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Basement and Crustal Controls on Hydrocarbons Maturation on the Exmouth Plateau, North West Australian Margin

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INTRODUCTION

Advanced burial and thermal geohistory modelling carried out on the Exmouth Plateau is an extension of similar work undertaken earlier in the Bremer Sub-basin (Goncharov et al., 2006). This work is a further step in developing new generation of tectonically constrained geohistory, paleotemperature, and HC maturation models. As in the Bremer Sub-basin, the Exmouth Plateau modelling was carried out without relying on default values (such as heat flow or geothermal gradient) commonly used in basin modelling. This modelling was conducted using Fobos Pro v3.2 finite element 1-D basin modelling software developed by Aceca Ltd (www.aceca.co.uk).

The tectonic elements of the Exmouth Plateau (Fig. 1) developed as a result of several phases of rift tectonics initiated in Palaeozoic and continuing until the Late Jurassic, preceding the final continental separation of Greater India from Australia. The Carnarvon Basin is believed to contain up to 18 km of Palaeozoic to Recent sedimentary infill (Figs. 2,3 and 4).

DATA INTEGRATION

All available OBS and sonobuoy velocity models were integrated to provide estimate of crustal thickness in the area (Fig. 5), and to enable accurate depth conversion of reflection seismic data. Thicknesses of Permian and Triassic sections were also calculated (Figs. 3 and 4). Depth conversion utilising OBS-calibrated stacking velocities was implemented to minimize over-estimation of depth to horizons (Goncharov, 2004). Estimation of depth to horizons and interval velocities derived from the interpretation of the OBS data suggest (Figs. 6 and 7) that IKODA interpretation of reflection seismic data may have overestimated Triassic thickness in the area. Earlier 'thin Triassic' interpretations of reflection data (Stagg and Colwell, 1994, Fig. 8) and Longley et al. (2002) appear to be more consistent with OBS data interpretation of Fomin et al., 2000. Estimates of total crustal thickness (only 30-34 km) prior to rifting were derived from onshore refraction work in the Pilbara Craton (Fig. 5). Crustal thickness and composition underneath major depocentres of the Exmouth Plateau were constrained by results of OBS studies in the area indicating that total crustal thickness (excluding up to 18 km of sediments) is reduced to just ~4 km. There are some indications of possible underplating in the lower crust of the Exmouth Plateau, particularly in the western part of the study area where lower crustal velocities exceed 7.1 km/s in thick and laterally continuous layer (Fig. 9).

HEAT PRODUCTION

Measurements of radioactive elements contents in rock samples taken from outcrops of Pilbara Craton (see Fig. 5 for the location of samples) allowed estimation of heat production in the Exmouth basement and crust below it. Original data for heat production calculations were sourced from Geoscience Australia's database OZCHEM. Anomalous values in some groupings are due to a few highly enriched rocks in the grouping, particularly for U or Th contents. These anomalies were excluded from further analysis due to their limited spatial extent, and due to the close spatial association of these samples with rock samples of more 'normal' heat production. An interesting outcome of this analysis is that Exmouth basement appears to be colder and less diverse in heat production compared to Bremer basement where 0.5 – 4.0 μw/m3 range was used for sensitivity tests (Goncharov et al., 2006).

GEOHISTORY MODEL DATA AND METHODOLOGY

Initial geohistory models for Jupiter 1 and Brigadier 1 were created using available stratigraphic interpretations with sub-TD interpretation based on Geoscience Australia/IKODA (2002) regional seismic interpretation (Fig. 10). These are the J-0 and B-0 models presented below, involving thick Triassic.

