A tale of three methods: Volcanics in the Abrolhos Banks, Brazil

Marianne Parsons and Dr. Jeffrey MacQueen, Fugro-LCT Inc., Tore Hansen Undli, Sverre Berstad and Dr. Idar Horstad, Fugro-Geoteam AS*

Summary

Near-surface flood volcanics can create havoc when attempting geophysical imaging and geological understanding of the sub-surface. Abrolhos Bank, offshore Brazil, is one such area, and recent licensing of offshore blocks nearby or on the Banks has increased the economic stake in this problem. Extensive 3 dimensional modeling has been conducted using recently acquired marine seismic, gravity and magnetics data. Integrated geophysical analysis of these complimentary datasets has greatly improved our understanding of the extent of the flood basalts, as well as the thickness of the sub-volcanic sediments and the basement structure. No single one of these geophysical methods would have given us all this information in isolation: only the joint use of all three methods allowed the full range of interpretation. We interpreted the seismic data together with magnetic depth estimation techniques to constrain the depth to basement. We inverted on the gravity data in 3 dimensions to produce an isopach of the basalt, which was in turn constrained with the seismic and magnetic data interpretation. We have considered the important question of the source of the flood basalts: we found no evidence of basaltic feeder dikes in any of the magnetic, gravity or seismic data in the area, so a distal source seems most likely.

Introduction

The Abrolhos Banks area is a frontier exploration area for which until recently there was little geologic and geophysical data. Historically, it was seen as a non-prospective area due to the flood basalts found on the Abrolhos Banks. Further complicating the issue are a multitude of questions about the area's tectonic history, the extent of basalts, the source of basalts, the thickness of sediments beneath the basalts, the location of the oceanic / continental crust boundary, and regional features such as the nature of the relationship between the nearby Vitoria-Trinidade chain and the Abrolhos Banks.

As more and more of this area is opened up for drilling, a number of new geophysical surveys on the Abrolhos Banks provide the necessary datasets to create an integrated geophysical model which helps to answer some of the questions about the area. The physical properties of widespread flood basalts, as well as gas chimneys and difficult geology, cause a range of problems when trying to get an accurate subsurface image. The combined constraints of seismic, gravity and magnetics data were critical in clearing up a murky picture, and in building a reliable geologic model.

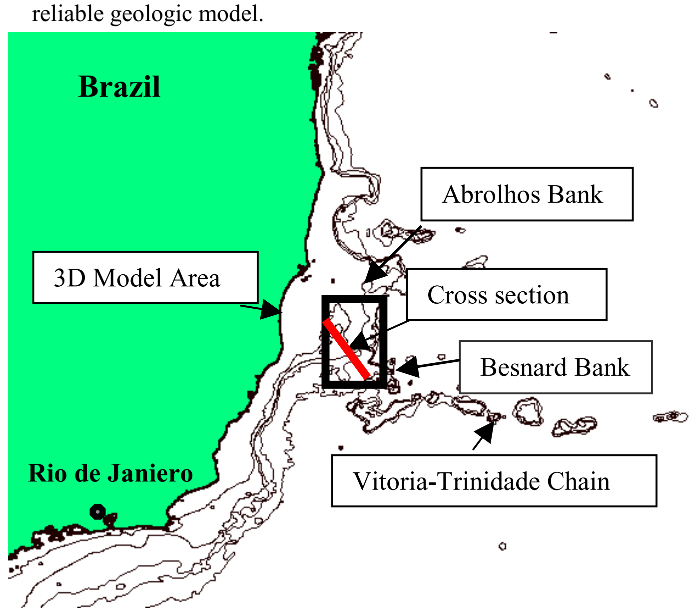

Figure 1 3D Model area displayed over bathymetry, Abrolhos Banks, Offshore Brazil

Using the recently acquired marine seismic, gravity and magnetic data, we have created an integrated model which better defines the extent of basalts, and the thickness of sub-basalt sediments, argues for a distal source of basalts and provides a more comprehensive tectonic framework for the region.

Setting of Case Study

The Abrolhos Banks are located offshore Brazil, and are marked by a bathymetric high (within 100 meters of sea level) that is surrounded by deeper water (approximately 1500 – 2000 meters) on all but the western (landward) side. See Figure 1. The bank is part of the Espirito Santo - Mucuri Basin. The Campos Basin is to the south and to the north are the Cumuruxatiba basin and the Royal Charlotte Volcanic Complex (Cainelli, C., and Mohriak W.U., 1998). On the magnetic maps, this area is marked by overall high frequency signals: these are partially caused by the bathymetric shallows of the Banks, but the primary source is the near surface volcanic flows. The Bouguer gravity data also shows high frequency features, including a nearly continuous curved anomaly across the Abrolhos banks.

