

An integrated approach to mapping crustal geology and structures in the NE Capricorn Orogen, Western Australia: Implications for uranium exploration

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SUMMARY

Geological, geophysical and remote sensing data have been used in the northwest Capricorn Orogen to map crustal scale structures beneath Paleoproterozoic Basins that may have focused mineralising fluids. The interpretations were largely based on upwardly continued bouguer gravity and magnetic data, then tested using petrophysically constrained forward modelling techniques. The most likely interpretation for deep crustal component of the region was found to be the Bandee Seismic Province modelled with a mafic petrophysical character. A small portion of the study area in the northern part of the study area was modelled as an extension of the Pilbara Craton with overlying Hamersley-Fortescue Groups. Various gravity lows observed in the data were tested to determine if they represented a sub-basin, granitoid intrusion or shallow batholith. The gravity lows were found to be most likely related to granitoid intrusions. One significant deep-crustal scale structure in the central-southern part of the study area can be related to a fault mapped at surface and from Landsat 8 data. The structure has had limited exploration along its extent. The integrated approach of mapping, including surface geological mapping, indicates potential carbonaceous sediments in the hangingwall of the southern major fault zone could be prospective for uranium and gold-silver mineralisation. The friable nature of the coarse grained sandstone of the Bresnahan Group, that un-conformably overlies the carbonaceous mudstone, indicates fluid flow interaction with the unconformity could have occurred which enhances the prospectivity for uranium.

Key words: Capricorn Orogen, crustal scale structures, geophysical interpretation, forward modelling

INTRODUCTION

Mineral system research has reinforced the importance of crustal scale structures in the formation of significant mineral deposits, e.g. O'Driscoll, (1986), Wyborn (1994), McCuaig et al. (2010) and Occhipinti et al. (2016). An attempt at mapping crustal scale structures in the NE Capricorn Orogen (Figure 1) is presented, which is a basin dominated terrane of dominantly Paleoproterozoic age. A number of structures at surface have previously been mapped by the Geological Survey (Tyler et al. 1990, Thorne et al. 1991) and during this project (Uren et al. 2016). Previous authors such as Drummond et al. (1983) and Hackney (2004) have provide some interpretation for crustal geology across the Pilbara and Capricorn Orogens, respectively, but not in the detail needed for mineral system analysis. A full evaluation of whether the structures mapped at surface in the region extend into the deeper crust (i.e. crustal scale) remains to be completed. This is a particular problem in basin dominated terranes as the significance of a structure at surface is not always apparent (McCuaig et al. 2010). The location of significant structures that could have acted as focused fluid pathways is an important consideration for exploration of uranium and gold-silver in the region.

The work integrates various techniques for mapping crustal scale structures. A surface geological map was previously created utilising mainly Landsat 8, airborne hyperspectral data, radiometric data as well as fieldwork mapping to ground truth the interpretation (Uren et al. 2016). The mapping of structures through the crust will be completed by using gravity and magnetic datasets that were upwardly continued to be more representative of features at depth (Figure 2).

An interpreted geological depth slice in the region akin to geology at greater than 3 km has been completed mainly from the processed gravity and magnetic data. A series of interpretations are presented (Figure 2). The interpretation of the geology at depth is important in order to constrain locations of the more important structures that may or may not be apparent at surface. Forward modelling of the gravity and magnetic datasets was used to test whether the different interpretations were realistic as well as to test different ideas regarding the dominant upper crustal geology (Figure 3). A preferred depth slice geological map interpretation is presented with comparison to the surface mapping interpretation to evaluate locations of crustal scale structures, along with historic drilling in the area and the more significant resources discovered (Figure 4). The area has been mapped at surface, with observations that enhance the prospectivity for uranium and gold-silver exploration noted (Figure 5).

