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

7-9 July 2022

Instituto Dom Luiz, University of Lisbon, Lisbon, Portugal

Summary

Natural hazards associated with the ocean can have a direct impact on coastal populations, and even affect populations located far away from the coast. These hazards may interact, and include tsunamis that result in major damage and catastrophic loss of life; and 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 episodic events, currently warming sea temperatures are resulting in more damaging tropical cyclones, severe and nuisance coastal flooding, and larger-scale disruptions to ocean and atmospheric circulation. Tectonically and climatically driven hazards operate and interact over timescales that are societally relevant, from seasonal to decadal; and their records are preserved in the geologic record.

The IODP's *2050 Science Framework* lists 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, restricted environments, or sea ice; they 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. MSPs therefore are particularly well suited to these aspects of the *Framework*.

28 participants from around the world attended the workshop, including 8 who attended some or all of the workshop virtually. Over 3 days, we heard keynote talks on natural hazards topics that can be addressed with scientific ocean drilling and short talks from postdoctoral researchers, and participated in breakout groups to develop hypotheses specific to natural hazards that can be addressed in specific locations by MSP drilling.

Objectives

The objectives of the workshop were (1) to form working groups to develop plans to address key questions developed at the meeting; (2) to identify locations where natural hazards, or preferably several different 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 to lay the groundwork for future preproposals.

Program

DAY 1 (7 July 2022)

09:00 Welcome and introduction

- Presentation of Workshop Objectives
- **Session 1: Natural Hazards at Active Margins**
  Keynote speaker: Rebecca Bell (Imperial College, London): IODP drilling combined with next-generation controlled-source seismic experiments to better understand fault slip
- Short talks:
  Lisa McNeill (University of Southampton: Direct quantification of fault slip rate and activity from scientific ocean drilling
  Katleen Wils (Ghent University): An amphibious approach to unravel cascading hazards on active margins: Ideas from 20 years of work in Chile
  Keynote speaker: Paraskevi Nomikou (University of Athens): Volcanism and tectonics in an island-arc rift environment: IODP Expedition 398
- Discussion

12:00 Lunch

Figure 1. Coffee break on day 1.

13:00 **Session 2: Natural Hazards at Passive Margins**
Keynote speaker: Gareth Davies (Geoscience Australia): From offshore to onshore probabilistic tsunami hazard assessment from far-field earthquake sources

- Short talks:
  Ángela Gómez García (GFZ German Research Centre for Geosciences): Exploring the temporal evolution of the potential gas hydrate stability zones in the Caribbean Sea considering the IPCC global warming scenarios

Keynote speaker: Michael Toomey (United States Geological Survey): Reconstructing tropical cyclone frequency using deep-sea sediments—prospects and limitations

- Discussion

15:30 Working group break-out
16:30 Results from working groups

DAY 2 (8 July 2022)

09:00 Start of Day 2

- **Session 3: Climate Risk in the Geologic Record**
- Short talks:
  Davide Gamboa (Instituto Português do Mar e da Atmosfera/Instituto Dom Luiz): Preconditioning factors for submarine landslides
  Álvaro González (Centre de Recerca Matemàtica, Barcelona): Size distributions of earthquakes and tropical cyclones motivate the quest for the record of extreme events
  Keynote speaker: Caroline Ummenhofer (Woods Hole Oceanographic Institution): Assessing multi-decadal Indian Ocean variability and climate risk
- Discussion

12:00 Lunch

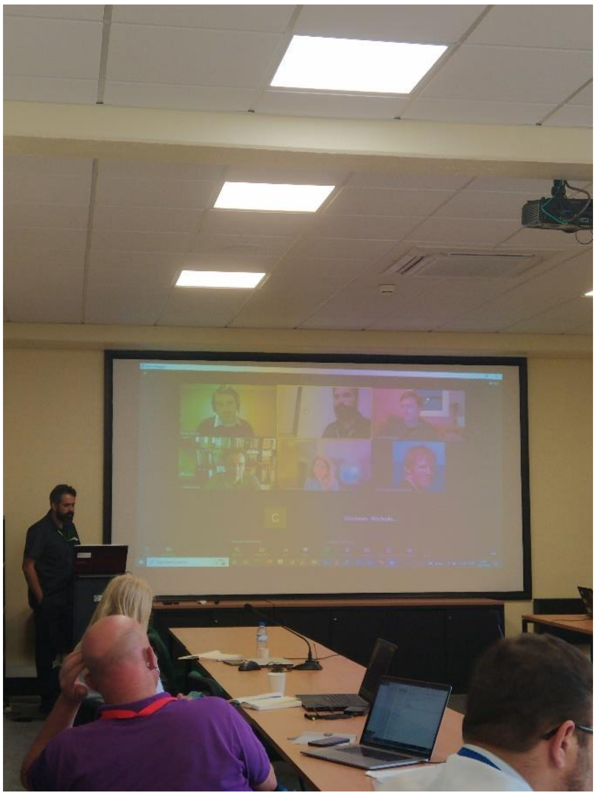

Figure 2. Davide Gamboa addressing the attendees in the room and online.

