Characterising the Subsurface Architecture and Stratigraphy of the McArthur Group through Integrated Airborne EM and Gravity Inversion

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SUMMARY

The Caranbirini sediment-hosted Zn-Pb-Ag prospect is located west of the Emu Fault, ~20 km north of McArthur River Mine (formally HYC), within the Batten Fault Zone of the McArthur Basin (Northern Territory). The Caranbirini area exposes stratigraphy from McArthur Group and shows some structural complexity with post-depositional folding and faulting. In order to better characterize the subsurface basin architecture we combine structural, sedimentological, and stratigraphic interpretations with 3D gravity inversion, and a 1D airborne electromagnetic inversion. Results are integrated to build a 3D model of the subsurface basin architecture, and identify prospective stratigraphy such as the Barney Creek Formation. 3D gravity inversions were performed using a preliminary 3D geological model of the project area as a reference model for a constrained property inversion. The gravity inversion identified an anomalous density zone immediately west of the Emu Fault. Interpretation of the inverted AEM data provided stratigraphic constraint for the geological model by defining the depth and geometry of the Barney Creek Formation. They also indicated the presence of several N-S trending faults to the west of the Emu Fault coincident with the western boundary of the anomalous density zone. The interpretation suggests that the depth to the Barney Creek Formation increases westwards of the Emu Fault. We interpret the increase in depth to the Barney Creek Formation, in combination with the zone of increased density as a fault-bounded sub-basin, bounded in the west by a paleo-high. Recognition of the sub-basin and controlling faults has implications for targeting Zn-Pb-Ag mineralization.

Key words: McArthur Basin, Barney Creek Formation, Gravity, VTEM, Inversion

INTRODUCTION

The Palaeo-Mesoproterozoic McArthur Basin (Fig. 1) forms part of a Proterozoic basin network that formed across large areas of the North and South Australian cratons (Betts, et al. 2008, Rawlings 1999). The Batten Fault Zone is a 50-80 km wide, N-trending fault zone that bisects the south-eastern McArthur Basin (Ahmad et al., 2013). This region is significant because it exposes sedimentary and volcanic sequences from the Tawallah, McArthur, Nathan and Roper Groups, which represent sequences from four stacked and superimposed basins. This region provides an opportunity to understand the architecture and relationship between these basin sequences, and how they relate to the tectonic framework of the North Australian Craton.

Previous studies in the Mt Isa Inlier and McArthur Basin regions have shown that the regional extensional direction changed as the basins evolved, likely related to far-field stresses from the southern and eastern margins of the Proterozoic Australian continent (Betts and Giles, 2006). This caused the orientation of fault systems within the basins to vary as they evolved. There is currently a poor understanding of the orientation of structures controlling the basin architecture at the time of the deposition of the McArthur Group (Glyde Package; Fig. 1), in particular structures controlling the prospective Barney Creek Formation.

This study focusses on the carbonate and shale-bearing units of the McArthur Group in the Caranbirini region, located within the Batten Fault Zone (Fig. 1). We integrate interpretations of airborne electromagnetics (AEM) and gravity inversions, with detailed sedimentological studies of available drill core to understand the 3D architecture of the Caranbirini area, and identify the subsurface extent and structural controls of the Barney Creek Formation. The Barney Creek Formation is significant as it hosts the world class SEDEX Zn-Pb deposit, McArthur River (Ahmad et al., 2013). Other stratigraphic units relevant to this work include the Yalco and Stretton Sandstones, Lynott Formation, Reward Dolostone and sediments of the Roper Group (Ahmad et al., 2013).

METHOD

We integrate interpretations of gridded geophysical and geological data with gravity and AEM inversion results to produce a 3D geological model using the workflow shown in Fig. 2. We initially test validity of an existing 3D geological model of Caranbirini through constrained 3D property inversion of high resolution gravity data. To improve the 3D geological model, we interpret radiometric, gravity and shallow AEM depth slices to map stratigraphy at the surface, and identify structural features such as folds and faults, including those which may be blind at the surface. Several updates to the geometry of the model were built based upon this new structural information, and the interpretation of VTEM sections. The updated model geometries were tested against the gravity data to determine if the new models improve the misfit between the observed and calculated data. Modelling results are then considered within the tectonic framework of the basin.

