BainGeo: GravDepth™

GravDepth™ is BainGeo's 3-D gravity interpretation toolkit. It combines state of the art 3-D gravity inversion methods with a correction for the lithospheric thermal gravity anomaly and includes a unique method for adjusting the regional field to better-match high quality depth constraints. GravDepth is a general-purpose gravity inversion tool for any type of layered earth geometry. The examples shown below illustrate its use for determining depth to Moho and crustal thickness.

Many published and commercial depth to Moho and modeling studies use an isostatic model – either as its starting point, or as the actual Moho. But we can see in margins across the world areas where a simple isostatic prediction falls short in terms of matching the actual Moho from refraction seismic studies. Figure 1 below shows the predicted Moho offshore Labrador using conventional density for sediments, crust and mantle (light and dark blue) resulting from a density contrast across the Moho of 0.30 to 0.50 g/cm^3. Note how incorrect these isostatic Moho horizons are compared with Moho provided in the CRUST1.0 (Laske et al., 2013) global model (dark green horizon), and from this published refraction line by Keen et. al. (1994). The magenta horizon shows a Moho from isostatic prediction that attempts to match the relief observed in the seismic data. This result requires an extremely low and unreasonable density contrast at the Moho to come even close to the measured depth to Moho. Accordingly, it is straight forward to identify the need for some additional density changes in the model, and particularly in the lithosphere.

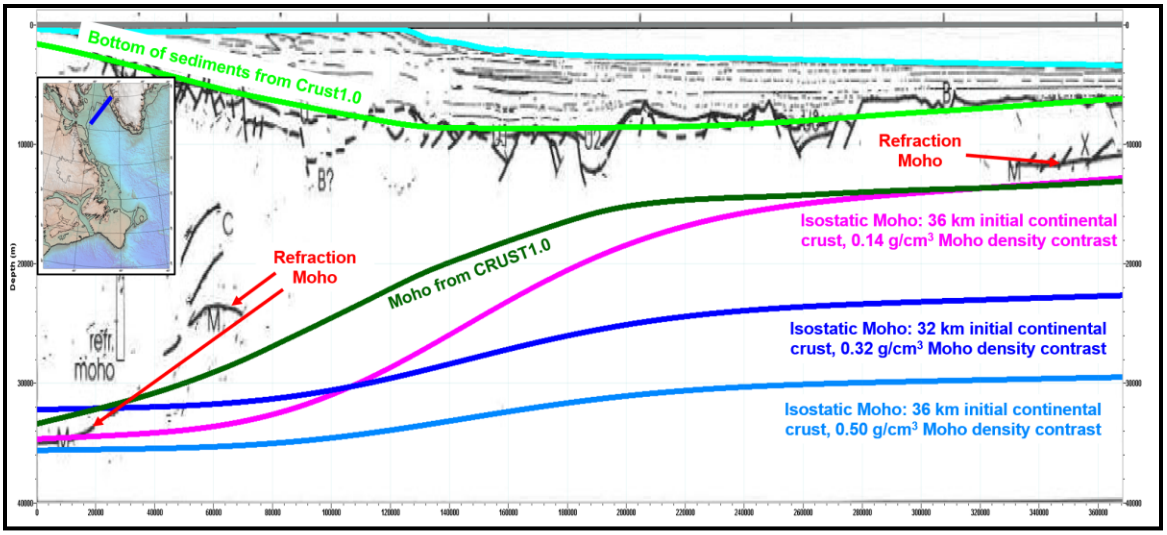


Figure 1: Moho depth constraints compared with isostatic Moho on Labrador line by Keen et al., 1994

Theoretical Basis for the Thermal Gravity Anomaly

Several authors (Greenhalgh and Kusznir, 2007 and Chappell and Kusznir, 2008) have expanded on work by McKenzie (1978) to predict the gravity anomaly associated with thermal expansion, and to apply this as a correction to achieve improved depth to Moho from gravity inversion.

The method predicts the temperature of the crust and mantle to 125 km depth, and then computes the density change and resultant gravity field associated with this "thermal anomaly". The "mantle residual anomaly" is the Bouguer minus the thermal gravity anomaly. It is this field that we then iteratively invert to obtain depth to Moho. By varying the assumptions and changing the questions, we can obtain the ocean-continent transition ("OCT") boundary [or continent-ocean boundary (COB), or limit of oceanic crust (LOC)], we can include new volcanic

melt addition (or not), and we can calibrate our results with seismic refraction control or common-sense model values.

