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Seismic and Acoustic Monitoring of Submarine Landslides: Ongoing Challenges, Recent Successes and Future Opportunities

Clare, M.A.[1*], Lintern, D.G.[2], Pope, E.[3], , Baker, M. [3], Ruffell, S[3]., Zulkifli, Z.[1,] Simmons, S.,[4], Urlaub, M.[5], Belal, M. [1], Talling, P.J. [3]

1) National Oceanography Centre, Southampton, SO14 3ZH, UK
2) Natural Resources Canada, Geological Survey of Canada, Sidney, British Columbia V8L 4B2, Canada
3) Departments of Earth Sciences and Geography, University of Durham, Stockton Road, Durham, UK, DH1 3LE, UK
4) Earth and Environment Institute, Hull, UK
5) GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany.

*Contact: m.clare@noc.ac.uk

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8) Departments of Earth Sciences and Geography, University of Durham, Stockton Road, Durham, UK, DH1 3LE, UK
9) Earth and Environment Institute, Hull, UK
10) GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany.

Abstract

Submarine landslides pose a hazard to coastal communities due to the tsunamis they can generate, and can damage critical seafloor infrastructure, such as the network of cables that underpin global data transfer and communications. These mass movements can be orders of magnitude larger than their onshore equivalents and are found on all of the world's continental margins; from coastal zones to hadal trenches. Despite their prevalence, and importance to society, offshore monitoring studies have been limited by the largely unpredictable occurrence of submarine landslide and the need to cover large regions of extensive continental margins. Recent subsea monitoring has provided new insights into the preconditioning and run-out of submarine landslides using active geophysical techniques, but these tools only measure a very small spatial footprint, and are power and memory intensive, thus limiting long duration monitoring campaigns. Most landslide events therefore remain entirely unrecorded. Here we first show how passive acoustic and seismologic techniques can record acoustic emissions and ground motions created by terrestrial landslides. We then show how this terrestrial-focused research has catalysed advances in the detection and characterisation of submarine landslides, using both onshore and offshore networks of broadband seismometers, hydrophones and geophones. We then discuss some of the new insights into submarine landslide preconditioning, timing, location, velocity and their down-slope evolution that is arising from these advances. We finally outline some of the outstanding challenges, in particular emphasising the need for calibration of seismic and acoustic signals generated by submarine

landslides and their run-out. Once confidence can be enhanced in submarine landslide signal detection and interpretation, passive seismic and acoustic sensing has strong potential to enable more complete hazard catalogues to be built, and opens the door to emerging techniques (such as fibre-optic sensing), to fill key, but outstanding, knowledge gaps concerning these important underwater phenomena.

1. Introduction

Submarine landslides can be orders of magnitude larger than those on land, occur on remarkably low angle (<2 degree) slopes, and can generate run-out that travels hundreds to thousands of kilometres into the deep-sea (Moore et al., 1989; Hampton et al., 1996; Nisbet and Piper, 1998; Piper et al., 1999; Carter et al., 2014). Underwater slope failures can generate tsunamis that inundate coastal communities that sometimes result in major loss of life (e.g. Harbitz et al., 2014; Tappin et al., 2014), and adversely impact critical seafloor infrastructure networks, such as the cables and pipelines on which we rely for global communications, the Internet, and energy supplies (Piper et al., 1999; Carter et al., 2014). To date, most studies of submarine landslides and their run-out have been based upon analysis of the deposits that past events left behind. These studies have used combinations of: i) seafloor surveys (e.g. multibeam echosounders and side scan sonars) to image submarine landslides in planform (e.g. Prior et al., 1982; McAdoo et al., 2000; Mountjoy et al., 2009; Casas et al., 2016; Normandeau et al., 2019; Brackenridge et al., 2020); ii) sub-surface geophysical surveys to determine the geometry and internal character of submarine landslide deposits (e.g. Gee et al., 2006; Bull et al., 2009; Vardy et al., 2012; Nwoko et al., 2020); iii) intrusive sampling or coring to calibrate geophysical interpretations, provide material for geochronological analysis (age and recurrence determination), and/or determine their source using geochemical and other analytical techniques (e.g. Geist and Parsons, 2010; Dugan, 2012; Urlaub et al., 2013; Vanneste et al., 2014); iv) in-situ or laboratory-based testing to understand geotechnical and geomechanical behaviour of submarine landslides (e.g. Sultan et al., 2010; Ai et al., 2014; Miramontes et al., 2018); v) analysis of ancient, exhumed submarine landslides from rock outcrops (e.g. Brookes et al., 2018; Bull et al., 2019; Ogata et al., 2019) and; vi) physical and numerical modelling to quantify slope stability, post-failure behaviour and resultant impacts (e.g. to seafloor infrastructure or the tsunami that they may initiate) (e.g. Sultan et al., 2010; Harbitz et al., 2014; Tappin et al., 2014; Puzrin et al., 2016).

These techniques provide valuable insights into the location, extent and nature of past failures, as well as providing the building blocks for generating models that enable inference of the likely behaviour of future events; however, they do not capture the behaviour of field-scale submarine landslides in action and do not reveal the in-situ conditions at the time of failure. Numerical models therefore remain relatively poorly constrained and many key questions remain unanswered; particularly with regards to the initiation, kinematics and impacts of submarine landslides. For instance, what are the preconditioning factors for failure and over what timescales are they important? Why are external triggers (e.g. earthquakes, tropical cyclones) more effective in some settings compared to others? What lag-times may be involved following cumulative or sudden perturbations that precede failure, and what controls that delay? Such information is critical to understand precisely how and when landslides are triggered and develop effective early warning systems, and to understand any climate change feedbacks (e.g. Maslin et al., 2004; Paull et al., 2007; Harbitz et al., 2014; Brothers et al., 2013; Normandeau et al., 2021). Key questions also remain unanswered on the kinematic behaviour of submarine landslides as they propagate. For example, what kinematics are involved during different styles of slope failure and how does that change as the mass travels down-slope? Why do some slopes fail suddenly, with major and rapid displacements, while others move much more slowly and progressively? Does failure type control the nature and extent of run-out, and if so, how? These, and many other, questions remain open, largely due to the challenges involved in monitoring failure processes and their precursor conditions in marine settings, in real time, that often cover very large areas.

Some of the challenges that inhibit monitoring of submarine landslides include:

- The *water depths* of many of the settings where submarine landslides occur place financial and logistical constraints on long-duration and continuous monitoring (e.g. Talling et al., 2013; Clare et al., 2017). While slope failures can occur in shallow water deltaic or fjord settings (e.g. Prior et al., 1989; Biscara et al., 2012), many occur in hundreds to thousands of metres water depth and have been documented in the deepest hadal trenches on Earth (Strasser et al., 2013; Kioka et al., 2019).

- The *remote nature* (i.e. location far from shore) of many submarine landslides provides constraints for power, communications and data transfer. This in turn limits the resolution and frequency of measurements that can be made due to a reliance on in-situ power supplies and recovery and redeployment of instruments by expensive vessels (Urlaub and Villinger, 2019).
- The *unpredictable nature of submarine landslides over time*. As many studies have suggested that submarine landslide recurrence may be Poissonian (i.e. approximately random), predicting when a specific seafloor slope may fail is a key challenge (Geist and Parsons, 2010; Urgeles and Camerlenghi et al., 2013; Urlaub et al., 2013). While relatively small (e.g. <1000 m^3) submarine landslides might be relatively frequent (e.g. one or more per year) in high sediment-supply settings (e.g. fjord-head deltas), the events that pose a greater threat to seafloor infrastructure or are tsunamigenic (e.g. >>1 km^3) tend to recur on much longer timescales (e.g. 100s->1000s of years). Continuous observations are required to capture these episodic events.
- The *large extent of areas affected by slope instability* means that monitoring at point-locations may completely miss events that occur elsewhere along the same margin (McAdoo et al., 2000; Urgeles and Camerlenghi et al., 2013; Casas et al., 2016; Collico et al., 2020; Gamboa et al., 2021). Being in precisely the right place at the right time is highly unlikely in all but a few settings where the controls on slope instability are well constrained (e.g. seasonally-active, spatially-focused sediment supply at steep submarine deltas; Lintern et al., 2016).
- The *powerful nature of the landslide and its run-out* poses a hazard to monitoring infrastructure that is placed in the way of a landslide (e.g. Inman et al., 1976; Khripounoff et al., 2003). Recent examples of field-based monitoring demonstrate how even relatively small flows can damage and displace sensors and associated equipment (e.g. Inman et al., 1976; Clare et al., 2020 and references therein). Large slope failures would likely completely destroy monitoring arrays in their path.

1.1. Recent advances in direct monitoring of submarine landslides

Despite these challenges, recent technological advances have enabled monitoring of several aspects of submarine landslide behaviour. Geotechnical monitoring provides information in relation to the preconditioning of submarine landslides, through use of in-situ devices that monitor changes in subsurface conditions, such as pore pressure (e.g. Prior et al., 1989; Strout and Tjelta, 2005; Stegmann et al. 2011). Technological advances have triggered a recent growth in geophysical monitoring of aspects of submarine landslides including: i) repeated seafloor surveys (at timescales from decades to minutes in some cases) to document elevation changes, evolution of the landslide itself, the effects of landslide run-out on the seascape, and subsequent reworking by other marine processes (e.g. Smith et al., 2007; Biscara et al., 2012; Kelner et al., 2016; Mastbergen et al., 2016; Fujiwara et al., 2017; Chaytor et al., 2020; Heijnen et al., 2020; Guiastrennec-Faugas et al., 2021; Normandeau et al., 2021); ii) time-lapse reflection seismic surveys to monitor changes in subsurface conditions (e.g. Blum et al., 2010; Hunt et al., 2021; Roche et al., 2021; Waage et al., 2021); (iii) direct monitoring of turbidity currents (some of which likely initiated from submarine landslides) using moored or vessel-based, active acoustic sensors, such as Acoustic Doppler Current Profilers (ADCPs) and multibeam sonars, that enable measurement of flow velocity and estimation of suspended sediment concentrations (e.g. Xu et al., 2010, 2011; Hughes Clarke et al., 2012; Khripounoff et al., 2012; Simmons et al., 2020); and iv) monitoring changes in seafloor movement and elevation via geodetic location of acoustic transponders (e.g. Campbell et al., 2015; Paull et al., 2018; Urlaub et al., 2018; Zhao et al., 2021). Such studies tend to involve either campaign-style surveys (often with years between individual campaigns), short duration (i.e. weeks to months-long) continuous measurements (as they are limited by power supply and data storage), or else require cabled connection for data transfer and external power supply. Therefore, while they provide detailed (i.e. temporally or depth/laterally-resolved) measurements, such approaches necessarily cover short time periods and limited areas relative to the full extent of continental slopes that may be affected by slope instability, as well as the extent of an individual landslide event itself (Urgeles and Camerlenghi et al., 2013; Urlaub and Villinger, 2019; Brackenridge et al., 2020; Fan et al., 2020). These studies also primarily focus on slope preconditioning, or the run-out produced by slope failures; hence, significant knowledge gaps remain with regards to the inception of slope failures, their kinematics, and their transition from slope failure to more dilute run-out, which are key, but poorly constrained parameters in tsunami modelling, impact assessments for critical seafloor infrastructure, and in understanding deep water sediment transport in general.