GEOPHYSICAL INTERPRETATION

A solid geological map of the project area was produced through the interpretation of existing geological data, and newly acquired and historical geophysical data (Figure 3). This interpretation focused on mapping stratigraphy under younger cover and identifying structural features such as folds and faults, including those which may be blind at the surface.

The geology and major structural features of Caranbirini are well-defined in the high-resolution ground gravity (500 m station spacing) (Fig. 3a-b), AEM (Fig. 3e-f) and the regional radiometric data (Fig. 3d). The major structure in the area, the NNW-SSE trending Emu Fault is defined by a sharp gradient between a N-S trending gravity high to the west, and a gravity low to the east. The sharp gradient suggests a steep west-dipping structure, which is consistent with interpretations of seismic data which crosses the Emu fault north of the project area (Rawlings, et al. 2004). In the AEM data, the Emu Fault is defined by a linear conductive anomaly, and also appears to dip to the west. Other linear features, predominantly trending in a N-S orientation can be observed in the AEM data. These are interpreted to be faults (Fig. 3g), and may indicate either the margins of a sub-basin within the McArthur Group, or post-depositional faulting related to minor deformation in the area.

The region east of the Emu Fault is defined by a gravity low and is coincident with the extent of the Roper Group. The radiometric signal is typically Th-enriched, but can be variable due to the presence of younger cover. The region west of the Emu Fault is defined by a N-S trending gravity high which corresponds to dolomitic units in the stratigraphy. This includes the Reward Dolostone, and the overlying Lynott Formation which is outcropping and coincident with the extent of the gravity high. The gravity high exhibits some complexity, which is evident in the 1VD grid (Fig3b). Superimposed on the broader N-S trending gravity high are shorter-wavelength NNW-SSE trending high and low amplitude anomalies. The high amplitude anomalies correlate with the mapped location of anticlines in the region, while the low amplitude anomalies correlate to the synclines (Fig3g). These subtle gravity variations are interpreted to be caused by relative increases or decreases in the depth of the carbonate units, and by structural thickening/thinning of the stratigraphy in the fold hinges.

The Stretton Sandstone and Yalco Formation which outcrop on the western margin of the project area are coincident with a low gravity anomaly. The 1VD of the gravity data is able to resolve these two formations, with the Yalco Formation having a higher amplitude than the Stretton Sandstone. These formations are also resolvable in the radiometric and AEM data, with the Yalco Formation having a moderate Th-enriched to signal, and a moderate to low conductivity, while the Stretton Sandstone is K-enriched.

AEM PROCESSING AND INVERSION

AEM data over the Caranbirini area was acquired with a VTEM (Versatile Time-Domain Electromagnetic) heli-borne electromagnetic system (Witherly et al., 2004). It employed a central loop configured transmitter with a loop area of 962 m^2 and a dipole moment of approximately 870,099 nIA. The nominal Tx-Rx loop altitude was 30 to 35 m above the ground. A total of 904 line kilometres of data were acquired along E-W oriented lines between the 18th and 21st November 2010. Line spacing was 200 m.

Although both X (inline) and Z (vertical) component data are recorded, only the Z component data were used in the modelling of the Caranbirini VTEM survey dataset. The full nonlinear inversion algorithm AarhusInv (Auken et al., 2015) was employed, and the data were inverted for a set of 1D models to a depth of 1500m. A Laterally-Constrained Inversion (LCI) methodology described by (Auken and Christiansen, 2004; Auken et al, 2005) was applied with spatial constraints, which are defined for adjacent soundings, allowing prior information (e.g., the expected geological variability of the area) to migrate along the flight lines. The use of constraints along lines enhances the connection of layer parameters between adjacent soundings. In the context of McArthur Basin this approach encourages the definition of laterally continuous conductive layers which is an aid to target definition and geological interpretation. A 30-layer model was used for the inversion. The first layer thickness was chosen to be 10 m with logarithmically increasing thicknesses to a depth of 1500 m, which is the depth of the last layer boundary. The starting model for the inversion was a homogenous half-space with a resistivity of 40 Ohmm (25 mS/m). The regularization constraints were set to a value which allows some vertical structure, without introducing artefacts caused by overfitting the data. The inversion solved for Z-component data as well as the transmitter height using the one model. This approach yields the maximum possible resolution of model parameters.

To ensure that the observed variations in measured conductivity reflect changing ground conditions, rather than inversion or model dependent changes arising from the inversion process, an estimate of the depth of investigation was calculated. Modelled conductivities across the Caranbirini study area result in a DOI that varies significantly; from several 100 metres in the east where conductive sediments of the Roper Group outcrop, to greater than 500 m below the surface in the western portions of the survey area where resistive dolostones of the McArthur Group are present.

