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Advanced Seismic Data Processing of a Deep Seismic Reflection Survey of the Great Sumatra Earthquake Zone that Caused the Indian Ocean Tsunami.

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Introduction

The massive earthquake that struck offshore Sumatra on 26th December 2004 was the second d largest earthquake to have been recorded by the modern system. It ruptured 1300 km of plate boundary over a 150km wide area. The tremor and the subsequent tsunami caused massive devastation and loss of life. In January 2005 a group of academic geoscience organisations formed the Sumatra-Andaman Great Earthquake Research (SAGER) group to gain more understating of the area and the tectonics that caused the earthquake and consequent tsunami. SAGER is coordinated by Laboratoire de Géoscience Marines, Institut de Physique du Globe (IPG) Paris, and comprises many geoscience organisations. In total the SAGER group composes 16 International organizations and over 50 scientists. The group proposed a set of seven marine experiments including, side scan sonar bathymetry, OBS seismic monitoring and marine streamer seismic acquisition.

As part of WesternGeco/Schlumberger's response to the 2004 disaster it joined the group as an industry partner, WesternGeco/Schlumberger donated vessel time and services to acquire and process deep crustal 2D seismic reflection marine streamer data offshore Sumatra.

We describe the planning, design and processing of this survey and highlight some of the unique challenges of imaging deep crustal reflectors up to 40 kilometres depth in addition to near sea bottom faults and reflectors. Images of the final data are shown. These data are now being interpreted and assimilated with the other data that has been acquired to date. Full integrated interpretations will be published in scientific journals later in 2008 and beyond. Further experiments and even drilling may occur in the future, contingent on funding.

The Challenge/Geologic 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. 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=9.3, making this the second most powerful ever recorded since the advent of modern seismological networks. The devastating tsunami was caused by a significant vertical displacement at the sea floor. The vertical displacement is estimated to be 12 m on average and up to 20 m, affecting a 1300 km-long region of the plate boundary, from Sumatra to the north of the Andaman Islands.

It has been proposed that the main December 26th earthquake suggests a rupture occurred on a low dipping (8-12 degrees) plane, at a depth of ~30 km. Prior studies of the regional seismicity and GPS studies of present ground motion suggest that stresses have accumulated over a long period of time (100-300 years) prior to the earthquake and tsunami. Tsunami modeling indicates vertical ground motions = 10 m near the source region.

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. (see Figure 1). 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.

The distribution and geometry of these faults should control seafloor displacement and are therefore critical parameters to understand the mechanism of tsunami generation. However, in the past it has not been possible to image structures down to 30 km below the surface using academic research seismic vessels. Use of "state of the art" seismic reflection imaging systems and processing has enabled this deep imaging.

