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# Bathymetric Survey Images Structure off Sumatra

PAGES 165, 168

Fault rupture models and aftershock activities of both the 26 December 2004 $M_w$ 9.3 and the 28 March 2005 $M_w$ 8.7 earthquakes postulate a strong structural segmentation of the Sumatra fore arc, or the region between a subduction trench and the volcanic arc. The 2004 earthquake rupture propagated some 1200–1400 kilometers to the northwest from the epicenter along the plate boundary. Yet the rupture ended abruptly at a southern boundary crosscutting the upper plate from the trench to the island of Simeulue. Similarly, the rupture plane and aftershock distribution of the 2005 earthquake are confined to a zone some 300–400 kilometers around the epicenter off Nias Island, clearly distinguishable from the northern rupture zone.

To investiagte this along strike structural segmentation, offshore of the northwestern Sumatran islands of Simeulue, Nias, and Siberut new bathymetric swath mapping has been conducted that covers the main structural units from the deep-sea trench to the outer arc high of the Sumatra subduction zone (Figure 1). The first bathymetric images, seen here, reveal a multitude of morphological features depicting the structural setting of the fore arc.

This bathymetric survey is the first part of two multidisciplinary geophysical-geological projects named 'SeaCause' and 'Sumatra.' During this survey, 20 ocean-bottom seismometers and hydrophones were deployed around Simeulue Island. These stations recorded the ongoing aftershock activity until March 2006. This network of ocean-bottom seismometers and hydrophones will allow precise determination of the aftershock epicenters and deliver valuable information to delineate the segment boundary in the area.

The target of this experiment is to identify the subduction interface and its along-strike variations, especially concerning the development of a detachment, giving clues about the degree of coupling of the upper and lower plates. Concurrent with all seismic profiling, gravimetric and magnetic surveys are performed, as well as swath mapping and high-resolution subbottom profiling. The investigations will be completed with rock and sediment sampling of the fore arc and trench in August–September 2006. The projects are conducted in close international collaboration with scientists from France, Germany, Indonesia, Japan, Russia, the United Kingdom, and the United States. The geoscientific data and results will be utilized for implementation of the German Indian Ocean Tsunami Early Warning System (GITEWS).

*First Results of Bathymetric Mapping*

The first images of the bathymetry acquired to date cover the area offshore the islands of Simeulue, Nias, and Siberut, as well as a vast part of the deep-sea trench along Sumatra (Figure 1). The frontal slope of the upper continental plate can reach a 15° inclination angle, and frontal collapse structures and underwater landslides are prevalent.

