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Seismic Reflection Image of the Great Sumatra Earthquake Rupture Zone Using Seismic Industry Technology

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SUMMARY

Following the 9.2 magnitude earthquake offshore Sumatra and the devastating associated Tsunami of 26th December 2004, 950 km of 2D deep crustal seismic reflection data was acquired in July 2006 on board the WesternGeco vessel M/V Geco Searcher in the vicinity of the earthquake epicenter. A very large air gun (10,170 cubic inch) source towed at 15 m water depth was used to general low frequency energy for deep penetration, which was recorded on a very long streamer (12 km) also deployed at 15 m depth in order to have record low frequency energy from deep crust and remove multiples. Our results show seismic reflection image unprecedented nature down 60 km depth in the Sumatra earthquake region. In this paper we will present survey design and special processing required along with seismic image that could change our understanding of subduction zone processes and related megathrust earthquakes.

Introduction

The great earthquake of 26th December 2004 offshore Sumatra was the second largest earthquake to have been recorded by the modern system. It ruptured 1300 km of plate boundary over a 150 km wide area from northern Sumatra to all way to Andaman Islands (Figure 1). The tremor and the subsequent tsunami caused massive devastation and loss of life. Three months later, another 8.7 magnitude earthquake occurred on March 28 2005, 300 km further south. On 12 September 2007 the third great earthquake (Mw=8.5) occurred at 1300 km further south. There is a 500 km gap between the 2005 and 2007, which is likely to break in the coming years.

Soon after the 2004 earthquake, Institut de Physique du Globe (IPG) Paris formed the Sumatra-Andaman Great Earthquake Research (SAGER) group, comprises several earth science organisations, to gain more understating of the area and the tectonics that caused the earthquake and consequent tsunami. The group proposed a set of seven marine experiments including, side scan sonar bathymetry, OBS seismic monitoring and marine streamer seismic acquisition.

WesternGeco joined the group as an industry partner as part of Schlumberger's response to the 2004 disaster. Vessel time and services were provided *pro bono* to acquire and process deep crustal 2D seismic reflection marine streamer data offshore Sumatra. We describe the planning, design and execution of this survey, highlight some of the unique challenges of imaging deep crustal reflectors up to 40 km depth in addition to near sea bottom faults and reflectors, and show some important results.

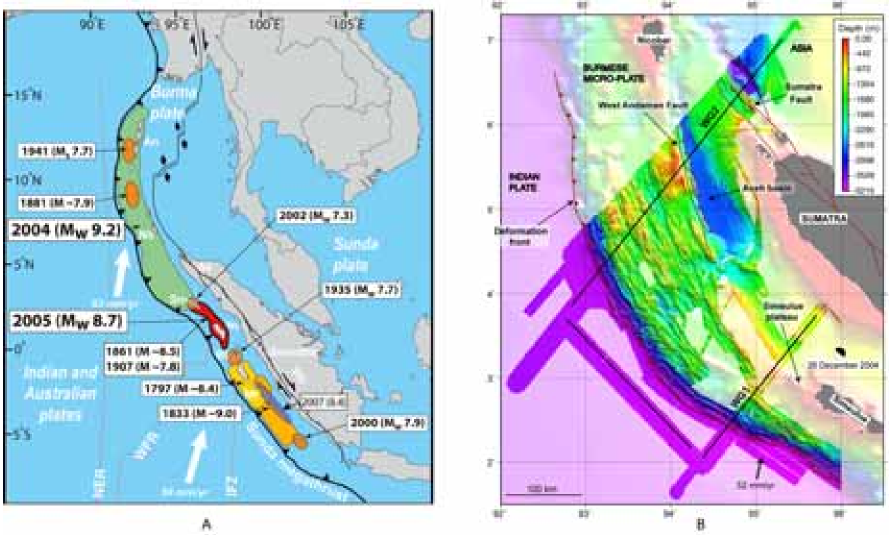

Figure 1 *(A) Historical and recent earthquake and their rupture areas (in color): green-2005, red-2005 and purple-2007 earthquakes. Re-drown from Biggs et al. (2006). (B) Map of the three deep reflection lines, seafloor bathymetry, and location of the 26^{t} December 2004 earthquake (USGS solution).*

The challenges/geological setting

The earthquake of 26th December 2004 occurred on the interface of the Indian and Burmese plates. It was caused by the release of stresses that developed as the Indian plate subducts beneath the overriding Burmese micro-plate at a rate of ~5.2 cm/year (Figure 1). More specifically, the convergence is oblique with approximately 4 cm/year displacement orthogonal to the trench and 2 cm/yr strike-slip motion on the Sumatran Fault. Due to the exceptional size of the 26th December 2004 event, its magnitude could not be estimated by the means used for smaller earthquakes and was eventually estimated to Mw=9.2-9.3, making this the second or third most powerful ever recorded since the advent of modern seismological networks.

