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Crustal Interpretation by Gravity, Magnetics, and Seismic Data over the Gulf of Mexico

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EXTENDED ABSTRACT

Thick salt limited the ability of early 2D seismic to effectively image deep structure (basement, syn-rift basins, early stages of oceanic opening) of the Gulf of Mexico (GOM). Potential field studies were more effective at imaging deep structure but assembling a suite of gravity and magnetic data over the entire U.S. Gulf of Mexico (USGOM) took nearly 40 years and involved many different acquisition systems and vintages. Conversely, a similar density of coverage in the Mexican GOM (MGOM) was acquired in less than 2 years. With the 2015 opening of the MGOM to international exploration, TGS acquired a dense grid of ship-borne 2D seismic, gravity and magnetic surveys (Gigante) over the entire MGOM. TGS and Bain Geophysical Services (BainGeo) have teamed up to create the "Gigante Crustal Study" covering offshore Mexico and the regional Gulf of Mexico. This work combines the Gigante survey data with public domain data sets to give coverage over the entire GOM. We present here some of the results of this work, which better illustrate the deep crustal structure of the GOM. The results also provide a detailed conjugate analogue to better understand the pre-salt sediments and crustal architecture in the USGOM. Furthermore, the implications of the new interpretations and models provide insights that could help elucidate the early evolution of the GOM.

Data Available to the Study

Seismic data: The Gigante 2D seismic survey, acquired 2015–2016, comprises 186,425 km of long-offset broadband 2D seismic data covering the entire MGOM and the Alaminos Canyon area in the U.S. sector (Fig. 1). Pro-

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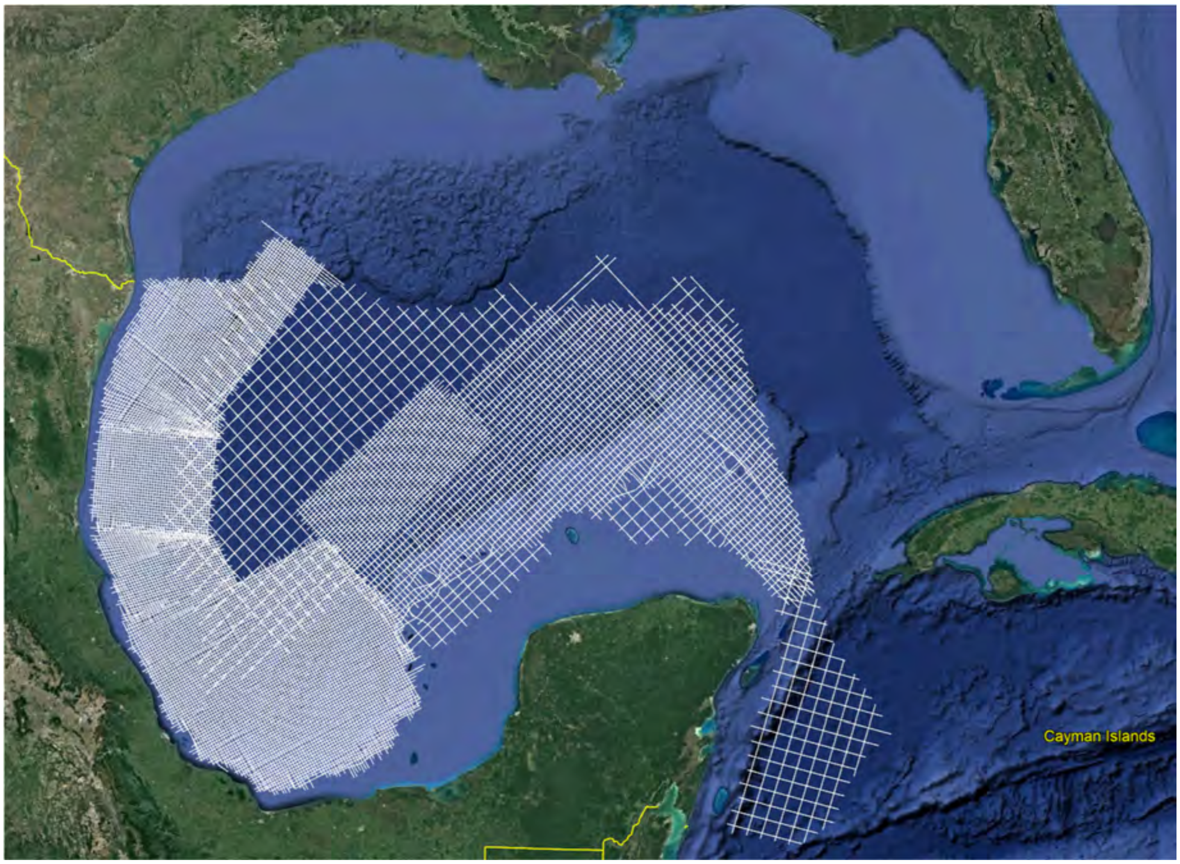

Figure 1. Location of the study area.

cessing to pre-stack depth migration imaging (PSDM), including a full 3D velocity volume, was completed in 2017. Interpretation of 10 regional horizons from basement to seafloor (covering the major source rock and reservoir units) was completed in early 2018, tied to key PEMEX wells. A major focus of the Gigante interpretation was to document and categorize the structural styles in the different basins of the MGOM (O'Reilly et al., 2017) such as the deep syn-rift basins on the edge of the Campeche Escarpment (Fig. 2).

Potential fields data: Gravity and magnetic data were acquired in tandem with the seismic over the entire Gigante survey area. The Gigante ship-borne data were merged with public domain gravity data (Sandwell et al., 2014) and magnetic data (Quesnel et al., 2009; Meyer et al., 2017) to create maps for the entire GOM area. Refraction seismic data (Marton and Buffler, 1994; Eddy et al., 2014) were used to calibrate gravity inversion to determine depth to Moho.

