Multi-frequency Imaging of the Sunda Trench: A Scientific Research Proposal

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(Dated: 17 September 2013)

SUMMARY

We propose a 10 science-day cruise to collect data critical to improving our understanding of earthquake, tsunami and climate-related hazards in Indonesia. The Mentawai patch of the Sumatran section of the Sunda Megathrust is a seismic gap that has produced great ($M_w > 8$) earthquakes in historical times and is the largest unbroken segment of the Sumatran subduction zone. We propose to collect high-resolution multi-beam swath bathymetry and sub-bottom CHIRP profiling data along both recently broken and unbroken segments of the subduction zone. We also propose to acoustically image a segment of the backthrust with the goal of assessing the recent deformation and tectonic activity and to collect shallow sediment gravity cores for tectonic and paleoclimate assessment.

We expect the data collected on this cruise to help elucidate the structural setting of the megathrust. Characterization of shallow features in the region that ruptured during the 2010 Mw7.8 Mentawai earthquake will shed light on the efficient mechanisms of tsunami generation by large earthquakes on the subduction front. Geomorphic interpretation and stratigraphic correlation of the Mentawai fault will help infer recent seismic history and behavior. These measurements will be critical to better define seismic hazards along this section of the megathrust.

Some data will also serve as a pre-event baseline to a subsequent survey following a large earthquake in the same region. The value of such repeat surveying and interferometric processing techniques has been demonstrated to uniquely constrain the trench-proximal deformation for the Mw9.0 Tohoku-Oki event. These data would provide unparalleled measurements of shallow coseismic slip, and would allow us to better understand the dynamics of subduction earthquakes and the generation of tsunamis.

We propose a student-led cruise with international collaborations from 3 partner institutions in the US, Indonesia and Singapore. 11 University of California PhD Students, 4 Indonesian, and 8 EOS students will perform the bulk of the data collection, processing and geophysical interpretation. Thus, the benefits of this research cruise go beyond scientific investigation, and include a large social component. Our project fosters international collaborations and provides a unique opportunity of learning for students. Young investigators will be exposed to geophysical research (in one of the most interesting tectonic regions of the world) and be uniquely prepared to continue exploring the oceans during their career.

I. SOCIAL MOTIVATION

The primary motivation of this research is to foster scientific cooperation amongst research institutes in the region and partner universities in the US. The ship time is funded through the **University of California Ship Funds** program, which allows graduate students to propose and lead marine scientific research expeditions. This particular mission, the Multi-frequency Imaging of the Sunda Megatrhust (MIST), is led on the U.S. side by 4 Ph.D candidates from the Scripps Institution of Oceanography at the University of California, San Diego.

Thus, from its conception and at its core this mission has as its main objective to prepare the next generation of graduate students to lead pioneering scientific expeditions. It is recognized that the scientific goals must be accompanied by partnership with national and regional research institutions. As such this proposal involves significant cooperation with a national research institutes (Research Center for Geotechnology – Indonesian Institute of Sciences, University of Bengkulu) and a regional partner (Earth Observatory of Singapore – Nanyang Technological University). The 4 partner institutions have agreed through a memorandum of understanding (MOU) and a further implementation agreement (IA) to collaborate not only with the goal of furthering knowledge but also of preparing their students for future challenges in the field of Earth science and forging strong and long-lasting bonds in the region.

A total of 11 graduate students from the University of California, 4 from the Research Centre for Geotechnology and the University of Bengkulu and 8 from the Earth Observatory of Singapore will be participating in the expedition. The science plan has been entirely devised by the students and all of the data acquisition, processing and interpretation will be carried out by them. At the end of the cruise we expect that the students from the 4 institutions will all be competently trained in the acquisition of marine acoustic data (swath bathymetry and sub-bottom profiling) and collection of shallow sediments through gravity coring. These are important and recurring techniques that should be part of the fundamental toolkit of any marine geoscientist.