1.2. Aims

There is thus a compelling need for low power-consumption sensors that can cover large spatial domains, which are capable of monitoring a wide range of environmental conditions (including the timing, location and behaviour of submarine landslides), and for systems that are deployed offshore to generate sufficiently small data volumes, such that sustained, long-endurance, autonomous monitoring is possible. Here, we show how passive acoustic and seismological monitoring has started to address these constraints and can contribute to filling key knowledge gaps. First, we explore the application of passive acoustic and seismological monitoring of terrestrial landslides, and the relevance of those techniques in the marine realm. Second, we discuss which aspects of submarine landslides may be detected using passive acoustic and seismological monitoring. Here, we explore the kinds of environmental noise or ground motion that are generated by submarine landslides, and therefore what signals we should anticipate recording. Third, we present examples from recent marine studies that have successfully monitored precursor conditions, initiation, movement and impacts of submarine landslides using passive acoustic and seismological approaches. Finally, we conclude with some of the on-going technological developments, and the future application of other techniques, including those detailed in other chapters of this volume.

2. Passive geophysical monitoring of terrestrial landslides

Early terrestrial studies successfully identified subsurface mining blasts and earthquakes using seismometers, which stimulated further research into the potential of passive geophysical monitoring to detect onshore slope failures (Galitzin, 1915; Jeffreys, 1923; Antsyferov, 1959; Cadman and Goodman, 1967). The elastic straining of soils and rock, friction due to displacement along a failure plane, within the sliding mass, and collision of the landslide mass at its down-slope limit were subsequently recognised as signals that could be recorded by seismologic monitoring techniques (e.g. Cadman and Goodman, 1967). It is now well known that progressive failure and detachment of unstable masses can generate local ground motions that are equivalent to earthquakes; hence, land-based seismological networks are increasingly used to determine the timing and location of slope failures, particularly in remote settings where repeat topographic surveys are rare or non-existent (e.g. Hibert et al., 2019). Such studies enable identification of many landslides that would otherwise be missing from historical records, thus providing significant improvements in the completeness of hazard catalogues (Ianucci et al., 2020).

In addition to creating ground motions, terrestrial landslide activity can also generate acoustic emissions, most of which tend to have a frequency content similar to, or just below, the spectrum of audible sound (Chichibu et al. 1989; Rouse et al. 1991; Dixon and Spriggs, 2007; Dixon et al., 2015). Acoustic emissions are generated as a slope is subjected to stress, shear and/or the landslide mass starts to move downslope (Dixon et al., 2015); hence, both acoustic emission and seismological monitoring have started to gain recognition as an onshore early warning tool to identify the early stages or precursors to slope failure (e.g. Mainsant et al., 2012; Dixon et al., 2015; Michlmayr et al., 2017; Le Breton et al., 2021). Analysis following the Anak Krakatau volcanic sector collapse in Indonesia (which generated a devastating tsunami in December 2018) revealed that broadband seismic and infrasound monitoring networks detected not only the landslide event, but also potential triggering events that preceded the collapse (Walter et al., 2019; Figure 1). Regional tsunami monitoring networks did not detect the resultant surface wave due to its localised point source, as they were designed to detect longer line sources (Ye et al., 2020). The collapse itself was represented by a short-lived (one to two-minute-long) low frequency (0.01-0.03 Hz) signal; the first P-wave of which was detected at nine onshore seismometers across the Sumatra and Java region, pin-pointing its location at Anak Krakatau (Walter et al., 2019; Figure 1). This event had a moment magnitude (M_w) equivalent to 5.3. A higher frequency (0.1-4 Hz) seismic event was recorded 115 seconds prior to the sector collapse, while the collapse signal was followed by five minutes of a continuous tremor-like signal at high frequencies (0.7-4 Hz) that was attributed to post-failure eruptive activity. Infrasound arrays as far afield as Australia (>1000 km to the south-west) recorded a high-energy impulse that matched the origin times of the short-period seismic signal corresponding to the collapse event (Walter et al., 2019). This example is particularly pertinent, not only because it demonstrates the capability of passive seismological and acoustic monitoring to detect terrestrial landslides onshore, but also because approximately half of the failed mass was actually under water (Hunt et al., 2021).

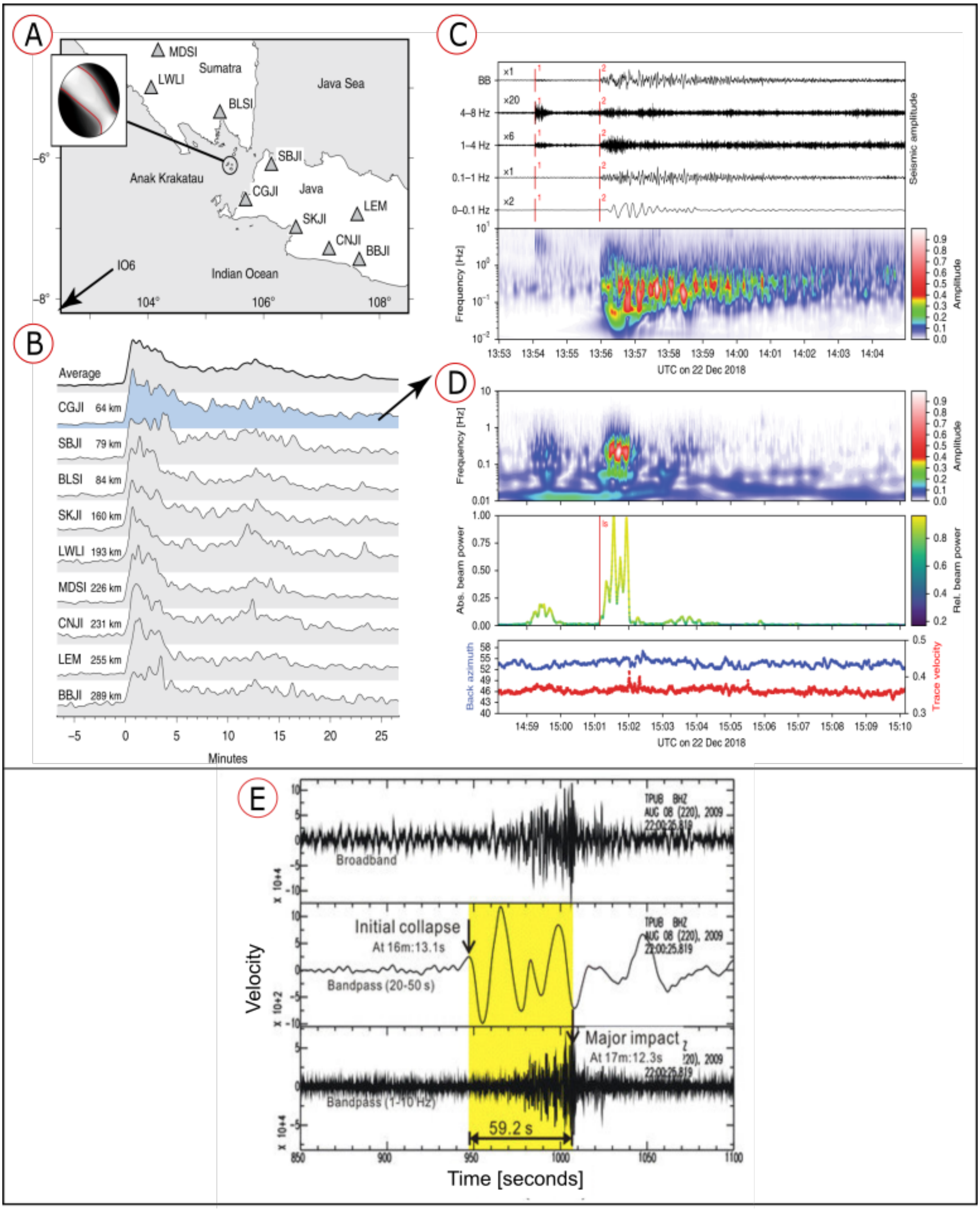

Figure 1: Seismic and infrasound records of the 2018 Anak Krakatau volcanic island collapse from Walter et al. (2019), including: A) location of regional seismic monitoring network; B) vertical

component of 0.4-1Hz seismic records at various stations; C) Normalised seismic amplitudes at the station nearest to Anak Krakatau recording a high frequency event prior to the collapse (1) and a low frequency signal that is related to the landslide (2); D) infrasonic spectrogram records of frequency, beam power and back azimuth used to locate the event from a seven-element infrasound array. E) Broadband seismogram (above), and band pass filtered by 20-50 seconds (middle) and 1-10 Hz as recorded before, during and after the 2009 Hsiaolin onshore landslide in Taiwan by Lin (2015).

Onshore seismologic networks have been used to detect terrestrial landslides, including the Hsiaolin hillslope landslide, which occurred when Typhoon Morakot hit Taiwan in 2009. Broadband seismic data recorded: i) very long period seismic signals (20-50 seconds) that were interpreted to be related to elastic rebound of exposed stratigraphy as the overlying landslide mass was evacuated and moved downslope; and ii) large amplitude high frequency signals (1-10 Hz) that were interpreted to result from the impact of the landslide mass at the base of slope (Lin, 2015). Based on the time between these seismic events and the documented run out distance of 2,500 m, Lin (2015) estimated a maximum velocity of >80 m/s. A total of 51 other landslides were also detected on the same day by the same broadband network (Lin et al., 2010). Perhaps most remarkably, 14 of these were detected offshore. Hence, in instances where broadband seismic networks are sufficiently dense, they can provide a useful tool for hazard monitoring.

