e.g., Gauer et al., 2005). If the cascading failures are efficiently conveyed into a large debris flow, the tsunami generation can yet become pronounced (Løvholt et al., 2017). With a certain time gap between the individual stages, the landward tsunami can be even higher than for a one-stage event (Løvholt et al., 2005).

Historically, the first evidence of a truly massive landslide-induced tsunami was due to the 1929 Grand Banks Slide with a slide volume larger than 150 km^3 (e.g., Piper et al., 1999), possibly caused by a combination of a large slump and translational landslide that later evolved into a turbidity current (Løvholt et al., 2018). A well-known prehistorical event is the Storegga submarine landslide

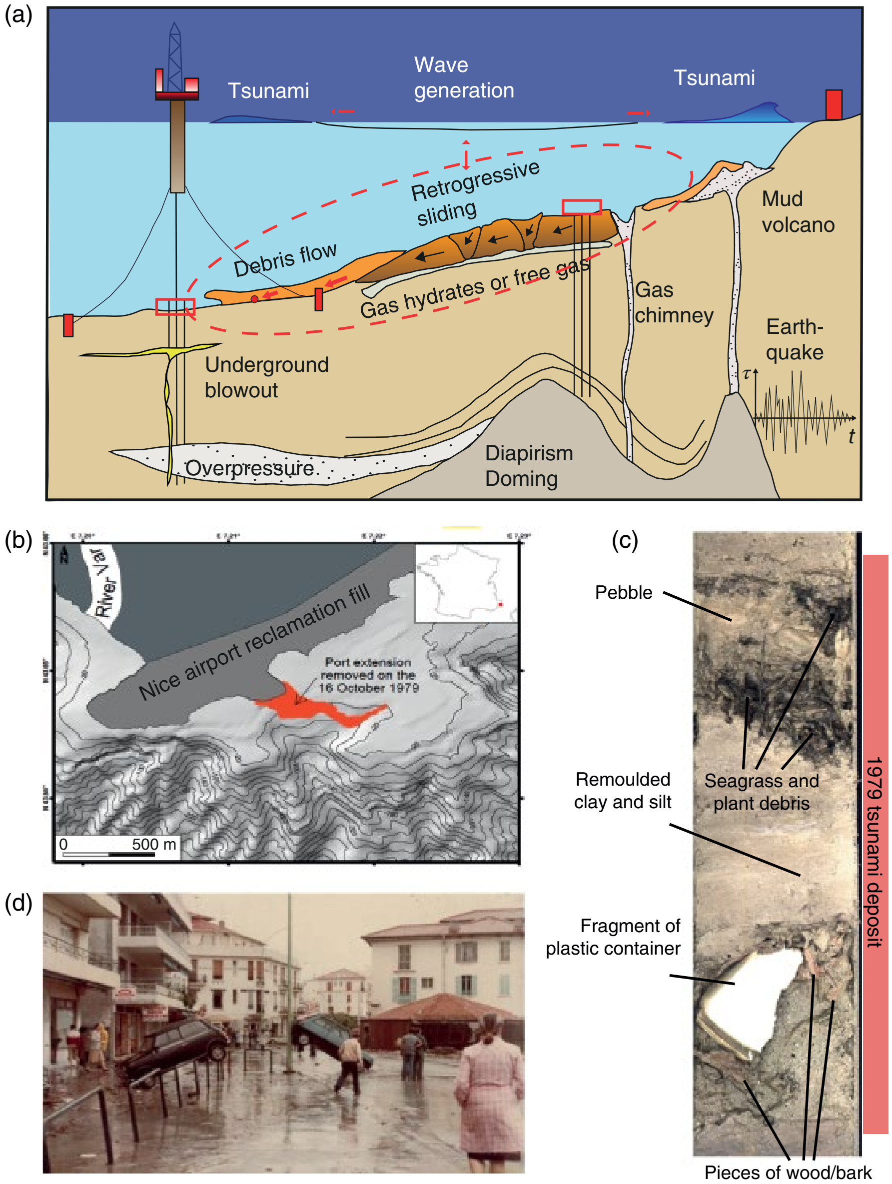

Figure 12.6 (a) Offshore geohazards. Submarine slides generated by human activity are recognized as submarine geohazards for first party (seabed structures) and for third party (population) because of their potential to generate tsunamis. Source: After Camerlenghi et al. (2007). Submarine slides are known to occur also as a consequence of the natural evolution of continental margins. (b) Map of the Nice Airport Slide that occurred on 16 October 1979. Red contour shows collapsed pier construction that caused the landslide and 2–3 m high tsunami; inset shows map of France. Source: After Kopf et al. (2016). (c) Photograph of dislocated cars and flooded streets in the village of Antibes west of the Nice landslide. Source: https://www.nicematin.com/faits-divers/il-y-a-39-ans-un-tsunami-faisait-onze-morts-sur-la-cote-dazur-267342. (d) Photograph of core (detail) taken north of the Nice landslide scar that shows the tsunamite deposited after the 1979 event; note the plastic and wood/bark pieces and remolded nature of the deposit. Source: After Kopf et al. (2016). (*See electronic version for color representation of this figure*)

