Advancing from subaqueous mass movement case studies to providing advice and mitigation

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There are many challenges facing submarine mass movement researchers and engineers. This book comes at a time when, in the past five years, a number of high-profile submarine landslide disasters have reached the world’s attention. In September of 2018 a magnitude 7.5 strike-slip-type earthquake in Palu, Indonesia, generated a short-wavelength tsunami of height over 2 m and run-up on shore of over 8 m. The waves took the lives of hundreds of people, yet uncounted, many of whom were gathered for a festival on the beach. The combination of these wave dimensions with observations of the wave timing and directions indicate strongly that a submarine landslide was the source of this devastation (Arikawa et al. 2018; Heidarzadeh et al. 2018; Muhari et al. 2018; Carvajal et al. 2019). Sadly, barely 3 months later the same nation suffered a tsunami formed by the underwater collapse of the Anak Krakatua volcano, which killed at least 500 people. On the other side of the globe, in June 2017, many houses in the village of Nuugaatsiaq, West Greenland, were destroyed and some lives were lost from a coastal landslide-generated tsunami (Gauthier et al. 2018). Another event in 2014 saw the small village of Nord–Statland, Norway badly damaged by a submarine landslide (Sylfest et al. 2016).

For decades, researchers have been mapping mass movements. Their significance on Earth in distributing sediment on phenomenal scales is undeniable (Talling et al. 2015) and their importance in the origins of buried resources has long been understood (Sanders & Friedman 1997). Their hazard potential ranges from damaging to apocalyptic, frequently destroying local infrastructure and sometimes devastating whole coastlines (see examples in Tappin 2017 and throughout this text). With modern technologies, mass transport deposits (MTDs) continue to be discovered and described in greater detail. Some, such as the recent examples above, have damaging or disastrous consequences. What is clear in hindsight is that there is a possibility that some of these tsunamis could have been foreseen, or at the very least detected and an early warning given. In most cases, the authorities were aware of a pre-existing hazard. In all cases, instrumentation was available that could have warned of an oncoming tsunami. The science of measuring subaqueous flows needs to be put into practice.

This paper outlines a number of different case examples of landslides which are presented in this book. Beyond mapping, the work has moved into a successful period of observation from within flows using landslide-resistant instrumentation, which is described in the following paragraphs. Submarine mass movement practitioners are now focussed on the consequences of mass movements, modelling, analysing hazard and mitigating consequences, and examples are given in this book. Recently for instance, in 2015 Chevron undertook the technological challenge of installing a 140 km-long pipeline beneath the Congo River Submarine Canyon (Marine Executive 2015). The company completed this multibillion dollar project to mitigate the damaging effects of turbidity currents rushing down the channel. Other organizations have provided advice on frequency, magnitudes and triggers for the construction of coastal infrastructure (see the section below). This book describes newly mapped MTDs in lakes, fjords and coastal areas. It describes their role in continental margin development. The work
then describes the roles that seismicity, fluid flow and gas hydrates play in initiating events, and in one case, the reverse – the role that MTDs play in forming ideal gas hydrate conditions (Yamamoto et al. 2018). All of the chapters describe cutting-edge and forward-thinking techniques available as of 2018. A considerable segment describes recent successful attempts to measure mass transport events, including turbidity flows and landslides. This section was extended because of the very rapid progress in the past 5 years, which has increased the number of directly measured flows from fewer than a dozen to hundreds. This book then describes multi-disciplinary research, risk analysis, classification, policy and mitigation. The release of a book outlining new techniques in this area is timely owing to the many lives lost in recent years, significant advances in mapping and monitoring technology, and the real possibility that some of these disasters could have been foreseen, measured, warned of and even mitigated against.

Real-world flow measurement techniques advancing rapidly

Owing to their destructive nature and the cost of damage avoidance, recent efforts have been made to safely measure the frequency and magnitude of submarine mass flows, particularly turbidity currents. Researchers have devised a variety of moorings and platforms for the purpose of withstanding (or even taking advantage of) strong flows and rapid erosion and deposition, which traditional science platforms often cannot survive.