The recent seismic data has higher resolution than the originally acquired coverage, and in many areas it shows strong basement definition. See figure 2. The seismic data also shows the extensional faults and the large sediment basins under the areas of known volcanic deposits.
We chose the location of the model area to cover the majority of the Abrolhos Banks, including the smaller Besnard Bank to the southeast. See figure 1. The model area was restricted by the edge of the salt basins and the areas surrounding the Banks. In order to limit the unknowns in the modeling process to a tractable number, the area chosen has little or no salt. One theory on the absence of the salt holds that a sediment wedge, prograding from North to South, has pushed the salt deposits away (Hongxing, G. et al., 1997) from this area towards the Espírito Santo Basin and possibly eastwards over the shelf edge to deeper offshore areas. Extensive salt deposits in southern Espírito Santo Basin and good indications of salt diapirs on the eastern flank of the bank support this hypothesis.

Modeling Process

1) *Seismic definition of initial model*
To construct our model, we started by selecting 14 seismic lines, which provided adequate coverage, and 6 key horizons interpreted from these seismic sections. See figure

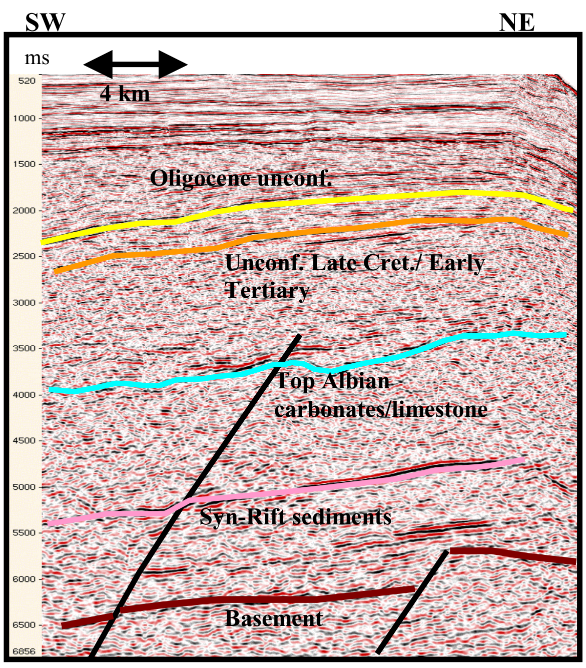

Figure 2 Section of seismic showing significant horizons.

2. The chosen horizons were: 1) top of Basement, 2) top of Neocomian Barremian syn-rift sediments, 3) top of Albian carbonates and limestone, 4) unconformity within the Urucutuca fm of upper Late Cretaceous/Early Tertiary age, 5) Oligocene unconformity which represents approximately top Abrolhos Volcanics and 6) water bottom. These horizons were chosen for their relative density contrasts and geological significance. We fit surfaces to the profile horizons and used the results in the 3D modeling software.

2) *Using Magnetics for Depth estimates*
We determined depths to magnetic basement using magnetic interpretation methods such as Euler deconvolution, the Peter's half slope method, and spectral analysis. Over most of the Abrolhos Banks, the magnetic depth estimations were dominated by the near surface basalts, usually picking depth to top of basalt flow rather than basement. This correlated extremely well with the Top Abrolhos Volcanics on the depth converted seismic cross sections. On areas towards the edge of the Abrolhos bank, we obtained deeper magnetic depth estimation picks of basement: these were confirmed in the seismic data by strong basement reflectors and the absence of basalt.
On Besnard Bank (figure 1), where the basement was difficult to resolve on the seismic sections, the magnetics produced some useful depth estimations of basement. Magnetic depth estimations showed that the basement on Besnard Bank was the higher of the possible interpretations of the basement in the seismic. Magnetic depth analysis also suggested that the flow basalts on Besnard Bank were not as thick or extensive as on the rest of Abrolhos Banks, as there was little interference at the near surface when doing magnetic depth estimations.

3) *Readjusting the basement interpretation and 3D model*
We adjusted the 3D model surfaces with the help of the Besnard basement magnetic depth estimations to reflect the new basement interpretation. We produced a depth to basement surface map which indicated that the Besnard Bank basement was higher than the rest of the Abrolhos Bank.
Our depth to basement map shows a deepening down to 12400m in the middle of our case study area, which is located to southeast, on the shallow Abrolhos Bank. The shallower edges of the area are between 8000 and 10000m. This depression in the basement, which represents a relief of up to 4000m, probably developed in Late Cretaceous. On the Abrolhos Bank, Late Cretaceous is represented by extensive clastic turbidite deposition. Also indicative of subsidence of the basin during the deposition of the Urucutuca formation in Cenomanian to Mid Tertiary, is the relatively constant thickness of the syn-rift sequence and the Albian carbonates, compared to the basin infill trend of the clastic sediments of Late Cretaceous and Early Tertiary age.

