The Mw 9.3 Indonesian Earthquake and the Holocene Great Earthquake Record from the Northern Sumatran Subduction Zone

Project Summary

Intellectual Merit  
The December 26th, 2004 Mw 9.3 subduction earthquake off northern Sumatra was the second or third largest ever recorded. While we will learn a great deal by studying this event, quantifying the temporal and spatial patterns of earthquakes along plate boundaries remains elusive because our observations often span only one or two seismic cycles. Fundamental issues such as the seismic gap hypothesis, clustering, recurrence patterns, and applicability various earthquake models remain difficult to address because we rarely have a long enough time series to discriminate between models. In the Indian Ocean, the lack of information is extreme, with great loss of life because there was little expectation that an event like 2004 could occur. The Sumatran-Andaman-Nicobar segments of the Sunda Subduction Zone were considered poorly coupled, highly oblique, and at low risk for great earthquakes. Paleoseismology has the potential to address these questions directly using a longer time span than available to geodisists and seismologists. Recent work in Cascadia and along the Northern San Andreas Fault has shown that developing a Holocene time series of earthquakes from the marine sedimentary record is possible, and can yield invaluable information about recurrence intervals, segmentation, fault interaction and temporal patterns. The Cascadia turbidite record of great earthquakes, now 10,000 years long, has revealed clustering, a repeating temporal pattern, and a possible stress linkage to the NSAF.

In 2007 we began this project with a modest proposal to collect a regional set of piston cores along the Sumatran margin to test whether similar records could be developed for the Sunda subduction zone. At the time, little was known about the Sumatran submarine forearc, and no US research ship had been in Indonesia in 25 years. Thus we proposed a modest project based on some hope of success, but with little certainty of what would be required. Now, after successful collection of an extensive core dataset, multibeam bathymetry, and shallow reflection profiles, and successful dating and stratigraphic correlation of turbidites so far, we are confident that a long term paleoseismic record can be constructed for Sumatra. To date, we have developed criteria to address the origins of a ubiquitous turbidite record observed in the Sumatran trench and slope basins. Our evolving criteria depend on correlation between isolated trench and slope basin sites, supported by 14C ages and tephra stratigraphy. The isolation of slope basins and trench segments from eachother, and from shallow water sediment sources offers a robust method of testing the turbidite stratigraphy for common origin, effectively reducing the chance of non-earthquake origin. These sites are also isolated from land sources of sediment transport, somewhat simplifying the problem. We now can infer from a ~7500 year record along the northern Sumatran margin, that there are 17 distinct correlable turbidite events that appear to have been generated by a common source, with 2-3 additional events that appear limited to the southern part of the 2004 rupture area. The average recurrence interval was ~400 years. This series ends with the turbidite likely generated in 2004, and appears to include clustering, with long gaps of 700-1000 years between clusters. From these records we can infer that the 2004 earthquake was not unique, and also attempt to calibrate the turbidite response to this well known event. We are beginning to understand something of the variability of great earthquakes in time, and whether such common assumptions as a long repeat time following a great earthquake are at all justified.

This proposal seeks to continue our investigation of the turbidite history along the northern Indonesian/Indian convergent margin. We will continue to use AMS 14C techniques to date correlated turbidites and test the sequences for common origin and characteristics indicative of earthquake or other origins. We will apply criteria developed in Cascadia, Japan and Sumatra thus far to discriminate such events from those triggered by other mechanisms. We will continue to use magnetic and density signatures, CT scans, u-channel magnetics, and tephra correlation that have been successful in the “fingerprinting” of individual events. This project is designed to compliment the extensive geologic and geophysical efforts currently underway or proposed by international colleagues.

Broader Impacts: As in Cascadia, this project should result in a Holocene record of great earthquakes along the Sunda margin. For probabilistic hazard assessment, such a time series will have a significant and immediate impact on hazard assessment for Indonesia, and tsunami hazard around the Indian Ocean, as well as developing thee techniques that can be used on other subduction margins. The data from this project will be publicly available via publications, international meetings, and our web site. We expect to include two full time graduate students, and have supported 8 Indonesian colleagues and 16 students in the sea-going phase of the project from the US and collaborating institutions.
**Introduction** On December 26, 2004, a magnitude ~9.2 earthquake struck Sumatra and the Andaman and Nicobar Islands of India (e.g., Park et al., 2005). Within hours, resulting tsunamis inundated coastal communities around the Indian Ocean, killing over 290,000 people. The earthquake ruptured the megathrust between the subducting India-Australia Plate and the overriding Burma-Sunda microplate (Fig. 1). Seismic rupture nucleated offshore Sumatra at ~30-40 km depth and ruptured mostly northwards for ~1300 km over a period of ~550 s (Lay et al., 2005; Ammon et al., 2005; Wu and Koketsu, 2005; Stein and Okal, 2005; Park et al., 2005).

While the heterogeneous and exceedingly long rupture process is now the best documented great earthquake, having been recorded on global and regional seismic networks, and continuous GPS stations (e.g., Vigny et al., 2005), the basic tectonic elements of the margin that yield during rupture and control its propagation, versus the elements that terminate rupture and suppress it, are essentially unknown. The tsunami from this event was recorded in deep water as sea-surface height changes by the Jason-1 and TOPEX/Poseidon satellites (e.g., Titov et al., 2005), and by tide gauges around the world. The rupture initiated in the south, near Simeulue Island, and propagated updip and northwestward at 2-2.5 km/sec (Ammon et al., 2005; Ishii et al., 2005). Moment release was concentrated in patches; however, despite modern techniques debate still exists over slip distribution patterns (Fig. 2).

Subduction earthquakes represent one of the largest releases of energy on earth, and the December 26th 2004 Sumatran earthquake was the second or third largest earthquake ever recorded (Fig. 1). Quantifying the temporal and spatial patterns of these great events remains elusive because our observations span too little time to encompass more than a few seismic cycles at most, and because the ability to directly measure the associated accumulation and dissipation of strain energy has only recently been developed. GPS technology now makes it possible to measure elastic strain accumulation at plate boundaries with a high precision in only a few years. However, real-time strain measurements can only represent a fraction of one strain cycle. Fundamental questions such as the utility of the seismic gap hypothesis, clustering, and the applicability of slip-predictable, time-predictable and stress transfer models remain unanswered because we rarely have a long enough earthquake record. Paleoseismology addresses these questions directly using a larger time span than available to geodesists. The use of paleoseismology in subduction settings is now advancing rapidly. In the past decade, discovery of rapidly buried marsh deposits and associated tsunami sands along the Pacific Coast of the US Pacific Northwest has led to the recognition that the Cascadia subduction zone, once thought aseismic, has generated great (Mw 8-9) earthquakes in the past. The questions of how large and how frequent these events are, and their spatial and temporal distribution are now the active areas of research in Cascadia and elsewhere.

**Figure 1.** ~ 1300 km long Rupture region of the 26 December, 2004, 9.2 earthquake. Harvard focal mechanisms including 6 weeks post-main shock are shown. Main shock NEIC epicenter shown in red. Faults from Curray (2005).
Off fault paleoseismic techniques must demonstrate that the geologically recorded events are uniquely generated by earthquakes, and not some other natural phenomenon. These problems can be overcome, and the techniques can be powerful tools that offer in many cases, very long seismic time series (Goldfinger, 2007; 2008; 2009; 2009a). Coastal marsh paleoseismology has defined the Cascadia record, and is now being used in the Japan, Nankai, Kurile, Alaskan, Chilean, Iberian and Sumatran subduction systems. These records can define the record over the past 1000-3000 years typically, with scattered longer records. In Sumatra, a very high precision paleoseismic and geodetic record has been developed by Kerry Sieh and his colleagues and students (Zachariasen et al., 2004, Natawidjaja et al., 2003; Sieh et al., 2008), though this record extends only ~700 hundred years into the past, and is mostly south of the 2004 zone. The marine sedimentary record contains a long and uninterrupted turbidite record extending back as much as ~10,000 years in a useful paleoseismic context (can be sampled with high volume piston coring), more than enough to encompass many earthquake cycles. In recent years, turbidite paleoseismology has been attempted in Cascadia (Adams, 1990; Goldfinger et al., 2003 a, b, 2008; 2009; 2009a), Japan (Inouchi et al., 1996; Shiki et al., 2000; Nakajima et al., 2004; Noda, 2004; Okamura, 2004; Soh, 2004), the Mediterranean (Kastens, 1984; Nelson et al., 1995; Cita et al., 2000; Pareschi et al., 2006), the Dead Sea (Niemi and Ben-Avraham, 1994), northern California (Field et al., 1982; Garfield et al., 1994; Goldfinger et al., 2007; 2008) the Arctic ocean (Grantz et al., 1996), and a number of inland lakes (Karlin and Abella, 1992; Karlin et al., 2004; Kumon et al., 1998; Schnellman et al., 2002).

