Chapter 1

Introduction and Synthesis

Motivation: inadequacy of data for understanding earthquake cycles

Understanding the behavior of active faults over multiple seismic cycles has been an elusive goal of earthquake science. The extent to which fault behavior—including both strain accumulation and relief—varies over centennial to millennial time scales remains poorly resolved. Outstanding questions concern the regularity of fault rupture, the repeatability of the pattern of slip on a fault, and the roles of geologic structure and rheology in governing ruptures and their terminations. Instrumental records of earthquakes and ground deformation are commonly far too short to observe faults over more than a fraction of the cycle of interplate strain accumulation and release—which can last hundreds to more than hundreds of thousands of years—let alone over multiple earthquake cycles. Consequences of this inadequacy of observations include an inability to rigorously test many models of fault behavior and, in many parts of the world, an under-appreciation of seismic hazards. Probably the most devastating and tragic example of this is along the northern Sunda megathrust, where the magnitude 9.2 earthquake of 26 December 2004 and its associated tsunami caused widespread destruction and nearly 230,000 fatalities along coastlines of the Indian Ocean. In general, no significant threat had been perceived along this section of the megathrust, because no instrumental or historical record suggested earthquakes like this had occurred in the past [*Bilham*, 2005; *Bilham et al.*, 2005; *Subarya et al.*, 2006], and because the accepted models of megathrust potential productivity [*Ruff and Kanamori*, 1980; *Kanamori*, 1983] lacked sufficient data to be adequately tested.

The instrumental and historical records can be extended back in time in many places by careful examination of the geological record. Paleoseismology has contributed to understanding serial fault ruptures. This is a slow process, however, because relevant data bearing on how past strains have accumulated and been released along faults are difficult to obtain. Progress has been hampered by imprecision and incompleteness of most records, the difficulty to find suitable sites, and the long periods of time required to develop good sites once they are identified. The biggest obstacles in conventional trenching paleoseismology—both along continental faults and above subduction zones—have been the distance between well-developed sites with good records (often tens of kilometers or more) and limitations in the precision of dating (seldom better than ±30 years) afforded by radiocarbon techniques. The large uncertainties in the timing of past earthquakes and the long distances between sites have made the correlation of events along a fault ambiguous and subjective [*Weldon et al.*, 2005; *Biasi and Weldon*, 2009]. Furthermore, even in places where long records exist or precise details of past earthquakes are known—for example, along parts of the San Andreas [*Sieh et al.*, 1989; *Liu et al.*, 2004; *Weldon et al.*, 2004; *Scharer et al.*, 2007] and North Anatolian [*Stein et al.*, 1997] faults, and above the Cascadia [*Atwater and Hemphill-Haley*, 1997; *Atwater et al.*, 2005; *Kelsey et al.*, 2002, 2005; *Witter et al.*, 2003] and Nankai [*Ando*, 1975; *Sugiyama*, 1994] megathrusts—paleogeodetic data for interseismic periods are sparse or lacking.

Off the west coast of mainland Sumatra and on the Nicobar and Andaman Islands, there is an opportunity to address many of the outstanding questions of fault behavior over multiple earthquake deformation cycles. During Earth's two largest earthquakes of the past 44 years (1966–2009)—the M_W 9.2 Sumatra-Andaman earthquake of 2004 and the M_W 8.6 Nias-Simeulue earthquake of 2005—adjacent segments of the Sunda megathrust ruptured from the Equator to 15° N, with nearly 20 m of slip in 2004 [*Chlieh et al.*, 2007] and more than 11 m of slip in 2005 [*Briggs et al.*, 2006]. Like typical megathrust ruptures, these earthquakes produced regions of uplift above the elongated rupture patches, with troughs of subsidence immediately landward (away from the trench). The presence of outer-arc islands directly above the seismogenic regions of the Sunda megathrust—and within the uplift regions of these earthquakes—allowed for unprecedented documentation of the surface deformation associated with these megathrust earthquakes [*Meltzner et al.*, 2006; *Subarya et al.*, 2006; *Briggs et al.*, 2006]. In addition, coral microatolls on fringing reefs of the tropical archipelago record past vertical deformation, allowing us to examine details of past behavior of the Sunda megathrust.

Coral microatoll paleogeodesy, with its ability to provide continuous century-long or multi-century records of high precision paleo-elevation data with remarkably precise ages, yields unparalleled resolution in the reconstruction of both the pattern of interseismic strain accumulation and the timing and extent of past megathrust ruptures. The abundance and high precision of the data allow us to correlate events with high confidence, or to distinguish distinct events separated by a few decades or sometimes less. This, in turn, permits us to begin addressing questions about the timing and similarity of past ruptures, about earthquake recurrence models, about the persistence of barriers to rupture, and about the variability of strain accumulation over the seismic cycle and over multiple seismic cycles. The availability of such data is restricted to portions of the outer arc with islands, but, fortunately, suitable sites can commonly be found at spacings of less than 20 km on these islands and can be developed in a matter of a few days or less.

