BainGeo: CurieDepth™

CurieDepth™ is BainGeo's toolkit for interpreting depth to the "Curie isotherm" in three dimensions (3-D). This process is more accurately described by stating that BainGeo computes 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 – 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. As described in our companion paper on MagDepth™, having an estimate of the thickness of the magnetic crust dramatically improves our depth to magnetic basement results.

Curie depths are estimated using either peaks in the lowest wavenumber (longest wavelength) portions of radial power spectra, or by fitting a curve to the peak character. BainGeo has implemented and rigorously tested a number of methods, including: Blakely, Parker, Li, Bansal, Bouligand, etc. We have found the methods of Li and Bansal to show the highest consistency over a number of projects.

A 3-D fractal magnetization model has a power spectrum of magnetization proportional to the norm of the wave number raised to a power (Li, 2013). This power function is defined as "β" by many authors, including Li and Bansal, and is reflective of changes in geology and magnetic field response (2D vs. 3D fields, for example, and geometry of the source). β for Li's approach is generally regarded as being one unit higher than that for Bansal's method, based on differences in the theory and computations (see Li, 2013 for more information).

Our implementation of these various methods invokes a selection of a portion of the power spectrum over which to interpret the depth to an "ensemble of causative sources" – a term generally attributed to Spector and Grant (1970). Moving windows are used to compute power spectra over (typically) large areas. The spectral plots can (oftentimes) be used to identify additional shallow layering, by identifying multiple slopes. These slopes are related to the calculated depth of an "ensemble" or set of sources that lie within the same average depth. For the spectral plot below we could consider 3 (or more) such slope-depth relationships.

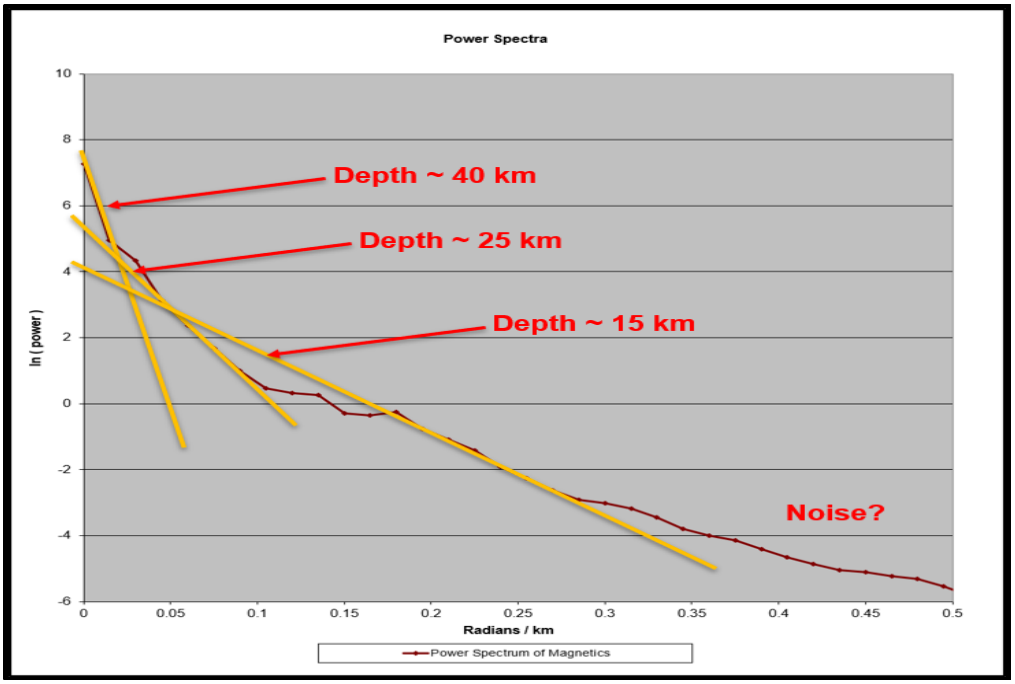

Figure 1: Power spectral method for estimating depth to magnetic layers

Power Spectral Method: Selection of Ideal Window Sizes

For the "Curie depth" method the first step is to search for large-enough windows that begin to identify where the spectrum "rolls over" near the longest wavelengths (or lowest frequency). This is the leftmost area of the power spectrum below. This "rollover" indicates that we are "imaging" the bottom of the magnetic layer. Here we see that a 150 km window does not exhibit a rollover, while a 200 km window shows a clear "peak" in the spectral anomaly.