Turbidity currents were first directly measured decades ago in Bute Inlet, Canada by ingenious stand-alone current-triggered impeller devices by the Geological Survey of Canada (Prior et al. 1987). The experiment was repeated in Bute and Knight Inlets five years later (Bornhold et al. 1994). This book is dedicated to the pioneer of these activities, Brian Bornhold. The mechanical devices used would measure every 10–20 min. In the past 10 years the Geological Survey of Canada has taken advantage of the nearby scientific cable of Ocean Networks Canada (ONC) to confirm that the upward-dipping sand waves on the slope of the Fraser River delta are in fact a result of hyperpycnal turbidity flow (Lintern et al. 2016), rather than shallow rotational sliding or creep deformation as previously thought. This significantly changes the hazard potential for the area. Monitoring platforms have evolved that are now very stable in strong flows (Fig. 1). The first of the platforms deployed in 2008 was of typical ONC design. The large feet that stopped it sinking into the consolidating sediment made recovery very difficult as they acted as anchors when

Fig. 1. Evolution of the Delta Dynamics Laboratory on the Fraser Delta. (a) Original design based on the typical ONC platform. This design had large feet, which acted as anchors and prevented recovery in the high-sedimentation environment of the delta. (b) A more hydrodynamic design, low lying with weighted legs, and snap-off feet. This design had major benefits regarding manageability on the ship, and did not topple (it did, however, translate sideways down-slope). Several methods were tried to extend instruments out from the platform. (c) The current design is deployable in that it can be compact on board the research vessel, but deployed at the seabed by an ROV (in this photograph one of the three arms are swung outward). Piling legs and ejectable ballast have kept this platform avalanche resistant since 2016.
buried by high rates of delta sedimentation. These feet were replaced with ones that would break free on retrieval. The platform had a large sail area; it tumbled downslope owing to the flows and had to be replaced by one with a much lower profile and heavily weighted legs. Various mechanisms (hinged arms, telescoping poles) were used to extend instruments away from the platform-induced vortices, towards the upstream flow to trigger other instruments, and more importantly to reach above the 2 m powerful flows that were being detected. This second platform remained upright, but sometimes slid downslope owing to the strong flows. To keep the platform manageable on deck and over the side of a typical research vessel, researchers have now designed a platform that is compact, but with extension arms deployable on the seabed with an ROV. When deployed it has large enough horizontal and vertical reaches to capture the data required. To make it ‘avalanche resistant’, the legs penetrate into the seabed up to 1 m, acting as pilings. Over 2000 lb of ballast is suspended below the platform, which is ejectable for easier recovery. These platforms have measured turbidity current flows in excess of 6 m s\(^{-1}\), and possibly as high as 9 m s\(^{-1}\) (Lintern et al. 2016). Velocity and sediment concentration profiles near the bed match those of laboratory experiments. These flows are novel, not only because the network allows laboratory bandwidth (10 samples per second) and multi-instrument measurements, but also because they occurred on an open slope outside of any channel (Lintern et al. 2016). In addition, hydrophones reporting live on the network have been used to detect slides (Fig. 2). This new innovation allows the measurement of submarine mass movements without necessarily having to put expensive moorings directly in the path of the flow (especially where the flow is restricted to channels). Owing to the array of instruments on the network, the exact environmental conditions under which the flows occur are understood to be strong freshet combined with spring tides, and their onset can be reliably predicted to the exact week annually.

An ambitious project in Monterey Canyon (Paull et al. 2018) has seen the deployment of six acoustic Doppler current profiler moorings down-channel. These measure water column velocity profiles every 30 s, from 70 m above the seabed. As the

Fig. 2. Hydrophone spectrograms showing turbidity current events in British Columbia. (a) Passing directly through an LF hydrophone at the delta dynamics laboratory at the Fraser Delta. (b) Passing below a mooring in the Bute Inlet Channel.
profilers at this distance cannot measure the conditions very close to the bed, the research team designed benthic event detectors, which are motion sensors encased in boulder-sized housings. These are deployed by burying them in the seafloor and when flows occur they are picked up and carried within flows. Over an 18 month period, the instrument array detected 15 turbidity currents. The data confirm fast and dense near-bed layers, caused by remobilization of the seafloor, overlain by dilute clouds that outrun the dense layer. Like the project on the Fraser River, the turbidity currents were able to translate instruments weighing over 800 kg downslope, and of importance to hazard assessment for offshore structures, caused liquefaction of the sediment beneath the heavy anchors. Other spectacular results have been obtained using taut line moorings in the Congo canyon (see Azpiroz et al. 2017), and in a mixture of vessel-based and mooring-based research at the Squamish Delta, British Columbia (Clare et al. 2016; Hughes Clarke 2016). Researchers from all of the above programmes have now combined their efforts and reconvened in Bute Inlet with their methods. In a 4 month deployment during the summer of 2018, six ADCPs and two hydrophones have measured the timing, the sound characteristics and the runout distances of over 80 turbidity flows.

