UNRAVELING DEEP STRUCTURES ALONG A RIFTED-TRANSFORM MARGIN: INSIGHTS FROM AN INTEGRATED GEOPHYSICAL STUDY OF THE NORTHERN PERTH BASIN

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SUMMARY

The Houtman Sub-basin lies adjacent to the Wallaby-Zenith Transform Margin, an under-explored region of Australia's continental margin located at the transition between the non-volcanic margin of the northern Perth Basin and volcanic province of the Wallaby Plateau. New seismic data acquired in the northern Houtman Sub-basin enables better understanding of the structural architecture and rifting development along a rifted-transform margin and provides the framework for a detailed integrated margin-scale basin evaluation. Profile modelling of potential field data, combined with 2D seismic, reveals complex along-strike and dip variability in the crustal thinning of the Houtman Sub-basin, with extreme thinning (<5 km thick) beneath the main Permian depocentre. Outboard of this hyperextended zone, along the basin margin, is a zone of volcanic SDRs. Five different structural domains have been mapped across the margin, reflecting abrupt change in crustal thinning and volcanic emplacement. These domains trend roughly NW-SE to NNW-SSW, parallel to major basement terrane boundaries. Magnetic modelling suggests that the nature of the basement underlying the proximal domain and the hyperextended domain in the central Houtman Sub-basin are different and that a major Proterozoic basement terrane boundary lies beneath the necking domain.

The margin was structured during polyphase Permian and Late Jurassic rifting events which led to hyperextension prior to continental magmatic break-up and formation of oceanic crust during the Early Cretaceous. Our results suggest that the distribution of Early Permian rifts localised strain during Jurassic—Early Cretaceous rifting and strongly controlled the location and style of rifted margin during Valanginian continental break-up.

Key words: Perth Basin, Houtman Sub-basin, potential field modelling, crustal architecture, hyperextended margin

INTRODUCTION

The (GA349) regional 2D seismic project acquired by Geoscience Australia in 2014, part of the Geoscience Australia's regional petroleum program, was designed to better understand the rift structures and crustal architecture of the Houtman Sub-basin, a largely unexplored offshore frontier area covering 57 000 km^2 of the western Australian margin in the northern Perth Basin (**Figure 1** - Borissova et al., 2017). The survey extends across the northern part of the Houtman Sub-basin at the transition between the non-volcanic margin of the northern Perth Basin (Rollet et al., 2013) and the volcanic province of the Wallaby Plateau (Symonds et al., 1998). To the southwest lies the Wallaby-Zenith Transform Margin (WZTM) and oceanic crust of the Perth Abyssal Plain suggesting that the Houtman Sub-basin developed in a strike-slip to transtensional setting (e.g. Hall, et al., 2013). To the southeast, lies the relatively unextended continental crust of the Bernier Platform of the early Paleozoic Southern Carnarvon Basin (Iasky et al., 2013).

Previous studies have proposed that the Houtman Sub-basin contains more than 12 km of sediment (Hall et al., 2013; Jones et al., 2011; Rollet et al., 2013). Regional correlation of the newly acquired 2D seismic stratigraphy across the northern Perth Basin suggests a much thicker sedimentary package including up to 16 km of Permian—Cretaceous succession (Borissova et al., 2017). Three petroleum wells have been drilled in the southern part of the sub-basin (Gun Island 1, Houtman 1 and Charon 1 - **Figure 1**), all of which reached TD within the Jurassic-Cretaceous succession (Jorgensen et al., 2011). Wells from the adjacent Abrolhos Sub-basin intersect older Permian-Triassic stratigraphy and provide the only direct age control for the deeper stratigraphy within the Houtman Sub-basin. In addition, basement rocks directly underlying Permian strata have been drilled in exploration wells in the northern Perth Basin located to the south of the Houtman Sub-basin. These wells indicate that Permian clastic sediments rest upon a crystalline crust that consists of Proterozoic to Early Cambrian igneous and metamorphic rocks of the Pinjarra Orogen (e.g. Collins, 2003; Fitzsimons et al., 2003; Bodorkos et al., 2016).