Since our Sumatra project began, we have been developing these methods for application to the turbidite history along the Sumatra margin, where the great earthquake of December 26, 2004 struck. The physiography and sedimentation of the Sumatra-Nicobar-Andaman section of the trench is quite similar in some ways, but very different in detail to the nearly ideal Cascadia margin. In the following sections we briefly discuss our methods and results from Cascadia, and the principles we are applying to the Sumatran turbidite record. Continued development of the turbidite paleoseismic technique advances fundamental tectonic and seismic hazard methods that can be applied in any continental margin system, where major fault systems and population centers commonly coincide.

**Turbidite Methodology and Application to Sumatra, Cascadia and the Northern San Andreas**

Following the discovery of the first buried marsh sequences on land, Adams (1990) used existing cores to test the possibility that the Cascadia cores contained a record of Holocene great earthquakes of the Cascadia margin. Fortunately, Oregon and Washington cores all contain a unique datable event, the ash layer from the eruption of Mount Mazama, at 7630 ± 150 cal yr BP (Zdanowicz et al., 1999). The ash was distributed to the channel system via the drainage basins of major rivers.

Adams (1990) examined core logs for Cascadia Basin cores, and determined that nearly all of them had 13 turbidites overlying the Mazama ash, and argued that these 13 turbidites correlate along Cascadia channel and its tributaries. Adams observed that cores from Juan de Fuca Canyon, and below the confluence of Willapa, Grays, and Quinault Canyons, contain 13-15 turbidites above the Mazama ash.
The correlative turbidites in Cascadia channel lie downstream of the confluence of these channels. If these events had been independently triggered events with more than a few hours separation in time, the channels below the confluence should contain the sum of the tributaries, from 26-30 turbidites, not 13 as observed (Figure 2). The importance of this simple observation is that it demonstrates synchronous triggering of turbidite events in tributaries separated by 50-150 km. This elegant relative dating technique and its variants are used extensively in our Cascadia, Sumatra and NSAF work.

Using 54 new cores in Cascadia, we have confirmed and extended the event record temporally and spatially, where we find 19 Holocene events along ~660 km of the margin in the Cascadia, Barclay, Willapa, Grays, and Rogue Canyon/Channel systems between latitudes 42N and 48N (Figure 2). The most recent event took place in 1700 AD (Satake et al., 1996; 2003; Atwater et al., 2004), and in all, 19 turbidite events have occurred during the preceding 9820 years, yielding a mean recurrence time of ~530 years. 20 smaller events are correlated over shorter distances with variable rupture lengths, yielding a shorter southern margin recurrence interval of ~250 years (Goldfinger et al., 2008; 2009).

Triggering mechanisms: Are they Earthquakes?

Are these events all triggered by earthquakes? Common sense suggests that such a scenario is absurdly simplistic, yet our Cascadia work has led us to the unlikely conclusion that Adams (1990) was correct. We now discuss the methods used to test the hypothesis and why it seems to work. Adams (1990) suggested four plausible mechanisms for turbidity current triggering: 1) storm wave loading; 2) great earthquakes; 3) tsunamis; and 4) sediment loading. To these we add 5) crustal earthquakes, 6) slab earthquakes, 7) hyperpycnal flow (several other mechanisms such as structural tilting, and gas hydrate destabilization reduce slope stability, but are not direct triggering mechanisms, Goldfinger et al., 2008a). All of these mechanisms can and do trigger a turbidity currents, but can earthquake-triggered events be distinguished from others? Two techniques can be used to distinguish seismic from non seismic events:

1) Sedimentological determination of individual event origin.
2) Regional correlations that require synchronous (i.e. earthquake) triggering.

Individual event determination can in some cases distinguish seismic turbidites from storm, tsunami, and other deposits using several methods. Nakajima and Kanai (2000) and Shiki et al. (2000) report that seismo-turbidites can in some cases be distinguished sedimentologically. They observe that historically known seismically derived turbidites in the Japan Sea and Lake Biwa are distinguished by wide areal extent, multiple coarse fraction pulses, variable provenance, and greater depositional volume than storm-generated events. These investigators traced known seismo-turbidites to multiple slump events in many parts of a canyon system, generating multiple pulses in an amalgamated turbidity current, some of which sampled different lithologies that are separable in the turbidite deposit. In general, these investigations observe that known storm triggered events are thinner, finer grained and have simple normally graded Bouma sequences, although complexity is also a function of proximity to the source, and some reports reach different conclusions (e.g. Mulder and Syvitski, 1996). While there may be global, regional or local criteria to make such distinctions, these are at present poorly developed and somewhat contradictory.

Synchronous Triggering, Relative Dating, and Regional Correlations

Taking advantage of favorable physiography, we have used spatial and temporal patterns of event correlations that are unlikely be the result of triggers other than earthquakes. We use multiple techniques to test for physical and temporal linkage between specific events and event series, and thus test for synchronicity. Typically, paleoseismologic investigations use radiocarbon constraints to establish these linkages, but often are unable to determine synchronous event chronology due to the inherent limits in dating techniques. Relative dating techniques, if available, can be a strong supplemental or primary test for synchronicity. The “confluence test” of Adams (1990) is powerful in that it requires synchronous triggering within a few hours. Numerical comparison of events between time markers can also be useful.

We have found it is possible to correlate the physical property signatures (proxies for grain size distribution) of individual turbidites from site to site down individual channels (Figure 3). This indicates that some first order structure of the turbidity current maintains integrity for long distances within channels. This in itself is quite surprising, and offers the opportunity to use direct correlations to extend and strengthen the turbidite event stratigraphy. What is more surprising is that we have been able to
Figure 3. Example of correlative sequences of turbidites from the Cascadia margin using grape density (left) and mag. sus. Right, supported by 14C ages (2σ ranges shown. Right panel shows two core segments 450 km apart, that do not meet. From Goldfinger et al., 2009).

correlate event signatures not only down individual channels, but between channel systems that never meet. Our current working hypothesis is that the coarse pulses represented in the magnetic and density “fingerprints” of individual events could represent some source characteristic of the triggering earthquake. For example, the Great Sumatran earthquake had three separate subevents (Chlieh et al., 2007; Ammon et al., 2005; Figure 2). Our model predicts that these subevents, minutes apart, may be recorded as discernible coarse pulses within the turbidite that can be correlated over distances. That appears to be the case for Sumatra as shown in Figure 8. The 1906 earthquake generated turbidite also bears a resemblance to the seismograms showing a two pulse event.

Ongoing experimental work in our lab has demonstrated that this mechanism is viable, with pulse separation of as little as 1 second able to generate multiple fining upward sand pulses, though much more work is required (Goldfinger et al., 2004; 2007; 2007; 2009). We have begun collaborative work on Cascadia turbidites with Bill McCaffrey of University of Leeds, head of the Turbidite Research Group, to better understand the relationships between source mechanisms and hydrodynamics of turbidity currents.

