The Structural Evolution of the North West Shelf: a Thermomechanical Modeling Approach Using Stratified Lithospheric Rheologies and Surface Processes

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SUMMARY

The processes involved in the structural and stratigraphic evolution of the North West Shelf (NWS), one of the most productive and prospective hydrocarbon provinces in Australia, remain controversial. The complex structural characteristics of the NWS include large-scale extensional detachments, difference between amounts of crustal and lithospheric extension and prolonged episodes of thermal sagging after rifting episodes. It has been proposed that– the succession of different extensional style mechanisms (Cambrian detachment faulting, broadly distributed Permo-Carboniferous extension and Late Triassic to Early Cretaceous localised rift development) are best described in terms of variation in deformation response of a lithosphere that has strengthened from one extensional episode to the next. However, previous models invoking large-scale detachments fail to explain changes in extensional styles and over-estimate the structural importance of relatively local detachments (e.g. Scholl Island Fault). Here, we hypothesize that an initially weak lithosphere would distribute deformation by ductile flow within the lower crust and that the interaction between crustal flow, thermal-evolution and sediment loading/unloading could explain some of the structural complexities recorded by the NWS. To test this hypothesis we run a series of fully coupled 3D thermo-mechanical numerical experiments that include realistic thermal and mechanical properties, as well as surface processes (erosion, sediments transport and sedimentation). This modeling approach aims to provide insights into the thermal and structural history of the NWS, and a better understanding of the complex interactions between tectonics and surface processes on the margin scale.

Key words: North West Shelf, Numerical Modeling, Extension, Thermal Sagging, basin evolution

INTRODUCTION

The North West Shelf (NWS) of Australia (Figure 1) comprises a series of marginal basins (North Carnarvon, Offshore Canning, Browse and Boneparte basins) developed as a result of multiple phases of extension during the dismantlement of eastern Gondwana (Veevers, 1988; Gartrell 2000). As one of the most productive hydrocarbon provinces in Australia, the North Carnarvon Basin has been the focus of many seismic and areomagnetic surveys which have provided important information on the general structure of the NWS (Geoscience Australia).

The North Carnavon basin (Figure 1), and the NWS in general, is characterized by a dominant northeast-southwest trending fabric established during a Late Carboniferous to Early-Permian extension phase that resulted in the formation of the broader Westralian Superbasin system (Yeates et al. 1987). The basin width is believed to have reached over 500 km-wide in some areas (Kopsen & McGann 1985). Deep-seismic data reveals significant pre-Jurassic subsidence and lower crustal thinning in the thickest part of the basin but minimal evidence for upper-crustal extension (Figure 2). It also clearly shows continuous flat-lying reflectors underlying most of the Exmouth Plateau at mid-crustal levels which has been interpreted as a mylonitised boundary (Mutter et al. 1989). From Late Triassic through Early Cretaceous, extension resulted in two break-up events with the separation of Argoland (ca 155 Ma) and Greater India (ca 131 Ma). Localized extension during the Mesozoic also generated the deep Exmouth, Dampier and Barrow sub-basins with clear high-angle normal faults overprinting the older Permo-Carboniferous superbasin.

The major depocentres of the Exmouth, Barrow, Dampier and Beagle Sub-basins follow the northeast-southwest trend. Their sedimentary sequences are approximately 10-15 km thick, with sediment ages ranging from Palaeozoic to Caenozoic age, but are predominantly of Mesozoic age. The sequences also include a relatively thick (about 5 km) Triassic post-rift sequence which suggests prolonged episodes of thermal sagging after rifting.

The extensive width of the shelf and the discrepancies between amounts of upper crustal and lower lithosphere extension have led to the interpretation of large-scale extensional detachment mechanisms. Detachments can explain some structural aspects of the basins, they do not explain the spatial and temporal variations in extensional style. Furthermore, they do not provide a mechanism to explain the evolution from distributed extension (Carboniferous to Early Permian) to localized extension (Mesozoic).

