Subaqueous mass movements in the context of observations of contemporary slope failure

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Abstract: The consequences of subaqueous landslides have been at the forefront of societal conscience more than ever in the last few years, with devastating and fatal events in the Indonesian Archipelago making global news. The new research presented in this volume demonstrates the breadth of ongoing investigation into subaqueous landslides, and shows that while events like the recent ones can be devastating, they are smaller in scale than those Earth has experienced in the past. Understanding the spectrum of subaqueous landslide processes, and therefore the potential societal impact, requires research across all spatial and temporal scales. This volume delivers a compilation of state-of-the-art papers covering regional landslide databases, advanced techniques for *in situ* measurements, numerical modelling of processes and hazards.

This Geological Society Special Publication volume comes at a key time in the discipline of subaqueous mass movement research. Catastrophic recent events (e.g. at Anak Krakatau and during the Sulawesi Earthquake in 2018) have demonstrated the substantial hazard that can be associated with subaqueous landslides, with multiple fatalities directly attributed to landslide tsunami. Public awareness is greater than ever given the easy proliferation of information through new media formats (e.g. social media, live streaming, blogging). While a significant amount can be learned from these contemporary events, in the geological past there is a much larger range of mass movement scales and variability in processes that is preserved in seafloor and lakefloor geomorphology and in the sedimentary record. Untangling the controls on past slope failures remains arguably the main challenge in subaqueous mass movement research, but one that can benefit greatly from considering the context of direct observations of contemporary subaqueous slope failure.

There have been many instances over the past 50 years where subaqueous or partially subaqueous slope failure have been directly observed and the hazard has been significant (Dan *et al.* 2007; Parsons *et al.* 2014). The events that have happened in the past decade may not be as large or as devastating, but they occurred in a time of rapidly advancing technology in the field of Earth observation.

In this introductory paper, we review recent subaqueous mass failure events, some of which have received widespread media coverage. We look at these events in terms of how they can help us better study subaqueous mass movements, particularly from a hazard and risk perspective. We follow this review with a summary of the papers in this Special Publication volume and emphasize why, in light of contemporary events, they offer important and timely contributions to the discipline.

Volcanic flank collapse at Anak Krakatau

On 22 December 2018 a volcanic flank collapse of the Anak Krakatau volcanic island in the Sunda Straits, Indonesia, created a tsunami that generated waves up to 1.4 m high at the coast, killing over 400 people (Williams *et al.* 2019). This event is defined by unprecedented remote sensing observations when compared with previous historical volcanic sector collapses, most notably the 1888 Ritter Island event (Day *et al.* 2015). Anak Krakatau first

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grew above sea-level in 1929 and had risen to 300 m elevation by December 2018, with changes documented by repeat satellite observations. Sentinel satellite footage from just 8 h after the tsunami shows the western flank failure and the collapse of the summit (Williams *et al.* 2019). Using these observations, combined with geomorphic interpretation, a subaqueous component of the failure is calculated to be a modest 0.1 km^3 and the subaerial component 0.004 km^3. Previous work had identified the tsunami hazard associated with flank collapse on Anak Krakatau, modelling a 0.28 km^3 failure in approximately the same location, which generated the same tsunami height in some locations but with significantly slower arrival times (Giachetti *et al.* 2012). For post-event modelling of the tsunami, Grilli *et al.* (2019) used a similar volume (0.27 km^3 failure). In both of these studies, a large component of the subaerial cone is assumed to have failed concurrently with the subaqueous flank; however, Williams *et al.* (2019) demonstrate that the cone did not fail and the subaerial component of the flank collapse was minor. New unpublished bathymetric data show that blocks up to 90 m high lie on the seafloor and the total slide mass volume is calculated to be 0.19 km^3 (http://www.bbc.com/news/science-environment-50798253). This event most probably will, and should, become the touchstone for tsunami model validation and volcanic island flank collapse hazard assessment. It was a catastrophic event in terms of loss of life, injury and displacement, despite the tsunami waves being comparatively small. The fact that this hazard had been well modelled in advance provides affirmation of the value of undertaking research into subaqueous mass movement hazards. A key outstanding question in our understanding of the Anak Krakatau landslide tsunami is the discrepancy in the calculated volumes of the failure, which is something to which studies of the failure history on volcanic cones can make a significant contribution. Understanding the mechanism behind contemporary events such as this one provides crucial context for landslide tsunami hazard studies when specific single-event failure mechanisms can be demonstrated. Conversely, the study of historical cone collapse can reveal long-term behaviour, as **Barrett *et al.* (2020)** show for past flank collapses in the Cape Verde Islands, where the deposition of volcanic debris on the slope may have triggered a chain of slope failures.

