MagellanPlus Workshop: Mission-specific platform approaches to assessing natural hazards that impact society

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Abstract. Oceanic natural hazards pose threats to coastal communities worldwide. These include earthquakes, tsunamis, submarine landslide, volcanic eruptions, and tropical cyclones. Scientific ocean drilling can contribute to our understanding and assessment of these hazards through rapid response measurements of hazardous events, learning from past hazard records, and subseafloor monitoring and observation. With the impending retirement of the *D/V JOIDES Resolution* and operational limitations of the *D/V Chikyu*, it is important to consider other options for achieving scientific ocean drilling goals. We convened a workshop in Lisbon, Portugal in July 2022 to identify locations where natural hazards, or preferably several different hazards, can be addressed with mission-specific platform (MSP) drilling, with consideration of further location-based workshops. Participants split into 3 working groups to develop hypotheses surrounding climate and tropical cyclones, slope failure, and processes at active margins that can be tested with MSP drilling and can be addressed using the unique capabilities of these platforms. We produced 13 questions or hypotheses with recommendations on specific areas or locations for drilling. Our hope is that the results of this workshop will lay the groundwork for future preproposals.

1 Introduction

Natural hazards associated with the ocean, including earthquakes, tsunamis, submarine landslides, volcanic eruptions, and tropical cyclones, can have a direct impact on coastal populations, and even affect populations located far away from the coast (Koppers and Coggon, 2020). These hazards may interact, such as when tsunamis result in major direct damage and loss of life and also trigger submarine landslides, which themselves can produce tsunamis and damage subsea infrastructure like communications cables, oil and gas pipelines, and offshore wind turbines. In addition to these events, sea level rise and warming sea temperatures are resulting in more damaging tropical cyclones (Walsh et al., 2016), severe and nuisance coastal flooding (Morris and Renken, 2020; Vega et al., 2021), and larger-scale disruptions to ocean and atmospheric circulation

(Caesar et al., 2018). Tectonically and climatically driven hazards operate and interact over timescales that are societally relevant, from seasonal to decadal (Telesca, 2007); and their records are preserved in the geologic record. Natural hazards can be investigated in locations threatened by only one hazard, or locations where several different hazards are present. While earthquakes and associated tsunamis more commonly originate on active margins, tsunamis triggered by