An integrated geological and geophysical interpretation encompassing available seismic and potential field data has been completed. Gravity models coincident with each seismic transect were developed to aid in the structural interpretation of the deep crust and Moho to better define the basin's crustal architecture (**Figure 1, Figure 2**). This margin-scale study provides information on the depth and nature of the crystalline basement and the total crustal thickness. In addition, it better constrains the extent and distribution of Seaward Dipping Reflector (SDR) sequences and intra-basinal volcanics associated with development of the Wallaby Plateau volcanic province and the WZTM. Study results highlighted the transition between non-volcanic and volcanic margin segments, improved understanding of the timing, distribution and magnitude of multiple basin forming events and provided insights into the control of underlying basement structures and rheology on basin development.

Regional context

The present-day northwest–southeast trending architecture of the Houtman Sub-basin resulted from two separate rifting episodes, Early- to Mid-Permian and Early Jurassic to Early Cretaceous, culminating in the Early Cretaceous breakup of Australia and Greater India (Gibbons et al., 2012; Hall et al., 2013). The first major stage of rifting was marked by Early- to Mid-Permian extension, which resulted in the formation of a series of northwest-oriented half graben filled with up to 10 km of synrift succession (Borissova et al., 2017; Southby et al., 2018). The second major rifting event began in the late Early Jurassic leading to Valanginian–Aptian transform margin development and associated regional uplift and erosion (Hall et al., 2013).