4) *Using gravity inversion to determine extent of basalts*
After the basement had been constrained in the 3D model using a combination of seismic data and magnetics data, we did a gravity inversion starting with a thin basalt layer to determine the extents of near surface basalt. We chose gravity since it was difficult to determine whether there were areas of basalt inter-layered with sediment, or purely sedimentary layers, using only the seismic data. The magnetics also shed little light on the extent of the basalt,

since the flows occurred over a period of time, and probably had a large range of remanent magnetizations. Initially we placed a thin layer (30 m) of basalt in the model just below the base of the Oligocene unconformity. See Figure 3. During the inversion process, the basalt layer thickened, allowing the lower layer of the volcanic

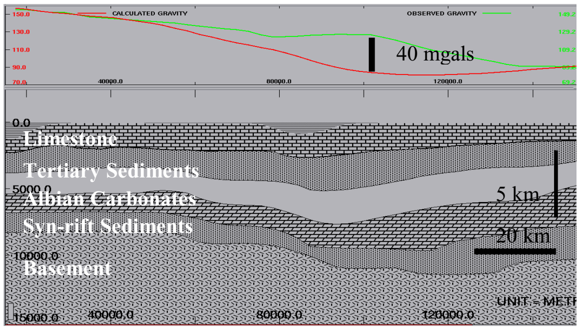

Figure 3 Cross section of model prior to inversion

sequence to extend downwards into the model as needed for the calculated gravity of the 3D earth model to match the observed gravity data. A detailed integration of the seismic and gravity data constrains the distribution and thickness of the basalt layer in the region. The Abrolhos Volcanics seem to be deposited as infill in a paleo-relief, which also supports the theory that the basalt was deposited

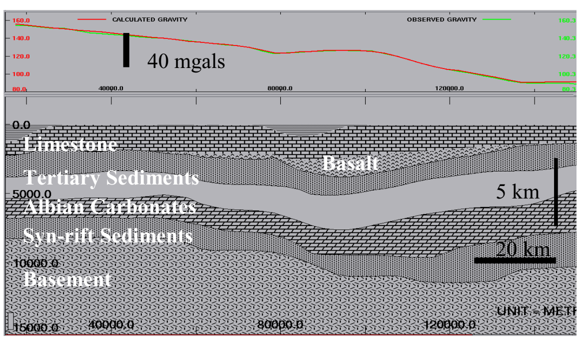

Figure 4 Cross section of model after inversion on basalt

as a flow. It was interesting that on Besnard Bank there was little basalt, as suggested by the magnetics, with the greatest thickness on the eastern and northern areas of the main body of the Abrolhos Banks, and also some to the west of Besnard Bank. Overlaying an outline of thicker parts of the basalt isopach over the magnetics shows a good correlation with high-amplitude magnetic anomalies.

After we inverted the gravity data, significant thicknesses of sediment still remained between the flow basalts and the basement, in some instances as many as ten kilometers. See Figure 4.

The Source of The Volcanics: Local or Distal?

Through this case study so far, we can indicate the thickness, the general trends and the lateral extents of the basalt deposits. However, an important geological question still remains unanswered: where is the source for the shallow Abrolhos Volcanics? One major consequence of a local intrusive source is that the increased heat flow could possibly overcook the petroleum system and decrease the prospectivity in the area. To help answer the question of source we looked to analogous areas where flood basalts have occurred, such as the Columbia River flood basalts of the Northwestern USA and the Deccan Traps of India. In the case of both the Columbia River basalts and the Deccan basalts, the basalts were intruded in long fissures, following areas of crustal weakness, and spread over large areas due to the low viscosity of basaltic magmas. Continental extension from rifting probably created weakness trends in the crust offshore Brazil, and it is possible that basaltic feeder dike swarms may have followed these weaknesses. In examining the possibility for a local source of the flood basalts in our model area, we considered two criteria:

1. Where is there evidence of weakness in the crust, or faulting in the sediment?
2. Is there evidence of basalt fissures or dikes in the seismic data, the magnetic data or the gravity data?