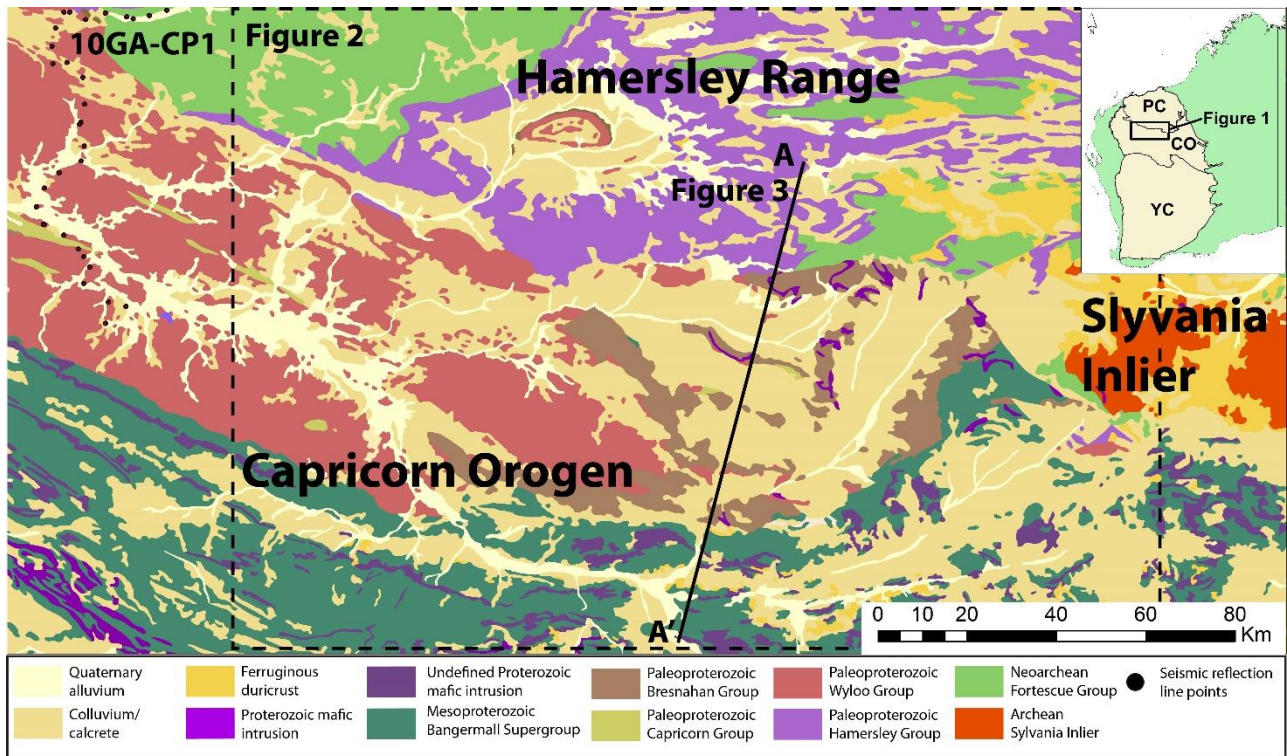


Figure 1: A geological group map of the region with the main geological terranes indicated. The Hamersley Range is defined by the Hamersley and Fortescue Groups and the Capricorn Orogen by the Ashburton, Bresnahan Groups and Bangermall Supergroup. The location of the map in Western Australia is shown as well as a trace of a seismic line 10GA-CP1 that is presented by Johnson et al. (2013). PC = Pilbara Craton, CO = Capricorn Orogen and YC = Yilgarn Craton.

METHODS, RESULTS AND DISCUSSION

The spherical cap bouguer gravity and magnetic datasets were processed and then used to interpret the geology at depth (Figure 2). The gravity station data and magnetic line data were obtained from the Geoscience Australia Data Delivery System portal (www.geoscience.gov.au/geophysical-data-delivery, 2016). The total magnetic intensity (TMI) data was gridded using a minimum curvature algorithm and was reduced to the pole. The gravity stations have several generations of data collection, hence the image was gridded in two blocks. One block with 2 km gravity station spacing, comprised data that was collected in 2010-11 and was gridded via a minimum curvature algorithm with a grid cell size of 400m. The second block with a station spacing of 5 km, that also includes gravity stations along roads, is derived from 1990 and 1970 aged data collection respectively, and was gridded using a minimum curvature algorithm with a grid cell size of 1 km. The two gridded gravity blocks were then stitched together. In order to remove shorter wavelength features that represent nearer surface features both the gravity and magnetic gridded datasets were upwardly continued by 3000m. The 3000m upwardly continued gridded bouguer gravity has an additional 15,000m upwardly continued gridded data subtracted to create a residual grid, which removes any deeper regional trends, for example caused by the Moho.

The interpretations in Figure 2 represent a range of possibilities for the geology and structures at depth in the NE Capricorn Orogen. The purely granitoid model (Figure 2c), where gravity lows are interpreted to be related to granitic bodies is one end member possibility, with the other end member possibility being the extensional model, where gravity lows are instead related to Ashburton Basin sub-basins (Figure 2d). The granitoid age of emplacement is not defined; they could be related to original existing Archean basement, been emplaced after the Hamersley-Fortescue Group deposition or emplaced late after Ashburton Basin deposition. While the final interpretation (Figure 2e) is a mix of the granitoid and Ashburton Sub-basin interpretations, it includes the possibility that a thrust fault exists in the centre of the image to explain the change in geophysical properties from strongly magnetic to weakly magnetic, high density rocks. A thrust fault is interpreted to be related to earlier thrust tectonics such as those that can be observed in the Hamersley Range to the north. Various Capricorn Orogen aged extensional faults cut across or potentially reactivate the earlier weaknesses. The potential of these interpretations will be tested via forward modelling of the gravity and magnetic data.