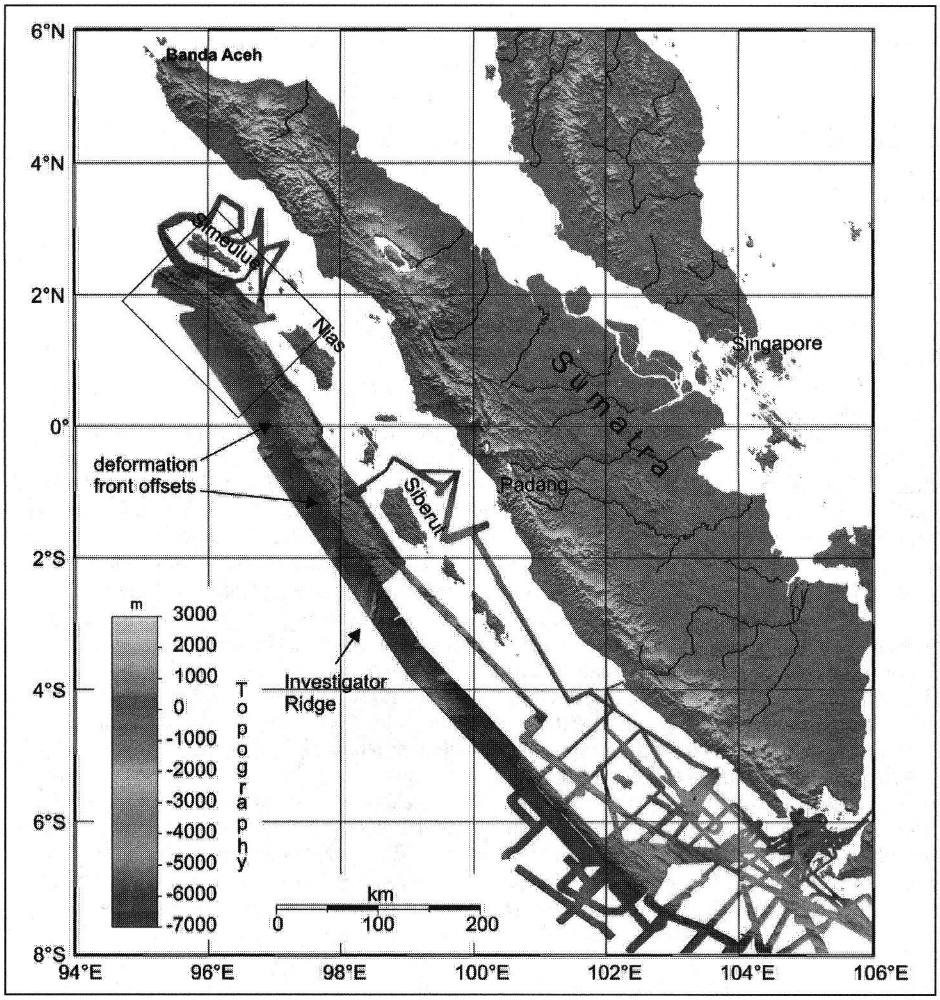


*Fig. 1. Compilation of bathymetric data offshore Sumatra. Data are from SeaCause I cruise SO186 carried out with the German R/V* Sonne *in October 2005 as well as from former cruises (SO184, SO137-139). Topography is from digital elevation data of the Shuttle Radar Topography Mission SRTM30 data set. The black box indicates the three-dimensional view shown in Figure 2. Original color image appears at the back of this volume.*

By S. Ladage, W. Weinrebe, C. Gaedicke, U. Barckhausen, E. R. Flueh, I. Heyde, A. Krabbenhoeft, H. Kopp, S. Fajar, and Y. Djajadihardja

Despite this, morphologically most striking is a prominent 15-kilometer oblique offset of the base of the slope and deformation front offshore Nias. Preliminary interpretation indicates that this feature delineates one of two first-order segment boundaries of the upper plate, which may act as a boundary during earthquake propagation and aftershock distribution. Supporting evidence is that the axis of the outer arc high (i.e., the fore-arc island chain axis) also experiences an eastward shift in this region, indicating that segmentation may affect the whole outer fore arc and not merely the lower slope units. This segment is termed the Nias segment, and accordingly the adjoining northern one is termed the Aceh-Simeulue segment and the southern one the Siberut segment, because of their proximity to nearby islands.

The lower slope is built up of a few frontal folds at the deformation front. Piggyback basins, which evolve during folding and uplift between the folds, trap the gross part of sediments coming from upslope (Figure 2). Larger midslope basins appear offshore Simeulue and Siberut. These basins each are fed by two canyons up to 200 meters deep commencing from the islands. The overall picture of the lower slope and outer fore arc from the map view so far is that it is lacking a significant accretionary prism, an important observation in respect to the possible modes of subduction and coupling/decoupling along the subduction plate interface.

Furthermore, the slope exhibits secondary features, for instance, in the Siberut segment, where the lower slope units are obliquely crosscut by a set of north-south (N-S) trending offsets of the deformation front. This segment seems to be affected by the recent subduction of the Investigator Ridge on the oceanic plate, an extinct, also N-S trending fracture zone system built up of a set of four ridges up to 200 meters high. The Investigator Ridge can be traced through the trench fill, as it is only partly buried by trench sediments.