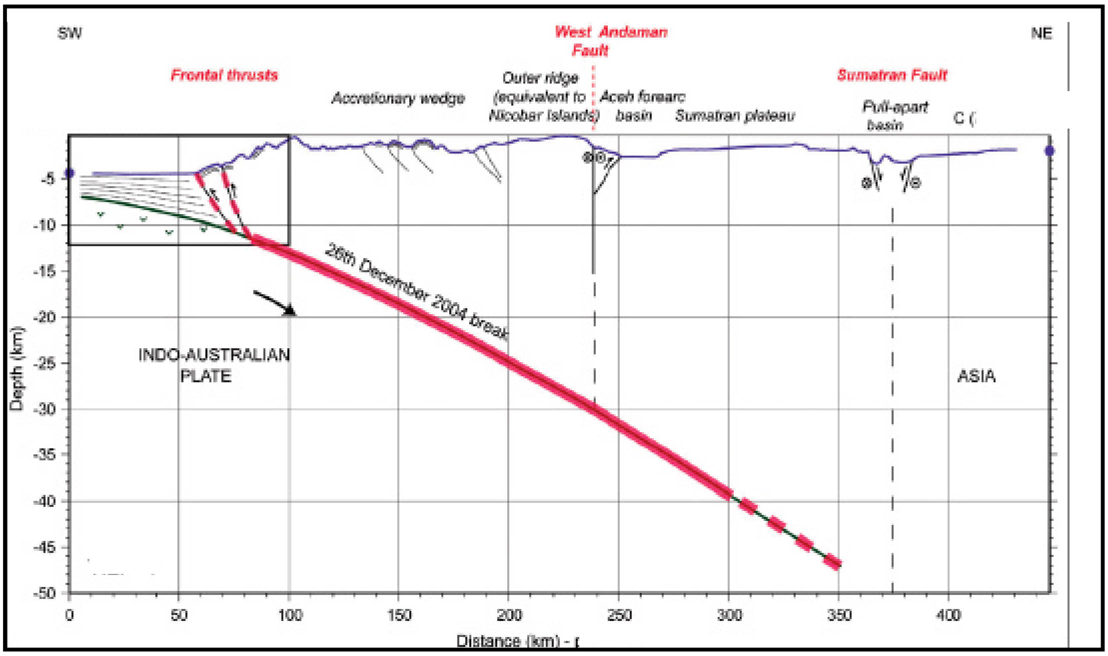

Figure 1. A schematic diagram showing the subduction of the Indian plate beneath the overriding plate and the location of the possible 26th December 2004 rupture. (S. Singh, 2006)

Survey Design

This plate boundary is entirely covered by sea and unlike Alaskan or South American unidirectional rupture zones, can be imaged with marine seismic systems. The survey design studies started in 2005, the acquisition planned to take place when a suitable vessel was in the region. Obviously for such a deep target it was essential to deploy a large, powerful seismic source. Modeling studies suggested that reflections from 30 kilometres depth would have a two way travel time of approximately 12 seconds and undergo considerable earth attenuation. Source and cable tow depths were also modeled for optimum signal strength. One such model is shown in Figure 2.

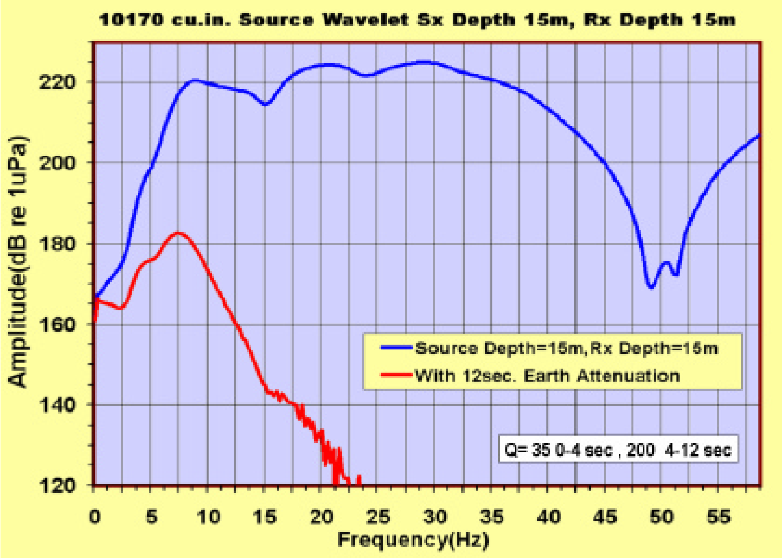

Figure 2. Modeled source signature spectra - with and without earth attenuation (Q) for a 12 second travel time.