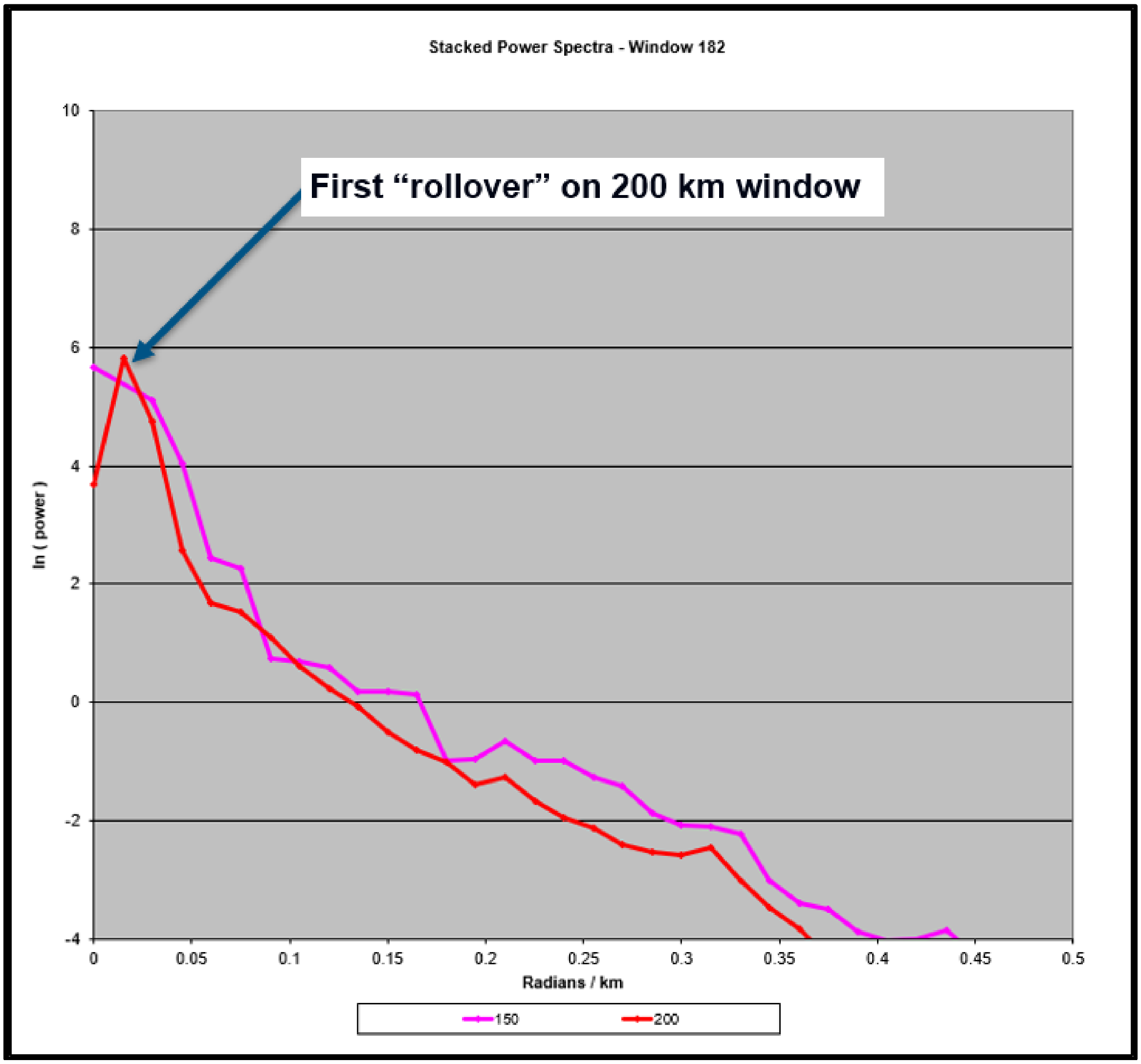

Figure 2: Selection of ideal window size from the spectral plots

Ideal window sizes should be determined for each area and sub-area. We generally run a selection of various window widths for each study area. Below, a series of separate areas were selected with center points shown by the red inverted triangles. We chose a sweep of windows from 50 to 400 km in 50 km increments. The power spectrum for each window was computed and used to determine the optimal window size for each selected center point location, by identifying the window width at which a rollover is first detected.