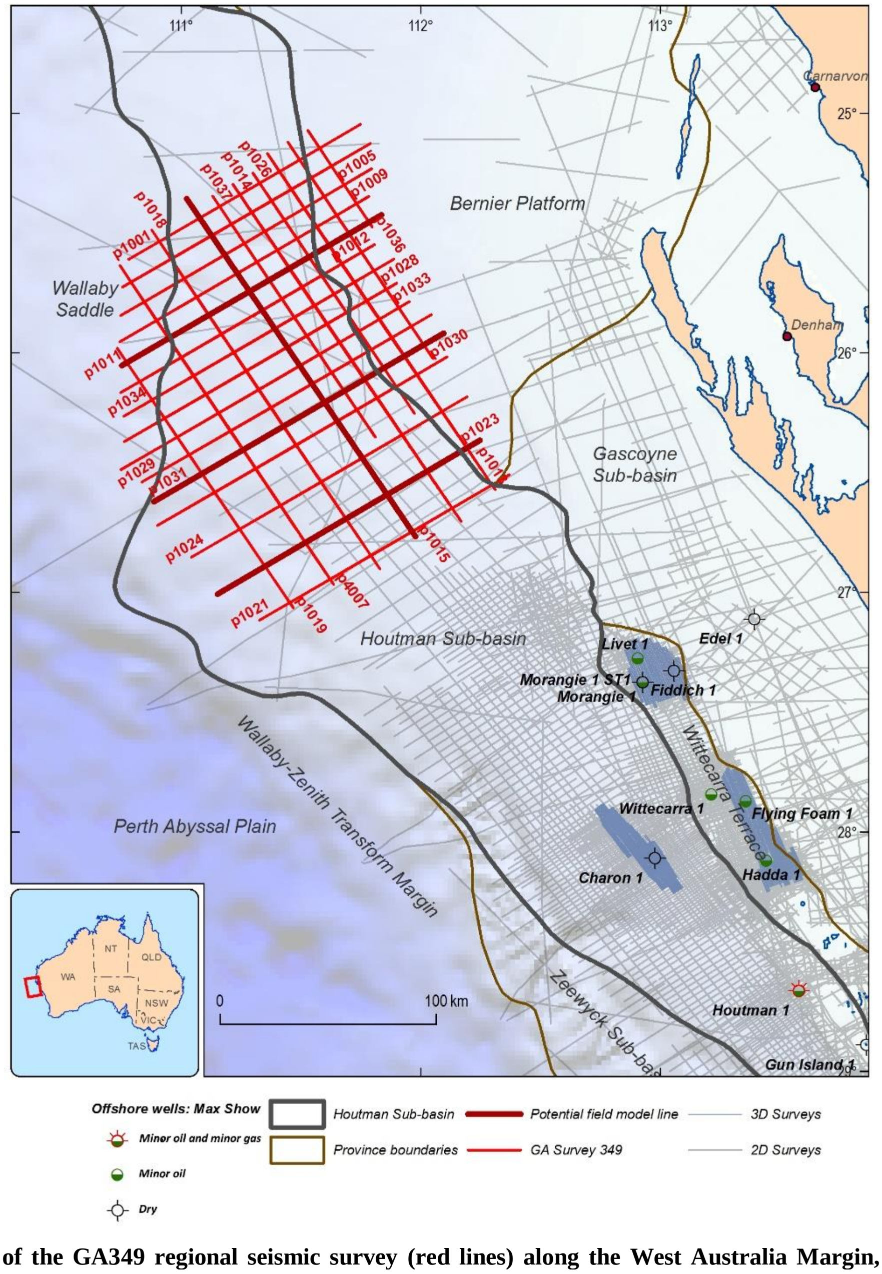

Figure 1: Location of the GA349 regional seismic survey (red lines) along the West Australia Margin, overlain on digital elevation model. Wells and hydrocarbon shows are shown on the map. Location of structural and basin elements are labelled in italic. Thick red lines represent potential field model lines undertaken during this study to test structural seismic interpretation and developed a crustal model. The line 1031 is shown in Figure 3.

METHODS AND RESULTS

Data constraints and Potential field modelling workflow

Between November 2014 and January 2015, Gardline's M/V Duke acquired 3300 km of deep broadband 2D seismic data providing a regional grid over the northern part of the Houtman Sub-basin (**Figure 1;** see Southby et al. (2016) for more details on the GA349 project). The data were acquired using a deep-tow configuration with 8.1 km streamer towed at 15.6 m below the sea surface. The data was processed to Pre-Stack Time Migration (PSTM) and Pre-Stack Depth Migration (PSDM). Ship track gravity and magnetic data were acquired with the seismic and swath bathymetry data (Foster et al., 2009; Hackney, 2012). These datasets were merged and levelled with an existing Australia-wide dataset to provide a consistent dataset that covers the southwest margin of Australia (106–120°E and 19–37°S), including the northern Perth and Southern Carnarvon basins, as well as the Wallaby Plateau (**Figure 2A, Figure 2B**; Hackney, 2012). In addition, Satellite gravity datasets is available across the entire region (**Figure 2B** - Sandwell and Smith, 2009) and was used for gravity modelling (Sanchez et al., 2016).

Gravity modelling was carried out coincident with seismic lines from the GA349 2D seismic survey in the north and a composite line in the south (**Figure 2C;** Sanchez et al., 2016). As magnetic ship track data were not acquired during the GA349 seismic survey, magnetic modelling was performed parallel to the line 1031 (GA349 survey) along the profile 135/10 from the GA310 potential field program (**Figure 2C**). The 2.5D forward model was performed using the software ModelVision™ (v.15) developed by Tensor Research, which computes the gravity and magnetic field effect of all source bodies along a section as a function of their 3D location and physical properties (location, size/volume, orientation, type/density and susceptibility/remanence). Density values of the sediments were averaged and adapted based on the range of lithological variability between 2.20 and 2.65g/cc considering age, lithology and pressure (depth) dependence. Densities assigned to basement units are mainly based on common rock properties and the average composition of each terrane as no basement wells were drilled in the sub-basin. Magnetic susceptibilities were calculated automatically during inversion and then compared to drilled samples in wells located further south (Schmidt, 2010).