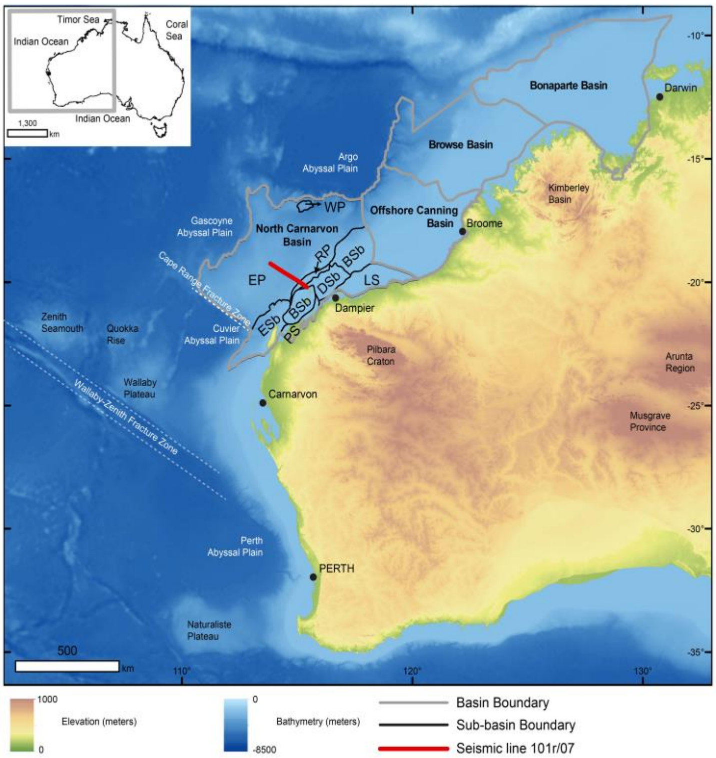

Figure 1: Map showing the location of the North-West Shelf of Australia as well as topography, bathymetry with major bathymetric elements and main basin subdivisions. Elevation data are based on the 2009 Australian Bathymetry and Topography grid (Geoscience Australia). EP=Exmouth Plateau, WP=Wombat Plateau, RP=Rankin Platform, BSb= Beagle Sub-basin, DSb=Dampier Sub-basin, BSb=Barrow Sub-basin, LS= Lambert Shelf, PS=Peedamullah Shelf. Rectangle on inset shows the location of the area within Australia.

It has been proposed that the succession of different extensional styles mechanisms has resulted from the rheological evolution of an extending and cooling lithosphere (Gartrell, 2000). The different phases of extension could thus be best described in terms of variation in deformation response of a lithosphere that has strengthened from one extensional episode to the next (Gartrell, 2000; Figure 3). The validity and the consequences of such a model remains to be tested and quantified.

Thermo-mechanical numerical models and analogue experiments with a layered lithosphere have emphasized the role played by the composition and thermal state of the lithosphere on the style of extension. The variation in rheological properties and the coupling between lithospheric layers promote depth-dependent extension with the potential for complex rift evolution over space and time. Local changes in the stress field due to loading / unloading of the lithosphere can perturb the syn- and post-rift stability of the margins.

Here, we hypothesize that an initially weak lithosphere would distribute deformation by ductile flow within the lower crust and that the interaction between crustal flow, thermal-evolution and sediment loading/unloading could explain some of the structural complexities recorded by the NWS. To test this hypothesis we first run a series of numerical experiments to study the relative importance of mechanical (amount of total and upper vs lower extension) and thermal effects on the rheological behaviour of the lithosphere. We then use those results to constrain a series of fully coupled 3D thermo-mechanical numerical experiments that include realistic thermal and mechanical properties, as well as surface processes (erosion, sediments transport and sedimentation).

We investigate how erosion of the margins and sedimentation within the basins integrate with the thermo-mechanical processes involved in the structural and stratigraphic evolution of the NWS. Our modeling approach aims to provide insights into the thermal and structural history of the NWS, and a better understanding of the complex interactions between tectonics and surface processes at the scale of the margin.

METHOD AND PRELIMINARY RESULTS

Thermo-Mechanical Modeling

We use Underworld2, an open-source particle-in-cell finite element code. The code provides a python-friendly front end to all functionality of the code running in a parrallel High Performance Computing (HPC) environment. This allows for the setup of complex geodynamic problems, analysis at runtime and facilitate coupling with other codes.

