circulation events along the coast and offshore, which aided the understanding of field measurements and the damages to oil and gas facilities. In addition, the operational formulae, such as equation (1) for estimating the maximum significant wave height from minimum sea level pressure during a hurricane, were further verified.

Also, the ideal location of the mooring on the Mississippi shelf relative to the track of Ivan allowed new insight into the current and temperature field. Additionally, the "conservation of barrier mass" concept, which was noted for previous historic events such as Opal in 1995, was further verified for Ivan.

While Ivan did not produce extensive storm surge when compared to, for example, Katrina, extremely high waves resulted in extensive scour along the most severely affected structures located on the open coast and in bays. Given the likelihood that the southeastern United States is currently in a multidecadal period during which storms more intense than Ivan (e.g., Katrina) may occur more frequently, future societal implications associated with these events are enormous.

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Sumatra Earthquake Research Indicates Why Rupture Propagated Northward

PAGES 497, 502

The Sumatra earthquake of 26 December 2004 ($M_w = 9.3$) was one of the largest megathrust earthquakes ever recorded using a modern seismic network. The rupture initiated around 3°N near Simeulue Island and propagated northward for about 1250 kilometers up to the Andaman Islands. Nearly three months later, on 28 March 2005, a second large earthquake occurred ($M_w = 8.6$) about 150 kilometers farther southeast.

The aftershocks of these two events (Figure 1) do not overlap, with one lying east and the other west of Simeulue Island. This observation, along with modeling studies [*Lay et al.,* 2005; *Ammon et al.,* 2005] of the earthquake ruptures suggest that there should be a lithosphere-scale boundary around Simeulue, which could be either in the lower plate or in the upper plate. Such a boundary will act as a barrier for rupture propagation from an earthquake initiated on the other side of the boundary.

New results show that the lithospheric-scale boundary starts near Simeulue Island, continues up to the east of the Nicobar Islands and joins the Sumatra Fault in the north. The 26 December earthquake rupture might have initiated just west of this boundary near Simeulue Island; therefore, it did not cross the boundary towards east but propagated northwards up to the Andaman Islands.

By S. C. Singh

The channeling of the earthquake rupture in a narrow zone between the trench and this boundary may explain the large size of the 26 December event ($M_w = 9.3$) and the associated large tsunami. If stress is being accumulated along this boundary, then a major earthquake may occur along it in the near future (years to decades).

In order to understand the relationship between the source region at depth and deformation on the seafloor, the Sumatra-Andaman Great Earthquake Research Initiative (SAGER) is conducting a series of marine experiments offshore of west Sumatra. This research initiative was launched by the Institut de Physique du Globe de Paris (IPGP) after the earthquake, and involves 50 scientists associated with more than 15 international institutions, and industry partners.

West Andaman Fault

The first SAGER experiment, Sumatra-Aftershocks, was carried out from 15 July to 9 August 2005, on the French research vessel *Marion Dufresne*. Initial results indicate the presence of an active strike-slip fault, the West Andaman Fault (WAF), which might be a reactivated lithospheric boundary. This boundary could have channelled the rupture propagation northward during the 26 December earthquake and subsequently acted as a barrier for the 28 March earthquake rupture.

Swath bathymetry, imagery, and 3.5-kHz echo-sounder data were collected in a 380 × 80 square kilometer area that extends from the Sunda Trench in the Indian Ocean to the north of the Sumatra Fault (SF) (Figure 2). An active feature was found on the western flank of the Aceh fore-arc basin that seems to be connected with the WAF in the north. It is clearly visible for about 200 kilometers, but one can follow it for about 400 kilometers, close to the trench southwest of Simeulue. The feature could be an extension of the WAF in the south.

The feature is segmented on the scale of tens of kilometers into restraining and releasing bends leading to compressive and extensive regimes along the fault, suggestive of a right lateral strike-slip motion. The feature's azimuth varies from 345° in the north to 325° close to Simeulue as it approaches the trench. It is very likely that the WAF is bifurcated into different small segments as it approaches the trench, but the present data do not permit the imaging of these segments. In the north, the WAF joins with the SF around 7°30'N, and seems to be connected with the Eastern Margin Fault, the Sagaing Fault in Myanmar through a set of back-arc spreading centers, and transform faults in the Andaman Sea [*Curry,* 2005] (Figure 1).

The freshness of the fault trace and 3.5-kHz data suggest that the WAF has been active recently and could be a reactivated lithospheric boundary (Figure 2). Two strike-slip aftershocks occurred close to the WAF within the first few days after the 26 December event, and the northern branch of the WAF (7°–10°N) seems to have been very active (Figure 1a).