The thermal gravity anomaly is computed from the temperature anomaly, which models the change in temperature with compression depth (Chappell et al., 2008):

$$T_z = \frac{2T_m}{\pi}\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{n}\left[\frac{\beta}{n\pi}\sin\left(\frac{n\pi}{\beta}\right)\right]\times\exp\left(\frac{-n^2 t}{\tau}\right)\sin\left(\frac{n\pi z}{a}\right)$$

Temperature anomaly (Tz) equation where:

Tm = base-lithosphere temperature = 1333° C
τ = lithosphere cooling thermal decay constant = 62.8 Myr
a = equilibrium lithosphere (plate) thickness = 125 km
β = lithosphere stretching factor, where
β = tc0 / tcnow for 1 < β < βcrit
β = tc0 / (tcnow – tcmag) for β > βcrit
t = age of lithosphere (from isochrons)

Largest driver is age t followed by β. Accordingly, errors in t can be important, and β is heavily influenced by basement depth

This temperature anomaly reduces the density of the lithosphere, which in turn decreases the gravity field by a calculated amplitude with (generally) long wavelength, owing to the depth at which these density changes occur.

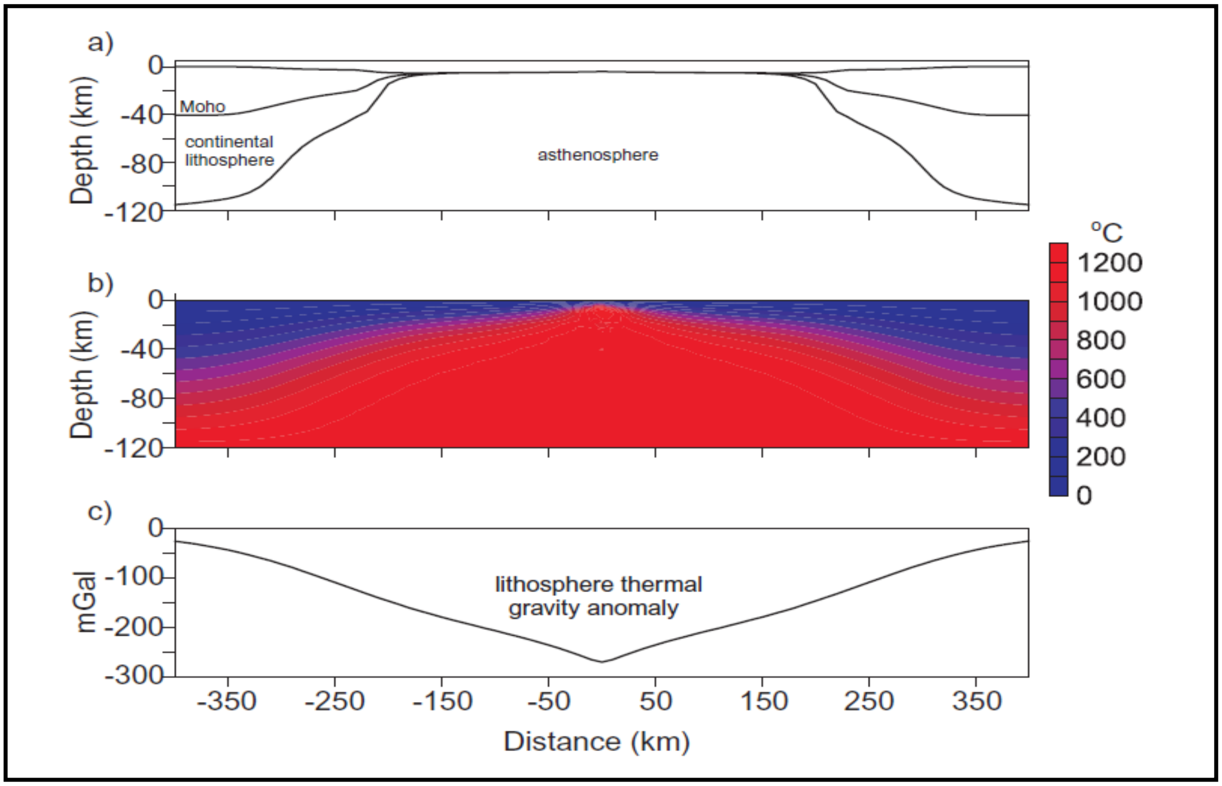


Figure 2: (Chappell and Kusznir, 2008): (a) Lithosphere cross section through a model of continental breakup and seafloor spreading at 20 Myr after breakup. (b) The associated temperature field at 20 Myr showing the large lateral changes in lithosphere temperature which generate the lithosphere thermal gravity anomaly. (c) The lithosphere thermal gravity anomaly produced by the above model is very large at the ocean ridge and still substantial (>100 mGal) for the rifted continental margin.

Figure 2 above taken from Chappell and Kusznir (2008), which shows the described effects across the mid-Atlantic ridge. As the Moho and continental lithosphere rise (cross section in upper panel), the temperature effect increases (middle panel), causing a decrease in density, and a lowering of the earth's gravity field (lower panel in Figure 1). Figure 3 below shows the improved results for gravity inversion of Moho depth when the thermal gravity correction is applied.