To properly test the geological scenarios illustrated in Figure 2 an evaluation of the dominant upper crust geology underlying the area is required. Johnson et al. (2013) suggest the Bandee Seismic Province underlies the Ashburton Basin, the high amplitude semi-continuous seismic texture unit coincides with a high density, magnetic crust that could be interpreted in a number of different ways. One interpretation would be that the strongly magnetic, high density Hamersley-Fortescue Group rocks overlay Pilbara Craton granitoid that has low density and magnetic properties. An alternative interpretation could be that the Bandee Seismic Province represents a high density, moderate to high magnetic upper crust that has been modelled using mafic petrophysical properties. Both scenarios have been tested by forward modelling (Figure 3), in conjunction with the various geological interpretation possibilities from Figure 2.

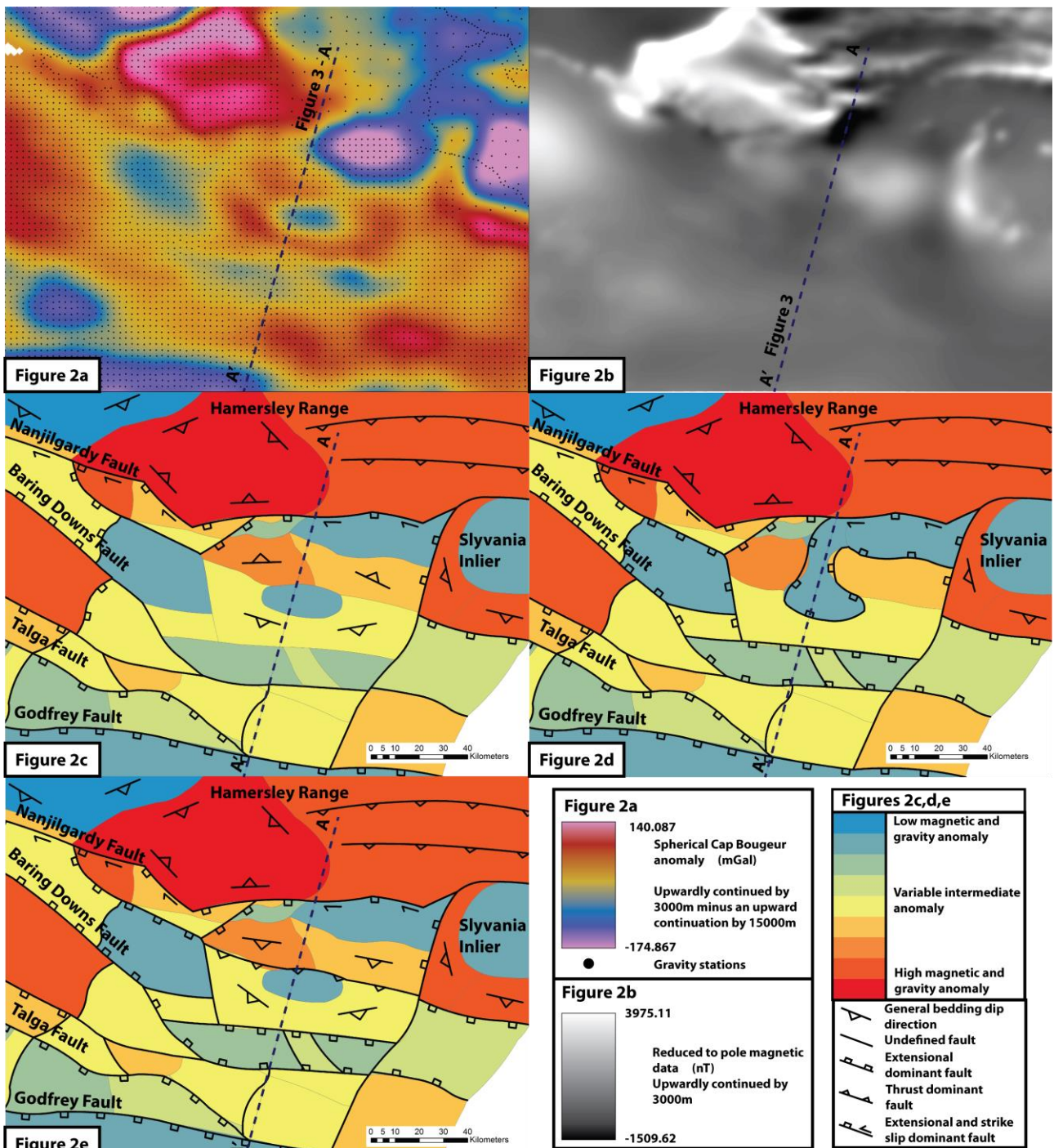


Figure 2a: A gridded bouguer gravity image with the gravity stations indicated. It is upwardly continued by 3000m with an 15,000m upwardly continued grid subtracted from the grid to create a residual image, **Figure 2b:** A reduced to pole magnetic grid that has been upwardly continued by 3000m, **Figure 2c, d, e:** A geological depth slice interpretation derived from the magnetic and gravity grids, the colours are derived from the intensity of the gravity and magnetic data and the overlying geological structural interpretation is derived mostly from the interpretation of the geophysical images. Surface geological features locations have been included for the Sylvania Inlier and Hamersley Range, **Figure 2c:** The interpretation is gravity lows in the central portion of the image is mainly derived from granites with a gravity high or gravity and magnetic highs related to intervening geology such as Hamersley-Fortescue Group or basement igneous-metamorphic rocks, **Figure 2d:** The interpretation is that all gravity lows are related to subbasins of the Ashburton Basin with gravity highs or gravity-magnetic highs being similar to those described in Figure 2c, **Figure 2e:** The interpretation is that some of the gravity lows are related to granitic bodies and others are related to Ashburton Basin sub-basins, a thrust interpreted in the centre of the image is considered early compared to the surrounding later extensional faults.

