Mapping of sediments and crust offshore Kenya, east Africa: a wide aperture refraction / reflection survey

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Summary

In order to better understand the continent/ocean transition in the deep water Kenya, a 180 km seismic refraction line was acquired using 87 Ocean Bottom Seismographs (OBS). The Common Station Gathers were used to develop a velocity model using first break tomography, layered tomography and forward modeling. The Vp-velocity structure of the sedimentary basins and the crust was obtained and the continent/ocean transition was defined. The crustal thickness at the continental domain ranges from 18 Km at the western end of the line, thinning to 11.4 Km at its transition to the oceanic crust. Average thickness of sediments with Vp-velocities ranging from 1.8 to 4.45 Km/s, covering the stretched continental crust, is 4.8 Km. The oceanic crust is 10.8 Km thick, covered by 3.8 Km of sediments with Vp-velocities ranging from 1.8 to 3.3 Km/s. The upper part of the continental crust is laterally inhomogeneous with Vp-velocities increasing from 5.8 to 6.1 Km/s, from west to east. The oceanic crust is divided into three layers: layer 2a has Vp-velocity 4.7 Km/s, while layer 2b has Vp=5.3 Km/s, and layer 3 is fairly homogeneous with Vp-velocity 6.8 Km/s. Evaluation of PS converted phases defined a Vp/Vs ratio ~1.78 in the upper continental crust, while in the oceanic domain this ratio is ~2.00. The stretched continental crust extends eastwards for nearly 290 Km from the coast of Kenya to the oceanic domain.

Introduction

The wide-aperture reflection refraction profiling (WARRP) method, using node technology, exploits the wide-angle reflected energy, diving waves, as well as normal incidence reflections (Makris and Thießen, 1984; Dell'Aversana P. et al., 2000), thus provides accurate velocity models. Node technology has the advantage over streamers in that the length of the seismic array can be adjusted to the target depth, in order to map the velocity correctly and allow reliable migration. PS converted phases are also recorded, defining shear wave velocity and Vp/Vs ratios for better understanding lithological variations.

The aim of this survey was to define the crustal structure and thickness of sediments in the deep water offshore Kenya along a pre-existing Multi Channel Seismic (MCS) line and delineate the continent/ocean transition. MCS data had defined the structure of the sediments with high accuracy but were unable to delineate the limits of the various crustal types. Also the depth to basement was ambiguous.

In the following we present the seismic velocity model developed by wide aperture seismic observations using Ocean Bottom Seismographs. The results will be discussed in connection to the existing MCS data.

Methodology and Field Operations

A 2D seismic line of WNW-ESE orientation, east of the Kenyan coast, was designed to be coincident with a portion of the 2007 GXT-Ion EA Span KA-2000 line (see fig. 1). Bathymetry along the line varies from 1800 m in the west to 3200 m in the east. 87 OBS positions were deployed along 166 Km and shots were extended at both ends by 10 km. Spacing of OBS nodes varies from 2 Km at the western, 1.5 Km at the central, and 3 Km at the eastern part. Shots along the line were fired at 100 m spacing. The air gun array had a volume of 48 l (2800 cu in) and was fired at 2000 psi. OBS data acquisition was performed using the Tug M/V SOLAND vessel.

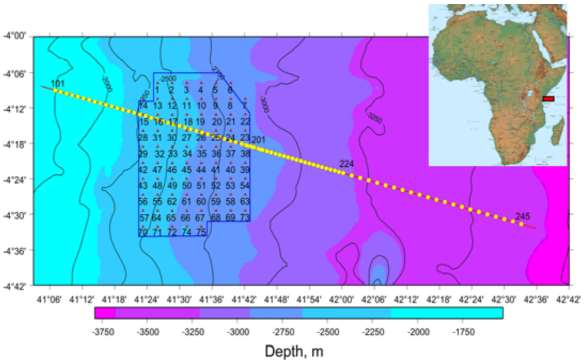

Figure 1: Location of the 2D seismic profile offshore Kenya. OBS positions are shown in yellow

The instruments used (see Makris and Moeller, 1990) are 4C component stations recording three geophones and one hydrophone. The seismic sensors, A/D converter and microprocessor used in programming and managing the recorded seismic signals are housed in a glass sphere of 17" diameter (see fig. 2). The internal clock of the system is initially triggered by a GPS receiver and has a time stability of 10^{-8}.