Bathymetric data: Gigante multibeam bathymetric data was used to determine the 3D Bouguer / terrain correction to the gravity data in the MGOM. Public domain bathymetry data was used to compute the full 3D Bouguer correction for gravity data beyond the MGOM.

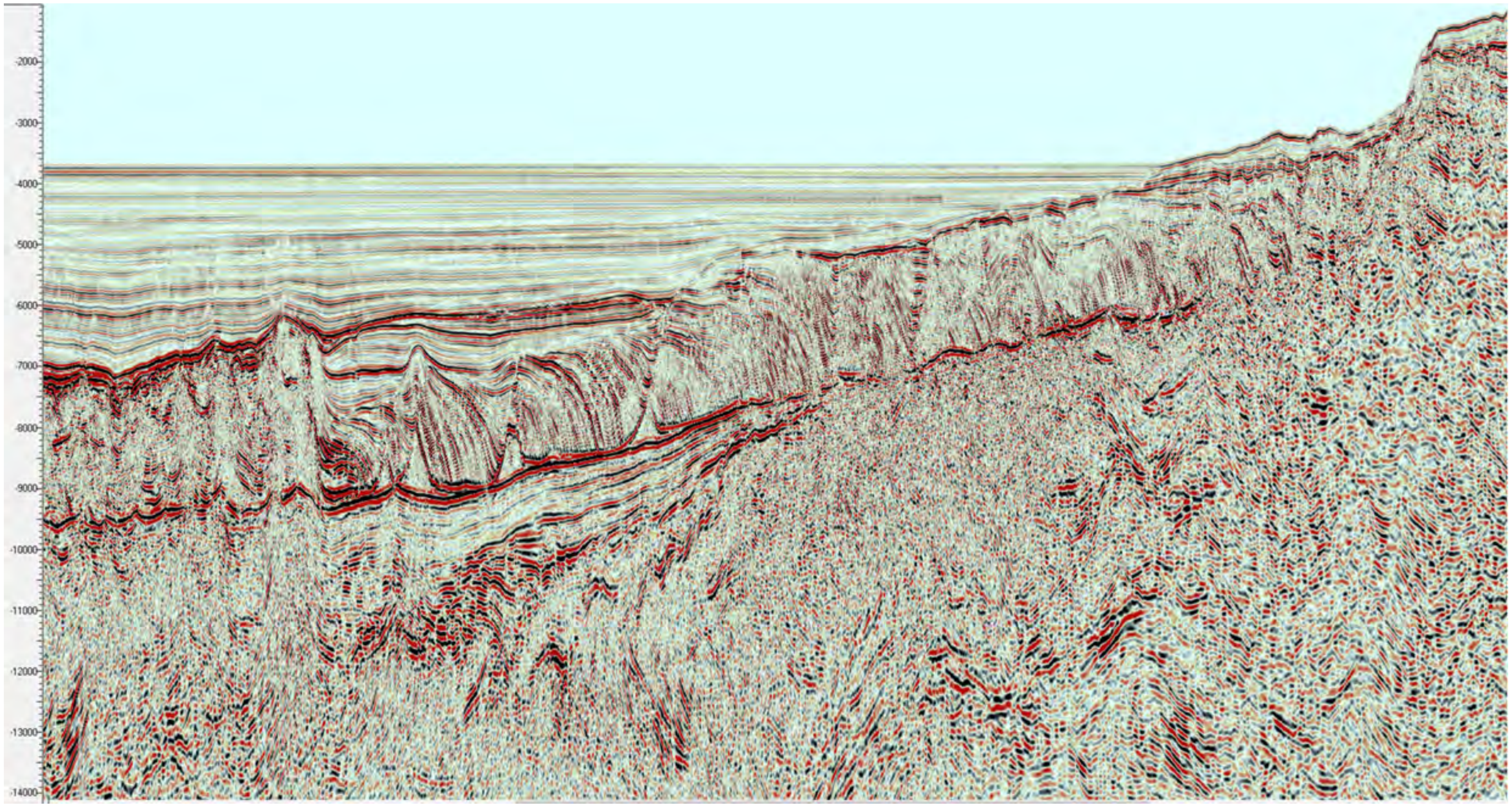

Figure 2. Part of a regional Gigante seismic line extending northwest from the Yucatan Platform through the Sigsbee Knolls area into the Abyssal Plain. A thick pre-salt syn-rift basin is developed at the foot of the Yucatan Platform.

Methodology

Depth to Magnetic Basement Theory and Calculation

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, 2012a, 2012b, 2013). In the case of the GOM region, 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 using the depth-extent approach (Flanagan and Bain, 2013), was integrated with the seismic interpretation of syn-rift and original rift structures. Early notions on the possibility of deep to very deep crystalline (magnetic) basement and thin to very thin crust, were exchanged, tested through integrated modeling (gravity/magnetic/seismic), leading to a comprehensive set of acoustic basement and magnetic basement horizons. These basement horizons are different and complementary. It should be recognized that the seismic, gravity and magnetic methods are each responding to different rock properties (seismic: acoustic impedance = velocity*density; gravity: density; magnetics: magnetic susceptibility). Accordingly, there are strong and valid geological reasons for these different “basement” horizons (acoustic basement (seismic), high-density basement (gravity) and crystalline (magnetic) basement) to, at times, be coincident, while other times, occur at significantly different depths. For example, in the GOM, deep carbonates can very easily complicate the interpretation of both the acoustic basement and high-density basement, while the crystalline basement from magnetics is not impacted by these large velocity/density changes. Similarly, whereas the density and velocity of deep sediments approach those of basement, the magnetic susceptibility contrast at basement generally remains very high.

