Synopsis

Tsunami hazards were greatly underestimated along the coasts of countries bordering the northeastern Indian Ocean until the occurrence of the 26 December 2004, M_w 9.2 earthquake and its ensuing tsunami. Sourced off the coast of northern Sumatra, on the plate boundary between the Indo-Australian and Eurasian plates, the rupture of the 2004 earthquake propagated ~1300 km northward. The magnitude of this earthquake and the reach of its tsunami exceeded all known precedents, based on instrumental and historic records. The coseismic deformational and post-tsunami depositional features facilitated opportunities to conduct tsunami geology studies along the coasts of countries bordering the Indian Ocean. Several questions are being posed, the answers of which have implications for tsunami hazard assessment. How did this plate boundary behave prior to and after the great earthquake? Was the 2004 earthquake the first of its kind on the Sumatra-Andaman plate boundary? If it had a predecessor, when did it occur and was it a true predecessor in terms of its rupture dimensions and tsunamigenic potential? What types of depositional evidence are preserved and how can we use them to develop the history of past tsunamigenic earthquakes? Researchers are exploring the affected regions and using the imprints left by the 2004 event, to address these questions.

There are two components to this study: one, a seismotectonic analysis of the region from the perspective of plate driving forces and their relative roles in the interseismic and post-seismic phases. This study uses global data catalogs like the NEIC PDE (National Earthquake Information Centre Preliminary Determination of Epicenters) and the Global Centroid Moment Tensor (CMT) solutions for earthquake source parameters to understand the along-strike variations in seismicity patterns before and after the 2004 earthquake.

The 2004 experience was unprecedented in South Asia. Unaffected by tsunami hazards in the past, tsunami geology is a nascent field for most South Asian researchers. Very little background field data is available on the deformational features of great earthquakes along this plate boundary and the depositional characteristics of extreme coastal surges, such as tsunamis and storms. Where do we begin our search for evidence of past tsunamigenic earthquakes? How best can we use

the 2004 tsunami and its deposits as a proxy? What problems are encountered in the interpretations? This thesis addresses these questions in part and presents observations from the Andaman Islands (the ~400 km, northern segment of the Sumatra-Andaman subduction zone) and the southeast coast of India, towards developing a reliable database of tsunami geology for 2004-type events.

The premise is that regions affected by the 2004 earthquake are more likely to conserve signatures from older events. Based on the stratigraphic context of the proxy and quality of age estimates, this work presents evidence for past earthquake related deformation and tsunami deposition. In this work we use deformational and depositional features from the Andaman Islands, falling within the 2004 rupture zone and from one location on the Tamil Nadu coast of India (Kaveripattinam). From a perceptive understanding of the features related to tectonic deformation of the Sumatra-Andaman subduction zone, we have selected the Andaman segment that demonstrates explicit evidence for deformation and tsunami deposition through geomorphological and stratigraphic features, which are key to our exploration. A gist of each chapter is given below.

The introduction **(chapter 1)** presents the background, motivation and scope of this work and the organization of this thesis, also summarizing the contents of each chapter. **Chapter 2** provides a review of literature on subduction zone earthquakes and updates on tsunami geology, to place this study in the global context. The next two chapters discuss the seismotectonics of the Sumatra-Andaman plate boundary, the important earthquakes and their source processes. In **chapter 3** we discuss the Andaman segment (from 10–15° N), characterized by relatively lower level seismicity, but distinctive, as it falls within the northern limit of the 2004 rupture. The deformational and depositional features here are better exposed due to availability of land straddling the hinge line separating the areas of 2004 uplift and subsidence. Here, the pre-2004 earthquakes used to occur along a gently dipping subducting slab, up to a depth of about 40 km. Post-2004, the earthquakes moved up-dip, extending also to the outer-rise and outer-ridge regions, expressing post-earthquake relaxation [*Andrade and Rajendran*, 2011]. The southern Nicobar segment (5–10° N) differs from the Andaman segment in its style of deformation and seismic productivity. The decreasing obliquity of convergence, the likely influence of a subducting ocean ridge on the subducting plate and the character of the subducting oceanic plate make this segment distinctly different. In **chapter 4** we present an analysis of its seismotectonic environment based on the well-constrained focal mechanisms of historic and recent earthquakes. We report that left-lateral strike-slip faulting on near N-S oriented faults control the deformation and the style of faulting is consistent to ~80 km within the subducting slab [*Rajendran, K. et al.*, 2011]. The 11 April 2012 sequence of earthquakes on the subducting oceanic plate, between the Sumatra Trench and the Ninety East Ridge are the more recent among the oceanic intraplate earthquakes that demonstrate the reactivation of N-S oriented fossil fractures.