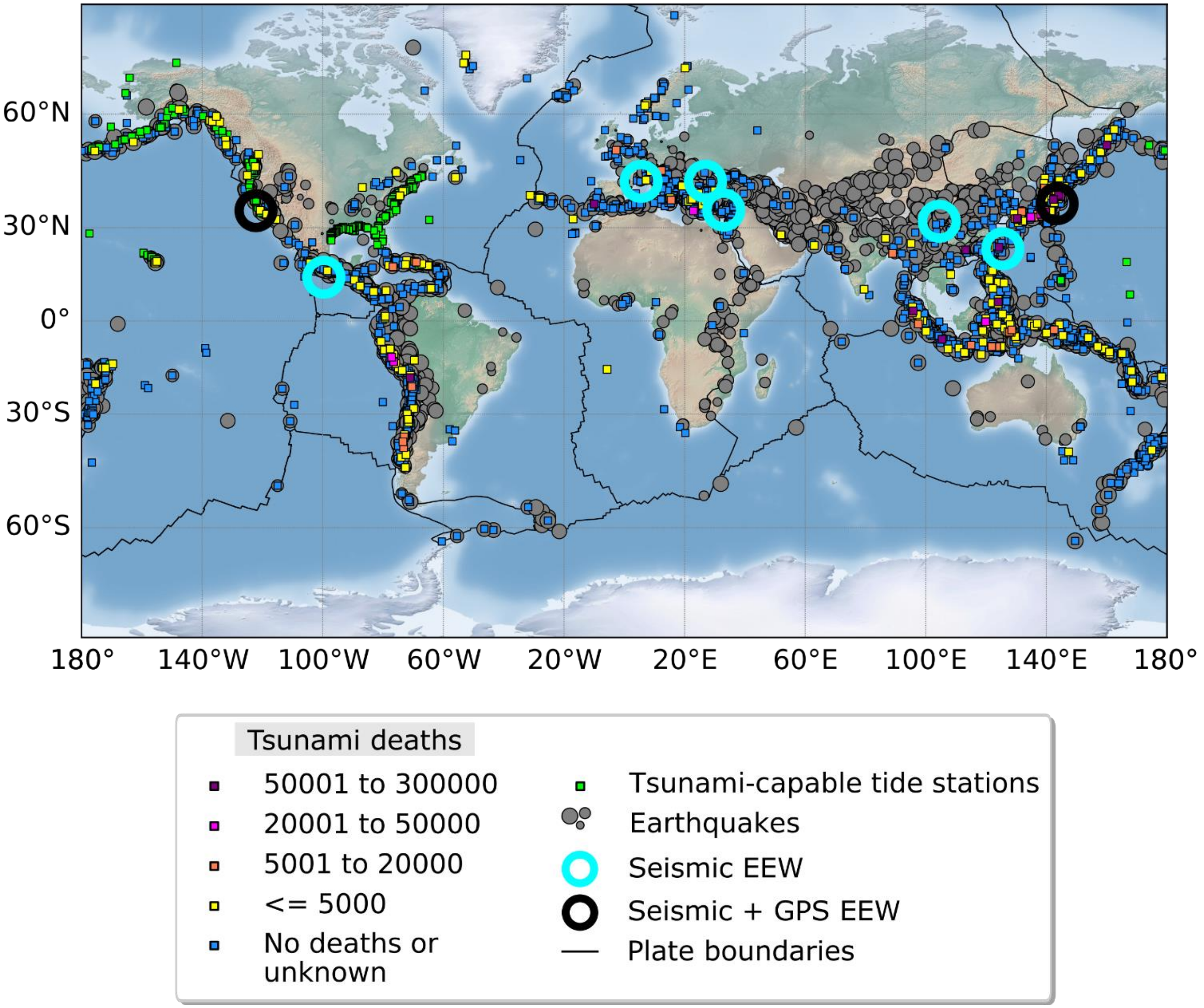

Figure 1: Historic earthquakes 2150 B.C.E-present (NGDC/WDS, 2023a), along with tsunami events 2000 B.C.E.-present (NGCD/WDS, 2023b), tsunami-capable tide stations (NOS/CO-OPS, 2023), and earthquake early warning (EEW) systems (Minson et al., 2015). Earthquakes shown meet at least one of the following criteria: caused at least US$ 1M in damage, resulted in 10 or more deaths, had a magnitude of 7.5 or more, had a Modified Mercalli intensity of X or greater, or generated a tsunami,

submarine landslides can occur on oceanic islands and passive margins as well (Fig. 1). Submarine landslides can themselves be triggered by earthquakes even on passive margins (Schulten et al., 2019), or through cyclic loading by large waves during tropical cyclones, which primarily affect the tropics but also the European Atlantic coast (Sainsbury et al., 2020). The prevalence of various hazards throughout geologic history could be investigated as well as linkages with longer-term trends in climate, ocean circulation, and tectonics. The paucity of warning systems for earthquakes and tsunamis (Fig. 1) demonstrates a particular opportunity in devising monitoring networks in other areas with high natural hazard prevalence.

The International Ocean Discovery Program (IODP) *2050 Science Framework* (Koppers and Coggon, 2020) lists investigating natural hazards impacting society as a strategic objective, with rapid response measurements of hazardous events, learning from past hazard records, and subseafloor monitoring and observation identified as areas where scientific ocean drilling can contribute to understanding. Assessing earthquake and tsunami hazards is specifically identified as a flagship initiative in the *Framework*, while climate-related hazards fall under the flagship initiative to ground-truth future climate change. Mission-specific platforms (MSPs) can provide a significant advantage over large drillships in investigating natural hazards as they can potentially operate in shallower waters, more restricted environments, or in sea ice; MSPs can be specially tailored for deployment or monitoring of instrumentation; and they have the potential for more rapid deployment in response to new events, or repeat deployment over months or years to visit monitoring stations. They do have drawbacks as well, including limitations on water and coring depths as well as a restricted ability to perform shipboard analyses. MSPs are also usually smaller than the IODP vessels but are always be able to carry out the minimum of IODP measurements. MSPs therefore have promise for advancing scientific ocean drilling, but the circumstances in which they can be used requires definition.

MSPs are chosen by IODP to fulfill specific scientific objectives in certain conditions where the use of IODP vessels (*D/V JOIDES Resolution* or *D/V Chikyu*) is not appropriate. Whereas the *JOIDES Resolution* and *Chikyu* are dedicated drilling vessels, MSPs will be adapted to suit IODP needs as far as possible. Approaches for sample recovery of past MSPs include the use of wireline coring from geotechnical vessels or mining rigs on liftboats; and giant piston corer or seabed drills deployed from research vessels. There also exists the possibility to install borehole observatories, though this has not been tested on MSPs to date. The ECORD Science Operator (ESO) typically provides the necessary equipment for core curation and laboratory measurements onboard, usually in containerized facilities that are placed on-deck for the length of the cruise. Overall, the science party for an MSP expedition is oftentimes smaller than on an IODP vessel, and needs to be more flexible, as scheduling is more variable due to contracting of MSP vessels. After an MSP expedition, the majority of sampling and analysis takes place at the Onshore Science Party (OSP) Facility in Bremen, Germany, attended by the full science party.

