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

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The consequences of subaqueous landslides have been at the forefront of societal conscience possibly 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 GSL volume demonstrates the breadth of investigation taking place into subaqueous landslides, and shows that while events like the recent ones can be devastating they are at the smaller end of what the 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 to advanced techniques for *in situ* measurements to numerical modelling of processes and hazards.

This SP-GSL 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 with 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 are preserved in seafloor and lakefloor geomorphology and in the sedimentary record. Untangling the controls on past slope failures remains arguably the main challenge of 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 and more where subaqueous or partially subaqueous slope failure has 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 have 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 from the perspective 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 Publications volume and emphasise why, in light of contemporary events, they offer important and timely contributions to the discipline.

Volcanic Flank Collapse at Anak Krakatau

On December 22 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 at the coast, killing over 400 people (Williams et al., 2019). This event is defined by unprecedented remote sensing observations when compared to previous historic volcanic sector collapses, most notably the 1888 Ritter Island event (Day et al., 2015). Anak Krakatau first 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 hours 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 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 shows that blocks up to 90 m high lie on the seafloor and that the total slide mass volume is calculated to be 0.19 km^3 (www.bbc.com/news/science-environment-50798253). This event most likely 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 for understanding the Anak Krakatau landslide tsunami remains the discrepancy in the volume 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 like 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 **Barret et al (this volume)** 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 Mw. 7.5 Sulawesi earthquake on the 28 September 2018 was accompanied by a tsunami with runup of 6-11 m (Takagi et al., 2019). The combined event resulted in >4000 deaths but the number associated with the tsunami alone remains unclear. Slope failures have been inferred as having a role in tsunami generation, supported by video observations of localised wave generation and evidence for 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 (Figure 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, leaving no doubt as to the mechanism will most likely require an event to occur in a location where high-resolution bathymetry has previously been collected. As regional bathymetric datasets covering active continental margins are being collected and analysed this becomes ever more likely. In this volume **Watson et al.** analyse regional bathymetric coverage across the entire offshore component of the Hikurangi Subduction margin, New Zealand; **Hill et al.** present a study of full coverage multibeam data along almost 300 km of the Cascadia Subduction Zone; **Stacey et al.** and **Lintern et al.** present analyses of full-coverage bathymetric datasets in two active margin fjord systems; **Leon et al.** 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.

While 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 this event provides is that the extent of landslide occurrence around the fault rupture could be mapped, partly from 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, as 0.32 g, and a return period to be calculated (Mountjoy et al., 2018). 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 does little to address, is “what causes very large subaqueous landslides?”. Despite widespread 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 could be documented and this is for composite failure of the canyon floor rather than 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 vs 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 have in fact the opposite, strengthening effect (Sawyer and DeVore, 2015; De Vore et al., 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 section 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. (this volume)** provide an overview of lessons learned from recent field campaigns, including those at submarine deltas (e.g. Squamish Delta, British Columbia, and 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 and that landslides of up to 150,000 m^3 are ultimately triggered by tidally-controlled pore pressure fluctuations (Hughes Clarke et al., 2012; Hizzett et al., 2017; Clare et al., 2016). **Chaytor et al (this volume)** 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/yr for blocks measured in the 2016-17 period and potentially 150 m/year 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. Repeated failure of larger deep-seated landslides can also occur in the same location are now being recognised as well, but differ as these 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 hypothesised for the Tuaheni Landslides (TLC) offshore New Zealand (Mountjoy et al., 2009). **Couvin et al. (this volume)** use new IODP drilling data in combination with P-Cable 3D seismic to propose a new model for the failure history of the TLC. The new data show that only the top 40 m of the landslide is likely to be repeatedly reactivated, and that this unit 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 therefore improved understanding of the preconditioning factors, frequency and dynamics of these events is 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 runup 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, their extent, age and frequency become increasingly important. Several papers in this volume directly address this topic. **Stacey et al. (this volume)** 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; Moernaut et al; Strasser et al; Strupler et al; all in this volume)**.