13:00 **Session 4: MSP Drilling, Logging, and Monitoring: Issues and challenges**

Keynote speaker: Margaret Stewart (British Geological Survey): Capabilities of IODP mission-specific platforms (MSPs)

- Short talks

Tiago Alves (Cardiff University): Submarine slope instability and associated geohazards: How can the IODP consortium go a step forward on the current knowledge?
Keynote speaker: Laura Wallace (GNS Science, New Zealand): Investigating slow slip events at the Hikurangi subduction zone with IODP observatories: implications for future drilling proposals to investigate transient deformation at active margins

- Discussion

15:30 Working group break-out
16:30 Results from working groups
17:00 Drinks, snacks and posters

DAY 3 (9 July 2022)
09:00 Start of Day 3

- Dedicated to hypothesis writing in working groups

14:00 Synthesis and outcome of workshop (organizers)
15:00 End of workshop

Figure 3. Breakout groups working on slope failure and tropical cyclones/climate (left) and active margin processes (right).

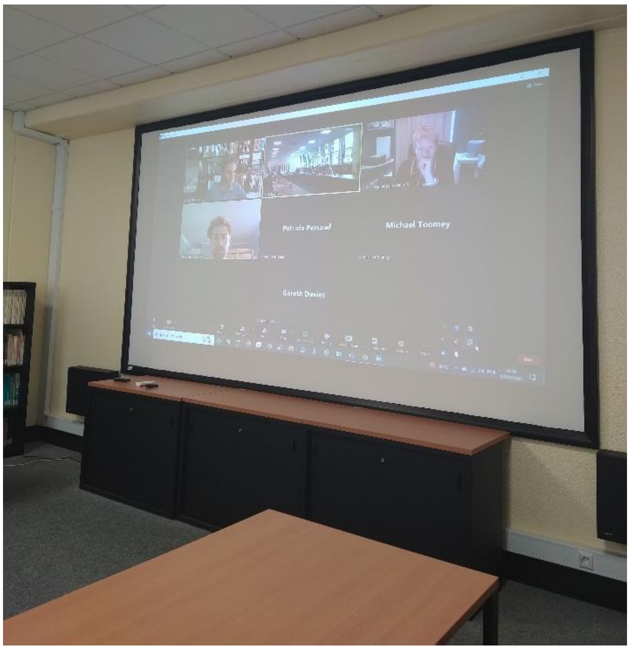

Figure 4. Some of our intrepid remote participants, some calling in from the USA and Australia.

Outcome and future plans

The working groups developed hypotheses and questions focused on three topics: climate and tropical cyclones; slope failure; and processes at active margins. These hypotheses and questions are planned to be used for drilling proposals to be developed for specific locations.

Climate and tropical cyclones

The climate and tropical cyclones working group agreed that the northern Gulf of Mexico presents the best location for answering questions about climate change and its influence on tropical cyclone frequency and intensity due to its overall thick sediment column and well-preserved sedimentary sections in minibasins and other features produced by salt tectonics.

Question 1: How have hurricane frequency and intensity in the Gulf of Mexico in the past 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). 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 variability in the Gulf Stream dynamics has on Gulf of Mexico storms. MSPs could be used to collect very high resolution storm and SST records from salt basins along the margin of the Gulf of Mexico spanning the Holocene and late Pleistocene. 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 the Gulf of Mexico.

Question 2: How have historic storms impacted oil and gas infrastructure in the Gulf of Mexico? Storm induced mudflows can severely damage offshore infrastructure leading to release of oil into the ocean. Sediment cores could be used to reconstruct the frequency of these events prior to rigorous monitoring and understand their impact on benthic communities.

Question 3: What impact has storm frequency had on precipitation and streamflow in the western Gulf of Mexico and southwestern United States? Hurricane Harvey (2017) dropped more than 60 inches of rain in parts of southeast Texas and storm-related precipitation is expected to increase as climate warms over the 21st century. Cores from the Gulf of Mexico have previously been utilized to look at large flood events on the Mississippi River (e.g. deglacial meltwater pulses) and salt basins offshore the mouth of the Rio Grande could be used to reconstruct hurricane driven flooding during past climate intervals warmer than present day such as the mid-Holocene or previous inter-glacials (MIS5e etc.).

MSP drilling to answer these questions could include:

1. long cores in several deep salt basins along the periphery of the continental shelf;
2. equipment to monitor development of mud flow events and establish modern analogs;
3. seismic survey of the continental shelf to map potential sediment source areas.

Slope failure

Hypothesis 1: The presence of similar preconditioning factors tend to cause submarine landslides to localize repeatedly at the same location through the Neogene. Preconditioning factors can include sediment properties, pore fluid pressure, fluid chemistry, mechanical stratigraphy, and oversteepening/slope angle. These can be investigated with piston cores down to 1000 m water depth in most cases. Required measurements include 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 2-axis caliper. Observatories can help establish trends in pore pressure, heat flow, and stress over time.

Hypothesis 2: Preconditioning factors are necessary but not sufficient for submarine landslides; an external trigger is needed. External triggers include earthquakes, storm wave loading, abrupt shifts in sedimentation, tectonic oversteepening, changes in ocean temperature, gas hydrate dissociation, volcanism, and diapirism. This hypothesis can be tested by recovering cores, fluid samples, and pore pressures to demonstrate that the slope in an area 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.

Hypothesis 3: 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. 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 in most locations.

Hypothesis 4: 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, so slope failure on an active margin would tend to require a large amount of sediment to accumulate between earthquakes. To test this hypothesis you need seismic data, core data to understand strength and sedimentation rate, and a good paleoseismological record. A drilling strategy to test this hypothesis would consist of a transect across an accretionary prism with perched basins that preserved mass transport deposits.

These hypotheses could be tested at many locations worldwide, but in particular we feel that the western North Atlantic margin would be a good target area for passive margin processes, while the Nankai Trough would be a good location to test active margin hypotheses. We note that a high-resolution 2D seismic survey is planned in 2023 across the Cape Fear and Cape Lookout submarine landslide complexes offshore North Carolina, USA, and that these data will be extremely useful for future proposals.