MSP expeditions also aim at collecting *in situ* downhole logs. There are multiple approaches to collect downhole logs, with the standard one for MSP (and the *JOIDES Resolution*) being wireline logging, where tools are sent downhole connected to a cable, a winch, and acquisition equipment. Wireline logging allows real time data acquisition against depth. The datasets acquired with this method on MSP expeditions can include borehole diameter, total and spectral gamma ray, formation resistivity or conductivity, magnetic susceptibility, acoustic velocity, borehole fluid properties and borehole wall images. Aswith MSP expeditions' flexibility for drilling platform and strategy, the logging equipment can be adapted to various operational setting and scientific objectives. For example, the European Petrophysics Consortium (EPC), part of ESO, has a set of wireline logging tools referred as “slimline” and designed by ALT, Mount Sopris, Antares and Geovista. These tools are relatively short (<2.5 m) lightweight (<20 kg) and narrow (4-6 cm diameter), and they can be run downhole as stand-alone sensors or combined into toolstrings of up to four tools and less than 40 kg. ESO-EPC provided wireline logging services on five MSP expeditions (see the methods section in Camoin et al. 2007; Mountain et al. 2010; Webster et al. 2011; Morgan et al. 2017; McNeill et al. 2019). Wireline logging services have also been provided by other service companies (see the methods section in Backman et al. 2006; Andrén et al. 2015). ESO also deployed logging-while-tripping slimline tools from seabed drills during Expedition 357 (see the methods section in Früh-Green et al., 2017).

With the impending retirement of the *D/V JOIDES Resolution* and operational limitations of the *D/V Chikyu*, it is important to consider other options for ocean drilling research. To explore the potential to use MSPs to address natural hazards impacting society, we convened a workshop in Lisbon, Portugal in July 2022 that brought together 28 researchers from around the world, including 9 early-career researchers, both in person and virtually (Daigle et al., 2023).

2. Workshop Objectives

The objectives of the workshop were (1) to form working groups that would develop plans to address key scientific questions discussed at the meeting; (2) to identify locations where tsunamis, submarine landslides, volcanic eruptions, and tropical cyclones, or preferably several of these hazards, can be addressed with MSP drilling, with consideration of further location-based workshops; and (3) to develop a set of hypotheses that can be tested with MSP drilling which would lay the groundwork for future preproposals.

3. Working Group Discussions

During the workshop, we created three working groups that developed hypotheses and questions focused on three main topics: climate and tropical cyclones, slope failure, and processes at active margins. These hypotheses and questions can be used to develop drilling proposals for specific locations. Specific locations mentioned by the working groups are shown in Figure 2.

3.1 Working Group 1: Climate and Tropical Cyclones

The climate and tropical cyclones working group agreed that the northern Gulf of Mexico presents the best location to address questions about climate change and its influence on tropical cyclone frequency and intensity. The Gulf of Mexico is ideal because of its overall thick sediment column (up to 20 km; Galloway, 2008) and well-preserved sedimentary sections in salt-withdrawal minibasins, growth faults, river deltas, and basin-floor fans (Martin, 1978). The group phrased two hypotheses of global significance that may be addressed in the Gulf of Mexico.