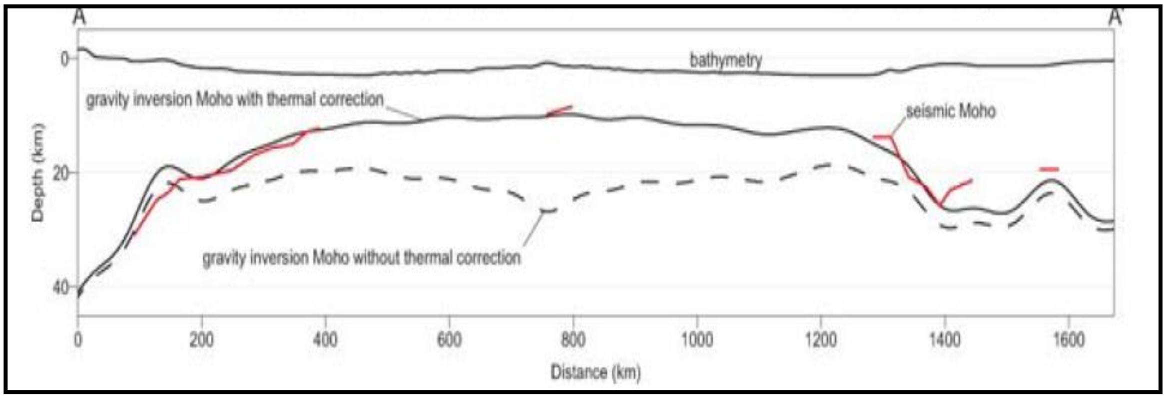


Figure 3: (Chappell and Kusznir, 2008): (a) Cross-section comparing Moho depths from gravity inversions with and without the lithosphere thermal gravity anomaly correction (solid and dashed black lines, respectively). Moho depth predictions from the gravity inversion including the lithosphere thermal gravity anomaly correction are consistent with seismic estimates, while Moho depth predicted by gravity inversion excluding the thermal gravity anomaly correction are too deep.

These results clearly show that the application of a thermal gravity anomaly correction to the observed gravity field prior to inversion for Moho depth can dramatically improve inversion results. This is particularly true when the ocean crust is young, as the thermal correction is largely driven by age (t in red circle above) and secondarily by thickness (β in red circle above).

In Figure 4 below, we show a cross section from Labrador on the left to Greenland on the right. The top panel shows the pieced-together interpretations from literature (Chalmers et al., 1995 and Delescluse et al., 2015), with BainGeo's depth to magnetic basement points shown as colored symbols (each color represents a different depth method using BainGeo's MagDepth™). The bottom panel illustrates the density change caused by the thermal gradient.