Active margins

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., Tohoku-Oki 2011; Iquique 2014) (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. Due to the high-noise ocean environment, the most viable tool to undertake this type of monitoring are 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). Highly active transform faults that are the site of frequently recurring moderate to large magnitude earthquakes, could also be ideal targets to investigate potential precursors through installation of borehole observatories. Amphibious experiments complementing the already existing infrastructure could be developed in the Marmara Sea. Salton Sea and the Gulf of California may also be potential sites, as a southward extension of the Parkfield network, but are complicated by transtensional deformation.

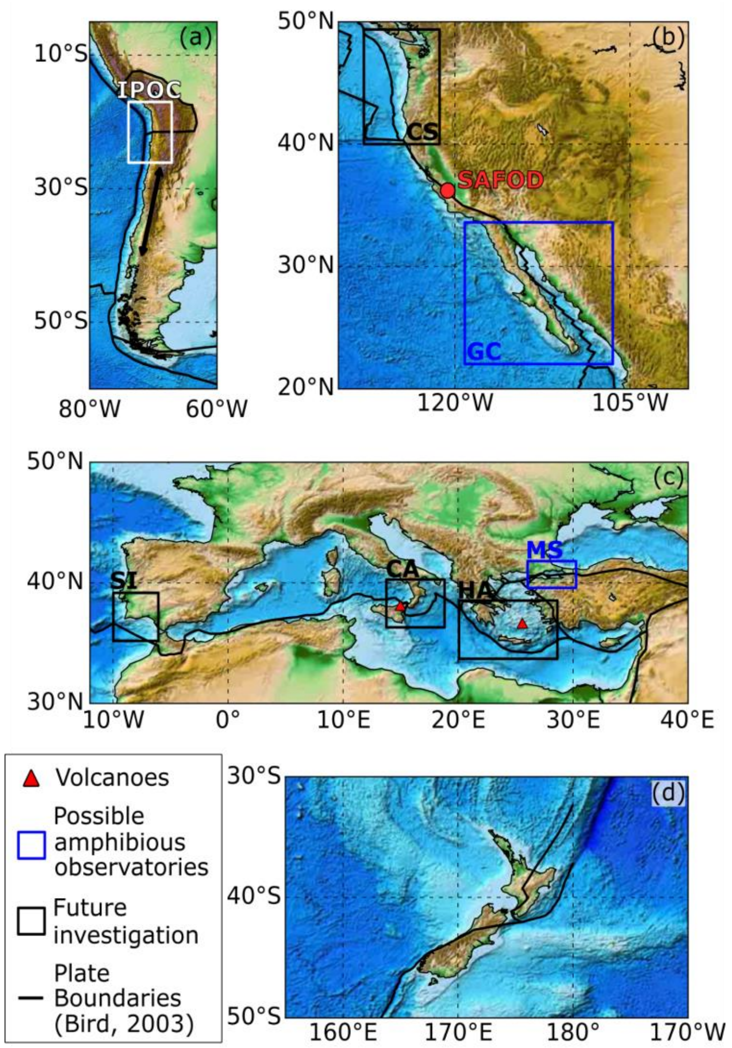

Figure 5. Priority study areas defined during the workshop include subduction zones, transform faults, oblique-slip (or transtensional/transpressional) systems and volcanoes. (a) The Chilean margin has been defined as a suitable location for a long-term amphibious observatory due to the wealth of available geophysical data onland. This includes diverse networks such as the IPOC observatory (white rectangle). The black arrow represents other areas where different geophysical arrays have been deployed by diverse institutions (e.g: IRIS, Servicio Sismológico de Chile, IPGP-CalTech, GFZ Potsdam) and availability of long-term (spanning 2-3000 years) paleo-tsunami and paleoseismology archives along the coast and inland lakes (e.g., Kempf et al., 2017, Moernaut et al., 2018, Wils et al., 2020). (b) The western margin of North America has the potential for developing an amphibious observatory, in particular in the Salton Sea and the Gulf of California (GC), as a southward continuation of SAFOD, taking advantage of the well-monitored San Andreas Fault system onland but recognising complexities of a transtensional system. The Cascadia subduction (CS) was also proposed as an area where data are available and future investigations are needed. (c) In and around the Mediterranean, the Marmara Sea (MS) was proposed as a potential site for an amphibious observatory, as a seaward extension of the present ICDP observatory. Other areas where further investigations are required due to potential geohazards include: southwestern Iberia (SI), the Calabrian arc (CA), and the Hellenic arc (HA). The Etna (Sicily) and Kolumbo (Santorini) volcanoes were also recognised as high priority regions, noting there is already drilling planned for Santorini. (d) The Hikurangi margin (New Zealand) was also proposed as a potential area for an amphibious observatory. The Mediterranean Sea, and the Hikurangi and Cascadia margins were also identified as priority locations in the 2015 Magellan Plus submarine paleoseismology workshop in Zurich (Strasser et al., 2015; McHugh et al., 2016).