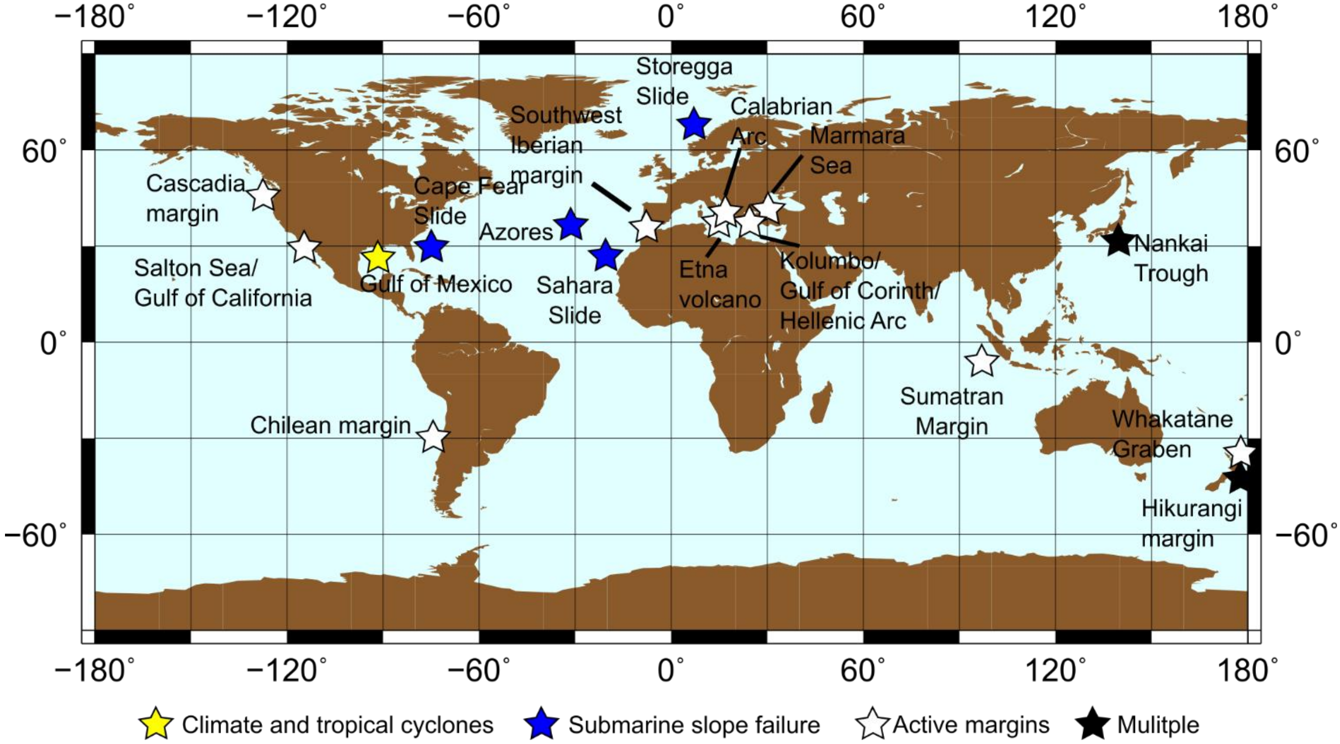

Figure 2. Locations recommended in the workshop color-coded by working group.

3.1.1 Hypothesis 1

We hypothesize that past hurricane frequency and intensity in the Gulf of Mexico has responded to changes in the strength of ocean circulation patterns, most notably the strength of the Gulf Stream and the Atlantic Meridional Overturning Circulation (AMOC). Warm core eddies spun off the Loop Current can cause rapid intensification of hurricanes (e.g. Hurricane Katrina in 2005; Scharroo et al., 2005). Reconstruction of sea surface temperatures (SSTs) and storm frequency from sedimentary deposits in the Gulf of Mexico could be used to understand how much influence the variability in the Gulf Stream dynamics has on Gulf of Mexico storms.

Drill site needs and potential outcomes. MSPs could be used to collect very high-resolution storm and SST records in areas with continuous late Pleistocene to Holocene sedimentary sections. These time intervals contain many episodes of AMOC slowdown (Heinrich Events, Younger Dryas) that would allow us to understand the impact of AMOC variability on hurricane development in this region.

Potential drill sites. Salt withdrawal minibasins along the Gulf of Mexico's margin contain suitable deposits, typically representing a sediment thickness of 100-200 m.

3.1.2 Hypothesis 2

Storm frequency has a strong influence on precipitation and streamflow in the western Gulf of Mexico and southwestern United States. Hurricane Harvey (2017) dropped more than 1500 mm of rain in parts of southeast Texas in less than a week and storm-related precipitation is expected to increase as climate warms over the 21st century (Bacmeister et al., 2018). Cores from the Gulf of Mexico have provided evidence for past occurrence of large flood events on the Mississippi River (e.g., deglacial meltwater pulses; Clark et al., 1996; Brown and Kennett, 1998).

Drill site needs and potential outcomes. Drill sites should be located offshore of rivers that provide sedimentary flux from catchments that are affected by tropical cyclones. These locations can provide information on flooding events, particularly those during past climate intervals warmer than present day such as the mid-Holocene or previous interglacials. MSP drilling could include long cores, which could be combined with borehole or seafloor monitoring of development of mud flow events to establish modern depositional system analogs, and seismic surveys of the continental shelf to map potential sediment source areas.

Potential drill sites. Suitable locations can be found offshore the mouths of the Rio Grande, Colorado, Brazos, Sabine, and other rivers on the western Gulf of Mexico coast. Salt withdrawal minibasins offshore the mouth of the Rio Grande may make the best locations as they tend to preserve more continuous sedimentary records.

3.2 Working Group 2: Submarine Slope Failure

3.2.1 Hypothesis 1: Preconditioning factors cause repeat landslides

We hypothesize that through the Neogene, the presence of similar preconditioning factors has typically caused submarine landslides to occur repeatedly at the same location. Preconditioning factors can include sediment properties, pore fluid pressure, fluid chemistry, mechanical stratigraphy, and oversteepening/slope angle (Hampton et al., 1996). These can be investigated with hydraulic piston cores (equivalent to the *JOIDES Resolution* advanced piston coring (APC) tool) down to 1000 m water depth in most cases. Required measurements include core physical properties and pore fluid chemistry, in situ pore pressure and heat flow measurements, and anything that can provide evidence of changes in stresses, e.g., borehole breakouts or drilling-induced tensile fractures obtained from multi-axis caliper or borehole image logs. In situ observatories can help establish trends in pore pressure, heat flow, and stress over time.

Drill site needs and potential outcomes. Drill sites should be located near the headscarp of a submarine landslide. Core analysis, downhole measurements, and in situ observatories will provide evidence of the presence or absence of preconditioning factors, and how these change over time.