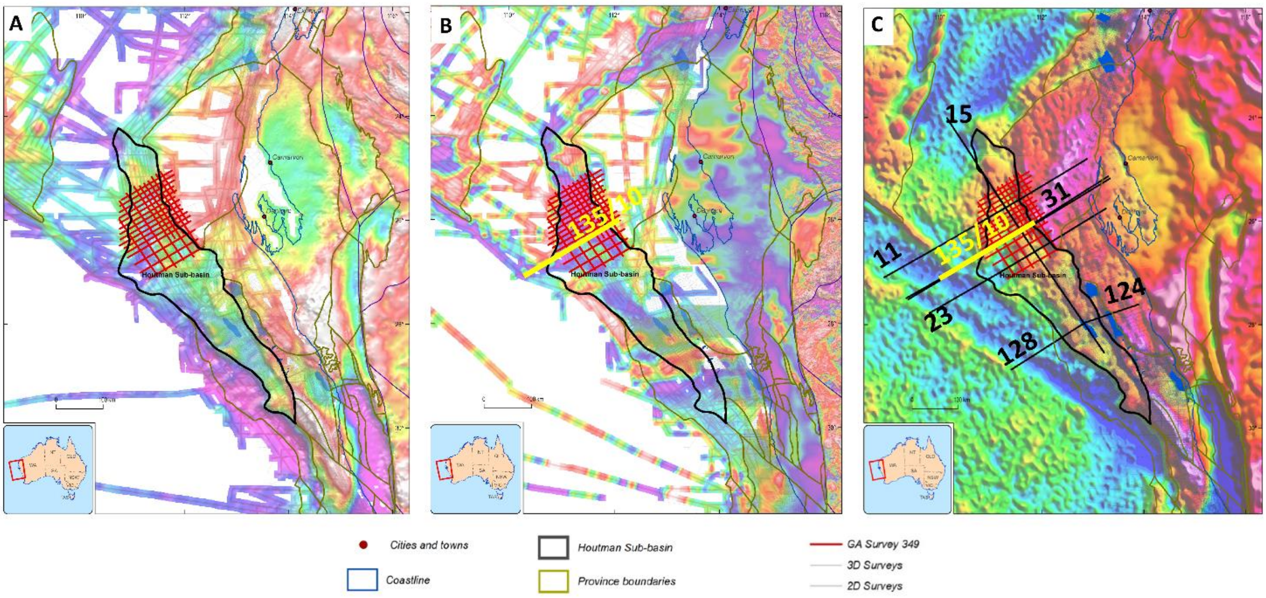

Figure 2: A and B - Merged gravity and magnetic anomaly dataset with ship track data distribution (Transparent red lines) (from Hackney, 2012). C - Satellite FA gravity data (Sandwell and Smith, 2009) including location of the GA349 regional seismic survey (red lines) and gravity modelling profiles in the Houtman Sub-Basin. Black lines show the location of gravity model profiles and the yellow line indicates the magnetic model profile location.

Results – Regional overview of crustal architecture

The GA349 regional seismic has clearly imaged pre-rift and major syn-rift sedimentary sections across the Houtman Sub-basin, and in many areas pre-Permian basement and the Moho interface are also imaged (**Figure 3A**; Borissova et al., 2017; Southby et al., 2018). Extremely thin basement has been interpreted beneath the main depocentre bounded on the eastern side by a major southwest dipping fault that dies out at mid-crustal level (~18–20 km). The new seismic also shows smaller-scale west-dipping and antithetic crustal faults associated with rotated blocks. Near-top-basement reflective package represents Pre-Permian pre-rift and Permian syn-rift sequences overlain by a Triassic post-rift sequence and a thin Late Jurassic-Early Cretaceous syn-rift sequence, marking the magma-rich break up. Strong reflectors, gently dipping eastward at ~17–18 km depth, are imaged on the western basin margin beneath the eastern onlap edge of the SDRs. This reflective horizon deepens (21-22km depth) toward the northeast beneath the Bernier Platform and is interpreted to be the mantle-crust boundary (i.e. Moho discontinuity).