Part of the correlation process includes observation of such parameters as turbidite size and character as reflected in separate channels, as well as correlatable details such as the number of coarse pulses (density and magnetic peaks). For example, in Figure 4 events T5, T10, and T12 are small events in all cores at all sites. T11 and T16 are very large events in all cores. This information supports the notion that there may be some fundamental relationship to the underlying earthquakes. Though the explanation is pending, we have been able to use these persistent characteristics to build a correlation method. Physical property correlations are common practice with ODP cores, in the oil industry, and have recently come into use for paleoseismology (i.e. Abeldayem et al., 2003; St-Onge et al., 2003; Hagstrum et al., 2004, Iwaki et al., 2004; Karlin et al., 2004, Schnellmann et al., 2002). Turbidite “fingerprints” have been recognized and used for regional correlation in Lake Baikal (Lees et al., 1998), off Morocco (Wynn et al., 2002), and elsewhere.

Determination of synchronous triggering can eliminate non-earthquake triggers with the possible exception of storm wave loading or multiple hyperpycnal flows for very large storms. West Coast physiography favors filtering of non-seismic events from the record because a wide shelf separates river sources from canyon heads. Hyperpycnal flow, or direct turbid injection from rivers, can produce turbid flows, and can even mimic earthquakes in that they may affect several rivers over a span of days. We have found that while this certainly occurred during the Pleistocene when lowered sea-level resulted in direct river-canyon connections, during high stand conditions this does not occur (e.g. Sternberg, 1986). Two exceptions are the Eel river record, which probably contains storm events, and the Viscaino channel.
along the northern San Andreas. Both channels head at a very narrow shelf, and river injection is possible. Further discussion of these aspects can be found in Goldfinger et al., 2009; 2009a).

**Cascadia Result Summary: What the Onshore Offshore Paleoseismic Record Can Do**

In summary, the Cascadia record has revealed 19 Holocene turbidites along the northern, central and southern margin, and 21 interspersed additional smaller events limited to the central and southern margin. The Holocene turbidite record passes several tests for synchronous triggering, and correlates well with the shorter onshore paleoseismic record. The synchronicity of a 10,000 year turbidite event record for 500 km along the northern half of the Cascadia Subduction Zone is best explained by paleoseismic triggering by great earthquakes. Similarly, we find a synchronous record in southern Cascadia, including correlated additional events along the southern margin. The average age of the oldest Holocene turbidite event is 9820 +/- ~200 cal BP and the youngest was deposited in AD 1700, (250 cal. BP) thus the northern events define a Holocene great earthquake recurrence of ~ 500 years. The recurrence times and averages are also supported by the thickness of hemipelagic sediment deposited between turbidite beds. At least two Northern California sites, Trinidad and Eel Canyons, probably also record numerous small sedimentologically or storm triggered turbidites, particularly during the early Holocene when a close connection existed between these canyons and associated river systems. The combined stratigraphic correlations, hemipelagic analysis, and 14C framework suggest that the Cascadia margin effectively has three rupture modes: 19 full or nearly full-length ruptures; 1 or 2 ruptures comprising the southern 50-70% of the margin, and 20 smaller southern margin ruptures during the Holocene. The shorter rupture extents and thinner turbidites of the southern margin correspond well with spatial extents interpreted from the onshore paleoseismic record, supporting margin segmentation of southern Cascadia (Goldfinger et al., 2008; 2009). The 40 Cascadia events define a Holocene recurrence for the southern Cascadia margin of ~240 years. Time-independent probabilities for segmented ruptures range from 7-9% in 50 years for full margin ruptures, to ~18% in 50 years for a southern segment rupture. Time dependent failure rates indicate probabilities rise to 25% in 50 years for the northern margin, to 80% in 50 years in the south.

The long earthquake record established in Cascadia allows tests of recurrence models rarely possible elsewhere. Turbidite mass per event along the Cascadia margin reveals a consistent record for many of the Cascadia turbidites, from which we infer that larger turbidites likely represent larger earthquakes. Mass per event and magnitude estimates also correlate well with following time intervals for each event, suggesting that Cascadia full margin ruptures may follow a time-predictable model moderately well (Goldfinger et al., 2009). The long paleoseismic record also indicates a repeating pattern of clustered earthquakes that includes three and possibly four Holocene cycles of 5 earthquakes followed by an unusually long interval. We suggest that the pattern of long time intervals and longer rupture for the northern and central margin may be a function of high sediment supply on the incoming plate smoothing asperities and potential barriers. The smaller southern Cascadia segments correspond to thinner sediment supply and potentially greater interaction between lower plate and upper plate heterogeneities.

**Sumatra Tectonics**

The Sunda trench results from the subduction of the oceanic Indo-Australian plate beneath the continental Burma Microplate (Figure 1). In the southern portion of the Sunda trench, convergence is directed towards the northeast, nearly normal to the margin, and the convergence rate decreases along the strike of the trench from 60 mm/yr off western Sumatra to ~ 50 mm/yr off the Andaman Nicobar margin (McCaffrey et al, 2000; Bock et al., 2003). Along the Sumatran margin, the frontal thrust is landward vergent in the south, and mixed vergence in the north (shown in seismic profiles in Karig et al., 1980, Franke et al., 2008; Singh et al., 2008). In this region spanning the mainshock and extended rupture zone of the 2004 earthquake, the Nicobar Fan, a lobe of the larger Bengal Fan is being accreted and or subducted. The NinetyEast Ridge physically separates the Nicobar and larger Bengal fan lobes, and may have recently blocked sediment input to the trench from northern sources (Curray, 2005; Figure 1). Moore et al. (1976) report that a large Pleistocene submarine landslide also blocks the trench from northerly input at 14°N. Incoming sediment thickness of the Nicobar fan is 2-4 km along the Andaman Nicobar area, thickening northward toward its source (Bandopadhyay and Bandyopadhyay, 1999).

The obliquity of subduction increases to the north, from near orthogonal at the Sunda Strait, to nearly pure strike-slip north of the Andaman Islands. Opening of the Andaman Sea backarc spreading center has added a local component of motion to the forearc region, maintaining an element of convergence along the trench even in the Andaman Islands region (Curray et al., 2005). The forearc is transported north and
stretched as obliquity increases northward (Fitch, 1972; McCaffrey et al., 1991). Motion of the forearc sliver is accommodated by the Sumatran fault near the arc onshore, and by the Mentawai and West Andaman strike-slip faults in the submarine forearc (Figure 1; Sieh et al., 2000; Curray, 2005).

GPS results from Sumatra and the offshore islands of the outer arc high strongly suggest a segment boundary between a southern strongly coupled segment, and a northern poorly coupled segment (McCaffrey et al., 2000). The boundary between the two segments lies near the north end of Siberut Island at ~ the equator. GPS vectors south of this point are close to parallel to the expected plate vector, indicating strong coupling of the forearc, while motion north of Siberut is nearly parallel to the arc, suggesting poor coupling and northward movement of the forearc sliver plate along the Sumatran fault, and also perhaps by strike-slip faults in the submarine forearc. The mainshock of the December 26th earthquake occurred in the inferred poorly coupled region.

Sumatra Results: Continental Margin Morphology and Sedimentation

The morphologic details of the continental margin offshore Sumatra and the Andaman Nicobar forearc have now been imaged by numerous expeditions including ours in 2007, and these bathymetry data have been merged to cover much of the northern Sumatran slope (Ladage et al., 2006).

Three important issues that bear on the applicability of turbidite paleoseismology to the Sumatran margin are 1) the presence of channel systems to deliver seismically triggered turbidites 2) the presence of planktonic Forams for radiocarbon dating, and 3) the favorability of physiography for limiting turbidites from other sources.

Figure 4. Left: Deformation from at ~3° N, showing landward vergent folds, and slope/abyssal plan channel systems. Right: Five channels systems feeding the abyssal plain between mainland northern Sumatra and Simulue Island. We intend to focus on these deeper systems, with selected cores in forearc basin sites. Images courtesy of the British Geological Survey/Royal Navy/Southampton Oceanography Centre Team & the United Kingdom Hydrographic Office.