Continuing beneath the slope, the subducted ridge modulates the relief of the lower slope. In fact, it is presumed that the N-S trending oblique faults developed in response to subduction of this ridge and led to tectonic overprint of the lower slope. Geometrically, it even appears that the Nias-Siberut segment boundary coincides with the northern extent of the Investigator Ridge. Thus, an important influence of the crustal structure of the oceanic plate on the development of the fore arc has to be considered.

A further observation is that the frontal folds at the deformation front of the Nias segment are crosscut by a dense, transverse pattern of short tributaries to the trench. In front of these, smaller sediment aprons are piled on top the trench fill. This setting provides a clue to the timing of events. The tributaries crosscutting the folds may only have developed during or after the folding events. Thus, the frontal folds of the Nias segment may be older than in the other segments or may not have been tectonically reactivated recently.

In contrast, in the Siberut segment to the south the frontal folds are intact, with trapping

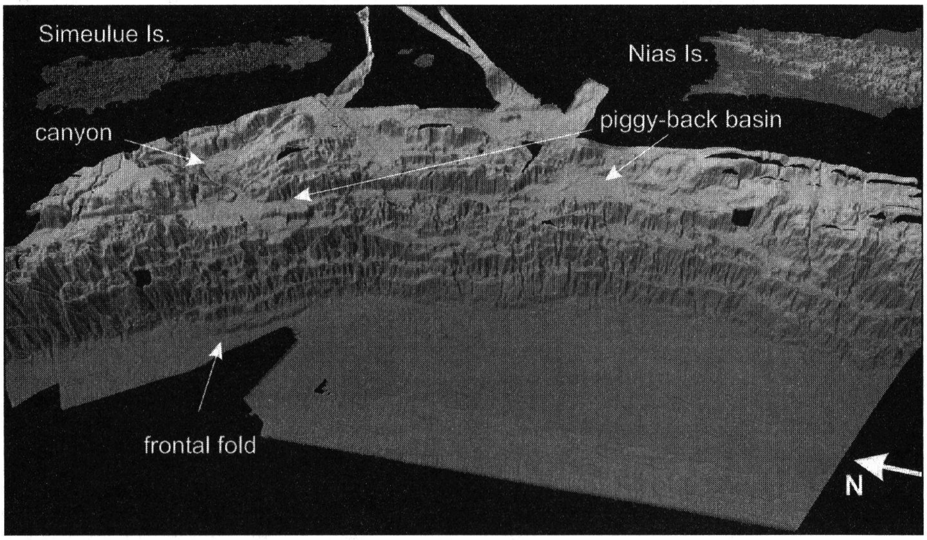


*Fig. 2. Bathymetry in three-dimensional view off the islands of Simeulue and Nias. The bathymetry depicts the structural inventory of the deep-sea trench (more than 6000 meters deep) and the steep lower slope with a small accretionary complex. The middle slope is dominated by piggyback basins, fed by canyons, following tectonic lineaments. Original color image appears at the back of this volume.*

of sediments in piggyback basins. Farther north in the Aceh-Simeulue segment, the deformation front differs significantly [*Henstock et al.*, 2005]. Here a frontal, slightly southward plunging anticline, possibly above a protothrust, is developing in the trench fill in sequence in front of other (stacked) folds in the slope unit. This incipient anticline at the moment is likely the best candidate for the tsunami-generating structure on the seafloor [*Moran et al.*, 2005]. The absence of a comparable, recently active fold in the Nias segment could therefore be a possible clue as to why the March 2005 earthquake did not cause a mentionable tsunami. Resolving these issues remains a demanding task for the international geoscientific community.

