

Tectono-stratigraphic development of the northern Houtman Sub-basin, Perth Basin

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SUMMARY

The northern Houtman Sub-basin is an under-explored region of Australia's western 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. In 2014-15, Geoscience Australia acquired new 2D seismic data (GA-349) across the northern Houtman Sub-basin to assess its hydrocarbon prospectivity.

This study integrated interpretation of the recently acquired GA-349 survey, with Geoscience Australia's existing regional interpretation of the Houtman and Abrolhos sub-basins, to develop a 2D structural and stratigraphic interpretation for the study area. As there are no wells in the northern Houtman sub-basin, the age and lithologies of the mapped sequences were derived from regional mapping, stratal relationships and seismic facies. The new data clearly images a large depocentre, including a much thicker Paleozoic section (up to 13 km) than previously recognised. Extending the length of the inboard part of northern sub-basin are a series of large half-graben (7-10 km thick), interpreted to have formed as a result of Permian rifting. Overlying these half-graben, and separated by an unconformity, is a thick succession (up to 6 km) interpreted to represent a subsequent late Permian to Early Jurassic phase of the thermal subsidence. A second phase of rifting started in the Early Jurassic and culminated in Early Cretaceous breakup. The sedimentary succession deposited during this phase of rifting is highly faulted and heavily intruded in the outboard part of the basin, adjacent to the Wallaby Saddle, where intrusive and extrusive complexes are clearly imaged on the seismic. In contrast to the southern part of the Houtman Sub-basin, which experienced rapid passive margin subsidence and regional tilting after the Valanginian breakup, the northern sub-basin remained mostly exposed sub-aerially until the Aptian while the Wallaby Zenith Fracture Zone continued to develop.

Key words: Houtman Sub-basin, North Perth Basin, Tectonostratigraphy, Petroleum prospectivity.

INTRODUCTION

The Houtman Sub-basin is the largest structural element in the Perth Basin, Western Australia, covering an area of 52,900 km² (Copp *et al.*, 1994). It is an elongate, NW-SE trending depocentre, extending approximately 700 km (Figure 1). Sediment thickness is variable, but is interpreted to reach up to 19 km in the northern sub-basin (Borissova *et al.*, 2017). Despite a long and continuing record of exploration and production in the broader Perth Basin, prior to Geoscience Australia's (GA) acquisition of new 2D seismic data in 2014-15, data coverage in the northern Houtman Sub-basin was sparse and seismic data coverage was limited (Totterdell *et al.*, 2014). The existing data suggested that the northern Houtman Sub-basin contains only a relatively thin (5-6 km) Paleozoic section. The new GA-349 seismic data, acquired with an 8 km streamer with a deep-tow, reveals deeper crustal architecture for the northern Houtman Sub-basin down to 25-30 km. The new data clearly images a large depocentre, controlled by basement-involved faults, with a maximum thickness of 19 km, including a thick Paleozoic section (up to 13 km). The new data allows mapping of the Moho, basement, pre-rift sequence and major syn-rift and post-rift sequences (Borissova *et al.*, 2017). Geological and geophysical modelling of the GA-349 seismic data and its initial interpretation undertaken by Sanchez *et al.* (2016) was used to constrain and refine the interpretation of the overall architecture of the depocentre. Magnetic modelling results were also used to gain an improved understanding of the distribution of magmatic rocks. Integration of seismic interpretation of the GA-349 data with GA's regional seismic interpretation of the northern Perth Basin allowed us to assign ages and lithological characteristics to the mapped seismic sequences and to develop a tectonostratigraphic framework for the study area.

Regional studies of the northern Perth Basin (Bradshaw *et al.*, 2003; Rollet *et al.*, 2013a, 2013b) have shown that the depocentres formed as a result of two major stages of rifting, the first in the Permian and the second in the Early Jurassic-Early Cretaceous. Permian rifting led to the development of NNW-oriented half graben across the northern Perth Basin, including the northern Houtman Sub-basin (Jones *et al.*, 2011; Norvick, 2004; Rollet *et al.*, 2013a, 2013b). Early Jurassic-Early Cretaceous rifting led to accumulation of thick stratigraphic successions in the outboard part of the central Houtman Sub-basin and the adjacent Zeewyck Sub-basin, and culminated in continental breakup of Australia and Greater India in the Valanginian (Gibbons *et al.*, 2012; Hall *et al.*, 2013). In the far north, where the new data is located, breakup included the development of a Large Igneous Province over the Wallaby Plateau and the Wallaby Saddle (Symonds *et al.*, 1998).