Of the outstanding major questions which exist about turbidity currents, two involve the exact velocity or turbulence structure and the concentration profiles within the flow. These have implications for the power of a turbidity current. Some information is being revealed in real-world measurements, as above, but the laboratory is still required for detailed observations. Nomura et al. (2018) have examined in detail the interfaces within a laboratory-generated turbidity current. The researchers used carefully positioned acoustic Doppler techniques for velocities and image analysis techniques for sediment concentrations to determine that sediment transport is greatest just behind the front of the head, and sedimentation occurs just below the maximum velocity.

For mass transport events which are not fluid flow, the instrument platforms simply cannot withstand either creeping seabed flow or more catastrophic failures. Also, the instruments must remain powered and transmitting data for long periods of time. There are very few dedicated scientific cabled networks with scheduled maintenance cruises which measure slope failure features, such as that on the Fraser Delta (Lintern & Hill 2010; Lintern et al. 2016), offshore Nice (Stegmann et al. 2012). A temporary networked instrument-based observation platform has been used to measure a scarp-like crack extending east from the headwall of the Gaviota slide towards the Goleta complex offshore Santa Barbara Basin (Blum et al. 2010). The ingenious latter experiment shows the complexity of not using a real-time network however, as the total length of measurement achieved was less than two years (with a gap in the middle), and some instrument programming parameters upon deployment affected the accuracy of the results. This illustrates the need to design a monitoring platform for power, survivability over long time periods and data transmission. Urlaub & Villinger (2018) ponder which instrumentation is suitable for detecting the onset of such flows. In a reverse engineering approach, they cleverly use modelling first to determine which characteristics of the seafloor (tilt, pressure and strain) are likely to change under different types of failure conditions, and then to match up available off-the-shelf instrumentation to suit the monitoring purpose. This monitoring would complement the multidisciplinary approaches described in Vanneste et al. (2012). Indeed, a combination of multidisciplinary and real-time monitoring approaches is being used in Kitimat, BC, where the magnitudes, frequencies and triggers of tsunami-genic submarine landslides has been deduced over 4 years of expeditions, and real-time underwater instruments are now monitoring for rock movements, audible and seismic indications of earthquakes and landslides, and seismic seiches and tsunamis (Lintern et al. 2019).

The initial modelling of Urlaub & Villinger (2018) uses a very simplified model of the seafloor to induce changes to tilt, pressure and strain. They advise that, owing to the higher complexity on the real seafloor, geotechnical testing should still be used to quantify the factors that impact failure behaviour. An excellent example of the level of information that can be provided with modern geotechnical testing is provided by Dugan & Zhao (2018) for Ursa Basin sediments in the Gulf of Mexico. The tests can not only determine how the initial stress level influences failure behaviour, but also characterize pore-pressure genesis during failure, which impacts failure evolution. The researchers completed experiments on intact samples and resedimented samples to innovatively investigate the effects of soil fabric on strength properties. For these particular sediments, shallow burial does not cause increased stability. Instead, owing to the cohesive-sized particles, compaction actually causes interparticle repulsive forces to decrease the cohesion. Following this, the closer packing of grains during shearing failure causes pore pressures to rise and decreases the effective stress. Together, these indicate that the failure potential increases during shallow burial, and remains high during shearing failure.

Modern geophysical tools on the MTDs can be used to identify the volume and kinematics of the slope failure in order to understand the geohazard
potential. A Mw 7.2 earthquake centered beneath the SW Newfoundland continental slope triggered a turbidity current and tsunami in 1929 which broke telecommunication cables and killed 28 people. Previous investigations have shown only shallow mass failures and the turbidity current, not a single large failure, so it has not been understood how such events could lead to a devastating tsunami (Hughes Clarke 1988; Piper et al. 1988; Mosher & Piper 2007). Ultra-high-resolution seismic reflection data have revealed new information about debris flows with evidence of translational, retrogressive sliding in deeper water (>1700 m) and instantaneous sediment failure along fault scarps in shallower water (730–1300 m). Given these two types of failure, it was determined that the latter would have generated a tsunami (Schulten et al. 2018).