Figure 5. Core locations are plotted as brown diamonds over bathymetry. Historic subduction zone earthquake ruptures are outlined in red (reference). Ninety East ridge, Wharton ridge, Investigator fracture zone, and other unnamed fracture zones are demarcated with labels. Inset map shows the global context of the Sumatra cores.
**Channel Systems:** The available bathymetry, merged with the data we collected in 2007 showed that sediment transport pathways exist, although they tend to be relatively short. **Figure 4** shows typical example in a landward vergent region, where the seaward flank of a large fold has been incised by a canyon system that delivers material to an intra-trench basin partially enclosed by the initial thrust ridge, and then to the trench axis. Other similar examples deliver material to completely enclosed basins. Our GIS analysis of the basins and drainages is shown in **Figure 6.** In our 2007 and subsequent analysis, we found that sediment pathways can be divided into 1) isolated slope basins that have no input from land sources and no exits; 2) slope basins with no input from land sources with exits to the trench or other basins; 3) a few slope basins that may have input from forearc island sources, and 4) trench basins that are partially or completely isolated from other trench segments by basement structures.

**Foram abundance:** The regional CCD was reported to be ~4500-5100 m depth along the Sumatran margin (Tucker and Wright, 1990; Shulte and Bard, 2003). We found that the regional CCD in our core set (**Figure 5**) is closer to 4000 m based on foram abundance and preservation in our cores. We discovered this onboard during the 2007 cruise, and developed a strategy to minimize the effect of the shallower than expected CCD.

**Margin Physiography:** A key feature that made Cascadia Basin a good paleoseismic recorder proved to be the relatively wide continental shelf of Oregon and Washington (Goldfinger et al., 2003b; 2004; submitted). Under high-stand conditions, the shelf separates rivers from their associated canyons, which are completely infilled by transgressional sediments. This configuration largely prevents hyperpycnal flows from connecting to canyon systems and generating turbidity currents (Sternberg, 1986) except where the shelf remains narrow. In Sumatra, the separation is even greater, with a wide forearc basin and forearc high completely separating land sources from lower slope and abyssal plain channels. In addition, the reported blockage of the trench from northern (Himalayan sourced) sediment input appears to limit that source as well. A number of slope basin sites appear to be subject to possible input from the forearc islands (Simeulue, Nias, Siberut, North and South Pagai). The bathymetric compilation has allowed a detailed analysis of drainage pathways at our core sites (**Figure 6**). This analysis is being done to evaluate the potential sources and drainage areas, as well as sources overlaps for each 2007 core site.

![Figure 6. Catchment basins linked to 2007 core sites, Sumatra margin, from the GIS study of drainage flowpaths we determined the linkage of each core site to its sediment sources.](image)

**Paleoseismic Strategy:** The strategy that emerged at sea during our 2007 cruise revolved around using slope basin and trench cores to both date turbidites and test the observed stratigraphy for seismic origin. The lack of datable forams in the trench cores meant that all age control would come from basin core sites shallower than ~ 4000 m. We therefore collected cores at sites in pair transects across the slope, trench cores paired with basin cores along the margin. We anticipated that if the cores were of seismic origin, they should correlate between basin and trench sites stratigraphically, and age control would come from the basin cores. Furthermore, basin sites with synchronous earthquake stratigraphy should correlate both stratigraphically and temporally with each other within seismic segments. This strategy forms the basis of tests of earthquake origin for this project and is summarized in Table 1.

**Paleoseismic Results:** The results summarized in Table 1 suggest that the Sumatran turbidites investigated thus far in our project generally pass the tests so far devised to test for earthquake origin in the 2004 rupture zone. The criteria based on the 2004 rupture and the basic sedimentological tests are
criteria that are consistent with but do not require seismic origin. Our current correlation diagram is shown in Figure 9, and detailed examples of event correlation are shown in Figures 7 and 8. Temporal and stratigraphic correlations are beginning to show a coherent pattern of turbidites that satisfy the available criteria for seismic origin in the 2004 rupture zone. We have correlated basin sites.

<table>
<thead>
<tr>
<th>Table 1.</th>
<th>Criteria for seismic origin</th>
<th>Results from 2007 core data</th>
<th>Pass/fail</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trigger criteria</strong></td>
<td><strong>Basin–Basin temporal correlation</strong></td>
<td>Required for seismic origin within segments, random otherwise</td>
<td>Temporal correlation of turbidites good, mostly non-overlapping 2σ error ranges and tight age groupings, some exceptions</td>
</tr>
<tr>
<td></td>
<td><strong>Basin-Basin stratigraphic correlation</strong></td>
<td>Required for seismic origin within seismic segments, random otherwise</td>
<td>Good stratigraphic correlation between basin sites with no drainage connections</td>
</tr>
<tr>
<td></td>
<td><strong>Basin-Trench stratigraphic correlation</strong></td>
<td>Required for seismic origin within seismic segments, random otherwise</td>
<td>Good stratigraphic correlation between basin and trench sites with and without drainage connections</td>
</tr>
<tr>
<td></td>
<td><strong>Trench-Trench stratigraphic correlation</strong></td>
<td>Required for seismic origin within seismic segments, random otherwise when isolated</td>
<td>Good stratigraphic correlation between trench sites with and without drainage connections</td>
</tr>
<tr>
<td></td>
<td><strong>2004 consistency</strong></td>
<td>Youngest turbidite in 2004 rupture zone should be consistent with 2004 origin</td>
<td>Youngest turbidite has no hemipelagic overlay, has excess Pb210 activity. Cs 137 results not yet available</td>
</tr>
<tr>
<td></td>
<td><strong>Consistency with land paleoseismic record</strong></td>
<td>Are offshore turbidites temporally consistent with available land paleoseismic records?</td>
<td>Approximately consistent with penultimate event in Thailand, Andaman, and previous two events in Mentawai. Smaller southern events below 2004 may be consistent with 1861 and 1907 tsunami.</td>
</tr>
<tr>
<td></td>
<td><strong>Sedimentologic criteria</strong></td>
<td>Sharp bases, fining upward sequences, fine tail only above last pulse required for seismic origin</td>
<td>Most events pass these basic criteria for an impulsive turbidity current. Consistent with but does not require seismic origin</td>
</tr>
</tbody>
</table>

**Figure 7.** A turbidite pair (event 8 and event 9) is correlated to 3 slope cores with unique sedimentary sources. Entire cores are plotted in Figure 9. A. From left to right, gamma density (g/cc), CT density (grey-scale digital number), lithologic log, CT imagery, and point magnetic susceptibility (SI x 10^-5) are plotted vs. depth (in m, grey bar = 0.5 m) for each core. Cores are vertically aligned roughly based on the basal contact for turbidite event 9. Calibrated ages are plotted with an inverse red triangle symbolizing the sample location in the core. Event numbers are based on total events in the 2004 rupture region increasing from event 1 (2004, Figure 8) at the surface of some cores. Core section breaks are in brown. B. Core data are plotted vs. depth, with vertical scales normalized based on stratigraphic correlations in A. Green tie lines show how data in A and B relate. Older age of event 9 in core 108PC is due to basal erosion, clearly visible in the CT data.
that have no drainage connections over a margin length of 330 km with the physical property and CT data, supported by the in-progress series of 14C ages.

Similarly, we can correlate basin to trench and trench to trench sites over the same distance. While more 14C data are needed, the evolving correlation framework suggests a coherent pattern of turbidite deposition linked by event ages and event “fingerprints”. There are no tephra layers in the Holocene stratigraphy of the 2004 rupture zone, however tephras are more common further south along Sumatra.