METHODS AND RESULTS

This study integrated the interpretation of GA-349 seismic data, with regional interpretation of the Houtman Sub-basin which was underpinned by ties to adjacent wells, potential field data, and geophysical modelling to develop a regional 2D structural and stratigraphic interpretation. The seismo-stratigraphic interpretation of Geoscience Australia's new GA-349 seismic data was used to define the major seismic sequences and associated sequence boundaries across the study area (Borissova *et al.*, 2017). A total of 17 sequences were identified and were assigned probable ages and lithostratigraphic equivalents (Figure 4) through regional correlation with wells in the Houtman and Abrolhos Sub-basins and the Southern Carnarvon Basin. Age assignments for: i) all pre-breakup sequences were based on the associated biostratigraphic definitions of the corresponding sequences of Jorgensen *et al.* (2011), and ii) all post-breakup sequence ages were largely assigned according to the biozonation definitions as summarised by Kelman *et al.* (2013) for the Northern Carnarvon Basin.

The tectonostratigraphic development of the northern Houtman Sub-basin from the Permian to the present can be broken down into five main basin phases, each of which is discussed below. Figure 2 shows a reconstructed cross-section across the northern Houtman Sub-basin (line GA349/1030) at four stages of basin development from 250 Ma to the present. Figure 3 shows isochore maps of four major tectonostratigraphic packages. Figure 4 presents a summary of the tectonostratigraphy of the northern Houtman Sub-basin.

Early–middle Permian rifting

A series of large half-graben (7–10 km thick) extend the length of the inboard part of northern sub-basin (Figure 2, Figure 3). These half-graben are bounded by large NW to SE trending, SW dipping en-echelon faults with >10 km throw (Southby *et al.*, submitted) and separate the northern Houtman Sub-basin from the Bernier Platform. NH-P1 and NH-P2 are mapped as two, eastward thickening packages which are interpreted to represent early–middle Permian syn-rift deposition (Figure 4). The base of NH-P2 is interpreted as an unconformity and in some cases it is observed to onlap the underlying NH-P1 sequence.

There are no direct lithostratigraphic or age constraints on seismic sequences NH-P1 and NH-P2. Based on the stratigraphy of the broader northern Perth Basin, sequence NH-P1 is tentatively interpreted to contain Asselian–Artinskian glacial to proglacial marine sediments of the Nangetty Formation and Holmwood Shale, and glacially influenced paralic to fluvial and coal-rich sequences equivalent to the High Cliff Sandstone and Irwin River Coal Measures (Jones *et al.*, 2011; Mory and Iasky, 1996; Norvick, 2004). However, an alternative correlation is for sequence NH-P1 to be equivalent in age to the Silurian, Devonian and/or early Carboniferous successions of the onshore Southern Carnarvon Basin (Mory *et al.*, 2003). The base of NH-P2 is interpreted to correspond to a major marine flooding event that occurred across the north western Australian margin (Haig *et al.*, 2014), and peaked in the Artinskian in the Perth Basin (Jones *et al.*, 2011) where this event is represented by the base of the Carynginia Formation (Haig *et al.*, 2014). The NH-P2 sequence is, therefore, interpreted to consist of shallow marine shales equivalent to the Cisuralian–Guadalupian Carynginia Formation (Figure 4), which is widespread in the northern Perth Basin (Jorgensen *et al.*, 2011; Mory and Iasky, 1996).

Late Permian–Early Jurassic thermal subsidence

A thick succession (up to 6 km) overlies the Permian syn-rift sequences (Figure 2, Figure 3) and is interpreted to represent a late Permian to Early Jurassic phase of thermal subsidence which resulted in the formation of a broad sag basin. This succession is separated from the underlying syn-rift succession by a prominent unconformity (NH-P3 seismic horizon), correlated to the regional middle Permian unconformity (Thomas, 2014), and is comprised of five seismic sequences; NH-P3, NH-TR1, NH-TR2, NH-TR3 and NH-TR/J1 (Figure 4).