that occurred 8200 years ago offshore Norway and involved >3000 km^3 of sediment. It generated a tsunami that ran up to heights of up to 20 m around surrounding European coasts (Bondevik et al., 2005). Yet high mobility dynamics is integral for generating a large tsunami, and a slower evolution and more gradual mass release is hypothesized to be the reason for the clear lack of tsunami evidence from the giant Trænadjupet Slide (with a volume of about 500 km^3) just north of the Storegga Slide (Løvholt et al., 2017).

However, even small landslides, such as the ~4 km^3 1998 Papua New Guinea landslide, can cause tsunami run-up exceeding 10 m (Synolakis et al., 2002; Tappin et al., 2008), illustrating that moderately large submarine landslides can damage important seafloor and coastal constructions. Similarly, the well-studied 1979 Nice Airport landslide mobilized ~0.0022 km^3 near the airport of Nice and ~0.0062 km^3 in the mid-slope and displaced sufficient water to generate a tsunami wave of 2–3 m along the French Riviera (Dan et al., 2007; Kopf et al., 2016; Figure 12.6b).

Submarine landslides and associated tsunamis are an international challenge, crossing national and oceanographic boundaries. Although landslide-tsunamis may be just as large as earthquake-triggered tsunamis, it is more difficult to provide warning for landslide-triggered tsunamis compared to earthquake-triggered tsunamis, because earthquakes are recorded on global seismological networks serving as precursors (Løvholt et al., 2015). However, current efforts are trying to mitigate offshore geohazards by implementing global monitoring systems, such as tsunami detection and early warning systems recently installed in the Pacific Ocean. Additionally, an array of in situ instruments has been connected to the EMSO seafloor cabled network offshore Nice, France. These EMSO-connected systems have proven powerful in unraveling the governing factors that lower effective stress in sediments and hence impose significant landslide risk to densely populated areas (e.g., Stegmann et al., 2011). Nevertheless, much more is needed to unravel processes governing hazards such as submarine landslides over time.