**Tectonics and mass movements**

Submarine mass movements are often associated with tectonics. Marine seismo-turbidites deposited by major landslides during earthquakes can be a useful tool for obtaining long-term earthquake records. The examination of this relationship continues. Katz & Hamiel (2018) analyse 278 small to medium earthquakes over a 30 year period on the coast of Israel, where there are some very large submarine slides. These small earthquakes are probably triggering the landslides, and future hazard analysis must account for this. It is not always the case that earthquakes lead to well-stratified deposits though. At at the Nankai accretionary wedge, of over 600 identified slide scars, most are completely disintegrative (Lackey et al. 2018). That is, landslide deposits are almost absent. Still the search for deposits in the sediment record can be fine-tuned. In doing so, Okutsu et al. (2018) reveals deposits associated with *in situ* remobilization of surface sediment during earthquakes, thus major landsliding events may not be required to date earthquakes. In observations from the accretionary prism of the Cascadia subduction zone Riedel et al. (2018) identify two very distinct types of failure scars, which lead to two distinct types of debris flow deposits. The linkage seems to be related to the kinetic energy of the failures; curved steep scarps are associated with chaotic deposits, whereas rectangular scarps are associated with large blocky deposits. The cause of these two distinct failure types is puzzling, despite an exhaustive search for forcing factors (earthquake waveform directions, soil properties, hydrates). All of this indicates that continued research on slide coordinates, energetics, morphologies and even orientations may reveal information about earthquake frequencies and magnitudes that previously relied on just finding sediment deposits.

Various groups of researchers have recently completed mapping of the Queen Charlotte–Fairweather Fault System off the NW coast of North America. A series of papers outline the number of MTDs uncovered during these surveys. Brothers et al. (2018) concentrate on the northern end of this fault, while Greene et al. (2018) report on the southern portion. To the north, SE Alaska, the sediment-dominated northern part of this area leads to frequent MTDs with dendritic submarine canyon/channel networks and retrogressive failure complexes along relatively gentle slope gradients (Brothers et al. 2018). The central portion of the reported area of this area is tectonically dominated. The rugged topography leads to sediment bypass, and the MTDs mainly result from failure of consolidated material along the flanks of tectonic features (Brothers et al. 2018). Yet further south, near the Queen Charlotte Fault zone where earthquakes are frequent, shaking did not cause slope failure, but instead has had the opposite effect. Here, there is a relative lack of submarine landslides, which Greene et al. (2018) surmise is the result of seismic strengthening (compaction) of an already sediment-starved shelf. Interestingly though, there are two medium-sized slides on the flanks of a newly discovered actively venting mud volcano, and the researchers believe that the slope is locally unstable because of the presence of gas and other fluids in the sediment. Together these papers identify beautifully, and for a large portion of a continental margin, the relationships between form and process dominance.

On the opposite side of the Pacific Ocean, Horozal et al. (2018) similarly investigate a stretch of the Ulleung Basin, East Sea, Korea. They interpret over 38 submarine failures of large magnitude with headwall scarps in excess of 500 m high. The scarps and volumes transported are much higher in the southern margin compared with those from the western margin. Similar to the conclusions drawn for the Queen Charlotte–Fairweather Fault System, the differences in these features seen between the southern and western margins of the Ulleung Basin appear to be related to the morphology of the shelf and the sedimentation rates, broader and higher, respectively, on the south margin.

Given that MTDs are ubiquitous in sedimentary basins, various authors have shown that they can be used as structural markers by constraining the timing of fault growth and MTD emplacement (e.g. Omosanya & Alves 2014, and references cited within Omeru et al. 2018). The research team tests this method to determine if MTDs can be used as markers for fault propagation on four MTDs within the Scotian Basin. They determine that fault propagation is not affected by the presence or lithological contrast of the MTDs, and surmise that this might be due to these particular MTDs being fine-grained and
more homogeneous than those areas where MTDs do represen barri ers.

A very well-orchestrated multidisciplinary effort was undertaken to understand features of the Licosa submarine landslides in an active volcanic continental margin off the west coast of Italy (Sammarti

ini et al. 2018). Several open questions were answered after assessment of the landslide. Rapid sea-level rise is the most likely factor contributing to generating excess pore pressure. The relationship between the landslide and the underlying channel and the occurrence of older pockmarks are ruled out. The basal layer of the slide appears to be related to an ash layer in this volcanic environment. Evidence of displacement in the channel allows speculation that there is an active fault and that this is the likely cause of the landslide between 14 and 11 ka BP.