Earthquake triggering of subaqueous landslides

Shortly preceding the Anak Krakatau tsunami, in the same region, the 2018 M$_w$ 7.5 Sulawesi earthquake on the 28 September 2018 was accompanied by a tsunami with run-up of 6–11 m (Takagi *et al.* 2019). The combined events resulted in >4000 deaths, but the number associated with the tsunami alone remains unclear. Slope failures have been inferred to have a role in tsunami generation, supported by video observations of localized wave generation and evidence of coastal failures (Arikawa *et al.* 2018; Carvajal *et al.* 2019). While it is clear from the extraordinary video footage collected at the time that delta collapse and coastal landslides caused tsunamis (Fig. 1), the role that subaqueous slope failures played in the main wave generation remains speculative, and no more conclusive than for comparative previous events where earthquake mechanisms could not clearly be reconciled with tsunami generation (e.g. Tappin *et al.* 2001). In essence, we are still in a situation where there is no direct evidence for large, wholly subaqueous landslide-generated tsunami. To make this link in the future, with no doubt as to the mechanism, will most probably require an event to occur in a location where high-resolution bathymetry has previously been collected. This becomes ever more likely as regional bathymetric datasets covering active continental margins are being collected and analysed. In this volume, **Watson *et al.* (2020)** analyse regional bathymetric coverage across the entire offshore component of the Hikurangi Subduction margin, New Zealand; **Hill *et al.* (2020)** present a study of full-coverage multibeam data along almost 300 km of the Cascadia Subduction Zone; **Stacey *et al.* (2020)** and **Lintern *et al.* (2020)** present analyses of full-coverage bathymetric datasets in two active margin fjord systems; and **León *et al.* (2020)** present a landslide database for offshore Spain. These comprehensive studies, amongst others, will set a valuable baseline for analysing the impact of large earthquakes in the future.

Although no tsunami has been directly linked to subaqueous landslides, the November 2016 Kaikoura Earthquake, New Zealand, is one of the best documented earthquake-triggered, wholly subaqueous seafloor-failure events to date (Mountjoy *et al.* 2018). The difference between 2 m-resolution pre- and post-earthquake bathymetry shows widespread shallow-seated slope failures around the rim of Kaikoura Canyon in close proximity to the documented seafloor rupture of the Hundalee Fault (Mountjoy *et al.* 2018). Landslide failure depth is shallow (2–10 m) so it is unsurprising that no clear landslide tsunami signal was detected. The significant information that this event provides is that the extent of landslide occurrence around the fault rupture could be mapped, partly using multibeam differencing and partly from the geomorphic signature of fresh slope failures. Identifying the distribution of slope failures enabled the ground motion threshold for landslide triggering in this area to be defined,