Potential drill sites. There are many locations that could be targeted on both active and passive margins. The Cape Fear Slide, Storegga Slide, and Sahara Slide are potential targets on passive margins, while active margins such as the Nankai Trough, the Sumatran Margin, and Hikurangi Margin could be investigated.

3.2.2 Hypothesis 2: Landslides are externally triggered

Preconditioning factors are necessary but not sufficient for submarine landslides, and in most cases an external trigger is needed. Triggers include earthquakes, storm wave loading, abrupt shifts in sedimentation, tectonic oversteepening, changes in ocean temperature, gas hydrate dissociation, volcanism, and salt diapirism (e.g., Urlaub et al, 2013). This hypothesis can be tested by recovering cores, fluid samples, and pore pressures to demonstrate that slope failure could occur in an area that would otherwise be stable. Note that, if hypothesis 1 is true, then one initiation can cause the area to be prone to failure for many years afterwards.

Drill site needs and potential outcomes. Ideal sites to test this hypothesis should be locations with no evidence of slope failure, but near known submarine landslides. Measured properties could be used as inputs for models to predict conditions for slope failure.

Potential drill sites. This hypothesis could be tested at the same locations as the previous hypothesis, with the addition of volcanic islands such as the Azores.

3.2.3 Hypothesis 3: Retrogressive failure leaves a signature

Retrogressive failure leaves a detectable perturbation of pore pressure and heat flow. The pore pressure perturbation is related to failure propagation upslope, and the heat flow perturbation is a leftover signature of it. Anomalously high heat flow also could be evidence of salt diapirism. This technique can also be used to infer gas hydrate (in)stability. This hypothesis would best be tested with in situ measurements and longer-term monitoring with dense spatial sampling. One particular location that should be targeted is the distal toe of a submarine landslide, although these may be deeper than MSP capabilities (~1700 m) in most locations. For example, the toe of the Cape Fear Slide is at about 5.4 km water depth (Popenoe et al., 1993), while that of the Storegga Slide is at 3-3.5 km water depth (Bugge et al., 1988).

Drill site needs and potential outcomes. Potential sites should be located at submarine landslides with known retrogressive failure. Long-term measurements of pore pressure and heat flow can provide evidence of the current state of the subsurface around submarine landslides and its response to external perturbations.

Potential drill sites. The Cape Fear Slide is a well studied example of retrogressive failure that could be targeted to test this hypothesis.

3.2.4 Hypothesis 4: Active margins have more earthquakes than landslides

Submarine landslides occur less frequently than earthquakes on active margins because of (a) seismic strengthening and (b) sediment accumulation rates. It is established that seismic shaking tends to increase the shear strength of sediments (Sawyer and DeVore, 2015), so slope failure on an active margin would tend to require a large amount of sediment to accumulate between earthquakes.

Drill site needs and potential outcomes. To test this hypothesis, high-resolution seismic data, core data to understand strength and sedimentation rate, and a good paleoseismological record are required. A drilling strategy to test this hypothesis would consist of a transect across an accretionary prism with perched basins that preserved mass transport deposits.

Potential drill sites. The Nankai Trough or Hikurangi Margin make excellent candidates to test this hypothesis due to the large volume of existing data.

3.3 Working Group 3: Active Margins

3.3.1 Hypothesis 1: Major earthquakes have precursors

Transient events are observed at plate boundaries worldwide, but we currently do not understand how these relate to the timing of larger earthquakes. In a few cases, slow slip events at subduction zones have been observed in the weeks to months prior to great megathrust earthquakes (e.g., the Tohoku-Oki 2011 and Iquique 2014 earthquakes) (Ito et al., 2013; Ruiz et al., 2014). Resolving whether great earthquakes have precursors is a societally important question, critical for more effective, short-term earthquake forecasting. As most subduction zone earthquakes nucleate on offshore megathrusts, detailed offshore monitoring of potential transient deformation is required.

Drill site needs and potential outcomes. Drill sites should be located near active faults in areas with large earthquakes. Due to the high-noise ocean environment, the most viable tool to undertake this type of monitoring is borehole observatories, specifically detecting volumetric strain using changes in formation pore pressure as a proxy; as done in boreholes offshore subduction margins in Costa Rica, Japan, and New Zealand (Davis et al., 2015; Araki et al., 2017; Wallace et al., 2019).

Potential drill sites. Highly active transform faults that are the site of frequently recurring moderate to large magnitude earthquakes, such as the Gofar transform fault with quasi-periodic Mw 6-7 events every 5-6 years (McGuire, 2008), could be ideal targets to investigate potential precursors through installation of borehole observatories. Amphibious experiments complementing the already existing infrastructure could be developed in both the Chilean Margin (Barrientos et al., 2018) and the Marmara Sea (MARSite; Özel et al., 2017). The Salton Sea and the Gulf of California may also be potential sites, as a southward extension of the U.S. Geological Survey Parkfield, CA network, but are complicated by transtensional deformation (Brothers et al., 2009). In addition, the Hikurangi Margin, Hellenic Arc, and Southwest Iberian Margin could be other locations targeted to test this hypothesis.