On the temperature depth calibration models data shown include undifferentiated log derived bottom hole temperatures and Horner plot estimates from the GA database RESFACS. This data is considered variable, and in the study the only requirement was that the predicted model be at or higher than all temperature data at all depths. Maturity depth data used for this study is from the Geoscience Australia's database ORGCHEM, with analyst indicated where possible, except the VIRF Newman (2006, pers.comm.). Lack of reliability in conventional vitrinite reflectance is well known and is usually due to misidentification of suppressed vitrinite as normal (e.g., Kaiko, 2002). Newman et al (2000) discusses the VIRF methodology which uses fluorescence to determine true vitrinite from suppressed. VIRF data was only available for Jupiter 1 and thus the Brigadier 1 thermal interpretation has followed that of Jupiter 1. Mantle lithosphere thickness (depth to 1300ºC) was set at 100km, giving a total lithosphere thickness of 132 km, consistent with results from Simons and van der Hilst (2002) for the western Pilbara craton (Fig. 11).

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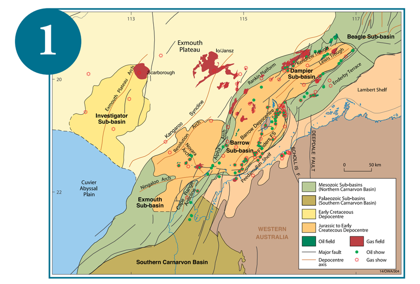
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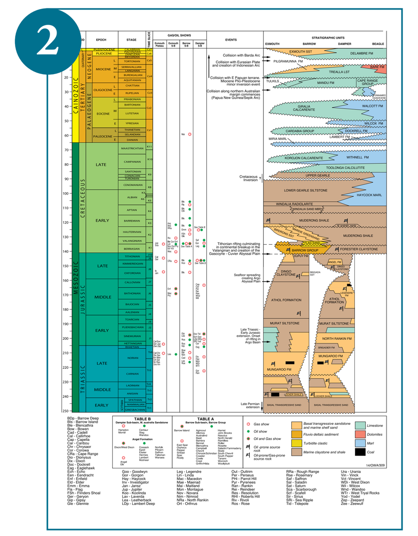
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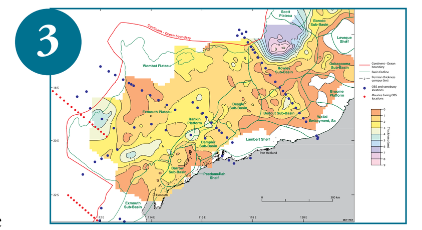
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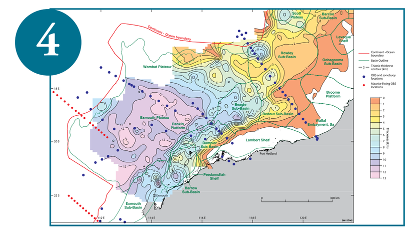
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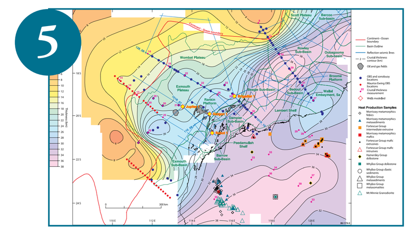
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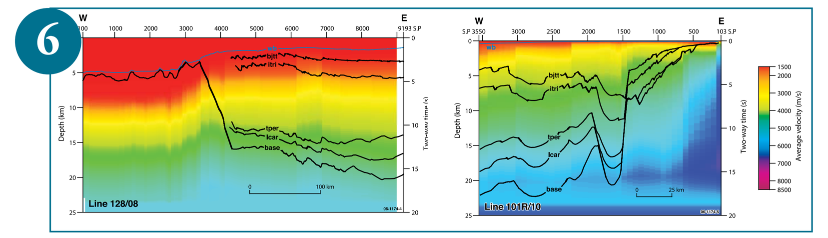
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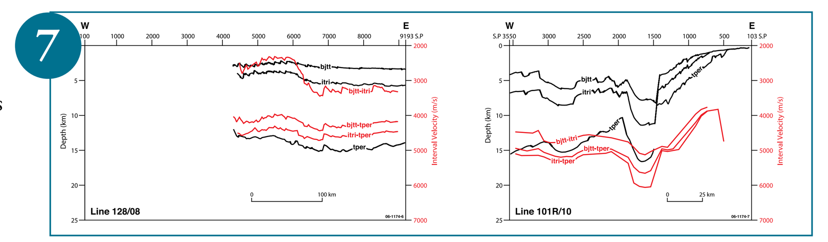
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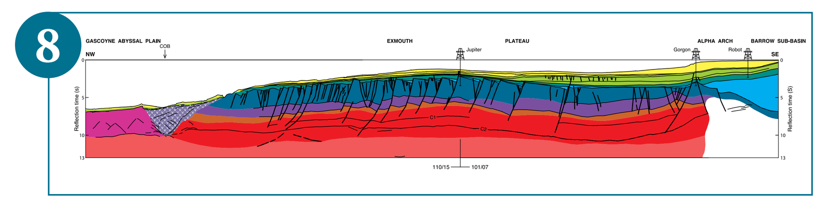
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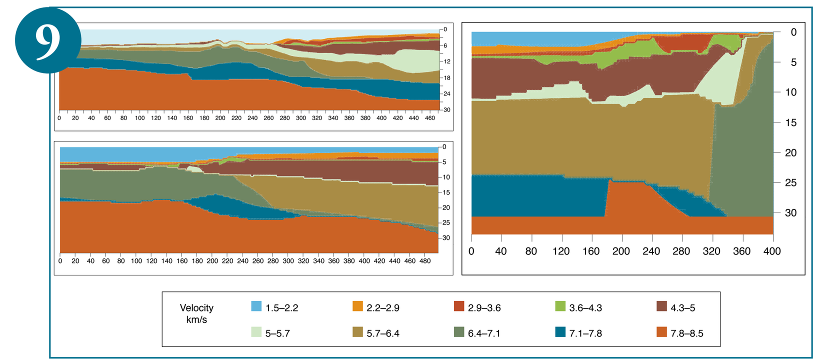
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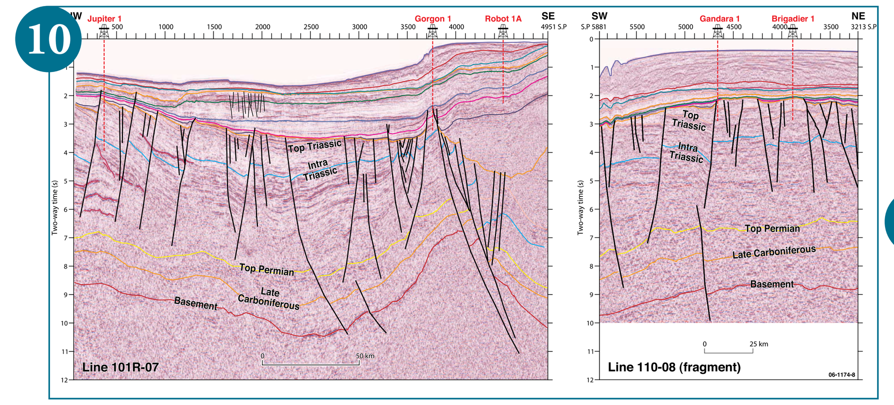