Depth to magnetic basement solutions were computed using labor-intensive interpretation of the magnetic field gradients extracted from the grid, and later applied to the entire Gigante magnetic dataset (186,425 line km). Results were compared against early seismic interpretation, particularly on oceanic crust, where the two results are anticipated to coincide, geologically. It should be noted that these depth to magnetic basement solutions are determined where allowed by the magnetic field gradients. Accordingly, given the large depth to magnetic basement, there are areas where no solutions can, nor should, be computed, owing to the lack of any meaningful changes in the magnetic field. A higher priority is placed on so-called manual depth methods, (primarily tilt-depth, Bean Ratio A and similar methods that have been calibrated for magnetic crustal thickness – see Flanagan and Bain (2013)). These methods that incorporate the depth-extent (or thickness/depth) parameter are used to derive the first pass, or base line depth to basement result. Then, other methods are carefully applied and screened, and used to infill the picture (Figs. 3-5).

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Determine Thickness of Crust and Depth to Moho by Constrained Gravity Modelling and Inversion

Total Sediment Thickness in the MGOM was determined as the thickness between the Gigante multibeam bathymetry seabed map and the depth to magnetic basement (see above; Fig. 4). Total Sediment Thickness beyond the MGOM was taken from public domain data sources (Laske et al., 2013). Sediment density used a 3D density cube derived from the Gigante velocity model for MGOM, and sediment density functions for the remainder of the model. Salt thicknesses were used in both MGOM and USGOM (provided by TGS)—this is very important in that large salt accumulations across the GOM area have a large gravity signature, with both short and very long wavelengths.

Bathymetric data was used to correct the Bouguer gravity data (Fig. 6). Inversion of the Bouguer gravity field yields the depth to Moho, crustal

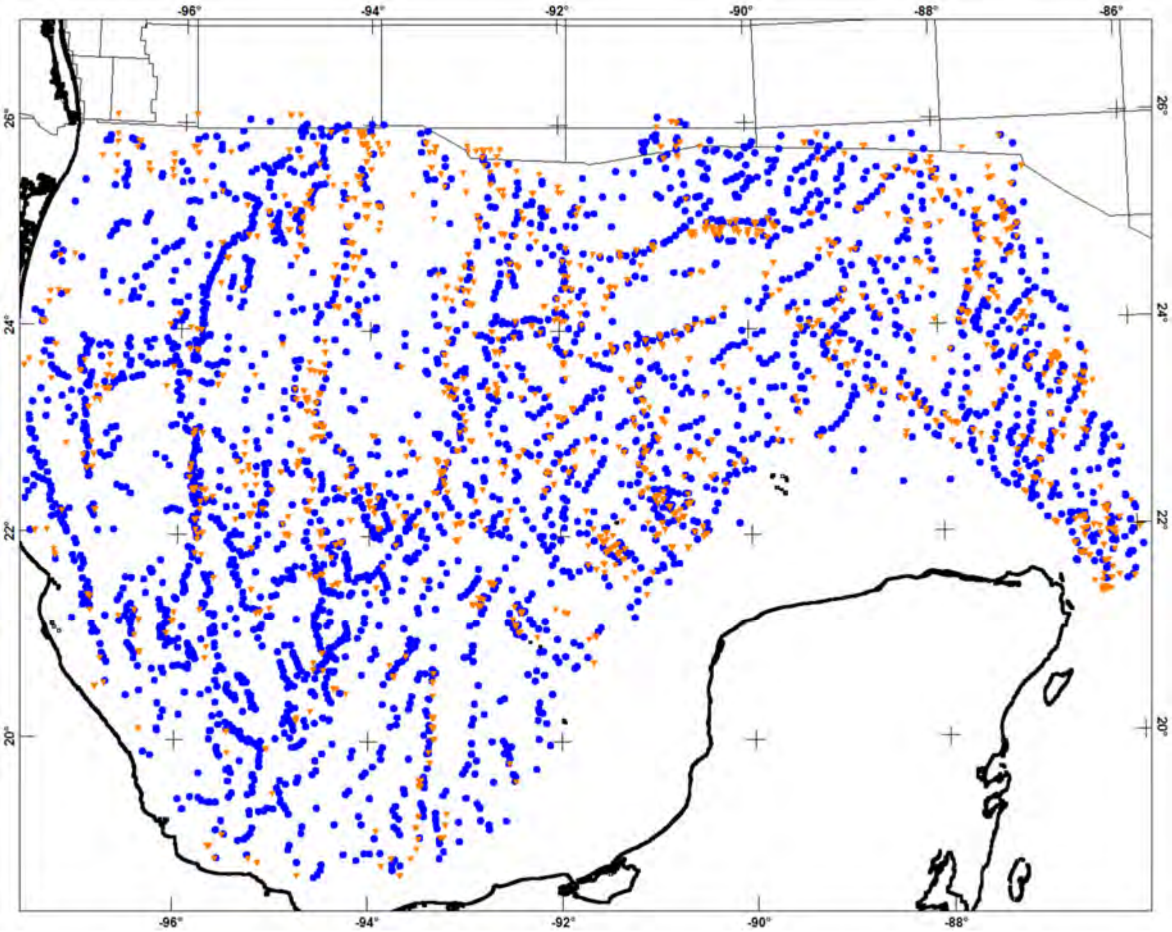

Figure 3. Map of magnetic depth estimates in the MGOM. Blue dots represent depth points from the manual methods, primarily tilt-depth and Bean Ratio A. Different methods are used to test every magnetic anomaly. Orange triangles represent depth solutions from semi-automated Euler and Werner methods.