We set up a series of 2D and 3D thermo-mechanical models which include multiple non-linear temperature and strain dependent visco-plastic rheologies. The thermo-mechanical models comprise the upper 120km of the continental lithosphere and the upper mantle over a 360km wide region (360km x 360km in 3D). The crust initial thickness is between 30-50km, has a uniform density of 2700kg/m^3 and a wet quartz rheology. The mantle lithosphere has a uniform density of 3300kg/m^3 and a wet Olivine rheology. All models have uniform resolution across their domain (500m to 1km) for a total of 360-720 x 120-240 elements. The temperature field is initialized to a steady state, based on rock properties and prescribed boundary conditions (20^{o}C at the surface, 550^{o}C at the moho and 1350^{o}C at the base of the models, lateral boundaries are insulated). Plastic behaviour is simulated using a Mohr-Coulomb criteria and strain weakening is implemented through a linear decrease of both the internal angle of friction and cohesion of the materials with increasing accumulated strain. All models are run over periods of 10's Myr.

Lithospheric extension at rate *V* is driven by side boundary conditions where horizontal velocities, *V/2* are applied on each vertical side. All models have variable extension rates (0. to 3cm/year). The base of the model is allowed to move freely in the horizontal directions. A traction force is applied to compensate for the initial lithostatic pressure at the base of the model in order to simulate an isostatic compensation depth.

Two kinds of model setups are investigated. The first kind involves a horizontally layered lithosphere which is extended and allowed to thermally relax. Extension results in depth-dependent extension with progressive necking of the mantle lithosphere and development of brittle faults in the upper-crust. The amount of thinning at the rift axis depends on the rheology of the layers and the extension rate applied to the lithosphere. Extension is stopped at some time *t* and the lithosphere is simply allowed to cool down. Those models are used to investigate the effect of the Carboniferous to Early-Permian extension phase and the subsequent thermal sagging phase that accompanied the accumulation of the Triassic post-rift sequence. Depending on the rheology, the deformation is accompanied by lower-crust flow which progressively affects the integrated strength of the lithosphere and the style of deformation. The second kind of model assumes an initial geometry by defining the initial depth of the 550ºC and 1350ºC isotherms that respectively define the Moho-depth and the base of the lithosphere. The models are first allowed to isostatically equilibrate followed by cooling in order to trigger thermal subsidence of the crust and sagging of the basin. We explore the effect of the initial amount of Carboniferous to Early Permian extension on the basin subsidence.

Surface Processes Modeling

The thermal-mechanical models are coupled to a surface process model (SPM) in order to investigate the effects of the sediment loading/unloading on the basin structural evolution.

Simple surface process approaches are used in the 2D cases where erosion is implemented through diffusion of the surface and sedimentation is implemented using a simple geometric algorithm which simulates progressive prograding of sediment into the basin. The 3D thermo-mechanical models are fully coupled to a state-of-the-art SPM code Badlands (Salles and Hardiman, 2016). Surface processes include fluvial erosion using a classical stream-power law and predefined rock erodibilities, hillslope processes via surface diffusion, and offshore sedimentation. Among other features, the code offers the possibility to track sediments and to extract the sedimentary sequences in the basin (vertical profiles and Wheeler diagrams). The vertical net displacement associated with the velocity field returned by the thermo-mechanical model is translated into a net vertical uplift which is interpolated on the SPM model surface. The landscape evolution model generally requires smaller time steps than the tectonic model. Therefore, the Thermo-mechanical model time step is broken down into sub-timesteps, thereby ensuring the stability of the SPM. The SPM surface is then used to update the configuration of the Thermo-mechanical model at the end of each tectonic time step and a new time step is initiated.

The absolute sea level is initialized at the start of the model and remained as constant throughout the duration of experiments. We investigate the effect of erosion efficiency by using variable surface erodibilities between model setups.

Preliminary results show that the transfer of sediments at the surface affect the stress field in the lithosphere. However, as erosion needs some topography to occur, the amount of erosion is controlled by the strength of the lithosphere through its ability to sustain topography. Accumulation of sediment at the margin has the potential to localize deformation and can thus facilitate the development of faults in the upper crust.

