PSCrustal Structure and Tectonic Evolution of the Northern Perth Basin, Australia*

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Search and Discovery Article #11027 (2017)**
Posted December 11, 2017

*Adapted from poster presentation given at AAPG/SEG 2017 International Conference and Exhibition, London, England, October 15-18, 2017

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Abstract

The Houtman Sub-basin is an under-explored region of Australia's continental margin. It is located at the transition between the non-volcanic margin of the northern Perth Basin and the volcanic province of the Wallaby Plateau and lies adjacent to the Wallaby-Zenith Transform Margin (WZTM). In 2014, Geoscience Australia acquired new 2D seismic data (3300 km) across the northern Houtman Sub-basin to better image deep crustal structures in this frontier province. Interpretation reveals that this depocentre contains up to 19 km of sediments and regional correlation of the seismic stratigraphy across the northern Perth Basin suggests this includes up to 16 km of Permian—Cretaceous succession. However, the depth and nature of the crystalline basement, the total crustal thickness as well as the extent and distribution of Seaward Dipping Reflector Sequences (SDR) and intra-basinal volcanics associated with development of the Wallaby Plateau volcanic province and the WZTM remain poorly constrained. An integrated geological and geophysical study, based on available seismic and potential field data was undertaken to aid the structural interpretation of the deep crust and Moho in order to better define the basin's crustal architecture. In addition, the transition between non-volcanic and volcanic margin segments was delineated and, in conjunction with the regional seismic interpretations, better understanding of the timing, distribution, and magnitude of multiple basin forming events was gained. The Ocean-Continent Transition (OCT) shows along strike and dip variations from extended and hyperextended (<5 km thick) continental crust beneath the main Permian depocentre to a zone of volcanic SDRs located outboard. Continental thinning and stretching phases occurred during both the Permian and Late Jurassic extensional phases. Volcanic margin development began in the Early Cretaceous, immediately prior to the separation of Greater India and Australia, suggesting that the volcanic margin experienced a phase of hyperextension before the magmatic break-up. Structural inheritance played an important role in basin development. It is likely that Early Permian graben formation was influenced by rheological contrasts in the underlying Proterozoic basement. The distribution of Permian rifts in turn further localised strain during Jurassic—Early Cretaceous rifting, strongly influencing the location and style of rifted margin development during Valanginian continental break-up.

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Introduction

Houtman Sub-basin prospectivity study

The Houtman Sub-basin is a largely unexplored offshore depocentre in the northern Perth Basin on the western margin of Australia (Figure 1). It is located 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. To the southeast, lies the relatively unextended continental crust of the Bernier Platform, of the early Paleozoic Southern Carnarvon Basin (Iasky et al., 2013).

The crystalline basement beneath the Houtman Sub-basin is most likely to comprise Proterozoic to Early Cambrian igneous and metamorphic rocks of the Pinjarra Orogen (e.g. Collins, 2003; Fitzsimons et al., 2003; Bodorkos et al., 2016). The basin formed during two separate rifting episodes (Early- to Mid-Permian and Early Jurassic to Early Cretaceous; Rollet et al., 2013; Owens et al., 2017), culminating in the separation of Australia and Greater India (Figure 2; Gibbons et al., 2012; Hall et al., 2013).

Previous studies have suggested the Houtman Sub-basin contains more than 12 km of sediment (Rollet et al., 2013), however the northern Houtman Sub-basin remains an exploration frontier (Totterdell et al., 2014). No wells have been drilled in this region and historically seismic data distribution remained very sparse (Figure 1). As a result, the depth and nature of the crystalline basement, the total crustal thickness, as well as the extent and distribution of Seaward Dipping Reflector Sequences (SDR) and intra-basinal volcanics associated with development of the Wallaby Plateau volcanic province and the WZTM remained poorly constrained.

This study presents the results of an integrated geological and geophysical study, based on data from a newly acquired regional 2D seismic survey (GA349) covering the northern Houtman Sub-basin (Figure 1) and public domain potential field datasets (Figures 3 and 4). Results have improved the structural interpretation of the deep crust and Moho, better defining the basin's crustal architecture. In addition, the transition between non-volcanic and volcanic margin segments was delineated and, in conjunction with the regional seismic interpretations, an improved understanding of the timing, distribution and magnitude of multiple basin forming events was gained.

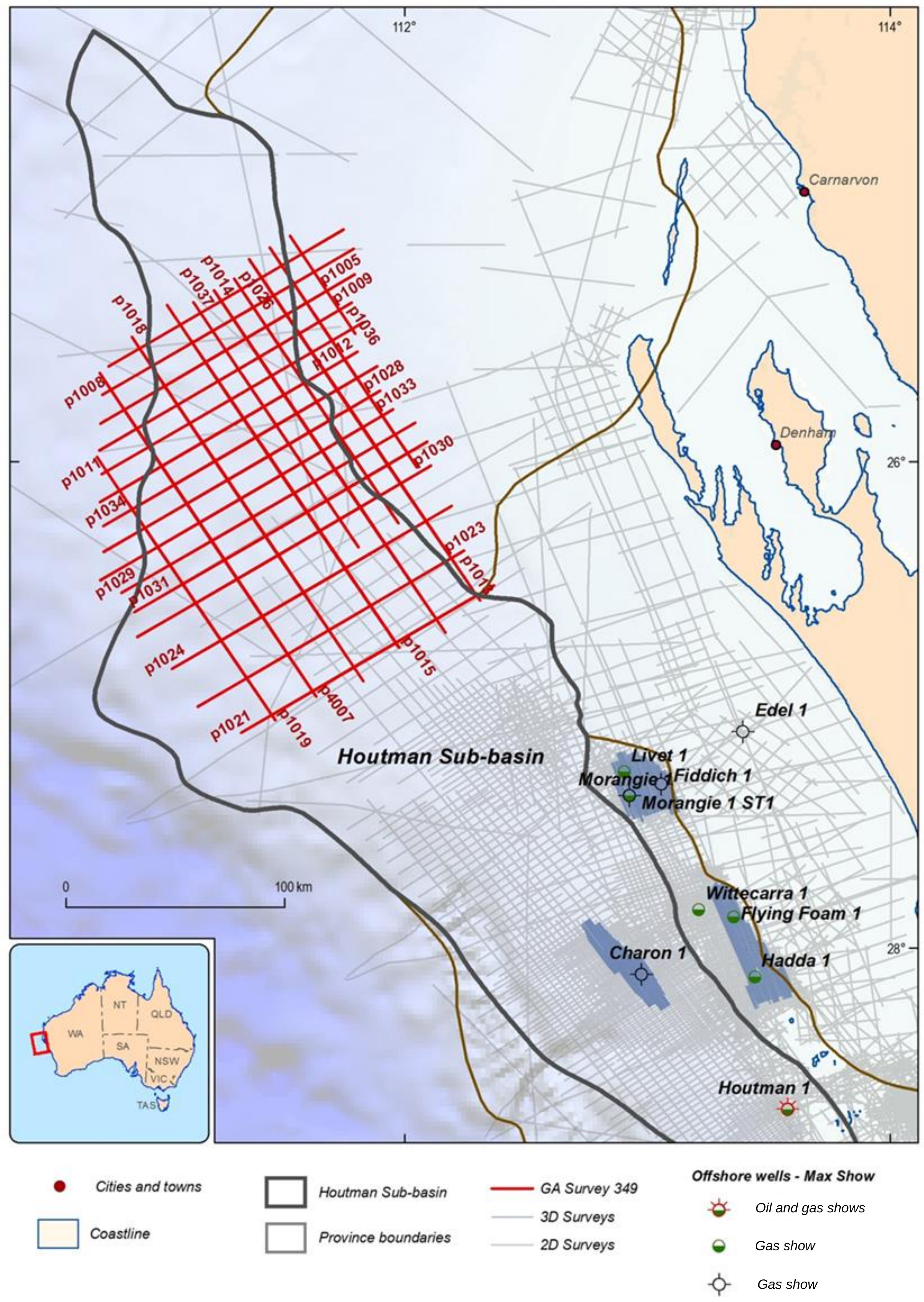

Figure 1. Houtman Sub-basin location map. Offshore petroleum wells are displayed by maximum show and well locations are sourced from Geoscience Australia's petroleum wells database. Red lines represent the newly acquired GA349 2D seismic survey (Owen, 2016). Blues lines represent existing regional open file 2D and 3D seismic survey navigation data (Soames et al., 2014). Thick black lines represent basin and sub-basin boundaries (Stewart et al., 2013).