12.7. LONG-TERM MONITORING

Although long-term monitoring is valuable for continental slopes threatened by recurring destabilization and those which are heavily used by various infrastructure, direct monitoring is still in its infancy. The reasons for that are (i) challenging environments and remote settings, which were previously prohibitively costly (Talling et al., 2013; Kelley et al., 2014); (ii) technological issues related to positioning accuracy, data resolution, and communications (Hughes Clarke, 2012); (iii) equipment limitations in measuring key parameters (e.g., measuring fast and/or high-concentration flows with acoustic instruments; Hughes Clarke, 2016); and (iv) the often destructive nature of the events that may damage the monitoring devices (Khripounoff et al., 2003). Perhaps the most difficult problem to solve is knowing which location on a continental slope will fail next and then whether such failure occurs over short enough time scales (two to five years) of most science projects. Landslide monitoring may thus be restricted to locations (e.g., delta fronts; Hughes Clarke, 2016) where failure occurs very frequently and such landslides tend to be small in volume. Nevertheless, geotechnical monitoring of offshore sites is becoming more commonplace, such as the deployment of in situ piezometers and tiltmeters to understand slope stability issues at specific locations (Figure 12.7; e.g., Strout & Tjelta, 2005; Stegmann et al., 2012; Clare et al., 2017). Besides, repeated seafloor surveys using high-resolution multibeam systems revealed not just the scale but also the frequency of submarine landslides in several systems worldwide (e.g., along the Nice slope (Kelner et al., 2014); at active pro-deltas (Hughes Clarke, 2016; Obelcz et al., 2017); in deepwater submarine canyons (Mountjoy et al., 2018; Smith et al., 2007)). Such measurements have proven to be suitable particularly in areas with large displacements and shallow-water conditions. For instance, annual seafloor surveys at the submarine delta of the Ogooué River, Gabon, between 2004 and 2009 revealed slope failures (up to 2.5 million m^3) that occur on at least annual basis (Biscara et al., 2012).

Beyond morphologic changes, monitoring with instruments such as broadband ocean bottom seismometers (OBS) can provide information on the timing and nature of slope failure. In the southern Tyrrhenian Sea, OBS monitoring revealed not only earthquake-related seismicity but also low-frequency seismicity events related to volcanic degassing and its relationship with submarine landsliding (Sgroi et al., 2014). Similar interpretations have been made from multiple moored hydrophones offshore West Mata volcano in the Lau Basin near Tonga (Caplan-Auerbach et al., 2014) where velocities of submarine landslides were estimated from triangulation. Even shore-based monitoring may provide insights into submarine landslide activity. For instance, offshore landslides have been detected in the Kaoping Canyon, offshore Taiwan, using terrestrial broadband seismic networks (Lin et al., 2010). Furthermore, most recently, advances in seafloor geodetic monitoring have enabled monitoring of the slow displacement of the volcanic flank offshore Mount Etna, thus providing the first detailed, direct quantification on conditions prior to, and during, large-scale slope instability (Urlaub et al., 2018b). Following this excellent example, further volcanic flanks and continental slopes, which are characterized by landslides, should be monitored with geodetic tools in the future in order to obtain comparable data sets to gain a deeper insight into displacement rates at different geological settings.

Other major recent advances have been made through directly measuring turbidity currents (e.g., Xu et al., 2004; Azpiroz-Zabala et al., 2017; Paull et al., 2018). Indeed, it could be argued that the most compelling future need is to monitor conditions before and during submarine landslides. Without such direct measurements of events, it may be challenging to make major advances or test models. However, monitoring large submarine landslides may be more challenging than for turbidity