PRELIMINARY CONCLUSIONS

The models presented represent a first step toward a better understanding of the thermal-mechanical evolution of the Australian North West Shelf. The strength of the lithosphere which depends on the rock rheologies and its geodynamic history controls the style of extension. However, the complex interaction between surface processes and tectonics have the potential to affect the behaviour of the lithosphere: accumulation of sediment in the basins can thus locally strengthen the lithosphere and localize the deformation at the margins. The amount of sediment arriving in the basin, depends essentially on the erodibility of the rocks and the climatic conditions, may affect the development of the basin, at least locally. This points to the importance of integrating information from both the onshore (exhumation rate) and onshore (stratigraphy) to constrain the model.

If the succession of extensional styles, from distributed extension to localized extension, could be due to the strengthening of the lithosphere from one phase to the next, erosion and local accumulation of sediment may also play a role in the development of localized normal faults.

Modeling complex geological systems where lithospheric scale deformation is integrated with surface processes evolution is rapidly developing and provide interesting opportunities. The main challenges reside in the high computational time cost which still limits the 3D model in resolution for large-scale models, typically to a few kms.

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REFERENCES

Gartrell, A. P., 2000, Rheological controls on extensional styles and the structural evolution of the Northern Carnarvon Basin, North West Shelf, Australia. Australian Journal of Earth Sciences, 47(2), 231–244. https://doi.org/10.1046/j.1440-0952.2000.00776.x

Geoscience Australia, 2015. Regional Geology of the Northern Carnarvon Basin., pp.1–34. Available at: http://archive-petroleumacreage.industry.slicedtech.com.au//2015/geology/northern-carnarvon-basin/geology

Salles, T., & Hardiman, L., 2016, Badlands: An open-source, flexible and parallel framework to study landscape dynamics. Computers & Geosciences, 91, 77–89. https://doi.org/10.1016/j.cageo.2016.03.011