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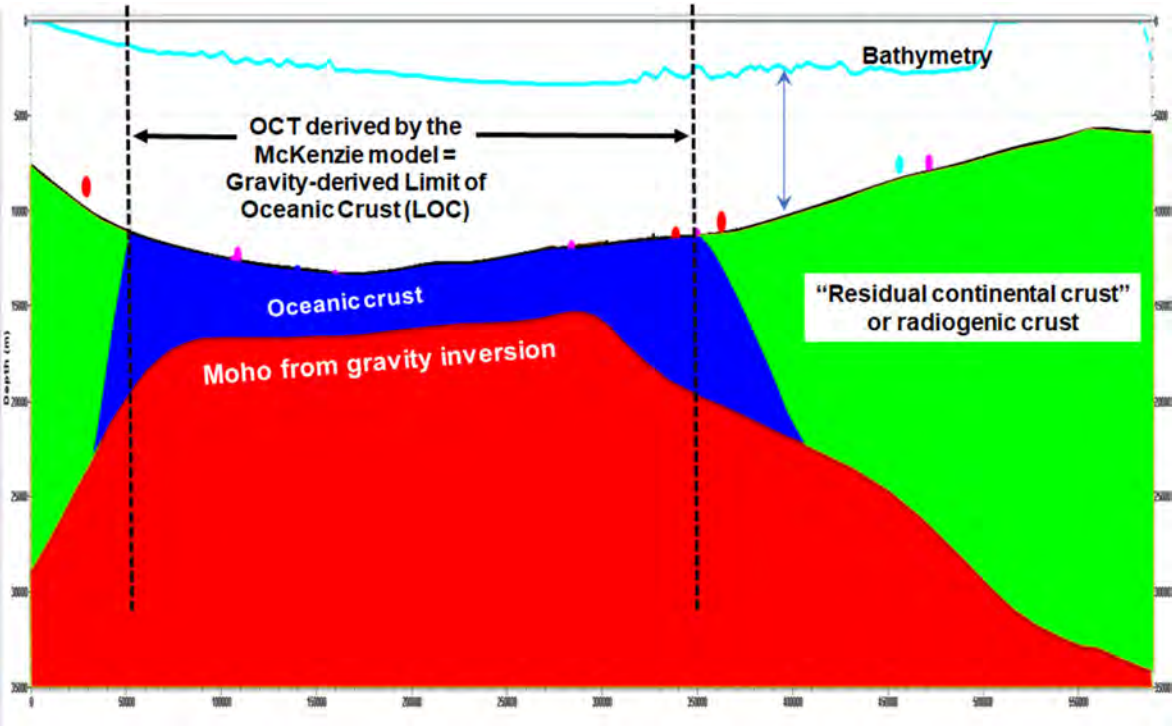

Figure 4. Cartoon showing method for determining crustal thickness using gravity modelling and inversion. The elliptical points shown are depth to magnetic basement solutions. Gridding of these points gives a map of the depth to magnetic basement (i.e., the top of the crust).

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, 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 allow the inversion to simultaneously invert for structure, while also endeavoring to satisfy multiple Moho depth control points, thus significantly improving the crustal thickness result over previous inversion methods.

Results

Moho depth over the entire marine GOM, as determined by the calibrated and constrained gravity inversion, falls within a range of 13 km deep to ~40 km deep north of the Chicxulub impact site. Combination of the Depth to Moho map and the Depth to Magnetic Basement (Ultra Thin Crust model: Fig. 5) map allows construction of a crustal thickness map. Results from the crustal thickness map show very thin crust (2–5 km thickness) in the area immediately east of the interpreted transform fault variously called Western Main Transform (Marton and Buffler, 1994) or Western Gulf Transform (Pindell et al., 2015).

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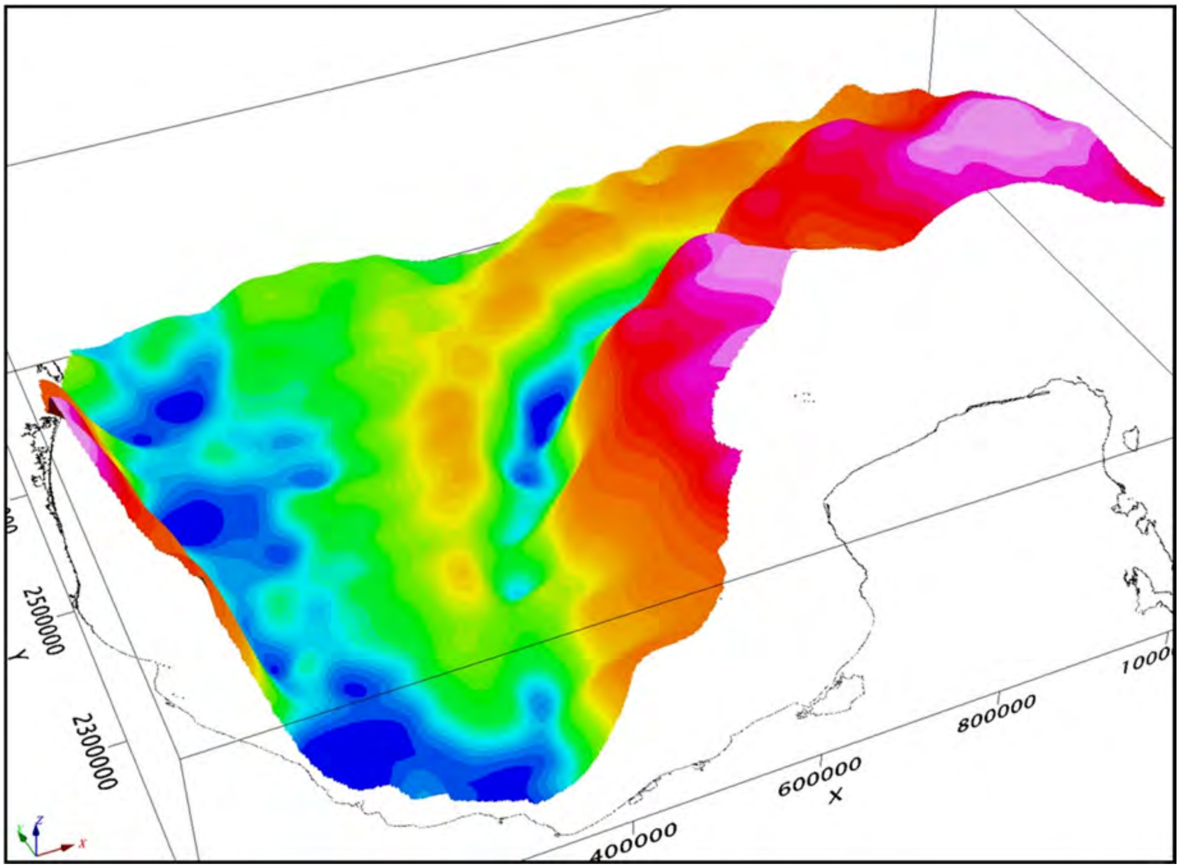