The starting model for timing of crustal stretching followed that of Karner and Driscoll (1999). The Fobos Pro methodology involves altering stretching to match total subsidence throughout the model's geologic development. The palaeo water depth model has been treated as relatively constrained from benthonic foram studies in the well completion reports. Fobos Pro calculates the change in temperature due to change in thickness caused by the modeled stretching and also the change in density during thermal cooldown after stretching. An important corollary of the method is that present water depth is itself a calibration parameter, as is final crustal thickness, which is constrained by accurate velocity models from OBS interpretations discussed above. Hence a feature of the Jupiter, but not the Brigadier, models is a depth dependent phase of stretching at breakup in the Valanginian that is required to produce the present bathymetry of the Exmouth Plateau at Jupiter 1. This stretching occurs only in the lower crust and mantle and is thought to be common in marginal plateaus worldwide (Kuznir et. al., 2005).

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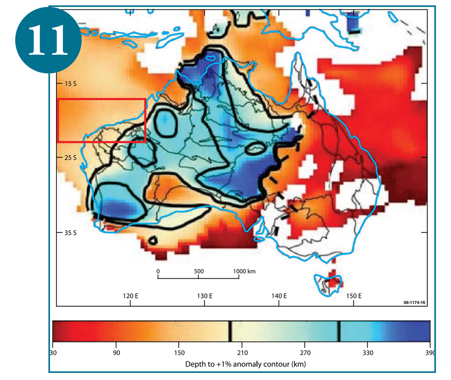

SENSITIVITY TO TRIASSIC THICKNESS

First tests of the starting model indicated that 'thick Triassic' seismic interpretation is hard to reconcile with subsidence predicted by the model, particularly in wells on the shelf (Gorgon 1, Robot 1). Extreme stretching rates would be required to match subsidence observed in 'thick Triassic' scenario. So, testing sensitivity of the results to Triassic thickness has become the first priority. Further test models were created by reducing depth to base Triassic in 1-2 km increments, and moving deeper horizons (including basement) up accordingly. Thus, J-1, J-2, B-2, then J-4, B-4 models, etc., were generated. Stretching rates were then adjusted in each model to match total basement subsidence. As a result, total stretching rate is less for the thinner Triassic models (Table 1).

Fig. 18. Densities and heat generation attributed to various basement models. Examples of approximate equivalent rock types are also shown, covering a spectrum of potential basement lithologies.

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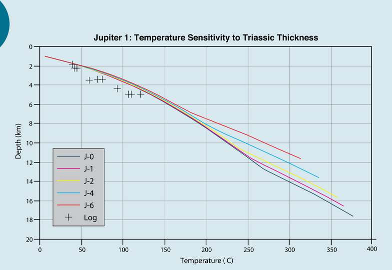
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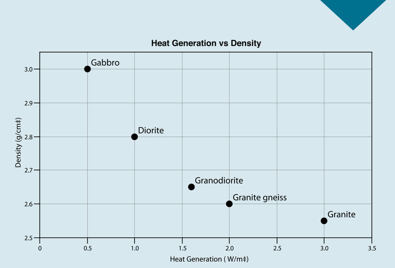
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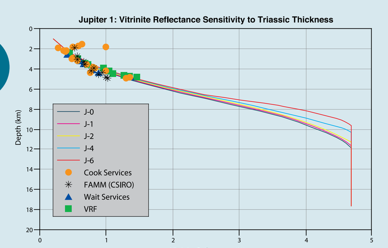
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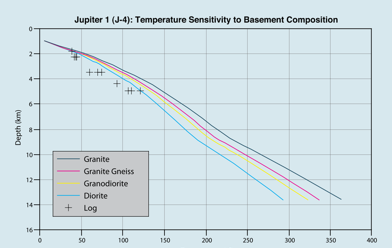
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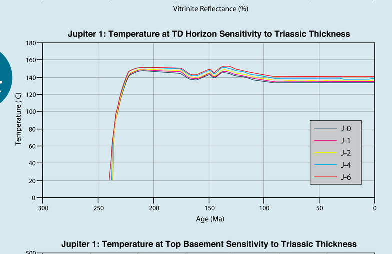
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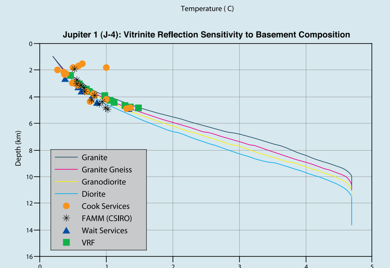
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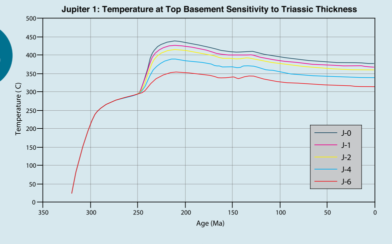
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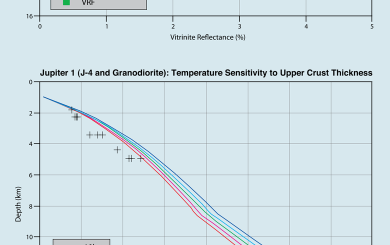
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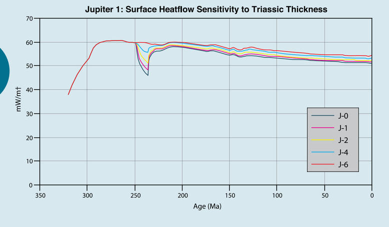
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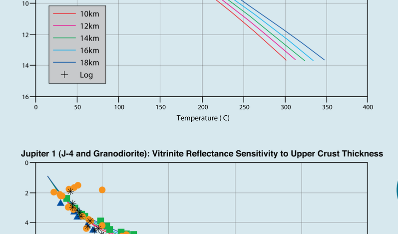
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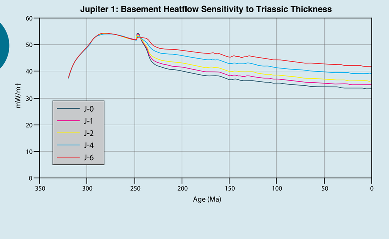