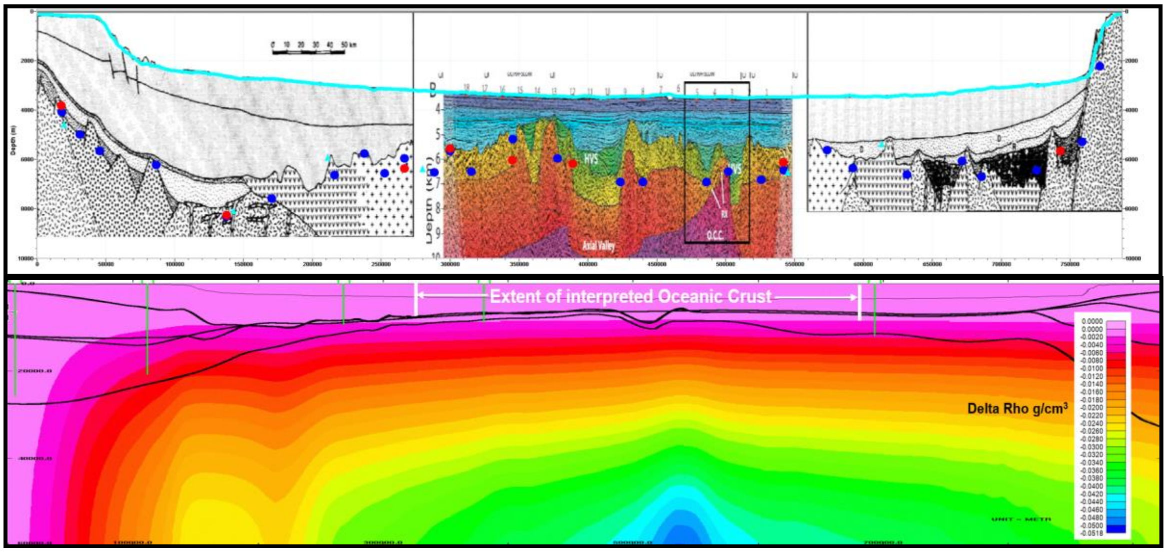
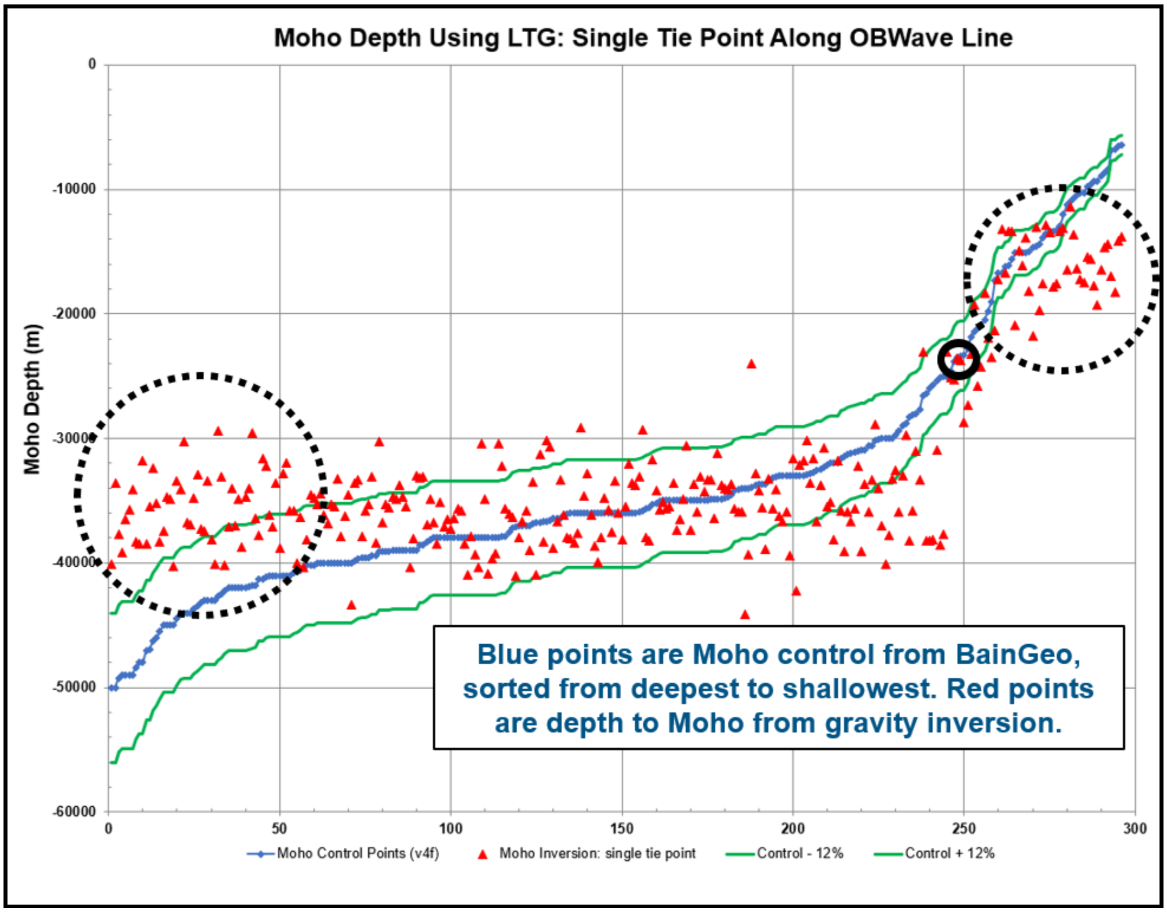


Figure 4: Change in density computed using thermal model of lithosphere. This is the change in density caused by the heating of the lithosphere - the density of the lithosphere is decreased by the heating action

Gravity Inversions: Imposing Constraints Using Single vs. Multiple Tie Points

Many commercial and academic gravity inversion packages depend on single tie point to constrain the inversion to specific depth (to Moho, or basement, etc.). This can work well over small, localized model studies. But this method is not optimal for large or extremely large model areas. Figure 5 below shows Moho control points from refraction studies as blue points, sorted from deepest (left) to shallowest. It should be recognized that this is not a geologic cross section – the points are scattered across a very large study area of Eastern Canada. Sorting by depth allows us to form some ideas about our inversion convergence in deep vs. shallow Moho areas. The red triangles show the depth from gravity inversion at these same points, when the entire model area gravity inversion was "tied" or forced to match at the single tie point highlighted by the black circle.

We see that gravity inversion points (red triangles) fall nicely around the Moho control points for Moho depths ranging from 20 to 40 km. However, for Moho depths > 40 km, gravity inversion depths tend to be significantly shallower than the control (dashed circle on far left). Similarly, for Moho depths < 20 km, the gravity inversion depths tend to be deeper than the control (dashed circle on right). This is very curious. Could it be indicating that regional density of upper and/or lower crust is changing across this large area (in addition to the thermal effect described above, which is already included in this inversion)? Or perhaps mantle density varies across the area, given that reports of exhumed mantle and serpentinized mantle occur often in various papers for this study area of Eastern Canada? Green lines represent a statistical rejection criterion discussed below.