GRAVITY MODELLING

Constrained three-dimensional gravity inversions were applied to understand density distributions within the subsurface and refine the geometries of key structures and stratigraphic units. Inversions were performed using VPmg (Vertical Prism magnetics and gravity; (Fullagar, et al. 2000, Fullagar and Pears 2007, Fullagar, et al. 2008)), using a workflow similar to that used by Armit, et al. (2014) and Blaikie, et al. (2014), where successive homogenous and heterogeneous property inversions are applied to understand the density distribution within each region of the geological model.

A volume of interest was defined around the gravity data (an area 13 x 16 x 4 km in the x, y and z direction). An existing 3D geological model was used as a starting reference model and was discretised into 100 m^3 voxels for inversion. Each model region represents a key stratigraphic unit and was assigned a density based upon observed data for the McArthur Group stratigraphy (Hallet, 2016). Forward models were run prior to, and after each inversion and the misfit between the observed data can be compared numerically (e.g., RMS misfit, % of the total dynamic range) and visually by examining the residual gravity anomaly. Regions in the model are defined as the Roper Group, Stretton Sandstone and Yalco formation (merged), the Lynott Formation, Reward Dolostone, and a basal region which includes the Barney Creek Formation and stratigraphy below it. The basal region of the model is unconstrained because the thickness of the Barney Creek Formation and stratigraphy below it were not defined in the initial reference model. Gravity inversions were performed on this reference model to determine if it could be reconciled with the gravity data, and if any structural changes are warranted. Both homogeneous and heterogeneous density inversions styles were applied to reduce the model misfit. Homogeneous inversions were used as an initial step towards optimising the density of each region. This was followed by heterogeneous inversion to calculate an optimum property distribution within each model region. Each inversion allowed the density of a region to vary between and minimum and maximum value, which was constrained by values measured for each stratigraphic unit (Hallet 2016).

Inversion of the reference model produced good results in terms of the model being able to reproduce the observed gravity anomaly. However the inversion produced anomalous density zones within certain stratigraphic units, which indicates a structural problem with the reference model. As the inversion was not able to modify the geometry of this region, an increase in density was modelled to compensate. Density anomalies were observed primarily within the Reward Dolostone, where a zone of increased density extends approximately 4-5km west of the Emu fault. There are several possible geological interpretations of this result. It may indicate either that density of the overlying stratigraphy is too low, or its thickness was overestimated and the Reward Dolostone and underlying carbonate units are shallower than initially modelled. The concentration of dense material immediately adjacent to the Emu Fault however, and not towards the west of the project area may indicate a thickening of carbonate units (either the Reward Dolostone, or units below, such as the Barney Creek Formation) towards the Emu Fault. Interpretation of AEM data suggests there may be a N-S oriented fault located at the margin of this anomalous zone. This could indicate the presence of a fault-bounded sub-basin, where there is a local thickening of carbonates units towards the Emu Fault. Alternatively, this fault could be a result of later deformation, and indicate inversion of the stratigraphy in this region, however this interpretation is inconsistent with results of AEM inversion.

REVISED GEOLOGICAL MODEL

The existing 3D geological model was refined based upon the gravity inversions, digitised polylines constrained by a geological interpretation of the inverted AEM data linked to previous mapping, cross-sections and drill-core logging. Two new models were constructed which include a new interpretation of faults and updated surfaces representing the tops of the Barney Creek Formation, Reward Dolostone, Lynott Formation and simple representations of the Yalco and Stretton formations.

New surfaces constructed for the top of the Barney Creek Formation were based on two conductive units that are prominent in many of the AEM 1D conductivity-depth sections. The first new 3D model assumes that the top of the shallow conductive unit is the Barney Creek Formation (Fig. 5b). The second model assumes that the shallow conductive unit is actually in younger stratigraphy (most likely the Caranbirini Member of the Lynott Formation) and that the Barney Creek Formation is represented by a deeper conductive unit (Fig. 5c). The interpretation in model 1 indicates that there is a subtle trough or sub-basin to the west of the Emu Fault. This is not particularly evident in the initial reference model or in model 2. The sub-basin in model 1is consistent with one of the interpretations of the density anomaly adjacent to the Emu Fault from 3D gravity inversions.