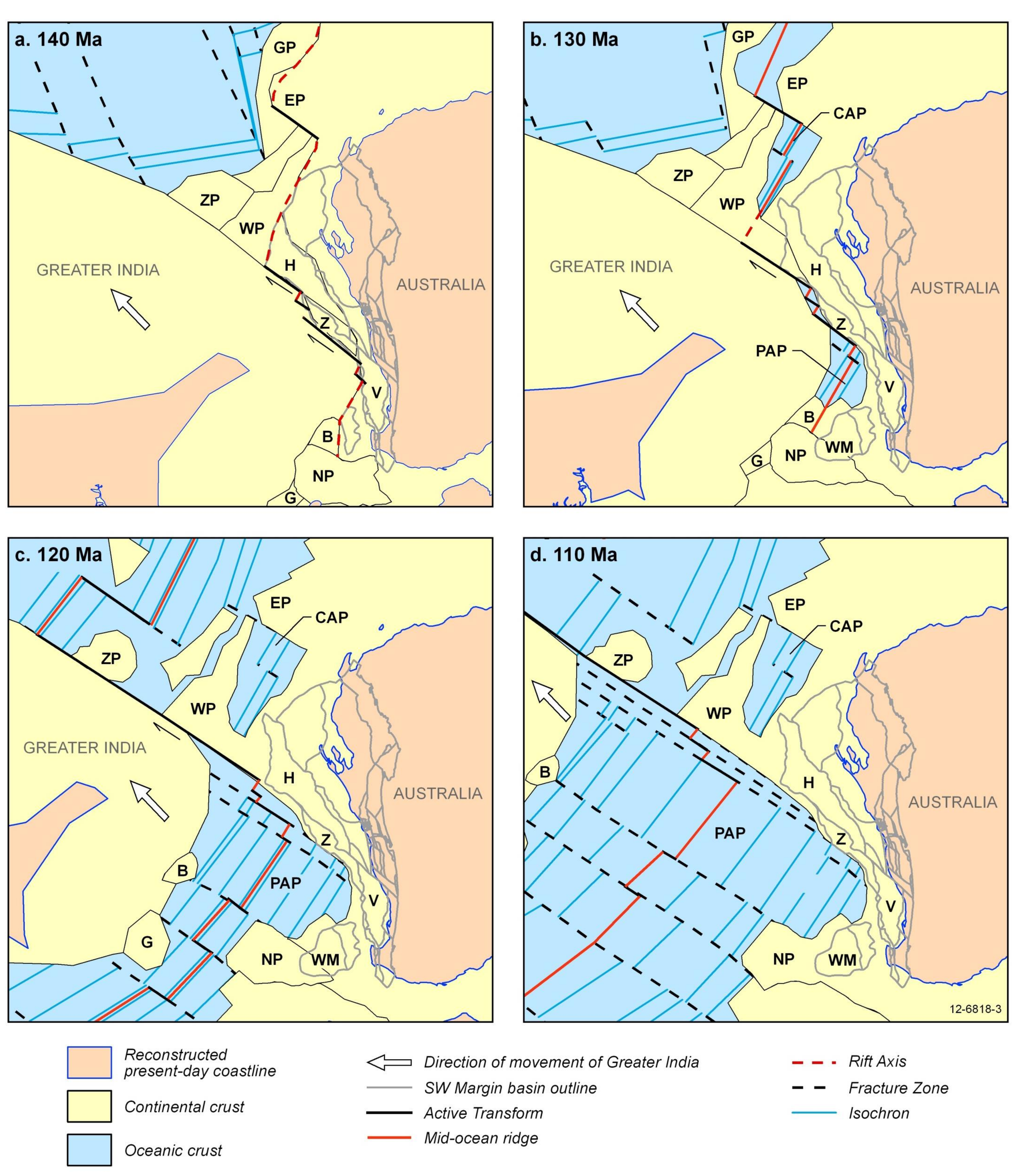

Figure 2. Tectonic plate reconstructions of the SW Australian margin at (a) 200Ma (b) 150Ma (c) 130Ma and (d) 120Ma (from Gibbons et al., 2012; Hall et al., 2013). B: Batavia Knoll; CAP: Curvier Abyssal Plain; EP: Exmouth Plateau; G: Gulden Draak Knoll; GB: Gascoyne Block; H: Houtman Sub-basin NP: Naturaliste Plateau; PAP: Perth Abyssal Plain; V: Vlaming Sub-basin; WM: Western Mentelle Sub-basin; WP: Wallaby Plateau; WZTM: Wallaby-Zenith Transform Margin; Z: Zeewyck Sub-basin; ZP: Zenith Plateau.

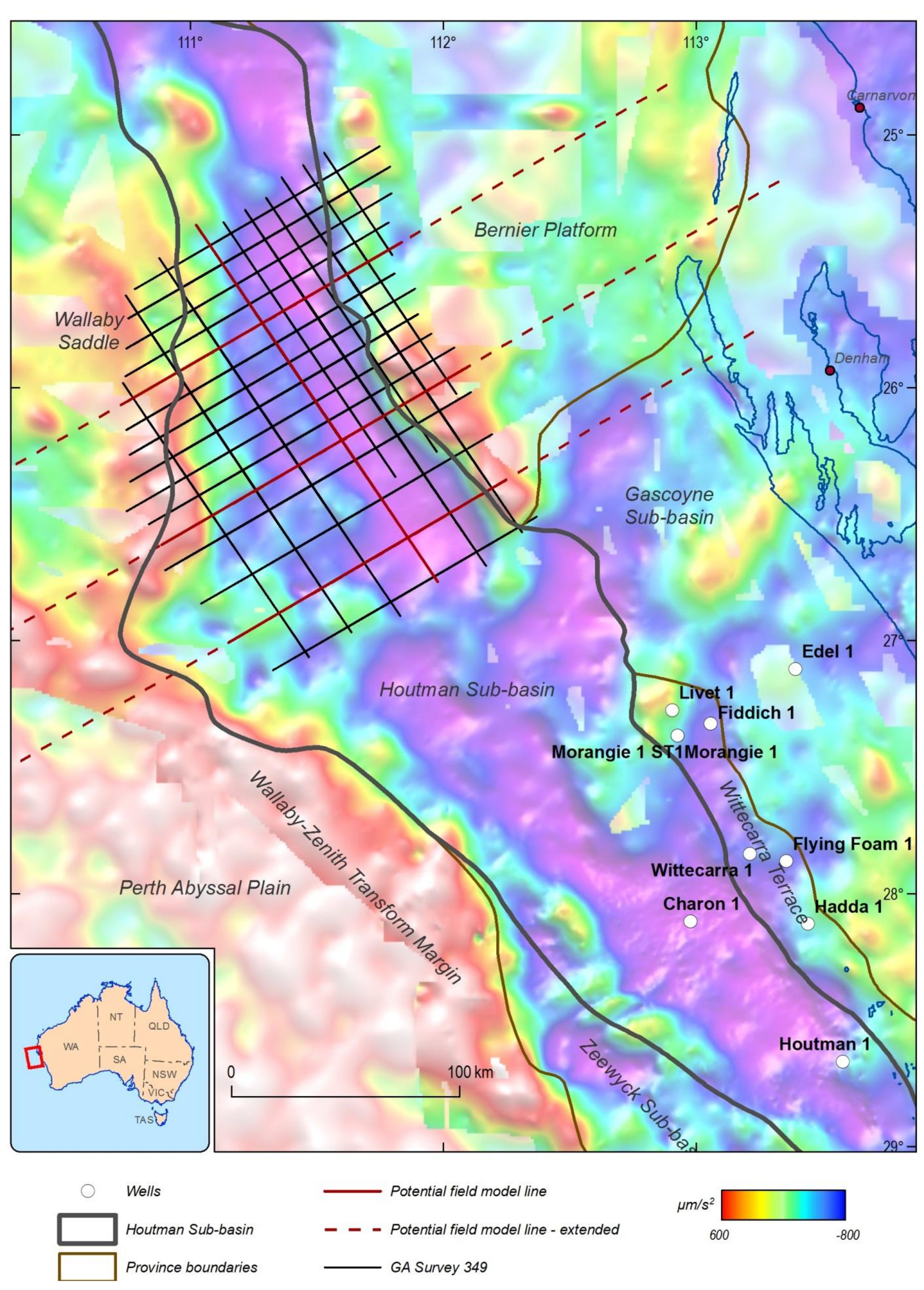

Figure 3. Satellite free air (FA) gravity data (Sandwell and Smith, 2009). Levelled and stitched ship track data (Hackney, 2012) is also available but satellite gravity resolution was sufficient for this study (see discussion in Sanchez et al., 2016). Red lines mark the location of the potential field model lines in Figure 7.