Figure 10 shows the in-progress space-time diagram for these data, summarizing the stratigraphic linkages, 14C data, and probability density functions for these data. For correlated events with multiple 14C ages within 2σ of each other, we used OxCal (Ramsey, 2005) to do a Bayesian “combine” of the multiple ages. We plot the data at the youngest of these ages in Figure 10. The probability density functions (PDF’s) of these combined ages, along with single age PDF’s are shown along the left margin of Figure 10. We can see graphically that the 14C data for each event generally do not overlap adjacent events at the 2σ level, and form tight temporal groupings across core sites. The mean 2σ range for single and combined 14C data per event is less than 100 years, much less than the average recurrence interval of 400 years. Only events 7, 8, & 9 have overlap of their 2σ PDF’s. We can immediately see from this figure that the stratigraphic correlations and 14C data are mostly consistent, indicating

that the basic stratigraphic correlations are working well. Problems are indicated by correlation lines (green) that are not horizontal. These may be due to mis-correlation or problematic individual 14C ages. Overall, these results compare favorably to the equivalent tests for synchronous origin of turbidity.
Figure 9. Regional stratigraphic correlations and source areas. A. Core locations (red dots) on bathymetric map also showing key channel flow paths (light blue) to eight core sites. Some of the slope basins are sedimentologically isolated as shown with red. While the region that drains to core 104PC then drains to the trench, the three other slope basins are internally drained. B. Flow path profiles depth (km) vs. latitude are plotted in brown for basin flow paths and blue for trench flow paths. Location of these profiles plotted in A. C. Stratigraphic correlations between key cores using lithology, CT, physical property and 14C data. Slope cores labeled brown; trench cores labeled blue. Location of stratigraphic details in figure 7 are outlined by shaded rectangles for events 8 & 9 (cores 108PC, 014PC, and 103PC). (trench sites (blue) do not have 14C age control).
Because land sources have been all but excluded from the Sumatran lower slope, the triggering mechanisms that could be responsible for these apparently synchronously deposited turbidites are reduced, from 1) hyperpycnal flow; 2) regional storm wave loading; 3) sediment self failure; 4) earthquakes; to just earthquakes. The first two are precluded from the lack of a land source or shallow water affected by storm waves, and sediment self-failure is addressed by the regional correlation of sedimentologically isolated sites, leaving earthquakes as the most likely source. The evolving turbidite record compares well with the similarly evolving land paleoseismic record.
How does the offshore turbidite record compare to the nascent land paleoseismic record? Land records suggest that past tsunamis are recorded in coastal Thailand, where tsunami overwash sands have been identified in swales between coastal beach ridges at Phra Tong Island, north of Phuket (Jankaew et al., 2008). At Phra Tong, at least three well preserved significant tsunami sands are found. The youngest is from 2004, and the penultimate sand is 550-700 years old, similar to our second major event in the northern 2004 rupture area, where we observe a closely spaced pair of events 620-950 years old. The older sands at Phra Tong are not dated. At Meulaboh, Aceh Province in northern Sumatra, two similar sand sheets underlying the sand deposited in 2004 have been reported by Monecke et al., 2008. The penultimate sand is 610-720 years old, similar to Phra Tong and our penultimate pair of turbidites in the northern 2004 rupture area. The third event at Meulaboh is 1020-1230 years old, close to our next older event that is 1140-1340 years old. In the southern 2004 rupture area, we have two additional smaller turbidites which may correspond to the 1907 and 1861 events near Simeulue Island (Lay et al., 2005).

**Figure 10** shows a number of immediately interesting results. First, the 7200 year average recurrence time for 19 probable earthquake generated turbidity currents in the 2004 zone is 400 years, with two events recorded in the southern portion that are not recorded further north. The temporal distribution of these events shows apparent clustering, with several 700-1000 year gaps.

In summary, our initial work with Sumatra turbidites has yielded a record of possible past earthquakes spanning ~7200 years, and is consistent with onshore paleoseismic evidence developed thus far. Preliminary work further south along Sumatra shows promise for extending this record much further south along the Sumatran margin, with the additional assistance of the more numerous and prominent tephras and a better developed onshore paleoseismic and historical record of earthquakes.

**Tephra Correlation Results:** To date we have successfully analyzed 9 individual tephra layers from nine separate cores for both major and trace elements using the Cameca SX-100 electron microprobe and LA-ICP-MS, respectively (**Figure 11**). Eight of these cores were collected within a ~120 km radius from the Sunda trench near 1.5ºS. The ninth sample is a high-silica rhyolite from a core collected near the trench over 400 km to the south. This southernmost sample (group I) from a low sed. rate site shows very distinct chemical characteristics and is likely correlated with the 74 ka Youngest Toba Tuff (Pattan et al., 2002). The remaining eight samples are divided into two groups based on both major and trace-element concentrations. Six of these samples (group II) are dacitic to rhyolitic in composition and may represent a single eruptive event based on considerable overlap of all trace-elements analyzed. The final two samples (group III) are distinctly andesitic to dacitic in composition and are likely correlated with each other. These data demonstrate the ability to distinguish tephra layers based on major and trace-element analyses.

**Figure 11.** Representative trace-element bivariate plot showing distinct geochemical groups. Group I is a high silica rhyolite from the southern Sunda trench. Group two includes six samples of dacite-rhyolite composition. Group three is two samples of andesite-dacite composition. The three groups show distinct differences in nearly all major and trace-elements analyzed. Note: circles are for reference and some analyses fall outside these arbitrary boundaries.

Further sampling and data analysis show promise to: a) provide stratigraphic markers to aid in stratigraphic correlations of the cores; b) identify possible volcanic sources, and c) estimate the distribution of the respective eruptions. We could conceivably also see earthquake-eruptive correlations were they to exist. Results from our initial phase of offshore paleoseismic work in Sumatra have been submitted as Patton et al., (submitted to Nature).
RESEARCH PLAN

Approach

This proposal seeks expand and continue the development of the turbidite paleoseismic record for Sumatra and continue the preliminary work begun in 2007. Although technical problems resulted in a shorter record than hoped, our 7500 year record is ~ 7 times longer than any available land records that have been found, and the methods have shown so far that along strike correlation is not only feasible but likely to succeed. Our goal remains to develop a comprehensive paleoseismic record along the Sunda trench to address the long term earthquake record from the mainshock region and adjacent segments along the Sumatran subduction zone. The lack of this type of information certainly contributed to the unprecedented disaster of December 26th, and the upcoming one that faces Padang, now the largest city in western Sumatra (Sieh et al., 2008). Our intent is not to simply catalogue the earthquakes, though in itself that would be a boon to seismic hazard assessment in Indonesia. The power of long paleoseismic records will allow is to address such questions as: 1) Does the apparently low orthogonal convergence rate in the north mean a very long recurrence interval? Or 2) have we underestimated the convergence due to poor GPS coverage and poorly known rates of Andaman Sea opening? 3) Can we identify robust patterns of clustering (super cycles)? And what do they mean? 4) Can we identify persistent patterns of stress triggering, as apparently happened with the 2004-2005 pair? 5) Can we identify other patterns in the along strike sequencing of great earthquakes? 6) Can we see evidence of rupture dynamics in the turbidites?

The earthquake history of this subduction zone is of great scientific and societal interest, and we believe it can be determined through a concerted effort using the turbidite record, in conjunction with concurrent paleoseismic efforts on land, and the extensive geophysical investigations now underway offshore. Unlike Cascadia, where marsh paleoseismology was needed to establish that there was a great earthquake record, this is already known in Sumatra. Of further interest, the calibration of the turbidites deposited during the recent earthquakes (2004 and 2005) will aid in calibrating the seismic history of Sumatra, and perhaps of Cascadia, which has parallels to the Sumatran system. Combined, the land and marine records should, as in Cascadia, provide a Holocene earthquake record complete to ~ the M8 level.

We propose three principal objectives, which form the basis of addressing these questions:

• To establish the turbidite event history with AMS $^{14}$C, hemipelagic thickness and multiple correlation techniques.

• To test the event record using both synchronous triggering criteria between sites, and sedimentological origin (Japanese partner) to test for earthquake origin.

• To test for segmented and multiple segment ruptures using radiocarbon and physical property correlations, and establish the long term frequency and pattern of earthquakes in the Holocene.