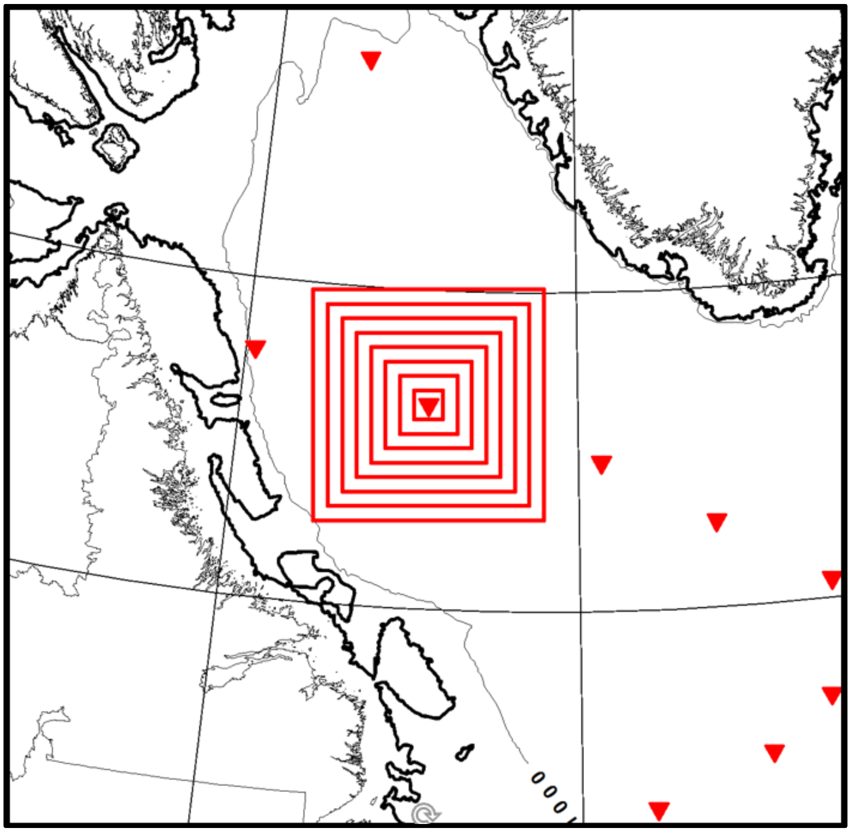

Figure 3: Set of windows queried for optimal window size analysis

Power spectra are computed for each window, and the smallest window that produces a peak, or rollover in the spectrum, is defined to be the optimal window size for that specific area. As mentioned above, a spectral peak indicates that the method is detecting the bottom of the magnetic layer for the given window size. In the display below, the full spectra are shown on the left window, while a zoom to the lowest frequencies is shown on the right. Here we see for window 335 that 150 km and smaller windows are not "imaging" the bottom of the magnetic layer (evidently), while 200 km and larger window sizes are all able to do so.

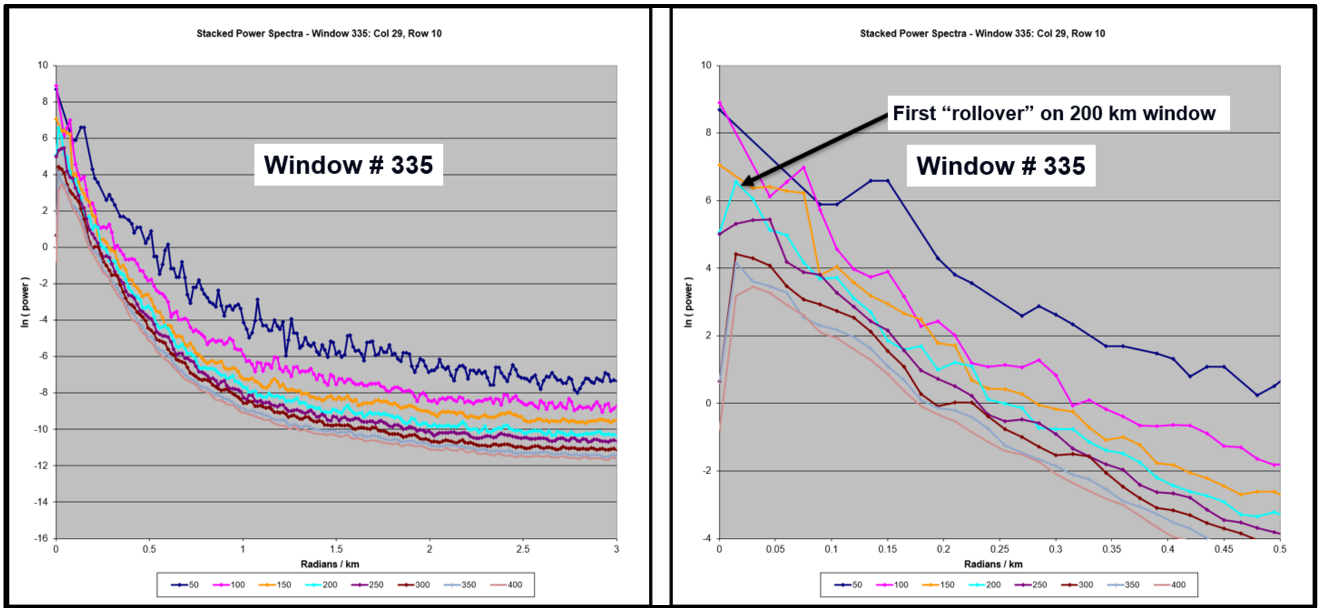

Figure 4: Power spectra for selected window – to identify optimal window size

Each selected window was analyzed to identify the optimal window size. The number of such windows is shown below. This chart indicates that a 200 km window size seems to fit the largest number of windows, with 150 km coming in a distant second place. We often run the entire area using multiple windows, but this optimal window analysis helps us to focus our sizing to obtain best results.