Furthermore, while on the cruise the data will be reviewed with the aid of senior scientists from all 4 institutions with experience in interpretation. This means that the students will practice the full cycle of scientific investigation, from data collection to post-processing, to geological interpretation. To further prepare all students and expose them to international research, we will hold regular short seminars while in transit. Students will be asked to give brief presentations about their work and discuss their scientific interests. We believe expeditions such as this one will not only prepare the students, but also foment long-lasting research bonds between them. It is our goal to foster long-term cooperation as the students move from the doctorate and into research positions worldwide. Similarly as has been delineated in the MOU and IA, all scientific publications that result from this research will be performed jointly between all the partner institutions. We recognize we are equal in this endeavor and we strive to work for our mutual benefits.

We also recognize that it is of the utmost importance that scientific expeditions such as this one acknowledge the social background in which they happen. To this end we also propose to devote one of our science days to have an open ship event in or near the port of Padang. This outreach opportunity will focus on the local government and selected general public as well as representatives of the US government in Indonesia. The event will inform the audience about the research goals of the cruise and their relevance to natural-hazard resilience in Indonesia and to demonstrate the vibrant spirit of cooperation between the research institutes home countries.

II. SCIENTIFIC MOTIVATIONS

A. Seismic and tsunami hazards

A first goal of the research cruise is to collect critical data from a seismically active region to better understand the underlying mechanisms behind earthquake and tsunami hazards.

Near Sumatra, the north-south convergence between the Australian and Eurasian plates is accommodated by subduction of the ocean plate beneath Sumatra along the Sunda Megathrust and its splay faults, and horizontal motion along the Sumatran Fault. After about 170 years of relative quiescence, the Sunda Megathrust generated a sequence of large earthquakes during the last decade. In 2004, a moment-magnitude (Mw) 9.15 earthquake ruptured the plate boundary from Banda-Aceh in northern Sumatra to the Andaman Islands in India (Bilham, 2005; Chlieh et al., 2007; Subarya et al., 2006), generating a tsunami that devastated coastal regions all around the Indian Ocean, taking the lives of more than 230,000 people, and leaving in its wake tremendous economic disruption. The sequence continued southward with the 2005 Mw 8.6 Nias earthquake and tsunami, which killed more than 1,300 people (Hsu et al., 2006), and the 2007 sequence of Mw 7.9 and Mw 8.4 ruptures (e.g., Konca et al., 2008) that displaced 30,000 people, creating a risk for disease outbreaks. These great earthquakes also produce a transient change in relative sea level that affects the coastlines of neighboring countries. More recently, the 2010 Mw 7.8 Mentawai earthquake ruptured a near-trench patch of the megathrust (Hill et al., 2012; Lay et al., 2011; Newman et al., 2011), generating a large tsunami that devastated the Mentawai Islands, Indonesia, killing more than 500 people.

This temporal cluster of great-to-giant earthquakes has increased the likelihood of great earthquakes in adjacent regions. Up to now, the largest unbroken section is the Mentawai segment of the Sunda Megathrust, which last ruptured during the 1797 Mw 8.8 and the 1833 Mw 9.0 earthquakes (Fig. 1). The partial rupture of the Mentawai segment in 2007, 2009 and 2010 relieved only a fraction of the slip deficit accumulated since the event that occurred in 1833 (Konca et al., 2008). Currently the greatest and most imminent seismic hazard in the region thus comes from this segment (e.g., Nalbant et al., 2005).

A major unknown relating to seismic and tsunami hazards along the Sunda Megathrust is the role of the Mentawai Fault. Originally identified as a strike-slip fault (Schluter et al., 2002), recent active-source studies (Singh et al., 2010, 2011; Mukti et al., 2012) interpret it as a steeply dipping backthrust. Wiseman et al. (2011) also showed that during 2005 and 2009 a cluster of events with a cumulative magnitude of Mw 6.9 was most likely produced on this backthrust. Fault slip on the backthrust would cause vertical displacement of the seafloor that would be an efficient mechanism to generate a large tsunami. Additionally, as the backthrust is closer to the mainland than is the megathrust, travel time to the mainland would be significantly reduced. It is thus important to better understand this structure and characterize its recent activity to better assess hazard vulnerability of the Sumatran coast line.

Recent work in heavily instrumented regions has shown that many aspects of the fault evolution, such as the location of microseismicity, the position of hypocenters of large earthquakes and the patterns of surface displacements due to recent earthquakes can be explained in a single simulation (Barbot et al., 2012). These advances in comprehensive modeling of seismic phenomena make observations of the Mentawai patch very appealing to test the applicability of these models to subduction zones. The model would allow us to explore what scenarios of future seismicity are possible, based on theoretical knowledge of fault and rock mechanics, and past observations.