We propose to use both the synchronous testing we have used in Cascadia, the San Andreas, and Sumatra thus far, and also use sedimentological criteria under development by Japanese investigators as described in the preceding sections (e.g. Nakajima and Kanai, 2000). Takeshi Nakajima, a leading sedimentologist with the Japanese National Institute of Advanced Industrial Science and Technology (AIST), and Ken Ikehara have joined our team, sailed with us in 2007, and are conducting this part of the investigation in collaboration with us. They will lead the effort to apply these criteria to the Indonesia cores (see attached letter). This parallel approach, we believe, should serve well to build a robust great earthquake record.

Age Control: We will apply dating techniques as we have thus far to directly date planktonic forams either just above or just below the turbidites. Foram abundance is good, and large forms are abundant, increasing age precision. We have used forams below the turbidites in most cases, particularly where the turbidites themselves are silty and show no evidence of erosion of the paleo-seafloor. In some cases we may use samples from above and below the turbidite tails where we suspect erosion. The abundance of planktonic forams shallower that 4000m is more than sufficient. We need a minimum of approximately 150 individuals depending on species and size for each AMS date to reach the 1 mg minimum sample weight requirement. Forams will be sieved @ 63m, and washed, identified and picked at our laboratory at OSU. This group is highly experienced in processing and identification of late Quaternary microfossils. AMS ages will be determined at the UC Irvine Accelerator Mass Spectrometry facility.
Raw AMS ages will be reservoir corrected and converted to calendar years by the method of Stuiver and Braziunas (1993) using reservoir values for the Indian Ocean (Southon et al., 2003; Hua et al., 2004). The application of AMS dating to marine microfossils is an evolving field tied to advances in paleoceanography. We will keep abreast of ongoing work in order to apply the most recent findings to the $^{14}$C calibration of our samples, as well as continuing to investigate reservoir variability in the region as we are presently doing in Cascadia.

**Physical Property Correlation:** We are using point and loop magnetic susceptibility, Gamma density, P-wave velocity and high resolution line scan imagery with our Geotek MST system as we have done in Cascadia and SAF work. We use 0.5 cm sample interval or better for these measurements. Magnetic susceptibility and gamma density have proven invaluable for event correlation as discussed above. We have now acquired a full set of high resolution 0.35 mm resolution CT imagery from the Sumatran cores. These imagery have proven invaluable in interpreting the internal structure of the turbidites, providing additional details that can aid correlation, interpreting the basal and upper boundaries, and identifying core disturbances. In order to further improve our ability to correlate event in the cores, we will also employ U-channel technique as a pilot study to add paleomagnetic secular variation to the suite of correlation tools available. This study, originally supported in 2007, has been delayed by late delivery of the 2G magnetometer to OSU, but will be done in 2010. U-channel paleomagnetic measurements can provide a way of facilitating correlation of sediment sequence through reconstruction of past changes of the geomagnetic field and through the development of tracers of lithologic variability that go beyond what can be done using an MST track alone (Stoner et al., 1996; Stoner and Andrews 1999). The u-channel sample comes from the pristine center part of the core, minimizing disturbance, and therefore improving not only magnetic but also physical properties measurements (or it can be located elsewhere guided by the CT imagery). Measurements are made at 1 cm intervals and through deconvolution (i.e., Guyodo et al., 2002) the ~4.5 cm of stratigraphic smoothing (Weeks et al., 1993) can be significantly reduced. The resultant paleomagnetic, rock magnetic and physical properties data can be used to develop directional paleomagnetic secular variation (PSV) and relative paleointensity (RPI) curves as well as records of environmental variability. Systematic century to millennial changes in the Earth's magnetic field when properly recorded in sediments provide chronocratigraphic templates that can be use for regional (PSV) (e.g., Thompson 1984; Lund 1996; Stoner et al., 2004) and to global (RPI) correlations (Stoner et al., 2000; Laj et al., 2004). PSV has a long history in lake sediment studies (e.g., Thompson 1973; Thompson and Turner, 1979, Verosub et al., 1986; Lund 1996; Brachfeld and Banerjee, 2000; Ojala and Tiljander, 2003) and recent work on marine sediments demonstrate (Lund and Schwartz 1996; Kotilainen et al., 2000; Verosub et al., 2001; St-Onge et al., 2003) that PSV can provide a viable means of marine/marine and marine/terrestrial correlation at resolutions equivalent to, and in some case better than, what can be achieved through radiocarbon dating (Lund 1996; Hagstrum and Champion, 2002; Stoner et al., 2004;
Recently acquired and unpublished data from Steve Lund (Fig. 12) show that the Indonesian region is characterized by well-resolved centennial to millennial scale PSV. Spherical harmonic global field models (Korte and Constable 2005) suggest that this applies to the RPI records as well and show that Lund’s data from eastern Indonesia would be valid as an initial dating curves for the Sumatra region.

**Ash stratigraphy:** Ash-bearing turbidites are common in the Holocene Sumatra trench fill (e.g. Martin-Barajas, A. and Lallier-Vergas, 1993). The Toba Ash, erupted from the Toba Caldera, Sumatra, is a major stratigraphic marker in the Indian Ocean that is correlable in deep sea cores from the Bay of Bengal (Pattan et al., 2002). We will continue our major and minor Microprobe and ICP-MS work as described in Results to help constrain stratigraphic correlation with the Holocene tephras found in middle to southern Sumatran cores. The tephra analytical work is supported in a supplement to our 2007 award.

**Responsibilities of Investigators and Collaborative Statement**

C. Goldfinger will be the principal investigator and direct the proposed program. Co Pi Joseph Stoner will conduct U-channel magnetic work and develop a radiocarbon supported paleomagnetic time line (Previously supported work, deferred to 2010). Adam Kent will take the lead on ongoing tephra work with PhD student Morgan Salisbury. This work is supported by the existing supplement to this project. We also are collaborating (at no cost to the proposal) with Takeshi Nakajima and Ken Ikehara, leading sedimentologists specializing in turbidite/fan systems and paleoseismology at AIST in Japan, and Kerry Sieh and his Tectonic Observatory lab in Singapore (formerly at Caltech). Sieh has pioneered the record of onshore paleoseismology in Sumatra over the last decade, with unprecedented success. Sieh is actively engaged in mapping the uplift and subsidence signature of the recent earthquake on the ground in Aceh Province, and our labs are working collaboratively to expand this ground truth to a regional representation of vertical motion with satellite imagery. We are collaborating with Yusuf S. Djajadhardja, of BPPT, one of the two primary Indonesian science Agencies. We are also directly collaborating with the Russ Wynn of the UK Sumatra team that has recently conducted new seismic profiling and collected several new cores in Sumatra. Their core sites were designed to complement our core set. See attached letters of support. The lead investigators from France, the UK, Germany, Japan and the US are all proponents of an IODP proposal to drill the Sumatran margin, led by Goldfinger.

**Broader Impacts**

This project will compliment efforts underway to establish baseline tectonics and seismic data for the Sumatran subduction zone. Studies underway and proposed include high-resolution seismic reflection, OBS, GPS, and other geophysical efforts, and land paleoseismic studies focused on raising our level of understanding of seismogenic zones while providing critical information needed to assess seismic risk in the region. We expect that this project will have significant impact and improve earthquake and tsunami hazard assessment for Indonesia, India, Sri Lanka, and Thailand. The data from this project will be publicly available via publications and our web site as soon as they are processed and in accord with MARGINS data policies. We will support two graduate students (one from Indonesia), and have worked with 12 colleagues and 16 other graduate and undergraduate students who participated in the sea-going phase of the project. These students have received training in paleoseismology, sedimentology, seismic reflection and seafloor mapping.