The two new geological models were tested against the gravity data to determine if the new geometries improve the misfit, and remove the large density anomalies observed in the initial model. Both models produce good results with a low misfit between the observed and calculated data. The updated geometry of the Reward/Barney Creek Formations for both model 1 and 2 remove the density anomalies observed in the initial model. This indicates an improved model geometry, with two plausible models that satisfy the gravity data. However, we consider the geometry of the Barney Creek Formation in model 2 geologically less plausible as the deeper conductive anomaly in the AEM inversions is close to the depth of investigation and may be an artefact of the inversion process.

CONCLUSIONS

This work demonstrates how the comparison and integration of geological data, gravity inversions and inverted AEM sections can be used to produce a 3D geological model of an area. The updated architecture and 3D geological model of Caranbirini significantly changes the understanding of the area, and may allow better targeting of prospective stratigraphy in future exploration programs. Our preferred model suggests there is a fault-bounded sub-basin adjacent to the Emu Fault. This sub-basin likely formed in a local transtensional zone confined by N-S trending strike-slip (e.g., Emu Fault) and E-W to NW-SE trending normal faults. This interpretation is consistent with interpretation of sub-basins along strike of the Emu Fault, for example the Glyde River sub-basin.

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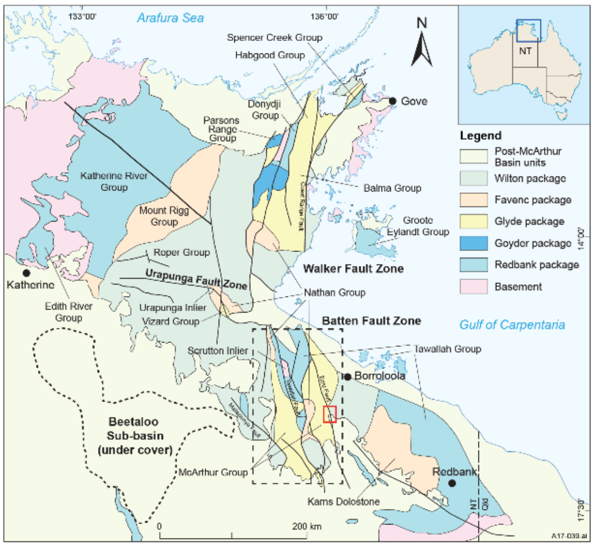

Figure 1: Distribution of major basin sequences and structural features within the McArthur Basin (After Ahmad et al., 2013). Inset shows location of Caranbirini.