## *Current Developments and Future Research*

At the end of March 2006, geophysical profiling within the SeaCause project offshore Sumatra was completed. A dense net of about 40 multichannel reflection seismic profiles with a three-kilometer-long digital streamer imaged the subseafloor structures of the subduction zone traversing the oceanic plate, the trench, and lower to upper slope units with the outer arc high, as well as parts of the fore-arc basins. Along selected profiles, ocean-bottom seismometers and hydrophones were deployed to conduct refraction seismic studies to identify the velocity structure, and to image even deeper structures. Furthermore, at the base of the slope along short trench-parallel profiles, near-incidence reflection seismic experiments were conducted with ocean-bottom seismometers and hydrophones. Data from this suite of experiments is currently being processed. The geophysical and geological investigations offshore Sumatra will be carried on from August to September during the Sumatra cruise, and will focus on the evolution of the fore-arc basins.

Detailed knowledge of the tectonic setting of the plate boundary is essential for earthquake and tsunami hazard assessment in the region. Moreover, this bathymetric data set is a prerequisite for modeling tsunami wave propagation and predicting run up heights offshore Sumatra for different earthquake scenarios. However, further detailed bathymetric mapping of the shallower fore arc basins is needed to incorporate local topography in the models, which will help hazard mitigation analysts identify vulnerable areas.

Close coordination of ongoing and future geoscience research projects offshore Sumatra is necessary to efficiently employ available resources. This is a focus of the upcoming 22–24 May workshop "Offshore studies of the Andaman-Sumatran-Earthquakes," in Hanover, Germany. For details, visit http://www.bgr.bund.de/EN/Sumatraws or e-mail sumatraws@bgr.de

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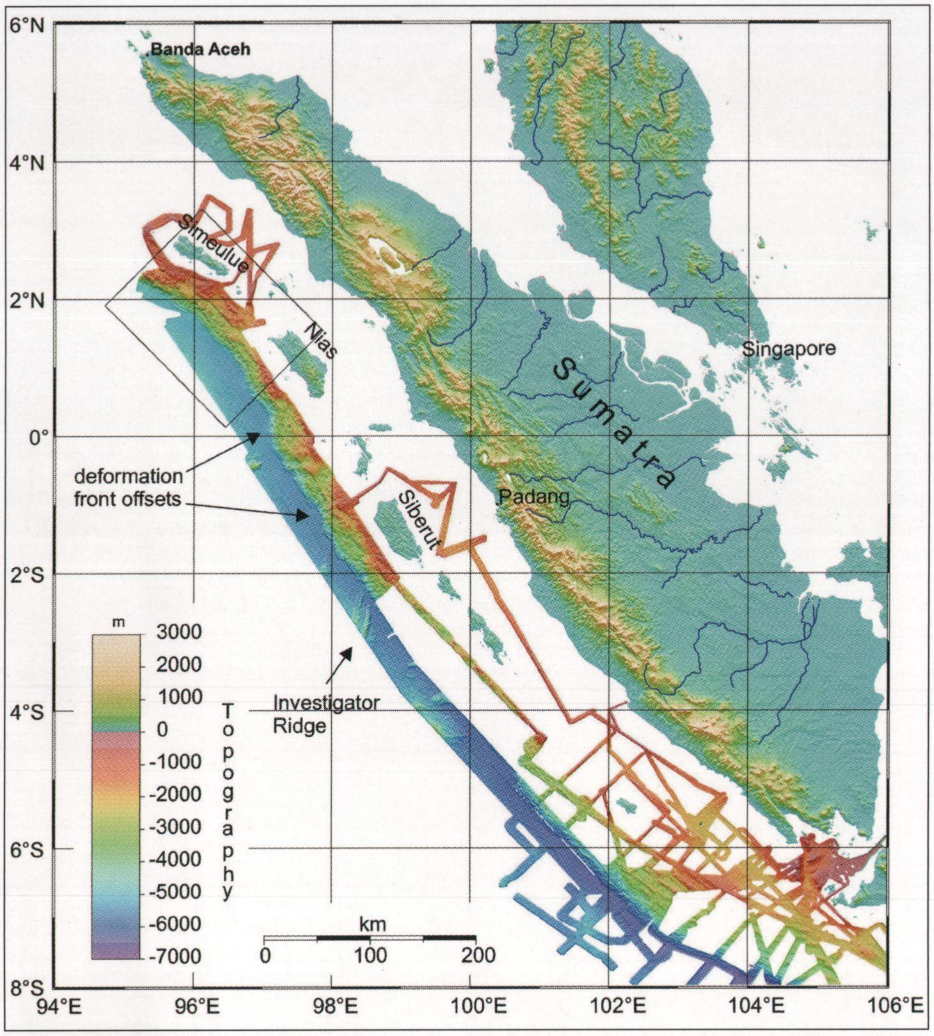
## *Author Information*