Mass transport deposits, fluid flow and gas hydrates in passive margins

Many of the largest MTDs exist in areas where seismic processes are not at play. On the passive NW African continental margin, there is also very little evidence of gas hydrate occurrence. There are, however, ample and wide-ranging failure types, including well-publicized but controversial landslide on the flanks of the Canary Islands (Hunt et al. 2013 and references therein). This passive margin offers an opportunity to examine the distribution, causes and timing of large landslides in the absence of these major forcing mechanisms (Krastel et al. 2018). The research opens up a number of differences and some similarities between disparate landslide types. In terms of hazard assessment, although many of the MTDs are very old, and they occur infrequently, at least one has occurred in the past 2000 years. One important similarity is that all of the large slides progress along a pronounced glide plane parallel to the stratigraphy. It remains an important objective to determine the exact nature of this glide plane.

Other examples of major MTDs in a passive margin include the five major landslide complexes and numerous smaller failures found on the passive US Atlantic Margin. These are in areas of low-gradient seafloor. In these areas, thick accumulations of regionally continuous strata can contribute to lateral propagation of high sediment pore pressure caused by some, often distant process. In the Cape Fear Slide complex, the origin of slides has been attributed to hydrate dissociation and salt tectonics (diapirism) owing to the pervasiveness of these features (e.g. Carpenter 1981; Cashman & Popenoe 1985; Schmuck & Paull 1993). On taking a closer look with high-resolution seismic data, however, it appears that the slide headwalls are not necessarily directly connected to these processes. Instead, these headwalls appear to be located above antecedent failures which have since been buried by deposition of thick strata during the Quaternary. It is these buried failure scars that act as conduits to pore pressure transfer (Hill et al. 2018).

Similar to the above example in the US Atlantic Margin, the formation of MTDs in the western part of the Bay of Bengal, India, is due to the genesis of a huge sediment flux from the Greater Himalaya since the late Miocene (Ramprasad et al. 2011). The high abundance of MTDs above the hiatus and the depositional ages of the interbedded coherent layers indicate that large-scale MTDs occurred repeatedly during the Pleistocene. Such repeated MTDs contributed to maintaining the high sedimentation rate in this area and potentially provided stable pressure and temperature conditions for the formation of gas hydrates (Yamamoto et al. 2018).

It is well established that overpressure in sediment caused by fluid flow of various mechanisms would weaken beds and lead to slope failures. One form of this fluid flow is related to the formation and then dissolution of gas hydrates, which is reported in many papers to have caused mass transport events. It is also conceivable that MTDs deposited by other mechanisms can create optimal traps for the formation of gas hydrates.

Recent analyses have been performed on data collected during a rare opportunity in the South Scotia Sea in Antarctica. Although the data were collected between 1997 and 2008, the recent analyses and interpretations provided by Somoza et al. (2018) are providing spectacular detail of enormous submarine landslides, with headwalls 250 m high and 7 km wide. It is proposed that diagenetic alteration of biogenic opal-A to opal-CT causes a dramatic reduction in porosity, allowing sediments to consolidate at depth. This results in overpressuring and a decrease in the effective stress. The diagenetic boundaries formed under the influence of the heat of magmatic events acted as basal surfaces for the giant MTDs from the early–middle Miocene.

Other new landslides which have been observed using modern techniques include those offshore Yamba, NSW, Australia, in which the authors not only describe the timing of the features but also model the downslope motion (Hubble et al. 2018).

Mass transport deposits in modern and outcrop sedimentology

Study of MTDs in modern and outcrop sedimentology continues, particularly as it relates to how petroleum-bearing beds were deposited. Outcrops provide an accessible opportunity to determine what a researcher might be seeing in subaqueous
seismic surveys and cores. Megaclasts are blocks of relatively undeformed strata that can be carried by mass flows owing to the high cohesive strength of the muddy matrix. They are identified and characterized in outcrops and high-resolution seismic reflection data (Hodgson et al. 2018 and references therein). Megaclast morphology and placement can give valuable information about flow kinematics, stresses and evolution. Hodgson et al. (2018) outline this topic well, and interpret modern seismic reflection data from several continental slopes to determine how megaclasts affect flow behaviour. Slide planes can be formed where one sediment layer meets a different type in the stratigraphic record. Deposition of ash from volcanic activity certainly matches these criteria. In fact, Utsunomiya et al. (2018) consider this scenario in a Pleistocene forearc basin in east-central Japan. At that location a bed of pumiceous coarse-ash and lapilli-tuff appears to have behaved as a rigid plate on top of hemipelagic sediment. The slide plane in between appears to have been triggered by excess pore pressures, indicated by some of the lower deposit injected into the upper deposit. The combination of the solid upper mass and the excess pore pressure sustained the translational slide on the gentle continental slope. Of chief importance to understanding the hazard is to look at the sedimentary outcrops laid down by tsunamis.