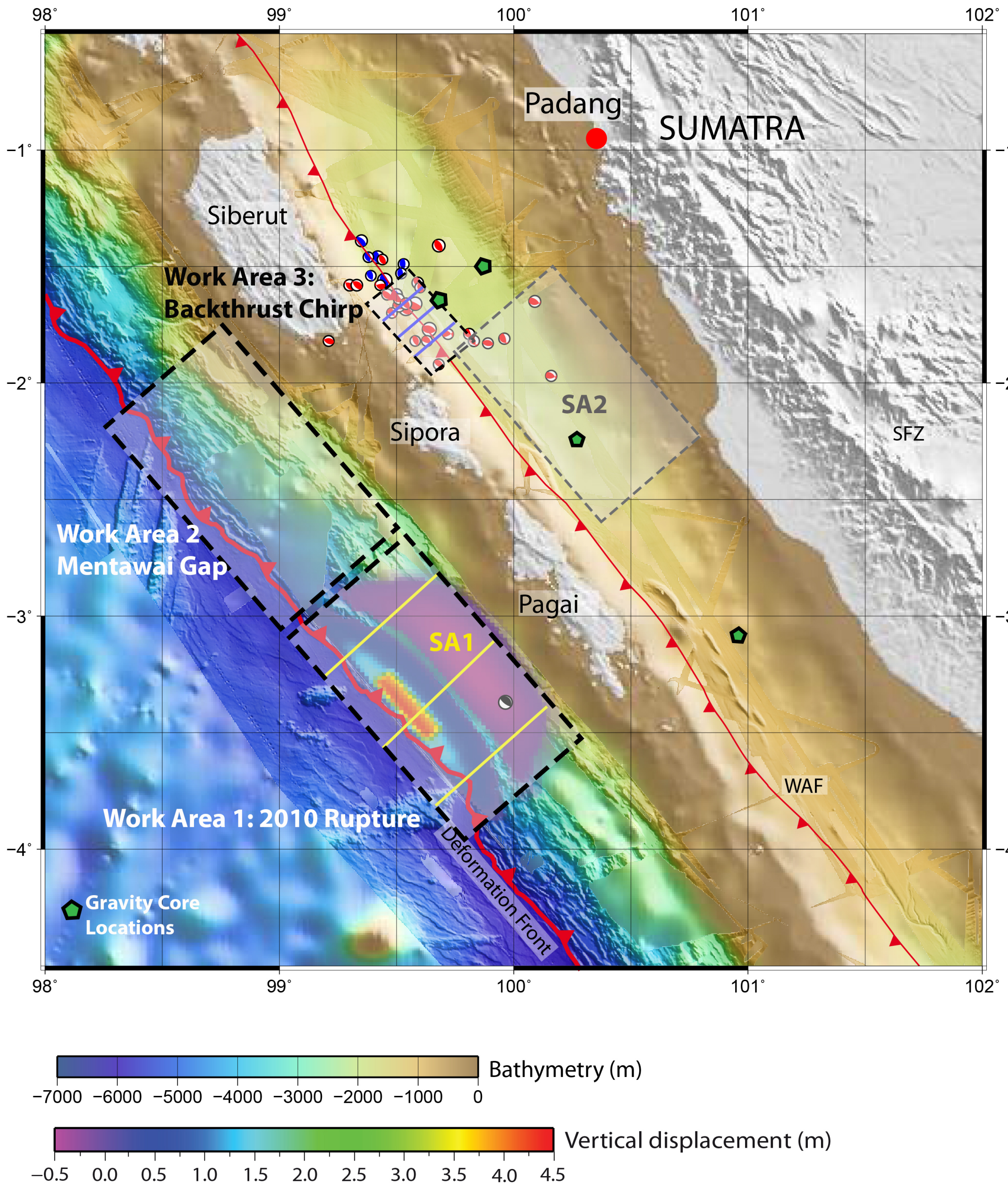

FIG. 1. Tectonic framework and proposed study area. The plotted bathymetry is currently available high-quality multi-beam data from rpevious expeditions. The 3 proposed worka reas are shown. **Work area 1** is the site of the 2010 tsunami earthquake, also plotted is the computed seafloor deformation from the earthquake (Hill et al., 2012) which we will map in detail. **Work area 2** is the unbroken segment of the megathrust, also known as the "Mentawai gap". **Work area 3** is the segment of the backthrust with recent clusters of activity (plotted in red and blue) in 2005 and 2009. The supplemental activities to be assessed during the cruise are **SA1** which is collection of high quality chirp on the deformation front of the 2010 earthquake and **SA2** which is bathimetric mapping of unmapped areas in the Mentawai basin.