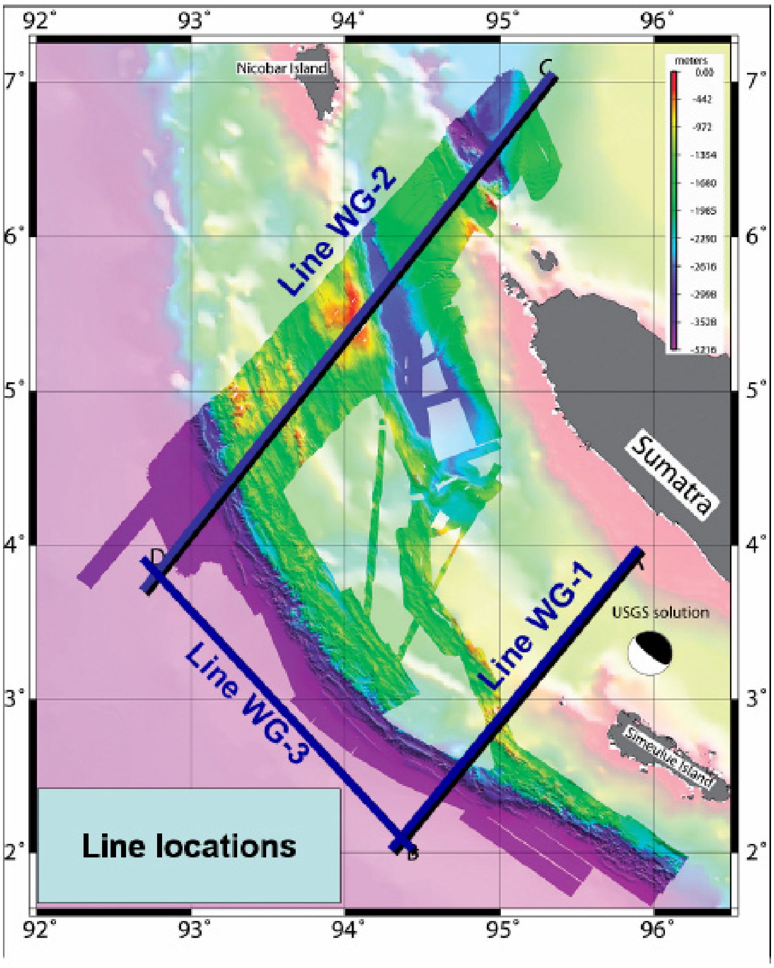

Figure 3 Map of the three deep reflection lines, sea floor bathymetry and location of the 26th December 2004 earthquake (USGS solution).

Essentially, this shows that for the deep reflections there will be minimal signal beyond 12 Hz. Even the peak energy at 7-9 Hz will be weak and could be weaker than environmental noise that is often encountered at these frequencies. It was a design requirement that the acquisition system could temporally and spatially sample both the low frequency signal and particularly the noise. By using the Q-Marine system with 3.125m spaced single sensors the low frequency, very slow, swell noise can be separated from signal at the same frequencies (Martin et. al, 2000). In addition to a powerful source and fine spatial sampling, the data acquisition system needed to be configured to collect offsets and recording times as long as possible. Further modeling studies showed that a 12 kilometre cable, 20 second recording time with a source interval of 50m was possible. In addition a special ultra low cut recording filter was applied.

The challenge for the data processing is then to separate the weak signal from the noise particularly in the low frequency range of 3-12Hz. Scattering, spherical divergence and multiple reflections add to the challenge.

Data Acquisition And Raw Data

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 3). Line WG-1 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 (WG-2) provides a complete transect of the Sumatran subduction system. This line also tracked the location of OBS receivers that were part of another experiment run by the SAGER group. The source from the M/V Geco Searcher was recorded by these OBS stations and used for long offset refraction studies. In addition, the transit from Line WG-1 to WG-2 was recorded as a third line providing images of the deep water ocean crust. In total, 950 kilometres 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. All planned acquisition parameters were achieved.

Initial Data Analysis

Following acquisition, the raw data was analysed to evaluate agreement with the model predictions. Time variant analysis of summed spectra (Figure 4) 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 seconds the observed signal peak frequency was 8Hz with very little bandwidth.

Spectral analysis of a data window above the first reflection arrivals, which is mostly composed of environmental noise, demonstrated that the application of the single sensor LACONA filters and digital group forming (Martin et. al. 2000) has attenuated most swell/bulge noise in the 3-15Hz range. The bulk of the remaining environmental noise is below 3Hz where little source generated signal energy would be expected (See Figure 5).

Data Processing

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 kilometres depth). Consequently, it was essential to preserve as much low frequency signal as possible. The use of LACONA filters to separate the signal from noise within this band was very useful. Additional data processing techniques used to attenuate noise also included; a 2.25Hz 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.

Multiples presented a large challenge. The "hard" and rugose sea floor produced multiples that were strong, diffracted and often out of the plane of the 2D acquisition line. In addition there was uncertainty in the velocity profile. The final processing flow included a combination of several demultiple techniques. Initially, five cascades of targeted radon demultiple, using a range of velocities, was implemented to combat obvious, slow multiple modes. This was followed by a traditional weighted least squares radon demultiple filter once a reliable velocity field was developed. Before stacking, time and space variant inside muting and spectral editing were used to further 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. Due to the variability in data quality and depth, combinations of velocity analysis tools were used. In the "shallow" part of the section (approximately to 5 kilometres depth) where there was often some sedimentary data to be 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 8000 metres per second.

To provide flexibility in iterating for the optimum image, the final imaging steps were normal moveout, stack, post stack time migration and a post migration stretch to estimated depth. Ideally with higher signal to noise ratio data this could have been done in one step of Prestack depth Migration.