Testing this hypothesis largely hinges on the installation of borehole observatories to observe precursory transients, preferably in arrays of several sites or more (rather than just two to three sites in a profile as is typically done). To identify the best subduction zone candidates, margins with the highest likelihood of large ruptures in the coming years to decades are the best candidates to do this. However, given that the chances of capturing a large event (and any precursory signals) is not guaranteed, any site that is chosen must also have additional scientific objectives that can be addressed by the observatories. These additional objectives could include determining the distribution of transient slip behavior on the shallow megathrust, and resolving the spectrum of transient deformation events, including recurrence, duration, magnitude, and spatiotemporal migration characteristics and relationship of these to seismic phenomena. It would also be advantageous to co-locate such observatory efforts with regions where onshore geophysical networks (seismic and geodetic) are well-established. Parts of the Chilean margin have a high likelihood of great earthquakes in the coming years to decades, and is also the site of onshore geophysical infrastructure, and existing offshore seafloor geodetic and seismic data acquisition by scientists in Chile and Germany (e.g: the Integrated Plate Boundary Observatory Chile -IPOC, https://www.ipoc-network.org/welcome-to-ipoc/). Central Sumatra also has large potential for a great earthquake (Konca et al., 2008), but is logistically more challenging. For other types of plate boundary faults, the GOFAR transform represents an outstanding opportunity, as it experiences Mw 6-7 events quasi-periodically every 5-6 years (McGuire, 2008), and capturing an event (or multiple events) would be highly likely in a 5-10 years time frame.

Hypothesis 2: 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. 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.

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.

Sufficiently detailed paleoseismological data may not be available, and earthquake cycles may be too long to compare directly observed interseismic periods. A more indirect approach is to understand the physical controls on coupling, and whether the controlling parameters change in time and space. Potential hypotheses then include:

1. **Fluid pressure controls coupling.** In this case, there should be differences in fluid pressure state between well and poorly coupled areas, with high pore-fluid pressure zones associated with poorly locked domains and vice versa (Moreno et al., 2014). This could be tested with geophysical techniques as well as drilling (for direct measurement of fluid pressure, observatories to monitor fluid pressure over time, and sampling to calibrate models of permeability, porosity, seismic velocity, etc). In this case, coupling patterns are only persistent on the same time-scale as fluid pressure distribution is persistent.

2. **Downgoing plate roughness controls coupling.** Smooth seafloor has been related to large earthquake rupture areas and large magnitude earthquakes (reviewed in van Rijsingen et al., 2018). Conversely, rough subducting seafloor has been correlated with limited earthquake magnitudes (Ruff, 1989; Wang and Bilek, 2011). While this hypothesis is probably best tested with detailed geophysical imaging, drilling can serve to ground-truth interpretations of geophysical data and provide samples to calibrate physical properties. The hypothesis that smooth, commonly sediment-covered, subducting seafloor promotes large events also implies the presence of a persistent, localized, rupture plane, and drilling may allow sampling of either a shallow part of such an interface, or more likely, target the equivalent material in the input sequence and test whether the physical and frictional properties are consistent with earthquake slip at appropriate conditions.

3. **Rock's physical properties control coupling.** The seismogenic potential of fault rocks is highly dependent on their composition and physical conditions at depth, including temperature and pressure. However, additional factors controlling their velocity-strengthening behavior (aseismic slip) or velocity-weakening behavior (seismic slip) are grain size, mineral assemblages and the presence of fluids/volatiles (Scholz, 2019; Chen at al., 2013). If there is sufficient geophysical constraint (e.g. reflection seismic) to identify the active plate interface and trace it to the incoming sequence, then drilling may provide direct control on plate interface composition (e.g. past drilling in Nankai, Sumatra, Hikurangi, and Costa Rica), and allow testing whether there are compositional differences and/or changes on the physical conditions between well and poorly coupled areas. Deformation experiments on incoming materials, at appropriate conditions, can also test whether different materials will have different frictional properties that may explain coupling characteristics (e.g. Boulton et al., 2019; Ikari et al., 2013; 2018; Rabinowitz et al., 2018; Shreedharan et al., 2022). Such experiments may also be used to test whether the frictional properties (and by inference coupling characteristics) may change in space and time as conditions (such as fluid pressure or velocity) change.

Hypothesis 3: 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, to changes in upper plate/lower plate properties and/or geometrical changes, stress heterogeneity, and the presence of positive relief structures such as seamounts. However, no conclusive evidence exists 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 current 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 sites 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.
A recent study showed that lakes are capable of separating imprints resulting from earthquakes that were only hours apart (Wils et al., 2021), thus showing their potential to distinguish between rupture cascades and through-going ruptures for megathrust earthquakes. Addressing the question of rupture boundaries will also aid in evaluating the variability in fault coupling characteristics over time, as well as the identification of potential cyclic behavior of megathrust earthquake recurrence over multiple timescales.

Depending on the proxy used (e.g. turbidite records), testing this hypothesis would require multiple drilling or piston-core sites. Some records (e.g. offshore Tohoku) have not only a layer of remobilized coarse-grained sediments, but they are actually detailed enough to record finer layers corresponding to aftershocks (Kioka et al., 2019a, b, Strasser et al., 2019). So the largest earthquakes may actually be represented by a cluster of event layers, not one layer only.

Needs for a potential drilling location for hypothesis 3:

i) Need to have historic earthquake records that show earthquake boundaries.

ii) Importance of geophysical data and hence physical explanation for why a boundary is there and that it is likely to have been persistent over 1000 yrs.

iii) 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.

iv) A straight margin to avoid complications of changes in fault geometry (unless testing the role of plate margin geometry on arresting earthquake rupture is one of the hypotheses).