Stefan Ladage, Christoph Gaedicke, Udo Barckhausen, and Ingo Heyde, Federal Institute for Geosciences and Natural Resources-BGR, Hanover, Germany, Email: s.ladage@bgr.de; Wilhelm Weinrebe, Ernst R. Flueh, Anne Krabbenhoeft, and Heidrun Kopp, Leibniz-Institute of Marine Sciences, IFM-GEOMAR, Kiel, Germany; Suryono Fajar and Yusuf Djajadihardja, Agency for the Assessment and Application of Technology, BPPT, Jakarta, Indonesia.




Page 165

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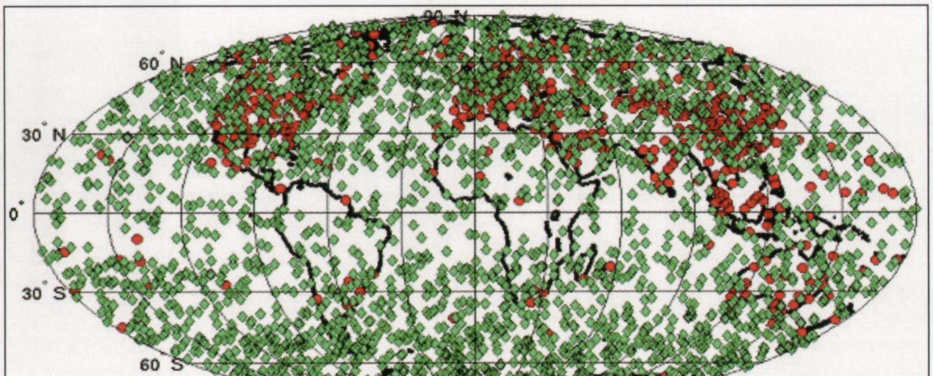
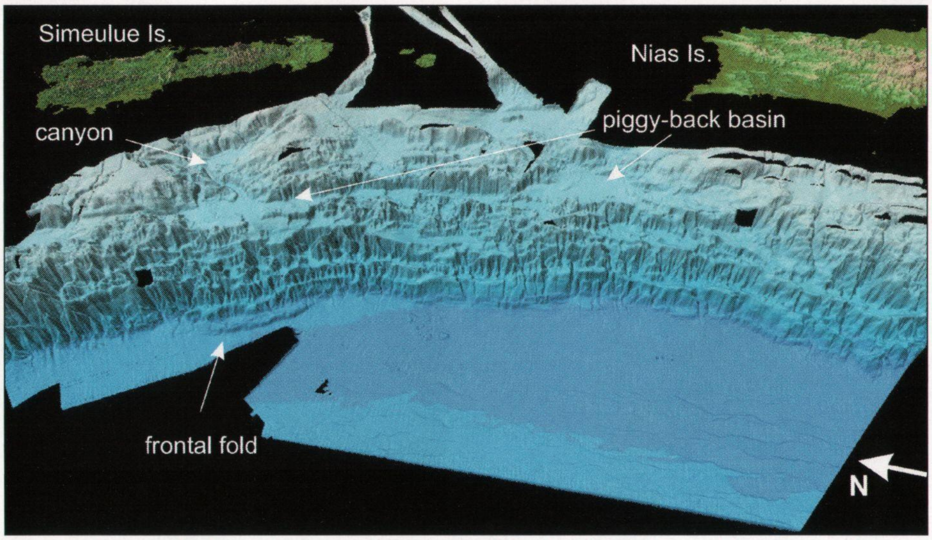