Several physical models may explain the data equally well while producing different predictions, and this can be addressed by a suite of models that inform us of the possible range of future seismic behavior. By providing quantitative predictions, such as maximum peak ground acceleration, tsunami height, or relative sea-level change, this analysis can form the basis of more informed decisions and better planning for earthquake resilience and survival around the Indian Ocean.

Recently, Lay et al. (2012) proposed a model for subduction zones with depth-varying frictional properties that could potentially explain the breadth of seismic behaviors typically observed (Figure 2). The data collected on this cruise would allow us to expand this model and incorporate more realistic fault geometry and to better identify lateral variations of fault friction properties, including mapping of the location of persistent barriers that limit the propagation (and eventual size) of earthquakes.

B. Paleoclimate

Understanding climate change is particularly important for Southeast Asian countries because sea-level change may affect its coastlines and threaten food security and coastal infrastructure. There are a number of modes of climatic variability within the Indian Ocean region. The Indian Ocean Dipole (IOD) operates on interannual to decadal timescales, and may experience some influence from the Pacific-dominated El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). The IOD has been shown to significantly affect the strength of the monsoon season and assessment of its past contributions can help to better understand its future behavior. These modes have been documented fairly well over the last century, but having a record of the strength of variability through the past 20,000 years or so would provide invaluable data regarding the evolution of the Indian Ocean region's climate since the Last Glacial Maximum (LGM). Thus we propose to obtain sediment cores along the Sumatra/Mentawai margin. Equatorial regions around the Indian Ocean represent a large data gap for paleoclimate studies and the data collected on this cruise will significantly expand the global database, allowing for new regional analyses.

Assuming that we are able to collect a suite of useful sediment cores, proxy information from microfossil analysis of foraminifera (which determines past water temperatures) will help to answer a number of open questions regarding the evolution of Indian Ocean climate dynamics since the LGM. By translating oxygen isotope data to temperature we will be able to map in detail how the water temperatures in which the foraminifera grew changed through time. Intra-basin water temperature gradients are demonstrably linked to the climate modes mentioned previously. Thus data on the temperature evolution of water in the Mentawai basin can be used to compare against temperature data from elsewhere in the region. Such a spatial analysis of temperatures is currently lacking across the Indian Ocean. The cores collected on this cruise can, for example, be paired with a western tropical Indian Ocean core collected in previous missions by paleoclimatologists at the Scripps Institution of oceanography. While sediment core resolution will not be high enough to pick out individual ENSO/IOD/PDO events, we will be able to determine how the strength and recurrence of such events has varied on roughly centennial timescales giving an important first order control on the climactic evolution of the Eastern Indian Ocean.

III. SCIENCE PLAN: METHODS AND OUTCOMES

To study the tectonics of the Sunda Megatrust we will use acoustical soundings of two types. (i) High-resolution swath bathymetry using the hull-mounted EM122 Simrad multi-beam equipment onboard the R/V Revelle. This will provide high precision measurements (with an uncertainty of 0.1-0.2% of the water depth) of the shape of the sea floor. This high quality sounder provides data at higher precision levels than previous expeditions on the megathrust. This information serves two purposes. It can be directly interpreted and geomorphic features correlated with the state of stress of the subduction front. It can also be directly compared to the existing bathymetric measurememts of Figure 1. Thus we can examine the motions of the seafloor during the 2010 Mw 7.8 Mentawai earthquake. (ii) We will collect sub-bottom (3.5 kHz) acoustical data using the hull mounted Knudsen 3260. This provides a high-resolution (1m) image of the top 20-30 m of sediments. With this information we can analyze recent deformation of both the subduction front and the backthrust.