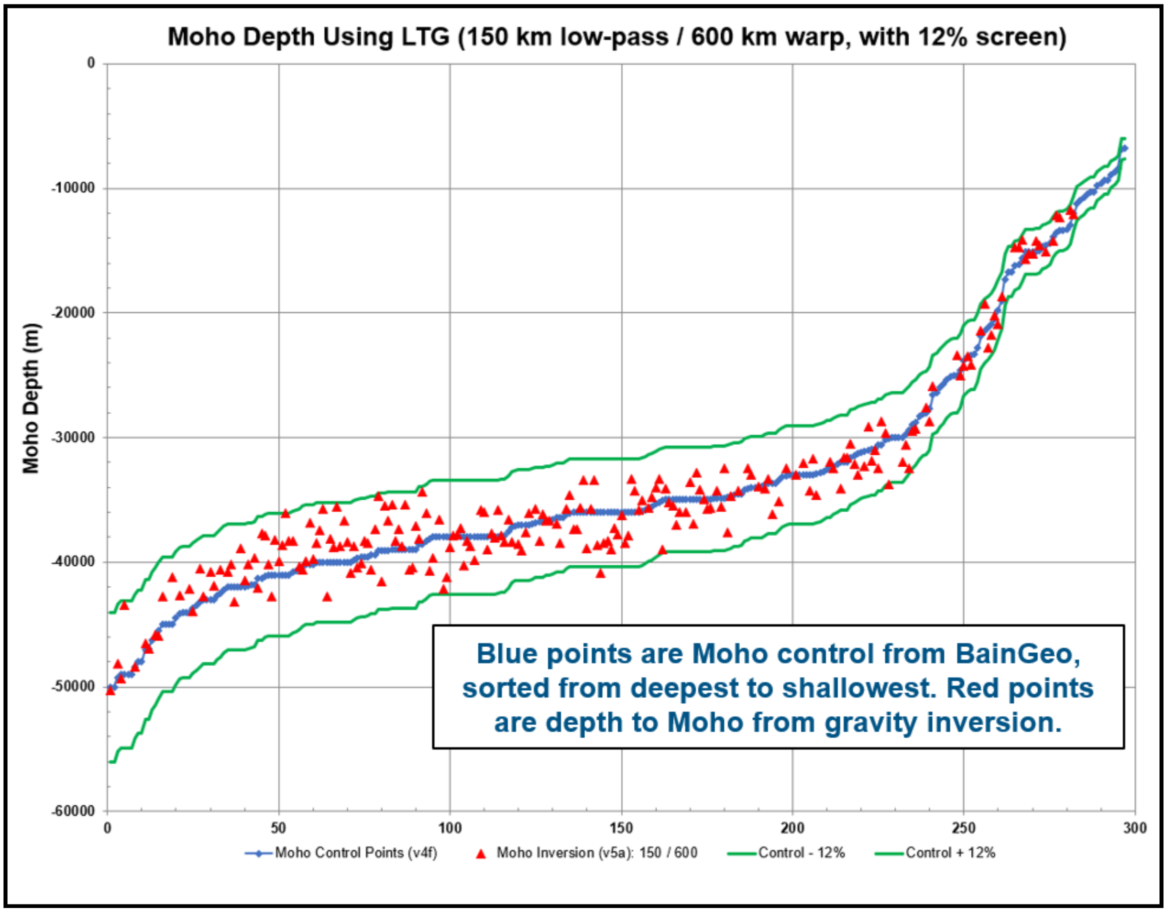


Blue points are Moho control from BainGeo, sorted from deepest to shallowest. Red points are depth to Moho from gravity inversion.

Figure 5: Moho control vs. gravity inversion using a single tie point constraint

These trends suggest that there is some unrecognized, second-order regional gravity field that could explain the poor match above between shallow and deep Moho areas, possibly reflecting deep density changes related to associated continent building and rifting processes.

BainGeo has implemented a method to compute a very long wavelength "second-order regional" field which, when applied to the observed gravity (with or without thermal correction), allows a significantly improved match to the refraction control points. An example is shown below as Figure 6, which shows the same misfit graph, after first removing points that fall beyond the selected green rejection criteria lines and using a 600 km second-order regional gravity or "warping" field.



Blue points are Moho control from BainGeo, sorted from deepest to shallowest. Red points are depth to Moho from gravity inversion.

Figure 6: Moho control vs. gravity inversion using BainGeo's proprietary method involving use of a second-order regional gravity "warping" field to improve the match to the observed refraction control on Moho. 600 km warping field correction used.

This second-order regional gravity field can be optimized to provide a tighter match to the observed control points, or it can be maintained at extremely long wavelengths, thus allowing different geologic possibilities to be tested. Figure 7 below shows the results of shortening the warping effect on the second-order regional gravity field from 600 km to 400 km. We see that a shorter field provides a much tighter grouping of the gravity inversion points around the Moho refraction control. However, given that these Moho (and most such) control points have their own level of interpretation errors involved, we tend to relax the warping parameter and assume that our control points are accurate at very long wavelengths, but should not be taken as strict or "hard" spot control, given their own internal error budgets and uncertainties.