State of the art

The recent events reviewed here highlight the consequences of subaqueous mass movements, however 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 laboratory experimental research. The power of this special publication of the GSL volume lies in the breadth of studies from across the World's ocean basins, fjords and lake environments (Figure 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 to 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 as well as subaqueous slope failure. In this issue, a case study at the base of Fogo Volcano (Cape Verde Islands; ***Barrett et al., this volume***) 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 to 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., this volume**).* Tsunami models are often based on very simplified concepts considering the landslide source, such as the sliding block model. In this volume, a more sophisticated approach is presented where slump motion is modelled using a viscoplastic flow, allowing to evaluate the influence of soil parameters and failure plane geometry on frontal tsunami wave height by simulating the 1929 Grand Banks tsunami using updated geological source information *(**Zengaffinen et al., this volume**).*

The main motivation of 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 as well as earthquake ruptures as potential tsunami sources (***Sulli et al., this volume***), in this way 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., (this volume***) present a workflow for rapid screening of landslide-generated tsunami hazard related to poorly-investigated lakes, building on the 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., this volume**)*. 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 associated with subaqueous landslides, they can have other consequences which may even be indirectly beneficial to society. For example, it is suggested that the subduction of large chaotic MTDs can influence the megathrust seismogenic behaviour at convergent margins, by forming a rough boundary which may impede the propagation of earthquake ruptures. Based on data comparison from different convergent margins, a study in this volume presents an evaluation of different controlling factors which define whether trench MTDs are subducted with the downgoing plate or are accreted to the upper plate (***Geersen et al., this volume***). 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 analyzes the (in-situ) physical properties of very young and shallowly-buried MTDs in a lake, to better understand the role of MTDs on fluid flow during their earliest stage of burial (***Moernaut et al., this volume****)*, concluding that shallow MTDs can form a relatively rapid seal for fluid migration, but this seal can be locally degraded by rafted blocks.

Section B: Initiation, Triggers, and Preconditioning

Subaqueous landslides occur when a large number of physical conditions for sediment failure are met or exceeded. Understanding what the physical conditions are that precondition the sediment, trigger and initiate movement, and that 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 role different geologic, oceanographic, climatic, and seismic conditions have on 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., this volume)*** and active ***(Brackenridge et al., this volume)*** regions. ***Gatter et al. (this volume)*** demonstrate that failure on sheeted contourite drifts localises at contrasting lithological interfaces. ***Brackenridge et al. (this volume)*** 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. (this volume***) look in detail at the effect of channel erosion and knickpoint formation in influencing the overall stability of coarse-grained deltas and find that when knickpoint slope direction is close to the bedding plane dip direction breaching and liquefaction may ensue. The response of seafloor environments to changes in global climatic conditions remains an area of intense debate and active study. The impact of indirect (***Daxer et al., this volume***) and direct influence of ice sheets on sediment pore pressure (***Urlaub et al., this volume***) and sea-level variation on sedimentation patterns (***Micallef et al., this volume***) continue to inform the discussion on the mechanisms by which these climate-influenced processes impact instability and the magnitude of their effects.

Defining the role of gas 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. (this volume)*** 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 to 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., this volume***) and laboratory observations (***Silver and Dugan, this volume***) further our understanding of the way in which each of these physical parameters control 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. (this volume)*** explore the relationships between subduction of the extinct Sandra Ridge under the South American Plate and location and timing of landslides on the trench margins.

Section C: Characterisation and Regional Controls

The triggering and characteristics of MTDs is 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 or the presence of ice sheets influences the volume and rateof 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 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 mass transport deposits (MTDs) with varying degrees of lateral transport, characterised by blocks, ridges and scarps (**Boggild et al., this volume**). The new information also shed light into the likely origin of the deposits, ruling out a previous interpretation of a bolide impact and instead consider a more likely seismic trigger associated with tectonism in or around the Alpha Ridge.

New high-resolution data brings new insights into MTDs occurring even in well-studied regions, such as the Mediterranean Basin. **Cattaneo et al. (this volume)** revisit a turbidite mega-bed in the Balearic Basin deposited during the Last Glacial Maximum (LGM). 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 (this volume)** investigate recurrent mass-wasting in the Gulf of Lions and revisit the Rhône western and eastern MTDs, triggered during the peak of the LGM. Using new high-resolution geophysical data, 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 (this volume)** use the taphonomy of foraminiferal assemblages to evaluate the deformation in debrites offshore Israel which are estimated to be contemporaneous with or slightly predating the transition to the Holocene. A case study from NE Sicily by **Casalbore et al. (this volume)** focuses on the morphometrics of numerous landslide scars at submarine canyons and show a prominent role of slope gradient on the size and character of landslide scars, particularly on steep slopes.