Processes that generate ground motion and create collisions within similar gravity-driven mass movements have also been successfully recorded using various passive geophysical techniques, including: i) submerged hydrophones and microphones to measure bedload transport based on noise generated by impacts caused by granular material in rivers and streams (Downs et al., 2016; Geay et al., 2017; Rickenmann, 2017; Geay et al., 2020); ii) bespoke geophone and infrasound arrays that detect self-generated noise and vibrations related to snow avalanches (Suriñach et al., 2005; Bessason et al., 2007; van Herwijnen and Schweizer, 2011; Lacroix et al., 2012; Van Herwijnen et al., 2016); and iii) use of existing seismological stations to detect ice avalanches, rock falls and glacial outburst floods from sudden ground movements as the mass impacts the ground (Caplan-Auerbach and Hugel, 2007; Deparis et al., 2008; Cook et al., 2018, 2021). The successful demonstration of passive geophysical tools to monitor terrestrial mass movements has opened the door for the application of similar techniques in offshore settings, with a view to overcoming some of the many shortcomings of active source monitoring tools (e.g. particularly in relation to power and spatial limitations). Resolution and signal-to-noise ratio are often orders of magnitude poorer for submerged instruments, as a result of: i) poor coupling with the seafloor arising from their crude placement (i.e. where instrument frames are dropped from a ship, as compared to the precise placement of instruments onshore; and ii) the environmental noise of the water column, which is affected by a variety of natural processes and human activities.

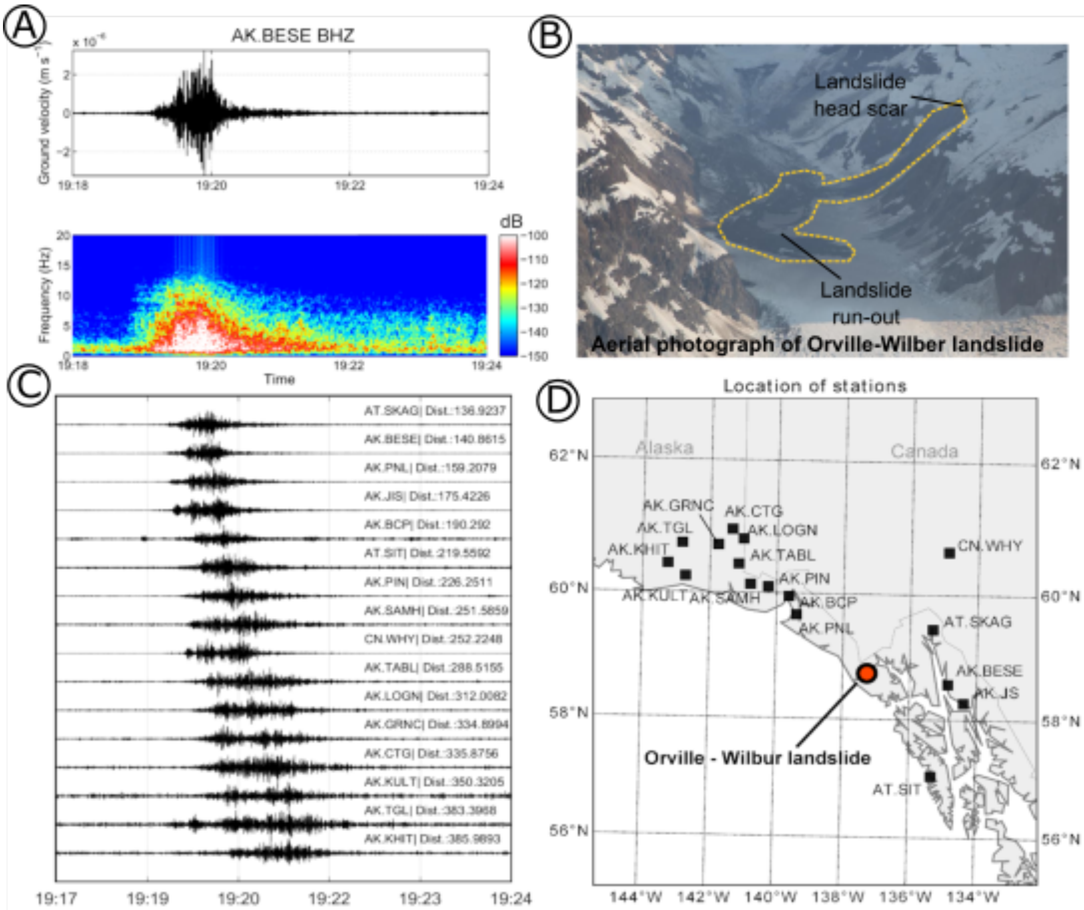

Figure 2: Example of seismic records of terrestrial landslide, from Hibert et al. (2019), which was detected by 17 stations between 136 and 385 km from the event itself. A) Seismic signal filtered between 1 and 10 Hz. B) Aerial photograph of the landslide which provided the validation of the signal interpretation. C) Seismic signals related to the same landslide at 16 locations, which are shown in D) in relation to the landslide location.

3. Which aspects of submarine landslides should we be able to detect with passive systems?

Based on these past studies, a range of information can theoretically be recorded from submarine landslides by passive seismic and acoustic monitoring (Figure 3). We now discuss some of these aspects, broadly in the order in which they would occur (i.e. prior to, during and then following a slope failure). First, data can be acquired in the build up to a slope failure, providing information on preconditioning, including temporal variations in volcanic or subsurface fluid flow activity, as well as potentially identifying any plausible external triggers such as earthquakes, tropical cyclones, storms or rapid sediment delivery by floods. Next, the timing and location of failure can potentially be ascertained by triangulating seismic signals (e.g. the case of the Anak Krakatau event), as a result of ground motions and/or noise generated as shearing occurs along the basal failure surface (and potentially also along its lateral margins), and as that shear propagates through the subsurface (Puzrin et al., 2016). As the landslide mass becomes mobile, ground motions and noise will likely be generated by friction created along the failure plane (Campbell et al., 1995; Brodsky et al., 2003; Gee et al., 2005), due to internal deformation of the moving sediment mass (e.g. Mountjoy et al., 2009; Buss et al., 2019; Sammartini et al., 2021), and if the mass starts to disintegrate as it entrains and mixes with ambient seawater (e.g. Masson et al., 2006). A reduction in vertical effective stress caused by evacuation of overlying sediments, or temporary loading and unloading as a result of the transit of an overriding landslide mass can trigger elastic rebound, producing long period signals (Kanamori and Given, 1982; Kawakatsu, 1989; Lin, 2015) that may occur suddenly, or steadily over prolonged timescales (e.g. >months in onshore examples; Lin, 2015; Leung and Ng, 2016). The displaced mass that moves downslope may travel considerable distances (tens to hundreds of km), over relatively low angle (<1-2 degrees) slopes. The ground motions and noise generated will depend on the changing rheology and kinematics of that moving mass, and its interactions with the seafloor and any topography with which it encounters (e.g. Mountjoy et al., 2018). Friction arising from displacement and erosion at the base of the moving mass should be detectable, however the nature of the seafloor substrate may enhance or attenuate any signals that are generated. As the landslide disintegrates, it may switch from a plastically deforming mass of sediment, to a dense slurry dominated by grain to grain collisions, or a more dilute flow that is characterized by sediment suspended primarily by turbulence (e.g. Talling et al., 2007; Sumner and Paull, 2014; Paull et al., 2018). Each of these modes will likely generate different signals. Where the moving mass generates a sudden physical impact and comes to rest, such as at breaks in slope (ten Brink et al., 2006), following a sudden height drop (Moernaut and De Batist, 2011), or where it meets pronounced topographic barriers (Frey-Martínez et al., 2006), strong, high frequency signals should be anticipated (Caplan-Auerbach and Hugel, 2007; Deparis et al., 2008). Finally, the indirect effects of the landslide may also generate a seismic signal, such as where displacement of the overlying water mass generates a tsunami (e.g. Yuan et al., 2005).

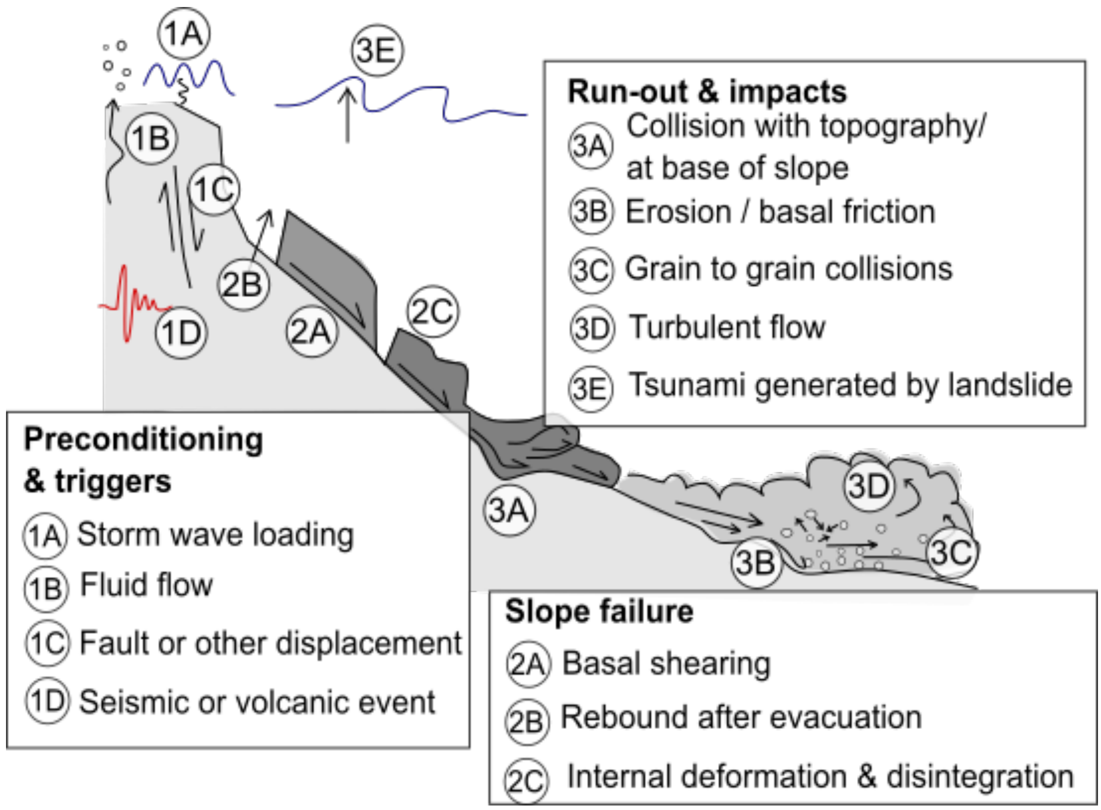

Figure 3: Schematic illustration of some aspects of submarine landslides capable of generating seismic and/or acoustic noise as discussed in this chapter, relating to preconditioning and triggering (1A-D), landslide inception and down-slope displacement (2A-C) and its subsequent evolution and impacts (3A-E).