Potential field modelling supports this new interpretation of the Houtman Sub-basin (**Figure 3B**). Modelled depth to basement is ~5-6 km beneath the Bernier Platform and deepens abruptly at the basin-bounding fault to depths of ~12–17 km beneath the main Permian depocenter to the west. The depth to Moho is modelled at 25 km beneath the Bernier Platform and shallows toward the west to ~15 km. The combination of a rising Moho and a thick sedimentary section within the Houtman Sub-basin supports drastic crustal thinning of ~15 km over a horizontal distance of 100 km. The new interpretative model suggests that the Houtman Sub-basin is a hyperextended rift with tilted fault blocks of continental crust detached at the top of a possible serpentinised mantle (i.e. Moho interface).

Although basement geometry is not well imaged to the west on seismic data, the outer edge of the basin is bounded by east-dipping faults which offset basement beyond the western end of the seismic data, by up to 8–10 km beneath the onlap edge of the SDRs (**Figure 3A, Figure 3B**). The Moho deepens sharply at the western flank of the Houtman depocentre and then resumes the shallowing trend toward oceanic crust. To fit the FA gravity signal associated with the Early Cretaceous volcanic margin, a dense upper crust of 2.8g/cc at a depth of ~8–10 km (possibly Precambrian) and a denser lower crustal body (LCB; 3.05g/cc) are required underneath the SDR wedge. The LCB is lens-shaped with a relatively constant thickness of 2–4 km and may be interpreted as being related to magmatic underplating due to its location beneath the SDR package.

In this new interpretative model, the Houtman Sub-basin extreme thinning and possible serpentinisation is likely to be the result of a combination of both Permian and Early Jurassic-Early Cretaceous rift phases. The lack of volcanics beneath the main depocentre favours a hyperextended rift model. SDRs and volcanics subsequently developed in the outboard part of the margin during a large magmatic event associated with Early Cretaceous breakup. Similar geometries across the Houtman Sub-basin are observed with the crust thinning from 30–35 km to the west to less than 5–10 km beneath the main depocentre. This variation in crustal thickness reflects the different basement response to extension controlled by the basement rheology along the margin. Magnetic modelling suggests that two different types of basement are present beneath the Houtman Sub-basin with a well-defined boundary along the major basin-bounding fault system (**Figure 3C**). Another region of hyper-thinned crust is modelled in the southern part of the basin across the transform margin. The hyperextended domain is, however, much narrower and reflects the development of the transform margin during the Late Jurassic-Early Cretaceous.

