# Integrated Crustal Interpretation from Seismic/Gravity/Magnetics with Full-Lithosphere Modelling - Offshore Newfoundland and Labrador

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## Introduction

Integrated crustal and basin modelling Offshore Newfoundland and Labrador provides a bottoms-up petroleum systems evaluation to aid exploration teams in high-grading areas before lease sales, as well as to improve understanding of existing acreage. Our study (Fig 1) included interpreted seismic horizons from regional 2D and 3D seismic, gravity and magnetic surveys, extended using public domain data sets. Crustal surfaces were created in a joint study by BainGeo and TGS/PGS, resulting in depth to magnetic basement (top of crystalline crust), mid-crust, and Moho depth. Magnetic data were interpreted to produce magnetic basement depth and Curie depth (depth to bottom of the magnetic crust), thus providing an estimate of the magnetic crust thickness. This thickness is an important input to the depth to magnetic basement work, as well as full-lithosphere thermal modelling, which was calibrated to well temperature data and surface heat flow measurements.

This work combines the extensive TGS/PGS survey data (Fig 1) with public domain data sets to give coverage over the entire offshore Newfoundland and Labrador region. We present here some of the results of this work, which allows us to interpret the deep crustal structure of the study area. Detailed 2D and 3D potential field models were used to create full-lithosphere basin subsidence and thermal models, calibrated at key wells, and modelled regionally across the region. This insightful and thorough workflow enhances our understanding of the basin’s petroleum system, enabling improved play and prospect generation and analysis.