4. Recent advances and opportunities in passive monitoring of submarine landslides

Motivated by successful terrestrial landslide monitoring, and enabled by advances in offshore geophysical monitoring (as highlighted by the other chapters in this volume and Baumgartner et al. 2018), several recent studies have demonstrated that passive monitoring of several aspects of submarine landslides is no longer just a possibility, but a tangible reality. Many challenges remain; most notably the fingerprinting of seismic and acoustic signals. The paucity of direct submarine landslide monitoring studies (for reasons discussed earlier in this chapter) means that many of these signals remain poorly calibrated; hence, understanding the precise cause and source of signals is often unclear. That being said, recent studies have provided important forward steps in understanding previously unresolved aspects of submarine landslides and provide opportunities to fill other outstanding knowledge gaps. We now highlight studies that illuminate three of these areas: i) timing and location; ii) kinematics; and iii) run-out.

4.1. Determining the timing and location of submarine landslides at a margin scale using land-based seismological networks

Using networks of land-based seismological monitoring stations, seismic sources that did not correspond to catalogued earthquakes or storms have been located from radiating surface waves sourced in the Gulf of Mexico and the South China Sea. In the case of the Gulf of Mexico, 85 such non-earthquake seismic signals were identified between 2008 and 2015, located in various locations on the offshore continental slope, and have been attributed to submarine landslide activity (Fan et al., 2020; Figure 4). Individual landslide locations have previously been proposed from analysis of onshore seismological monitoring (e.g. Dewey & Dellinger, 2008; Ten Brink et al., 2008), but this is the first study to identify multiple submarine landslides. The seismic energy recorded is presumed to have arisen from the fast downslope movement of relatively rigid landslide masses (Fan et al., 2020). Given the density of offshore oil and gas infrastructure in the Gulf of Mexico (which is known to be vulnerable to damage by submarine landslides and their run-out), this study provides a much-improved understanding of the locations that are prone to slope failure (Chaytor et al., 2020). As well as identifying a number of seismic signals attributed to terrestrial landslides from an onshore broadband seismometer network, Lin (2015) also interpreted arrivals from offshore-generated ground motions in a region offshore SW Taiwan, to relate to submarine landslides, occurring shortly after the passage of the powerful Typhoon Morakot (8th August 2009). The triangulated location of these seismic sources was found to be clustered around submarine canyon flanks and steep continental slopes, which are known to be more prone to slope instability from previous seafloor surveys (Yeh et al., 2021). Submarine sediment flows, that were likely triggered by slope failures and related to this event, damaged a number of telecommunications cables that crossed the Gaoping Canyon (Carter et al., 2014; Pope et al., 2017).

The ability to identify the timing and location of submarine landslides using existing onshore seismological networks (i.e. without the need for deployment of bespoke underwater sensors) offers a potentially game-changing opportunity to fill gaps in hazard catalogues that are required for the robust and resilient design of offshore engineering projects (e.g. oil and gas, renewables, subsea cables) and for developing hazard assessments for coastal communities (e.g. to inform tsunami warning and guide any related civil response planning). There is still a need to calibrate these interpretations through follow up seafloor surveys to document the true efficacy of the method and determine which landslide types are reliably detected. Indeed, Fan et al. (2020) point out that this approach will likely only detect landslides that generate sufficient seismic energy; hence, slow (e.g. creep-like) or small landslides are unlikely to be detected. While submarine landslide catalogues may become more extensive using this method, they will remain incomplete for such events that do not generate discernable seismic noise. Given the fact that tsunamigenic landslides tend to be faster and larger, this method therefore provides a very promising step forward in submarine landslide detection across very large areas, and will only be strengthened as broadband seismic networks are expanded. A further positive is that these passive detection methods provide a low cost approach to tackle the current biases in submarine landslide studies, given that the majority of these presently focus on the North Atlantic and offshore from more economically developed countries (Clare et al., 2019).

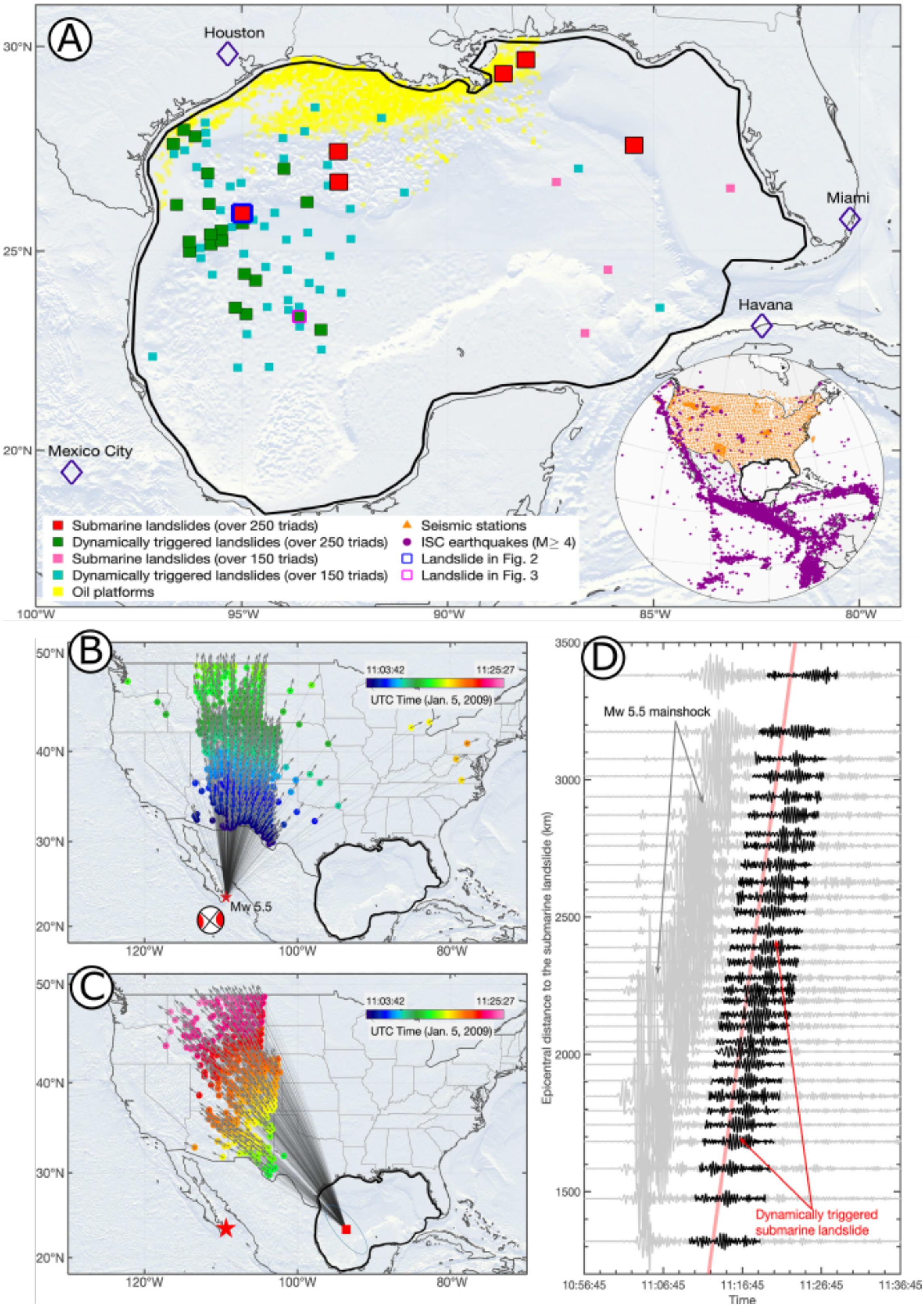

Figure 4: Identification of submarine landslides using terrestrial seismometer networks from Fan et al. (2020). A) Locations of seismic signals interpreted to relate to submarine landslides in the Gulf of Mexico using the onshore seismic monitoring network. Inset shows earthquakes in the

monitored time period (2008-2015) of magnitude 4 or above. B) Rayleigh wave arrival times (colours of circles) and propagation directions (lines) for an earthquake, and C) a submarine landslide that is thought to have been triggered by that same earthquake (red star). D) Bandpass filtered (20-50 seconds) waveforms for a selection of the seismic stations used to locate the submarine landslide. Grey signals show precursor earthquake and black shows the signal of the landslide itself.

4.2. Quantifying landslide kinematics using hydrophones

Submarine landslide-generated noise has been used to determine the existence of events in remote oceanic settings that would otherwise have likely gone unnoticed. Networks of hydrophones, including the Hawaii Undersea Geo-Observatory in the Pacific Ocean, recorded a combination of partly-subaerial and fully-submarine landslides on the flanks of volcanic islands, which generated acoustic signals that were recorded up to 7000 km from their source; sometimes exceeding the amplitudes generated by volcanic eruptions by up to an order of magnitude (Caplan-Auerbach et al., 2001; Chadwick et al., 2012; Caplan-Auerbach et al., 2014; Figure 5). The distinctive, extremely low frequency signals recorded are thought to relate to the collapse of large landslide blocks, composed of highly competent volcanic material, as well as from their disintegration as they travelled downslope as an avalanche (Chadwick et al., 2012). In these instances, the triggering event generally seems to relate to enhanced volcanic activity, such as at the West Mata volcano near Tonga, and at Kilaeuea volcano, Hawaii (Caplan-Auerback et al., 2001; 2014). In addition to pinpointing their location, and identifying the timing relative to volcanic activity, the multi-pathing of the propagated sound waves enabled determination of the landslide transit velocities, which are estimated at between 10 and 25 m/s (Caplan-Auerbach et al., 2014). The location (in particular the water depth) of a landslide source, and its initial velocity, are key inputs for tsunami modelling (e.g. Løvholt et al., 2015). Typically, these parameters remain poorly or entirely un-constrained, which results in a wide uncertainty in any predictive tsunami modelling. Therefore, these and future observations using similar hydrophone networks can play an important role in improving our understanding of a globally significant hazard (e.g. Tappin et al., 2008; Harbitz et al., 2014; Goff and Terry, 2016). Again, calibration of the hydrophone signals is needed; hence, field studies that make multiparameter measurements of submarine landslide activity will contribute significantly to the fingerprinting of different acoustic responses, and will enhance confidence in the future acoustic detection and characterization of submarine landslides.