Reactivated Plate Boundary

Historical seismicity also shows the occurrence of strike-slip earthquakes along the WAF (Figure 1b), suggesting that the fault has been active for the last thirty years. The exact age of the WAF is difficult to determine, but it has been suggested that it existed around 30 million years ago [*Curry,* 2005]. Seismic reflection data from the Aceh fore-arc basin that is bounded by the old WAF in the west show 1.2-second flat-lying sediments [*Kemal,* 1993], suggesting that the original WAF has not been active for the past few million years. However, the sharpness of the fault trace along the western flank of the Aceh basin requires the strike-slip component of WAF on the flank to be active.

A reactivated strike-slip lithospheric boundary will have different friction coefficients on either side of the boundary, leading to a discontinuity in coupling (locking) strength between the subducting Indian plate and the upper plate. Assuming an average of dip of 10º–15º of the slab and a distance of 150 kilometers from the trench, the locking depth would be 30–40 kilometers near the WAF. Therefore, it is possible that the WAF is the northeastern boundary of the seismogenic zone between 4° and 9°N, where the distance of the WAF from the trench is about 150 kilometers (Figure 2).

The relationship between the WAF system and the seismogenic zone could be more complex in the diffuse deformation zone farther south, near Simeulue. The presence of the lithospheric boundary would permit the propagation of the rupture to the north, up to Andaman, within the corridor guided by the lithospheric boundary, and would hinder the transfer of energy to the southeast of the epicenter.

The rupture may have initiated at shallow depth west of Simeulue in the diffuse zone, then propagated northward for about 100 kilometers where the seismogenic depth reaches 30-40 kilometers and accelerated up to the WAF-SF junction close to Nicobar and farther up to Andaman as suggested by seismological observations [*Ammon et al.*, 2005]. The maximum displacement along the fault plane occurred from the epicenter to the north of the WAF-SF junction [*Ammon et al.*, 2005]. Therefore, this zone from 4°N to 7°30’N might have been fully locked and produced a significant displacement during the earthquake [*Ammon et al.*, 2005].

The discontinuity in the upper plate, and hence in the locking zone between the upper and lower plates, would then lead to unidirectional rupture propagation. The stress released in one area of the locked zone would induce stress in its continuum vicinity, leading to a domino effect and producing a megathrust earthquake.

It should be noted that the epicenter of the 28 March event was at the center of the broken segment as suggested by aftershocks and modeling study, whereas the 26 December event was at the eastern extremity of the faulted segment (Figure 1).

Global positioning system measurements [*McCaffrey et al.*, 2000] in Sumatra reveal that strain associated with the oblique convergence of the Indo-Australia plate with the Eurasia plate is partitioned between the trench-normal compression within the fore-arc and trench parallel strain along the SF. However, the inferred slip rate along the SF is one-third less than the full margin parallel component of plate motion, and the WAF might be accommodating this ex-