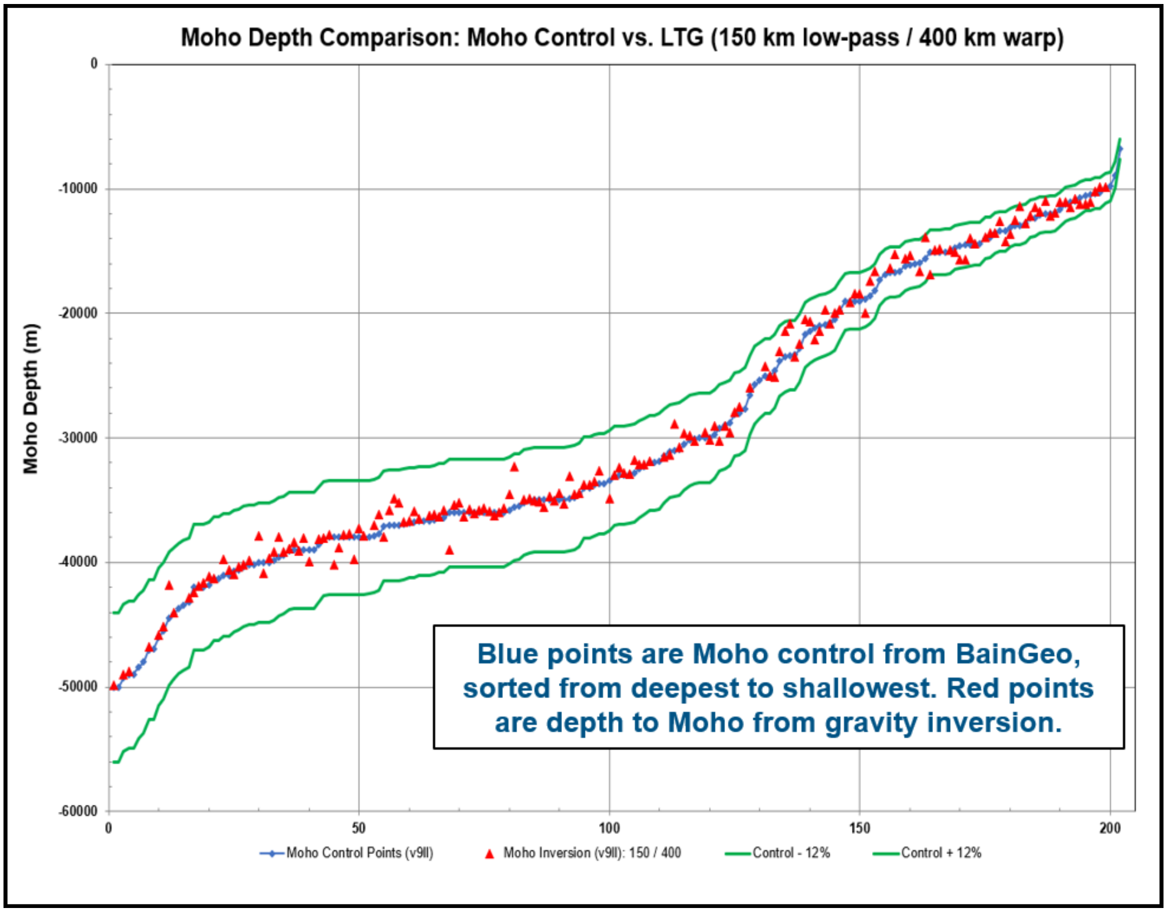


Figure 7: Moho control vs. gravity inversion using BainGeo's proprietary method involving use of a second-order regional gravity "warping" field to improve the match to the observed refraction control on Moho. 400 km warping field correction used.

Figure 8 below shows the results of our constrained 3-D gravity inversion extracted along a published cross section by Welford et al. (2020). Notice the excellent match of the control points on and near this line (projected on to this line). With this high confidence result obtained along a seismic control line such as this, we can then step away from the control (lines and points) using our gravity inversion results with confidence.