Seismic sequence NH-P3 is mapped above the Permian graben as a relatively transparent 500–1000 m thick package with a sag-fill geometry (Figure 2d). The sequence is interpreted to comprise early post-rift sands equivalent to the upper Permian Dongara Sandstone and mixed shales, limestones and clastics equivalent to the upper Permian Beekeeper Formation. NH-TR1 is mapped above the regional Permian unconformity and overlies sequence NH-P3, where it is present (Figure 2d). It blankets the Permian half-graben where it reaches a maximum thickness of 1500 to >2000 m. On the basis of: i) stratigraphic position, ii) seismic character, and iii) an indirect basal tie to Livet 1 on the Wittecarra Terrace (~100 km to the SE), NH-TR1 is interpreted to be equivalent to the Lower Triassic Kockatea Shale that is widespread in the Perth Basin (Figure 4). The Kockatea Shale comprises shale, claystone and siltstone, with minor sandstone and limestone (Playford *et al.*, 1976) deposited in a shallow marine environment and records a major marine transgression (Jones *et al.*, 2011; Jorgensen *et al.*, 2011). This sequence may also include a highly prospective source rock – the Hovea Member (Thomas and Barber, 2004). Favourable conditions for deposition of a Hovea Member equivalent would likely have been present in localised depocentres, where post-rift thermal subsidence was the greatest.

The seismic sequences overlying NH-TR1 are interpreted to be equivalent to the Lower–Middle Triassic Woodada Formation (NH-TR2), Middle–Upper Triassic Lesueur Sandstone (NH-TR3) and Upper Triassic–Lower Jurassic Eneabba Formation (NH-TR/J1) (Figure 2c and Figure 4). In this part of the succession the character of the seismic is variable. Inboard the reflectors are high amplitude and continuous. Further outboard, as the interval deepens, reflectors are lower amplitude more discontinuous making interpretation harder and resulting in a loss of confidence in mapping. The NH-TR2, NH-TR3, NH-TR/J1 sequences are uniformly thick (about 4–5 km) throughout the central parts of the northern Houtman Sub-basin but thin to the east, where there is partial erosion by the Valanginian unconformity (NH-K1 seismic horizon). These sequences are interpreted as a gradual regional regression culminating in a lowstand in the Late Triassic–Early Jurassic (Jones *et al.*, 2011; Jorgensen *et al.*, 2011), with deltaic to fluvial siltstones and sandstones of the Woodada

Formation transitioning to fine- to medium- and coarse-grained fluvial sandstones of the Lesueur Sandstone and fine- to very coarse-grained lowstand sandstones of the Eneabba Formation (Jorgensen *et al.*, 2011). Further south, in the offshore parts of the basin, the fluvio-deltaic system responsible for the deposition of the Woodada and Lesueur sequences had a northwards flow resulting in finer grained lithologies in the north, particularly for the Woodada Formation (Jones *et al.*, 2011; Mory and Iasky, 1996). Therefore, if these sequences (NH-TR2 and NH-TR3) are of the same depositional system, then finer lithologies may be expected in the northern Houtman Sub-basin.

Early Jurassic–Early Cretaceous rifting

A second phase of rifting from the Early Jurassic–Early Cretaceous consists of four seismic sequences; NH-J2, NH-J3, NH-J4 and NH-K1 (Figure 4). The succession is easily recognisable on seismic and is characterised by high frequency, high continuity reflectors and a large number of closely spaced faults, many of which are listric. The geometry of the Jurassic sequences shows that, similar to the southern Houtman and Zeewyck sub-basins (Rollet *et al.*, 2013b), the main Jurassic depocentre was located outboard of the Permian graben (Figure 2b; Borissova *et al.*, 2017). The Lower Jurassic to Lower Cretaceous syn-rift succession is thickest (about 4 km) in the southern part of the northern Houtman Sub-basin and thins to the north (Figure 3), where only the lower part of the Jurassic succession (NH-J2 and NH-J3) is present and most of the upper part (NH-J4) is missing. Inboard, this succession is thin or absent as a result of non-deposition and/or erosion during the Valanginian (NH-K2 seismic horizon).

Based on ties to the regional seismic interpretation and wells in the southern Houtman Sub-basin (Houtman-1 and Charon-1), the Lower Jurassic–Lower Cretaceous sequences are interpreted to be equivalent to the Cattamarra Coal Measures (NH-J2), Cadda Formation (NH-J3), Yarragadee Formation (NH-J4) and Parmelia Group (NH-K1). The base of the seismic sequence NH-J2 (Cattamarra Coal Measures) is a regional unconformity corresponding to the onset of the Jurassic rifting (Rollet *et al.*, 2013a). The rift-fill succession is predominantly non-marine, comprising fluvial sandstones, carbonaceous shales and coals, with the exception of the Middle Jurassic sequence NH-J3 (Cadda Formation equivalent), which represents a short-lived marine incursion (Jorgensen *et al.*, 2011; Mory and Iasky, 1996).