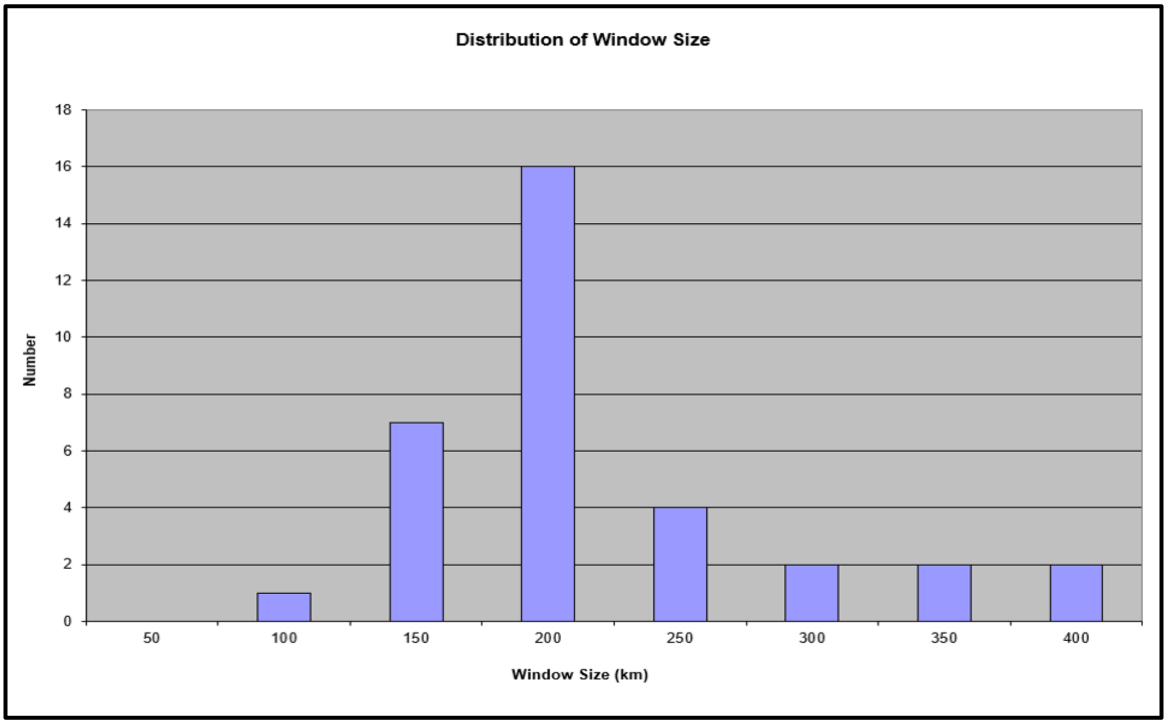

Figure 5: Optimal window size for bottom of the magnetic layer analysis

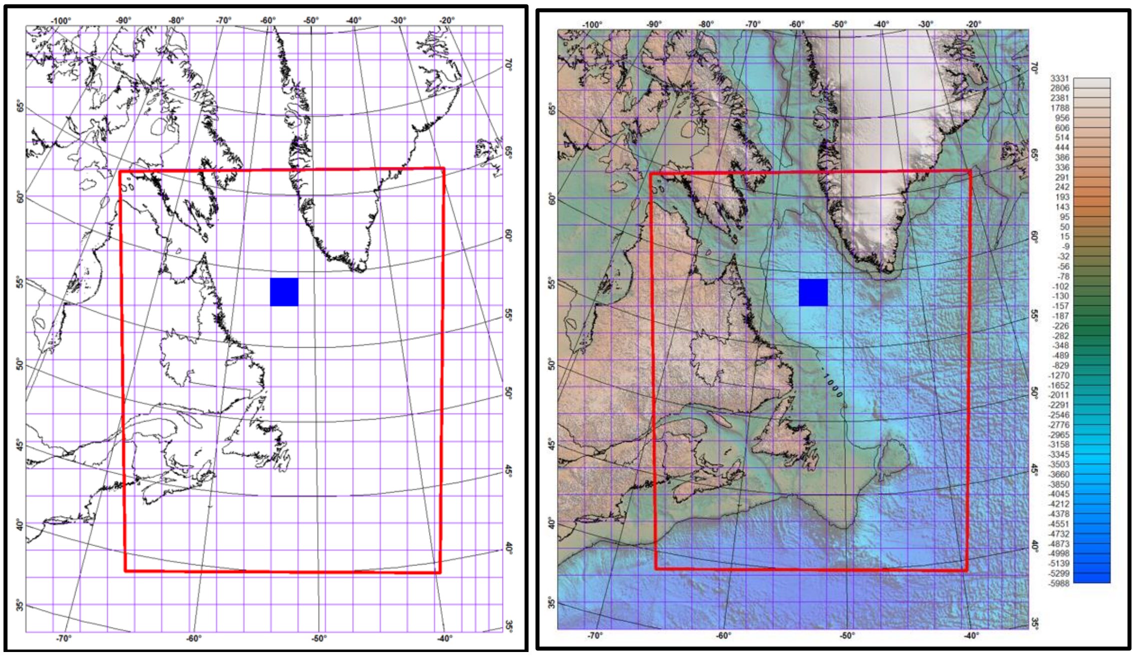

Figure 6: CurieDepth applied to super-regional area of Eastern Canada

BainGeo recently completed an exciting regional Crustal Study covering offshore Eastern Canada. This study included full CurieDepth™ analysis over the area shown above. The purple boxes are 200x200 km windows used for CurieDepth analysis. The moving windows were overlapped by shifting each window by 50 km in each direction across the study area. The red box shows the actual deliverable window. As with our 3-D gravity and magnetic inversion and modeling, we have extended our CurieDepth study area beyond the deliverable bounds, to allow for FFT extension using real magnetic data (rather than interpolation).

The power spectra were computed and scaled accordingly (see references). Both methods (indeed most of these methods) compute a top of the magnetic layer first, and the depth to the centroid of the magnetic layer. A simple function is then used to compute the bottom of the magnetic layer from these quantities.

Tests were run using various methods, with Li (2013, 2017) and Bansal (2011) providing the most consistent results over this study area of Eastern Canada. β factors were tested for both, and top-depth comparisons were checked against public domain basement (GSC and CRUST1.0). Computed bottom-depths (Curie) were checked against global Curie models (Li, 2017). Generally, we found our best comparisons and consistency came from using Li's method, with β = 3.

The left set of graphs below show the "top depth" method using Li (top) and Bansal (bottom), and the centroid depth on the right.