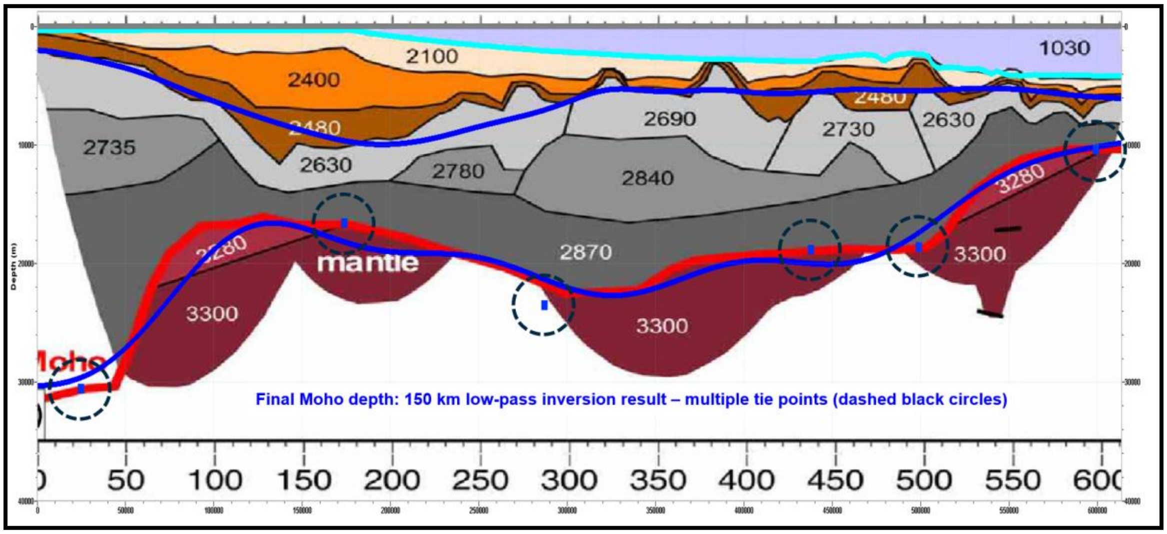


Figure 8: Above line from Welford's recent (2020) paper. The tie points along this line that were included in this inversion are identified with dashed black circles / blue boxes. BainGeo's final depth to Moho is shown as the solid blue line, which agrees very well with Welford's published depth to Moho (red line), from a combined seismic and gravity study.

Gravity Inversions Used to Interpret Limit of Oceanic Crust (LOC)

BainGeo's 3-D gravity inversion approach also provides an estimate of the limit of oceanic crust (LOC, COB), by applying a model after McKenzie (1978) and McKenzie and Bickle (1988) and described in Chappell and Kusznir (2008). The McKenzie model can be used to provide an estimate of the oceanic crust - the blue area in Figure 9 below (taken from Bain et al., 2019, 2020). Subtraction of the blue area from the total crust yields the separate area of "residual continental crust" (the green area in Figure 9). Thus, we can derive a semi-automated estimate of the limit of oceanic crust – the outline of the area where the continental crust pinches out – goes to zero thickness. The purple polygon in Figure 10 indicates the LOC predicted using a public domain base of sediments as the top crust. The green polygon in Figure 10 shows the LOC predicted using the top of magnetic crust calculated from depth to basement work using MagDepth™ in the area as the top of crust. These results are derived from a recently completed study by TGS & BainGeo covering the Gulf of Mexico – "Gigante Crustal Study" (Bain et al., 2020).

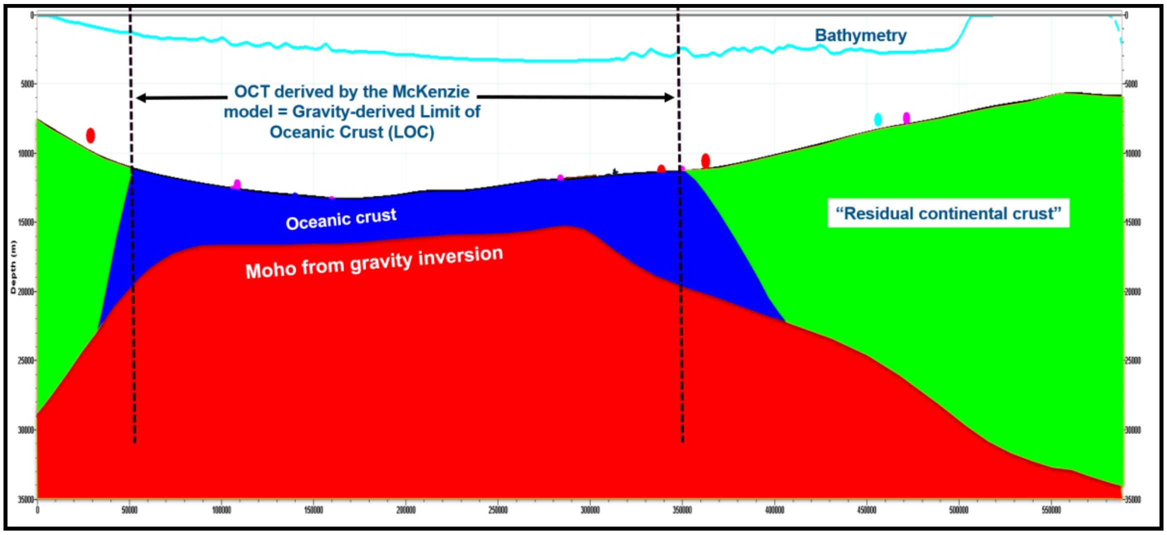


Figure 9: Derivation of Residual Continental Crust and Limit of Oceanic Crust (LOC), from Bain et al., 2019, 2020, by applying the McKenzie (1978), and McKenzie and Bickle (1988) model to BainGeo's gravity inversion for depth to Moho, following methods described by Greenhalgh and Kusznir (2007) and Chappell and Kusznir (2008).