In the western part of the Houtman Sub-basin depocentre, adjacent to the Wallaby Saddle, the Jurassic–Lower Cretaceous section is heavily intruded and in the northern part of the depocentre underlies the Seaward Dipping Reflector Sequences (SDRSs) that formed during the Valanginian breakup (Borissova *et al.*, 2017). The base of the NH-K1 sequence (Parmelia Group) appears to be an angular unconformity and is interpreted to represent the latest stage of syn-rift development during the Early Cretaceous. However, the NH-K1 sequence is only present on a few lines within the study area and its spatial distribution is not well constrained. Nevertheless, just to the south of the study area mapping of NH-K1 indicates the presence of an Early Cretaceous depocentre in the outmost part of the northern Houtman Sub-basin. High amplitude seismic reflectors, interpreted as likely lava flows, dykes and sills, are commonly associated with this sequence and impede interpretation.

Early Cretaceous–Cenozoic breakup and transform-to-passive margin development

Continental breakup of Australia and Greater India occurred during the Early Cretaceous. In the northern Houtman Sub-basin separation was accommodated by the development of the Wallaby-Zenith Fracture Zone (Gibbons *et al.*, 2012; Hall *et al.*, 2013; Norvick, 2004) and transform motion is interpreted to have continued from the Valanginian until at least the late Aptian (Borissova *et al.*, 2017). The Valanginian breakup unconformity is mapped at the base of the NH-K2 sequence. It is an angular unconformity which marks the boundary between the underlying highly structured syn-rift section, and the overlying predominantly unstructured and conformable post-rift section. Sequence NH-K2 is interpreted to have developed as breakup proceeded and the volcanic margin evolved and contains thick volcanic and volcanoclastic successions characterised by SDRSs. Lava flows and individual volcanoes are clearly imaged in the seismic data within this sequence, which is unique to the northern Houtman Sub-basin. The NH-K2 sequence deepens to the west and varies in thickness from thin to absent inboard to several kilometres thick in the western outboard part. The rapid thickening along the western boundary is due to the emplacement of SDRSs. The distribution of interpreted SDRSs and major sill and dyke complexes has been confirmed by magnetic modelling of one GA-349 survey seismic line (Sanchez *et al.*, 2016).

The post-rift succession is 500–1500 m thick over most of the study area (Figure 3a), and can be broadly classified into two major basin phases: an Aptian to Turonian early passive margin phase dominated by siliciclastic deposition; and a Turonian to Recent late passive margin phase dominated by calcareous deposition. Four major sequences were mapped: NH-K3, NH-K/T1, NH-T2 and NH-T3 (Figure 2a). Each sequence relates to a different phase of passive margin development and each are primarily linked to tectonic events. Constraints on ages and lithologies of the post-rift are limited; therefore, both onshore wells and outcrop studies and limited offshore wells in the Perth, Southern Carnarvon and Northern Carnarvon basins, were considered in the interpretation. The post-rift succession is interpreted to include equivalents to the Winning Group (Birdrong Sandstone, Muderong Shale, Windalia Radiolarite and Gearle Siltstone), the Toolonga Calcilutite, the Cardabia Calcarenite, Giralia Calcarenite, Mandu Formation, Tulki Limestone and Trealla Limestone (Owens *et al.*, in prep).

CONCLUSIONS

New 2D seismic reflection data acquired by Geoscience Australia in 2014–15 (survey GA-349) has been used to reassess the tectonostratigraphic evolution, structural architecture, major depositional phases the frontier northern Houtman Sub-basin. Interpretation of these data has enabled mapping of the Moho, basement, major faults and sequences. Regional correlation of the seismic stratigraphy has enabled development of a new tectonostratigraphic framework for the Houtman Sub-basin, which suggests the depocentre contains up to 19 km of Permian–Cenozoic succession, including a much thicker Paleozoic