Potential target for hypothesis 3: The South American subduction zone is the largest by area (Slab 2 model, Hayes *et al*., Science, 2018), potentially able to generate the largest earthquakes. This margin generated the largest earthquake recorded instrumentally in 1960 (Valdivia, Chile, moment magnitude M_w=9.6). Numerical models suggest that this margin has the potential to generate a largest maximum magnitude earthquake of up to M_w=10.0 (Graham *et al*., 2020). Other magnitude 9+ earthquakes in the historical and geoarcheological record attest the high frequency of such giant earthquakes along this subduction zone, e.g. M_w=9.1-9.3 in 1730 (Carvajal *et al*., JGR, 2017), and M_w~9.5 ca. 3800 B.C. (Salazar *et al*., *Science Advances*, 2022) making the South American margin a good candidate for this effort, pending on the availability of proper sedimentary deposits offshore and onshore. Part of the Chilean margin has been sediment-starved due to the dryness of the onshore climate (e.g. Ranero et al., 2006), and further input from the marine community is required in order to assess its true potential. In any case, the offshore records should be complemented by others gathered in fjords or lakes along the continent, as these have proven to be very successful in the southern part of the subduction zone, i.e., along the Valdivia segment (e.g. Moernaut et al., 2018, Wils et al., 2020).

Additionally, it would be useful to directly explore the present-day physical conditions of the proposed barriers along the South American margin, in order to understand why they acted as a termination for rupture propagation in recent events. For example, if a spreading ridge is being subducted, anomalously high temperatures are expected close to the ridge axis and could propagate up to the upper plate. Such thermal anomalies could affect the rheological behavior of both the subducting and the overriding plate, creating a “boundary” in terms of the physical conditions for brittle deformation and energy liberation in the form of an earthquake.

Hypothesis 4: Subduction earthquakes are cyclic at multiple time scales. The 2011 Mw 9.0 Tohoku-Oki Japan earthquake occured in an area where scientists, up to then, did not believe such large ruptures could take place (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.

Current analysis of megathrust seismic cycles mostly rely on the behavior of identified subduction zone segments (i.e., bounded by persistent rupture boundaries). These can be subdivided into several subsegments (i.e., asperities) that can either rupture individually or together in single earthquakes or earthquake sequences. Recent and historical earthquakes along various subduction zones (e.g., Nankai-Suruga Trough in Japan; Garrett et al., (2016); Valdivia segment in Chile; Wils et al. (2020)) support these interpretations, showing the occurrence of partial ruptures affecting any possible combination of neighboring asperities, rupture cascades and full-segment ruptures that rupture all asperities in a single major event (e.g. 1960 Valdivia earthquake, Chile). In most subduction zones, a variable rupture mode can be inferred from paleoseismic records. Contrary to the characteristic earthquake model, subsequent earthquakes along a similar portion of the subduction zone are thus not necessarily similar in extent and magnitude. Additionally, the succession of events can strongly vary between subduction zones. Some are characterized by the occurrence of temporal clustering of similar events, others by superimposed cycles or various other types of 'supercycles' (Philibosian and Meltzner, 2020). However, the timescale of this cyclic behavior typically exceeds that of historical records or even that of the currently available paleoseismic records. In order for probabilistic seismic hazard assessment to be reliable, long-term (multi-centennial) paleoseismic records are thus required. Moreover, this underscores that the largest event along any particular subduction zone might still remain obscured with our current knowledge.

This is related to the previous hypotheses, as it is unclear if inferred segment boundaries are persistent, and to what degree coupling along the various asperities varies in space and time. 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. Also, Poissonian behavior for earthquake recurrence (i.e. large earthquakes can occur any time with a low but on average constant probability (Mulargia et al., 2017)) as an alternative hypothesis to the earthquake-physics-based characteristic earthquake or supercycle hypothesis, cannot be confidently rejected if the long-term record does not span at least ~ 15 averaged recurrence intervals (Moernaut 2020). Thus, 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: This leaves 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.

Similar target areas as for the previous two hypotheses related to subduction earthquake occurrence can thus be considered to address the issue of cyclic megathrust behavior.

Long-term outlook- enigmatic subduction margins that need future investigation

Hellenic Trench and Calabrian Arc

We have identified the Hellenic Trench and Calabrian arc as areas that urgently require characterisation. The Hellenic Trench and Calabrian arc pose a very significant seismic hazard to populations of millions around the Mediterranean. The historical record and records of coastal uplift indicate that large historical earthquakes have occurred, yet almost nothing is known of the present-day coupling or the longer-term earthquake record. We suggest that the community focus on characterizing these areas using geophysical data (e.g. geodetic data, offshore pressure sensors, seismic reflection) to put them in a good position to be further investigated with ocean drilling in the future.

Southwest Iberian margin
The Southwest Iberian Margin (SWIM) is an area worthy of further characterisation. This seismically active region poses a significant geohazard risk for Europe, northern Africa and the American coasts. This was the locus of the Great Lisbon Earthquake of 1755 with an estimated magnitude of ~8.7 that produced a transoceanic tsunami. In 1969, another magnitude ~8 event hit the same region. This area encompasses the accretionary wedge of the Gibraltar subduction zone and several other major structures to the west that have been proposed to correspond to the location of an incipient subduction zone in the Atlantic (e.g., Duarte et al., 2013). Despite its interest, many geological aspects are still unknown. A structure capable of generating a 1755-like event was never identified, and the epicenter of the 1969 earthquake was located on a flat abyssal plain. The long-term stratigraphic record of paleo-seismology is fairly unknown, particularly on the distal regions. Yet, the abyssal plains and seamount flanks record numerous recent and ancient mass-wasting events ultimately associated with regional tectonics. Ocean drilling missions are thus crucial to unravel the long-term history of this hazardous margin.

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).