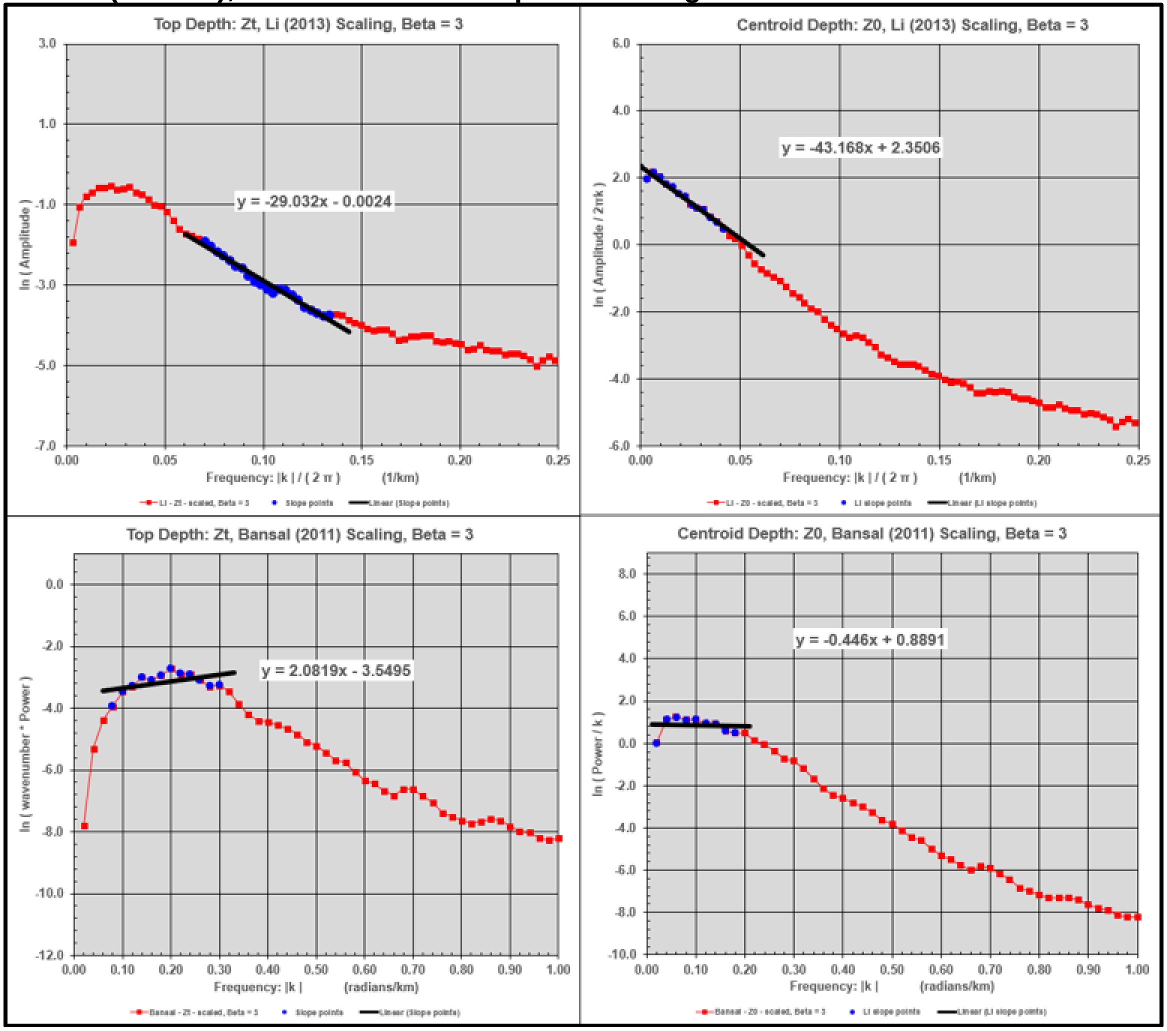

Figure 7: Li and Bansal methods applied to selected test window

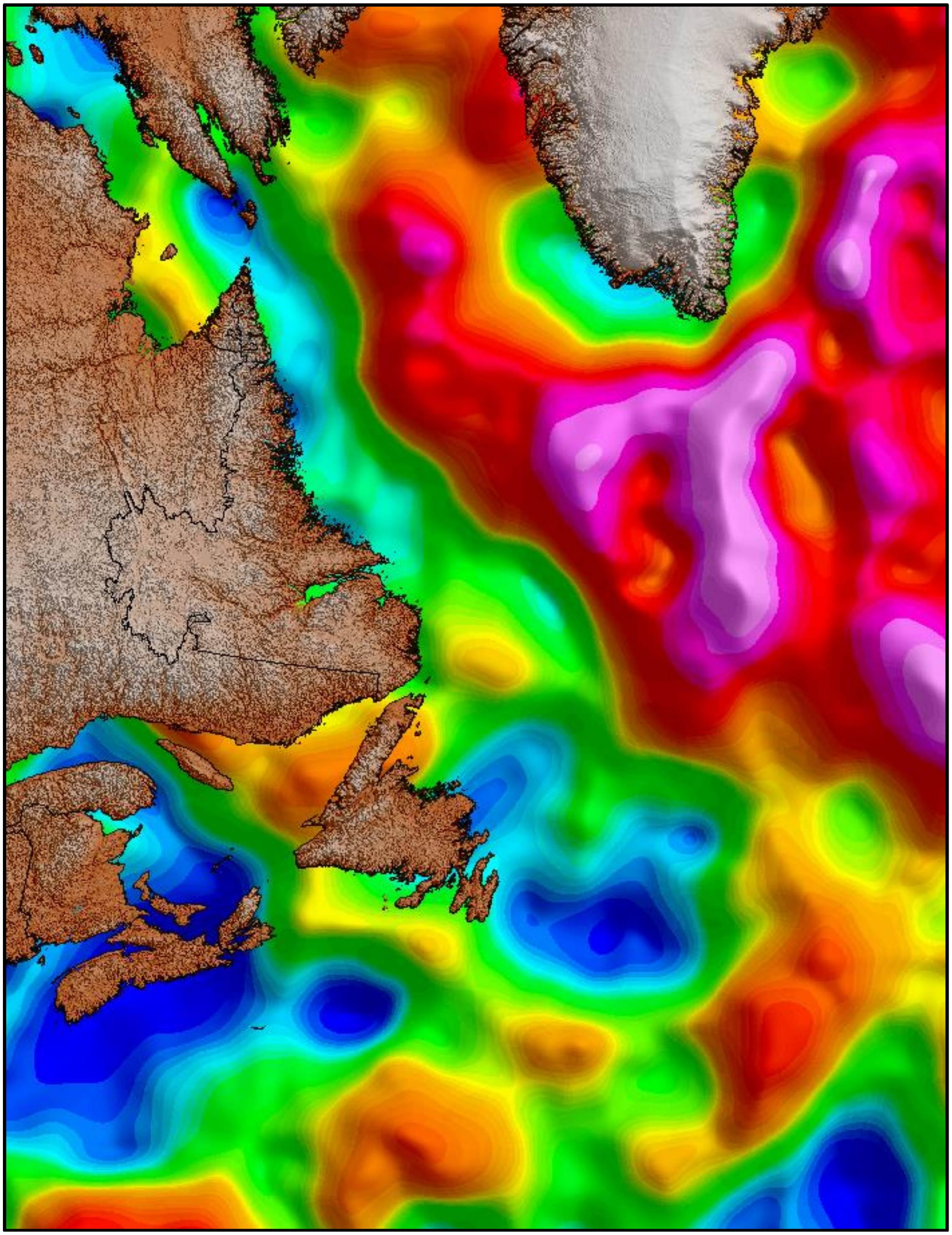

Figure 8: CurieDepth - Depth to the bottom of the magnetic crust layer

CurieDepth™ analysis was carried out across the full study area. Results were then culled to remove outliers, and the above Curie depth, or depth to the bottom of the magnetic crust layer was obtained. These results can then be compared with depth to Moho, incorporated into thermal and basin modeling, and used to study the heat flow over the area.