Forward modelling of the fit between the observed and calculated responses for gravity and magnetic datasets has been completed to test various geological interpretations as in Figure 2 as well as the upper crustal models (Figure 3). Petrophysical properties used for the Ashburton and Bresnahan Basins were derived from this project (Uren et al. 2016). The Hamersley and Fortescue Group magnetic properties for induced and remanent magnetisation were derived from Guo et al. (2011) and the density values from Guo (1999). Pilbara Craton granite magnetic susceptibility values were derived from Wellman, (1999) and Gascoyne Province granitoid magnetic susceptibility and density values were derived from Aitken et al. (2014). All models have surface geology features such as basin contacts and dolerites included. The Godfrey Fault in the south and Hamersley Range geology in the north are constant between all models lines, though petrophysical properties, and basin thicknesses are varied where deemed necessary. For all models, the fit to the magnetic data in the north over the Hamersley Range is poor. In order to balance the model lines properly requires the dense, magnetic and highly remanent rocks of the Hamersley Range to feature in it. However, a detailed model of the stratigraphy and its associated petrophysical properties would be required to fit the magnetic and gravity data properly, which is beyond the scope of this project.

The fit between the model lines observed and calculated responses for gravity and magnetic datasets has been problematic for all the models incorporating the underlying Hamersley-Fortescue Groups and Pilbara Craton granitoids in the region (Figure 3a, c and e). A model incorporating only Ashburton Basin extensional sub-basins to explain gravity lows, is unable to achieve a fit with both the magnetic and gravity datasets. A gravity low, magnetic high to the south of the possible extension of the Nanjilgardy Fault does not fit both datasets, while a shorter wavelength density feature in the centre of the line has a reasonable density fit, but the magnetic data does not fit the model. A higher magnetic response for the Hamersley-Fortescue Group in the southern portion of the model line is also likely not realistic. A model incorporating the Pilbara Craton granitoid basement highs and an Ashburton Basin sub-basin to explain gravity lows within the model line has a reasonable density fit, however, the magnetic response fit is poor in a number of locations (Figure 3c). The granitoid high, used to explain gravity low 2 doesn't allow for a reasonably thick and continuous magnetic body to feature within the models which is necessary to model the observed magnetic response. The gravity low 3, that coincides with a magnetic high is not modelled as a Pilbara Craton granitoid high as it illustrated a very poor fit to the magnetic data, instead an Ashburton Sub-Basin is modelled. To incorporate the magnetic high, a volcanic succession as part of the sub-basin fill is modelled, however, the model fit is still poor against the observed data. Figure 3e is similar to Figure 3c, apart from thrust features that are modelled to explain gravity low 2 in the central-northern section of the model line. The shorter wavelength gravity high featuring in the centre of the model line is not explained by a thrust anticline well. The magnetic fit is also poor for the central-northern section of the model line that is partly related to the discontinuous magnetic rocks of the Hamersley Group within the model. Hence, all models incorporating the Pilbara Craton granitoids and Hamersley-Fortescue Group rocks generally do not fit the observed and calculated geophysical responses completely.

The fit between the model lines observed and calculated responses for gravity and magnetic datasets is generally better with modelling the upper crust as the Bandee Seismic Province (Figures 3b, d and f). Within all model lines the Pilbara Craton is partly extended south beyond the Nanjilgardy Fault. This was done as extending the Bandee Seismic Province to the fault caused a very poor fit to the gravity data. The thin but magnetic rocks of the Hamersley Group and low density rocks of the Pilbara Craton granitoids fit the observed data better and, therefore, features in all models. In Figure 3b gravity low are modelled as solely related to Ashburton Sub-basins. Modelling gravity low 2 as a sub-basin creates a poor gravity fit, as in order to fit the data a 20 km thick sub-basin is needed to fit the anomaly. However, this would disrupt the magnetic fit as the Bandee Seismic Province would be modelled too thin. The sub-basin associated with gravity low 3 fits the gravity response reasonably, but does not fit the associated magnetic high, even with magnetic volcanic rocks included within the basin fill. Figure 3d models the gravity lows as mainly related to granitoids. The fit of the model lines to the gravity and magnetic dataset is good, and is the best result from all the models. The granitoids are modelled with a low density and reasonably high magnetic susceptibility, similar to values used to model the Durlacher Supersuite of the Gascoyne Province by Aitken et al. (2014). The only erroneous aspect of the model is that Bandee Seismic Province has increasing magnetic susceptibility towards the south of the line that might be unrealistic. Within the hangingwall of the possible Baring Downs Fault a thickening in the Ashburton Basin is modelled to provide a slightly better fit to the datasets, but is not entirely required by the model. Figure 3e has been modelled with a granitoid within a thrust block associated with gravity low 2. The magnetic fit is reasonable to poor around the granitoid which results in the model line being less likely than Figure 3d.