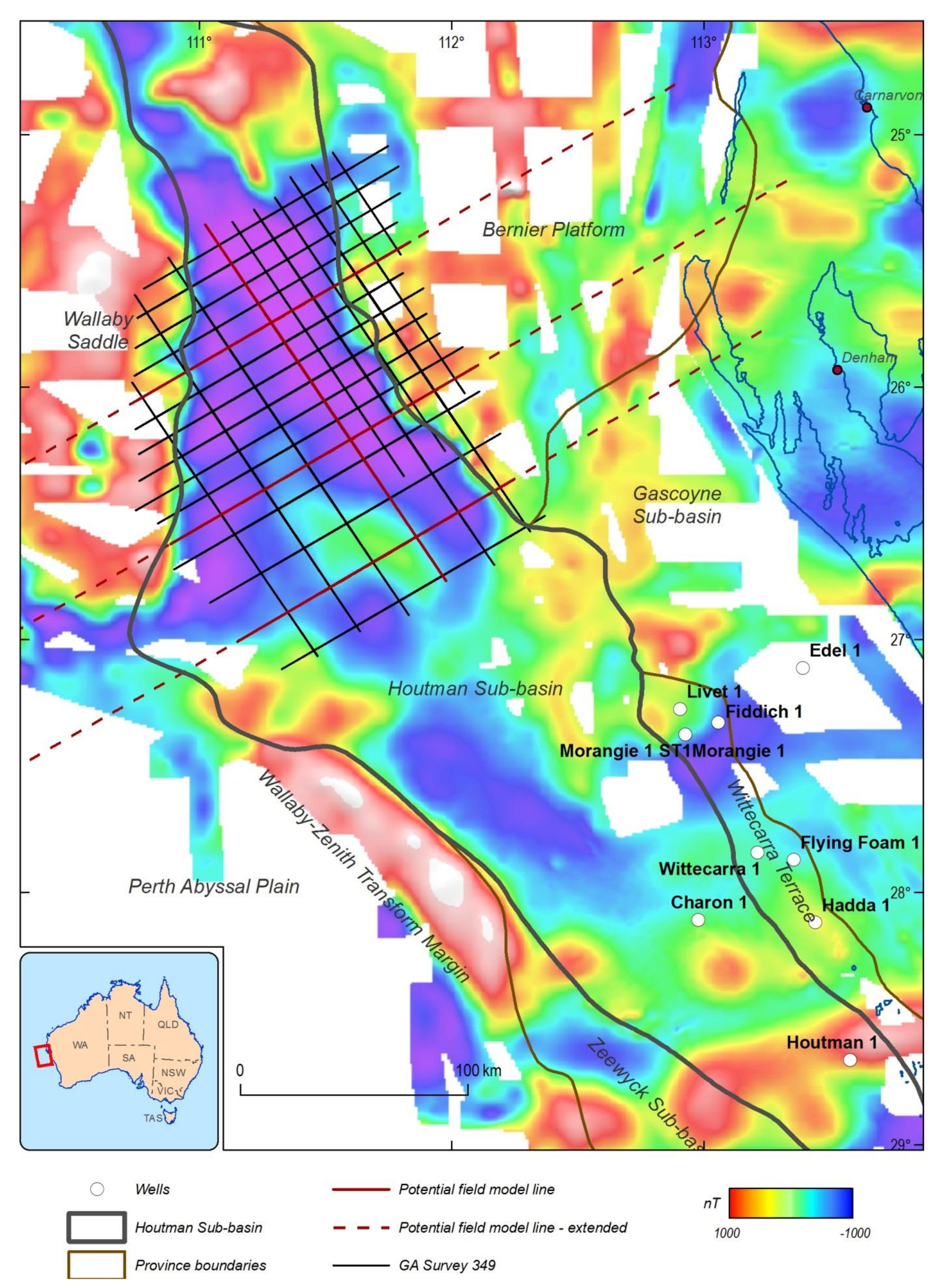

Figure 4. Levelled ship-track magnetic data coverage (Hackney, 2012). Red lines mark the location of the potential field model lines in Figure 7.

Acknowledgements

Thank you to our reviewers, Adam Bailey and Lidena Carr (Geoscience Australia) and to the crew of the M/V Duke and the Geoscience Australia survey management team for successful acquisition of the new GA349 seismic data in the northern Houtman Sub-basin. .

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Additional information

The Houtman Sub-basin 2D Seismic data (GA349) can be accessed using the National Offshore Petroleum Information Management System (NOPIMS), an online data discovery and delivery system for all Australian offshore petroleum wells and seismic surveys. http://www.ga.gov.au/nopims The potential field data from Hackney (2012) is available for download from the Geoscience Australia's Geophysical Archive Data Delivery System (GADDS). More information on other public domain datasets and results referenced in this study can be found on Geoscience Australia's website. www.ga.gov.au

Basin architecture

New seismic data and interpretation

In 2014, Geoscience Australia acquired 3300 km of new 2D seismic data (survey GA349) across the northern Houtman Sub-basin to better image deep crustal structures in this frontier province (Figure 1; Borissova et al., 2016). The new data have been processed to pre-stack time migration (PreSTM) and pre-stack depth migration (PreSDM) (Owen, 2016).

Figure 5 shows three interpreted seismic lines from the new survey, which extend from the Bernier Platform of the Southern Carnarvon Basin, across the main depocentre of northern Houtman Sub-basin, to the Wallaby Saddle. The interpreted sequence ages and their possible lithostratigraphic equivalents are shown in a newly updated tectono-stratigraphic chart (Figure 6; Owens et al., 2017).

Results show that the northern Houtman Sub-basin contains up to 19 km of sediments and regional correlation of the seismic stratigraphy across the northern Perth Basin suggests this comprises up to 16 km of Permian—Cretaceous succession, and 2–3 km of pre-Permian sediments (Borissova et al., 2017; Owens et al., 2017). The Permian synrift succession reaches up to 10 km thick and is confined to a series of large half-graben (Figure 5; Borissova et al., 2017; Owens et al., 2017).

The structure of the sub-basin is mainly dominated by normal faults which accommodated oblique extension during the Permian and the Late Jurassic-Early Cretaceous. The seismic data shows a major south-west dipping fault dying out at mid-crustal level at around 15–18 km along the eastern basin margin and smaller-scale antithetic crustal faults associated with tilted blocks along the western edge of the basin.

The seismic data also shows strong reflectors dipping eastward at ~20–17 km interpreted to be the mantle-crust boundary (i.e. Moho discontinuity). The Moho flattens and shallows westward beneath the eastern onlap edge of the SDRs (~16 km). Outboard, more detailed analysis of the volcanic margin elements of the Wallaby-Zenith Large Igneous Province (SDRs, lava flows, volcanic complexes) is now possible (Borissova et al., 2015).

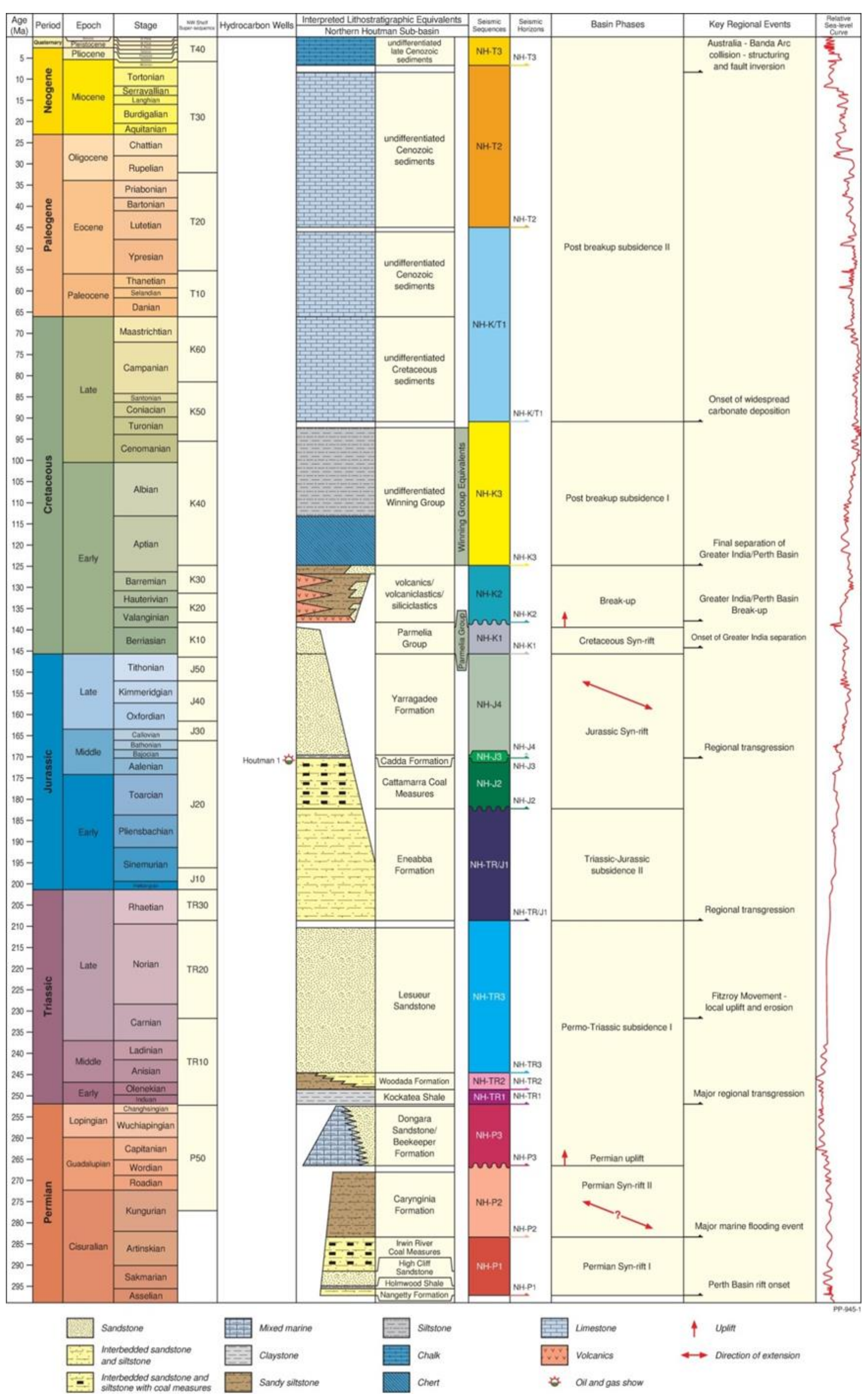

Figure 6. Tectonostratigraphic chart for the northern Houtman Sub-basin from Owens et al. (2017) based on mapping and interpretation of seismic survey GA349 and the regional stratigraphy of the Houtman Sub-basin, tied to the 2016 geological timescale (Ogg et al., 2016). NW Shelf Supersequences are updated from Marshall and Lang (2013).