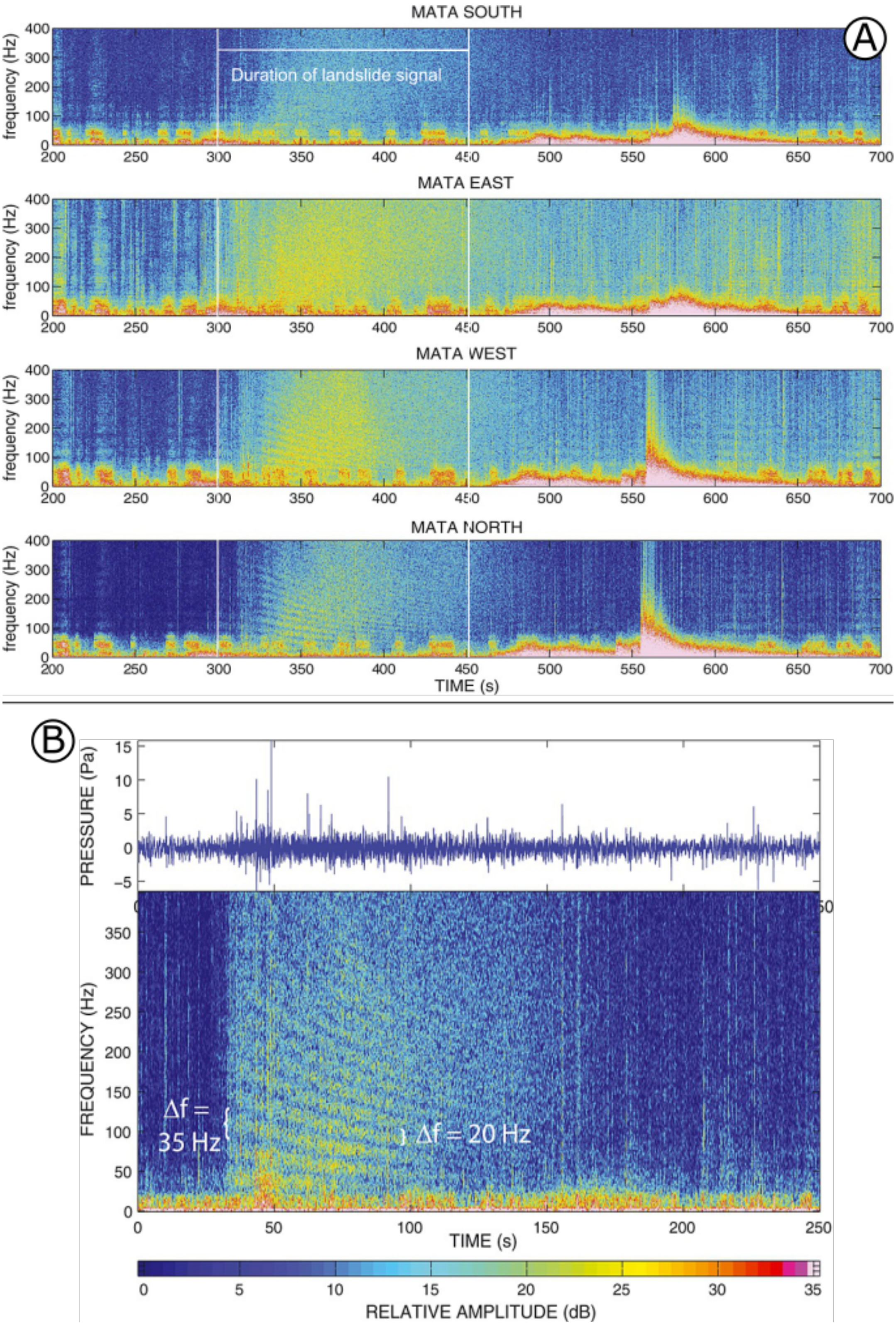

Figure 5: Hydrophone spectrograms showing evidence of submarine landslides in the SW Pacific from Caplan-Auerbach et al. (2014). A) The signal between 300 and 450 seconds is interpreted as a submarine landslide due to its broadband spectrum and variable frequency content. It is distinct from degaassing explosions (low frequency, <50 Hz) events and regional earthquakes (very low frequency between 470 and 600 seconds). B) Hydrophone time series and spectrogram for a submarine landslide. Interference bands are noted – at 35 Hz at the start of the landslide and 20 Hz near the end. The change in spacing of frequency bands indicates a moving source and is used to infer the vector velocity of the landslide.

4.3. Characterising landslide run-out to enhance hazard assessments

Submarine landslide run-out is often far more extensive than that on land, and may evolve dramatically with regard to its rheology, as flows mix with seawater and/or entrain seafloor sediment (Parker, 1982; Zeng et al., 1991; Mohrig and Marr, 2003; Gee et al., 2006; Heerema et al., 2020). As these mass flows can travel at high speeds and across large distances, they can damage sensors placed in their path (e.g. see several examples in Clare et al., 2020). Therefore the use of passive, remote sensing acoustic and seismic monitoring tools, placed out of the direct pathway of such flows, can enable undisturbed monitoring and reduce instrument damage or loss. Recent studies have demonstrated how hydrophones may record turbidity currents (some of which were triggered by landslides) in fjord settings that are fed by seasonally active rivers, including on the Fraser and Squamish deltas; both in British Columbia (Lintern et al., 2016; 2019; Hizzett et al., 2018; Hay et al., 2021; Figure 6). At the Fraser Delta, hydrophones are deployed on a seafloor observatory that is connected to shore via the VENUS cabled network, enabling real-time streaming of data, which also includes measurements by complementary active source geophysical sensors (Lintern and Hill, 2010). Sensors such as Acoustic Doppler Current Profilers, provide the calibration and confidence that the acoustic signals (which include both high (1-300 kHz) and low (Hz) frequency ranges) can be attributed to turbidity currents (Lintern et al., 2016; 2019). At the Squamish Delta, a hydrophone suspended from a vessel, 10 m above an active submarine channel, recorded the noise generated from sixteen turbidity currents that reached speeds of 2 m/s (Hay et al., 2021). Extensive calibration was provided by a pair of 500 kHz multibeam sonars placed on the same frame as the hydrophone, three echosounders (28, 200 and 70-110 kHz) mounted on the vessel itself, and a 1200 kHz ADCP suspended from a separate frame, also 10 m above the seafloor (15 m from the hydrophone frame). This novel study showed that where turbidity currents exceeded 1 m/s, they generated noise well above ambient ocean conditions, across a spectrum of 10-500 kHz; interpreted to result from highly energetic sand-sized particle collisions. Cross-reference of hydrophone and ADCP-derived velocity measurements, revealed that spectral density (at 100 kHz frequencies) is proportional to the speed of the flow front, where a 100-fold increase in spectral density relates to a doubling in frontal speed (Figure 7; Hay et al., 2021). Even more powerful sediment flows (i.e. >2 m/s, and potentially >10 m/s) that occur within larger submarine canyons and channels (e.g. Carter et al., 2014; Azpiroz et al., 2017; Paull et al., 2018), or that travel vast distances across open continental slopes (e.g. Piper et al., 1999), may generate similar acoustic signals, and/or are likely to also generate ground motions (depending on their velocity, interaction with, and the nature of the surrounding topography and seafloor substrate) that can be detected with seismometers, but this requires future investigation.

Seafloor cabled-networks, such as the Neutrino Mediterranean Observatory-Submarine Network 1 (NEMO-SN1), have demonstrated that offshore seismic monitoring can also play a future role in detecting the run-out from submarine landslides. While background environmental noise was often found to complicate conclusive signal identification, high frequency and long duration (at least longer than that of earthquakes) signals recorded by an ocean bottom broadband seismometer on the NEMO-SN1 network offshore Mount Etna were attributed to submarine landslide run-out (Sgroi et al., 2014). Therefore, this approach can apparently be readily applied using marine seismometer networks, and similar deployment of more than one seismometer would allow for greater characterization of events, including pin-pointing their source. These recordings were of particularly high quality because the dedicated installation procedure using a Remotely Operated Vehicle ensured excellent coupling with the seafloor. This is not always the case for Ocean Bottom Seismometer surveys, as these instruments are typically dropped from a surface vessel and land in a relatively uncontrolled manner on the seafloor.

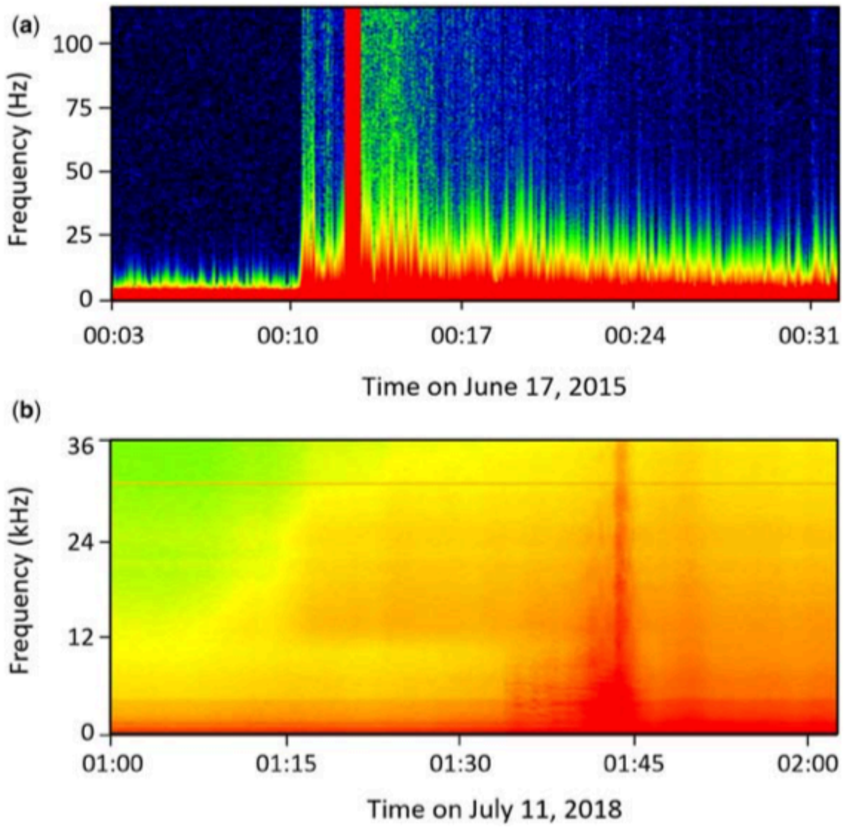

Figure 6: Hydrophone spectrograms showing turbidity current events in British Columbia. (a) Passing directly through a hydrophone at the delta dynamics laboratory at the Fraser Delta. (b) Passing below a mooring in the Bute Inlet Channel, British Columbia from Lintern et al. (2019).