The first criteria points to the area on the Abrolhos Banks that is parallel to the gully between Abrolhos Bank and Besnard Bank. The basalt isopach maps shows that this area has some of the thickest regions of basalt (up to 2km). The seismic data also shows evidence of extensional faulting. This area, however, does not meet the second criteria, that the distinctive features of basalt fissures should be evident in the gravity, magnetic or seismic data. In fact, we could not find anywhere within the model area where one might be able to interpret basalt fissures from any of the geophysical data available. The distinctive physical properties of basalt, and the semi-vertical orientation of any fissures, should be easily identified using magnetics and gravity. High-density fissures in relatively low-density sedimentary basins would produce a high frequency gravity signal. Similarly, with magnetics, the high susceptibility of the basalt in relation to the sediments would produce distinctive high frequency anomalies. To further illustrate this, we produced some simple 2D models. These verified that, particularly with the magnetics data, lineaments would be evident in the maps. There are no good indications of basalt fissures in the seismic data either.

Based on these results, it seems probable that the Abrolhos Volcanics did not have a local source, but a distal source instead. The Columbia flood basalts show areas where the source of the basaltic fissures produced flood basalts that flowed up to 500 kms (De Souza, N.N., 1999).

Indications that support a distal source for the Abrolhos Volcanics include

1) the basalt seems to be deposited in depressions, and
2) there are no obvious indications in the gravity, magnetics or seismic data of intrusions/fissures.

Deposition of the Basalt

The seismic data indicates that the basalt deposits consist of alternating layers of basalt and sediments, not a thick uniform package of basalt. The deposition of the basalt probably occurred over a period of time, 32.2 to 64.5 Ma, but older ages have also been suggested (64 to 83 Ma) (Earthmoves, 1998). A distal source of volcanic material may have followed the topographic lows to deposit in the basin. Analog settings can be found in the Deccan Traps in India, where these flow periods lasted from months to years and the thickness of the resulting individual flows ranges from a few meters to as much as 35-40 meters. The volcanic material in the Deccan Traps of India is of the same age as those in Brazil. Boreholes in the Deccan Traps have encountered up to 29 separate basalt flows, separated by sedimentary beds. These flat lying layers of basalt flows in India are very similar to what we find in Brazil.

Oceanic or Continental Crust?

The location of Oceanic/Crustal boundary, in relation to Abrolhos Banks, is an important factor in determining the exploration potential of the basins in this area. The gravity and magnetics data do not show the distinct signatures usually found with oceanic crust. We do not see the evident banding usually seen in the magnetics data parallel to the Mid Atlantic ridge. The bouguer gravity values are low, indicating the area is underlain by lighter continental crust rather than the more dense oceanic crust. In the seismic, salt diapirs can be observed outside the shelf break in the continental rise. We interpret this salt as being autochthonous. This indicates that we still are on the continental crust or at least in the transition between oceanic and continental crust. The bathymetry information also suggests that the Abrolhos Banks is probably not oceanic, as it still appears to be part of the continental platform.

Vitoria-Trinidade Chain

The Vitoria-Trinidade chain, probably the result of a hot spot, passes to the south of the Abrolhos Banks. It has been suggested that there is a relationship between this hot spot and the flood basalts of the Abrolhos Banks. In the analysis of the data within our model area, there is no strong evidence that Vitoria-Trinidade chain produced the basement high under the Besnard. Bank. The basement was modeled as homogenous with a good fit to the geophysical data, particularly in the relationship between Besnard Bank and the rest of Abrolhos Banks.

It is interesting to note, however, that many flood basalts have nearby hotspots at the time of their eruption. The Columbia River Basalts had the Yellowstone hot spot, though the hot spot track was offset (300-400 km) from the vents and fissures that produced the basalts (Hooper, 1997). The fissures of the Deccan traps of India would have been relatively close to the Reunion hotspot (Morgan, 1972). To understand the relationship between the Vitoria-Trinidade chain and the flood basalts of the Abrolhos Banks, the location of the fissures for the basaltic flows would have to be identified and followed up by a more regional study.

Conclusion

Through the integration of seismic, gravity and magnetics data, we have produced a 3D model which better defined the extent of the near surface flood basalts, the thickness of sediments beneath them, and the basement structure. These results could not have been obtained using any one of these geophysical methods and it was crucial to be able to iteratively revisit each type of data through each step of the modeling properties. Owing to the challenges that this geological environment provides, we required as many kinds of geophysical data as possible: when the physical properties required in one method are masked, another can be used. Using this model and the analysis of the data, we were able to eliminate the possibility of a local source for the volcanics within our model area. Other occurrences of flood basalts, such as the Deccan Traps and the Columbia River flood basalts, certainly support the idea that the source of these flood basalts could be more distant.

As far as the question of continental versus oceanic crust, there seems to be no strong indication that the Abrolhos Banks lie on oceanic crust.

The relationship between the Vitoria-Trinidade chain and the flood basalts is compelling, considering similar hotspot/flood basalt relationships in other areas of the world. More research into the location of the basalt fissures that created the Abrolhos flood basalts and the timing of the Vitoria-Trinidade chain would be required to reach a firm conclusion.

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