3.3.2 Hypothesis 2: Rupture barriers are persistent

Several hypotheses exist to explain rupture terminations that appear to be persistent over the timescale of available earthquake records. These range from the presence of plate boundary transitions (Wallace et al., 2012), to changes in upper plate/lower plate properties and/or geometrical changes (Collot et al., 2004), stress heterogeneity (Huang, 2018), and the presence of positive relief structures such as seamounts or ridges (Sparkes et al., 2010). However, no conclusive evidence exists to confirm that these historical or recent rupture terminations are persistent over longer timescales. Potential boundary-breaking earthquake ruptures could lead to earthquakes that substantially exceed historical or instrumentally observed magnitudes (maybe even M>10) and that have recurrence intervals of several 1000s of years or more (Goldfinger et al., 2013). This is much longer than the current length of available paleoseismic records along any subduction zone around the world, meaning we cannot reliably exclude their occurrence.

To evaluate the persistence of rupture/segment barriers and unveil (or discard) the existence of these larger-than-observed earthquakes, the available paleoseismic records need to be extended back in time. Long-term paleoseismic records are thus needed along the entire length of subduction margins. This requires sedimentary records in both the onshore (coastal and lake) and offshore realm, and relies on the identification of secondary seismic effects such as shaking imprints (e.g. turbidites, soft-sediment deformation) and tsunami deposits. Identification of synchronous deposits along an entire subduction margin could hint towards these extreme events, but the current limitations of dating accuracy do not allow distinguishing single, large events from short-term successions of ruptures (e.g. stress triggering). Therefore, key records at locations that are currently believed to form rupture barriers are essential to verify the existence of imprint stacks, resulting from rupture cascades, while the presence of a single deposit could hint towards large, through-going ruptures.

Drill site needs and potential outcomes. Drill sites need to have historic earthquake records that show earthquake boundaries; a detailed understanding of sediment routing systems and several preferentially isolated depositional basins spanning the entire margin and containing high-resolution, continuous paleoseismic event deposit stratigraphies, for which sedimentary source areas can be well constrained to allow for reconstruction of past rupture areas; and a straight margin to avoid complications of changes in fault geometry (unless testing the role of plate margin geometry on arresting earthquake rupture is desired). The outcome of drilling would ideally be a long-term extension of the paleoseismic record.

Potential drill sites. The South American subduction zone is a potential target to investigate this hypothesis. It generated the largest known earthquake (magnitude 9.6, in 1960), and it is potentially able to generate the largest earthquakes of any subduction zone (Graham et al., 2021). In addition, many lakes along the margin could be sampled by continental drilling to constrain the paleoseismic record (Bernhardt et al., 2015). Other potential locations include the Marmara Sea, the Salton Sea/Gulf of California, Hikurangi Margin, Cascadia, the Hellenic Arc, and the Calabrian Arc.

3.3.3 Hypothesis 3: Fault coupling characteristics are persistent in space and time

Subduction plate interfaces commonly have spatially variable interseismic coupling, where strongly coupled segments are most likely to produce large earthquakes and weakly coupled segments tend to slip aseismically (Fagereng, 2011; Saito and Noda, 2022). It is unclear whether geodetically-constrained coupling patterns persist over multiple earthquake cycles, and also to what extent poorly coupled regions may slip during earthquakes that nucleate in adjacent coupled areas. Controls on coupling could include fluid pressure (Moreno et al., 2014); downgoing plate roughness (Ruff, 1989; Wang and Bilek, 2011; van Rijsingen et al., 2018); or rock physical properties at depth, including grain size, mineralogy, and fluid composition (Chen et al., 2013; Scholz, 2019).

Drill site needs and potential outcomes. Direct evidence for temporal variation in locking may be sought from the paleoseismic record, by looking for evidence for past earthquakes, and how their spatial pattern compares with current geodetic locking. This would require a margin where the current geodetic locking pattern is well characterized, and where there are appropriate sites for paleoseismicity (e.g. Chilean margin). The expectation, if coupling characteristics are persistent in time and space, would be that in locked regions, there is evidence for large earthquakes (where the meaning of ‘large’ should be calculated from the size of the locked patch). These earthquakes should, however, not have propagated into poorly coupled segments. Another direct measure is variations in interseismic periods, if observatories can be installed and maintained over multiple earthquake cycles.

Potential drill sites. Sites with existing reflection seismic and other data that could be used to test this hypothesis include the Chilean Margin, Marmara Sea, the Hellenic Arc, Salton Sea/Gulf of California, Cascadia Nankai Trough, Hikurangi Margin, and Costa Rica Margin.