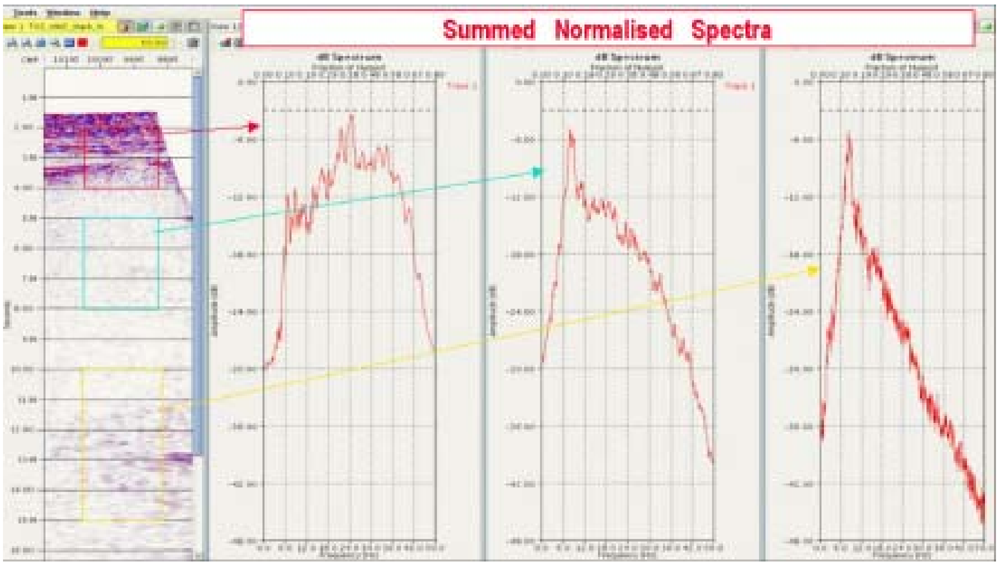

Figure 4 Summed spectra at three different travel time levels, the deepest window is 10-15 seconds TWT (frequency range of spectra plots is 0-50Hz)

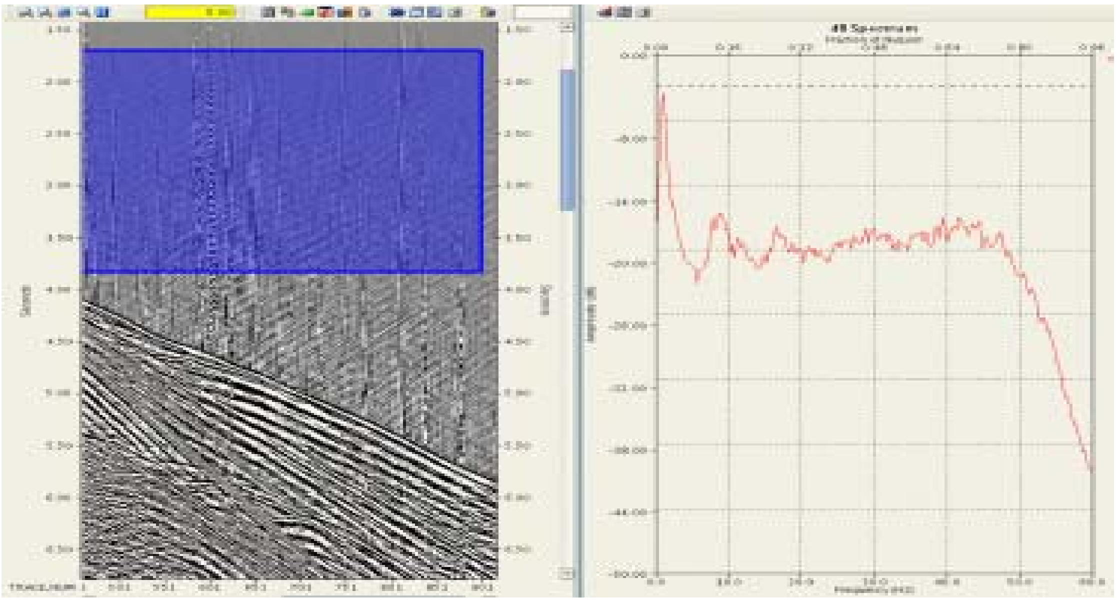

Figure 5 Spectral analysis of environmental/tow noise. Data has digital group forming applied but no other processing. (The spectra scale is 0-60Hz)