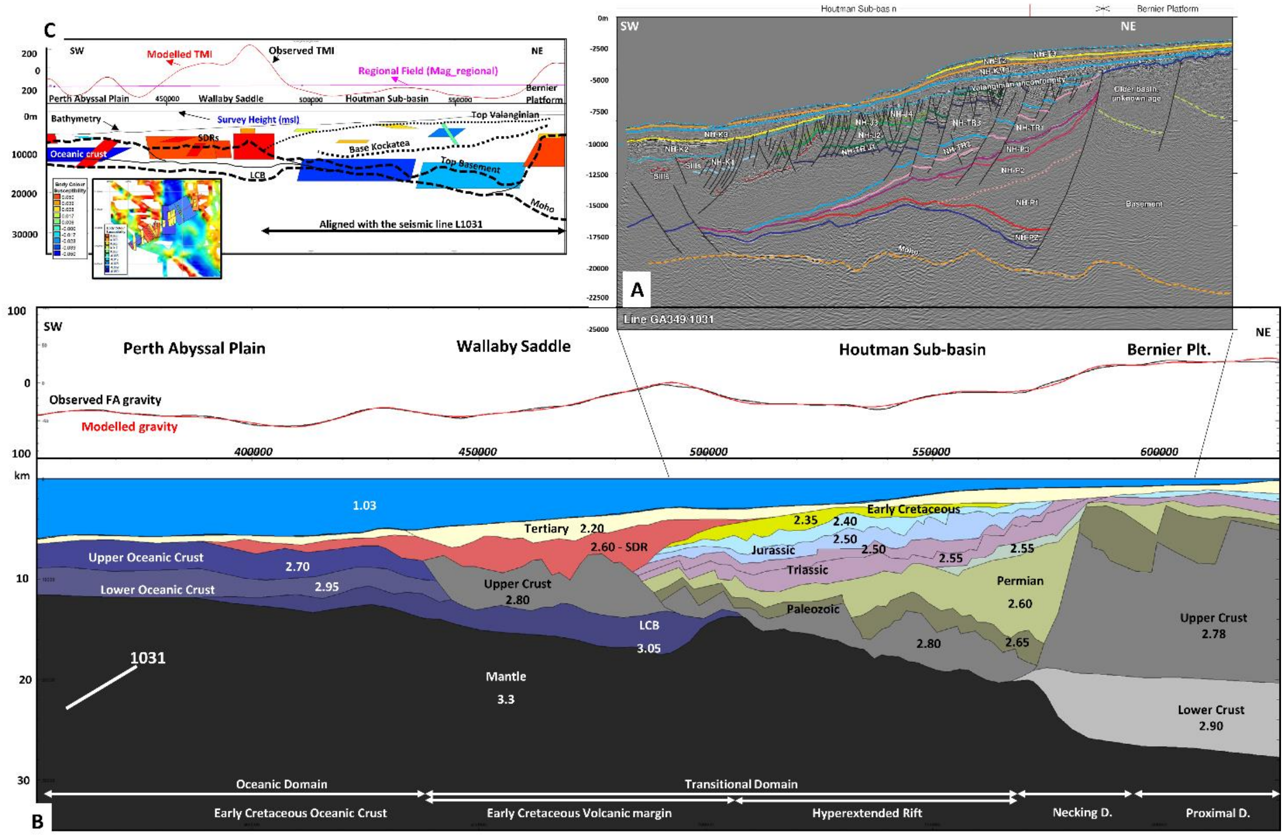

Figure 3: A: Interpreted GA349 seismic line 1031 showing overall geometry across the Houtman Sub-basin and Bernier Platform on the West Australia margin Shelf. B: Gravity profile modelled along the 1031 seismic line (GA349 survey) showing hyperextension and possible mantle exhumation interpretation consistent with gravity signal in the Houtman Sub-basin. The main Permian depocenter is flanked to the NE by a thicker continental crust beneath the Bernier Platform and to the SW by the Early Cretaceous volcanic margin and oceanic crust. C: Magnetic model performed along the 135/10 geophysical line (GA310), parallel to the 1031 seismic line (GA349). Magnetic model bodies coloured by magnetic susceptibility highlighting the extent of the SDRs and the depth and nature of the hyperextended crust. Insert: TMI image of the Houtman Sub-basin showing magnetic model bodies coloured by magnetic susceptibility. LCB: Lower Crustal Body, SDR: Sea-Dipping Reflectors. Dashed lines correspond to key horizons interpreted on the seismic lines.

CONCLUSIONS

The new seismic data acquired by Geoscience Australia significantly improves our understanding of structural architecture and tectonic evolution of the western Australian margin and the northern Perth Basin. The new data and interpretation challenges the idea that the northern Perth basin developed as a volcanic margin in a strike-slip/transform setting. Basin architecture and crustal structure are more consistent with a magma poor system, with hyperextension resulting from a combination of multiple Permian to Late Jurassic rifting phases. Volcanic margin development began subsequent to this in Early Cretaceous, immediately prior to the separation of Greater India and Australia. The distribution of Permian rifts in-turn further localised strain during the Jurassic—Early Cretaceous rifting, strongly influencing the location and style of rifted margin development during Valanginian continental break-up.

ACKNOWLEDGMENTS

The authors wish to thank Karen Romine for her constructive discussion, Cameron Mitchell for his assistance with depth conversions, as well as Christopher Pietrucha and Adam Kroll for their technical help. This work is published with the permission of the CEOs, FROGTECH Geoscience and Geoscience Australia.

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