A comparison, in a plan view depth slice, of the structures observed from the preferred interpretation of the forward modelling exercise and those mapped at the surface from remotely sensed data is shown in Figure 4. Structures observed at surface were mapped by remotely sensed data and have been ground truth with field work. The preferred interpretation is that gravity lows represent, low density, moderately magnetic granitoids. The structures mapped in the two datasets are similar in a number of areas, for example, a faulted contact at the southern contact of the Hamersley Range. In this instance, the use of gravity and magnetic datasets to map structures at the surface as well as at depth gives rise to the similarity in the interpretation. In addition, a surface structure mapped using mainly Landsat 8 data that trends W-WNW maybe an extension of the Baring Downs fault. The surface fault somewhat coincides with structures mapped at depth using the gravity and magnetic datasets. However, distinct differences are observed in the structural orientation of the fault hosting the Prairie Downs Zn-Pb-Ag deposit. At surface, the fault is mapped with a NW trend, while at depth, a structure in the area trends NE. It is unknown whether this suggests the Prairie Downs Fault may not be as significant as other faults in the region. Many short, minor faults in the region show no relation between the structures mapped at the surface and those at depth.

A comparison between historic drilling, mineral and uranium anomalies and the depth slice and surface structural interpretation highlights a number of interesting observations for mineral exploration in the area (Figure 4). For instance, the main uranium anomaly, the Angelo River Uranium resource, appears to be related to a splay structure of the Nanjilgardy fault as well as potentially to a disparate NE trending regional structure that is only apparent in the gravity image. The Turee Creek Uranium anomaly is also related to a potential splay of the Nanjilgardy fault, although cross cutting structures are not apparent in the either datasets. The Atlantis, Saltwater Pool and Monster gold projects, the first two also having significant uranium anomalies associated with them, are apparent close to but