Through a wealth of high resolution data, including historical records, **Strasser et al (this volume)** 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 intra-lake sediments. The larger dimensions of such MTDs present a significant geohazard that can have impacts on structures around the lake.

Comparable to lacustrine MTDs are landslides in fjords, where mass-failures derived from steep slopes entering shallow water environments can cause very large waves (e.g. Miller, 1960). **Stacey et al (this volume)** summarise a 5-year 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 (this volume).** 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 the main process for sediment accumulation on the abyssal plains, with implications for the considerations of paleoseismicity records on the margin. On the other side of the Pacific Ocean, on the tectonic margins of New Zealand, **Watson et al (this volume)** investigated over 2000 MTDs following the subaqueous landslide characterisation methodology in Clare et al (2018). Based on morphological parameters, an assessment of triggers and areas of high landslide density, the authors demonstrate 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 to the passive margin setting to the south. Another large-scale approach following Clare et al (2018) is presented by **Léon et al (this volume)** for the entire Spanish offshore territory. Three types of sources 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 which relate to their transport dynamics and internal heterogeneity. A series of intra-MTD features can be used as kinematic markers to understand their movement (Bull et al, 2009) and assess if MTDs derive from unidirectional flows or if 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 the understanding of mass-movement kinematics. Blocks exhibit different shapes and sizes, being often associated with glide tracks that provide quantitative clues to constrain remobilisation distance often in the order of several kilometres **(Nwoko et al., this volume).** However, the full assessment of total MTD remobilisation distance in three dimensions is an ongoing challenge. **Bull and Cartwright (this volume)** show how simple structural restoration techniques of length-balancing help address this challenge, and demonstrate the degree of underestimation of 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 has been made available that has proved crucial for the understanding of landslide dynamics. This dataset, in combination with a P-Cable 3D seismic cube, allowed **Couvin et al. (this volume)** to re-interpret 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 wider understanding of not only their emplacement but also wider controls on slope failure and sediment transport. **Roy et al (this volume)**, using internal deformation structures as kinematic indicators, show how five mega-scale 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 paleo-slope.

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. (this volume)**. 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, in 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 great challenges still lie ahead to mitigate equipment damage or loss on the harsh and challenging subaqueous environment. **Clare et al. (this volume)** 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 improve 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 in order 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., this volume**), small-scale geodetic measurements of seafloor displacement (e.g. Urlaub et al., 2018), and novel use of fibre-optic cables to monitor ground accelerations (e.g. Hartog et al., 2018). In the future, 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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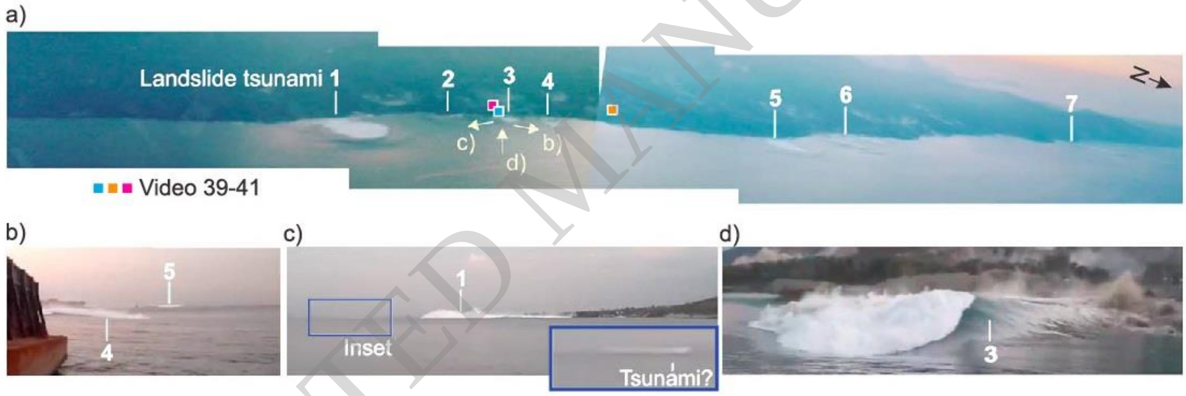
Figure captions

Figure 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). The numbers 1-7 in (a) refer to 7 separate locations of wave generation and panels (b-d) show near shoreline photos of the resulting waves.