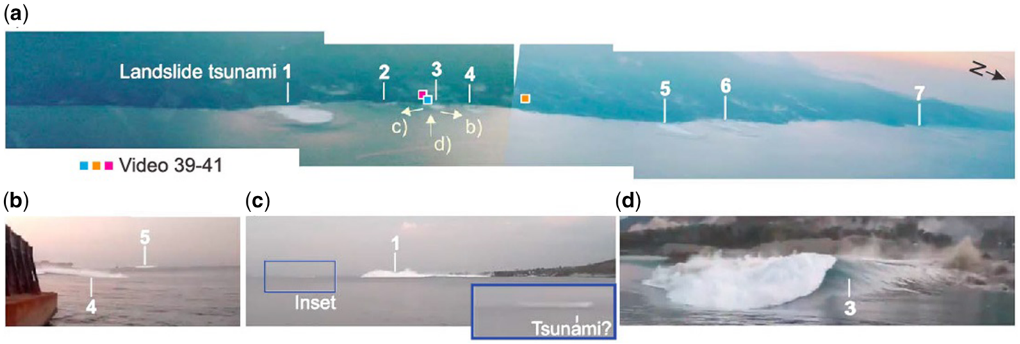

Fig. 1. Some of the only images ever captured of natural landslide tsunami generation, taken at the time of the Sulawesi earthquake in 2018 (Carvajal *et al.* 2019). Frames taken from (**a**) video footage and (**b–d**) near shoreline photos of the resulting waves. The numbers 1–7 refer to seven separate locations of wave generation.

by a peak ground acceleration of 0.32g, and a return period to be calculated (Mountjoy *et al.* 2018). The definition of a slope failure threshold has significant implications for hazard assessments where estimating the likelihood and distribution of subaqueous slope failure can be approached based on the proximity to fault rupture. An outstanding question, and one that observations following the 2016 Kaikoura Earthquake do little to address, is 'what causes very large subaqueous landslides?'. Despite the widespread occurrence of deep-seated landslides onland (Massey *et al.* 2018), multiple offshore fault ruptures (Litchfield *et al.* 2018), repeat mapping of over 4000 km^2 of seafloor – in an area with evidence for multiple deep-seated landslides – no landslides greater than 0.1 km^3 were documented for composite failure of the canyon floor, rather than for canyon wall areas where past landslide evidence is preserved. This follows from several repeat observations of the seafloor in the area of large earthquakes where no large landslides have been detected (Tappin *et al.* 2007; Völker *et al.* 2011). Comparisons of passive v. active margin open slopes show strengthening of the slope material on active margins due to earthquake shaking, demonstrating counter-intuitively that when earthquakes do not cause slope instability, they in fact have the opposite, strengthening effect (Sawyer and DeVore 2015; DeVore and Sawyer 2016; ten Brink *et al.* 2016; Sawyer *et al.* 2017; Molenaar *et al.* 2019). Whether this is the case for highly incised, canyon-dissected margins remains to be explored. This really highlights the value of advancing analytical, laboratory and case study research on the preconditioning and triggering of deep-seated landslides to advance our understanding of what makes large parts of the seafloor fail. Studying initiation, triggering and preconditioning of subaqueous mass movements forms a main focus in this volume.

Active landslides in dynamic sedimentary environments

Repeated failure (or contemporary 'active' landslide regions) in highly dynamic environments can significantly affect seafloor cables and oil field developments. This has been shown to be the case in submarine canyons (Clare *et al.* 2017; Pope *et al.* 2017) and on large deltas (Coleman *et al.* 1980). Significant efforts are being made to monitor and measure slope failure processes in these dynamic environments that include landslides, sediment bedform change and turbidity current processes. **Clare *et al.* (2020)** provide an overview of lessons learned from recent field campaigns, including those at submarine deltas (e.g. the Squamish Delta, British Columbia, and the Var Delta, Mediterranean). Repeat seafloor surveys and sediment flow monitoring at the Squamish submarine delta have revealed that short periods of rapid sediment accumulation can precondition the delta to fail and that landslides of up to 150 000 m^3 are ultimately triggered by tidally controlled pore pressure fluctuations (Hughes Clarke *et al.* 2012; Clare *et al.* 2016; Hizzett *et al.* 2018). **Chaytor *et al.* (2020)** document pipeline breaks on the Mississippi Delta, and use repeat seafloor mapping to track object displacement (shipwrecks, blocks). Their study shows that repeated seafloor failure results in downslope movement rates of 85 m a^{-1} for blocks measured in the 2016–17 period and potentially 150 m a^{-1} for the wreck of the SS *Virginia*. These repeat observations of seafloor change demonstrate that the Mississippi Delta is subject to highly dynamic conditions, and that slope failure can take place without major cyclonic events. It is now being recognized that repeated failures of larger deep-seated landslides can occur in the same location, but such events differ as they involve reactivation of the same material. Seafloor instrumentation has enabled measurements of downslope movement on the submerged flank of Mt Etna (Urlaub *et al.* 2018), and repeated movement is hypothesized for the Tuaheni Landslides offshore New Zealand (Mountjoy *et al.* 2009). **Couvin *et al.* (2020)** use new IODP drilling data in combination with P-Cable 3D seismic to propose a new model for the failure history of the Tuaheni Landslides. The new data show that only the top 40 m of the landslide is likely to be repeatedly reactivated, and that this portion is dominated by decimetre-scale sand units.