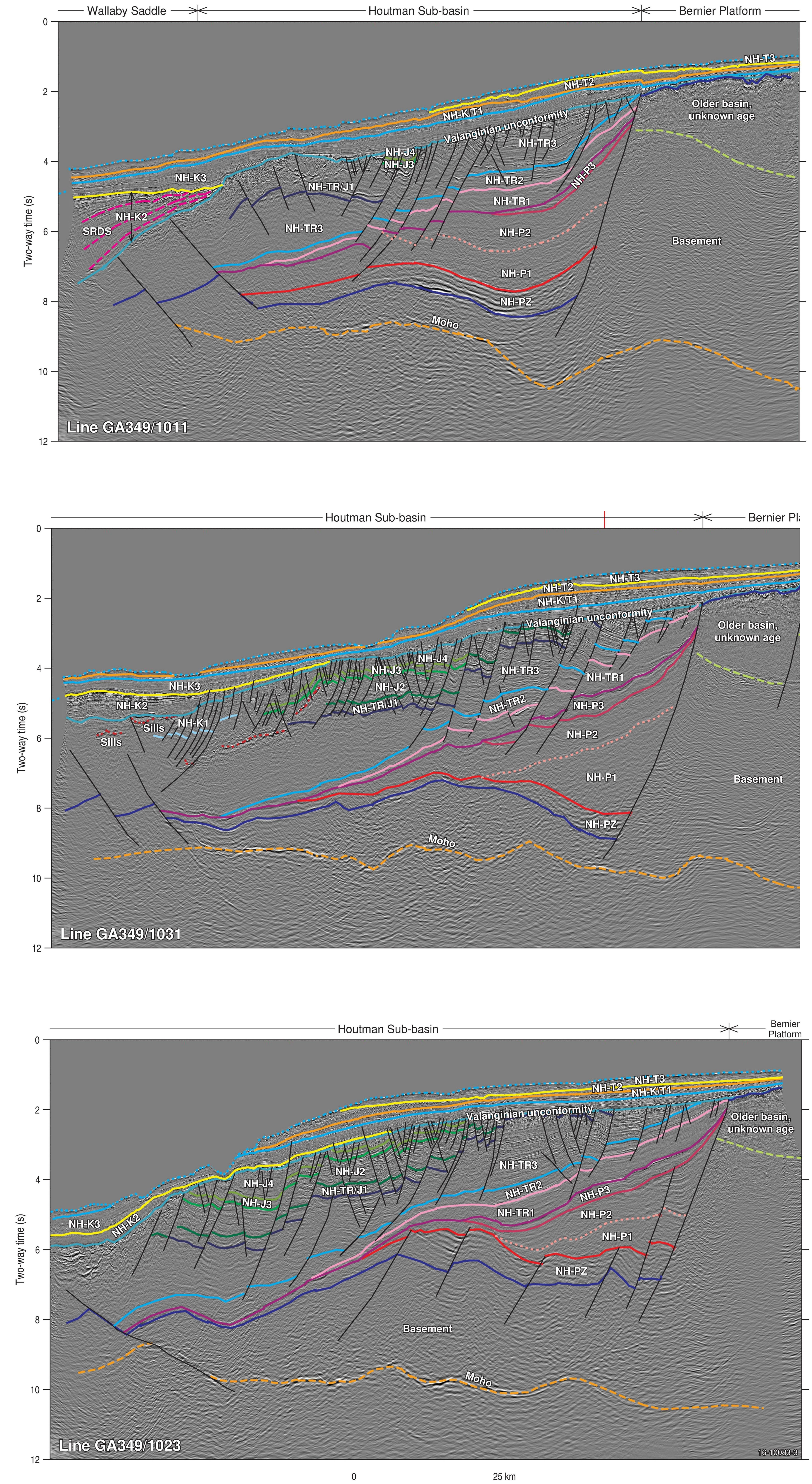

Figure 5. Interpreted seismic lines used to perform 2.5D forward modelling across the northern Houtman Sub-basin. See Figure 1 for seismic line locations.

The seismic sequences, interpreted ages and lithostratigraphic equivalents are shown on the tectono-stratigraphic chart in Figure 6. There are no wells within the northern Houtman Sub-basin, and as a result no direct age control on the sedimentary succession in study area. Three petroleum wells have been drilled in the southern part of the Houtman Sub-basin—Gun Island 1, Houtman 1 and Charon 1 (Figure 1), all of which reached total depth 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.

Potential field interpretation

Gravity modelling

Gravity modelling was carried out along five profiles coincident with seismic lines from the GA349 seismic survey in the north and a composite line in the south (Sanchez et al., 2016). Figure 7 shows the results for the three dip lines across the northern sub-basin. Free-air (FA) gravity and bathymetry profiles used in the modelling were extracted from satellite data (Figure 3) and the seismic interpretation was used to constrain the geometry of the sedimentary section (Figure 5). Density values of the sediments were averaged and adapted based on the range of lithological variability.

Modelling results (Figure 7) show that an elongated approximately north-south oriented, negative gravity anomaly in the northern Houtman Sub-basin corresponds to a large depocentre. To the northeast, the shallow basement of the Bernier Platform is coincident with a high amplitude gravity. The eastern edge of the Houtman Sub-basin shows a large crustal displacement with top basement occurring at 5–6 km on the Bernier Platform, deepening to a maximum depth of 16 km in the hanging wall. The basement underneath the Houtman Sub-basin is estimated at 13–16 km beneath the main depocentre. With a depth to Moho interpreted at ~16–18 km, there is <5 km of crust left beneath the basin. Thus, a hyperextended crust is interpreted beneath the Houtman Sub-basin which is likely to be highly faulted with numerous low-angle normal faults.

To the west, the transitional crust associated with the Wallaby Saddle is characterised by a lower amplitude positive gravity anomaly. This region encompasses the Early Cretaceous volcanic margin, clearly marked by the SDRs identified on the seismic data. Although basement is not clearly imaged beneath the SDRs, the geometry of the overlying sediment and volcanic sequences indicates the likelihood of basement-involved structures with east-dipping fault blocks. The presence of a broad, dense Lower Crustal Body (LCB - 3.05g/cc) beneath this transition zone is required to model the observed FA gravity signal.

Magnetic modelling

Magnetic modelling was performed along the 135/10 survey line (Hackney, 2012), following a profile crossing the Bernier Platform, the Houtman Sub-Basin, the Wallaby Saddle and the Perth Abyssal Plain (Figure 8 Sanchez et al., 2016). Key horizons and magmatic features identified on the seismic data were used to constrain model geometry.

Results suggest that most of the long wavelength magnetic signal beneath the Houtman Sub-basin and Bernier Platform is the result of different magnetic properties of the upper crust and mid-crustal rocks. The medium to short wavelength of the magnetic signal in the outer basin represent the abundant volcanic rocks (SDRs and sills) interpreted on the seismic. The long wavelength signal across the Wallaby Saddle provides further evidence of a possible LCB located underneath heavily intruded continental crust. The Perth Abyssal Plain shows a short wavelength magnetic signal, reflecting the highly remanent magnetisation of the oceanic crust.

Two deep, elongated north-south and northeast-southwest trending bodies occur in the deepest part of the Houtman Sub-basin, associated with a broad, negative magnetic anomaly. These bodies have significantly different susceptibilities to the magnetic body beneath the Bernier Platform, suggesting the location of the basin bounding fault coincides with a major change in basement composition.