TABLE 1. STRETCHING IN TRIASSIC THICKNESS SENSITIVITY MODELS

Model	Carboniferous			Early Triassic			Triassic-Jurassic			Mid. Jurassic			Jurassic-Cretaceous		
	UC	LC	ML	UC	LC	ML	UC	LC	ML	UC	LC	ML	UC	LC	ML
J-0	1.8	1.8	1.8	3	3	1.4	1	1	1	1	1	1	1	2	1
J-1	1.8	1.8	1.8	2.5	2.5	1.4	1	1	1	1	1	1	1	2	1
J-2	1.8	1.8	1.8	2.1	2.1	1.4	1	1	1	1	1	1	1	2	1
J-4	1.8	1.8	1.8	1.65	1.65	1.4	1	1	1	1	1	1	1	1.85	1
J-6	1.8	1.8	1.8	1.35	1.35	1.3	1	1	1	1	1	1	1	1.65	1
B-0	1.85	1.85	1.85	3.3	3.3	1.4	1.15	1.15	1.15	1.35	1.35	1.35	1	1	1
B-2	1.85	1.85	1.85	2.3	2.3	1.6	1.2	1.2	1.2	1.2	1.2	1.2	1	1	1
B-4	1.85	1.85	1.85	1.9	1.9	1.5	1	1	1	1.2	1.2	1.2	1	1	1
B-6	1.85	1.85	1.85	1.5	1.5	1.3	1.05	1.05	1.05	1.05	1.05	1.05	1	1	1

Figs 12 and 13 show that at the well depth, above TD, present day temperature and maturity are not sensitive to major changes in Triassic thickness. However, there are significant changes below TD. For example, the Locker Shale at the bottom of Triassic sequence at present may generate oil in the 'thin Triassic' scenario (J-6), but is in the dry gas zone in the thick Triassic' (J-0) scenario. Similarly significant variation will apply to earlier stages of subsidence history and thus time of oil generation and expulsion in the thick Triassic models. Fig. 14 shows that palaeo temperature at the TD in each well is not sensitive to major changes in Triassic thickness. However, from Fig. 15, palaeo temperature at basement depth is sensitive to the change. Note that the thickest Triassic models produce the higher palaeo temperatures at basement due to higher stretching rate and greater burial depth. The reason that TD level palaeo temperature are not sensitive to Triassic thickness, while basement palaeo temperatures are, is clear from Figs. 16 and 17. Basement heat flow is sensitive to depth to basement, because of the variation in stretching required. However, sediment radioactivity above basement compensates for the reduced stretching so there is much less variation in surface heat flow and that at TD.