Figure 5. Depth to magnetic basement—the ultra-thin crust model, showing a 3D perspective view of the study area. Note the basement low at the foot of the Yucatan Platform corresponding to the area of well-developed syn-rift basin(s).

This work also produces a more accurate derivation of the Limit of Oceanic Crust (LOC). The McKenzie and Bickle (1988) model can be used to provide an estimate of the oceanic crust (the blue area in Figure 4). Subtraction of the blue area from the total crust yields the separate area of continental crust (the green area in Figure 4). Thus, we can derive a semi-automated estimate of the limit of oceanic crust (Fig. 7). The purple polygon in Fig. 7 indicates the LOC predicted using just the public domain base of sediments as the top crust. The green polygon in Figure 7 shows the LOC predicted using the top of magnetic crust in the Gigante area as the top crust. The two polygons overlap in the U.S. sector, and diverge in the Alaminos Canyon and MGOM areas (where finer control from the Gigante data is available). The new LOC matches closely with the map of oceanic crust indicated from the Gigante seismic interpretation (Fig. 8). Comparison of the LOC polygons derived in this work with those published by other authors (Fig. 9) show some significant disparities; most notably in the area north and west of the Campeche Salt Province and along the Western Main Transform.

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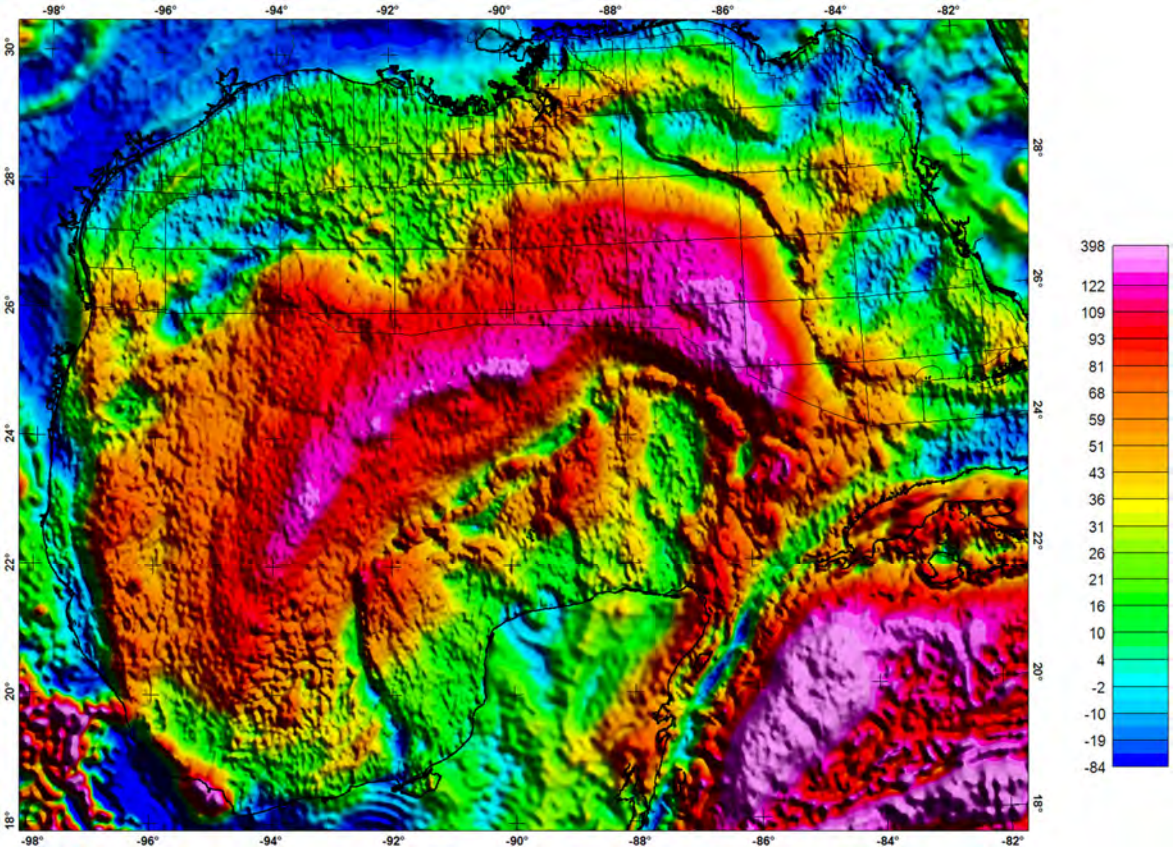

Figure 6. Merged Bouguer Gravity anomaly map for the entire GOM and its environs. Note: The actual gravity and magnetic data used for this study were taken from the TGS Gigante Mexico program: 185,000 line km of high resolution gravity and magnetic data acquired alongside the seismic program. The image shown in this figure is from public domain gravity data, which was used to fill-out the gravity coverage beyond the proprietary data. A 3D Bouguer / terrain correction was applied to the merged free-air gravity anomaly (merge of Gigante survey with Sandwell v24 satellite-derived gravity). A reduction density of 2.67 g/cm^3 was used onshore and 1.90 g/cm^3 (0.87 contrast) was used offshore.