The limited availability of land and the 2004 coseismic deformation dominated by subsidence, followed by prolonged waterlogging makes exploration difficult in the Nicobar segment. Thus, we focus on the Andaman Islands for deformational and depositional evidence, using observations that can be corroborated through multiple proxies and depositional environments that are not prone to other coastal surges, such as cyclones and storms. The criteria for selection of sites, evaluation of deposits and determination of limiting ages are discussed in chapters 5 through 9. In **chapter 5** we discuss different types of coastal environments and their response to high-energy sea surges. We also give a brief review of the comparative analyses of storm and tsunami deposits, a highly debated issue and then discuss important characteristics of these two deposits, using examples from the 2004 tsunami and the 2011 Thane cyclone that affected parts of the Tamil Nadu coast.

An important component of tsunami geology is the ability to identify and select datable material from tsunami deposits and chose an appropriate method for dating (**chapter 6**). The types of material used vary from peat layers, peat-rich soil, gastropod shells, wood, charcoal, organic remains such as bones, coral fragments, pottery sherds and buried soil. Techniques such as AMS Carbon-14 and Thermoluminescence are commonly used with appropriate calibrations and corrections. In addition to the dates generated in this study (based on wood and shell dates) we use some previous dates from the entire stretch of the rupture within the Indian Territory and assign a relative grading to these ages, based on the quality criterion evolved in this study. We believe that this is the first attempt to segregate age data obtained from coastal deposits, and assign them a specific quality grading based on their environment of deposition and the type of material dated.

Chapter 7 presents results of our investigations in the Andaman Islands, which cover ~30% of the rupture area. A coseismically subsided mangrove from Rangachanga (Port Blair, east coast of South Andaman) led us to a former subsidence during AD 770–1040, which we believe is the most convincing evidence for a previous tectonic event. Data based on inland deposits of coral and organic debris yielded a younger age in the range of AD 1480–1660. Both these dates fall in the age brackets reported from other regions of this plate boundary (mainly Sumatra) as well as distant shores of Sri Lanka, Thailand and mainland India. To understand the nature of distant deposits, we present observations from Kaveripattinam, an ancient port city on the east coast of India, where a high-energy sea surge deposit, found 1 km inland is attributed to a paleotsunami. The inland location of this archeological site at an elevation of 2 m and characteristics of the deposit that help discriminate it from typical storm deposition provide clinching evidence in favor of a 1000-year old regional tsunami (**chapter 8**).

In **chapter 9** we discuss the results of our study. We evaluate the nature of deformation/deposition and the calibrated age data in the context of their environments. Ages based on the organic material associated with coral debris (at Hut Bay and Interview Island) and the remains of mangrove roots, 1 m below the present ground level (at Port Blair) are considered as reliable estimates, due to their sheltered inland location and the *in situ* root horizon used for dating. Age data from Kaveripattinam is also considered reliable, based on its inland location beyond the reach of storm surges, sediment characteristics typical of tsunami deposition and ages based on multiple methods and samples. The age data based on the sites presented in this thesis are more conclusive about the 800 to 1100 AD and 1250 to 1450 AD tsunamis, and the former is represented from regions closer to the 2004 source as well as distant shores reached by its tsunami.

Chapter 10 presents our conclusions and the scope for future studies. We present this as the first study of its kind in the northeastern Bay of Bengal, wherein the coseismic vertical coastal deformation features along an interplate subduction

boundary and a variety of tsunami deposits are used to categorize depositional environments and ages of paleoearthquakes and tsunamis. To our knowledge, this is the first study of its kind where the effects of a recent tsunami have been used to evaluate paleodeposits based on their respective environments of occurrence. Our results have implications for tsunami geology studies in coastal regions prone to tsunami hazard.