Glacial alpine environments: locus of climate sensitivity

The largest potential tsunami hazard related to subaqueous mass movements comes from large rockfalls entering small water bodies (e.g. fjords and lakes) where an extraordinarily large amount of water can be displaced. This is exemplified by the 1958 Lituya Bay, Alaska, tsunami where a 1 km^3 rockfall generated a wave over 500 m high (Miller 1960; Weiss *et al.* 2009). These extreme events are rare and have mostly happened in remote areas; however, it is definitely a significant concern that something like this might affect populated areas (Harbitz *et al.* 2014) and improved understanding of the preconditioning factors, frequency and dynamics of these events is therefore very important. In 2015 in Taan Fjord, Alaska, a 0.147 km^3 rockfall generated a large tsunami, fortunately with no casualties (Haeussler *et al.* 2018). The tsunami run-up from this event was an astounding 193 m, making it among the largest ever recorded (Higman *et al.* 2018). Post-event mapping has enabled a detailed calculation of the scale of the deposit, and the characteristics of the source area (Dufresne *et al.* 2018; Haeussler *et al.* 2018). It is likely that landslides in glaciated areas will become more frequent as the climate changes and glaciers retreat (Grämiger *et al.* 2017). Furthermore, increasingly dynamic landscape processes in response to climate change will more rapidly obscure the onshore evidence for such events (Dufresne *et al.* 2018), further highlighting the value of the subaqueous record.

Given these points, the depositional characteristics of large landslides in alpine environments, as well as their extent, age and frequency, become increasingly important. Several papers in this volume directly address this topic. **Stacey *et al.* (2020)** derive a magnitude frequency relationship for slope stability in the 140 km-long Douglas Channel Fjord system in Canada, and show that potentially damaging landslides occur throughout the fjord. Several studies make basin-wide assessments for lakes, illustrating the widespread occurrence of lacustrine landslides, which are commonly little considered but potentially catastrophic, even when occurring on entirely submerged slopes (**Daxer *et al.* 2020**; **Moernaut *et al.* 2020**; **Strasser *et al.* 2020**; **Strupler *et al.* 2020**).

State of the art

While the recent events reviewed here highlight the consequences of subaqueous mass movements, they capture just a small part of the broader spectrum of scales, processes and event hazards. The revealing information about event timing and consequences (e.g. tsunami or infrastructure damage) is of great value to practitioners, but leaves many gaps that need to be filled in by the study of past events, through numerical modelling and experimental research in the laboratory. The power of this volume lies in the breadth of studies from across the world's ocean basins, fjords and lake environments (Fig. 2), going back through the depositional record to build up a picture of the controls and triggers of subaqueous mass movements, their flow behaviour and their impact on society. To develop a logical and easily readable structure to the volume, the papers are presented in four thematic areas.

