GeoConvention 2015
GEOSCIENCE
new horizons
Telus Convention Centre • 4-8 May 2015 • Calgary, AB Canada

Evidence for hyper-extended continental crust in the East Orphan Basin from seismic reflection data and potential field forward modelling and inversion

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Summary

In 2012 and 2013, PGS, TGS, and Nalcor Energy undertook a large-scale survey to acquire a network of regional long offset 2D seismic reflection and gravity profiles (22,500 km) across the East Orphan Basin, Flemish Pass Basin and Flemish Cap. Seismic interpretation of these lines has revealed regionally-extensive, thick sedimentary basins that can be subdivided into rift and post-rift megasequences. To aid in the seismic interpretation of the top of basement beneath these megasequences, 2D forward modelling of the coincident gravity data was undertaken using the boundaries of these megasequence packages as constraints and representative constant densities for each package. Assuming constant densities for the crust and the underlying mantle, the base of the crust (Moho) was then adjusted to fit the observed gravity data along each line. Insights obtained from the gravity modelling were subsequently used to update the seismic interpretation. Using these complementary geophysical datasets with this iterative approach, clear evidence for an extensive NE-SW-trending zone of hyper-extended continental crust (< 10 km thick) has been identified in the East Orphan Basin. The existence and spatial distribution of this zone was previously predicted based on extreme stretching factors, beta, obtained from regionally constrained 3-D gravity inversion work using satellite gravity data. This zone of hyper-extended crust appears to correlate spatially with overlying Cretaceous fans that exhibit AVO anomalies, suggesting that their evolution may be linked.

Study Area

The East Orphan Basin lies at the northeastern edge of thinned continental crust of the Newfoundland and Labrador margin, immediately to the northwest of the Flemish Cap (Fig. 1). The basin was formed and subsequently reactivated during three main rifting episodes that occurred during the Triassic, the Late Jurassic to Early Cretaceous, and the Late Cretaceous. These rifting episodes were oriented roughly NW–SE, W–E, and SW–NE, respectively, resulting in complex faulting within the basin (Enachescu *et al.*, 2005; Lowe *et al*., 2011). The sediments of the Orphan Basin overlie basement terranes that were stitched together during the closing of the Iapetus Ocean during the Caledonian-Appalachian orogeny in Paleozoic time. The original Mesozoic opening of the basin occurred along the pre-existing basement structures and tectonic fabrics from the Caledonian-Appalachian orogeny (Shannon, 1991).

Data Acquisition

Regional long offset 2D seismic reflection and gravity profiles were acquired by PGS, TGS, and Nalcor Energy in 2012 and 2013. A total of 57 lines were acquired resulting in a total coverage of 22,500 km. Lines were oriented either NW–SE or SW–NE and varied in length from 115 to 719 km. In addition to a number of sparsely distributed regional lines, a dense concentration of seismic and gravity lines was focused on the East Orphan Basin and the Flemish Pass Basin. TGS performed the seismic reflection data processing in time and also performed the Bouguer correction of the acquired gravity data (Fig. 1).

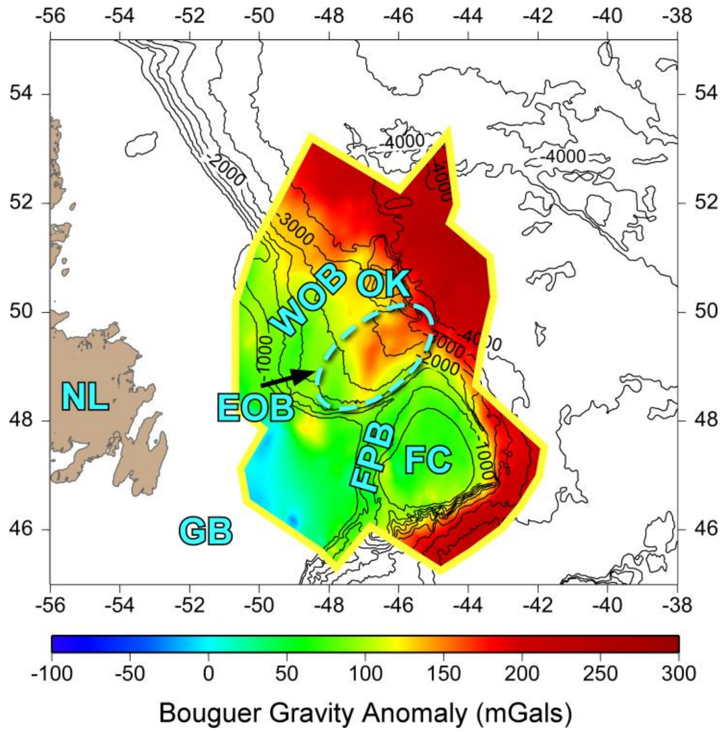

Figure 1. Bouguer gravity anomaly data interpolated across all the 2D profiles. The broad outline of the seismic and gravity survey is shown in yellow. The East Orphan Basin is highlighted with the dashed turquoise oval. Abbreviations: EOB – East Orphan Basin, FC – Flemish Cap, FPB – Flemish Pass Basin, GB – Grand Banks, NL – Newfoundland and Labrador, OK – Orphan Knoll, WOB – West Orphan Basin.