section than previously thought. Permian rifting produced a series of large half-graben (7-10 km thick) that extend the length of the inboard part of northern sub-basin. A thick Upper Permian to Lower Jurassic succession (up to 6 km) overlying these half-graben is interpreted to represent a phase of the thermal subsidence following uplift and erosion at the end of the Permian. A second phase of rifting started in the Early Jurassic and culminated in the breakup in the Early Cretaceous. The breakup was accompanied by extensive volcanism initiated by the Large Igneous Province of the Wallaby and Exmouth plateaus. After the final separation of the Wallaby Plateau from the Greater India (?Aptian) the area started to subside and a passive margin developed. Despite the absence of well control in the northern Houtman sub-basin, regional integration of the seismic and well data for the whole offshore northern Perth basin have allowed us to build tectonostratigraphic framework reflecting specifics of the area and to undertake preliminary assessment of the petroleum prospectivity of this frontier basin.

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FIGURES

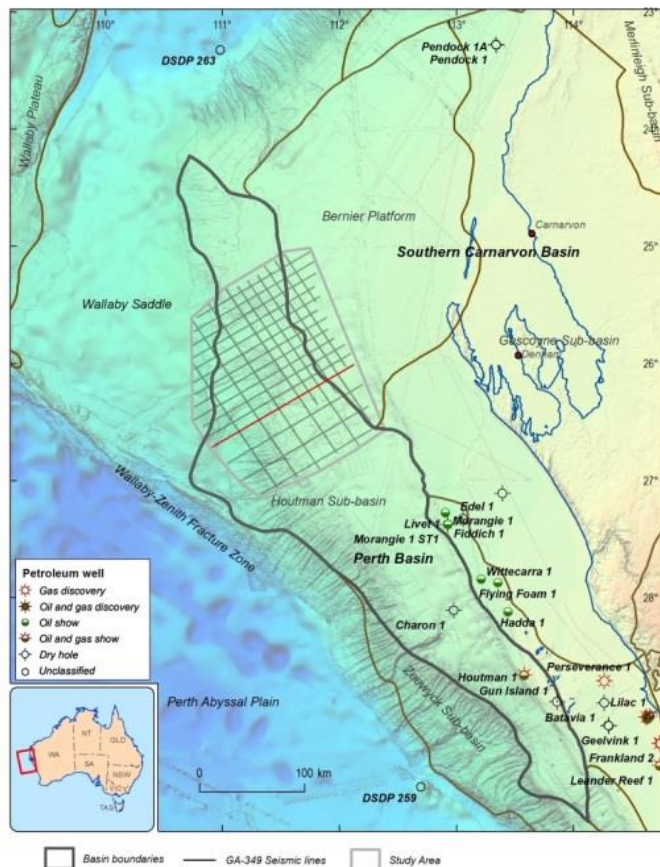


Figure 1: Location map showing structural elements of the Houtman Sub-basin and its bathymetry (Spinoccia, 2012). Location of cross-section in Figure 2 is highlighted in red.