Outcrops of the Boso forearc basin (Boso Peninsula) of central Japan are characterized by thick deposits and numerous MTDs. Geotechnical tests have been performed to determine why this is (Kamiya et al. 2018). The results indicate that the consolidation yield stress was smaller than overburden pressure would account for. At various locations in the basin sediment, a layer of excess fluid pressure was observed. This would readily explain the existence of these large-scale MTDs — only a small tectonic event would be required for liquefaction and mobilization of these sediments downslope.

Other examples of recent work to understand ancient mass transport events from their subaerial deposits follow. In the Cariboo Mountains in Western Canada, a several decametre-thick and kilometre-wide mass-transport complex is believed to be related to major changes in sediment supply and composition, which were possibly controlled by changes in sea-level, on the prograding passive continental slope of Neoproterozoic Laurentia (Navarro & Arnott 2018). These are the first fully documented MTDs within this region.

Tsunami risk assessment

The major risk associated with slope failures is the generation of tsunamis. Huntley et al. (2018) use a variety of field and laboratory techniques in an area with known tsunamigenic landslides, Kitimat Arm, to answer the difficult conundrum of whether sediment layers on shore have been deposited by large storms or by tsunamis. It is determined that tsunami waves, and not storm waves, struck the bays of Kitimat Arm, British Columbia, not only during the documented tsunami events in the 1970s (Murty 1979; Prior et al. 1984), but also at least once previously (Huntley et al. 2018).

To get a complete picture of the tsunami hazard, it is impossible to ignore the threat of near-shore terrestrial slides, which cause even larger tsunamis than their submarine counterparts (e.g. Fine et al. 2003). There are intensive modelling efforts underway such as those described in Turmel et al. (2018). In that paper, as in many others, the tsunami modelling reveals that a very large subaqueous failure in the St Lawrence Estuary — the largest actually — creates an initial large wave, but its size dissipates quickly as it moves along the coast. This is the case for many submarine landslide-generated tsunamis, generating enormous waves at the source and dissipating quickly down-channel.

The Black Sea rarely sees tsunamis, but when it does, owing to populated coastlines, the results can be catastrophic. Historical accounts are summarized in Ranguelov (2003). Recent studies uncovered related palaeotsunami deposits on the coast about 15–20 km south of Balchik (Ranguelov 2003). Other tsunamis have been reported too. The most recent of these is a rather small one occurring in 2007, but which had no associated earthquake (Ranguelov et al. 2008). Submarine landslide was implicated and has now been proven through modelling as a cause of the observed tsunami (Gusev et al. 2018).

A destructive and fatal tsunami followed the 1929 earthquake on the Laurentian Fan of Newfoundland, Canada. The earthquake triggered a landslide and turbidity current that severed many transatlantic cables, and the landslide in turn generated a tsunami which killed 29 people in Newfoundland (Doxsee 1948; Heezen & Ewing 1952). The landslide represents the largest to have been scientifically observed on Earth in modern times, and the only landslide in that time to send waves across transoceanic distances (Fine et al. 2005). Many papers have been written since on the deposits (see e.g. Piper et al. 1988; Piper et al. 1999; Mosher & Piper 2007). Yet, despite plentiful interpretations of the deposit, it is not well understood how this event generated a tsunami so large and so far reaching. The latest approach to understanding this hazard has modelled the resulting tsunami from combining landslide types (Lovholt et al. 2018). According to the model results, an initial slump provides the most likely source for the large run-up of the tsunami.
where people lost their lives, whereas widespread translational landsliding is probably responsible for the far-field tsunami. Another example of a recent successful model of a full-scale turbidity current is presented by Yang et al. (2018). The adapted open-source model was able to account for the coupling between flow, sediment transportation and bed evolution to produce results that mimic cores for the Moroccan Turbidite System, offshore NW Africa first reported in Talling et al. (2007).