Section A: consequences and implications

Understanding and quantifying tsunami hazards related to subaqueous landslides remains a significant challenge. Apart from fjord-wall instabilities, the most significant landslide-generated tsunamis are often attributed to the collapse of volcanic island flanks, typically involving both subaerial and subaqueous slope failure. In this issue, a case study at the base of Fogo Volcano (Cape Verde Islands; **Barrett *et al.* 2020**) highlights the need for high-resolution mapping of complex landslide deposits to accurately constrain the number of failures, the geometry of their deposits and the extent of possible loading-induced deformation of pre-existing seafloor sediments. This combined information is crucial for evaluating the tsunamigenic potential associated with volcanic islands. In addition to landslide geometry, the characterization of landslide material forms a basic input parameter for landslide modelling, determining how sediment rheology affects landslide processes. Such sedimentological analysis is presented for the Byron landslide, located on the east Australian continental margin, and serves to inform hydrodynamic models constraining the associated tsunami hazard (**Mollison *et al.* 2020**). Tsunami models are often based on very simplified concepts considering the landslide source, such as the sliding block model. A more sophisticated approach is presented in this volume, in which

Fig. 2. Distribution of studies in this volume. Red stars indicate studies at a specific site, whereas blue polygons show regional mapping studies. Some studies are represented by multiple stars. The papers by **Kaminski *et al.* (2020)** and **Silver and Dugan (2020)** are not related to a specific geographical area so are not shown on the map.

slump motion is modelled using a viscoplastic flow, allowing the influence of soil parameters and failure plane geometry on frontal tsunami wave height to be evaluated by simulating the 1929 Grand Banks tsunami using updated geological source information (**Zengaffinen *et al.* 2020**).

The main motivation for reconstructing past landslide and tsunami events is the prognostic forecasting of future events on different spatiotemporal scales. This can involve scenario-based tsunami inundation analysis, often adopting a worst-case credible scenario in terms of landslide size and location. Here, such analysis is carried out for the geodynamically very active north Sicily Continental Margin, including both subaqueous landslides and earthquake ruptures as potential tsunami sources (**Dignan *et al.* 2020**), improving the tsunami hazard assessment for this vulnerable, low-lying coast with numerous coastal villages and important tourist sites. High population density also characterizes the shoreline of large perialpine lakes in Europe, and although lake tsunamis do not occur often, a robust hazard evaluation is important. **Strupler *et al.* (2020)** present a workflow for rapid screening of landslide-generated tsunami hazard related to poorly investigated lakes, building on knowledge gained from previous lacustrine slope stability studies and mass transport deposit (MTD) mapping in a few well-investigated lakes. Another step towards developing adequate mitigation, prevention and adaptation strategies is taken by the Geological Survey of Canada, which developed a national subaqueous landslide database as part of the national tsunami strategy (**Lintern *et al.* 2020**). This major effort from a federal government geological survey incorporates the morphometrics and processes of dozens of major landslides and hundreds of smaller events.

Apart from the significant tsunami hazard, subaqueous landslides can have other consequences that may even be indirectly beneficial to society. For example, it has been suggested that the subduction of large, chaotic MTDs can influence megathrust seismogenic behaviour at convergent margins by forming a rough boundary that may impede the propagation of earthquake ruptures. On the basis of a data comparison from different convergent margins, a study in this volume presents an evaluation of different controlling factors that define whether trench MTDs are subducted with the downgoing plate or are accreted to the upper plate (**Geersen *et al.* 2020**). Moreover, deeply buried MTDs can be important (economically relevant) elements in hydrocarbon systems, acting as potential reservoirs or seals for migrating fluids. A specific case study analyses the (*in situ*) physical properties of very young and shallowly buried MTDs in a lake to better understand the role of MTDs in fluid flow during their earliest stage of burial (**Moernaut *et al.* 2020**), concluding that shallow MTDs can form a relatively rapid seal for fluid migration, but this seal can be locally degraded by rafted blocks.

Finally, **Bull *et al.* (2020)** show that MTD topography can have a controlling influence on sediment routing and deposition, based on the 3D seismic analysis of the relative timing of the emplacement of exceptionally large MTDs and high sediment flux slope channels offshore Taranaki, New Zealand.

Section B: initiation, triggers, and preconditioning

Subaqueous landslides occur when a large number of physical conditions for sediment failure are met or exceeded. Understanding which physical conditions precondition the sediment, trigger and initiate movement, and control the dynamics of the resulting landslide, continues to be of fundamental importance in evaluating past events and forecasting future instability. Papers in this volume continue the effort to illuminate the roles that different geological, oceanographic, climatic and seismic conditions play in subaqueous landslide occurrence.