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The geophones have a natural frequency of 4.5 Hz and are gimbal-mounted and placed at the bottom of the sphere. Their orientation can be reconstructed using an inbuilt compass integrated in the OBS. An acoustic communication system, a radio beacon and a lamp are also contained in the sphere, together with the batteries (D-size alkaline or Lithium-ion type) for the power supply of the electronic components. The system is attached to a metal frame of 17 Kg weight that anchors the OBS on the sea floor. For environmental purposes, sand bags were used for anchoring. At the external part of the glass sphere a transducer for the acoustic communication, a flag for visual observation of the station, and an antenna for radio locating it are attached.

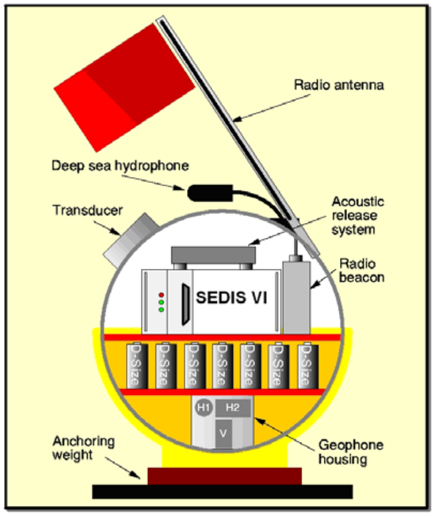

Figure 2: The GeoPro Ocean Bottom Seismograph

The new generation GeoPro SEDIS VI seismic unit permits direct communication with the seismic vessel, so that data can be retrieved for quality control, and the station can be re-programmed according to the project requirements. Downloading data can be accomplished by cable connection to the OBS or wireless transmission.

Data were compiled in Common Station Gathers (CStGs), using a linear move out of 6 Km/s as reduction velocity. An example of a CStG of OBS position 105, located at the western end of the 2D line, is presented in figure 3. First break arrivals from the sediments (Ps), arrivals from energy propagated along the upper crust (Pg), and Pn arrivals from critically refracted seismic energy at the crust/mantle boundary (Moho discontinuity) are indicated. PgP and PmP are wide angle reflections from the top of the crust and the crust/mantle boundary, respectively. A PS converted phase is also indicated.

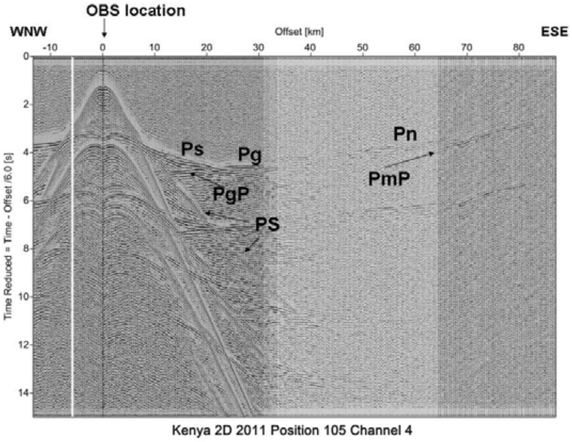

Figure 3: Common Station Gather of OBS 105 from the western end of the profile. Data are recorded by the deep sea hydrophone

Velocity Model

At the first stage, an initial Vp-velocity model was obtained by first-break tomography (gridded tomography) (see fig. 4). This provides an approximation of the velocity structure limited at depth by the penetration of diving waves. This process does not consider later arrivals of reflected phases, which are essential in delineating the thickness of layers and their velocity.

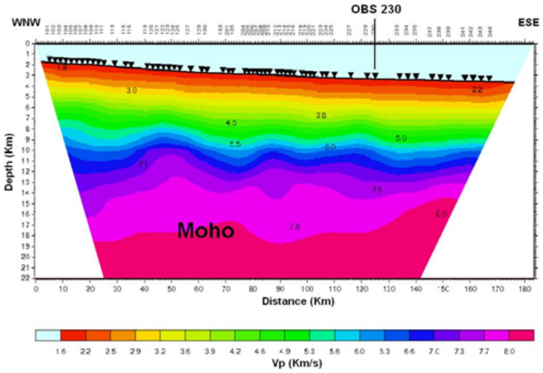

Figure 4: Velocity model from first break tomography

The gradient velocity model mapped the complete crustal section, delineating the transition between the crust and the mantle (Moho discontinuity). This was possible because seismic energy propagated very efficiently along the 2D line, and Pn phases were recorded at most OBS locations. It is interesting that to the west the crust thickens to about 20 Km, and thins significantly to the east, after OBS position 230, to approximately 14 Km.