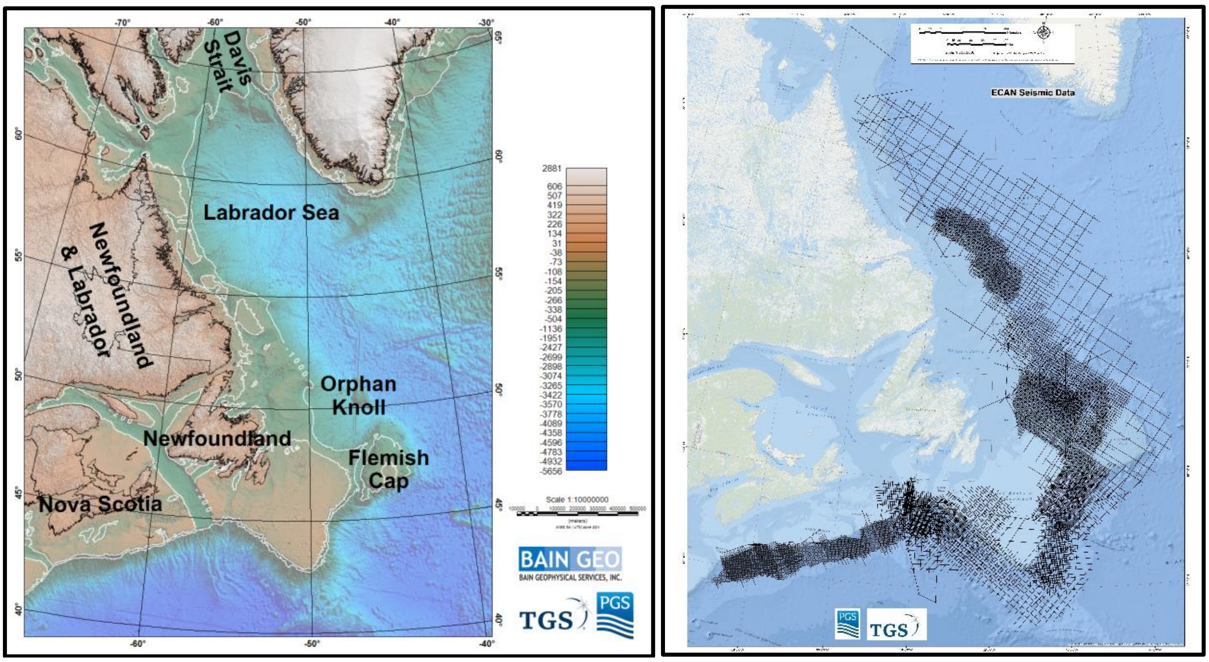


**Figure 1: Topography / bathymetry over the study area on left, with TGS/PGS 2D seismic coverage shown on right**

## Depth to Magnetic Basement - Theory and Construction

Depth to magnetic basement in stretched continental and oceanic crust has long been hampered by inaccuracies in the models used to compute the depth to the top of magnetic sources. The key reason for this is that most magnetic depth methods were conceived in the mid-1900s, when exploration was focused on shallow basement and very thick crust. Accordingly, many of these older methods depended on an infinitely thick magnetic crust to determine the depth to the top of the magnetic layer, or "top magnetic basement". In today's exploration of thinned continental and oceanic crust, magnetic depth methods have been updated to include an assessment of the thickness of the magnetic crust, which greatly improves the accuracy of the depth results (Flanagan and Bain, 2013). In some regions, magnetic depth estimates have been shown to be as much as 50% in error using the legacy methods. This method improvement allows us to move magnetic depth "imaging" to a much greater level of accuracy and utility.

Depth to magnetic basement solutions were computed using labour-intensive interpretation of the magnetic field gradients extracted from the grid, as well as being applied to the legacy GSC line magnetic data sets. These solutions were used to create a depth to magnetic basement map across the entire offshore study area (partial result in Fig 2). Results were compared against seismic interpretation, particularly on oceanic crust, where the two results are anticipated to coincide, geologically.

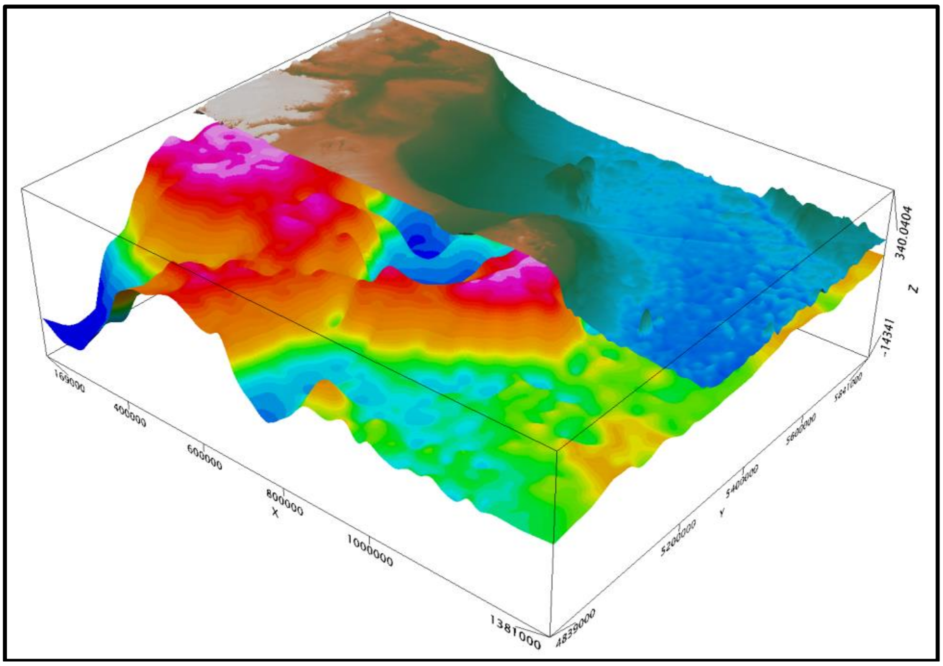


**Figure 2: Depth to magnetic basement over Orphan Basin & Flemish Cap, with bathymetry drape**

## Thickness of Crust and Depth to Moho from Constrained Gravity Modelling and Inversion

Inversion of the gravity field yields the depth to Moho, crustal thickness, and an estimate of the limit of oceanic crust (LOC) or continental / oceanic crustal boundary (COB). Recent improvements to gravity inversion methods allow the incorporation of a thermal gravity correction (see for example: Greenhalgh and Kusznir, 2007, and Chappell and Kusznir, 2008), which recognizes that stretching the lithosphere induces a long wavelength change in the gravity field caused by thermal effects altering the deep density field. Additional improvements (BainGeo) allow the inversion to simultaneously invert for structure, while also endeavouring to satisfy multiple Moho depth control points, thus significantly improving the crustal thickness result over previous gravity inversion methods.