When numerical analysis is used to determine hazard levels, the application can be simplified, but the results are powerful. In many cases where a mass transport deposit has been detected using a multibeam survey, it is impractical to investigate the stability properties using cores or further in situ geotechnical study. A way forward for the investigator to reduce the uncertainty on slope stability and mobility analysis is to more cost-effectively use the geomorphology provided by the multibeam bathymetry and basic geomechanical concepts. Locat (2018) introduces such a methodology, along with its restrictions. A typical assessment can yield strength of the material, pore water pressure conditions at the time of failure and rheological properties. The main geomechanical concepts related to slope formation involve some basic principles relating the morphology of a slope, i.e. slope height, slope angle, thickness of debris deposit and slope of slide debris, to the strength both before (soil mechanics) and after failure (fluid mechanics). Concepts considered here are limited to (1) sediment formation and strength, (2) factors of safety and stability analysis and (3) yield strength and mobility.

In a semi-empirical approach, Oppikofer et al. (2018) have devised a simple assessment tool so that knowledge of sophisticated hydrodynamic models is not required as a first assessment. A catalogue of landslide-generated displacement waves is used to develop semi-empirical relationships linking displacement wave run-up to distance from landslide impact and to landslide volume. This is a valuable tool for engineers in the first-stage preliminary hazard and risk assessment for unstable rock slopes above water bodies.

**Assessments of subaqueous mass movements in lakes, fjords and coastal areas**

With much of the subaqueous world still not mapped in detail, there are many striking discoveries being made in lakes, fjords and coastal areas. For instance, Deering et al. (2018) reports on submarine mass failures recently mapped in seasonally ice-covered areas of the Arctic. There are at least 246 of these, one for every 20 square kilometers in a unique embayment.

Even in a highly studied area of the seafloor, Normandeau et al. (2018) reveals a recently discovered major MTD on the western levee of the Laurentian fan in the North Atlantic. It is the largest MTD observed in the quaternary and deepest in the Western North Atlantic. In the southern Tyrrhenian Sea, Italy, within an area of smaller MTDs, Casalbore et al. (2018) describes two relatively large MTDs of 7 and 14 km² and the implications that this may have for tsunami generation.

Moving to inland waters, the risk of tsunami from lacustrine landslides is sometimes noted, yet remains poorly researched in the literature. Some exceptions include recent assessments for European lakes (Strasser et al. 2011; Hilbe & Anselmetti 2015; Strupler et al. 2017; Strupler et al. 2018). Perhaps this is due to subaqueous geohazard organizations and their research ships having a stronger focus on marine environments and developments. Perhaps this is due to lakes in mountainous settings often not having the large populations or industrial infrastructure to make hazard analysis worthwhile. Lake Tekapo, within the tectonically active mountain belt of New Zealand’s South Island, has both a tourist settlement and hydropower infrastructure. In addition, it has high sedimentation rates and previously noted landslide deposits (Clark et al. 2014). The high-resolution bathymetry and sub-bottom seismic profiles show a preponderance of stacked MTDs, probably emplaced during seismic events (Mountjoy et al. 2018). The modelling of these MTDs indicates that tsunami should indeed be considered a hazard to the infrastructure around this lake, particularly if concurrent slope failures occur (which was also modelled by Mountjoy et al. 2018). The researchers have refined the COMCOT modelling code of Wang & Power (2011) to enable probabilistic modelling of the landslide-generated tsunami hazard in lakes. In Lake Zurich, Switzerland, several dozen MTDs have been previously published (Strupler et al. 2017) based on sub-bottom profiling from portions of the lake. A full multibeam survey and morphometric assessment revealed details of 50 recent subaqueous landslides (Strupler et al. 2018).