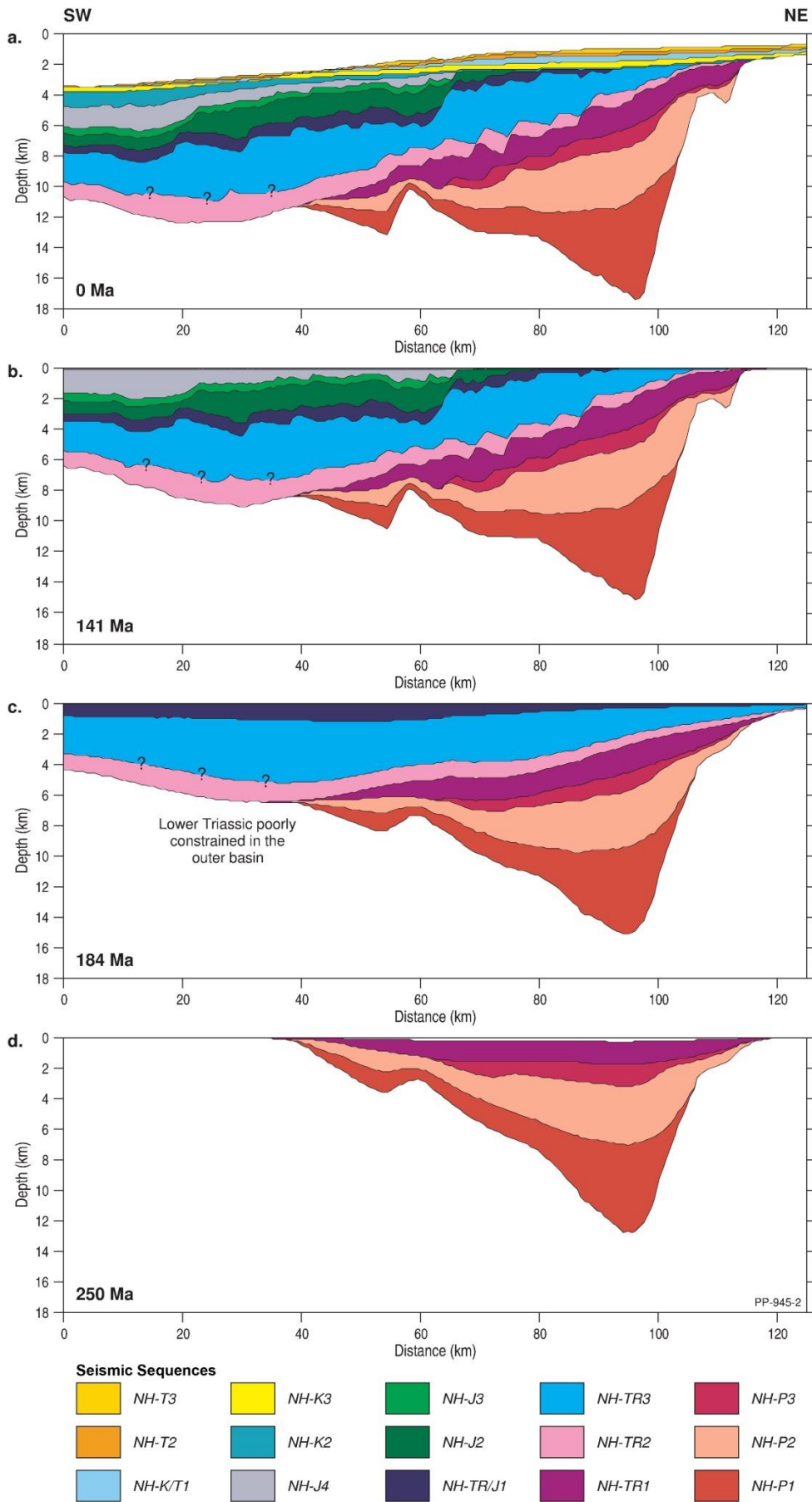
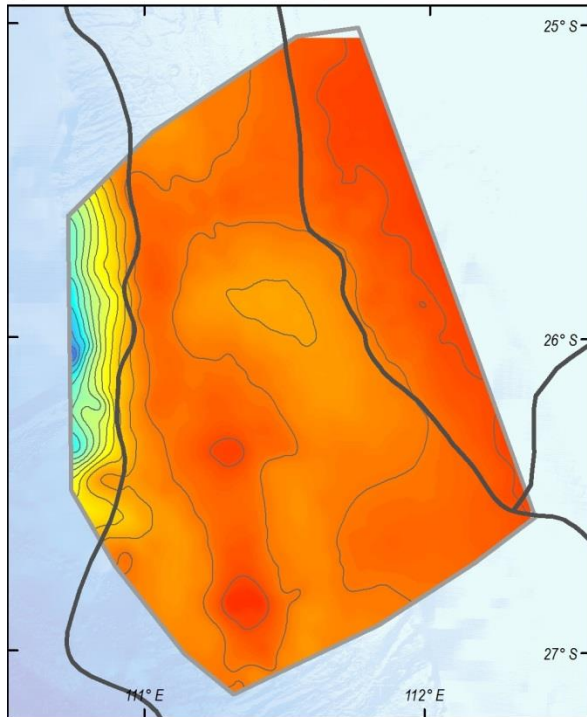
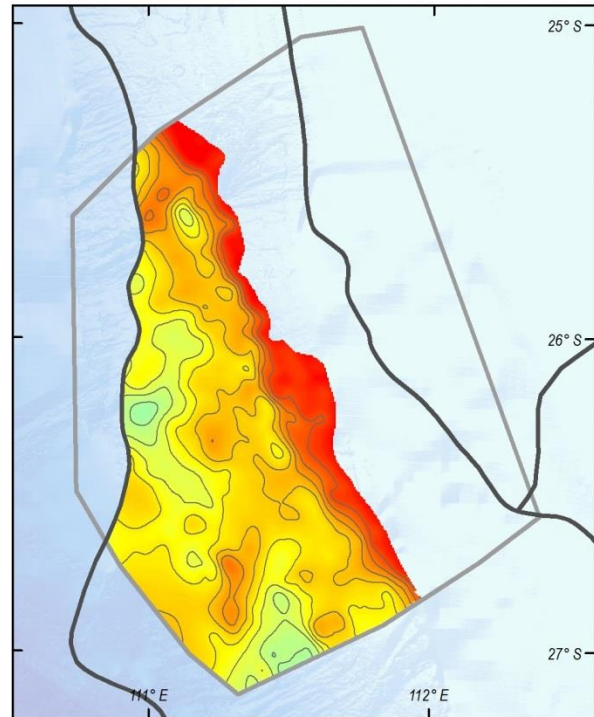