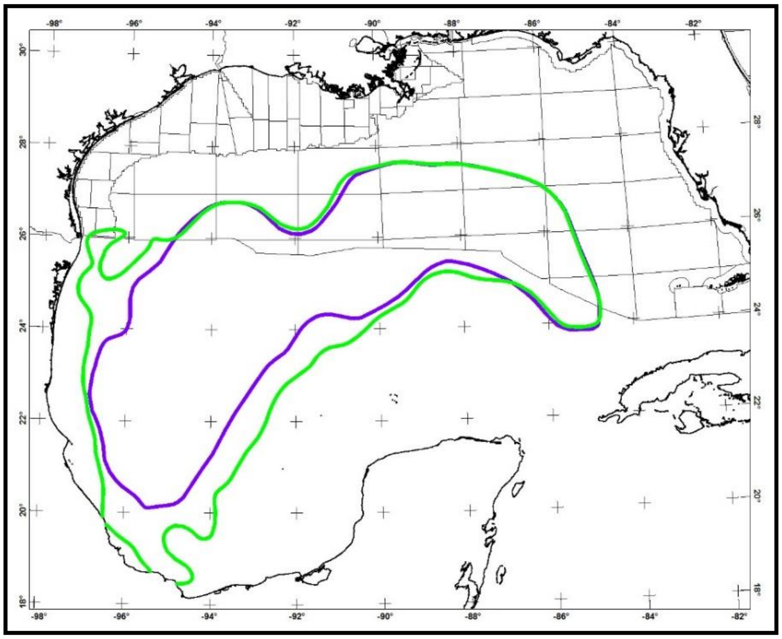


Figure 10: Limit of Oceanic Crust (LOC), from Bain et al., 2019, 2020. Purple uses public domain basement as top crust while green used top magnetic basement as the top of the crust.

GravDepth™: A General-Purpose Gravity Inversion Tool

Although the examples above focus on the use of GravDepth for depth to Moho studies, GravDepth is a general-purpose gravity inversion toolkit for any type of layered earth geometry. It is designed and well-suited for use in complex 3-D salt modeling and depth to high-density basement, or any environment in which there are useful density contrasts that can be investigated through gravity inversion.

The key benefit to GravDepth in these areas is the use of multiple control points to constrain our inversions, as shown by our examples above. No other gravity inversion tools (to our knowledge) allow this exciting benefit.

Typical Final Results

Results from our regional Crustal Studies, such as the above examples from Mexico and Eastern Canada, result in the following set of products:

- **Gravity & magnetic data merge and enhancements**
- **Gravity and magnetic modeling along key geological cross sections**
- **Regional 3-D gravity inversion to derive:**
  - **Depth to Moho**
  - **Crustal thickness**
  - **Limit of oceanic crust (LOC/COB/OCT)**
- **Magnetic analysis provides:**
  - **Curie Isotherm**
  - **Depth to magnetic/crystalline basement**
  - **Basement terrane mapping from magnetic inversion**

Please contact Bain Geophysical Services for any additional information on these methods, and on our Crustal Study results.

REFERENCES

Bain, Kegel and O’Reilly, “Crustal Interpretation by Gravity, Magnetics, and Seismic Data over the Gulf of Mexico”, *GeoGulf19 - GCAGS Extended Abstracts*, 2019

Bain, Kegel and O’Reilly, “A New Crustal Model of the Gulf of Mexico – From Seismic and Potential Fields Data”, *AAPG Hedberg Conference*, 2020

Chalmers and Laursen, “Labrador Sea—The extent of continental and oceanic-crust and the timing of the onset of sea-floor spreading”, *Marine and Petroleum Geology*, 1995.

Chappell and Kusznir, “Three-dimensional gravity inversion for Moho depth at rifted continental margins incorporating a lithosphere thermal gravity anomaly correction”, *Geophys. J. Int.,* 2008

Delescluse, Funck, Dehler, Louden, and Watremez, “The oceanic crustal structure at the extinct, slow to ultraslow Labrador Sea spreading center”, *Journal of Geophysical Research*, 2015

Greenhalgh and Kusznir, “Evidence for thin oceanic crust on the extinct Aegir Ridge, Norwegian Basin, NE Atlantic derived from satellite gravity inversion”, *Geophysical Research Letters*, Vol 34, 2007

Keen, Potter and Srivastava, “Deep seismic reflection data across the conjugate margins of the Labrador Sea”, *Canadian Journal of Earth Sciences*, 1994

Laske, Masters, Mas and Pasyanos, “Update on CRUST1.0 - A 1-degree Global Model of Earth's Crust”, *Geophys. Res. Abstracts*, 15, Abstract EGU2013-2658, 2013. http://igppweb.ucsd.edu/~gabi/rem.html

McKenzie, “Some remarks on the development of sedimentary basins”, *Earth and Planetary Science Letters*, 1978

McKenzie and Bickle, “The Volume and Composition of Melt Generated by Extension of the Lithosphere”, *Journal of Petrology*, 1988

Welford, Dehler and Funck, “Crustal velocity structure across the Orphan Basin and Orphan Knoll to the continent–ocean transition, offshore Newfoundland, Canada”, *Geophysical Journal International*, 2020