The earthquake rupture initiated at 30-35 km depth and propagated to the seafloor causing the uplift on the seafloor, lifting the water and hence generating the devastating tsunami. Tsunami modelling indicates a slip of up to 30 m along the rupture plane. A major question at this point is to understand how motion in the source region of the earthquake, at ~30 km-depth was transferred to the seafloor, then to the water column. For such a large earthquake, it is likely that the rupture continued up to the seafloor along one or more thrust faults in the sedimentary section.

Survey Design

This plate boundary is entirely covered by sea and hence can be imaged with marine seismic systems. Obviously for such a deep target it was essential to deploy a large, powerful low frequency seismic source. Modelling studies suggested that reflections from 30 km depth would have a two way travel time of ~12 s and undergo considerable earth attenuation. Source and cable tow depths were modelled for optimum signal strength at 8-15 Hz. We found that 15 m source and streamer depths provided highest energy at 8-10 Hz.

In order to image deep structure, it was necessary to lower the frequency further. Therefore, it was a necessary to have an acquisition system could temporally and spatially sample not only the low frequency signal but also the low frequency noise. By using the Q-Marine[1] system with 3.125m spaced single sensors the low frequency, very slow, swell noise can be sampled and separated from the signal (Martin et. al, 2000). In addition to a powerful source (10170 cubic inch) and fine spatial sampling (2 ms), the data acquisition system needed to be configured to collect offsets and recording times as long as possible. Further modelling studies showed that a 12 km cable, 20 s recording time with a source interval of 50 m was possible. In addition a special ultra low cut recording filter was applied (Bunting et al, 2008).

Data acquisition

In July 2006 a suitable vessel, the M/V Geco Searcher, was made available for the survey. Two long 2D regional lines were programmed (see Figure 1). Line WG1 is close to the estimated epicentre of the earthquake and crosses a frontal fold, on which the rupture of the 26th December 2004 event may have reached the surface. This line also crosses the West Andaman fault, which might have been responsible for the northward propagation of the rupture. A second line (WG2) close to the maritime border of India and Indonesia provides a complete transect of the Sumatran subduction system. The source from the M/V Geco Searcher was also recorded by 56 OBS stations deployed at 8.1 km interval along the line for the long offset refraction studies. In addition, the transit from Line WG1 to WG2 was recorded as a third line providing images of the deep water ocean crust. An additional streamer of 5.5-km length, towed at 7.5 m depth was also deployed to record broader bandwidth data of the shallow sedimentary section. In total, 950 km of 2D seismic data was acquired using the M/V Geco Searcher's Q-Marine technology. The data was initially processed onboard in "near real time" to provide a QC Brute stack.

Data processing

Following acquisition, the raw data was analysed to evaluate agreement with the model predictions. Time variant analysis of summed spectra derived from an initial brute stack, demonstrated that the decay of amplitude and frequency with depth was similar to the predicted model. At travel times of 10-15 s the observed signal peak frequency was 8 Hz with very little bandwidth (Figure 2).

One of the key objectives of this project was to produce structural stack sections particularly of the deep data around the seismogenic zone (12-30 km depth). Consequently, it was essential to preserve as much low frequency signal as possible. The proprietary filters used to separate the signal from

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[1] Mark of Schlumberger

noise, within this band, were instrumental in retaining signal bandwidth. Additional data processing techniques used to attenuate noise also included; a 2.25 Hz low cut filter, time variant beam forming - based on the size of the Fresnel zone and spectral edit for remaining swell noise and other noise transients.

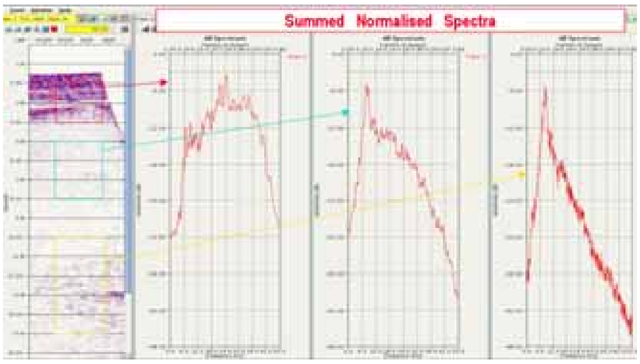

Figure 2 *Summed spectra at three different travel time levels, the deepest window is 10-15 seconds TWT. (frequency range is 0-50Hz)*

Multiple removal was a real challenge. The hard and rugose seafloor produced multiples, not just the first, that were strong, diffracted and often out of the plane of the 2D acquisition line. Initially, seven cascades of targeted radon demultiple, using a range of velocities, was implemented to combat obvious, slow multiple modes. This was followed by a weighted least squares radon demultiple filter once a velocity field was developed. Before stacking, time and space variant inside muting and spectral editing were used to attenuate remnant multiple segments. Despite all these methods, in a few locations, manual editing of obvious remaining multiple energy was required.