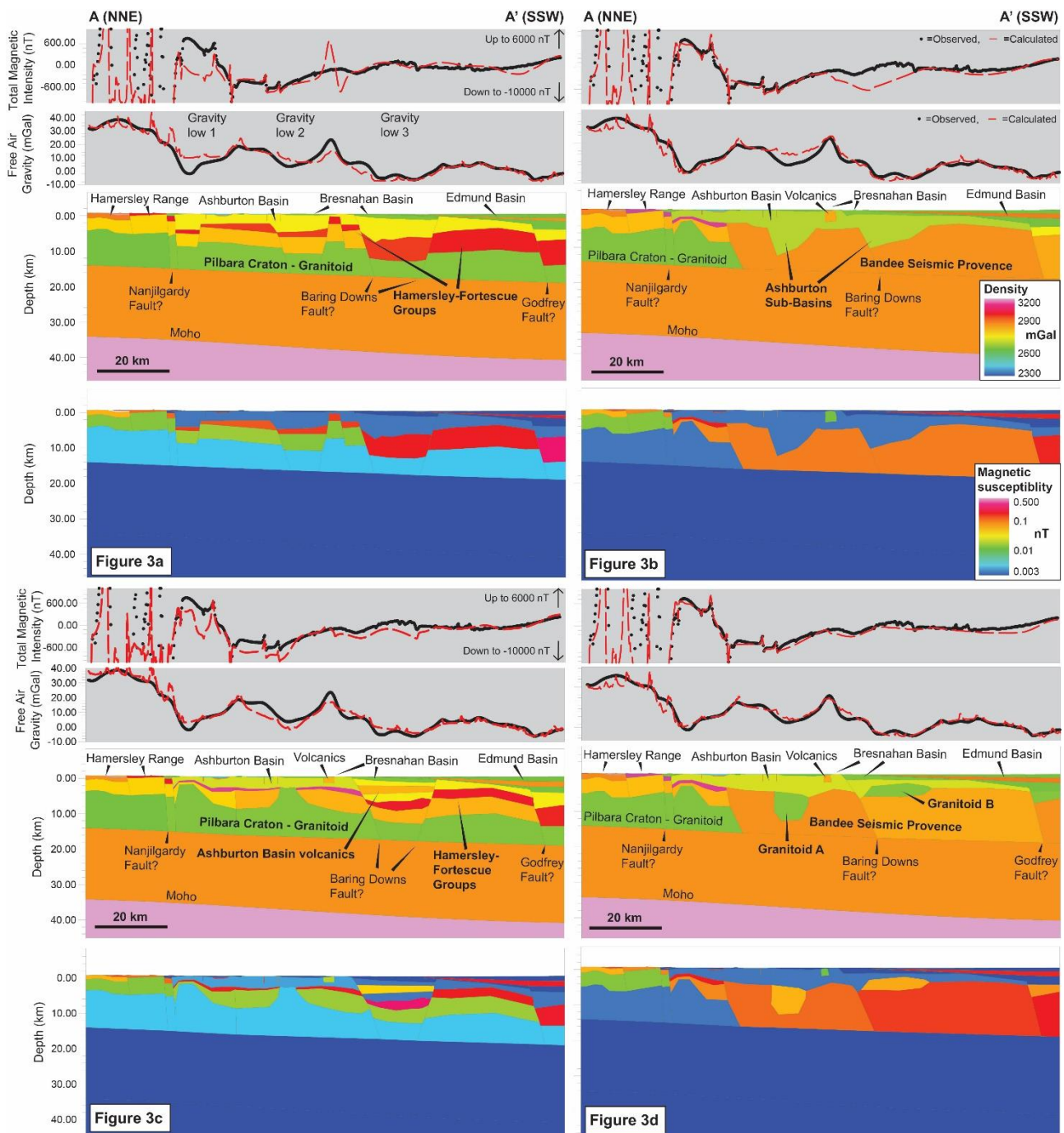


Figure 3: A series of alternative models for the upper crust beneath the NE Capricorn Orogen is tested by attempting to fit the observed and model calculated gravity and magnetic data within forward models in Geosoft's GM-SYS software. The line location is shown in Figure 2. The elevation model is from a 30m pixel Shuttle Radar Topography Mission (SRTM), (downloaded from www.geoscience.gov.au/geophysical-data-delivery, May 2016) across the area. The thickness of the upper crust beneath the Pilbara Craton is derived from Drummond et al. (1983) and the Moho depth change is derived from gridding values from Salmon et al. (2013), (downloaded from www.rses.anu.edu.au/seismology/AuSREM/Downloads/, March 2017). Detailed surface features derived from the geological map (Tyler et al. 1990, Thorne et al. 1991) are kept constant between the lines, with only minor variation in the depth and petrophysical character of the basins, in particular the remanent properties of the Hamersley Group. The total magnetic intensity axis for models is not representative of the data across the Hamersley Range with values up to 6000 nT and -10000 nT not shown. **Figures 3a, c and e** test the concept that the entire area consists of low density and low magnetic susceptibility Pilbara Craton granitoid, overlain by the high density and magnetic susceptibility Hamersley-Fortescue Group, while **Figures 3b, d and f** tests the concept that the highly magnetic and high density Banded Seismic Province exists in the area with a mafic petrophysical character. The various interpretations tested are derived from Figure 2 and focus on evaluating what gravity lows could be representing. A mainly extensional model is tested in **Figure 3a+b**, a granitoid model as either an intrusion or a batholith high in **Figure 3c+d** and **Figure 3e+f** tests the possibility that a thrust structure is present instead.