The contribution of oceanic bottom current erosion and deposition to controlling the mechanical properties of submarine slopes and localizing failure is addressed for seismically passive (**Gatter *et al.* 2020**) and active (**Brackenridge *et al.* 2020**) regions. **Gatter *et al.* (2020)** demonstrate that failure on sheeted contourite drifts localizes at contrasting lithological interfaces. **Brackenridge *et al.* (2020)** reveal the landslide hazard posed by the combination of high sediment supply from a delta and reworking and redistribution of that sediment by bottom currents to a specific location. **Locat *et al.* (2020)** look in detail at the effect of channel erosion and knickpoint formation in influencing the overall stability of coarse-grained deltas and find that breaching and liquefaction may occur when the knickpoint slope direction is close to the bedding plane dip direction. The response of seafloor environments to changes in global climatic conditions remains an area of intense debate and active study. The impacts of the indirect (**Daxer *et al.* 2020**) and direct influence of ice sheets on sediment pore pressure (**Urlaub *et al.* 2020**) and sea-level variation on sedimentation patterns (**Micallef *et al.* 2020**) continue to inform the discussion on the mechanisms by which these climate-influenced processes impact instability and the magnitude of their effects.

Defining the roles of gases and fluids in preconditioning sediment for failure, especially in terms of capturing the nature of *in situ* conditions, is fundamental in current subaqueous landslide research. **Kaminski *et al.* (2020)** investigate the role of free gas in influencing sediment shear strength via alteration of pore-space conditions and propose that the effect of trapped gas in sediment pores on the sediment's shear resistance is insufficient to trigger large-scale instability, but high gas pressures could lead to liquefaction. Modelling of sediment stability under changing fluid, pore pressure and sedimentological conditions based on field (**Mencaroni *et al.* 2020**) and laboratory observations (**Silver and Dugan 2020**) furthers our understanding of the way in which each of these physical parameters controls preconditioning and initiation.

Investigating submarine landslides along subduction margins, and relating them to characteristics of the incoming plate and the strength of the sediments on the overriding plate, continues to be a challenging task due to the large scale and heterogeneity of subduction margins. **Vargas *et al.* (2020)** explore the relationships between subduction of the extinct Sandra Ridge under the South American Plate and the location and timing of landslides on the trench margins.

Section C: characterization and regional controls

The triggering and characteristics of MTDs are primarily influenced by the region in which they occur. Regional tectonics is a key aspect to consider as seismicity is widely implicated as a major trigger for subaqueous landslides (Masson *et al.* 2006), although higher seismicity may not result in more landslides (ten Brink *et al.* 2016). Climatic controls play an important role, as well as hinterland precipitation, and the presence of ice sheets influences the volume and rate of sediment input to the basin. Locally, slope instability is controlled by sediment input, seismicity, slope steepness, geometry, geology and geotechnical properties (McAdoo *et al.* 2000; ten Brink *et al.* 2016). All of these parameters will influence the final character of the slide mass and associated kinematics, which can be analysed at multiple scales. The acquisition of data is key for the understanding of subaqueous landslide events in relatively unknown areas. New bathymetry and sub-bottom profiler data acquired during recent icebreaker expeditions to the Alpha Ridge in the Arctic Ocean revealed a highly disturbed seabed with numerous MTDs with varying degrees of lateral transport, characterized by blocks, ridges and scarps (**Boggild *et al.* 2020**). The new information also sheds light on the likely origin of the deposits, ruling out a bolide impact, as previously hypothesized, and instead supporting the presence of a seismic trigger associated with tectonism in or around the Alpha Ridge.