**Results of Prior Support**

"Holocene Seismicity of the Cascadia Subduction Zone Based on Precise Dating of the Turbidite Event Record: Collaborative Research between Oregon State University and the US Geological Survey"

**Grant EAR 9803081**

7/1/98 12/31/03 PI's: C. Goldfinger, C. H. Nelson, PhD student J. E. Johnson

This project is described above in some detail, as these results bear directly on the current proposal. Our results have been reported at the AGU 1999 through 2007 Fall Meetings, the SSA 2001 Annual Meeting, and at a Workshop on marine paleoseismicity in Tsukuba Japan (May 2004) organized by K. Satake and C. Goldfinger. Additional invited papers have been presented at the Cascadia Penrose Conference, The Stanford Conference on the Northern San Andreas, two AAPG meetings and Hokudan Active Faulting Symposium, January 2005, and in IPG Paris and Caltech. We have published our results as part of an SEPM Special Publication, and two review publications in Annali Geofisica and Annual Reviews, a BSSA paper in 2008, and USGS Professional Paper 1661-F, in press.
References Cited


Stoner, J.S., Channell, J.E.T., and Hillaire-Marcel, C. The magnetic signature of rapidly deposited D-8


Sugiyama, Y., 1994, Neotectonics of Southwest Japan due to the right-oblique subduction of the Philippine Sea plate: Geofisica Internacional, v. 33, p. 53-76.


BIOGRAPHICAL SKETCH - CHRIS GOLDFINGER

A. PROFESSIONAL PREPARATION:

• B.A. (Geology) Humboldt State University 1980
• B.S. (Oceanography) Humboldt State University 1980
• M.S. (Geology) Oregon State University 1990
• Ph.D. (Structural Geology) Oregon State University 1994

B. APPOINTMENTS

• Associate Professor of Oceanography 5/02-present
• Associate Professor of Oceanography (Senior Research) 6/00-5/02
• Assistant Professor of Oceanography (Senior Research) 4/95-6/00
• Consultant (Earthquake Hazards) 4/94-present
• Post-Doctoral Research Associate, Oregon State University 3/94-4/95
• Research Assistant, Oregon State University 4/89-3/94

C. PUBLICATIONS

Most Closely Related to Proposed Project


Other Significant Publications

2004  Active deformation of the Gorda plate: Constraining deformation models with new geophysical data, Geology v.32, p.353-356, (Chaytor, J.D., Goldfinger, C., Dziak, R.P., and Fox, C.G.)


D. SYNERGISTIC ACTIVITIES

Teaching Experience:
- Courses Taught in Geology of Earthquakes, Plate Tectonics, sonar principles, Great earthquakes, Geophysics, Structural Geology, Field Methods, Summer Field Camp,

Professional Service:

Field Experience (most recent):
• Chief Scientist, NNF, Stress transfer, Cascadia Subduction Zone-NSAF, RV Thompson, 2009.
• Chief Scientist, NSF cruise, Paleoseismology of the Sumatran Subduction Zone, RV Revelle, 2007.
• Chief Scientist, NSF cruise, San Andreas Fault Paleoseismicity, RV Revelle 2002
• Chief Scientist, NSF cruise, PROD Drill Sea Trial, RV Thompson, March, 2000.
• Chief Scientist, NSF cruise, Cascadia Subduction Zone Paleoseismicity, RV Melville, July, 1999.
• Scientist: NSF cruise, Peru-Chile subduction zone, coring, sidescan, multibeam, seismic, 1997.

E. COLLABORATORS AND OTHER AFFILIATIONS


ii) Thesis Advisor - R.S. Yeats, Post Doctoral Advisor, LaVerne D. Kulm

iii) Students advised (Graduate): Joel Johnson, Jason Chaytor, Andrew Lanier, Grant Kaye, Chris Romsos, Daniel Wisdom, Natalie Reed, Melinda Agapito
Name of Proposal: Sumatra phase II

PI Name: Chris Goldfinger

Salaries & Wages

<table>
<thead>
<tr>
<th></th>
<th>1/1/2010</th>
<th>FY 09-10</th>
<th>1/1/2011</th>
<th>FY 10-11</th>
<th>1/1/2012</th>
<th>FY 11-12</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.) Senior Personnel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chris Goldfinger</td>
<td>3</td>
<td>21,900</td>
<td>3</td>
<td>22,776</td>
<td>3</td>
<td>23,652</td>
</tr>
<tr>
<td>B.) Other Personnel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>student GRA</td>
<td>18</td>
<td>38,418</td>
<td>18</td>
<td>40,182</td>
<td>18</td>
<td>42,000</td>
</tr>
<tr>
<td>student hourly</td>
<td>9</td>
<td>21,770</td>
<td>9</td>
<td>22,760</td>
<td>9</td>
<td>23,780</td>
</tr>
<tr>
<td>Lab Technician</td>
<td>4</td>
<td>16,504</td>
<td>4</td>
<td>17,659</td>
<td>3</td>
<td>14,111</td>
</tr>
<tr>
<td>Total Salaries &amp; Wages</td>
<td>98,592</td>
<td>103,377</td>
<td></td>
<td>103,543</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C.) Fringe Benefits OPE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chris Goldfinger</td>
<td>0.47</td>
<td>10,293</td>
<td>0.48</td>
<td>10,932</td>
<td>0.5</td>
<td>11,826</td>
</tr>
<tr>
<td>GRA</td>
<td>0.1</td>
<td>3,842</td>
<td>0.1</td>
<td>4,018</td>
<td>0.1</td>
<td>4,410</td>
</tr>
<tr>
<td>hourly student (summer)</td>
<td>0.1</td>
<td>2,177</td>
<td>0.1</td>
<td>2,276</td>
<td>0.1</td>
<td>2,378</td>
</tr>
<tr>
<td>Lab Technician Morey</td>
<td>0.57</td>
<td>9,407</td>
<td>0.59</td>
<td>10,419</td>
<td>0.61</td>
<td>8,608</td>
</tr>
<tr>
<td>Total Fringe</td>
<td></td>
<td>25,719</td>
<td></td>
<td>27,646</td>
<td></td>
<td>27,222</td>
</tr>
<tr>
<td>Total Salaries, Wages &amp; Fringe Benefits</td>
<td>124,311</td>
<td>131,023</td>
<td></td>
<td>130,764</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D.) Equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total equipment</td>
<td>-</td>
<td>-</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>E.) Travel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Domestic, AGU meetings</td>
<td>1,000</td>
<td>1,000</td>
<td>1,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>International, travel to UK, Indonesia meetings</td>
<td>2,200</td>
<td>2,200</td>
<td>2,200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UC Irvine 14C lab</td>
<td>1,800</td>
<td>1,800</td>
<td>1,800</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Travel</td>
<td>5,000</td>
<td></td>
<td>5,000</td>
<td></td>
<td>5,000</td>
<td></td>
</tr>
<tr>
<td>F.) Subawards</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G.) Other Direct Costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Materials &amp; Supplies</td>
<td>1,500</td>
<td>1,500</td>
<td>1,500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Publications/Documentation/Dissemination</td>
<td>1,500</td>
<td>1,500</td>
<td>2,500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Computer Services</td>
<td>1,300</td>
<td>1,300</td>
<td>1,300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Shipping</td>
<td>500</td>
<td>1,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Tuition three terms per year, 2 students</td>
<td>19,742</td>
<td>20,406</td>
<td>21,080</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Communications</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. 14C ages</td>
<td>5,200</td>
<td>5,200</td>
<td>5,200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. software licences and maint agreements</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Other Direct Costs</td>
<td>30,242</td>
<td>31,406</td>
<td>34,580</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Direct</td>
<td>159,553</td>
<td></td>
<td>167,429</td>
<td>-</td>
<td></td>
<td>170,344</td>
</tr>
<tr>
<td>Modified Direct (total direct less tuition, sub-award in excess of $25K, equipment, pa</td>
<td>139,811</td>
<td>147,023</td>
<td>149,264</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facilities &amp; Administration Costs (formerly Indirect Costs)</td>
<td>64,593</td>
<td>67,925</td>
<td>69,960</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>224,146</td>
<td>235,354</td>
<td></td>
<td>239,304</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total project costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>698,804</td>
</tr>
</tbody>
</table>
The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