3.3.4 Hypothesis 4: Subduction earthquakes are cyclic at multiple time scales

The 2011 Mw 9.0 Tohoku-Oki Japan earthquake occurred in an area where scientists thought large magnitude earthquakes were less likely (Stein et al., 2012). In contrast, the 2010 Mw 8.8 Maule earthquake in Chile was somewhat expected, but extended beyond the boundaries of the seismic gap that was believed to be present (Métois et al., 2012). These recent, very high-magnitude earthquakes painfully highlight how little we still know about megathrust earthquake recurrence along subduction zones, despite recent advances and widespread paleoseismological studies. The concepts of seismic gaps and characteristic earthquakes are simplified, and need further refining.

Mapping the spatiotemporal behavior of megathrust earthquakes thus forms a crucial step towards validation of physics-based earthquake cycle models, but is currently not possible on sufficiently long timescales and/or spatial extents along any of the subduction zones. Instrumental and historical records are too short, and coastal records (tsunami deposits, uplifted terraces or corals, subsided paleosols) are affected by global eustatic sea-level change and do not extend far beyond the last maximum sea level high stand of the Holocene.

Drill site needs and potential outcomes. Scientific ocean (and continental) drilling and coring of high-resolution marine and/or lacustrine paleoseismic archives extending well into the Late Pleistocene and further back in time as the only reasonable approach to potentially deliver observational data on time-scales long enough to robustly test the earthquake (super-)cycle hypothesis. Therefore, drill sites need to have well preserved, continuous sedimentary sections.

Potential drill sites. Drilling to test this hypothesis could be conducted at the Chilean Margin, the Hikurangi Margin, and Cascadia.

3.3.5 Hypothesis 5: Fault slip rates vary over multiple seismic cycles

Fault slip rates are critical for seismic hazard assessment and can be calculated over a range of different time scales from < 1 yr to millions of years. Variations between short-term and long-term slip rates have been recorded, bringing into question the usefulness of slip rates calculated over a particular time period for seismic hazard assessment, i.e., are geological rates relevant to apply to modern seismic hazard estimates? Do modern satellite derived slip rates (from GPS) give a good indication of the areas most at risk from earthquakes (e.g., Bell et al. 2011, Cowie et al. 2012; Fagereng and Biggs, 2019)? Our understanding of fault growth and fault slip is least well-constrained in the 10^4-10^6 yr range (reviewed in Pan et al. 2022). There are a number of ways in which we can assess slip rates in the range of 10^4-10^6 yrs using offshore MSP drilling/piston core data, including targeted giant piston coring or short drilled sections on either side of a fault (or one side of the fault only if horizons can be confidently correlated) to calculate offset and slip rate; using submarine paleoseismology to identify evidence of individual earthquake slip events in high resolution seismic data with ground truthing of age and timing; or an onshore-offshore approach for comparison of slip rates over different timescales on an active normal fault.

Drill site needs and potential outcomes. Potential locations to study slip rates through time would ideally have: i) high sedimentation rates, ii) high slip rates (to give the greatest chance of slip rate variations being resolved), iii) a constrained onshore record of uplift rates to compare with results of ocean/lake drilling, and iv) high-resolution seismic reflection data imaging basin stratigraphy in the hanging wall and ideally also in the footwall.

Potential drill sites. Drilling to test this hypothesis could be conducted at active rift zones, and potentially at suitable transform zones and subduction margins, e.g., Corinth Rift (Greece), Salton Sea/Gulf of California, Marmara Sea, Chilean margin, Hikurangi margin.

3.3.6 Hypothesis 6: Faults grow rapidly to their full length

Seismological and geodetic data reveal that earthquake rupture patterns are complex and variable, often with temporal and spatial clustering of events (e.g., Wells and Coppersmith, 1994). In contrast, ancient normal faults commonly observed in high-resolution 3D seismic reflection datasets reveal strikingly consistent patterns of displacement accumulation along strike, commonly described as the classic ‘bell shaped’ cumulative displacement profile with greatest overall displacement in the center of the fault decreasing toward the tips (e.g. Cowie and Scholz 1992). Other mature faults within extended systems have consistent slip rates along strike, potentially indicating linkage of segments at depth. Exactly how faults evolve in terms of how multiple earthquake cycles and aseismic slip accrue to produce the long-term fault geometry is unknown. Most work into this problem has focused on normal faults, as they are associated with a convenient marker of fault growth in the form of sediment thickness increases in the hanging wall when a fault is active at the Earth's surface (i.e. it is a ‘growth fault’). Therefore, to address the question of “how faults grow” will likely require observations from active continental rifts. Understanding how faults develop has relevance to earthquake hazards because of how we interpret fault slip rates over different time periods (see section 3.3.5 above) and how earthquake slip builds up to fault slip over longer timescales. One category of normal fault relatively understudied is outer rise normal faults at subduction zones. These faults, caused by flexure of the downbending subducting plate, are a significant tsunami hazard and they are potential sites for investigating the normal fault evolution of this hypothesis.