Derivation of velocity fields for demultiple, moveout and migration also proved a challenge. In the "shallow" part of the section (approximately to 5 km depth) where sedimentary primary reflections were observed, normal semblance based velocity analysis was used. At intermediate depths, approximately 3-30 kilometres depth, constant velocity stacks (CVS) were employed. For the ultra deep part of the data, usually greater than 30 kilometres depth, the velocity trend was generally interpreted to provide an interval velocity close to 8 km/s. To provide flexibility in iterating for the optimum image, the final imaging steps were applied as normal moveout, stack, post stack time migration and a post migration stretch to estimated depth.

Results:

An image of the final section for line WG1 is shown in Figure 3 (Singh et al., 2008). On the diving plate, the top of the basalts is clearly imaged. They are capped by a thin layer of pelagic sediments, in turn covered by a thick, landward thickening (2.1 to 3.16 s) turbidite sequence. The oceanic Moho is also very clear. South of the accretionary wedge front, the oceanic crust and pelagic deposits are cut and offset by two landward-dipping thrust-ramps (CMP 25700 and 28200). A shallow NE dipping reflector, which we interpret as a thrust décollement within the oceanic crust, links the outer (R1) with the inner (R2) ramp. The down going oceanic crust (both top and bottom) can been imaged down to 14 s TWTT (40-45 km). A pair of reflective zone is imaged at 8 s beneath the fore arc basin as well the back thrust. The continental Moho is weakly imaged at 10 s TWTT.

Most exciting result of this survey is that we can image a set of landward dipping thrust faults that cut the down going oceanic crust as it descends beneath the accretionary wedge. Aftershocks of the 2004 earthquake suggest that these faults are active. Subduction megathrusts are generally thought to lie near the top of the subducting basaltic layer or in the overlying sediments. Here there is no evidence for a reflector in the sediments that could be interpreted as a décollement, which suggests a plate interface at or below the top of the igneous crust. In fact, fracturing and slicing of the oceanic crust along landward-dipping thrust faults can be explained by means of a décollement level mostly lying in the upper mantle of the downgoing plate, possibly just beneath the oceanic Moho. This is because the downgoing plate will deform locally during the stress accumulation that would be released by these thrust faults, therefore, it would be difficult to accumulate stress on a significant part of the décollement at basalt/sediment over a long period of time to produce an exceptionally large earthquake, such as the December 2004 earthquake.

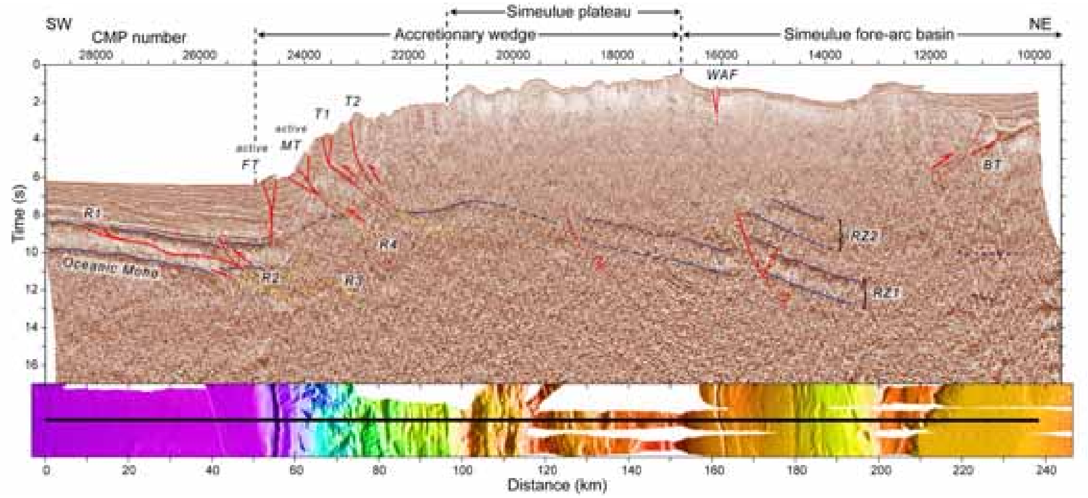

Figure 3 *Seismic reflection image along line WG1. The line is 254 km long. The subducting oceanic crust is marked by light blur lines and faults by red lines. FT is frontal thrust, MT is main thrust, and BT is back thrust. RZ1 and RZ2 are a pair of reflective zone. WAF: West Andaman Fault.*

Conclusions

This project demonstrated that given reconfigured state-of-the-art commercial hydrocarbon exploration seismic technology, ultra deep reflection images of Sumatra active margin area can be achieved. The new seismic images of unprecedented nature has led to the discovery of the possible presence of a Megathrust principally lying in the oceanic mantle, which suggest that perhaps the 2004 Sumatran event should be considered an example of a novel class of exceptionally large and infrequent megathrust earthquakes. The common occurrence of slices of mantle peridotites attached to oceanic crust in ophiolite complexes along most suture zones implies that such giant quakes, though fortunately rare, may be the rule rather than the exception along convergent plate boundaries.

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