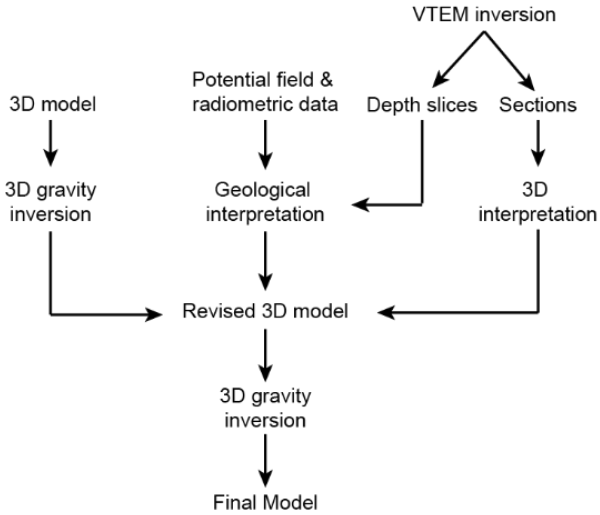

Figure 2: Workflow for the modelling and interpretation of geophysical data

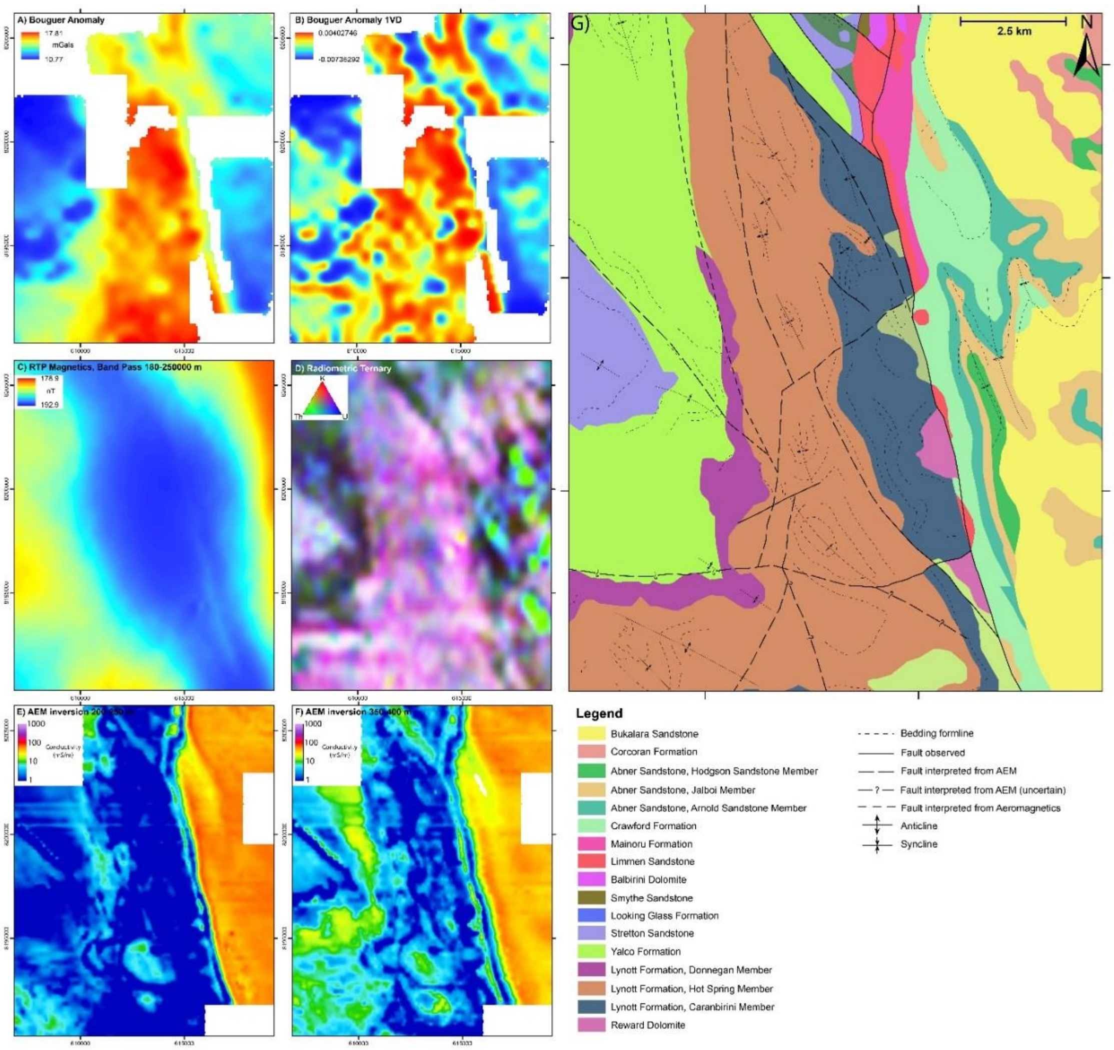

Figure 3. a) Bouguer anomaly; b) 1st Vertical derivative of the Bouguer anomaly; c) Reduced to pole magnetics, band pass filtered 180-25 000 m; d) Ternary plot of Radiometrics; e)AEM inversion depth slice at 200-250 m; f) AEM inversion depth slice at 350-400 m; g) Geological interpretation