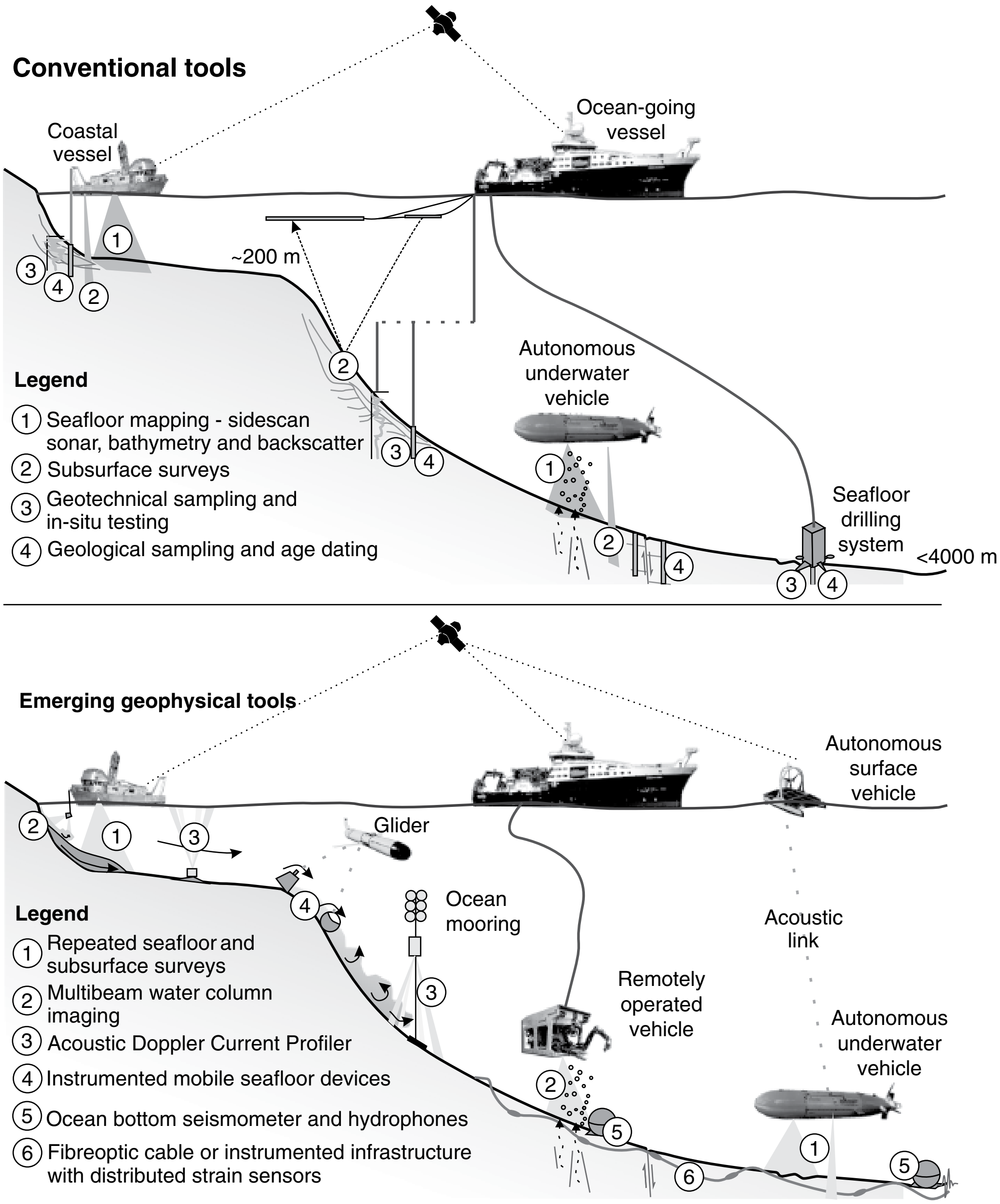

Figure 12.7 Conventional and emerging geophysical tools for monitoring offshore geohazards discussed in this paper. ROV image from neptunems.com. ASV image from asvglobal.com. Source: After Clare et al. (2017).

currents, as it is unclear where the next landslide will occur and some have recurrence intervals (>100–1000s of years) that are too long for most research (<5-year) projects. Perhaps monitoring will only ever be possible in locations where landslides are frequent, such as on prograding deltas (Hughes Clarke, 2016; Obelcz et al., 2017).

Initial monitoring work has provide new results such as that (presumably landslide-triggered) submarine flows can occur without an obvious external trigger (earthquake, storm wave loading, etc.; Paull et al., 2018) and not all submarine landslides trigger long runout flows (Hizzett et al., 2017). Such work suggests that slopes may be preconditioned and remain close to failure for long periods.

We currently have many studies and excellent data sets that investigate landslides from different perspectives; however, in order to fill outstanding but key knowledge gaps, future studies should become even more interdisciplinary, bringing more expertise together, and perhaps utilize new technologies.

12.8. SUMMARY

This chapter provides a very short review of submarine landslide studies, with some emphasis on the emerging needs in future landslide research. The wealth of publications, and the limited space for this article, ensures that it is not complete. However, we emphasize that, despite the wealth of studies over the past decades, much is still unknown or at least uncertain. There are many open questions and technological challenges that the next generation of researchers and the joint European Training Network (ETN) SLATE, whose members have contributed toward this chapter, have to address.

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