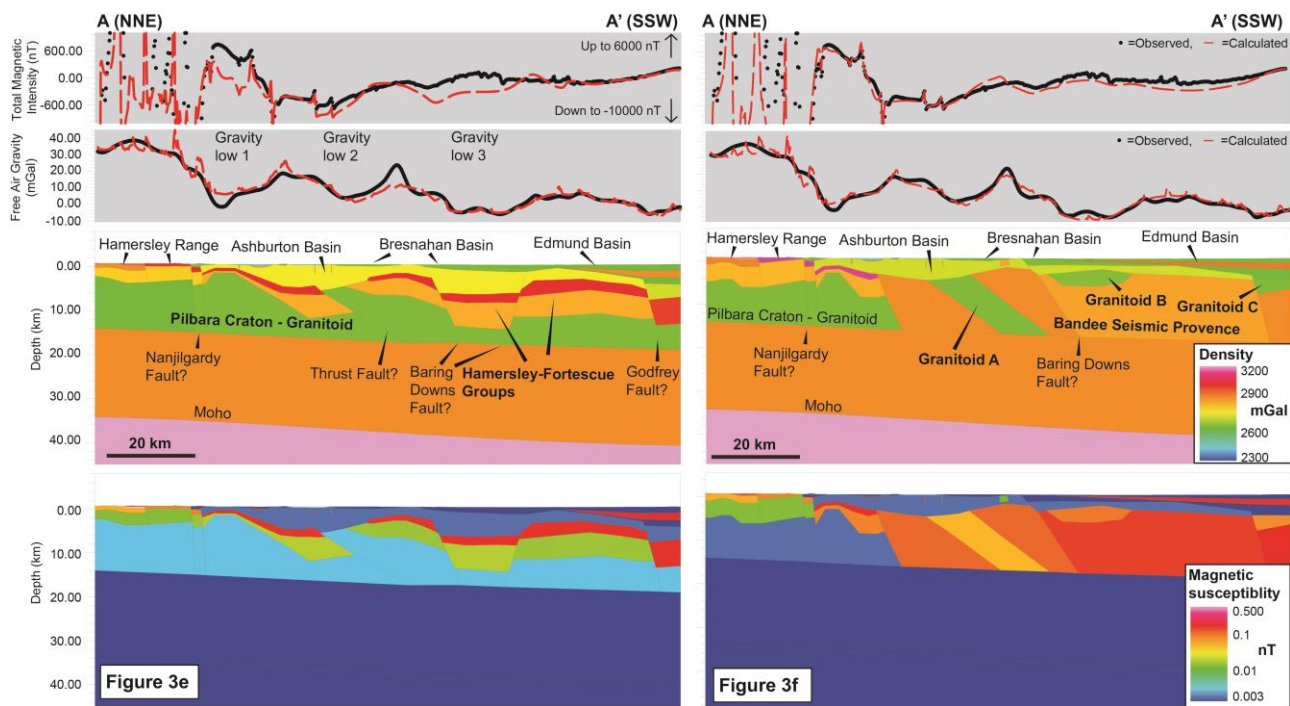


Figure 3: continued.

not directly associated with the structure interpreted to be an extension of the Baring Downs Fault. It is apparent that a number of the historic and more recent uranium exploration drill holes have not been drilled close to any significant structure mapped in the depth slice (Figure 4). In case of the partly extensional model for the south facing Baring Downs Fault the hangingwall side of the fault has virtually not been tested during exploration, apart from some shallow RAB drills holes associated with the Saltwater Pool project.

Observations made at surface in the footwall and hangingwall blocks of the interpreted extension of the Baring Downs Fault, could be of interest for uranium and/or gold-silver exploration in the area. Large sections of the footwall sediments are composed of carbonaceous mudstone (Figure 5a). The carbonaceous mudstone is part of the Wyloo Group, which likely extends into the hangingwall block beneath the unconformably overlying coarse grained sandstone of the Bresnahan Group (Figure 5b). The unconformity has been the focus for uranium exploration elsewhere in the area (Figure 4). The carbonaceous mudstone is a prospective geological unit for hosting uranium and possibly gold-silver deposits due to the redox contrast with the typically oxidised fluids (Jarieth et al. 2015). In addition, the presence of a major structure is an important mechanism for focusing the uranium and/or metal bearing fluids, the focusing being more likely within the hangingwall rather than the footwall block (Jarieth et al. 2015). The friable nature of the Bresnahan Group coarse grained sandstone (Figure 5b) indicates it is unlikely to have acted as aquitard for fluid flow down to and along the unconformity towards the fault, which is prospective for uranium exploration. Additionally, during mapping the occurrence of veins penetrating the Bresnahan Group is very rare. Therefore, the observation of common carbonate veins within the group close to the fault (Figure 5b), could indicate interaction of a chemically different fluid with the rock in the vicinity to the fault zone. The observations enhance the potential for exploration of uranium and/or gold-silver in the hangingwall block of the Baring Downs Fault, below the Wyloo-Bresnahan Group unconformity.

CONCLUSIONS

In order to constrain the location of crustal scale structures, a number of interpretations for a geological depth slice have been completed. A series of forward models indicated the most likely upper crustal geology underlying the area is the Bandee Seismic Province that was modelled with mafic petrophysical properties, rather than the Pilbara Craton granitoid overlain by Hamersley-Fortescue Groups. The Pilbara Craton is, however, interpreted to extend beneath a small area of the NE Capricorn Orogen basins in order for the observed and calculated geophysical responses to be fit. This is in agreement with the interpretation made by Wellman, (1999). Within the central study area, gravity lows are found to be best explained by granitoid intrusions that are reasonably magnetic, rather than sub-basin features with magnetic intervals. However, some component of a sub-basin is possible for the more southern of these gravity lows. Therefore, only one major crustal structure is interpreted to extend through the NE Capricorn Orogen which lies in the same vicinity as the Baring Downs Fault. The hangingwall block near the fault is interpreted to be prospective near untested for uranium and/or gold-silver exploration, beneath the Wyloo-Bresnahan Group unconformity.