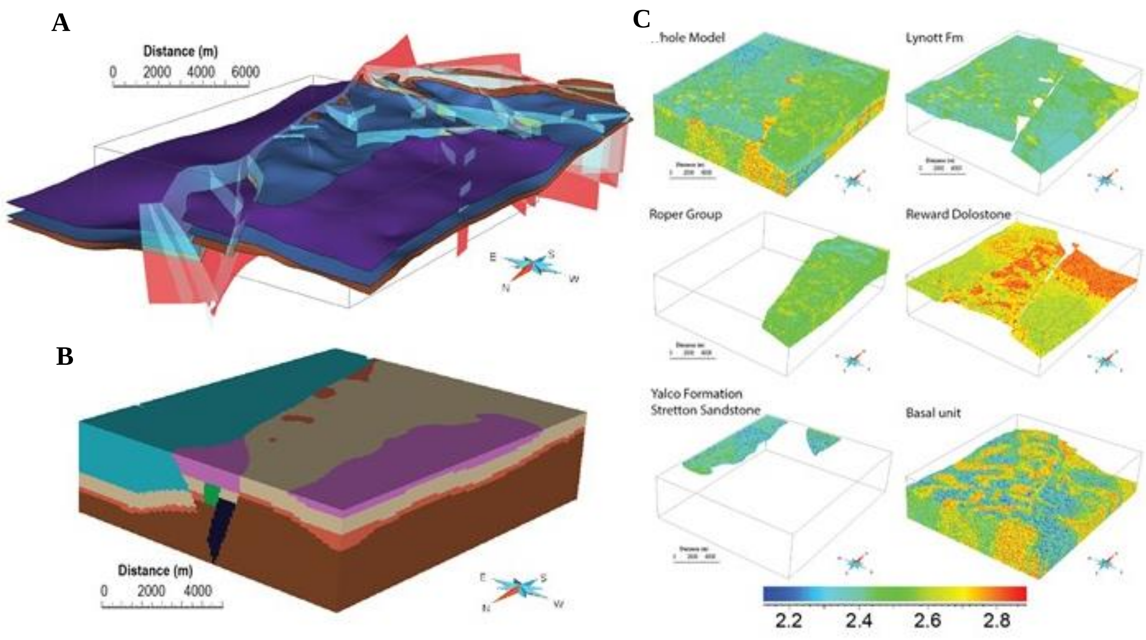

Figure 4. a) Initial geological model; b) Volume of interest for inversion; c) Density distribution within each model region.

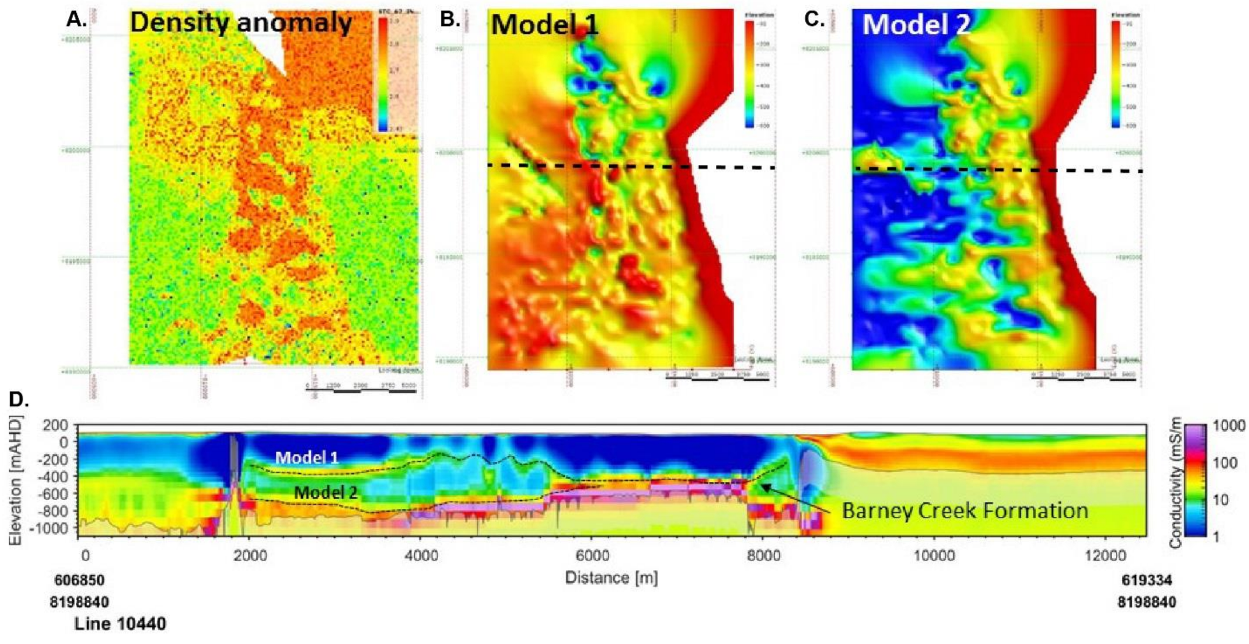

Figure 5. a) Depth slice of density anomaly from gravity inversions. Interpretation of depth to Barney Creek formation from VTEM data in b) model 1; and c) model 2; d) Section of 1D VTEM inversion showing two conductive anomalies interpreted to produce models 1 and 2 (section location shown in b and c).