There are a number of reasons why we might expect fault slip rates to vary over different timescales: i) Short term slip rates may be biased by recent earthquake clusters, ii) Slip rates may vary through time due to fault growth, linkage and interaction within fault networks (e.g. Cowie et al. 2017), and iii) There may be real variations in larger-scale tectonics that are reflected in varying fault slip rates. Although there are a number of examples in the literature of studies that compare long term geological (100’s kyr -Myrs averaged) slip rates with modern geodetic (years to decades) rates there are few (any?) examples that reveal how fault slip rates change on the full range of scales from < 1 yr to kyrs to Myrs.

The shortest term slip rates, < 1 yr to 10s yrs timescales, can be calculated using satellite methods that measure surface deformation (e.g. GPS, InSAR). Paleoseismology both in terms of onshore trenching and offshore core analysis can provide information on slip rates on the 100s yr to 10,000s yr timescales. Onshore, uplifted features such as wavecut notches, platforms and marine terraces can sometimes be dated and used to provide estimates of uplift rates, which can be converted to slip rates over timescales of 10s kyr to 100s kyr. Offshore, subsidence markers such as lowstand shorelines can be used to calculate subsidence rates, which can be converted to slip rates or used directly with onshore estimates of uplift rate to calculate slip rates (e.g., Bell et al., 2009). Offset of basin stratigraphic horizons imaged in seismic reflection data can provide information on slip rates on 100s kyr to Myr time scales, and potentially 10s kyr if seismic data have sufficient resolution and age constraints.

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:

1. 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. This approach has been used as part of the Corinth Rift drilling expedition using dated materials in boreholes and a high resolution seismic network (IODP 381; McNeill et al., 2019; Nixon et al., in prep.). A similar approach was used onshore on the Hetao normal fault system, northern China, for sediments dating from the last 65 kyr (Xu et al., 2022). This study used uplifted terraces in the fault footwall and a series of boreholes drilled up to 300 m below ground surface into the hanging wall to enable horizon dating and correlation across the fault.

2. A submarine paleoseismology approach, identifying evidence of individual earthquake slip events (e.g., a sediment wedge generated on the fault hanging wall post-event, commonly observed in terrestrial paleoseismology fault trenches) in high resolution seismic data with ground truthing of age and timing. This method has been developed and applied by Barnes and Pondard (2010) on the offshore Wairau fault, New Zealand, but using seismic interpretation of a single post-transgressive surface rather than direct ground truth for age control.

3. An onshore-offshore approach for comparison of slip rates over different timescales on an active normal fault. This would use onshore uplifted geomorphic features with radiocarbon or cosmogenic nuclide dating methods to quantify more recent fault activity (10s kyr), coupled with offshore drilling to capture the stratigraphic record of longer-term activity. In both cases, the uplift (footwall, short term) or subsidence (hanging wall, long term) component could be used with estimates of the uplift:subsidence ratio to estimate slip rates and therefore how slip rates have changed over time. In some cases independent values of uplift and subsidence could be used to quantify the uplift:subsidence ratio.

In most cases, these methods would be most straightforward for normal fault systems. These methods would be more challenging in terms of shallow fault zone structure and geometry for reverse/thrust fault systems, and challenging for strike-slip faults as lateral displacement has to be resolved (for oblique slip systems a combination of seismic, coring and seafloor geophysical imaging would work well, but other technique combinations may be more efficient for evaluating slip rates).

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.

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 & 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 do 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 Hypothesis 5 above) and how earthquake slip builds up to fault slip over longer timescales.

Empirical relationships have been developed between fault length (L) and displacement (D) (see Kim and Sanderson 2015 for a review), and the broadly linear, positive correlation between these parameters together with a consideration of the mechanics have led some authors to propose that faults grow by a synchronous increase in length and displacement (the "*Propagating*" fault model)(Walsh & Watterson, 1988). The analysis of fault growth strata observed in 3D seismic reflection data has, however, led to the proposition of a different model, the "*Constant length*" model, where faults establish their length very quickly and then accrue displacement on a fault which maintains a near-constant length (e.g. Meyer et al. 2002, Walsh et al. 2002).

In order to i) characterize how complex, incremental earthquake slip patterns ultimately develop into the long-term relatively simple and stable displacement patterns we see for ancient faults on geological timescales, and ii) determine how faults grow laterally, requires observations which span the 10^3-10^6 yr timescale, between modern geological/seismological observations and Myr averaged observations from seismic reflection data in rifts.

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 10's kyr scale, and hence how slip has accrued along different parts of the fault.

A drilling/piston coring campaign with the geometry outlined in Fig. 6 would provide a direct test of the "*propagating*" vs "*constant length*" fault models. Pairs of drill/core sites providing high resolution age constraints and horizon correlation on either side of a well characterized fault would allow expansion indices between the thickness of sediments in its footwall and hanging wall to be calculated along its length and sub-seismic-reflection scale episodes of thickening and fault activity could be investigated. If sufficient resolution is available, this could provide information on the recurrence of individual earthquakes or whether earthquake clustering occurs. If hanging wall sediment thickness is observed to increase at the tips of the fault later than in the fault center, this would point to the propagating fault model and lateral fault propagation rates could be established (Fig. 6a). Conversely, if hanging wall sediment thickness increases at both the tips and center of the fault for the earliest stage of faulting (e.g time period t_1 in Fig 6b) this would point to the constant length model.