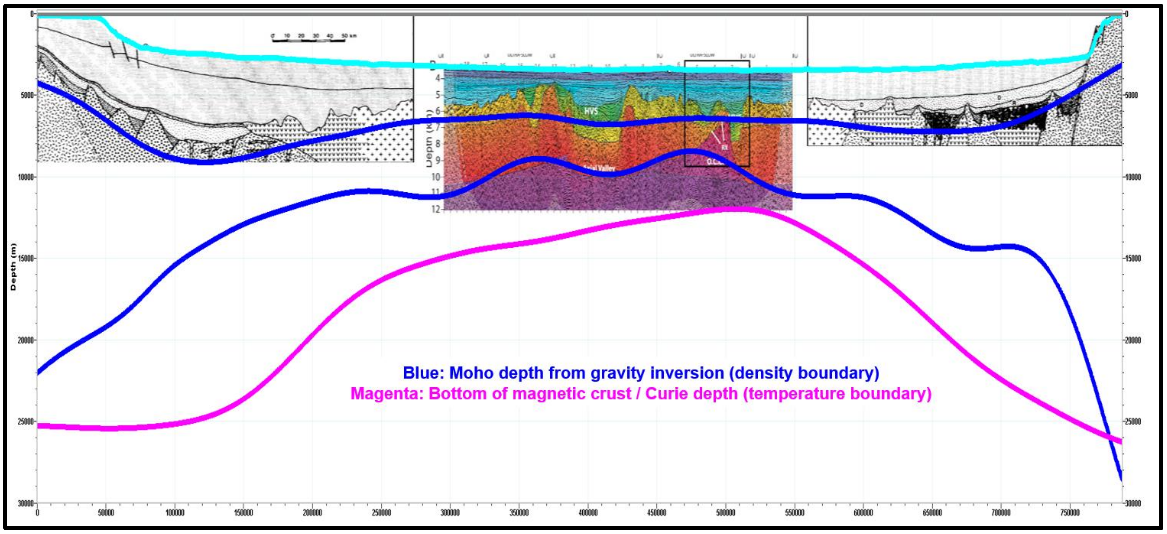

Figure 9: CurieDepth on published cross section in Labrador Sea (Chalmers et al, 1995 & Delescluse et al, 2015)

Figure 9 above illustrates BainGeo's depth to Moho (blue horizon) together with the Curie depth horizon (magenta horizon), or the bottom of the magnetic crust. These are both overlain on a composite cross section from Labrador on the west (left) to Greenland on the east (right). We note a general agreement between the Moho and Curie depth. Namely, when Moho is deep, Curie is also deep, and when Moho is shallow, Curie is similarly shallow. However, Curie depth is mapped considerably deeper than Moho over most of this cross section, indicating that the deep thermal boundaries are different than the velocity/density boundaries.

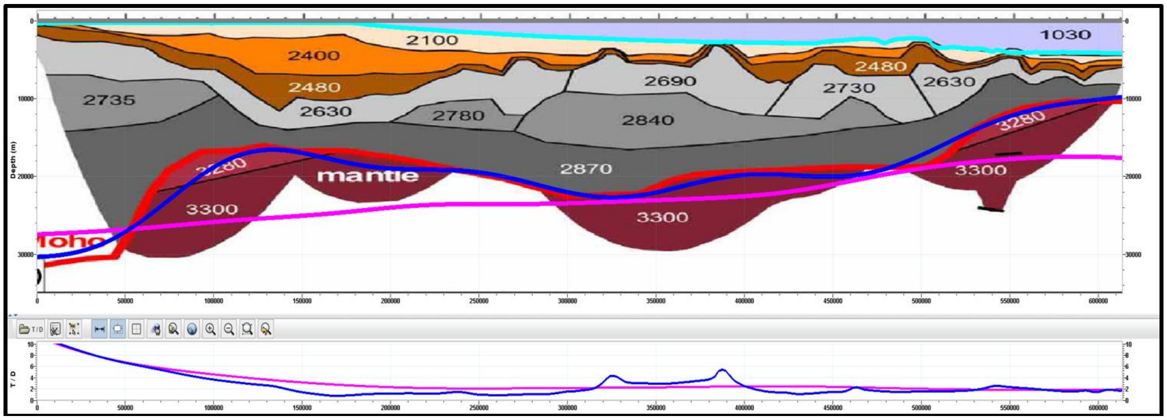

Figure 10: CurieDepth on published cross section in Orphan Basin, Eastern Canada (Welford et al. 2020)

Figure 10 above is a cross section from Welford (2020), with depth to Moho resulting from BainGeo's 3-D gravity inversion shown as the blue horizon. The Curie depth is shown as the magenta horizon. As mentioned above, we see similar trends, shapes and (oftentimes) relief between Curie depth and Moho, though the Curie mapping is generally much longer wavelength, owing to the type of moving window analysis performed. The two traces in the bottom panel show the thickness / depth, or T/D profile based on the Curie depth work (magenta) and using gravity inversion-derived Moho as our proxy for Curie (blue). These T/D profiles are viewed in real-time during the magnetic depth analysis, which dramatically improves the accuracy of our depth to magnetic basement results.