Further Work

Syn-rift basins of similar geometry and extent are known in the northern GOM in the Mississippi Canyon, De Soto Canyon, and Atwater Valley protraction areas where they underlie recent Norphlet discoveries. The results from the potential fields analysis and Mexican seismic interpretation concerning variations in crustal thickness and extent of the LOC has provided conjugate analogues that can be used to better understand pre-salt structures in the northern GOM (Fig. 10). Mapping of syn-rift sediments and crustal variations on both sides of the basin using both modern seismic and potential field analysis will further our understanding of the early stages of GOM opening and may have implications for the formation and charge of

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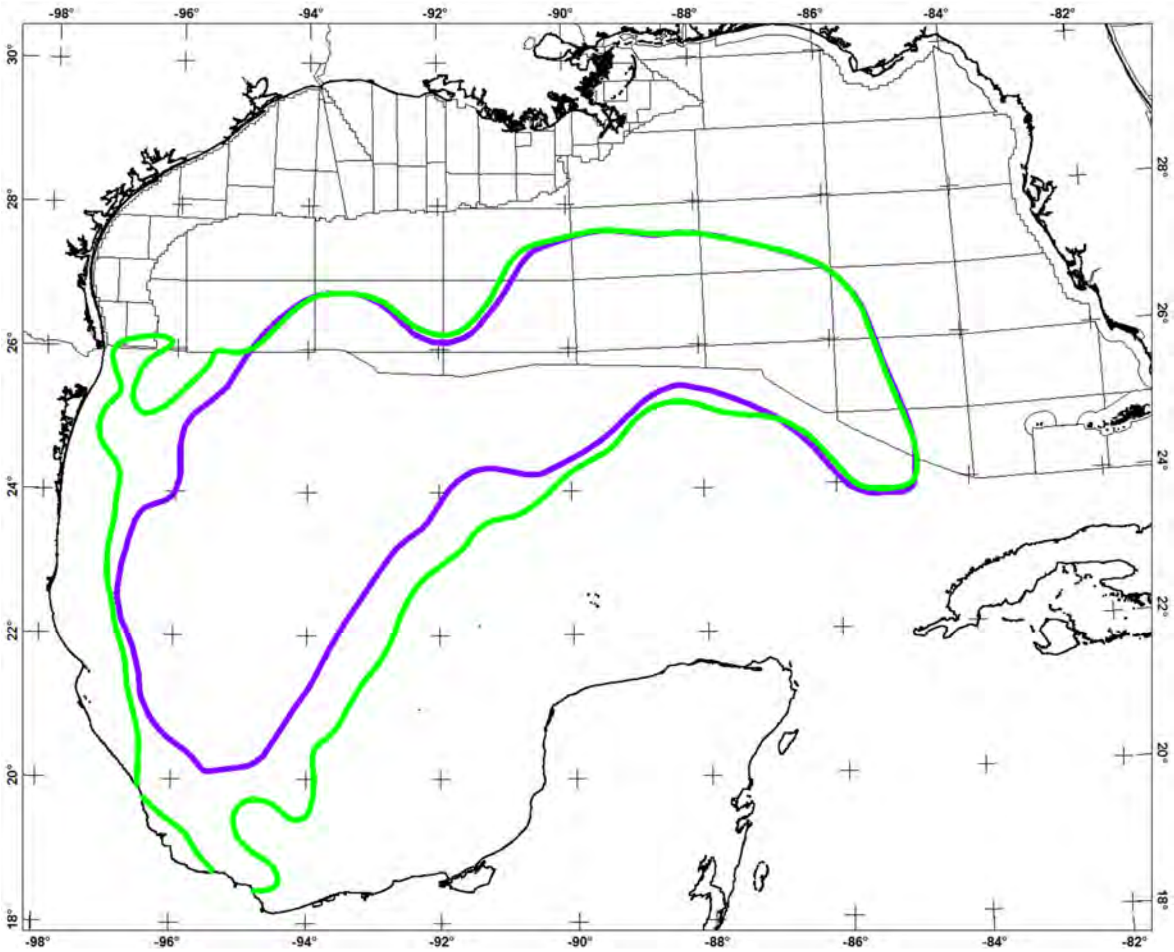

Figure 7. Limit of Oceanic Crust (LOC), as derived from the gravity inversions with thermal gravity anomaly.

Norphlet structures. Seismic interpretation of these structures is underway at TGS.

Summary and Conclusions

TGS and Bain Geophysical Services have concluded a two-year program of iterative potential fields analysis integrated with regional seismic interpretation. Some of the key results from this study include:

- Depth to magnetic basement determined throughout the MGOM
- Depth to magnetic basement mapping, combined with seismic basement maps, show the extent and architecture of the deep syn-rift grabens and half-grabens underlying the northern Campeche Salt Basin on stretched continental / transitional crust along the flanks of the mapped oceanic crust