New high-resolution data bring new insights into MTDs occurring even in well-studied regions, such as the Mediterranean Basin. **Cattaneo *et al.* (2020)** revisit a turbidite megabed in the Balearic Basin deposited during the Last Glacial Maximum. They used high-resolution geophysical data in conjunction with geotechnical data to remap the deposit and obtain a new age constraint. Within the same area, **Badhani *et al.* (2020)** investigate recurrent mass-wasting in the Gulf of Lions and revisit the Rhône western and eastern MTDs, triggered during the peak of the Last Glacial Maximum. They reveal previously unidentified internal structures in the MTD and, through integration with *in situ* measurements, they demonstrate that the recurrence of landslides in the area is influenced by the presence of clay-rich sediments. At the other end of the Mediterranean, **Katz *et al.* (2020)** use the taphonomy of foraminiferal assemblages to evaluate the deformation in debrites offshore Israel that are estimated to be contemporaneous with, or slightly predating, the transition to the Holocene. A case study from NE Sicily by **Casalbore *et al.* (2020)** focuses on the morphometrics of numerous landslide scars at submarine canyons and shows a prominent role of slope gradient in the size and character of landslide scars, particularly on steep slopes.

Through a wealth of high-resolution data, including historical records, **Strasser *et al.* (2020)** present a detailed study of MTDs in Lake Hallstatt (Austria), where earthquake-induced MTDs can be tied to historical events. These MTDs are not only larger than ones derived from flood events, rock falls or debris flows, but also present sedimentological and geochemical differences with evidence of mixing with intralake sediments. The larger dimensions of such MTDs present a significant geohazard that could impact structures around the lake.

Landslides in fjords are comparable to lacustrine MTDs; mass failures derived from steep slopes entering shallow-water environments can cause very large waves (e.g. Miller 1960). **Stacey *et al.* (2020)** summarize a five-year-long investigation of the Douglas Channel in Canada, where steep slopes, high precipitation and seismicity are responsible for the widespread occurrence of MTDs in this fjord environment. The larger and more frequent slope failures were active during deglaciation, but smaller and less frequent ones have also been occurring during the Holocene over the whole Douglas Channel system, all with tsunamigenic potential.

The relationship between tectonism, sediment bypass and slope morphology along the tectonically active Cascadia Margin is presented by **Hill *et al.* (2020)**. The results suggest that despite the presence of several canyons on the margin, few act as efficient sediment conduits to the deep sea. Instead, MTDs are likely to be the main process of sediment accumulation on the abyssal plains, with implications for interpretation of palaeoseismicity records on the margin.

On the other side of the Pacific Ocean, on the tectonic margins of New Zealand, **Watson *et al.* (2020)** investigated over 2000 MTDs following the subaqueous landslide characterization methodology in Clare *et al.* (2018). Based on morphological parameters, an assessment of triggers and areas of high landslide density, the authors demonstrate that landslides are most likely to occur in submarine canyons and, contrary to other studies, show that twice as many landslides occur on the active margin portion of the study area (the Hikurangi Margin) compared with the passive margin setting to the south. Another large-scale approach following Clare *et al.* (2018) is presented by **León *et al.* (2020)** for the entire Spanish offshore territory. Three types of source have been identified (deep-ocean ridges, volcanic islands and sedimentary continental margins) and, using a statistical analysis of MTD morphometrics, they distinguish between tectonic and non-tectonic triggers for the subaqueous mass failure.

Section D: mobility and kinematics

MTDs have shown a great variety of shapes and sizes that relates to their transport dynamics and internal heterogeneity. A series of intraMTD features can be used as kinematic markers to understand their movement (Bull *et al.* 2009) and assess whether MTDs derive from unidirectional flows or higher complexity is involved in a single episode or within complexes.

Internal MTD features such as blocks, folds, internal thrusts and extensional faults are key elements for understanding mass-movement kinematics. Blocks exhibit different shapes and sizes, as they are often associated with glide tracks that provide quantitative clues to constrain the remobilization distance often on the order of several kilometres (**Nwoko *et al.* 2020**). However, a full assessment of total MTD remobilization distances in three dimensions is an ongoing challenge. **Bull and Cartwright (2020)** show how simple structural restoration techniques of length-balancing help address this, and demonstrate the degree of underestimation in volume removal associated with the Storegga Slide. The availability of core and log data intersecting MTDs is generally limited. Thanks to a recent IODP expedition focusing on MTDs (Expedition 372, Pecher *et al.* 2019), invaluable additional data have been made available that have proved crucial to understanding landslide dynamics. This dataset, in combination with a P-Cable 3D seismic cube, allowed **Couvin *et al.* (2020)** to reinterpret the dynamics of the Tuaheni Landslide Complex offshore New Zealand and propose a new depositional model for it.