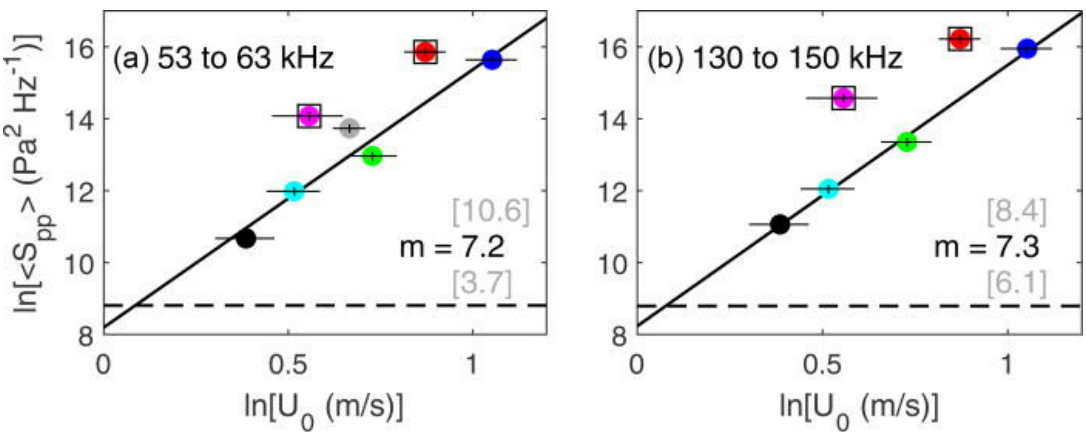

Figure 7: Cross-comparison of band-averaged noise spectral densities (S_{pp}) with frontal velocities (U_0) of turbidity currents recorded in the Squamish Delta, British Columbia for two frequency bands (from Hay et al., 2021). Coloured symbols represent different turbidity current events. Solid

black line is a best-fit trend and the dashed black line shows the detection threshold above ambient noise levels.

4.4. Opportunities using distributed cable-based sensing

Spatially-resolved distributed sensing along seafloor fibre-optic cables now enables broadband seismic and acoustic monitoring across long distances (over 10s-100s of km). Several recent studies have demonstrated temporally- and spatially-resolved monitoring of ground motion (acting like distributed networks of seismometers) generated by earthquakes, fault displacements, and acoustic noise created by ocean waves and deep-sea bottom currents that resuspend sediment at the seafloor (e.g. Blum et al., 2010; Marra et al., 2018; Ajo-Franklin et al., 2019; Lindsey et al., 2019; Williams et al., 2019; Zhan et al., 2020; Nishimura et al., 2021; Zhan et al., 2021; Wilcock, 2021; Figure 8). Distributed acoustic sensing data acquired along a fibre-optic cable in the Nankai subduction zone, western Japan, was found to have a comparable performance to adjacent broadband ocean bottom seismometers at seismic frequencies of >1 Hz, provided the cable was well-coupled to the seafloor (Ide et al., 2021). The same study concluded that, even though such distributed acoustic monitoring records one component of strain, seismic source localisation within tens of kilometres of the cable can still be achieved. At lower frequencies (i.e. 0.02-0.05 Hz) the distributed acoustic sensing observations were notably noisier compared to those from ocean bottom seismometers, thus making detection of such events challenging, unless events occur very close to the cable. The low frequency regime may be critical regional scale landslide detection (i.e. Fan et al., 2020); hence this technique may be most appropriate for detecting relatively local low or far-field high frequency signals, but more studies are required that provide similar comparisons, to test the sensitivities of different cable configurations, interrogator units and analytical approaches (Lindsey and Martin, 2021; Lior et al., 2021).

Recent advances have seen the application of sensing to detect changes in the State of Polarisation over the full length of a 10,000 km-long telecommunications cable, which enabled recording of moderate to large earthquakes, as well as pressure signals from ocean swells (thus illustrating the potential for real-time tsunami detection over transoceanic distances; Zhan et al., 2021). This distance far exceeds that reached by previous studies and did not require specialist interrogator units or ultra-stable laser sources; instead monitoring the State of Polarisation to detect anomalies that are attributed to strong seismic waves or long-period water waves (Zhan et al., 2021). It should be noted, however, that these long-range measurements were spatially integrated (i.e. averaged along the entire fibre length); hence, additional, independent information is required to locate and further characterise the hazard, besides the locally-recorded signal timing and magnitude. Zhan et al. (2021) also recognised that site-specific effects can affect the sensitivity of measurements, wherein the seabed coupling and nature of the seabed substrate on which the cable is placed can result in spatially variable signal attenuation. Indeed, the coupling of the cable with the seafloor may be particularly important for cable-based sensing. When assessing the efficacy of Distributed Acoustic Sensing to detect earthquakes, Lioer et al. (2021) found that performance was notably reduced in areas of highly irregular, rocky seafloor, where the cable is locally in free span, raised above the seafloor across sections, and enhanced in areas of low relief, soft seafloor, particularly where cables may become embedded or buried by sedimentation. Going forwards, cable sensing is likely to be complimentary to other approaches, but also has strong potential to fill in major geographic gaps in seismic monitoring, potentially making use of the existing global network of submarine cables and accessing new cables (Ranasinghe et al., 2018; Howe et al., 2019; Mizutani et al., 2020; Mecozzi et al., 2021; Wilcock, 2021).

While Distributed Acoustic Sensing can provide valuable information, such sensing is limited to no more than a few hundred km from shore; hence, additional sensors, that could include hydrophones or geophones, distributed at nodal locations along a cable may help to fill this gap over longer distances. This is the premise of the SMART (Science Monitoring and Reliable Telecommunication) Cables initiative, which proposes attaching instruments, including ground motion, pressure and temperature sensors, as external nodes on repeaters (typically spaced 60-80 km apart) on new or decommissioned submarine telecommunication cables (Ranasinghe et al., 2018; Howe et al., 2019; Mecozzi et al., 2021). The CAM (Continent-Azores-Madeira) Ring cable is likely to be the first operational SMART Cable system (coming online in 2024), connecting mainland Portugal with the Azores. As these nodes are powered and connected by cables, they will potentially provide opportunities for real-time seismo-acoustic monitoring far from shore. This is particularly relevant for the CAM Ring cable, as the strongest earthquakes occur far offshore, and many of the previously mapped submarine landslides are located on the flanks of remote submerged seamounts (Gamboa et al., 2021; Matias et al., 2021). Numerical modelling indicates that the CAM Ring SMART cable should significantly reduce uncertainty in pinpointing the location and timing of offshore earthquakes and identify events (such as submarine landslides) that are currently undetectable by the existing onshore and coastal monitoring networks, while detection of the passage and direction of tsunamis should provide improved early warning of coastal impacts, and thus time to prepare emergency responses (Matias et al., 2021).

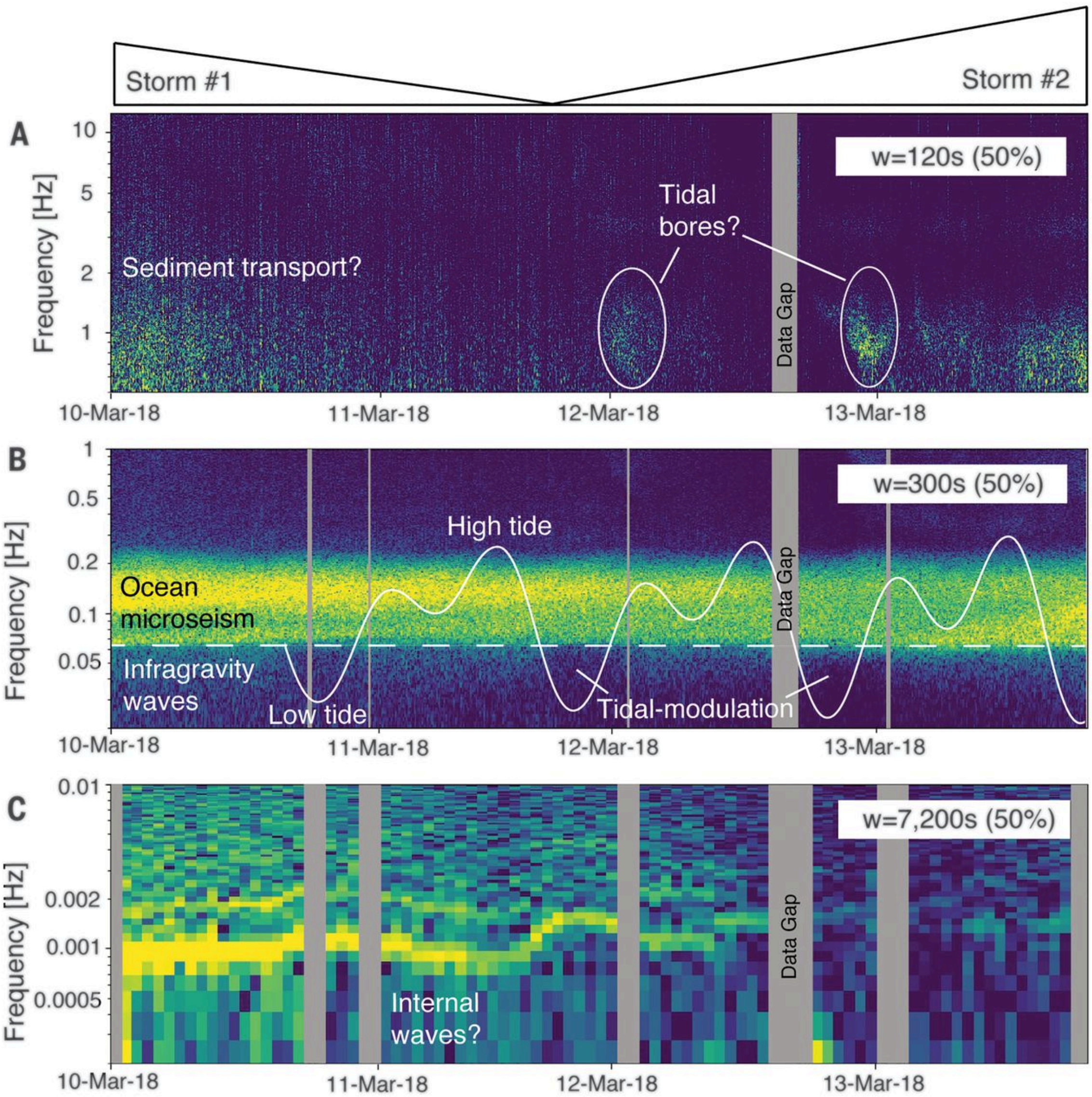

Figure 8: Frequency spectrograms from Distributed Acoustic Sensing along a seafloor fibre optic cable offshore Monterey Bay, California from Lindsey et al., 2019. These demonstrate how this

technique can be used to detect: A) short-lived tidal and near-bed currents; B) tidal effects due to pressure changes; C) and internal waves. Therefore, this approach may also be appropriate to measure aspects such as the run-out of submarine landslides (e.g. turbidity currents), displaced water masses in front of a moving mass or ground motions generated by the landslide itself.