## Curie Depth / Bottom of the Magnetic Crust

Depth to the "Curie isotherm" is computed in three dimensions using the regional magnetic data set. This process is more accurately described by stating that we compute the depth to the bottom of the magnetic crust layer. The inference is that the bottom of the magnetic layer is the depth at which rocks lose their magnetism – this is the so-called "Curie depth". However, in the scientific literature, this process is generally regarded as a direct mapping of the Curie isotherm. Curie temperature for magnetite (which is the primary source of magnetic anomalies in petroleum exploration studies) is 580 °C. Power spectral methods are used to compute the top and bottom of the magnetic crust (see for example, Li, 2013). The cross section below (Fig 3) is taken from Welford et al., (2020), with their interpreted Moho depth shown as the red horizon. BainGeo's Moho from constrained 3-D gravity inversion is shown as the blue horizon, and Curie depth extracted from the 3-D volume is shown as the magenta line. Each of these horizons provides insights on the geology of the basin and allow us to extract information regarding thermal gradients and heat flow. In this case, Curie depth is deeper and longer wavelength than Moho, but in many areas across this large region, the two surfaces intersect, (namely, Moho is shallower and deeper than Curie depth in some areas).

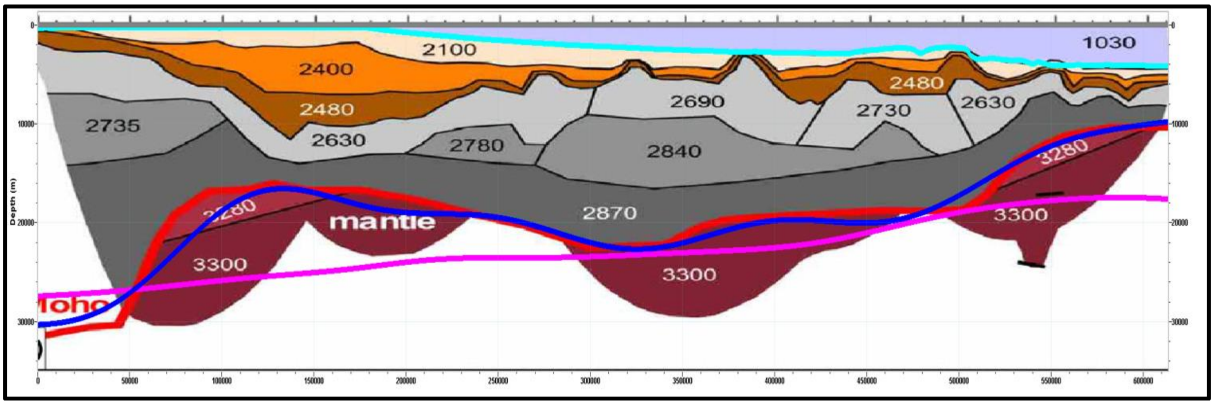


**Figure 3: BainGeo Moho (blue) and Curie Depth (magenta) on published cross section in Orphan Basin (Welford 2020)**

## Full Lithosphere Burial History and Thermal Modelling

BainGeo has developed an innovative and robust burial history and thermal modelling workflow, which integrates the crustal model and Curie depth, enabling improved prediction of temperature and thermal stress in more frontier parts of the basin. Key wells are used to calibrate full-lithosphere 1D models on the Newfoundland and Labrador shelf areas. This allows calibration of the apparent Curie temperature at the Depth to Base Magnetic Layer (DBML), which varies as a function of composition. We can then use the DBML and the apparent Curie temperature to improve prediction and reduce uncertainty of temperature and thermal stress in the frontier, deepwater part of the basin. This represents a major step forward in understanding and de-risking charge access in this large exploration area.