Over the course of four seasons of field work between May 2005 and February 2009, I, along with my advisor (K. Sieh) and field assistants, developed 27 paleogeodetic sites on the Sumatran outer arc islands between 0.5° and 3.0°N, many of which consist of two or three subsites separated by ~1 km or less. We sampled a total of 34 modern microatolls (microatolls that were living at the time of the 2004 earthquake) and 82 fossil microatolls and coral heads (those that died long ago, presumably in past uplift events), which combine to provide a rich archive of past deformation above this section of the Sunda megathrust. Results from 8 sites (comprising 9 modern and 28 fossil corals) are presented in this thesis, most of which will be submitted for publication soon after the defense; analyses of the remaining heads are still too preliminary to be presented at this time, but will be submitted for publication subsequently.

Content and organization of this thesis

This work is divided into five chapters. Chapter 2 contains the results of a study I led using satellite imagery and a handful of *in situ* measurements on coral microatolls to constrain the along-strike and downdip limits of the 2004 rupture of the Sunda megathrust. This chapter was published in the *Journal of Geophysical Research* [*Meltzner et al.*, 2006] and is reproduced here in its entirety without modification, except for changes to values in the "2sigma" column in Supplementary Table 1 (discussed in the next section) and for general reformatting of the auxiliary material. In addition to the changes in Supplementary Table 1, some of the measurements reported by *Meltzner et al.* [2006] that were derived from coral microatolls on northern Simeulue have since been revised slightly; however, rather than modify the content of the original paper, I discuss the revisions and corrections in detail, and I report revised values, in Chapters 3 and 4. None of the conclusions of *Meltzner et al.* [2006] are affected by these minor changes.

Chapters 3–5 contain results from paleogeodetic investigations above the Sunda megathrust. They focus on the region near the boundary of the 2004 M_W 9.2 rupture and the 2005 M_W 8.6 rupture to the south. The first two of these chapters focus on seven sites above the southern end of the 2004 rupture (see Chapter 3, Fig. 1): Chapter 3 is the main text, and Chapter 4 is the auxiliary material, of a manuscript that is in press in the *Journal of Geophysical Research*. Chapter 5 focuses on one site at the northern end of the 2005 rupture (see Chapter 5, Fig. 1) and contrasts the record found at that site with those from sites farther north. Chapters 4 and 5 both have appendices available as electronic supplements to this thesis. The electronic supplement for Chapter 4 contains high-resolution x-ray mosaics of the coral slabs and field photographs of the sites discussed in Chapters 3 and 4; the supplement for Chapter 5 contains high-resolution x-ray mosaics and field photographs for the site discussed in Chapter 5.

Uplift and subsidence associated with the 2004 earthquake

The primary objective of our work on the 2004 earthquake was to determine the limits of the region of uplift, and by extension, the downdip and along-strike extent of the rupture. While the most direct goal of paleoseismology and paleogeodesy is to extend the modern record of strain accumulation and relief into the past, it is important to document modern ruptures in as much detail as possible, in order to calibrate observations of deformation during past earthquakes. Furthermore, if we are to assess the earthquake hazard at present, we need to know not only what a fault is capable of over long periods of time, but also how it has behaved in the recent past, so that we may identify asperities or regions where substantial strain is accumulated at present.

Because the 2004 rupture was so long in length and duration, seismic inversions for the event were particularly non-unique and proved to be limited in their ability to resolve many details of slip, especially along the later, northern portion of the rupture. Moreover, because slip north of ~9°N generated little or no seismic radiation, the seismic inversions provide only a minimum constraint on the extent and amount of slip. Inversions of geodetic data (and joint inversions of both seismic and geodetic data) were critical to resolving the details of slip in the 2004 earthquake. Until the imagery-based geodetic observations in Chapter 2 were available, however, the sparse geodetic data obtained from a handful of campaign Global Positioning System (GPS) stations scattered above the 1600-km long rupture provided only limited constraints on the amount and distribution of slip [e.g., *Subarya et al.*, 2006]. Indeed, the observations of *Meltzner et al.* [2006] are still the most compelling evidence that the 2004 rupture was 1600 km long, extending northward to ~14.9°N.

Part of these efforts involved the development of a technique to combine information about tides with satellite images, in order to differentiate regions of coseismic uplift and coseismic subsidence. This method has since been used to study earthquakes along subduction zones elsewhere, such as the 2007 earthquake in the Solomon Islands [*Taylor et al.*, 2008].

Subsequent to the publication of the work on the 2004 rupture in the *Journal of Geophysical Research*, however, I became aware of certain phenomena, beyond tides, that influence sea surface heights; I also became aware of efforts by groups such as AVISO to extract from satellite altimetry data a near-global time series of sea level anomalies (available at http://www.aviso.oceanobs.com/en/data/products/sea-surface-height-products/global/msla/). Chapter 3 presents an improved methodology for determining water levels, and Chapters 3 and 4 both include revised estimates of the 2004 uplifts on Simeulue island.