The occurrence of multiple stacked MTDs allows a more comprehensive understanding of not only their emplacement, but also wider controls on slope failure and sediment transport. **Roy *et al.* (2020)**, using internal deformation structures as kinematic indicators, show how five megascale MTDs on the Rockall Trough associated with different episodes of expansion of the British–Irish Ice Sheet interacted in a flow convergence zone of the palaeoslope.

Most of the published studies used to understand the dynamics, run-out velocity and timing of MTDs available in scientific literature have the major limitation of relying on static ‘snapshots’ in time of what is effectively a dynamic system. More than a challenge, there is a necessity to improve the current technology to allow a 4D study of seafloor dynamics through repeated surveys to assess the mobility and associated geohazards, as exemplified by **Chaytor *et al.* (2020)**. The authors present high-resolution data from repeat surveys to evaluate and quantify the complex mobility of the Mississippi River delta front on a decadal to annual timescale. By quantifying the displacement on the order of tens or hundreds of metres from seabed infrastructures, shipwrecks and MTD blocks, a novel monitoring methodology is introduced that can increase our understanding of seasonal, annual or progressive mass-flow triggers. Monitoring technologies will be key in the future of MTD research, yet substantial barriers still lie ahead to mitigate equipment damage or loss on the harsh and challenging subaqueous environment. **Clare *et al.* (2020)** present insights on lessons learned and propose future directions regarding the design, preservation and safety of mooring devices for gravity flow monitoring and highlight how these can be applied to realize future monitoring techniques capable of high-quality data acquisition and applicable to a wider range of subaqueous settings.

Perspectives for the future

In the first section of this paper, we reviewed cases of subaqueous mass movements in the past few years. It is clear that the technology available to document subaqueous landslides is significantly better than it has been in the past, from terrestrial remote sensing to seafloor imaging to real time monitoring. What we have still not experienced in recent history is devastating loss of life from tsunami that can unequivocally be shown to be generated by large mass-failure events. Given what we know about the scale of ancient events, e.g. the tsunami associated with the subaqueous Storegga landslide in Norway (Dawson *et al.* 1988) and the potential of historical events that have happened in remote areas, e.g. the Lituya Bay tsunami (Miller 1960), it is probable that some populated part of the world will be catastrophically affected by this hazard in the foreseeable future.

The papers in this GSL volume cover a very broad range of approaches into studying subaqueous mass movement that are necessary to grapple with the processes, triggers, preconditioning factors, hazards, mobility and kinematics, and the temporal and spatial occurrence that will ultimately assist in building resilient societies through better hazard and risk assessments.

As we move forward into an increasingly advanced technological age, direct measurement and monitoring of subaqueous slopes is going to become routine. We are already making significant progress in this area and the research of the IGCP Project 640 – S4SLIDE (Significance of Modern and Ancient Submarine Slope LandSLIDEs) community is playing a leading role. Developments in monitoring now include subsurface sensors that measure pore pressure fluctuations (Sultan *et al.* 2004; Lintern and Hill 2010; **Clare *et al.* 2020**), small-scale geodetic measurements of seafloor displacement (e.g. Urlaub *et al.* 2018) and novel uses of fibre-optic cables to monitor ground accelerations (e.g. Hartog *et al.* 2018). It is hoped that these proven new technologies, and other emerging systems, will provide early warning systems to reduce the risk posed to coastal communities and increase the resilience of critical seafloor infrastructure. These highly detailed and advanced measurements will always need to be considered in the context of the broad understanding of subaqueous failure that the geological record provides.

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