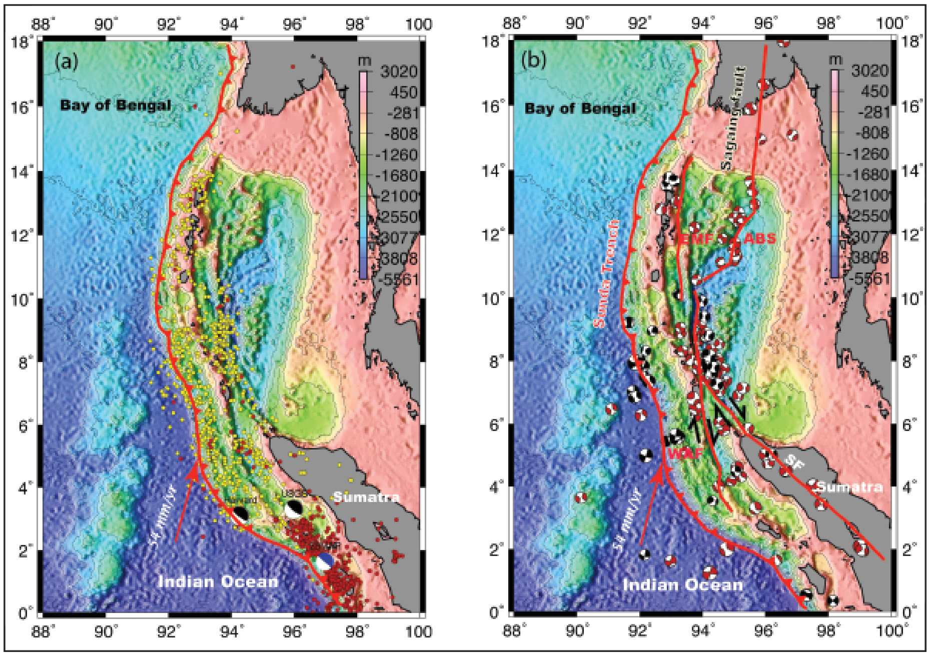

Fig. 1. (a) The epicenters and fault plane solutions of the 26 December 2004 (black, centroid moment tensor and U.S. Geological Survey (USGS) solutions) and 28 March 2005 earthquakes (USGS solution). Yellow-colored circles indicate the first 10 days of aftershocks of the 26 December earthquake. Red-colored circles indicate the first 10 days of aftershocks of the 28 March event. (b) Strike-slip aftershocks (black) and other strike-slip earthquakes since 1976 (red) with magnitude $M_w > 5$. *SF, Sumatra Fault; WAF, West Andaman Fault; EMF, East Margin Fault; ABS, Andaman back-arc spreading center.*

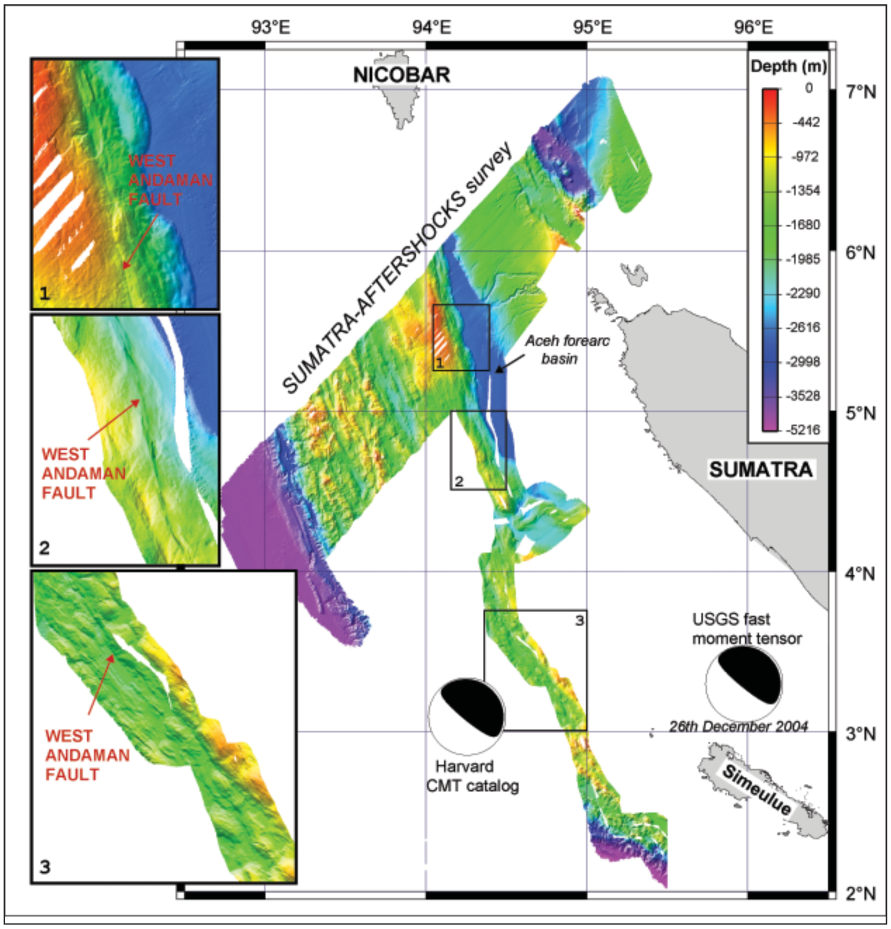

Fig. 2. Bathymetric map of the survey area and epicentral location of the 26 December earthquake. Detailed bathymetries of the WAF at three locations (5.5°N, 4.5°N, 3°N) along the fault are shown in the insets. The Harvard University and United States Geological Survey solution locations of the 26 December earthquake are also marked.

tra right-lateral motion [*McCaffrey et al.,* 2000]. The strong aftershock activity east of Nicobar could be associated with the interaction between the WAF and the SF.