J-0 present day basement temperature is almost 70ºC higher than J-6. However, at TD temperature is actually lower for J-0 compared to J-6 by ~10ºC. So, hotter basement at greater depth scenario transfigures into colder TD. This leads to higher temperatures at TD in the shallow basement scenario. However, the simple proximity of heat sources in the basement to TD is not the explanation of this phenomenon, which results from a more complex combination of reasons. The interplay between heat production above and below basement emerges as the main driver of model temperature prediction, particularly when heat generation in basement is low and sediments above it are thick.

SENSITIVITY TO CRUSTAL COMPOSITION

Using a mid range model (J-4 and B-4), sensitivity of temperature and maturity to upper crust composition was analyzed. The J-4 and B-4 models were selected because they gave the best fit to the VIRF data in Jupiter 1. Models of thicker Triassic require greater stretching (above 2.5). According to McKenzie (1978) this should lead to significant dyke intrusion and volcanism. Although some sill intrusions are present, they are limited and we prefer models that require lesser stretching. Heat generation and density vary widely in basement rocks, but hotter rocks are generally lighter and cooler rocks are denser. Fig. 18 shows the modelled trend of density/heat generation variation with some examples of approximate equivalent rock types. Like in the previous tests, stretching was varied to match total basement subsidence for each change in upper crust density.

Although shown in Fig. 18, a basic or "gabbroic" composition upper crust was not modeled as it was not possible to stretch the model enough to produce the observed thickness. This is because the density of the crust approaches that of the mantle (3.3 g/cm3) and lighter sediment finds it increasingly difficult to displace the heavier basement during stretching. The high rate of Carboniferous stretching required for the basic crustal model means that the thickness at the time of Triassic stretching is less than 18 km. McKenzie (1978) noted that for normal density crust and lithosphere (2.8 and 3.33 g/cm3 respectively), and lithosphere of 125 km thickness, any amount of stretching of crust thinner than 18 km will produce uplift. Dewey (1982) noted that a key parameter in determining ease of subsidence (or lack of relative uplift) was the ratio of crust to lithosphere thickness. However, from this study another important parameter controlling subsidence is the relative density of crust (including sediments) to mantle lithosphere. Sensitivity to crustal composition is illustrated in Figs. 19 and 20.

SENSITIVITY TO CRUSTAL THICKNESS

The J-4/B-4/granodiorite models were chosen to estimate sensitivity of temperature and maturation predictions to variation in crustal thickness, again because of the best fit to the VIRF data in Jupiter-1. Upper crust thickness was varied in 2 km increments. Stretching was again varied to match total geohistory subsidence. Sensitivity to crustal thickness is illustrated in Figs. 21 and 22. Predicted crustal thicknesses for the various models are shown in Table 2. The final preferred models, selected on the basis of best fit to VIRF data and to OBS derived crustal thickness, are the models with 16 km thick upper crust at the onset of rifting (Fig. 23). The predicted tectonic, thermal and maturity results for Jupiter-1 model are shown in Figs. 24-28.

TABLE 2. PREDICTED CRUSTAL THICKNESSES FOR VARIOUS MODELS.

Model	Initial Upper Crust Thickness (km)	Predicted Final Crust Thickness (depth to basement less waterdepth) (km)
J-4/granodiorite	10	16.59
	12	18.49
	14	20.29
	16	22.19
	18	24.24
OBS derived thickness		22
B-4/granodiorite	10	18.78
	12	20.23
	14	23.18
	16	24.78
	18	26.88
OBS derived thickness		26