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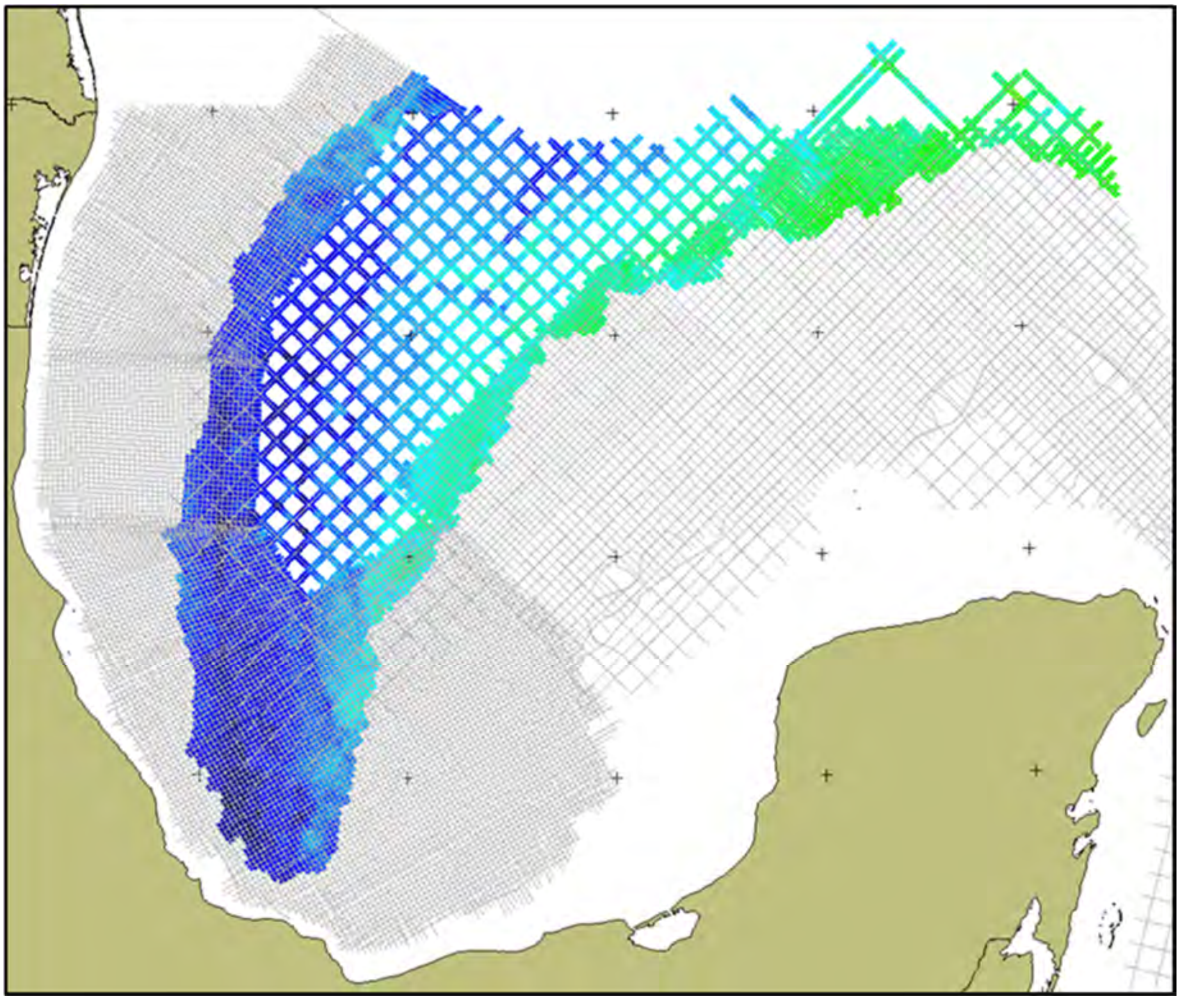

Figure 8. Ribbon map of the extent of oceanic crust mapped on Gigante PSDM 2D seismic lines.

- Gravity inversion (tightly integrated with depth to magnetic basement, regional seismic interpretation and public refraction control) is used to create a depth to Moho horizon and crustal thickness interpretation
- Gravity inversion and careful integration with seismic interpretation, supports an ultra-thin crustal model, with important implications for basin and thermal modeling
- 3D gravity inversion provides an independent estimate of the Limit of Oceanic Crust.

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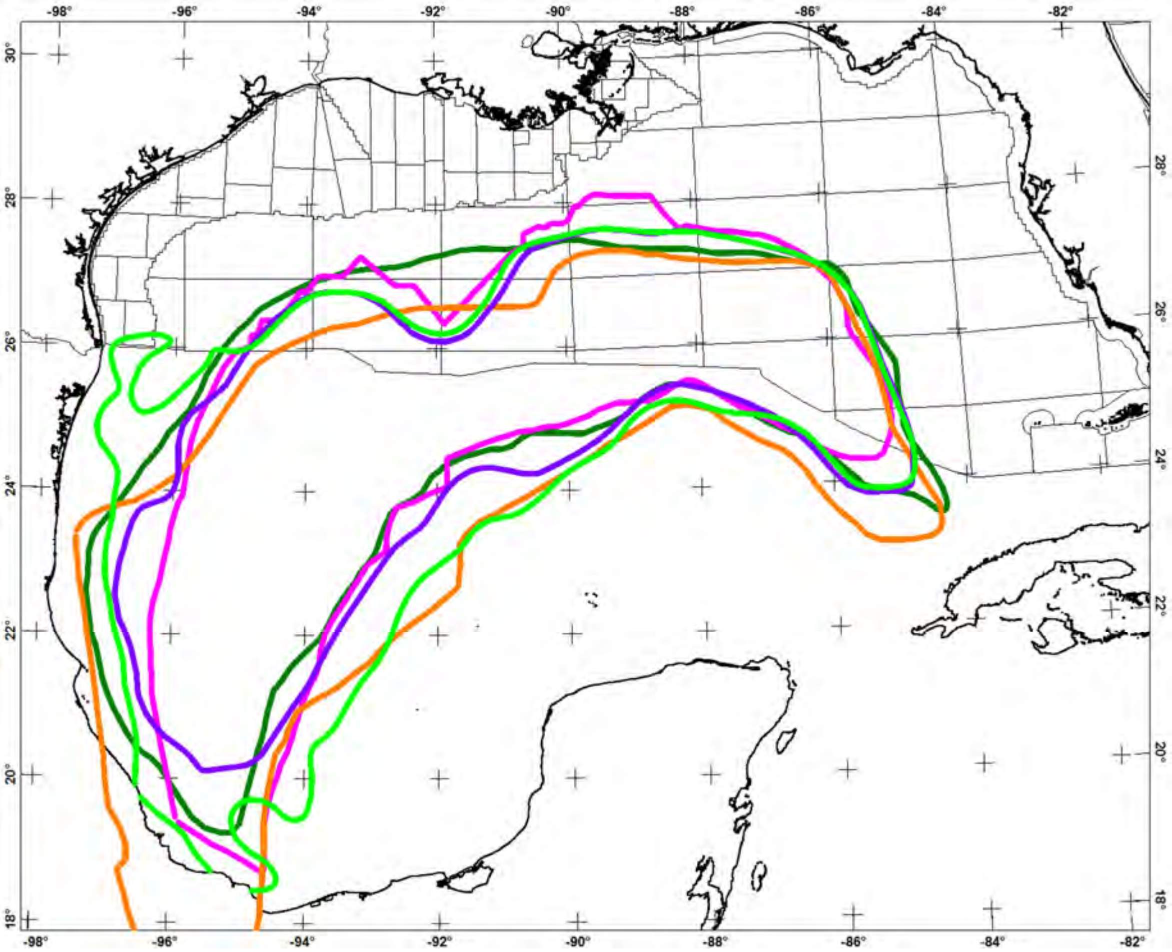