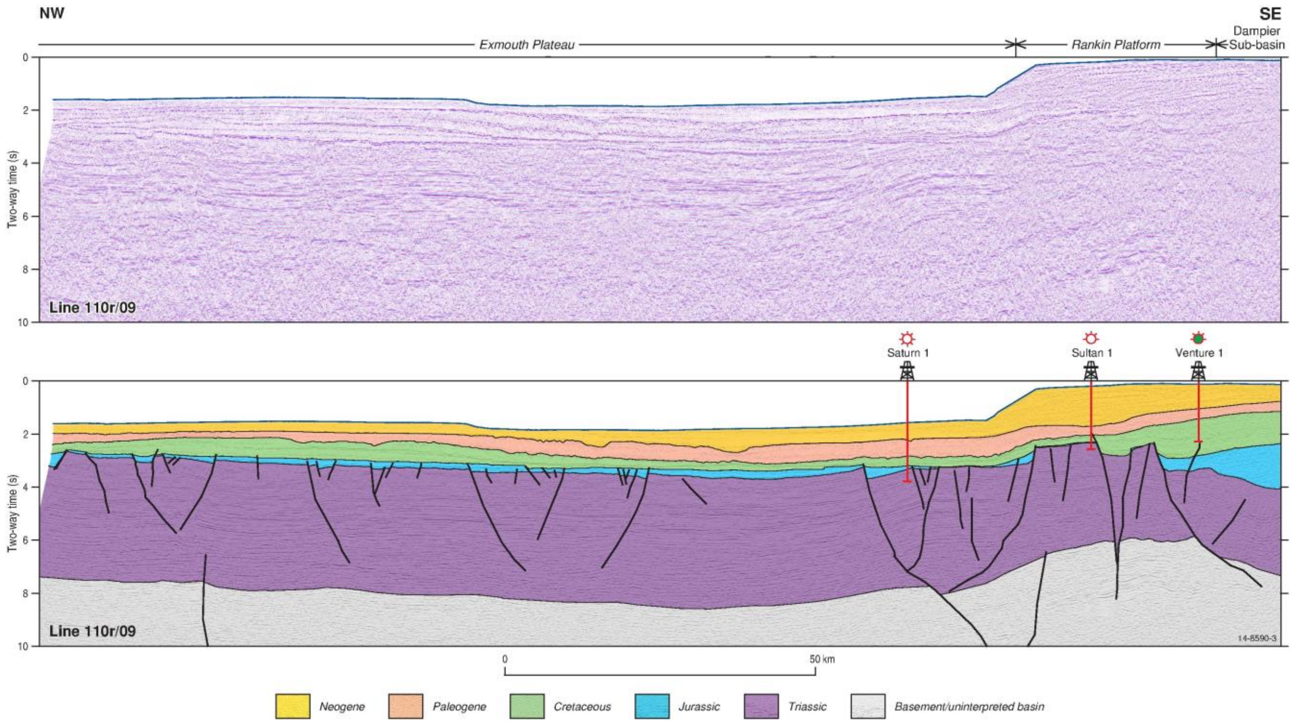

Figure 2: Composite seismic profile (lines 128/08 and 101r/09) across the Exmouth Plateau, Rankin Platform and Dampier Sub-basin. Notice how in the Exmouth plateau the Triassic sequence (Mungaroo Delta) has a gentle-dipping reflectors with no synsedimentary deformation and lack of extensive basement faulting and graben and/or half-graben formation. Interpretation by Geoscience Australia.

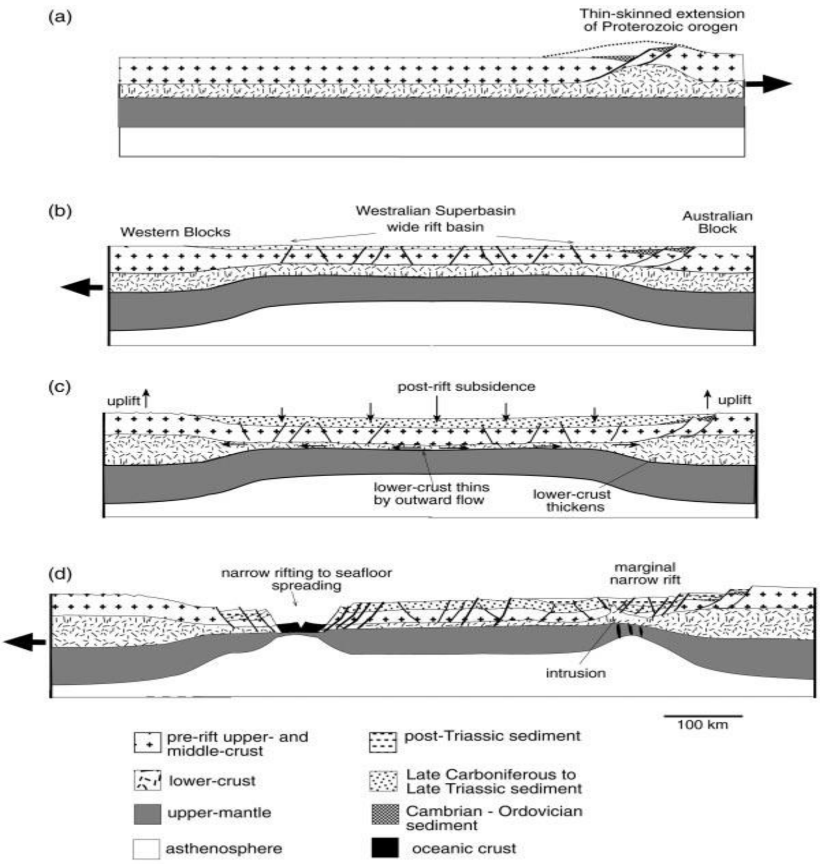

Figure 3: Non-detachment tectonic model for the devel- opment of the Northern Carnarvon Basin. (a) Metamorphic core complex mode or thin-skinned exten- sion localised in Proterozoic orogenic belt. (b) Permo- Carboniferous wide rifting. (c) Late Permian to Late Triassic sag phase, largely the result of outward flow of the lower crust. (d) Jurassic–Cretaceous extensional reactivation of a more brit- tle lithosphere results in narrow rift basins. Narrow rift on the western margin develops into a sea-floor spreading centre. Intrusion of crustal material occurs in eastern narrow rift but does not achieve sea-floor spreading ridge status.