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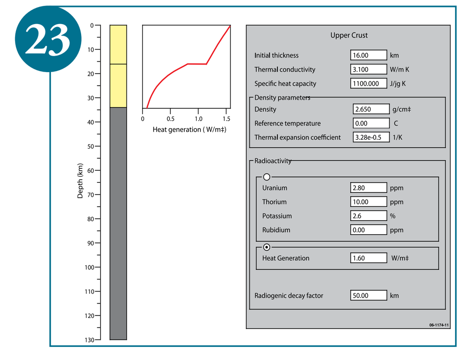
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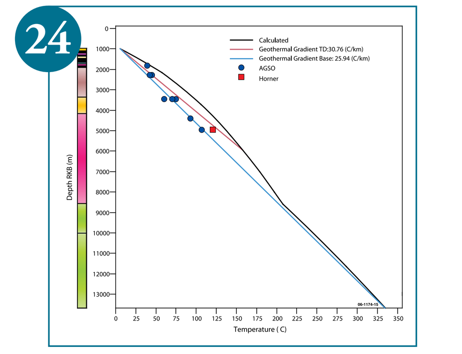
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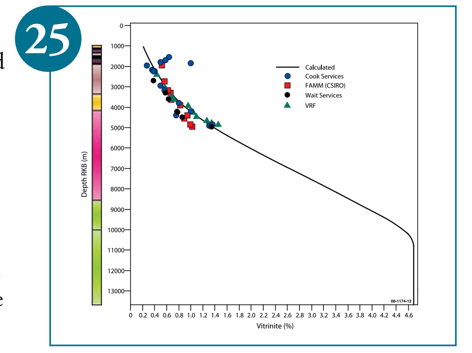
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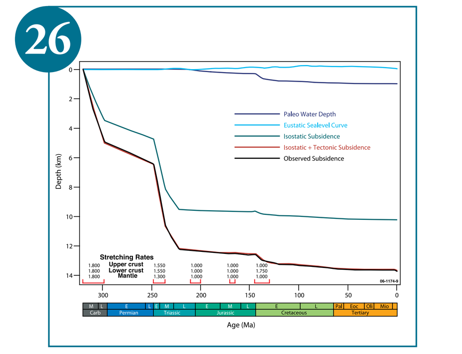
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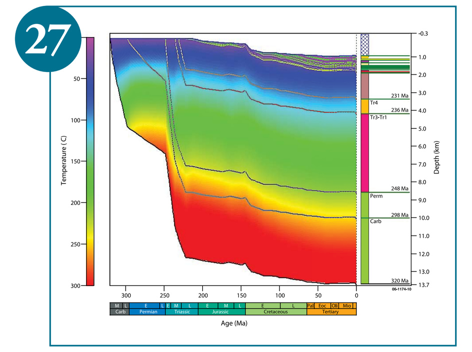
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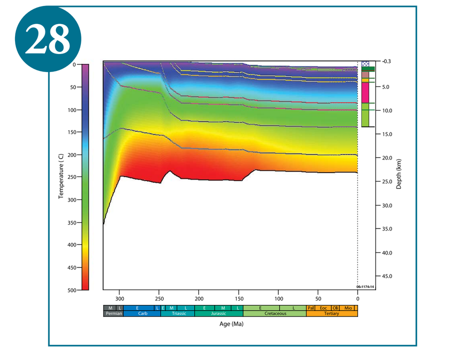

FUTURE DIRECTIONS

Results presented above allow accounting for geohistory/subsidence/HC maturation effects related to: heat production in sediments as they are being added in the process of basin formation, blanketing effect of sediments, heat production in crust of varying composition, whole lithosphere parameters of radiogenic heat and thermal conductivity through time, isostatic subsidence, tectonic subsidence related to stretching of the crust during and after rift formation. However, one significant component of subsidence and related thermal effects possibly is not accounted for in our methodology yet: that is so-called 'anomalous subsidence' related to mantle induced dynamic topography. It is very likely that the dynamic topography component is also present in the subsidence history of basins forming on continental margins. In that case exact matching of subsidence that we targeted (and reasonably well achieved − see above) in our models is methodologically not quite correct. However, due to the overprinting of vertical crustal motions due to rifting/block faulting and thermal subsidence, only qualitative statements about the relative vertical motions can be made up to this date. Comparison of dynamic topography curves for Jupiter well and Pilbara craton (Fig. 29) suggests that the time interval ~45 to 60 Ma is the only one where differential vertical movements between two locations due to mantle convection processes are noticeable. If our estimates are correct, then subsidence in our models should be 'over-done' for this time interval. In other words, our model should probably include some additional crustal stretching during 45 to 60 Ma to produce up to 150 m of excessive subsidence that is counter-fitted by Jupiter uplift relative to Pilbara during this time. We do not expect Brigadier/Pilbara residual dynamic topography to demonstrate substantially different trend. However, we are seeing some diversion between modeled and observed subsidence in Brigadier well, but not in Jupiter 1; causes of this effect require further research. Proper integration of dynamic topography in our methodology will, as we hope, take us one important step further towards development of holistic approach to geohistory and HC maturation modeling.