Drill site needs and potential outcomes. It may be possible to investigate in detail how faults establish themselves and evolve both laterally and in terms of displacement accrual by identifying a study location where a very young fault exists at a shallow depth, which is well imaged by 3D or pseudo-3D high-resolution seismic reflection data. If age-constraints are available from drilling/piston coring, interpretation of high-resolution seismic reflection data will allow variations in sediment thickness between the hanging wall and footwall to be investigated at the millennial scale, and hence how slip has accrued along different parts of the fault. This timescale links the supramillennial scale of modern geological and seismological observation, and the million-year averaged observations from seismic reflection data in rifts.

Potential drill sites. Drilling to test this hypothesis could be conducted at the following locations: Corinth Rift (Greece) (McNeill et al., 2019; Nixon et al., 2016); Whakatane Graben (New Zealand) (Taylor et al., 2004); and outer rise normal fault systems at subduction margins.

3.3.7 Hypothesis 7: Tectonic activity is linked to the timing of volcanic eruptions

Active submarine volcanoes are linked to several of the deadliest geohazards such as tsunami, earthquakes, landslides, pyroclastic material, and gas release. However, they pose difficult drilling conditions as they are covered by thin microbial crusts, and they have active hydrothermal systems and unstable slopes. MSP drilling presents an ideal way to sample these locations. Volcanic activity (frequency, volume, magma flux) is affected by tectonic activity at large length scales (e.g., plate tectonics) and smaller scales (e.g., development of preferential pathways for magma ascent due to local deformation). On the other hand, tectonic activity can also be affected by volcanism, for example in the case of magma ascent triggering localized seismic activity. This interconnection can be investigated through a high-resolution record of eruptive styles at individual centers that will give a characterization of their evolution in time, intensity, and spatial and temporal distribution. Large tectonic events recorded in sedimentary basins, like onlap surfaces, seismogenic turbidites, and homogenites, can correlate with activation/deactivation of different volcanic centers, changes in eruptive style, and particularly large explosive eruptions.

Drill site needs and potential outcomes. Drilling should be conducted at sites with a well preserved record of volcanism and tectonic events. Integration of paleoseismic and tephrachronological records need a good correlation between onshore and offshore records. Offshore geodesy would also be a priority to reconstruct the evolution of deformation around and within these volcanic centers. Possible correlations also exist with the paleoclimate record.

Potential drill sites. This hypothesis could be tested by drilling at the Chilean Margin, Kolumbo submarine volcano northeast of Santorini (building on recent IODP drilling), Etna volcano, the Hikurangi Margin, the Hellenic Arc, and the Calabrian Arc.

4. Conclusions

In this workshop, we defined questions and hypotheses about natural hazards that could be tested specifically with MSPs. The unique characteristics of MSPs compared to IODP drill ships require some shift in our thinking about how to interrogate the subsurface, but also present opportunities in terms of long-term monitoring, drilling in shallow water, and amphibious proposals. The workshop discussions recognized the growing needs of highly populated regions along tectonically active or hazardous settings for better assessment of earthquake, tsunami, volcanic, and climate hazards. A number of key questions/hypotheses, in combination with potential target locations and research strategies were formulated that urgently need to be tested in order to mitigate future risks.

MSP missions have the potential to contribute to the development of amphibious observatories, taking advantage of well-monitored onshore regions and leveraging partnerships with the continental drilling community. We considered that this strategy should be prioritized in the near future. The flexibility of an MSP and the relatively low costs in some cases make it worth the community effort in building a long-term infrastructure that allows us to monitor diverse geohazards from such observatories. The climate and tropical cyclones working group identified the Gulf of Mexico where key questions can be answered by MSP drilling. The submarine slope failure working group identified areas on both passive and active margins where hypotheses can be tested, including the Cape Fear Slide, the Storegga Slide, the Sahara Slide; the Nankai Trough, the Sumatran Margin, and the Hikurangi Margin; and volcanic islands such as the Azores. Finally, the active margins working group selected priority sites for the near future including the Chilean margin, the Hikurangi margin, the Marmara Sea, the Salton Sea/Gulf of California, Corinth rift, outer-rise normal fault systems. Other sites with high hazard exposure on active margins include regions around the Hellenic and Calabrian arcs, the Southwest Iberian, Cascadia, Sumatra, and Hikurangi margins. We hope that this work serves as the foundation for future drilling proposals in the regions we identified, or in other areas around the world.

Data availability

The datasets containing the historic earthquakes 2150 B.C.E-present (NGDC/WGS, 2023a), the tsunami events 2000 B.C.E.-present (NGDC/WGS, 2023b) and the tsunami-capable tide stations (NOS/CO-OPS, 2023) are available at their corresponding websites of the NOAA National Geophysical Data Center / World Data Service.

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Competing interests

The authors declare that they have no conflict of interest.

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Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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