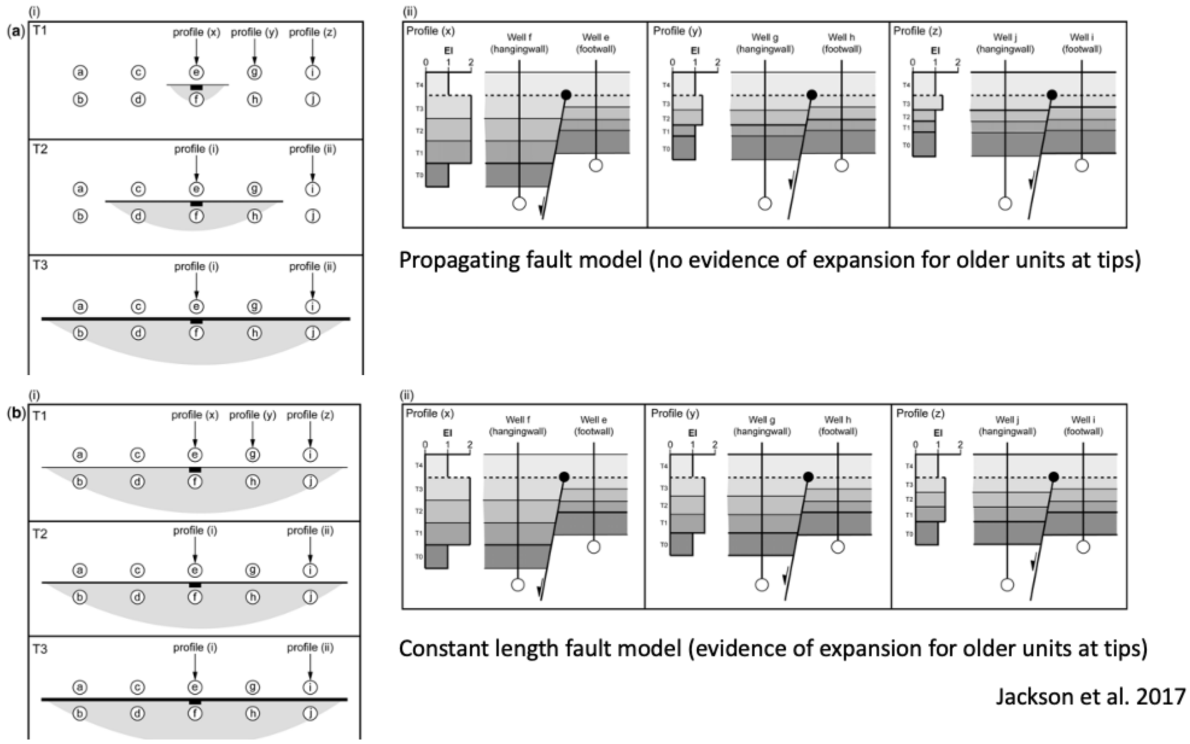

Figure 6. A possible drilling/coring strategy to test the Propagating fault model (faults grow by increases in their length and displacement at the same time) vs Constant length fault model (faults grow long very quickly and then accrue their displacement with a nearly constant length). After Jackson et al. (2017).

An ideal location to conduct such a drilling/piston coring experiment would require, i) high sedimentation rates to provide a rich sedimentary record of faulting and high temporal resolution, ii) a young fault where growth strata are shallow, iii) 3D or pseudo 3D seismic reflection imaging allowing correlation of 10s kyr or ideally kyr horizons along the length of and across the fault.

Locations that could be considered for such an experiment include:

The Gulf of Corinth, Central Greece- IODP Expedition 381 in the Corinth Rift, Greece (Shillington et al., 2019; McNeill et al., 2019) capitalised on an existing dense seismic network with horizons and faults already interpreted and correlated around the rift basin (Nixon et al., 2016). The aim of drilling integrated with the seismic data was to resolve a fault network at a resolution of 100-1000 m and with age resolution of 10 kyr. On the southern margin of the Gulf of Corinth a very young fault, the Aigion fault, has been imaged offshore by a pseudo-3D grid of high-resolution seismic data. Existing interpretations suggest the fault has grown in < 200-300 kyr (McNeill et al. 2007). A targeted drilling/coring campaign on this fault, similar to that shown in Fig 2 would provide valuable further age-constraint for existing seismic interpretations but also potentially hanging wall-footwall pairs of cores would reveal sediment thickness changes below the limit of seismic resolution to allow fault evolution to be reconstructed at the 1000's yr time scale.

Whakatane Graben, New Zealand- the youngest rift in the Taupo Volcanic zone has been seismically imaged in detail and existing seismic interpretations reveal interesting fault evolution patterns (Taylor et al. 2004). However, many of the horizons used in these interpretations would benefit from improved age constraints.

Outer rise normal faults- Subduction margins are the location of some of the largest and most dangerous normal faults on Earth. These structures result from flexure of the downbending subducting plate and are a significant tsunami hazard. They are a potentially good target for investigating both normal fault evolution and also improving our understanding of this somewhat neglected subduction margin geohazard.

Hypothesis 7: Tectonic activity influences the timing of volcanic eruptions. Active submarine volcanoes are linked to several of the most deadly geohazards such as tsunami, earthquakes, landslides, pyroclastic material, and gas release. However, they present difficult drilling conditions as they are covered by thin microbial crusts, they have active hydrothermal systems and they have unstable slopes. MSP can be the ideal way to go forward.