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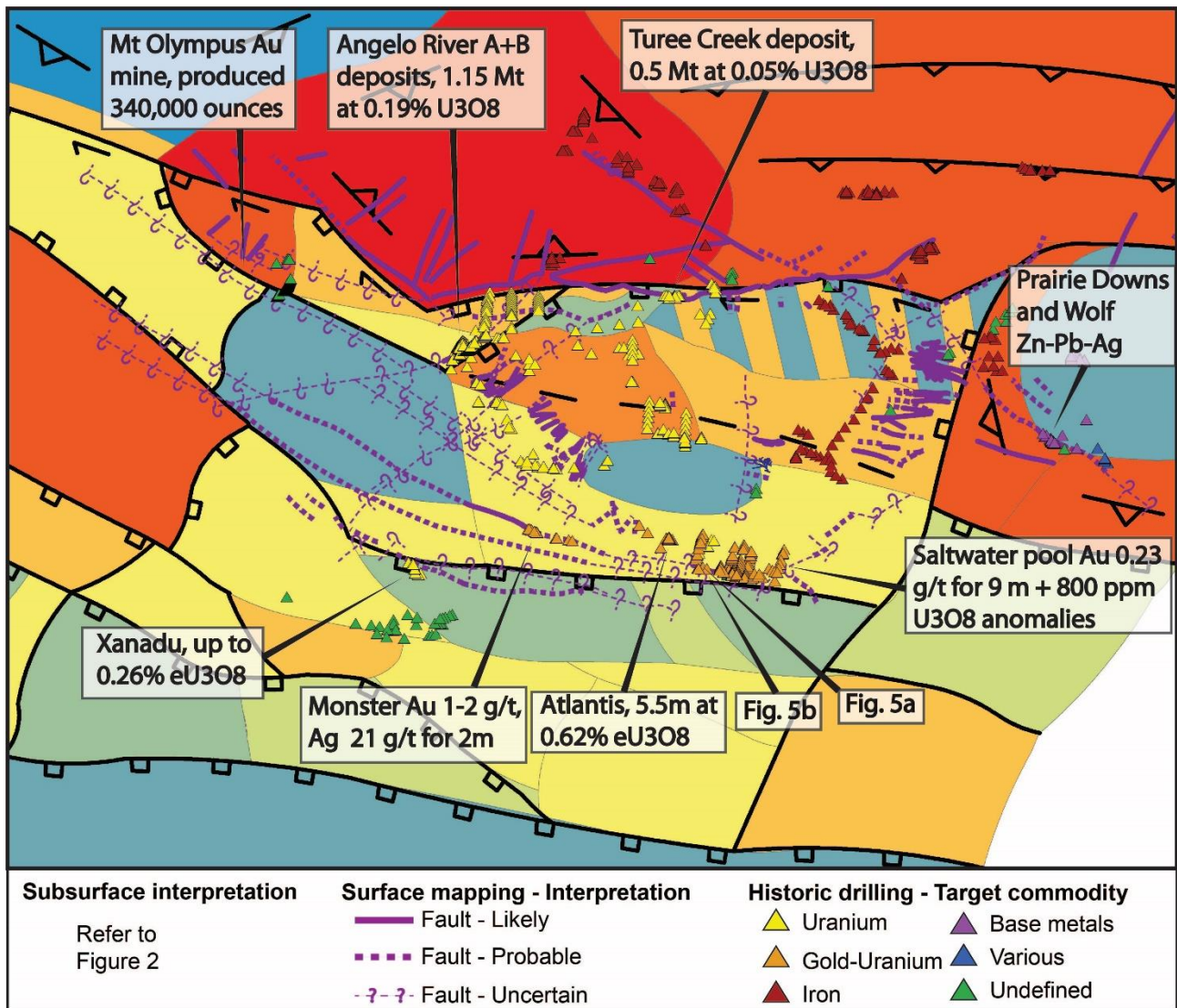


Figure 4: A structural interpretation is presented that has been constrained by forward modelling from Figure 3. Blue – light blue-green gravity lows in the centre of the image are interpreted to be as a result of granitoid intrusions, with the southern longitudinal feature interpreted to also have a sub-basin component. The structures from Figure 2 are compared to structures interpreted at surface, coloured in purple. Similarities and differences between the interpretations and, therefore, significance of crustal scale structures is discussed in the text. Also overlain are all the drillholes known in the area, coloured according to the main commodity/ies sought. The more significant mineral or uranium anomalies are indicated with the observed grade or weight percentage. Figure 5 observation locations are also indicated.

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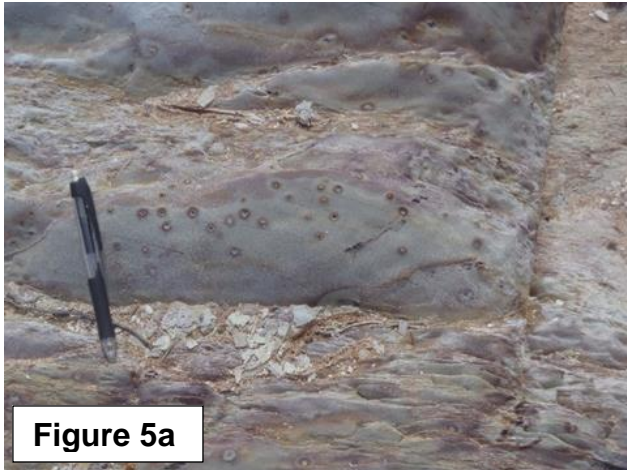


Figure 5a



Figure 5b

Figure 5a: a weathered Wyloo Group outcrop in the footwall of the southern fault zone, it is clay rich with common cubic pits that likely the original unweathered rock was a carbonaceous mudstone, otherwise known as a 'black shale', **Figure 5b:** the Bresnahan Group in the hangingwall of the southern fault zone; it is friable, with common carbonate veins and coloured white due to the removal of k-feldspar to most likely clays.

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