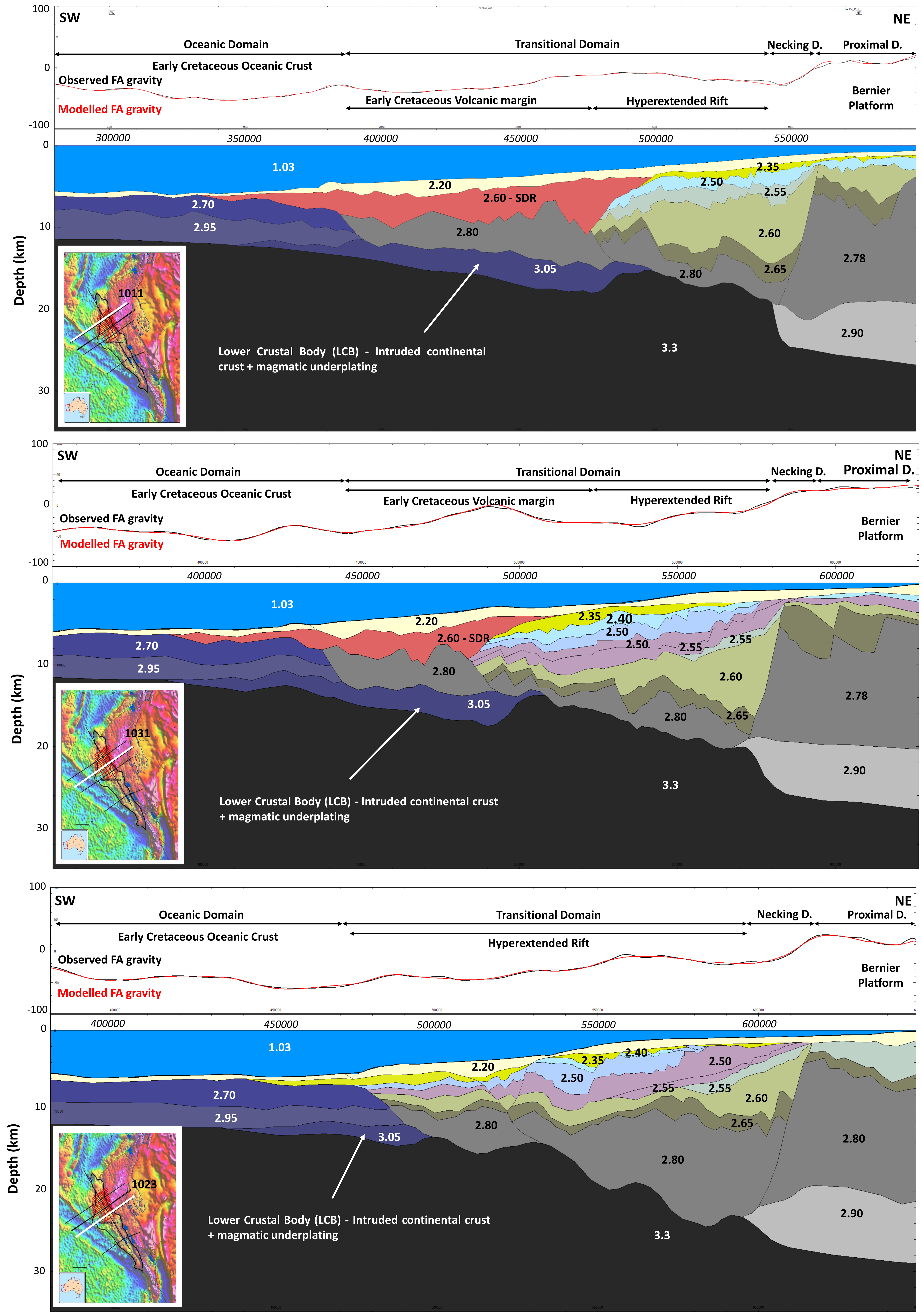

Figure 7. Gravity models along 3 profiles coincident with seismic lines from the GA349 survey.

The 2.5D forward model was performed using ModelVision™ (v.15) by Tensor Research which computes the gravity field effect of source bodies along a section as a function of 3D location and physical properties. The FA gravity signal was modelled by minimizing the residual between the measured and modelled values. '2.5D' bodies were extended 250 km along strike on both sides of the line. All lines were extended beyond the AOI in order to avoid "edge" effect anomalies and assure continuity of the modelled signal at the boundaries. For the purposes of modelling the crustal structure and broad basin features, a residual value of ~5 mGal was considered acceptable. To account for the regional tfield, a constant shift was applied to the data.

The proposed models are based on geologically-driven density contrast and basement thickness. They are not a unique solution, but represent one possibility that is consistent with the data and should not be used in isolation to draw definitive conclusions on a single geometry or lithology distribution. For further details on modelling procedure, see Sanchez et al. (2016).

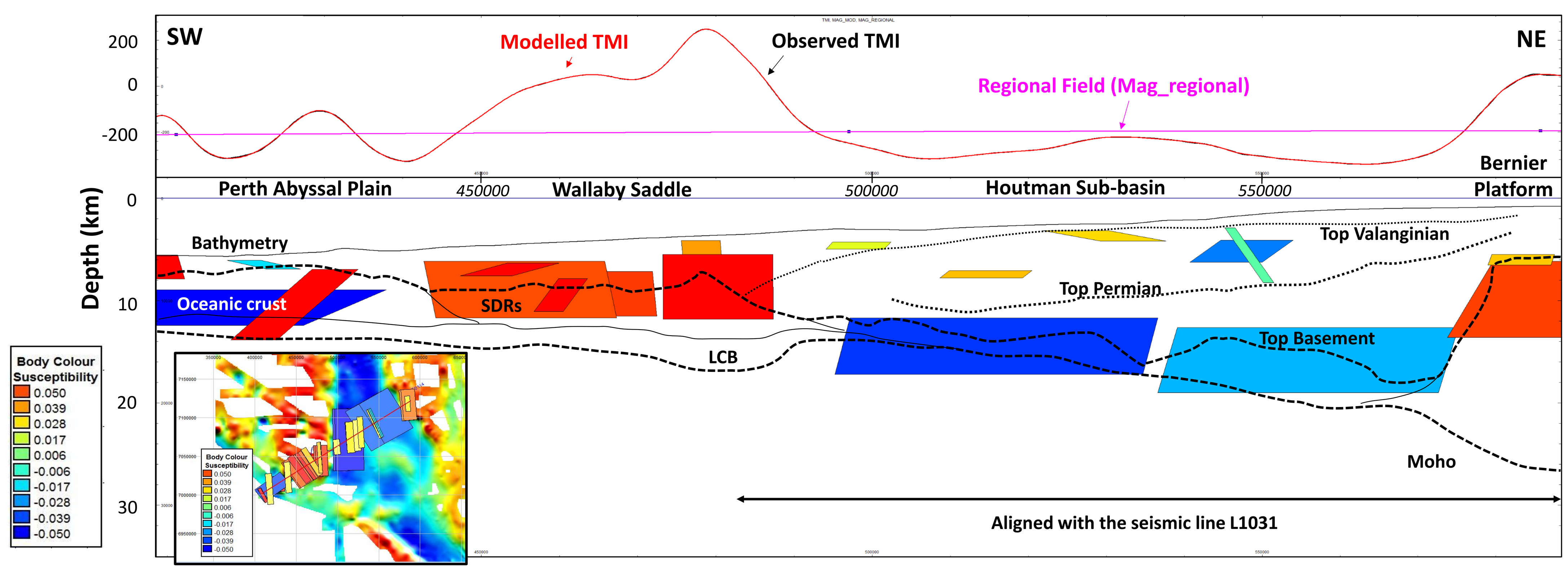

Figure 8. Magnetic modelling was performed along the 135/10 survey line (GA310, Hackney, 2012), paralleling the GA349 seismic line 1031. See Figure for line location.

Magnetic model bodies are coloured by magnetic susceptibility. Insert: Total Magnetic Intensity (TMI) image of the Houtman Sub-basin showing magnetic model bodies coloured by magnetic susceptibility. LCB: Lower Crustal Body. Depths are derived by modelling profiles through anomalies of interpreted geological source. This procedure allows the depth estimation to be closely integrated into the interpretation. Magnetic modelling was computed using the mean sea level. Modelling was conducted using the ModelVision™ software package developed by Tensor Research.

For further details on modelling procedure, see Sanchez et al. (2016).

Tectonic evolution

Polyphase rifting

A regional 3D geological model of the northern Houtman Sub-basin (Figure 9) was constructed from the interpreted seismic data (Figure 5), which was used to generate isochores maps of the main basin phases (Figure 10) and to reconstruct the basin evolution through time (Figure 11). Subsidence analysis was used to investigate the variation in extension factor across the margin associated with each rifting event (Figure 12). Results highlight how the margin developed through a combination of both Permian and Late Jurassic-Early Cretaceous extensional events. The resulting hyperextension and thick pre-Cretaceous sedimentary successions are consistent with a magma-poor system.

A large magmatic event is associated with Early Cretaceous breakup along some segments of the west Australian margin (Symonds et al., 1998). In the study area, the voluminous breakup-related volcanism is restricted to the Wallaby Saddle featuring thick SDR successions (Borissova et al., 2015). Both the magnetic and gravity modelling results provide better definition of the transition between the non-volcanic margin of the northern Perth Basin and volcanic province of the Wallaby Plateau. Early Cretaceous volcanism associated with the formation of SDRs along the breakup axis have modified the nature of the underlying crust at the western edge of the sub-basin. Deep magmatic bodies linked to the SDRs may have added mafic material to the hyperextended crust, thickening it distally.