**Policy, classification and providing advice to stakeholders for major projects**

Leading the charge in submarine mass movement research are government organizations, such as geological surveys and oceanographic institutes, industry engineering teams and, importantly, the Council
of the International Geoscience Programme, Project 640 – S4LIDE (Significance of Modern and Ancient Submarine Slope Landslides), under whose leadership this book is written. Attempts are being made to catalogue the ever-growing number of mass transport deposits. Standardizing data collection for subaqueous landslides should result in more accurate geohazard predictions and resource estimation. León et al. (2018) attempt to apply the rules and specifications following the Infrastructure for Spatial Information in Europe. Integration of sub-marine, as opposed to land, failures requires that the list of activity states be simplified into three categories: active, dormant and relict. It also requires the inclusion of new landslide typologies: debris avalanches and turbidites. Because submarine MTDs are relatively more difficult to examine than their terrestrial counterparts, León et al. (2018) recommend that a reliability rating (high, medium, low) be applied to the database entries. Clare et al. (2018) analyse the database quality control in detail. In a revealing survey, Clare et al. (2018) had multiple experts from different backgrounds measure MTD deposits and in so doing exposed the difficulties encountered and differences produced when practitioners of different backgrounds measure MTD deposits and in doing so exposed the difficulties encountered and differences produced when practitioners of different backgrounds are analysing different landslides and data types. The resulting paper outlines an approach specifically for consistent measurement of subaqueous landslide morphometrics to be used in the design of a broader, global open-source, peer-curated database. Examples from different settings illustrate how the approach can be applied.

Classification schemes (e.g. Mulder & Cochonat 1996; Locat & Lee 2002) clearly help governments and other stakeholders to understand the breadth of hazards within their jurisdiction. However classifications are by their nature somewhat static as they try to provide a simplified framework for a complex phenomena. Massive landslide deposits may routinely be recognized and classified, but this may miss a potential multistage failure or near-coeval events, and their deposits, as well as small-scaled (<1 m) deposits which indicate post-failure evolution (Kuhlmann et al. 2018). These two features of a failure may in fact dominate the morphological appearance of a landslide, making it difficult to classify. The only reasonable existing method to understand these aspects is to collect samples from within the modern surface expression and piece together the puzzle of different morphologies and ages, as has recently been done for a slide deposit complex in Kitimat Arm (Stacey et al. 2018), and for the Tuaheni landslide complex (Kuhlmann et al. 2018). In both cases, the new data confirm that multiple distinct types of process have formed these complexes, not necessarily just large tsunamiigenic failures.

Mitigating the hazard to coastal and offshore infrastructure

Because of the need to understand consequences and mitigation measures, not only industry, but also federal governments, have increased their role in the science. Multidisciplinary studies are often employed. Offshore industries, such as oil and gas and telecommunications, have long provided a hub of research on the topic of mass movements, particularly those which may pose a hazard to their infrastructure and crews. For example, the Ormen Lange gas field offshore Norway sits in the slide scar of the apocalyptic Storegga slide in which a 290 km-long portion of the continental shelf collapsed (Bondevik et al. 2003). The range has been studied extensively for geohazard risk (Bry et al. 2003; Solheim et al. 2005). Further north on the same continental margin several commercial hydrocarbon discoveries have made the SW Barents Sea an area of intense hydrocarbon exploration over the past few decades (e.g. Henriksen et al. 2011), and so similar investigations are underway there to determine risk and mitigate hazard (Bellwald & Planke 2018), with sophisticated high-resolution seismic equipment. Intraglacial reflections and MTD layers which are not visible in conventional seismic data can be clearly seen. A soft reflection is interpreted as a coarse-grained and possibly gas-filled turbidite draping an unconformity in the area. Overall, mapping of MTDs and related turbidites has revealed where trapping and capping of gas may be occurring, but importantly for risk avoidance and mitigation, the mapping has constrained the general mass movement directions and timings with high confidence.

In the past decade the Geological Survey of Canada and Norwegian Geotechnical Institutes, among others (as above), have successfully delivered multidisciplinary projects to attempt to calculate the hazard, and provide science advice for areas of large coastal infrastructure development within fjords. The Geological Survey of Canada has undertaken a multiyear and multidisciplinary study (Lintern et al. 2019) to understand the magnitudes, frequencies and causes of tsunamigenic landslides in Kitimat Arm, British Columbia, an area with high port development potential which happens to be a very well-known example of submarine mass movement. The Norwegian Geotechnical Institute has moved on from a similar multidisciplinary and multiyear study in coastal and deepwater areas (Vanneste et al. 2012) to now providing geotechnical advice to government on major infrastructure projects, such as a bridge project in the Norway’s Bjornafjorden (Carlton et al. 2018). Both of the above examples demonstrate the need for comprehensive and multidisciplinary geohazard analyses for any infrastructure projects conducted in fjords. They
both represent cases where major development needs hazard assessment, government policy needs science and science needs international collaboration. This book brings together chapters which cover all of these connections.

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