APPENDIX - V

Title: Advanced Seismic Characterization of the Andaman Subduction Dynamics for Geohazards Prediction.

Introduction

Elevated fluid pressure in accretionary prism thrust faults significantly influences fault mechanics and geometry, though precise estimates are elusive (Tobin et al. 1994; Saffer 2003). Fluids from compaction and mineral transformations migrate through high-permeability pathways like faults and fractures (MacKay et al. 1992; Moore et al. 1995). This pressure is linked to episodic tremors, slow-slip events, and very low-frequency earthquakes (Park et al. 2010, 2014; Jaeckel et al. 2018; Bangs et al. 2023).

Faults expel fluids during sediment compaction and mineral dehydration, affecting tsunami earthquake strain accumulation (Bangs et al. 2014; Park et al. 2014; Hüpers et al. 2017). Diagenetic processes and sediment characteristics influence fault formation and fluid migration, forming décollement structures in consolidated sediments. Less-accreted regions experience significant deformation due to weak, less-consolidated materials and high pore-fluid pressure.

Seismic reflections show negative-polarity reflections indicating reduced acoustic impedance in décollement zones (Byrne and Fisher 1990; Moore and Vrolijk 1992; Bangs et al. 1996; Shipley et al. 1997; Dean et al. 2010; Tréhu et al. 2019; Stevens et al. 2021). Elevated pore fluid pressure affects seismic properties, altering stress and causing slipping or rupture properties (Sibson 2000; Ellis et al. 2015). Changes in seismic velocities reflect impedance contrasts due to pressurized fluids (Floyd et al. 2001), impacting seismic responses (Bangs et al. 1996, 1999, 2014, 2023; Park et al. 2010; Collot et al. 2011; Plaza et al. 2015; Qin and Singh 2017; Manthilake et al. 2021; Gase et al. 2023).

The 2004 Sumatra-Andaman (Lay et al. 2005) and 2011 Tohoku-Oki earthquakes (Ujiie et al. 2013) demonstrate how sediment properties influence slip behavior and rupture dynamics. Active fluid dehydration and migration precede subduction trench involvement. Fluid dehydration occurs as (i) a smectite-to-illite reaction before subduction (Hüpers et al. 2017; Stevens et al. 2021) and (ii) smectite dehydration at the décollement level beneath the forearc (Fitts and Brown 1999; Moore and Saffer 2001).

Background

On December 26th, 2004, a magnitude 9.2 earthquake struck north of Simeulue Island, Indonesia, rupturing a 210,000 km^2 section of the Sumatra–Andaman margin plate boundary, challenging assumptions about high sedimentary subduction zones (Stein and Okal 2005; Lay et al. 2005). The event started with a small slip and slow rupture, then rapidly expanded north-northwest along the Andaman trough, causing significant crustal deformation (Ammon et al., 2005). GPS data showed co-seismic jumps over 3,000 km from the epicenter, with a rupture plane extending at least 1,000 km (Vigny et al. 2005). Seismic waves even triggered local earthquakes in Alaska (West et al. 2005; Titov et al. 2005).

Seismic reflection data revealed fractures in the subducting crust and oceanic Moho, with active thrust faults aligned with aftershocks, indicating ongoing underplating beneath the forearc basin (Singh et al. 2008, 2012). Active folding across the northern Sumatra forearc suggested near-surface shortening and uplift influencing tsunami genesis (Fisher et al. 2007). A high-amplitude negative polarity (HANP) reflector, or pre-décollement, was identified, indicating a low-density, high-pore-pressure zone (Dean et al., 2010).

Earlier studies focused on understanding the rupture dynamics of the December 26th, 2004 Tsunami