Volcanic activity can be linked to tectonic activity in that an increase of seismicity along nearby located faults can trigger a period of more intense volcanic eruption through the development of preferential pathways to magma ascent. On the other hand, magma ascent can trigger 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. Eruptive volumes and magma fluxes can also be influenced by tectonic activity. Large tectonic events recorded in sedimentary basins, like onlap surfaces, big seismogenic turbidites, homogenites, can correlate with activation/deactivation of the different volcanic centres, changes in eruptive style and particularly large explosive eruptions. Sampling rarely accessible silicic submarine volcanoes can help build a tectonic model for their formation.

Integration of paleoseismic and tephracronological 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.

Kolumbo submarine volcano, 7 Km NE of Santorini, is an ideal location because of its accessibility, active vent fields, IODP Exp 398 (Druitt et al., 2022), high hazard potential, nearby seismically active - in historical times - marginal faults, and dense onshore seismic network are (or will be) available for site survey.

Another potential system would be Etna in southern Italy where the normal faults to the east, one of them responsible for the 1908 Messina EQ and tsunami, are interacting with the volcanic activity. Also Etna has good accessibility, high hazard potential, dense network of monitoring instruments.

Other subduction margins with long onshore records of past eruptions and previous IODP drilling and piston coring that can provide turbidite (earthquake) and tephra records to underpin a more extensive proposal are the Japan Trench (Ikehara et al. 2016; Mahony et al., 2016),the Hikurangi subduction zone (Mountjoy et al., 2017; Hopkins et al., 2021), and the Central and South American margins (as targeted in upcoming Magellan+ VOCS Workshop, IODP proposal 1000). These margins are also excellent targets for addressing many of the earthquake cycle-related hypotheses in this report using long piston cores to acquire longer records of subduction earthquake processes. A proposal at one of these margins (or other margins with similar prospects for addressing earthquake and volcanic interactions) could benefit from addressing the earthquake cycle-related hypotheses outlined previously, in concert with hypotheses around the influence of earthquakes on eruptive events, as the same cores could be used to address both.

Table 1. Summary of the potential sites for investigating the different active margin hypotheses (H) identified in the workshop.

	H1	**H2**	**H3**	**H4**	**H5**	**H6**	**H7**
Potential short-term locations							
Chilean margin (potential observatory)	X	X	X	X	X	X	X
Marmara Sea (potential observatory)	X	X	X		X	X	
Salton Sea and the Gulf of California (potential observatory)	X	X	X		X	X	
Kolumbo submarine volcano (NE of Santorini)							X
Etna volcano							X

The Gulf of Corinth						X	
Whakatane Graben (NZ)						X	
Identified locations from the paleoseismology workshop (McHugh et al., 2016)							
Mediterranean sea		X	X	X			
Hikurangi margin	X	X	X	X	X	X	X
Cascadia margin		X	X	X			
Potential future locations that might contribute to these hypotheses							
Hellenic arc	X	X	X	X			X
Calabrian arc			X				X
Southwest Iberian margin	X					X	

Active margin conclusions
The workshop discussions recognized the growing needs of highly populated regions along subduction zones and other tectonically active or hazardous settings for better assessment of earthquake, 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. 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. Priority sites for the near future are the Chilean margin, Marmara Sea, and the Salton Sea and the Gulf of California.

Other sites with high hazard exposure include regions around the Hellenic and Calabrian arcs, the Southwest Iberian margin, as well as the Cascadia and Hikurangi margins. Further geophysical investigation is required at these locations in order to develop a future IODP proposal. These sites have a very good potential for answering some of the previously posted hypotheses.

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List of participants

Given name	Surname	Early career	Affiliation	Country	Virtual?
Organizers					
Hugh	Daigle		University of Texas at Austin	USA	
João	Duarte		University of Lisbon	Portugal	Yes
Ake	Fagereng		Cardiff University	UK	Yes
Raphaël	Paris		Université Clermont-Auvergne	France	*
Patricia	Persaud		Louisiana State University	USA	Yes
Keynote speakers					
Becky	Bell	Senior lecturer	Imperial College London	UK	
Gareth	Davies		Geoscience Australia	Australia	Yes
Paraskevi	Nomikou		University of Athens	Greece	
Margaret	Stewart		British Geological Survey	UK	Yes
Michael	Toomey		U.S. Geological Survey	USA	Yes
Caroline	Ummenhofer		Woods Hole Oceanographic Institute	USA	
Laura	Wallace		GNS/University of Texas at Austin	USA	
Other participants					
Tiago	Alves		Cardiff University	UK	
Fernando	Barriga		University of Lisbon	Portugal	
Julia	Carvalho	Phd Student	University of Pisa/University of Florence	Italy	
Yu-Chun	Chang	PhD Student	University of Manchester	UK	
Davide	Gamboa	Postdoctoral Researcher	IPMA/IDL	Portugal	
Ángela María	Gómez García	Postdoctoral Researcher	GFZ German Research Centre for Geosciences	Germany	
Álvaro	González	Postdoctoral Researcher	CRM Centre de Recerca Matematica	Spain	
Achim	Kopf		MARUM, Univ. Bremen, Germany	Germany	
Holger	Kuhlmann		MARUM, Univ. Bremen, Germany	Germany	
Erwan	Le Ber		University of Montpellier	France	Yes
Lisa	McNeill		University of Southampton	UK	
Uisdean	Nicholson	Assistant Professor	Heriot-Watt University	UK	Yes
Michael	Strasser		University of Innsbruck	Austria	
Mary	Thompson	MS Student	Texas A&M University	USA	
Paola	Vannucchi		Universitá di Firenze	Italy	
Katleen	Wils	Postdoctoral Researcher	Ghent University	Belgium	

*was unable to attend due to scheduling conflict