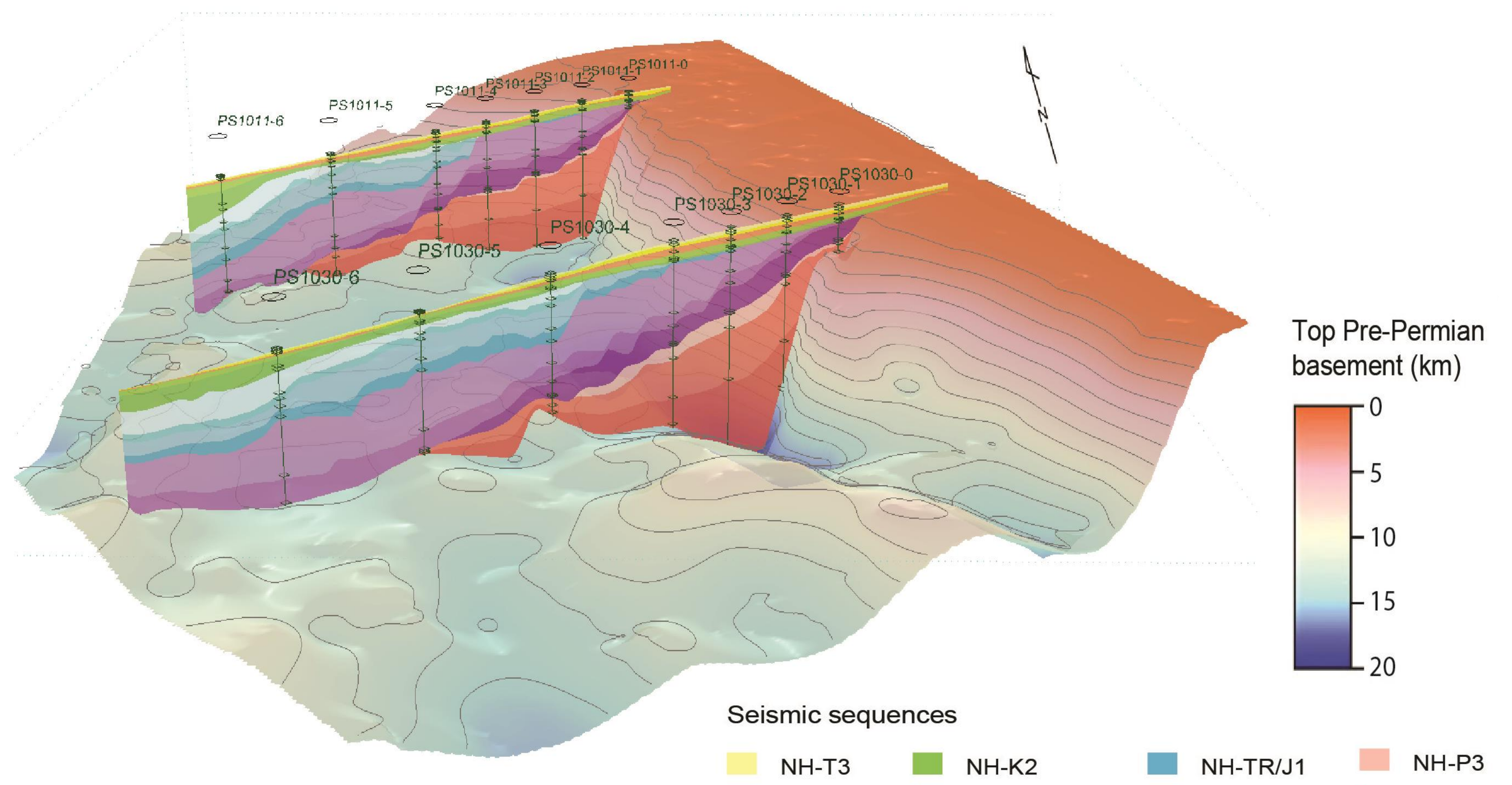

Figure 9. 3D perspective image of the regional 3D northern Houtman Sub-basin geological model.

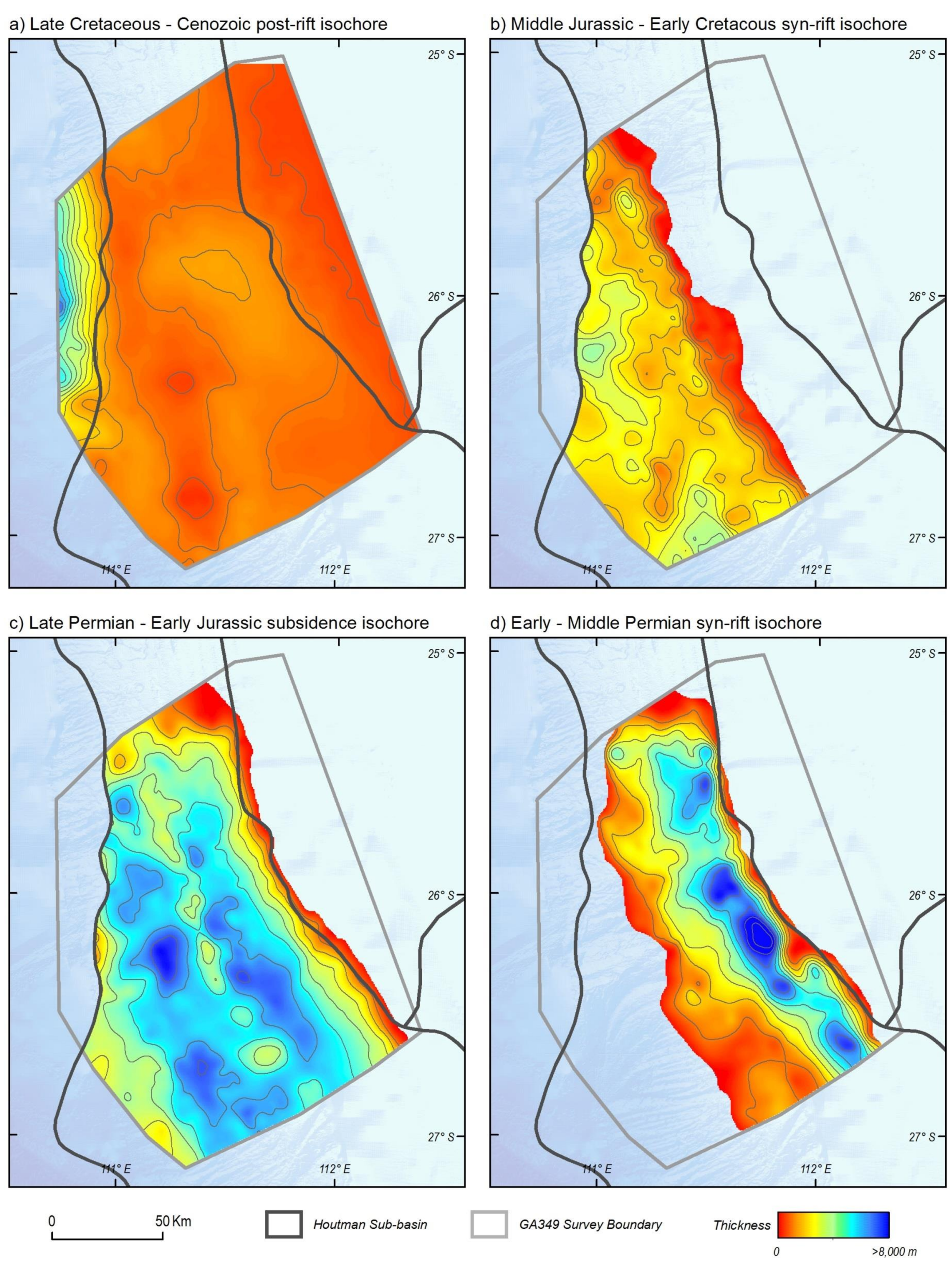

Figure 10. Gross thicknesses of the mapped major tectono-stratigraphic units representing major basin phases in the northern Houtman Sub-basin: a) Late Cretaceous to Cenozoic post-rift (NH-K2–NH-T3); b) Early Jurassic–Early Cretaceous rifting (NH-J2–NH-K1); c) Late Permian–Early Jurassic subsidence (NH-P3–NH-TR/J1); and d) Early–Middle Permian rifting (NH-P1–NH-P2). See also Owens et al. (2017).