<table>
<thead>
<tr>
<th>Investigator: Chris Goldfinger</th>
<th>Other agencies (including NSF) to which this proposal has been/will be submitted.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Support:</strong></td>
<td>X Current Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Future</td>
</tr>
<tr>
<td><strong>Project/Proposal Title:</strong></td>
<td>Stress Transfer Between the Cascadia Megathrust and the Northern San</td>
</tr>
<tr>
<td><strong>Source of Support:</strong></td>
<td>NSF</td>
</tr>
<tr>
<td><strong>Total Award Amount:</strong></td>
<td>$444,972</td>
</tr>
<tr>
<td><strong>Total Award Period Covered:</strong></td>
<td>2/1/09-1/31/12</td>
</tr>
<tr>
<td><strong>Location of Project:</strong></td>
<td>OSU</td>
</tr>
<tr>
<td><strong>Person-Months Per Year Committed to the</strong></td>
<td>Cal: 1/3/3  Acad:0  Sumr: 0</td>
</tr>
<tr>
<td><strong>Support:</strong></td>
<td>X Current Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Future</td>
</tr>
<tr>
<td><strong>Acquisition of a 2G Enterprises Superconducting Rock Magnetometer Optimized for U-Channel Samples</strong></td>
<td>Oregon State University</td>
</tr>
<tr>
<td><strong>Source of Support:</strong></td>
<td>NSF</td>
</tr>
<tr>
<td><strong>Total Award Amount:</strong></td>
<td>$440,450.00</td>
</tr>
<tr>
<td><strong>Total Award Period Covered:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Location of Project:</strong></td>
<td>OSU</td>
</tr>
<tr>
<td><strong>Person-Months Per Year Committed to the</strong></td>
<td>Cal: 0  Acad0:  Sumr: 0</td>
</tr>
<tr>
<td><strong>Support:</strong></td>
<td>X Current Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support Future</td>
</tr>
<tr>
<td><strong>Project/Proposal Title:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Source of Support:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Total Award Amount:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Total Award Period Covered:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Location of Project:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Person-Months Per Year Committed to the</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Support:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Project/Proposal Title:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Source of Support:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Total Award Amount:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Total Award Period Covered:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Location of Project:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Person-Months Per Year Committed to the</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Support:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Project/Proposal Title:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Source of Support:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Total Award Amount:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Total Award Period Covered:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Location of Project:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Person-Months Per Year Committed to the</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Support:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Project/Proposal Title:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Source of Support:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Total Award Amount:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Total Award Period Covered:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Location of Project:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Person-Months Per Year Committed to the</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Support:</strong></td>
<td></td>
</tr>
</tbody>
</table>

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

NSF Form 1239 (10/99) USE ADDITIONAL SHEETS AS NECESSARY
**Current and Pending Support**

*(See GPG Section II.D.8 for guidance on information to include on this form.)*

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

<table>
<thead>
<tr>
<th>Investigator: Chris Goldfinger</th>
<th>Other agencies (including NSF) to which this proposal has been/will be submitted.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Support:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Submission Planned in Near</strong></td>
<td><strong>Future</strong></td>
</tr>
<tr>
<td><strong>Project/Proposal Title:</strong></td>
<td><strong>Multibeam mapping of Oregon Territorial Sea for multi-use</strong></td>
</tr>
</tbody>
</table>

**Source of Support:** State Of Oregon  
**Total Award Amount:** $1,289,000  
**Total Award Period Covered:** 7/1/09-6/30/2011  
**Location of Project:** OSU  
**Person-Months Per Year Committed to the Project:** Cal: 3/3  
**Acad:**  
**Sumr:**

| **Support:** |  | **Pending**  |
| **Submission Planned in Near** | **Future**  |  |
| **Project/Proposal Title:** | **N.E. Pacific ¹⁴C Reservoir Variability Using Synchronous Holocene Earthquake Datums (This Proposal)**  |  |

**Source of Support:** NSF  
**Total Award Amount:** $281,376  
**Total Award Period Covered:** 3/1/06-2/28/09  
**Location of Project:** OSU  
**Person-Months Per Year Committed to the Project:** Cal: 1.5/1.  
**Acad:**  
**Sumr:**

| **Support:** |  | **Pending**  |
| **Submission Planned in Near** | **Future**  |  |
| **Project/Proposal Title:** | **Exploring the Undersea San Andreas Fault: Uncovering the Past, Present and the Centennial of the Great 1906 Earthquake**  |  |

**Source of Support:** NOAA  
**Total Award Amount:** 343,930  
**Total Award Period Covered:** 4/1/010-3/31/12  
**Location of Project:** OSU/NOAA  
**Person-Months Per Year Committed to the Project:** Cal: 3  
**Acad:**  
**Sumr:**

| **Support:** |  | **Pending**  |
| **Submission Planned in Near** | **Future**  |  |
| **Project/Proposal Title:** |  |  |

**Source of Support:**  
**Total Award Amount:**  
**Total Award Period Covered:**  
**Location of Project:** OSU  
**Person-Months Per Year Committed to the Project:** Cal:  
**Acad:**  
**Sumr:**

| **Support:** |  | **Pending**  |
| **Submission Planned in Near** | **Future**  |  |
| **Project/Proposal Title:** |  |  |

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.*

---

**NSF Form 1239 (10/99)**  
**USE ADDITIONAL SHEETS AS NECESSARY**
FACILITIES, EQUIPMENT & OTHER RESOURCES

FACILITIES: Identify the facilities to be used at each performance site listed and, as appropriate, indicate their capacities, pertinent capabilities, relative proximity, and extent of availability to the project. Use “Other” to describe the facilities at any other performance sites listed and at sites for field studies. Use additional pages if necessary.

Laboratory: Our lab facilities include a sea-going MST van which is used to scan cores, collecting GRAPE density, Magnetic susceptibility, P-wave velocity, X-radiography, and high-resolution line-scan imagery. A new feature is an automated high-resolution magnetic tool, which has become invaluable for core correlation. Onshore facilities include the NORCOR core-repository, at which all Pacific Northwest cores from academic institutions are stored. The facility includes complete lab capability for core processing, logging, sampling, micro-paleontologic analysis etc. OSU has a high-resolution Aquillon 64 slice Computed Tomography (CT) facility located adjacent to the Core Repository. This imager provides 3D imagery volumes of cores at 0.35 mm spatial resolution.

Clinical:

Animal:

Computer: The Active Tectonics/Sea Floor Mapping Lab at COAS(Marine geology) is a computer/GIS facility capable of acquisition and processing of many types of geophysical data including seismic reflection, magnetics, sidescan sonar, and multibeam bathymetry. Seismic reflection data is processed and imaged using Seismic Unix from the Colorado School of Mines, Sioseis from Scrippps, and Kingdom Suite. These data are integrated and interpreted in the ERDAS Imagine and Arc/GIS 9.3 GIS system using PC and Sun workstations. The lab currently has a storage capacity of ~ 50 TB, including all bathymetry data for the US west coast and Indonesia. We also use the Fledermaus 3D visualization system for data editing and real-time fly throughs of complex datasets for improved visualization and interpretation. COAS maintains a high-speed gigabit fiberoptic network, linking these workstations with high-end massively parallel processors and a variety of high-resolution output devices. The lab has been in operation since 1992.

Other:

MAJOR EQUIPMENT: List the most important items available for this project and, as appropriate, identify the location and pertinent capabilities of each.

OSU has complete sea-going and onshore facilities for acquisition, processing, and storage of deep-sea sediment samples of all types. OSU has several 4" diameter piston coring rigs, with 4" trigger corers, and a highly experienced full-time coring technician. We have a new 3m jumbo Kasten corer designed for large sample volume in young sediments, which are difficult to date due to the low abundance of forams. We also have smaller push and box cores designed for submersibles such as ROPOS and ALVIN.

OTHER RESOURCES: Provide any information describing the other resources available for the project. Identify support services such as consultant, secretarial, machine shop, and electronics shop, and the extent to which they will be available for the project. Include an explanation of any consortium/contractual/subaward arrangements with other organizations.