Final Data and Interpretation

An image of the final section for line WG-1 is shown in Figure 6. This data has been stretched to estimated depth based on the velocities derived from the reflection seismic survey. Please note that this line is over 240 Kms long and contains close to 20,000 traces to a depth of over 50 Kms, consequently it is very difficult to produce a useful image on a normal sized page. When loaded in a workstation the benefit of both zoom and decimated squash plot images can be appreciated. At the time of writing, interpretation of this data and its integration with other geophysical data is in progress. However, these data clearly show the subduction plate down to 30-40 Kms and active faults in the accretionary wedge. The general assumption that the deep earthquake initiation zone at 20-30 Kms subsurface was transmitted westwards to the sea bed appears proved. The faults in this area are certainly active. Although this survey confirms the broad concept of the mechanism of the tsunami generation it has also uncovered many unexpected details. For example the Oceanic crust is thinner than was expected. Integration work is progressing with other SAGER data and it expected that papers will be published by SAGER members in 2008 and beyond.

Conclusions

This project demonstrated that given reconfigured state-of-the-art commercial hydrocarbon exploration acquisition and data processing seismic technology, ultra deep reflection images of this active margin area can be achieved. The ability to generate and record very low frequency data, then separate signal from noise at these levels is not normally available to academic research organisations.

Acknowledgments

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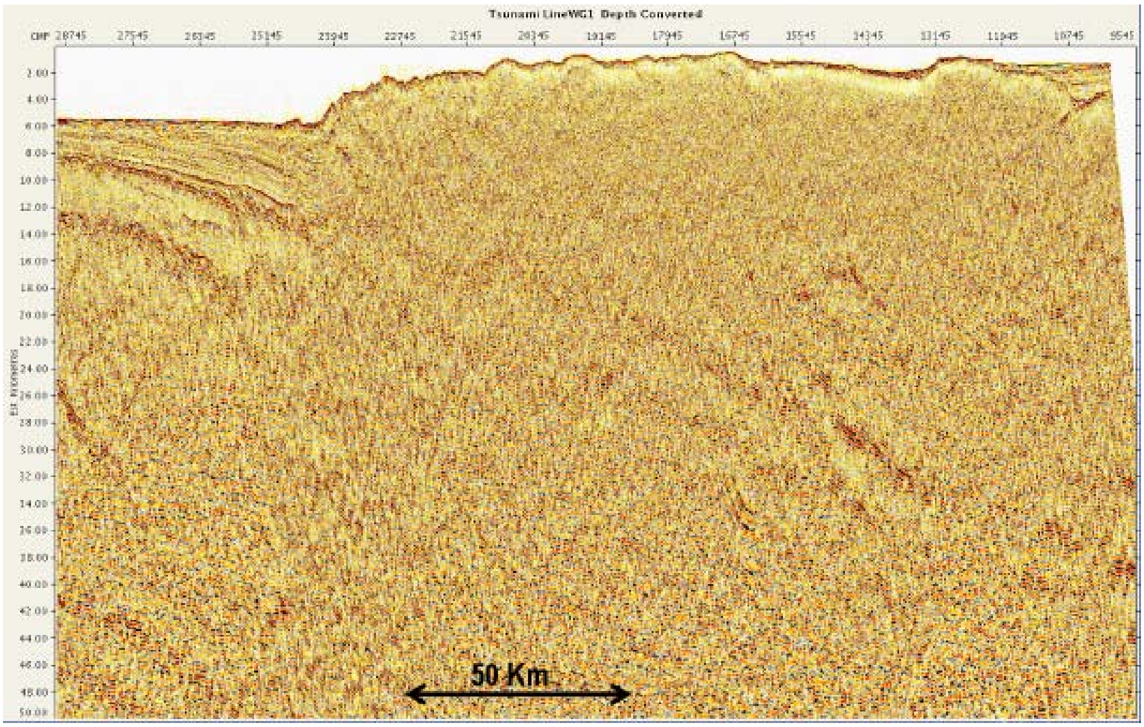

Figure 6. Line WG-1 final processed section converted to estimated depth
Vertical scale is in kilometres.

(note this display is highly decimated and "squashed")