Figure 2: Distribution of studies in this volume. Red stars indicate studies at a specific site while blue polygons show regional mapping studies. Some studies are represented by multiple stars.


a)
Landslide tsunami
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b)
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Inset
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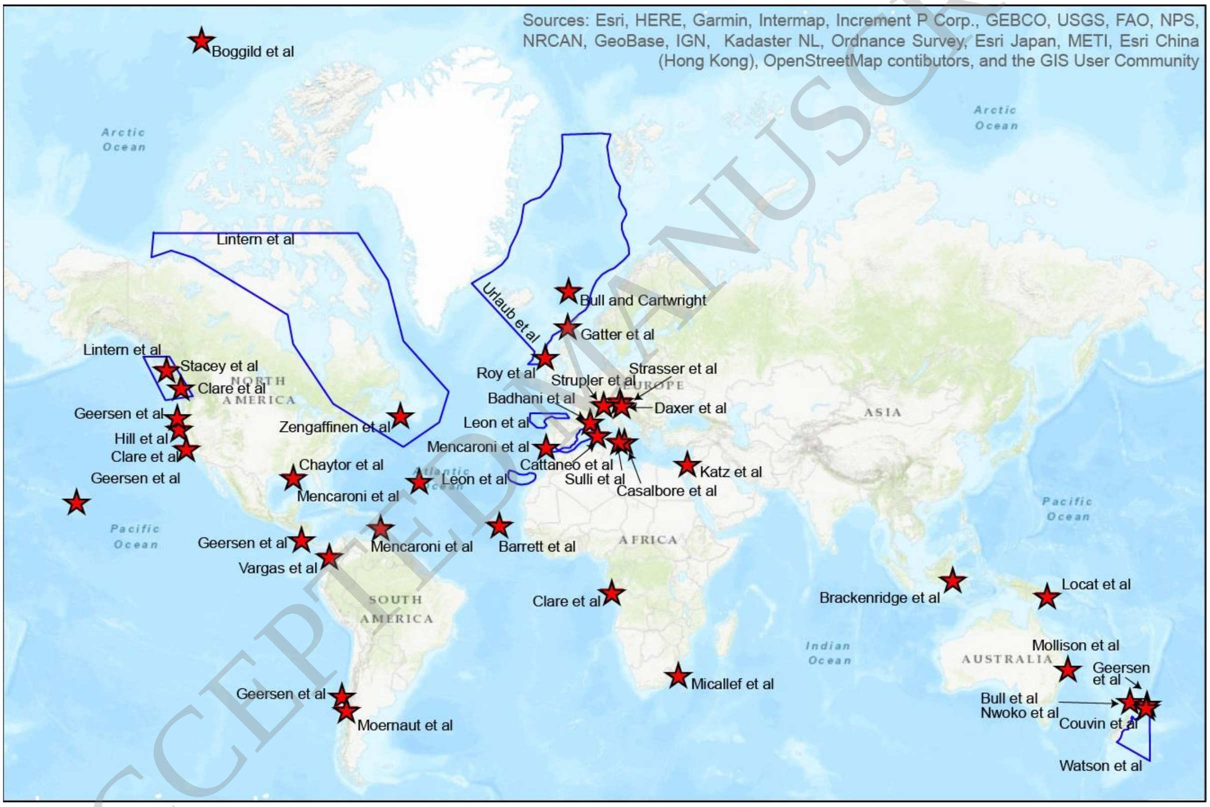
Sources: Esri, HERE, Garmin, Intermap, Increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), OpenStreetMap contibutors, and the GIS User Community
Boggild et al
Arctic Ocean
Arctic Ocean
Lintern et al
Urlaub et al
Bull and Cartwright
Gatter et al
Lintern et al
Stacey et al
Clare et al
NORTH AMERICA
Roy et al
Strasser et al
Strupler et al
EUROPE
Badhani et al
Daxer et al
Geersen et al
Zengaffinen et al
Leon et al
ASIA
Hill et al
Clare et al
Mencaroni et al
Cattaneo et al
Chaytor et al
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Sulli et al
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Atlantic Ocean
Casalbore et al
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Indian Ocean
Mollison et al
AUSTRALIA
Geersen et al
Micallef et al
Geersen et al
Bull et al
Nwoko et al
Couvin et al
Moernaut et al
Watson et al