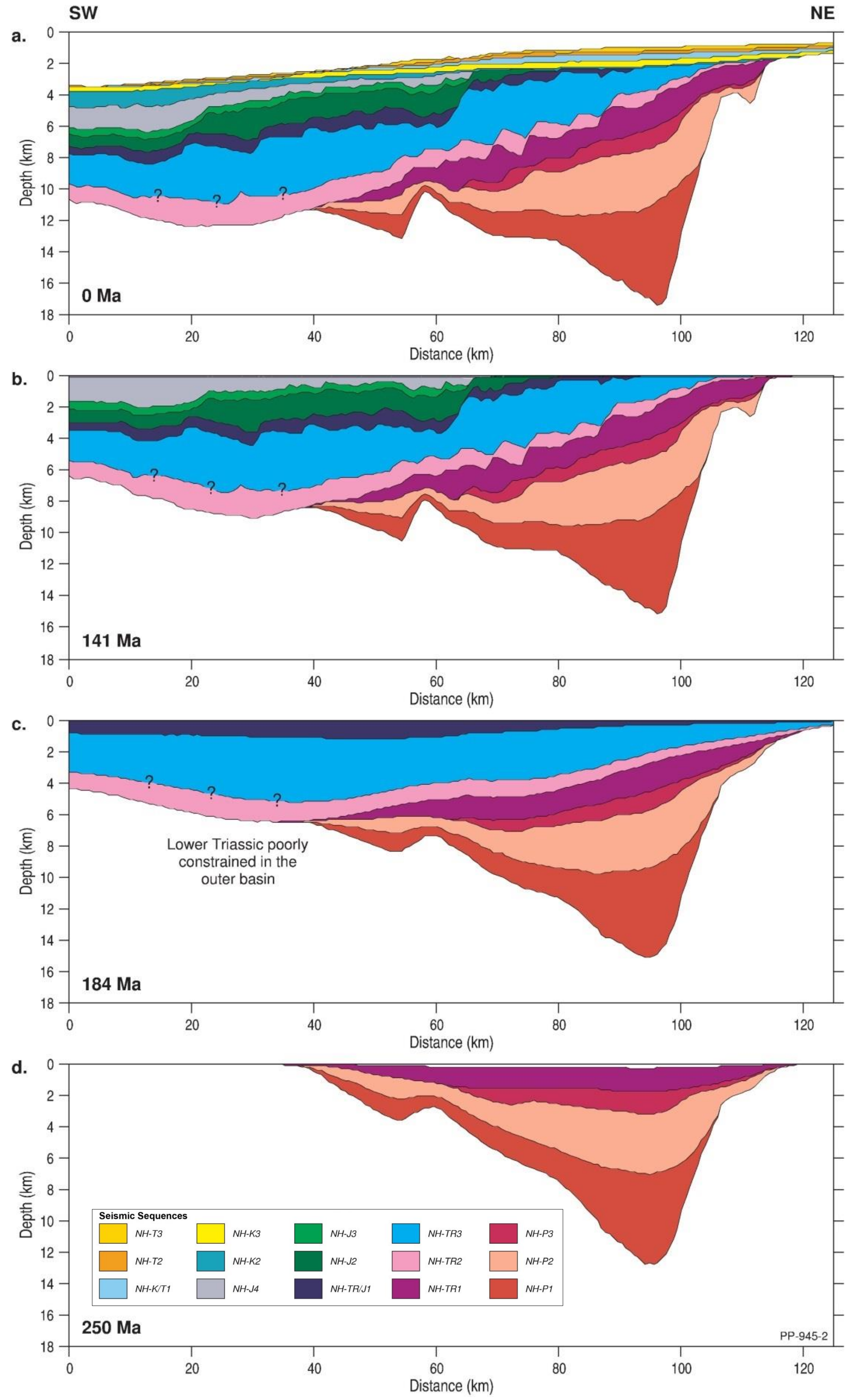

Figure 11. Regional time-slice cross-sections through the northern Houtman Sub-basin (line GA349/1030), showing regional basin evolution. See Figure 1 for line location.

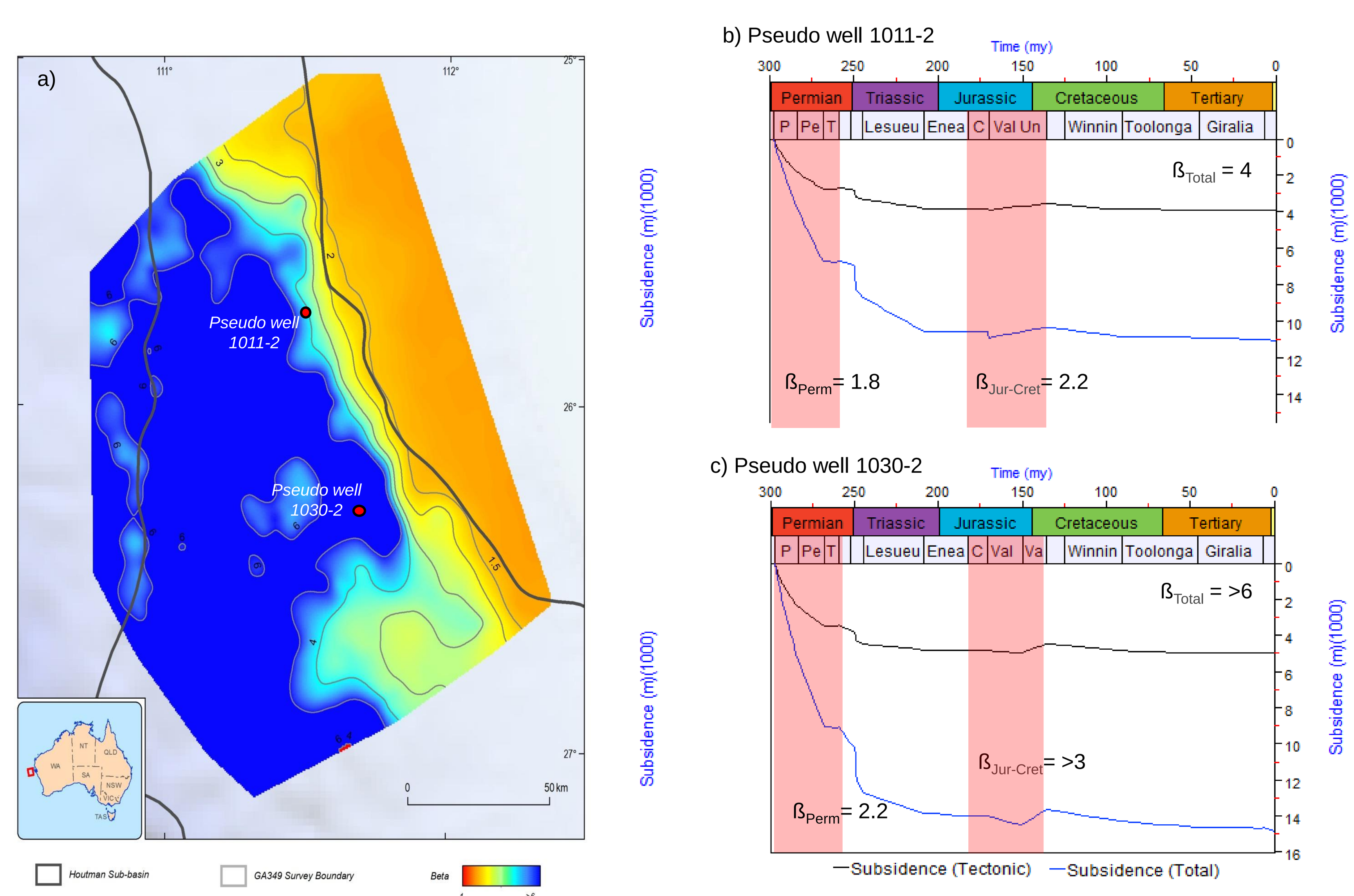

Figure 12. a) Total lithospheric extension ($ß_{total}$) calculated for the northern Houtman Sub-basin. b-c) Subsidence curves for 2 pseudo-wells, located over the main Permian graben, with estimated lithospheric extension for both Permian ($ß_{Perm}$) and Jurassic-Early Cretaceous rifting events ($ß_{Jur\text{-}Cret}$).

$ß_{total}$ = original crustal thickness/ present day crustal thickness. An original crustal thickness of 32 km was used based on gravity modelling results (Figure 7). Pseudo-well age-depth data was sourced from the seismic interpretation and tectonostratigraphic chart (Figures 5 and 6). Total subsidence was calculated accounting for decompaction and the relative contribution of tectonic subsidence was estimated using back-stripping (assuming Airy isostasy). $ß_{Perm}$ was estimated through comparison with theoretical McKenzie rift models. $ß_{Jur\text{-}Cret} = ß_{total} / ß_{Perm}$. Modelling was conducted using Genesis s (www.zetaware.com).

Discussion

Structural domains

The top Proterozoic basement and Moho grids derived from seismic interpretation and validated using the potential field modelling map out total sediment and crustal thickness across the northern sub-basin (Figure 13). Different structural domains can be identified across the margin based on the degree of crustal attenuation and the presence of significant volumes of volcanics (Figure 14).

- The proximal domain beneath the Bernier Platform of the Southern Carnarvon Basin is characterised by little crustal thinning.
- The necking domain is characterised by a narrow zone at the eastern boundary of the Houtman Sub-basin, where extended to hyperextended crust formed during successive extensional events. This extreme crustal thinning from 30–35 km to less than 5 km occurred mostly along major west-dipping faults and possible minor antithetic east-dipping faults resulting in low-angle, tilted continental blocks.
- The highly extended to hyperextended domain (Distal and Outer Domain) refers to the zone where crust is less than 10 km thick. Serpentinisation at the top of mantle may have occurred beneath the basement of the hyperextended domain.
- The transitional domain at the western sub-basin boundary corresponds to the volcanic margin and includes a thick (8–10 km) SDR wedge, volcanics and volcanoclastics related to Early Cretaceous breakup. Basement below the SDR wedge may include heavily intruded continental crust and serpentinised mantle.
- The oceanic domain to the southwest of the Wallaby-Zenith Fracture Zone is well characterised by magnetic anomaly stripes of Early Cretaceous age (Gibbons et al., 2012).