As mentioned above, one key use of Curie depth mapping is to provide a first order estimate of the thickness of the magnetic crust, which can then be used to

significantly improve depth to magnetic basement results (see Flanagan and Bain, 2013).

One other use of CurieDepth is in heat flowing prediction and basin modeling. On this point, Li (2017) suggests that "Good correlations between heat flow and Curie depth can be observed globally, i.e., high heat flow measurements tend to correlate with small Curie depths and vice versa". It is useful then to convert our Curie depth map into an estimate of heat flow. Several methods are described and listed in the bibliography by Li (2017) and Davies (2013)-see references below.

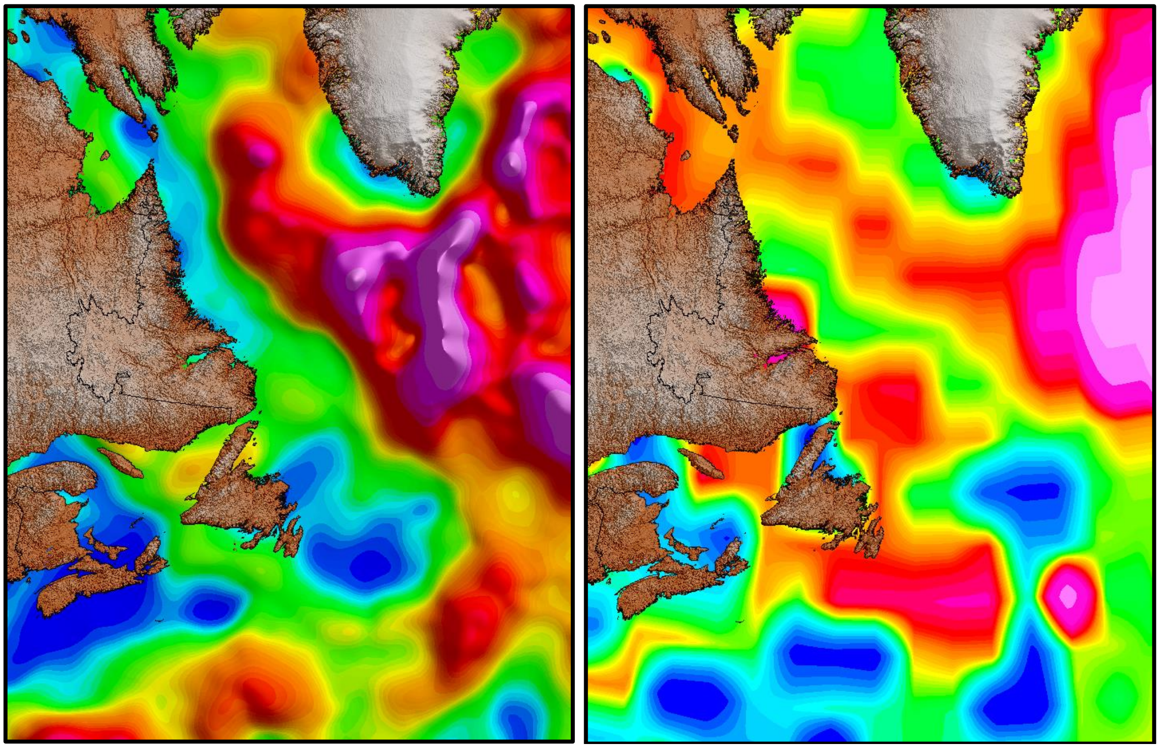

Figure 11: Predicted Heat Flow (mW/m^2) using Bain Geo's interpreted depth to Curie isotherm on left, compared with global heat flow map of Davies (2013) on right

Heat flow predicted using our interpreted depth to Curie isotherm is shown on the left map of Figure 11. Although many assumptions go into this model, it is interesting to recognize regional trends. We observe areas of high heat flow, for example, over oceanic crust, while primary continental masses are rimmed by large negative heat flow anomalies. We also observe large negative predicted heat flow southeast of Newfoundland, which decreases over the thicker crust under Flemish Cap, for example. The right map is extracted from a global grid from Davies (2013). While many of the primary trends are similar, there are areas of considerable differences. For example, note the general area of low heat flow predicted from our CurieDepth work east and southeast of Newfoundland mentioned above, while Davies represents this area with a heat flow anomaly high. Of course, these heat flow study results should be calibrated with actual heat flow observations whenever possible. Such calibration was not done in our work on the left map, as released in this public forum.

Please contact BainGeo for additional details on our CurieDepth and related heat flow prediction work for your exploration area.

Typical Final Results from Bain Geo's Crustal Studies

Results from our regional Crustal Studies, such as the above examples from Eastern Canada, completed in partnership with both TGS and PGS, 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.

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