The kinetic thermal model (KTM) has linked the release of freshwater and the dehydration of amorphous silica to shallow megathrust ruptures (Hüpers et al. 2017). Seismic full waveform inversion has identified a low-velocity Protodécollement layer that significantly influences megathrust dynamics (Qin and Singh 2017). In the context of the Nicobar Fan sediments, high temperatures lead to complete diagenetic dehydration of basal sediments, generating fluids that cause polarity reversals on Protodécollement reflectors (Stevens et al. 2021). These studies, based on seismic data primarily from IODP Site U1480 (Qin and Singh 2017; Hüpers et al. 2017; Stevens et al. 2021), acknowledge several limitations. The distance between Site U1480 and the deformation front (350 km) introduces uncertainties in the velocity model due to potential differences in geological conditions. Uncertainties in seismic velocities in the deepest sediments near the deformation front may affect the accuracy of thermal and dehydration models. Furthermore, the velocity model derived from full waveform inversion, while insightful, is constrained by the quality and resolution of seismic data and the assumptions made during inversion. Additionally, the interpretation of seismic amplitude reverse polarity on the proto-décollement, crucial for understanding fluid properties and sediment characteristics, relies on indirect evidence and may not fully capture subsurface complexities. Incorporating well-log data from distant regions introduces significant uncertainties in the kinematic model of fluid dehydration across the trench region, influenced by variations in geological properties, water content estimates, dehydration kinetics, depth estimates, and rates of fluid release. It is essential to carefully assess the applicability of well-log data to the specific geological setting of the study region and validate models with local data whenever feasible. Therefore, while these findings provide valuable insights, caution is advised when extrapolating to conditions at the less certain deformation front. Moreover, extending these studies to the Andaman-Nicobar subduction region is crucial. The absence of current observations of active fluid migration or dehydration in the Sumatra subduction zone underscores the need to investigate the Andaman-Nicobar region, where such phenomena may play a significant role in seismic activity and geological processes. Understanding fluid dynamics in this area could provide critical insights into earthquake mechanics, subduction dynamics, and hazard assessments, potentially informing mitigation strategies for seismic risks in the broader Indian Ocean region.

Present status of the seismic studies in the Andaman - Nicobar subduction region

The current status of Andaman-Nicobar studies focuses on understanding fluid migration and its role in earthquake dynamics using high-resolution 2D multi-channel seismic data. The analysis reveals that seismic velocities and amplitude variations in the proto-décollement and fault plane reflections indicate significant fluid presence and migration. These fluids, sourced from the compaction and mineral-phase transformations, influence earthquake rupture dynamics and tsunami generation. Negative polarity reflections, identified in both proto-thrust and frontal thrust zones, suggest high porosity and fluid content. However, uncertainties persist due to the distance of IODP data from the deformation front and variations in geological properties. While the findings provide valuable insights into the dynamics of fluid migration, they should be validated with local data to mitigate uncertainties and accurately extrapolate to less certain conditions (Sriram et al., under preparation).

Limitations of Seismic AVO Studies across the Décollement and Fault Plane Reflections

Seismic AVO (Amplitude Versus Offset) studies across décollement and fault plane reflections face significant limitations. These studies rely on indirect evidence, primarily amplitude variations with offset, which may inadequately capture the intricate complexities of subsurface fluid distribution and characteristics. Additionally, AVO analyses often simplify geological models and overlook variations in rock properties and fluid content, potentially leading to inaccuracies in interpreting subsurface conditions. The quality and resolution of seismic data used in these analyses further constrain their accuracy, particularly in detecting subtle variations in reflectivity associated with fluid presence and variations in shear strength. Moreover, depth uncertainties and the limited spatial coverage of seismic data pose challenges, particularly in regions with complex geological structures such as subduction zones, where comprehensive understanding requires more detailed and extensive data coverage and higher resolution imaging techniques like full waveform inversion (FWI) for more accurate results.

Importance of Full Waveform Inversion (FWI) across the Andaman-Nicobar Subduction Trench:

Full waveform inversion (FWI) plays a crucial role across the Andaman-Nicobar subduction trench for several key reasons. First and foremost, FWI provides exceptionally high-resolution images of subsurface structures by iteratively adjusting velocity models to match observed seismic waveforms. This capability allows for detailed insights into the complex geological settings typical of subduction zones, enabling precise mapping of structures like décollements and fault planes. Importantly, FWI aids in estimating overpressure zones within the subduction region by accurately characterizing seismic velocities and reflectivity variations associated with fluid-rich layers, such as the Protodécollement. Furthermore, FWI enables inferences about the shear strength of the subducting plate by capturing detailed velocity variations that reveal zones of differing mechanical properties. This information is critical for understanding earthquake dynamics and assessing seismic hazards in the region. By validating and enhancing the accuracy of seismic data interpretations, FWI mitigates uncertainties associated with simpler seismic analysis techniques like AVO studies, thereby contributing to more reliable geological modeling and hazard assessment studies across the Andaman-Nicobar subduction trench.

Objectives:

1. **Characterize Fluid Migration:** Utilize advanced seismic techniques, including Full Waveform Inversion (FWI), to characterize fluid migration within the study region, enhancing understanding of geological processes.

2. **Estimate Overpressure Zones:** Employ FWI and Machine learning to estimate overpressure zones within the region by accurately mapping seismic velocities and reflectivity variations associated with fluid-rich layers, with a particular focus on the impact of fluid migration.
3. **Assess Shear Strength Variations:** Evaluate variations in shear strength using FWI and rock physics models, providing insights into how fluid migration influences these properties.
4. **Validate Seismic Data Interpretations:** Validate and improve the accuracy of seismic data interpretations through FWI, specifically examining the effects of fluid migration on seismic properties and addressing uncertainties related to simpler seismic analysis techniques like AVO studies.