Figure 9. Limit of Oceanic Crust (LOC) polygons from this study (green and purple) contrasted with those of other works: pink (Hudec et al., 2013), dark green (Christeson et al., 2014) and orange (Pindell and Kennan, 2009).

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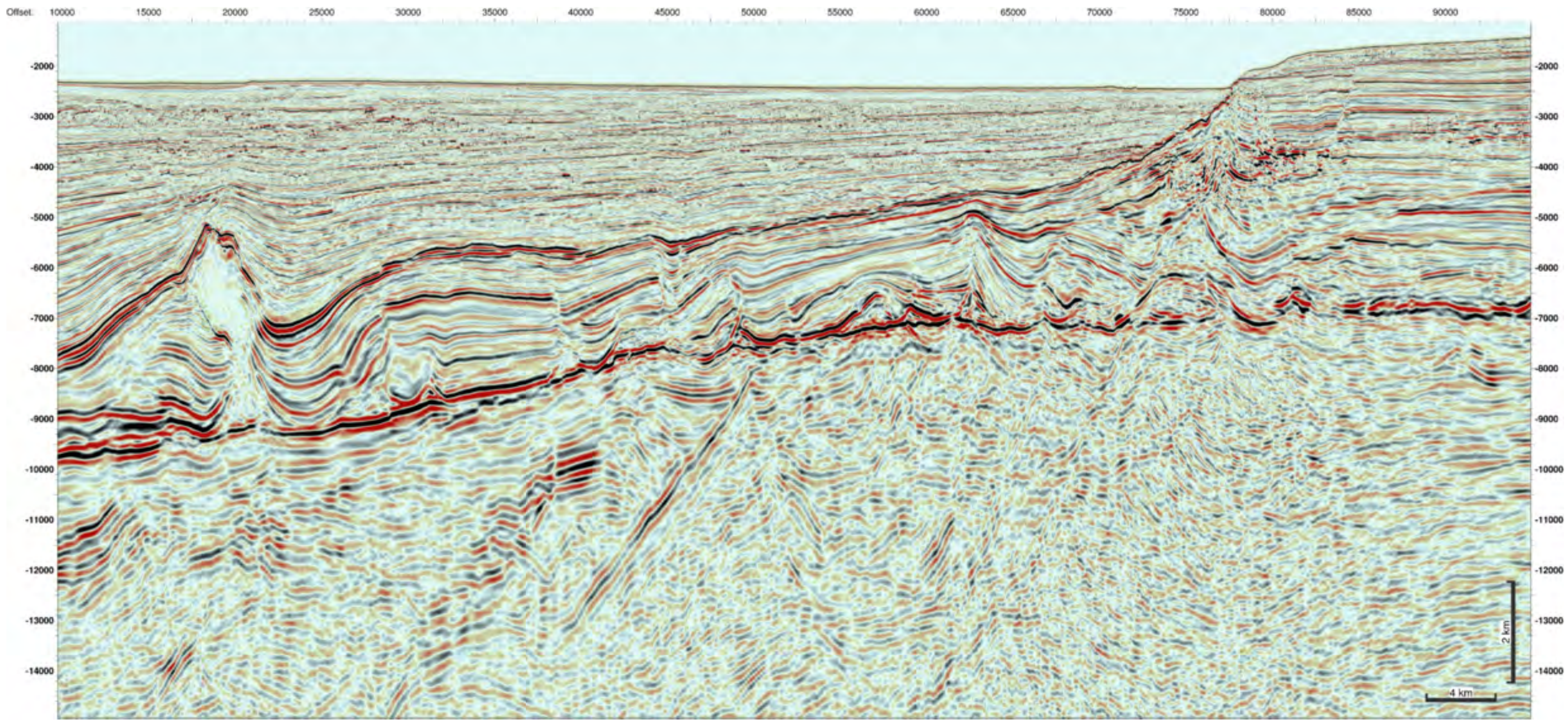

Figure 10. A view through the TGS Declaration 3D survey (De Soto Canyon protraction area in the USGOM) showing syn-rift architecture like that seen in Figure 2 in the MGOM.

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