5. The application of passive geophysical monitoring in advancing submarine landslide science

We now revisit the overarching challenges and science questions that were outlined in the introductory section, specifically addressing how emerging seismic and acoustic techniques can fill outstanding knowledge and capacity gaps, which uncertainties remain, and outline a proposed strategy for the forward steps to advance submarine landslide science.

5.1. Can passive seismic and acoustic techniques overcome the logistical challenges that have previously-hindered monitoring of submarine landslides?

First, we respond to the logistical challenges; namely the often-deep water and remote location of submarine landslides, and their unpredictable and powerful nature. Provided sensors and receivers are protected in appropriate pressure housing, passive seismo-acoustic landslide monitoring using hydrophones and geophones can be performed across the full range of water depths in the global ocean, from coastal (e.g. Hay et al., 2021) to thousands of metres water depth (e.g. Caplan-Auerbach et al., 2014). To date, we are not aware of any landslide monitoring in hadal water depths, but it is certainly logistically possible, and the use of ocean bottom seismometers and Distributed Acoustic Sensing along fibre-optic cables is increasing in many deep ocean settings to record earthquake and non-earthquake related noise (e.g. >4000 m offshore Chile, Batsi et al., 2019; Ide et al., 2021). Given the relatively early stages of many the techniques we have described, most previous studies have relied upon individual instruments, or limited networks of seabed or moored instruments, with narrow spatial coverage. Hence, widespread (i.e. basin- to ocean-scale) passive monitoring of submarine landslides very much remains an open and future challenge. However, onshore seismic monitoring networks are far more dense than those offshore and, where margin geometry permits, these can immediately be used to identify submarine landslides that may occur hundreds to thousands of kilometres from shore, where their location is not known *a priori* (Fan et al., 2020).

The Gulf of Mexico is perhaps an ideal candidate, as its physiographic geometry suits the use of triangulation from an onshore network to pinpoint the offshore location of submarine landslides. Arc-shaped convergent continental margins are also good future candidates for this approach, as are enclosed basins such as the Mediterranean, as they provide similarly well-suited geometries, and are often themselves 'blind spots' for landslide-tsunami hazard where new insights are required (e.g. Sunda Arc; Goff and Terry, 2016). The geometry of many margins will not suit this approach, however. As recognised by Lin (2015), deployment of wider and denser networks of onshore and offshore seismometers will be required in such settings for limitations to be overcome. Distributed Acoustic Sensing along fibre-optic cables provides opportunities for long distance monitoring, and potentially to fill several spatial gaps in offshore monitoring capacity, however, this technology cannot currently be extended beyond the first repeater, and is thus presently limited over distances of less than a few hundreds of kilometres from shore (Matias et al., 2021). This means that many submarine landslides, which occur far offshore, cannot yet be recorded by this technique. Longer range (i.e. tens of thousands of kilometres) monitoring is possible along cables that connect continents, either as integral measurements with limited spatial resolution (e.g. Marra et al., 2018; Zhan et al., 2021), or at powered SMART sensor nodes along the cable (e.g. Howe et al., 2019).

All of the passive monitoring approaches enable placement of sensing equipment out of the path of submarine landslides and their run-out, which has hindered many previous efforts where sensors, moorings and platforms have been damaged or lost (e.g. Khripounouff et al. 2003; Clare et al., 2020 and references therein). These new techniques therefore ensure that not only the timing initiation of a landslide can be recorded, but measurements can also be made during the landslide event itself, from which key aspects of landslide behaviour can be determined.

5.2. Which aspects of submarine landslides can we currently assess from passive remote sensing techniques and what needs to be resolved?

5.2.1. Landslide timing

The timing of submarine landslides has been determined from signals detected by submerged hydrophones and geophones, as well as land-based seismic monitoring systems. Therefore, observational passive monitoring datasets can provide new insights into the timing and frequency of submarine landslides; starting to fill a key knowledge gap. For example, the use of land-based seismic monitoring in the Gulf of Mexico identified 85 previously-undetected submarine landslide events (Fan et al., 2020). The ability to identify past submarine landslide signals provides important information to develop more robust hazard assessments and inform resilient routing and siting of offshore infrastructure (Chaytor et al., 2020), while the quick identification of landslide signals has potential to enhance existing tsunami warning systems (Fan et al., 2020; Matias et al., 2021). An immediate opportunity lies in back-analysis of legacy datasets, to explore whether past landslide signals exist, but have been ignored by previous studies as they focused on different frequency spectral ranges. Such an approach has already shown value in identifying gas or fluid flow-related processes from ocean bottom seismometers or ocean currents from Distributed Acoustic Sensing datasets (Baksi et al., 2019).

5.2.2. Landslide triggers and preconditioning

In addition to determining whether a landslide has occurred or not, ascertaining the timing of landslide inception allows us to investigate the environmental conditions in the build up to that event; and thus determine likely triggering and/or preconditioning factors. Limitations in the precise determination of submarine landslide timing (e.g. due to uncertainties in radiocarbon dating) has hindered identification of these links previously, but this is now possible, as highlighted by acoustic and seismic monitoring prior of the 2018 Anak Krakatau volcanic collapse (Walter et al., 2019) and offshore landslides following earthquakes in Taiwan (Lin, 2005). Future monitoring is likely to lead to the identification of new or potentially surprising triggers, such as the intriguing link between distant earthquakes and submarine landslides in the Gulf of Mexico (Fan et al., 2020). Passive monitoring technology is now sufficiently mature to test previous hypotheses on landslide triggering and investigate new ones; however, operational early warning systems (i.e. that automatically raise alerts ahead of a potential landslide event) still remains a future prospect for all but a few locations, as this requires a robust understanding of the conditions prior to failure or identification of a landslide as it happens. This will therefore be more feasible at sites where triggers and/or preconditioning are more predictable and closely linked to enhanced sediment supply from rivers (i.e. where landslides are more prone during or following periods of higher river discharge, such as the bedload-dominated Fraser or Squamish Delta; Lintern et al., 2020; Hay et al., 2021) or relate to heightened volcanic activity (e.g. Anak Krakatau, Indonesia; Mount Etna, Mediterranean; Urlaub et al., 2018; Walter et al., 2019).

5.2.3. Landslide location

It is possible to pinpoint the location of submarine landslides through triangulation (to a precision of approximately tens of kms; Caplan-Auerbach et al., 2014; Lin, 2015; Fan et al., 2020); however, as already noted, this approach is limited to locations where sensor networks are sufficiently widely and densely distributed. There is a wealth of existing onshore (and to a limited extent offshore) broadband seismic datasets in several regions where the same approach could be taken, to investigate whether similar landslide-like signals exist, if they can be located spatially, and if they correspond to any of the recent direct measurements of slope instability and their run-out, or existing maps of landslide vulnerability (e.g. Paul et al., 2018; Urlaub et al., 2018; Obelcz et al., 2020; Gamboa et al., 2021). We suggest that detailed bathymetric surveys should be performed in areas where seismic signals attributed to submarine landslides have been located to determine which types of landslide are recorded, as well as to the test the efficacy of landslide detection. The Gulf of Mexico, Mediterranean, Caribbean and regions offshore south-west Taiwan are prime candidates for this field calibration.

5.2.4. Landslide kinematics

If a landslide mass is known, it is possible to infer other aspects of submarine landslide behaviour from the resultant seismic and acoustic signals. For instance, inversion of these signals can be used to derive force histories, from which volume, velocity, changes in basal friction, run-out distance, and other important aspects of landslide kinematics can be determined, as demonstrated by successful application of these approaches in terrestrial settings (e.g. Brodsky et al., 2003; Ekström and Stark, 2013; Yamada et al., 2013; Moretti et al., 2015). These aspects will likely be more challenging to constrain than landslide timing and location, however; requiring concerted research and field calibration. Sites where passive and active monitoring are performed concurrently will provide valuable opportunities to calibrate the nature of seismic and/or acoustic signals, such as at the Squamish Delta, Canada, where variations in noise spectra were linked to changes in the concentration and grain size of sediment avalanches, and noise intensity corresponded to the velocity of the flow front of turbidity currents (Hay et al., 2021). Moored arrays of direct active sensors (e.g. ADCPs) have been used to track the passage and evolution of landslide run-out and turbidity currents down submarine canyons, over tens of kilometres (e.g. Paull et al., 2018). The addition of co-located hydrophones and geophones to such moored or seafloor arrays will enable calibration of seismic and acoustic signals as well as determining threshold limits for detection.

5.2.5. Site-specific effects

We suggest that different deployment configurations should be trialed to investigate how signals attenuate in different settings, as well as investigating the effects of increasing distance and differing angles of incidence from source. The effects of seafloor morphology may attenuate the signal generated by submarine landslides and complicate its propagation pathway, which is particularly important for directional instruments such as hydrophones. While hydrophones have been shown to detect events on relatively open delta slopes (Hay et al., 2021), to what extent the topographic effects of deeply-incised submarine canyons may limit detection of events by similar sensors placed outside the canyon, along narrow fjords or other irregular seafloor terrain remains poorly constrained. It is also important to identify and differentiate landslide-related noise from ambient seismic and acoustic noise that arises from natural background processes and human activities in the ocean. In noisy marine environments, ambient noise may overprint or entirely obscure the records of submarine landslides; hence, an understanding of the levels, frequency and time windows of that background noise is important when designing monitoring strategies (Lior et al., 2021). Societal lockdowns in 2020 and 2021 associated with the COVID-19 pandemic have been identified as periods of significantly reduced seismic noise both on land and at sea (Lecocq et al., 2020; Ryan et al., 2020), and may therefore provide a rare window of reduced background noise to explore local to global datasets. If signals can be sufficiently calibrated and confidently attributed to submarine landslides, historical records can be re-analysed to extend landslide catalogues in many regions worldwide, adding significant value to already valuable legacy datasets and providing new avenues for research and informing hazard management strategies.

5.2.6. Challenges in data transfer

As passive geophysical systems require much less power than active sensors (e.g. such as ADCPs), they can improve the endurance of offshore monitoring, lengthening monitoring windows in time. Future challenges still lie in transmission of data from sites that are far from shore (i.e. in abyssal to hadal water depths), particularly if an end goal is to support early-warning systems. This issue is largely moot for cabled systems as they support high bandwidth data transfer; although as already noted, the current reach of Distributed Acoustic Sensing limits long distance (>100s km) monitoring. For ocean bottom seismometers or hydrophones on seabed frames or moorings, there is currently no simple solution, as data file sizes typically exceed that currently permissible by acoustic data transmission.