## Predicted Heat Flow Mapping from Curie Depth

Once Curie depth has been determined, it is useful to convert this Curie depth map into an estimate of heat flow (Fig 4). Several methods are described and listed in the bibliography by Li (2017) and Davies (2013). We have been able to improve on these methods, adding more-important and impactful variables, and modelling the spatial heterogeneity of these variables through integration of key results from the calibrated full-lithosphere 1D models.

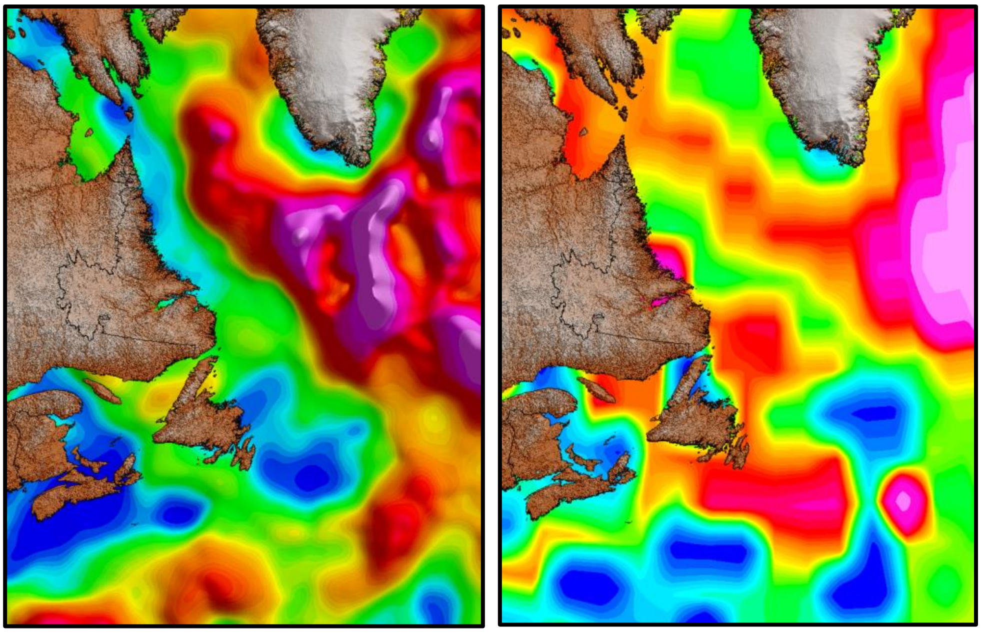

**Figure 4: Predicted Heat Flow (mW/m$^2$) using BainGeo's interpreted depth to Curie isotherm on left, compared with global heat flow map of Davies (2013) on right**

## Summary and Conclusions

TGS/PGS and Bain Geophysical Services (BainGeo) have concluded a two-year program of iterative potential fields analysis integrated with regional seismic interpretation. This study represents the first of its kind offshore Eastern Canada, available on a regional basis. A truly integrated geophysical and geological case study, covering the regional scale down to the prospect level necessary to assist the high-grading of potential oil-bearing zones in a basin with great variation of hydrocarbon phase.

Some of the key results from this study include:

- Depth to magnetic basement interpreted across the offshore Newfoundland and Labrador study area which, together with seismic mapping, illuminates the extent and architecture of the deep synrift grabens and half-grabens on stretched continental / transitional crust along the flanks of the mapped oceanic crust
- Gravity inversion was used to create a depth to Moho horizon and crustal thickness interpretation
- Curie depth was mapped and used to produce a calibrated estimate of heat flow, which serves as a useful exploration aid for assessing thermal maturity and prospectivity of this large study area
- Both Curie depth and the Crustal model are key inputs to generating improved temperature and maturity predictions in our integrated, full-lithosphere burial and thermal modelling workflow

## Acknowledgements

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