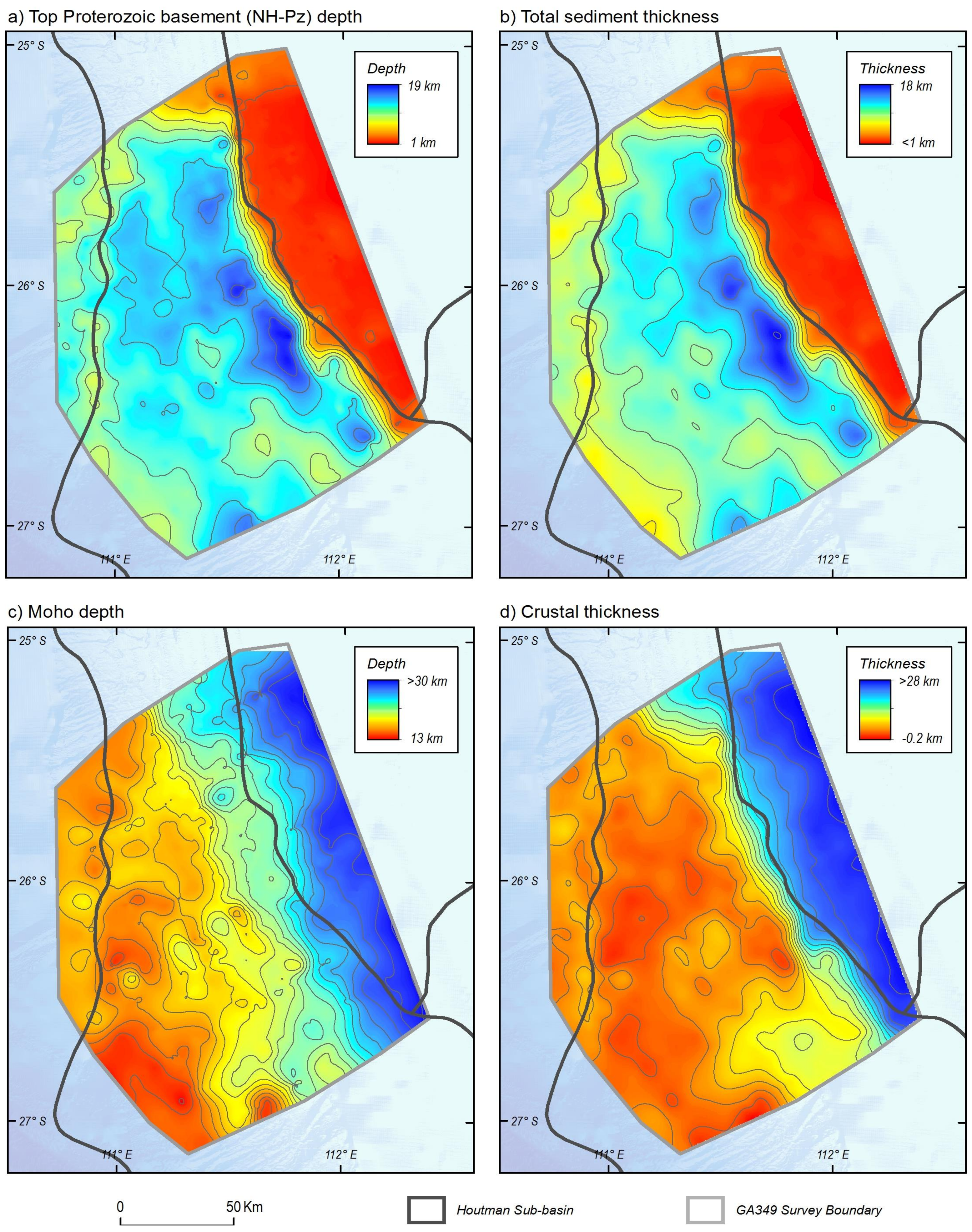

Figure 13. a) Depth to top Proterozoic basement; b) total sediment thickness; c) Moho depth; and, d) crustal thickness.

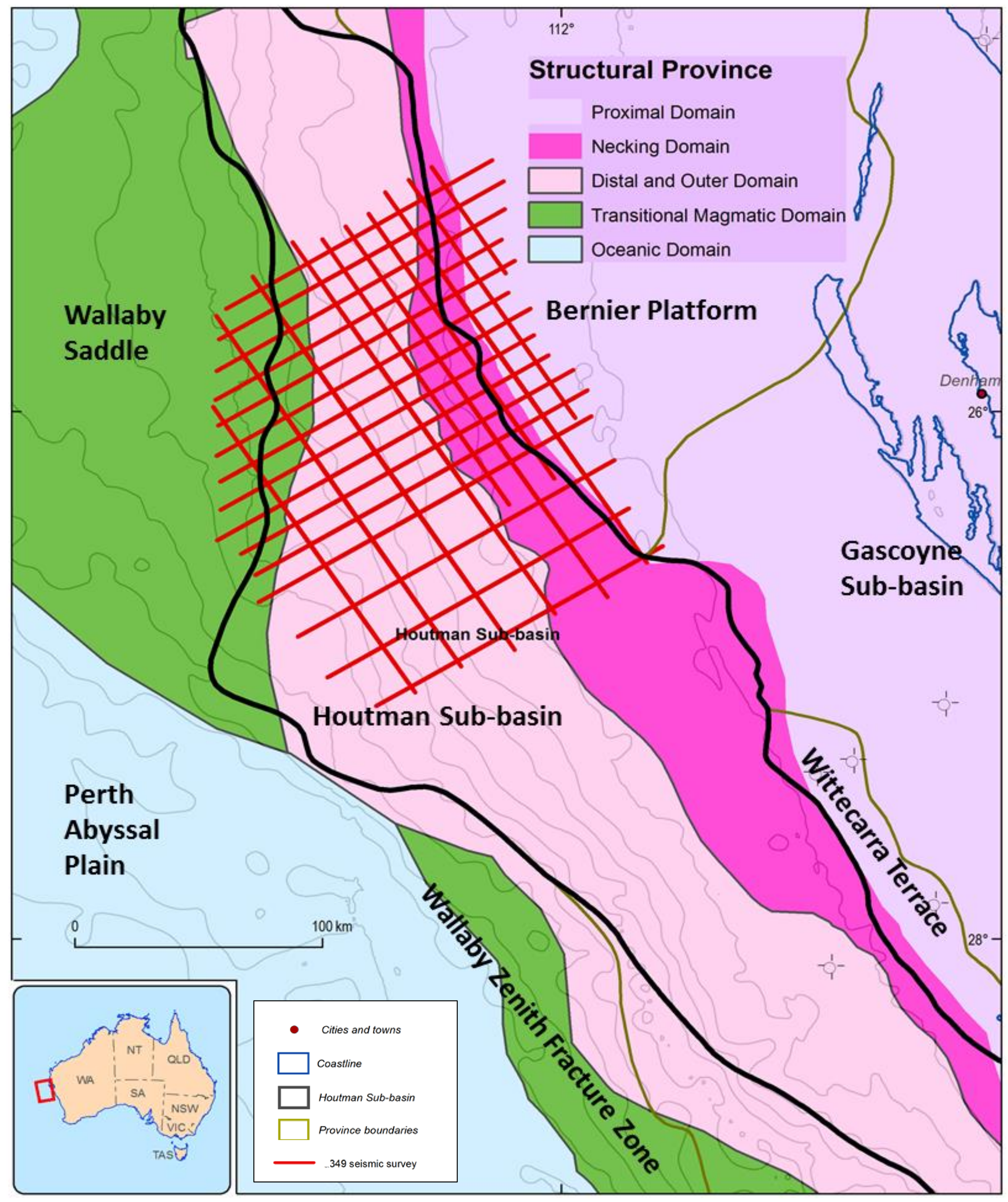

Figure 14. Interpreted structural domains of the northern Houtman Sub-basin.

Basement composition and structural inheritance

Magnetic modelling suggests that the nature of the basement underlying the proximal domain (Southern Carnarvon Basin and Wittecarra Terrace) and the hyperextended domain beneath the central Houtman Sub-basin are different and that a major Proterozoic basement terrane boundary lies beneath the necking domain (Figure 14). Proterozoic Pinjarra Orogen basement beneath the Perth Basin is characterised by a negative magnetic anomaly similar to the one observed beneath the Houtman Sub-basin. Thus, a north-westward extension of the Pinjarra mobile belt beneath the Houtman Sub-basin may be suggested, although there is no clear north-westward continuation of the magnetic anomaly beyond the northern part of the sub-basin.

Conclusions

The integrated geophysical interpretations presented here significantly improve our understanding of the tectonic evolution, structural architecture and major depositional phases of this part of Australia's western margin.

Hyper-extended margins are generally magma poor, where as crustal thickness remains thicker along magma rich margins. The northern Houtman Sub-basin lies at the transition between magma rich and magma poor margin segments. Overall basin architecture and crustal structure consistent with a magma poor system, with hyperextension resulting from a combination of multiple rifting phases. Volcanic margin development began later, immediately prior to the separation of Greater India and Australia.

Structural inheritance played an important role in basin development. It is likely that Early Permian graben formation was influenced by rheological contrasts in the underlying Proterozoic basement. The distribution of Permian rifts in turn further localised strain during Jurassic—Early Cretaceous rifting, strongly influencing the location and style of rifted margin development during continental breakup.

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