Figure 2: Regional time-slice cross-sections through the northern Houtman Sub-basin (line GA-349/1030), showing regional basin evolution. See Figure 1 for location.

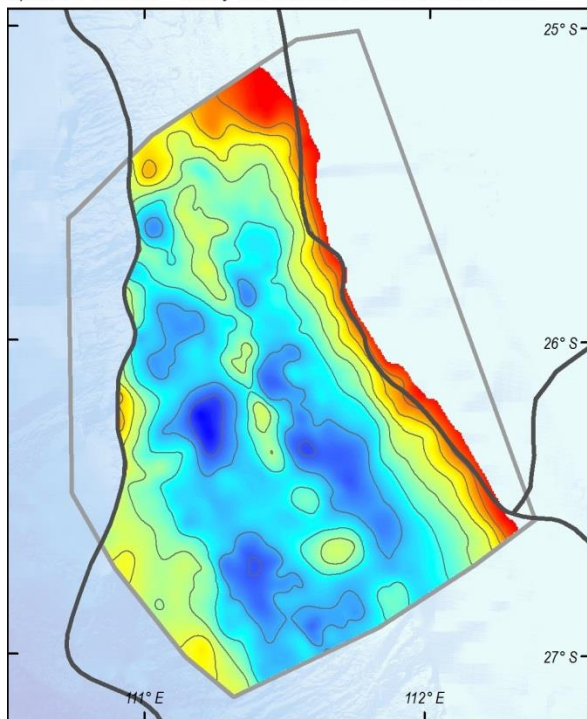
a) Late Cretaceous - Cenozoic post-rift isochore



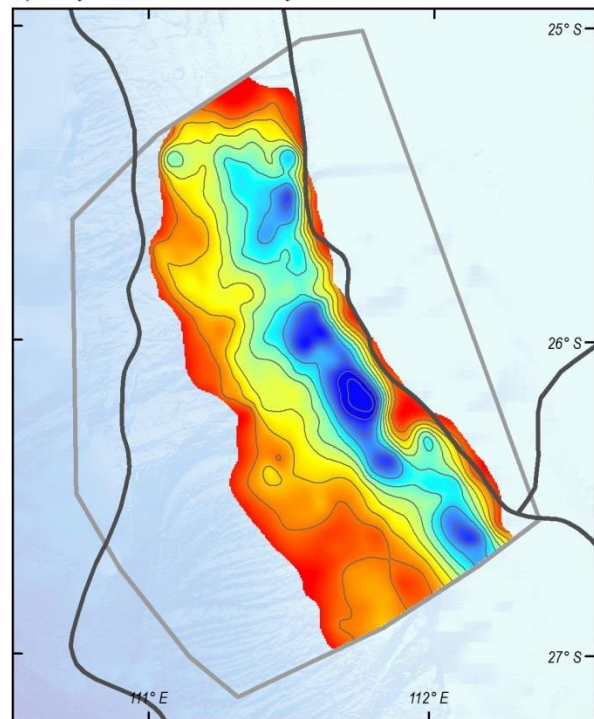
b) Early Jurassic - Early Cretaceous syn-rift isochore



c) late Permian - Early Jurassic subsidence isochore



d) early - middle Permian syn-rift isochore



0 50 Km

Houtman Sub-basin

GA349 Survey Boundary

Thickness 0 >8,000 m

Figure 3: Gross thicknesses of the mapped major tectono-stratigraphic units representing major basin phases in the study area: a) Upper 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).