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This is the approximate location of the continent/ocean transition offshore Kenya, as it will be seen in the final velocity model.

At a second stage, reflected arrivals are picked and assigned to specific layers in a top-down procedure by optimizing depth and geometry of the seismic interfaces by a least-square approximation between observed and calculated travel times. The layered velocity model developed by this procedure is used as input for a two-point ray tracing forward modeling, kinematic and dynamic. We applied the Cerveny and Psencik (1983) code. During this procedure both travel times and amplitudes of the different seismic phases are calculated and compared with the observed data.

An example of a ray traced model is presented in figure 5. Synthetic travel times are color coded and overlapped with the CStG of OBS 105.

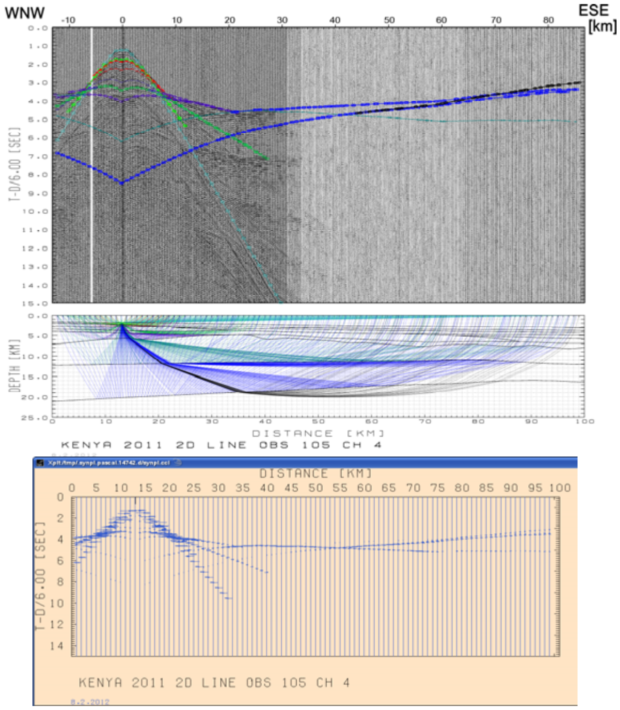

Figure 5: Ray traced model of OBS 105 (upper part) and synthetic amplitude (lower part)

In the middle part of figure 5 we present the ray propagation through the seismic section, and at the lower part the synthetic travel times and amplitudes. This process was applied at all 87 CStGs, and the result of the final velocity model is presented in figure 6.

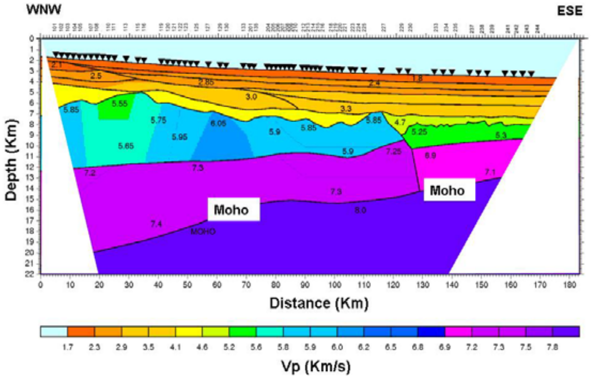

Figure 6: Final Vp- Velocity Model

The crustal thickness at the continental domain is 18 Km at the western end of the profile, thinning to 11.4 Km at its transition to the oceanic domain. Average thickness of the sediments, with Vp-velocities ranging from 1.8 to 4.45 Km/s, is 4.8 Km. Velocities in the upper part of the continental crust are laterally variable (light blue in figure 6). The highest velocity values were mapped at the central part of the profile, between Km 40 and 90. This indicates that mafic rocks may have intruded in form of dykes in the upper continental crust during stretching. The oceanic crust, following to the east beyond Km 120, is only 10.8 Km thick, covered by 3.8 Km of sediments with Vp-velocities ranging from 1.8 to 3.3 Km/s. Oceanic layers 2a and 2b have Vp values of 4.7 and 5.3 Km/s, respectively. The thickness of these two layers is 2.6 Km. Oceanic layer 3 is fairly homogeneous with a Vp-velocity of 7.1 Km/s and 4.0 Km thickness.

