Study of Great Sumatra Earthquake Subduction Zone Using Very Long Offset Seismic Acquisition and Processing Techniques

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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 the 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 (Figure 1a). There is a 600 km gap between the 2005 and 2007, which is likely to break in the coming years (Konca et al., 2008). During the 30th September 2009 earthquake (Mw=7.8) only a small fraction of energy was released, which led to a death toll of over 2000, and a bigger earthquake is likely to occur in the near future.

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 understanding 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. So far, five experiments have been carried out.

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

Figure 1: (A) Historical and recent earthquake and their rupture areas (in color): green-2005, red-2005 and purple-2007 earthquakes. Re-drawn from Biggs et al. (2006). (B) Map of the three deep reflection lines acquired by WesternGeco Tsunami Survey, seafloor bathymetry, and location of the 26th December 2004 earthquake (USGS solution).

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acquire and process deep crustal 2D seismic reflection marine streamer data (Tsunami Survey) offshore Sumatra in the 2004 earthquake epicentral region. In 2009, CGGVeritas provided their best vessel to acquire deep seismic reflection data in the locked zone near Padang (TIDES Survey). We describe the planning, design and execution of these surveys, highlight some of the unique challenges of imaging deep crustal reflectors up to 40 km depth in addition to near seafloor faults and reflectors, and show some important results.

The challenges/geological setting

Earthquake ruptures initiate at 30-35 km depth and propagate to the seafloor causing the uplifting on the seafloor, lifting the water and hence generating the devastating tsunami; slips of up to 30 m could occur along the rupture plane. A major question is to understand how motion in the source region of the earthquake, at ~30 km-depth get transferred to the seafloor, then to the water column.

Seismic reflection technology available in oil industry can be used to determine the precise geometry and some other characteristic of the rupture plane. However, there are three main problems in imaging such a rupture plane in subduction zone environments: (a) poor penetration of seismic energy through thick sediments, (b) scattering from rough seafloor surface and (c) water bottom multiples. For deep penetration, a low-frequency energy source is required whereas to remove multiples, long-offset data are required (Singh et al., 2008).

Survey Design

Tsunami Survey (Schlumberger): 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 system with 3.125 m spaced single sensors, the low frequency, very slow, swell noise can be sampled and separated from the signal. In addition to a powerful source (10170 cubic inch) and fine spatial sampling, 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 would be appropriate. In addition a special ultra low cut recording filter was applied (Bunting et al., 2008).

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 July 2006 a suitable vessel, the M/V Geco Searcher, was made available for the survey.

![Figure 2: TIDES Survey; Southwest Sumatra subduction zone and deep seismic reflection profiles. Profile CGGV010 traverses the Sumatra Seismic Gap, CGGV020 traverses the 2007 earthquake rupture zone, and CGGV040 traverses the aseismic zone. Profile CGGV011 was shot to study the Investigator Ridge whereas profile CGGV030 was shot to study the forearc basin. (b) Raw shot records for three streamers towed at depths of 7.5 m (left), 22.5 m (centre) and 15 m (right). The first and third streamers were 6 km long whereas the second streamer was 15 km long, the longest streamer ever deployed. Wide-angle reflections from the top of the oceanic crust is clearly visible on the long streamer record. Refraction arrivals are also observed at 9-15 offsets, which are absent on standard 6-km long streamers.](image-url)
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*TIDES Survey (CGGVeritas):* CGGVeritas mobilized one of its largest seismic vessels, the M/V Geowave Champion. The vessel acquired over 1700 km of deep seismic reflection data (Figure a) in May 2009 while towing a 15 km long solid streamer, which has the tensional strength and power transmission properties to achieve this record-breaking length. In order to record the low-frequency energy from deep down in the earth, this streamer was deployed at a 22.5 m water depth. Two more 6-km long streamers were also deployed at 7.5 m and 15 m water depth, respectively, in order to image shallow sediments and faults. An array of 48 airguns with a total volume of 9600 cubic inch towed at a 15 m water depth provided the very large energy source required to image deep targets. The airguns were fired at an interval of every 50 m as the vessel moved at a speed of 4-4.5 knots, making it the largest moving one-piece object on the Earth.

**Data Acquisition**

*Tsunami Survey:* Two long 2D regional lines were acquired (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. 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.

*TIDES Survey:* Six deep seismic reflection profiles were shot (Figure a). Three dip lines traverse the subduction zone; one going through the Sumatra Seismic Gap, one crossing the region that broke during the 2007 earthquake, and one going through the aseismic zone. A strike line joins two dip lines in the Mentawai forearc basin. One seismic line was shot to study the Investigator Ridge. The data is presently processed by CGGVeritas in Paris.

**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.

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. 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.

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.

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.
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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 be 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.

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. More results still come from the above two surveys.

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Reference