Additionally we will collect shallow sediment samples with an OSU-style gravity-coring rig. This will produce 3-4 m long cores that sample the topmost layer of sediments. These cores will be collected along the acoustic profiles of the backthrust so that we can correlate the sub-bottom profiler data with it.

Microfossil analysis of the sediment cores will be used for paleoclimate assessment. Once obtained, sediment core analysis is fairly straight-forward and the peer-reviewed methods are simple and well-tested. The object of taking a sediment core for paleoclimatic reconstructions is not necessarily to analyze the sediment itself, but to incrementally sift through the sediment and collect the shells of tiny, single-celled organisms called foraminifera. First the cores are split into depth sections of typically 1-2 cm, and each depth section is subsequently divided so that it can later be revisited, analyzed for other purposes, or shipped to other laboratories for collaborative work. Once split, analysis of an aliquot of sediment proceeds by drying the sediment of its inherent seawater in an oven overnight (or until dry). The sample is then rinsed through a 63 micron sieve (the standard size which removes the majority of seafloor sediment yet retains all foraminifera of interest) ionized water and gentle agitation are used to push the sediment through the sieve. What is left on the sieve is then collected and dried again to remove any remaining water. Once dry, a sample is placed under an optical microscope and is picked through for specific species of foraminifera. Species identification is important as certain species exhibit different chemical characteristics than others, and also because certain species grow in different depths of the water column (i.e. planktic foraminifera inhabit the upper photic zone of the ocean, while benthic foraminifera grow on the seafloor). Then 5-8 specimens of a species are taken per depth slice and analyzed on a mass spectrometer for their oxygen

(δ13C and δ18O) isotopic content, which can be used as proxies for water mass presence, water temperature, and ice volume at the time of the foraminifera growth cycle.

As such, the science targets of this expedition can then be subdivided in 3 (Figure 1), they are, ordered by priority

1. Collection of multi-beam data
2. Collection of sub-bottom profiler (Chirp) data
3. Collection of soft sediment gravity cores

Each one of these scientific targets has different relevance depending on the survey area (Figure 1). Within the Sunda megathrust we have identified 3 main survey areas taht help achieve our research goals:

1. Work Area 1:Site of the October 2010 $Mw7.8$ event: A 120 km $\times$ 50 km box defined by coordinates $(99.44°\text{E}, 3.39°\text{S})$ and $(100.57°\text{E}, 3.72°\text{S})$. We will collect multibeam and sub-bottom profiler data at an optimal velocity 0f 8 knots. We anticiapte we will need 6 profiles for a total time of 2.1 days.
2. Work area 2: Unbroken segment of the Mentawai Patch: A 120 km $\times$ 50 km box defined by coordinates $(98.46°\text{E}, 2.23°\text{S})$ and $(99.81°\text{E}, 2.94°\text{S})$. We will collect multibeam and sub-bottom profiler data at an optimal velocity 0f 8 knots. We anticiapte we will need 6 profiles for a total time of 2.1 days.
3. Active segment of the backthrust between Siberut and Sipora islands: We will first collect 2-3 a 20 km long high-qualith chirp line at 2 knots. This will take up to 1 day. Along this transect we will also collect 2 gravity cores. At 500-1500 m water depth. Each core collection should consume 1 hour of time.

These 3 science goals will consume a total of 5.3 days. At this point the science party will decide based on the findings, the data quality and the remaining science time which one of the supplemental activities to pursue. They can be:

1. Collection of high quality (2kts) sub-bottom profiler transects in work areas 1 and 2
2. Collection of multi-beam and sub-bottom profiler data in supplemental area 2 (the emntawai basin), a 120$\times$40km rectangle defined by coordinates $(100.49°\text{E}, 1.24°\text{S})$ and $(101.78°\text{E}, 2.06°\text{S})$. This will fill existing gaps in the currently available bathimetry. Thsi data is important to constrain tsunami propagation models in the region.
3. Collection of further sediment cores in the Mentawai basin

We expect the acoustic data will be fully processed by the students by the end of the cruise and a partial interpretation will be possible. At this point we will assess the importance of the results. Based on our findings we will begin discussion amongst collaborating partners on the elaboration of manuscripts for publication in peer-reviewed journals.

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