Page 166

*Fig. 1. More than 2500 radio occultation (RO) soundings (green dots) obtained by the GPS Occultation Experiment (GOX) each day. In comparison, radiosondes (red dots) provide only approximately 1500 soundings per day.*

Page 168

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Page 169

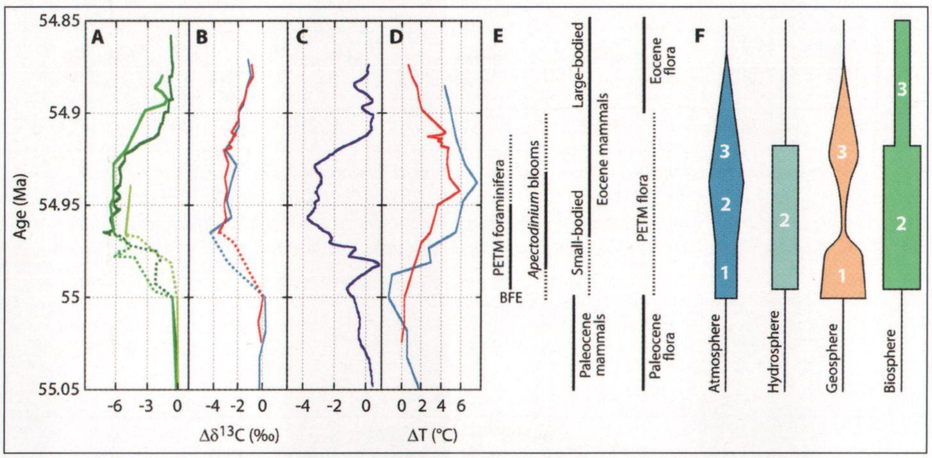


*Fig. 1. Environmental records and a three-phase model of Earth systems evolution through the PETM (age model and data from* Bowen et al. *[2004]). (a and b) Carbon isotope records of the PETM given as anomalies relative to the interval 55.05–55.00 Ma. Terrestrial paleosol carbonate records (a) from northern Wyoming (dark green), northern Spain (light green), and southern China (olive green). Marine planktonic foraminifera records (b) from the subtropical Pacific (red) and southern Atlantic (blue). Carbon isotope changes during the onset of the PETM (dashed lines) occurred as a series of abrupt (~1 thousand years) steps that are not clearly resolved in these records. (c) Difference of the averaged $\delta^{13}C$ curves for the three terrestrial and two surface ocean records. (d) Surface temperature anomaly records for the two oceanic sites, with colors as in (b). (e) Patterns of biotic change through the PETM, compiled from a number of sources (including* Kennett and Stott *[1991],* Thomas *[1998],* Crouch et al. *[2003], and* Wing et al. *[2005]). BFE indicates benthic foraminiferal extinction. (f) A synthesis of global change associated with the PETM. The width of each shaded region corresponds to the severity of change relative to late Paleocene conditions. Numeral 1 indicates initiation of the PETM: intrinsic or extrinsic trigger; carbon release from geospheric reservoirs to the ocean/atmosphere; buildup of carbon in the atmosphere; ocean acidification and dissolution of seafloor carbonate sediments, benthic foraminiferal extinction, and intercontinental mammal migration. Numeral 2 indicates the body of the PETM: low marine carbonate burial rates; altered hydrologic cycle; distinctive PETM biotic communities; gradual climatic warming. Numeral 3 indicates the recovery interval: rapid burial of carbon in marine carbonate sediments; climate cooling; restructured biotic communities persist into the early Eocene.*