The imagery-based constraints on land-level changes in the Andaman and Nicobar Islands in 2004, published by *Meltzner et al.* [2006], did not account for non-tidal sea level anomalies, and have not been recalculated. Fortunately, however, sea level anomalies in the Andaman and Nicobar Islands tend to be small: the standard deviation of those anomalies from 2000 to 2005 ranges from 5 to 7 cm over the Andaman–Nicobar region. These sea level anomalies, which are dominated by seasonal variability, should be effectively independent of the 5-cm standard deviation reported by *Meltzner et al.* [2006], which was determined based on 8 consecutive days of tide gauge data collected in January 2005. If the two independent errors are added in quadrature, the resulting 1σ error for the sea surface heights provided by the tide model would be 7–9 cm. The 2σ error for the difference in sea surface heights at the acquisition times of any pair of images, which was originally reported by *Meltzner et al.* [2006] as 14 cm for each pair of images, is corrected in Table S1 of Chapter 2 to be 24 cm for each pair of images. This larger error accounts for the fact that non-tidal sea level anomalies were not considered in the imagery-based uplift and subsidence calculations of *Meltzner et al.* [2006].

Imagery-based constraints on uplift or subsidence in the 2007 Solomon Islands earthquake also did not strictly account for non-tidal sea level anomalies, but the error bars provided by *Taylor et al.* [2008] implicitly accounted for those anomalies, just as the revised, larger error bars do in Table S1 of Chapter 2 of this thesis.

Paleogeodesy and paleoseismology of the Sunda megathrust

My research on the paleogeodesy and paleoseismology of the Sumatran outer arc from 0.5° to 3.0°N has yielded findings that can be divided into three geographical regions, based upon the regions' discrete rupture histories and the questions that are resolved in each region. The northern region of my field area is the southern part of the 2004 rupture: northern Simeulue and the Salaut islands to the northwest. Our foremost findings in this region involve documentation of evidence for a cluster of earthquakes in the 14th–15th centuries and an earlier event in the 10th century. If no great earthquakes are missing from the record, this suggests a 400- to 600-year recurrence interval for megathrust earthquakes or earthquake clusters at the southern end of the 2004 patch. The southern region corresponds roughly to the 2005 rupture—southern Simeulue, the Banyak Islands, and Nias—where we have solid evidence for an earthquake in 1861 and for several earlier ruptures. Central Simeulue, where cumulative uplift in the 2004 and 2005 earthquakes was half a meter or less, cooperates at times with the 2005 patch, but may also behave independently. We consider central Simeulue as a distinct region because of a complicated history of strain accumulation and relief along this section of the fault, and because the prehistoric record from this region, when contrasted with overlapping records from northern Simeulue, provides compelling evidence for a persistent barrier to rupture. The latter three chapters of this thesis include results from the northern region and from one particularly informative site in central Simeulue.

Chapters 3 and 4 are essentially two parts of a whole, both covering the six sites of northern Simeulue and the single site on Salaut Besar island to the northwest. Chapter 3 provides detailed analyses of the observations at our primary northern Simeulue site, an overview of the findings from northern Simeulue in general, and a discussion of potential implications; Chapter 4 is written as auxiliary material to Chapter 3, providing detailed results from the additional northern Simeulue sites. Chapter 3 also contains a thorough explanation of the methods employed and of assumptions that have been made in this study; while I have generally built upon methods developed by my advisor and previous graduate students [*Zachariasen*, 1998; *Zachariasen et al.*, 1999, 2000; *Natawidjaja et al.*, 2004, 2006, 2007], I have made fundamental advances and modified certain techniques. An interpreted line drawing of each coral slab cross-section in this study is included among the figures in Chapters 3 and 4; alternate versions of these cross-sections with high-resolution x-ray mosaics appear in the appendix (electronic supplement) to Chapter 4. Also in the electronic supplement to Chapter 4 are aerial photos of some of the sites, taken by helicopter in 2005 soon after the uplift, and field photos of some of the microatolls that were slabbed for analysis.

Chapter 5 contains detailed analyses of coral slabs from one site on the west coast of central Simeulue. This chapter is less polished than the preceding three chapters, and it is not structured to be submitted for publication in its present form, but it is sufficient to demonstrate that neither northern Simeulue ruptures nor central-southern Simeulue ruptures propagate far into each other's domain: during the times for which simultaneous records exist from both regions, all ruptures observed as significant uplifts in one region had little effect in the other. Ultimately, these results will be combined with observations from other central Simeulue sites that augment the evidence in Chapter 5, and all of this will be published together. Speculation and discussion are minimal at this early stage of the work in Chapter 5, but a thorough discussion of possible implications of the results will be presented in the eventual manuscript prepared for publication. Chapter 5 also has an appendix that is available as an electronic supplement. As with Chapter 4, this appendix includes versions of the cross-sections containing high-resolution x-ray mosaics, as well as field photos of some of the microatolls that were slabbed for analysis.

Altogether, the results from paleogeodetic investigations presented in this thesis provide a rich data set that sheds light on the rupture history of the southern end of the 2004 Sunda megathrust rupture patch and that constitutes compelling evidence that central Simeulue has acted as a persistent barrier to megathrust ruptures over, at least, the past 700 years.

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