These results have important implications for seismic and tsunami risk assessments and modeling studies. The northern portion of WAF (7º–10ºN) has been active after the Sumatra earthquake but the southern portion (4º–7ºN) has been less active (Figure 1b), and stress might be accumulated in this part. In this case, a large portion of the southern WAF may break in the near future, not the SF as previously suggested [*McCloskey et al.,* 2005], and the Nicobar Islands might be affected by a major strike-slip event. These new results also suggest that lithospheric boundaries in upper plates play a key role in the size and nature of megathrust earthquakes.

Thorough Investigation Planned

This experiment provides the first insight into the boundary of these two large earthquakes. A more thorough investigation is required and SAGER plans to address this problem by carrying out a series of seven to eight marine experiments. A shallow bathymetry and seismic reflection survey is planned in January 2006 around Simeulue Island in order to image the precise location of the above lithospheric boundary.

A deep seismic reflection study using a 12-kilometer streamer and a large air gun source is expected to take place in early 2006 using the state-of-the-art technology (Q-Marine System) of Schlumberger, which should provide a reflection image of unprecedented nature down to 30–40 kilometer depth. Two lines will be shot, one 250 kilometers long going through the epicenter of the main event and the second one, 350 kilometers long, traversing the Sumatra-Aftershocks box (Figure 2).

In order to determine the velocity structure of the crust, a deep seismic refraction survey is planned in July 2006 on the research vessel *Marion Dufresne*. These studies are likely to be followed by high-resolution seismic reflection, heat flow, deep-towed, and remotely operated vehicle surveys in 2007–2008.

Most of the marine surveys are limited in Indonesian waters, whereas seismic activities continue up to the Andaman Islands. Therefore, efforts should be made to acquire marine data in Indian waters, in particular around the Nicobar Islands, in order to understand the interaction between the WAF and SF and to assess the seismic and tsunami risk to the Nicobar Islands.

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NEWS

Using Magnetograms for Earthquake Magnitude Evaluation

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Recent research into the feasibility of calculating past earthquake magnitudes from old geomagnetic records on photographic paper has yielded promising results. Such a tool will help to complete seismic catalogues and thus more accurately assess seismic hazards.

Continuous recording of the geomagnetic field started circa 1850, almost 50 years before seismographic networks were available. Classic magnetometers, designed to measure local variations in the Earth's magnetic field by recording the motion of hanging magnets, are sensitive to earthquakes. In some sense, they behave as seismographs, because the earthquake ground acceleration shakes the suspended magnets when the vibration is sufficiently strong.

Earthquakes recorded by magnetometers are reported in old magnetic bulletins. A challenge has been to investigate if such records can be properly calibrated to develop a formula for magnitude determination. The goal is to have a tool for instrumental magnitude determination of earthquakes during the period of approximately 1860–1900 (in 1880, more than 30 magnetic stations with more than 10 years of continuous records were operating around the world).

As related to earthquake energy, earthquake magnitude is an important input parameter for further regional seismic hazard assessments. The underlying objective of this research is to enlarge the regular series of calculated magnitudes. Specifically, researchers seek to calculate past earthquake magnitudes in the Euro-Mediterranean area, where significant earthquakes found in magnetic records can be corroborated by historical accounts.

The first step of this process is to ascertain under which conditions such a magnitude determination is valid. For this purpose, a magnitude equation was fitted from magnetographic records with more recent known magnitudes already calculated from seismograms.

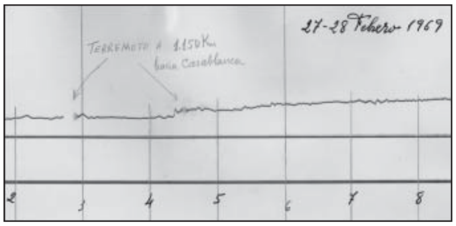

Fig. 1. Example of a magnitude 7.3 earthquake that occurred at a distance of 1103 kilometers from Ebre Observatory and was recorded by the H element of the La Cour variometer.

The proposal was tested using geomagnetic data from Ebre Observatory (EBR), which operated two types of classical magnetometers for continuous recording of the geomagnetic field: Mascart (from 1910 to 1958) and La Cour (from 1953 to 2000). Comparison of magnetometer records at EBR against seismic bulletins allowed the recognition of 85 earthquakes on Mascart recordings and 248 earthquakes on La Cour ones. The magnetic records used correspond to times with reasonably quiet magnetic conditions.

An empirical methodology, analogous to what is utilized for the construction of magnitude equations from seismograms, was used. After a thorough study of the characteristics