5.3. Suggestions for future directions

We now finish by making some specific suggestions with regards to the future activities, listed in a broadly prioritised order.

5.3.1. Focus on calibration of hydrophone and geophone records at specific, well-known, active sites

We suggest that efforts should be focused on specific sites and settings to provide the calibration needed to strengthen confidence in the characterisation of submarine landslides from passive monitoring data. It is sensible to target active sites where previous monitoring has demonstrated regular landslide activity, where pre- and post-event bathymetric data are available, and where passive instruments (hydrophones, geophones, fibre-optic cables etc.) can be deployed concurrently with active sensors that record key parameters such as event timing, subsurface pore pressure, elevation changes, and flow velocity and sediment concentration. The Fraser Delta is one such location, being connected by seafloor cables to

Ocean Networks Canada's VENUS network (that enable real-time data transfer to shore) in an area of high sediment supply with sub-annual landslide activity. Synchronous deployment of hydrophones and seismometers, with current meters, inclinometers and piezometers (among other sensors) provides an ideal test bed for calibrated interpretation of seismic and acoustic signals attributed to small-scale submarine landslides (Lintern and Hill, 2010; Lintern et al, 2020). Other cable-connected sites, such as the EMSO (European Multidisciplinary Seafloor and water column Observatory) Ligure-Nice observatory provide opportunities to monitor the development of potential precursor conditions, but landslide recurrence is orders of magnitude lower at this site compared to the Fraser Delta; hence, the likelihood of catching a landslide itself is much less likely (Bompais et al., 2019). Similarly, the DONET (Dense Oceanfloor Network system for Earthquakes and Tsunamis) cabled sensor network located offshore SW Japan provides opportunities to detect submarine landslides, but intriguingly no evidence for such activity was found within a few hours of two large (>6 M_w) earthquakes, with a study concluding that slopes may not be particularly susceptible to slope failure in that region (Gomberg et al., 2021). Indeed, most cabled observatories tend to avoid areas of very frequent landslide activity, so it will also be necessary to perform field calibration in other settings using more conventional landers or moorings that are not connected by cables, which requires sea-going research cruises. Sites with high, and predictable, sediment supply and where active field campaigns are planned will be the preferred candidates for synchronous deployment of active and passive monitoring equipment, such as major submarine canyons that connect to large rivers, or whose head intersects seasonally-variable littoral transport cells (e.g. canyons where sub-annual turbidity currents have previously been recorded: Congo Canyon, West Africa; Gaoping Canyon, Taiwan; Var Canyon, Mediterranean; Capbreton Canyon, Bay of Biscay; Khripounoff et al. 2012; Azpiroz-Zabala et al., 2017; Paull et al., 2018; Zhang et al., 2018). On a larger-scale, it will also be important to acquire data at active volcanic sites where onshore and offshore monitoring is on-going, such as the geodetic monitoring offshore Mount Etna, or land-based acoustic emission and GPS monitoring at Anak Krakatau (Urlaub et al., 2018; Walter et al., 2018). These activities should go hand in hand with efforts to determine site-specific effects on attenuation (e.g. due to topographic, substrate and other effects), which will benefit from numerical modelling to help identify and design the optimal sensor (e.g. where is the strongest or earliest signal expected?).

5.3.2. Explore and calibrate existing land-based seismic monitoring data

We suggest that more can, and should be, made of legacy broadband seismic datasets to explore past catalogues for evidence of submarine landslides. This method has been demonstrated offshore USA and Taiwan (Lin, 2015; Fan et al., 2020) and is more widely applicable, using data that have already been collected. Analysis of past time-series data should then be complemented with the acquisition of new seafloor survey data, to confirm that the spatial locations of landslide signals do indeed correspond with landslide events, and determine if a specific type(s) of landslide is more likely to generate a detectable seismic signal. This calibration will be most effective in areas where detailed swath multibeam echo-sounder surveys have already been performed (in particular high-resolution datasets acquired using Autonomous Underwater Vehicles), as differential elevations between multiple surveys provide a time window for a landslide, as well as its location. While repeat seafloor surveys are relatively rare, their use is growing, particularly in active submarine canyons (e.g. Smith et al., 2007; Paull et al., 2018), volcanic island flanks (e.g. Le Friant et al., 2010; Caplan-Auerbach et al., 2014; Hunt et al., 2021), offshore river deltas (e.g. Lintern et al., 2016; Obelcz et al., 2017), including across the Mississippi submarine delta where seafloor infrastructure is threatened by submarine slope failures (Chaytor et al., 2020; Obelcz et al., 2020). The footprint of these surveys tends to be quite limited; hence, it will most likely be necessary to target specific areas, focusing on acquiring high-resolution bathymetric data that enables identification of landslide scars and/or deposits. Evidence of landslide impacts on seafloor infrastructure (e.g. cable breaks, pipeline damage) may provide a useful addition point of calibration as this provides constraint on both timing and location of the event (e.g. Carter et al., 2014). Analysis of legacy seismic monitoring datasets, as well as new ones, will benefit from application of emergent machine learning techniques that permit analysis of vast datasets to train algorithms to automatically identify landslide events, and potentially identify previously-unrecognised environmental patterns that relate to landslide preconditioning (Thirugnanam et al., 2020; Deng et al., 2021).

5.3.3. Calibrate and test fibre-optic detection of submarine landslides

The emergence of fibre-optic sensing to monitor offshore geohazards (in particular Distributed Acoustic Sensing) is an exciting prospect, but one that currently remains unproven at field-scale for submarine landslide detection. The frequency ranges for detection appear to largely fall within the capabilities of Distributed Acoustic Sensing, although confident identification of low frequency (<<1 Hz) signals may be challenging, particularly in noisy environments (e.g. due to natural ocean processes and human activities) or where cables are poorly coupled with the seafloor. Synchronous deployment of arrays of ocean bottom seismometers and hydrophones in active landslide settings are needed to provide the confidence in interpretation of Distributed Acoustic Sensing data as well as assessing the distance (both along-cable, and adjacent to it) over which measurements can reliably be made of the different signals created by submarine landslides. When installing new pipelines and cable, or when seafloor structures are decommissioned and left in situ, consideration could be given to integrate passive monitoring instrumentation to complement that used for monitoring infrastructure integrity (Wilcock et al., 2021). As SMART cables are installed (planned from 2024), opportunities will arise for accessing distributed sensor packages that may include hydrophones and/or geophones, adding valuable new potential locations for submarine landslide detection (Howe et al., 2019; Matias et al., 2021).

5.3.4. Extending the global monitoring network to enable operational early warning systems

In the longer-term there is a need for expanded acoustic and seismic monitoring networks offshore; not only for detection of submarine landslides, but also for a host of ocean and earth science applications (Wilcock et al. 2021). Future opportunities may exist through collaboration with global monitoring programmes, such as MERMAIDS (Mobile Earthquake Recording in Marine Areas by Independent Divers), which employs a network of autonomous floats equipped with hydrophones (0.1-50 kHz) that passively drift across the ocean for deployments lasting up to five years; capable of transmitting seismograms in near real-time (Sukhovich et al., 2015; Hello and Nolet, 2020). Data gathered in such a manner may provide useful opportunistic snapshots of certain aspects of landslide activity, but may only yield limited data to answer outstanding science questions given the mobile nature of the floats and the lack of ground motion data. Therefore static seafloor sensors, rather than floating ones, will also be required, but a similar approach (i.e. that focuses developing low cost, and long endurance monitoring platforms) is an important future direction. Whether seismic monitoring networks are extended offshore attached to cables, via distributed fibre-optic sensing, or using stand-alone moorings, seafloor landers or nodes, the development of more cost-effective sensors that do not require regular servicing, and are capable of transmitting data remotely, will transform our ability to monitor and ultimately provide early warning for submarine landslides. It is unlikely that we will fully rely upon passive monitoring approaches, but a future outlook could include automated decision-making by smart networks that determine whether a significant event has occurred, prompting the release of pop-up floats to transmit data, or active (high power-use) systems that are triggered to start recording, or switch to a higher sampling rate, by passive (lower power-use) sensors.

6. Concluding remarks

While there are still many open questions concerning submarine landslides and the hazards they pose, the recent growth in marine geophysical monitoring is rapidly providing data to start filling many of those gaps. Passive seismic and acoustic monitoring is in its relative infancy in this field, but has already shown significant promise in enabling the detection of submarine landslides over large areas, to ascertain their precise timing (and hence determine likely triggers), provide constraints on their transit velocity and run-out distance, and their effects (e.g. tsunami generation). We consider that these longer endurance and often more cost effective techniques are likely to form a complementary addition to existing approaches, rather than replace them entirely, particularly as many aspects of landslides can generate ground motions and/or acoustic noise. Ongoing calibration needs to be a priority to reliably discern and interpret signals generated by submarine landslides. Greater understanding through modeling will help to identify optimal sensor configurations. Distributed sensing along fibre-optic cables is an intriguing proposition, however, there is a compelling need to understand precisely what a submarine landslide signal looks like and over what spatial scale such signals can be reliably recorded. Studies are immediately required that test the sensitivity of passive landslide detection (using onshore and offshore networks) through concurrent deployment of active sensors. Once that calibration is performed across a breadth of sites and settings, we suggest that passive seismic and acoustic monitoring has the potential to answer a host of key, outstanding questions and significantly advance the field of submarine landslide science.

7. Acknowledgements

Clare and Talling acknowledge funding from the Natural Environment Research Council (NERC), including 'Environmental Risks to Infrastructure: Identifying and Filling the Gaps' (NE/ P005780/1), 'New field-scale calibration of turbidity current impact modelling' (NE/P009190/1), "Developing a Global Listening Network for Turbidity Currents and Seafloor Processes" (NE/S009965/1 and NE/S010068/1). The authors also acknowledge discussions with collaborators as part of Talling's NERC International Opportunities Fund grant (NE/M017540/1) 'Coordinating and pump-priming international efforts for direct monitoring of active turbidity currents at global test sites'. Clare also acknowledges support from the International Cable Protection Committee. Talling was supported by a NERC and Royal Society Industry Fellowship hosted by the International Cable Protection Committee. Additional funding for Clare was provided by NERC National Capability Climate Linked Atlantic Sector Science Programme (NE/R015953/1). E. Pope was supported by a Leverhulme Early Career Fellowship (ECF-2018-267). We thank Bruce Howe and an anonymous reviewer for constructive feedback that improved the manuscript.

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