CONCLUSIONS

- Thick Triassic section of up to 13 km thick in the study area is unlikely.
- Seismic interpretation of deep basins stratigraphy and structure should be carried out interactively with quantitative analysis of possible basin formation mechanisms.
- Some very significant changes in variables tested are not differentiable by observable parameters in wells above TD, but there are significant changes below TD; deeper wells (?), new and better geophysical data are needed to better constrain subsidence and maturation models for Triassic and deeper section.
- Enhanced maturity studies, such as VIRF, are necessary to remove analyst bias in vitrinite reflectance determination.
- Basement heat flow is sensitive to depth to basement, because of the variation in stretching required. However, sediment radioactivity above basement compensates for the reduced stretching so there is much less variation in surface heat flow and that at TD.
- Interplay between heat production above and below basement emerges as the main driver of model temperature prediction, particularly when heat generation in basement is low and sediments above it are thick.
- A key parameter determining ease of subsidence (or lack of relative uplift) is the relative density of crust (including sediments) to mantle lithosphere, alongside with earlier reported ratio of crust to lithosphere thickness.
- There are some indications of possible underplating in the lower crust of the Exmouth Plateau, particularly in the western part of the study area.
- Effect of underplating on subsidence and hydrocarbon maturation requires further research.

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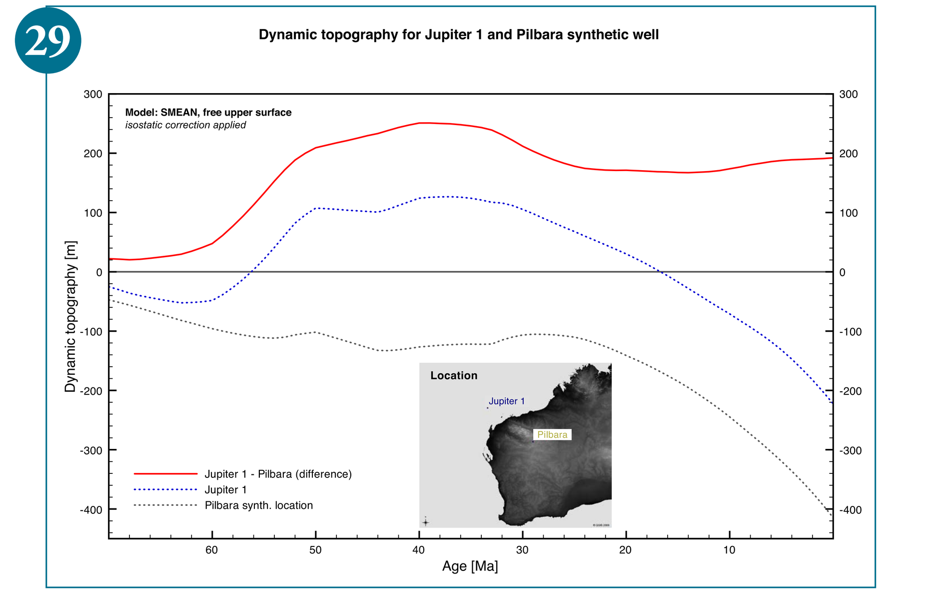

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