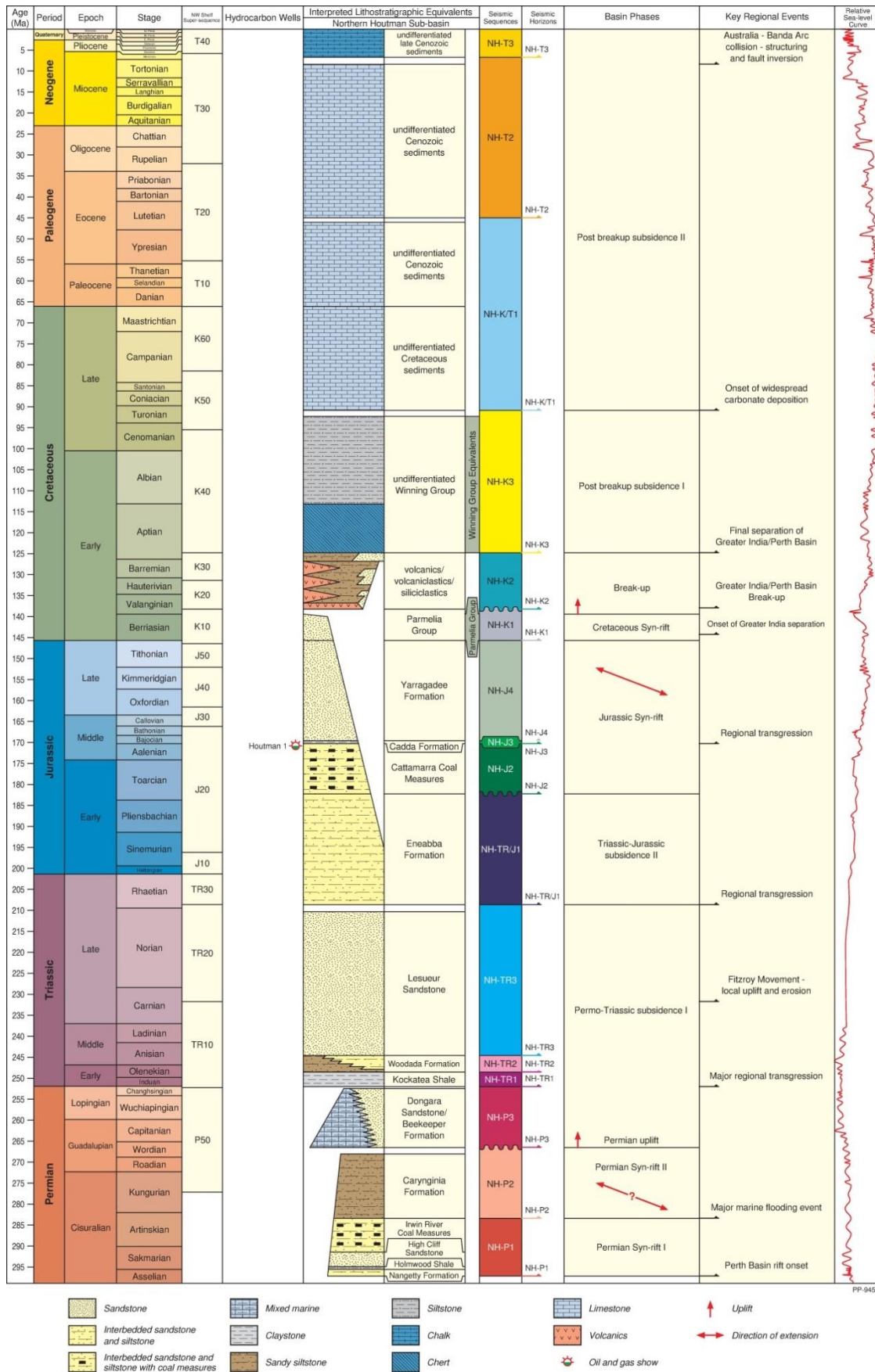


Figure 4: Tectonostratigraphic chart for the northern Houtman Sub-basin based on mapping and interpretation of seismic survey GA-349 and regional stratigraphy of the Houtman Sub-basin, tied to the 2016 geological timescale (Ogg *et al.*, 2016). Also shown are the NW Shelf Supersequences updated from Marshall and Lang (2013) and the short-term relative sea-level curve modified from Haq and Schutter (2008) and Hardenbol *et al.* (1998).