Seismic Interpretation

Interpretation of the processed time sections from the seismic reflection survey was undertaken at Nalcor Energy with the goal of identifying the main boundaries that subdivided the large sedimentary basins into rift and post-rift megasequences. These boundaries corresponded to the top of basement and the top of the Cretaceous sediments. Interpreting the top of basement was complicated by the complexity of the imaged rifted structures as well as the poorer data quality at depth. Gravity modelling was thus undertaken to reduce uncertainty in the seismic basement pick.

Gravity Modelling

In order to construct density models based on the time sections, the horizons were converted to depth using constant velocities for each megasequence. Once the depth of the boundaries had been determined, density models were constructed using constant densities of 2200, 2500, 2700, 2870, and 3300 kg/m^3 for the seawater, post-rift sequence, rift sequence, crust, and mantle, respectively. As the Bouguer data were used for the modelling, the seawater density corresponded to the reference density of 2200 kg/m^3 used for the Bouguer correction by TGS. A constant density was assigned to the entire crust for lack of available regional density constraints.

The gravity modelling was undertaken using the GM-SYS Profile Modelling software from GeoSoft Inc. Preliminary gravity modelling was done assuming that all of the interpreted sedimentary horizons were correct and that the depth conversion placed the boundaries at their true depth. The Moho, or base of the crust, was the only part of the model that was adjusted in order to fit the gravity observations. Suspect regions were flagged wherever the crust was effectively pinched out or where no adequate fit could be achieved without altering the sedimentary interpretation. For these regions, the seismic interpretation was re-examined and, if geologically reasonable and consistent with the seismic data, adjusted to better agree with the gravity data. The density models were then updated to reflect the new seismic interpretation. Through several iterations of seismic interpretation and gravity modelling, final density models were developed for all of the seismic lines in the survey.

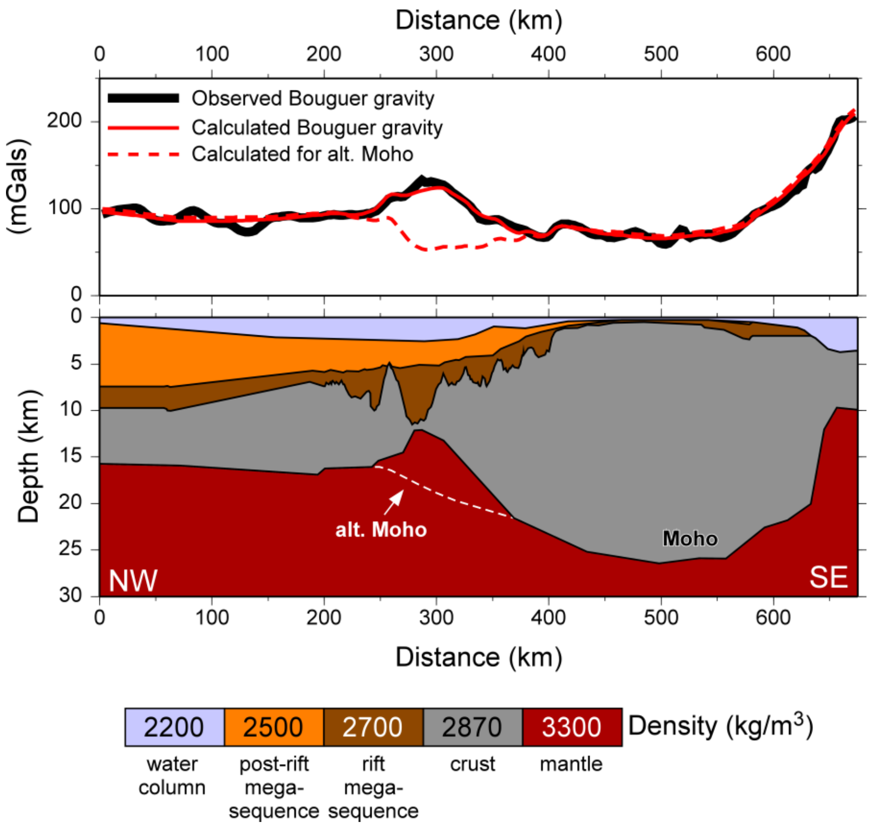

Figure 2. Density model (bottom) based on the seismic interpretation of key stratigraphic boundaries on a NW–SE oriented survey profile, with corresponding observed and calculated Bouguer gravity anomalies (above). To highlight the need for pinching out the crust, an alternative Moho was picked for comparison and the resulting calculated anomalies are plotted with the dashed lines.