PS converted phases for the different crustal types were also evaluated. For the continental upper crust Vp/Vs ratios range between 1.75 and 1.80, which are typical for this type of crust. For the oceanic domain, for layers 2a and 2b, Vp/Vs ratios varied between 1.95 to 2.05. These values are also typical for oceanic environment. Thus, the continent/ocean transition was identified not only by crustal thickness and velocity but also by defining shear wave velocities and Vp/Vs ratios.

Figure 7 shows an MCS, PSDM depth migrated line shot/processed by ION GX as part of the 2007 East Africa SPAN that coincides with the wide aperture 2D refraction line acquired for this program. Velocity and structure of the sediments are accurately defined by both MCS and OBS data. Both data sets produced nearly identical velocities and depth to first order discontinuities. The value added by the OBS over the MCS data is the delineated crustal thicknesses and the corresponding lithologies, and the ability to more accurately locate the continent/ocean transition. Also the depth to basement was more clearly identified and ambigouities resolved.

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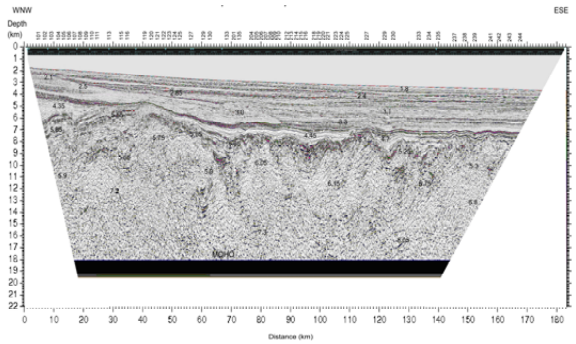

Figure 7: Reflection Line shot by ionGX

Figure 8 combines all of the information by overlapping the MCS depth migrated section with the velocity model of the OBS data .

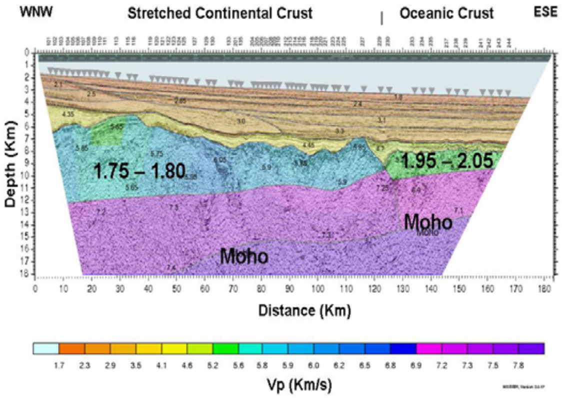

Figure 8: Reflection MCS line overlapped with the Velocity Model obtained from OBS observations. Vp/Vs values for the upper continental crust and layer 2 of the oceanic domain are given

The results provided by the MCS and OBS data are in very good agreement for the sedimentary section. First order discontinuities that limit the various velocities are in good agreement with discontinuities mapped by reflectivity. This means that the velocity analysis by both methods, for the sedimentary sequence, is of equally good quality. It is interesting that sedimentation at the eastern part of the section has been developed by a constant rate of subsidence, and velocity values of the sediment series to the east are higher than those to the west. Lateral velocity variations at the western part of the line are limited by an unconformity extending up to Km 85.

Reflectivity mapped between Km 65 and 95 of the section coincides with the high velocity zone mapped by the OBS observations. This supports the possibility of intrusion of mafic rocks in the upper part of the crust during stretching. Furthermore, the OBS data delineated the crustal thickness and its geometry along the profile that MCS data did not reveal.

Conclusions

Wide aperture refraction/reflection observations obtained by ocean bottom seismographs have provided accurate velocity models for the crust and sediments in the deep water offshore Kenya area. Furthermore, it was possible to locate the continent/ocean transition at 290 Km off the Kenyan coast. This area is floored by stretched continental crust of 25 Km thickness at the Kenyan coast, south of Mombasa (Prodehl et al., 1997), thinning to the east to about 18 Km at the western part of the 2D OBS line, approx. 110 Km off the coast, and 11.4 Km at the continent/ocean transition.

Accurate velocity information provided by wide aperture OBS seismic data combined with structural information by high resolution reflection seismic data permits a much more thorough illumination of the geological structures and a better understanding of the geological processes. The possibility to exploit Vp/Vs values that can only be obtained by OBS observations is essential in understanding the lithology of the various geological formations.

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EDITED REFERENCES

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