Methodology:

1. **Data Acquisition:** High-resolution multi-channel seismic data will be provided by the Host Institute, sourced from the Gulf of Mexico region, to implement Full Waveform Inversion (FWI). FWI will be employed to iteratively adjust velocity models, aligning them with observed seismic waveforms to generate detailed images of subsurface structures and fluid-rich zones.
2. **Fluid Influence Analysis:** Seismic velocities and amplitude variations will undergo rigorous analysis to assess the presence and impact of fluids derived from compaction and mineral transformations within the study area. This analysis aims to understand how fluid migration influences seismic properties and subsurface dynamics.
3. **Shear Strength Inferences:** Using FWI-derived velocity variations, zones of differing mechanical properties and shear strength will be inferred across the Andaman-Nicobar Subduction Zone. These findings will be correlated with seismic attributes and fluid characteristics to delineate areas prone to seismic activity and understand earthquake dynamics.
4. **Integration and Validation:** The results obtained from FWI will be integrated with existing geological models and validated using local geological data and cross-validation techniques. This rigorous approach ensures the reliability and accuracy of the interpretations, enhancing our understanding of geological processes and seismic hazard assessments in the broader Indian Ocean region.
5. **Documentation and Reporting:** Comprehensive documentation of methodologies, results, and interpretations will facilitate scientific dissemination and stakeholder engagement. Reports and publications will contribute valuable insights to geological modeling and seismic hazard assessments specifically tailored for the Andaman-Nicobar Subduction Zone, highlighting the role of fluids in achieving the study objectives.

Duration of the Planned research stay: Six Months (Feb – July 2025)

Conclusion

In conclusion, this proposal aims to advance our understanding of fluid dynamics and seismic properties in the Andaman-Nicobar Subduction Zone using Full Waveform Inversion (FWI). By analyzing high-resolution seismic data, FWI will provide detailed insights into fluid-rich zones and their impact on seismic behavior. Integrating these findings with geological models will enhance seismic hazard assessments and geological understanding across the Indian Ocean region. This research promises significant contributions to seismic studies and hazard mitigation strategies in complex tectonic environments.

Linkage of the Proposed Work with Priority Themes/Projects/Programmes of CSIR-National Institute of Oceanography:

This proposal aligns closely with several priority themes and ongoing projects at CSIR-National Institute of Oceanography (NIO). The study of fluid dynamics and seismic properties in the Andaman-Nicobar Subduction Zone directly supports NIO's efforts in understanding geological processes and seismic hazards in marine environments. By leveraging advanced seismic techniques like Full Waveform Inversion (FWI), the research aims to enhance the institute's capabilities in high-resolution imaging of subsurface structures and fluid migration pathways. This alignment underscores the project's contribution to NIO's broader initiatives in marine geophysics, tectonics, and natural hazard assessment, reinforcing its strategic goals in oceanographic research and resource management.

Commercial Implications of Geohazard Analysis?

Seismic Full Waveform Inversion (FWI) offers substantial commercial benefits across multiple sectors. In resource exploration, FWI enhances the accuracy of subsurface imaging, crucial for locating hydrocarbon reservoirs and mineral deposits, thereby reducing exploration risks and optimizing extraction strategies. It also supports geotechnical engineering by providing detailed subsurface assessments for construction projects, ensuring infrastructure safety and minimizing geological hazards. FWI's applications extend to environmental monitoring, aiding in groundwater assessment, pollution detection, and geological hazard prediction. For industries involved in seismic hazard assessment and insurance, FWI provides critical insights into earthquake risks, helping to assess vulnerabilities and mitigate potential impacts on urban areas and infrastructure. Furthermore, ongoing advancements in FWI technology drive innovation in geophysical software and consultancy services, offering specialized expertise in geological modeling and seismic interpretation. Overall, FWI's adoption enhances capabilities across various domains, fostering technological innovation and strategic opportunities in commercial markets.

Geohazard studies using advanced seismic processing methods like Seismic Full Waveform Inversion (FWI) hold immense potential for the greater good by maximizing the value of significant investments in geophysical data collection. Through advanced seismic analysis, we can extract more detailed and accurate information about subsurface structures and fluid dynamics, enhancing our understanding of earthquake dynamics and tsunami generation. This research not only improves seismic hazard assessments and disaster preparedness but also supports sustainable coastal development and marine resource management. Additionally, the project facilitates technology transfer and capacity building at CSIR-NIO, enabling the institute to apply these cutting-edge techniques to other datasets, thereby broadening the scope and impact of their oceanographic research and contributing to the development of robust methodologies for effective risk mitigation and resource management.

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