The final density models (example in Fig. 2) provide basement and Moho depth constraints across the study area. These constraints are consistent with the observed gravity and with the seismic reflection sections. In many instances, the density models revealed Moho depths that were consistent with coherent reflections on the depth converted seismic sections (not shown in abstract).

Crustal Thickness

Once the depth to basement was sufficiently constrained using the seismic reflection data and the gravity modelling, the modelled base of the crust was combined with the depth to basement in order to determine the crustal thickness across the survey area. Along many seismic lines across the East Orphan Basin, despite shallowing the basement as much as possible to allow for more high densities from the crust to contribute to gravity highs, the Moho also had to be brought up to a shallower depth to provide enough mass from the mantle into the model to satisfy the gravity observations (Fig. 2). Toward the northeast limit of the East Orphan Basin, several of the profiles even required two zones of mantle upwelling to reproduce the observed gravity anomalies. Low density salt does not appear to be present in the East Orphan Basin as its presence would require even shallower upwelling of the mantle to reproduce the observed gravity anomalies.

By combining the modeled results from all of the individual density models, zones of hyper-extended continental crust were identified and correlated across multiple seismic lines, revealing extensive zones of hyper-extended continental crust in the East Orphan Basin. Such zones had been previously postulated based on derived crustal stretching values, beta, from regional constrained 3D gravity inversion work over the same area using satellite gravity data (Welford *et al.*, 2012).

The map of crustal thicknesses derived from the individual 2D forward modeled gravity lines shows a zone of hyper-extended continental crust running along the axis of the East Orphan Basin that branches into two zones toward the northeast (Fig. 3). These zones and their branching character show a remarkable correlation with the locations of Cretaceous fans identified on the basis of AVO anomalies. These fans tend to align themselves with the northwestern limit of the hyper-extended zones and even line up with the northwestern limits of the two branches of hyper-extended crust to the northeast. These results suggest a linked evolution between the hyper-extension of the continental crust in the East Orphan Basin and the local development of accommodation space required for emplacement and preservation of Cretaceous fans, which requires further study.

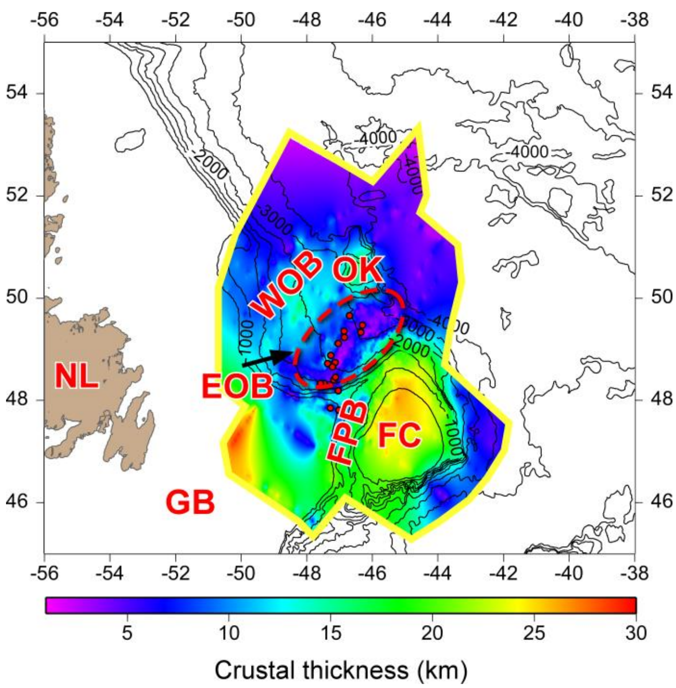

Figure 3. Crustal thickness derived from the seismically-interpreted basement and gravity-modelled Moho boundaries. The broad outline of the seismic and gravity survey is shown in yellow. The East Orphan Basin is highlighted with the dashed red oval. The small red circles correspond to Cretaceous fans inferred from AVO anomalies in the seismic reflection data. Abbreviations are defined in the caption for Figure 1.

Conclusions

Zones of hyper-extended continental crust have been identified across the East Orphan Basin using an iterative approach of seismic interpretation and 2D forward gravity modelling. The main zone of hyper-extension follows the axis of the East Orphan Basin and branches into two zones toward the northeast. The northwestern limits of these core and branched zones line up with Cretaceous fans identified on the basis of AVO anomalies, suggesting a linked evolution.

This study demonstrates the importance of combining seismic interpretation with gravity modelling in order to increase confidence in the seismic interpretation and ensure that the derived Earth models are consistent with all of the available geophysical information. A broader understanding of the crustal implications of the seismic interpretation of sedimentary basins can provide greater insight into the tectonic and thermal evolution of a basin or an entire margin.

References

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