

Evolution of “Tres Hombres” - A Mid-crustal Dome Structure within the Jurassic Northern Beagle Sub-basin Western Australia: An Integrated Geophysical Investigation

Gerry O’Halloran*

BHP Petroleum
125 St Georges Tce
Perth WA 6000
gerard.ohalloran@bhpbilliton.com

Chris Paschke

BHP Petroleum
1500 Post Oak Blvd
Houston TX
chris.paschke@bhpbilliton.com

Craig Dempsey

BHP Petroleum
125 St Georges Tce
Perth WA 6000
craig.dempsey@bhpbilliton.co

Chris Hurren

BHP Petroleum
1500 Post Oak Blvd
Houston TX
chris.hurren@bhpbilliton.com

Robert Scott

BHP Petroleum
125 St Georges Tce
Perth WA 6000
robert.scott@bhpbilliton.com

Guimin Liu

BHP Petroleum
1500 Post Oak Blvd
Houston TX
guimin.liu@bhpbilliton.com

**presenting author asterisked*

SUMMARY

The Tres Hombres structure is a large mid-crustal structural feature that underlies the Permian – Late Jurassic mega-sequences of the Northern Beagle Sub-basin, Western Australia. Originally identified on regional 2D seismic lines, the Tres Hombres structure has now, for the first time, been fully imaged by high quality, deep record modern 3D seismic data. The area is also covered by gravity and magnetic datasets which were acquired together with the 3D seismic survey. Seismic mapping reveals a dome-like structure with a diameter of more than 30km, and with vertical relief of over 5km. This paper integrates seismic and potential fields datasets to explore the origins of this intriguing structure.

Mechanisms considered for the emplacement of this feature include; basement cored compression, reactivated extensional basement faulting, remnant Palaeozoic topographic relief, salt-related diapirism, or plutonic/igneous intrusive activity. The actual mechanisms responsible for the evolution of Tres Hombres have obvious implications for adjacent and overlying petroleum systems within the Beagle Sub-basin.

Detailed mapping of new 3D seismic datasets enables structural and stratigraphic restorations to be generated, which provide valuable insights into the timing of the Tres Hombres feature. Variations in the thicknesses of overlying sequences show the influence that this structure had on the stratigraphic evolution of the basin. Gravity and magnetic datasets have also been integrated into this study, and provide valuable controls on potential lithologies within the core of the Tres Hombres feature. These in turn have important implications as to the origin of this structure, and relationships to the tectonic evolution of the Beagle Basin.

Key words: Carnarvon Basin, Beagle Sub-basin, 3D Seismic, Gravity and Magnetics, Batholith, Structural Evolution.

INTRODUCTION

The Northern Beagle Sub-basin is a failed arm of a Jurassic rift system within the greater Northern Carnarvon Basin (Figure 1A). The overall structural architecture of the Northern Beagle Sub-basin one of a rift-related depocentre flanked by contemporaneous structural highs (Figure 1B). An early phase syn-rift deposition is recorded in basin by the early Jurassic North Rankin and Athol Fms and was followed by a more extensive phase of basin subsidence, recorded by the deltaic successions of the Middle Jurassic Legendre Fm (Figure 2). This relatively “normal” rift architecture has been modified however by a large, mid-crustal structure that impinges on the basin and forms a large dome-like feature within the southern parts of the basin depocentre. This unusual feature, referred to here informally as “Tres Hombres” has had a major impact on the Mesozoic structural and stratigraphic evolution of the basin. Potential mechanisms for the origin of this feature are explored in this paper, via the integration of both high definition 3D seismic data as well as gravity and magnetic datasets.

GEOLOGICAL SETTING

The Beagle Sub-basin records the onset of major rifting and separation of continental fragments from the Australian continental craton during the Pliesnbachian - Oxfordian (Metcalf, 2011, Heine and Müller, 2005). Regionally this extension continued throughout the Jurassic – with subsequent phases of rifting recorded in the slightly younger Barrow and Exmouth Sub-basins to the southwest (Belgarde et al, 2015).

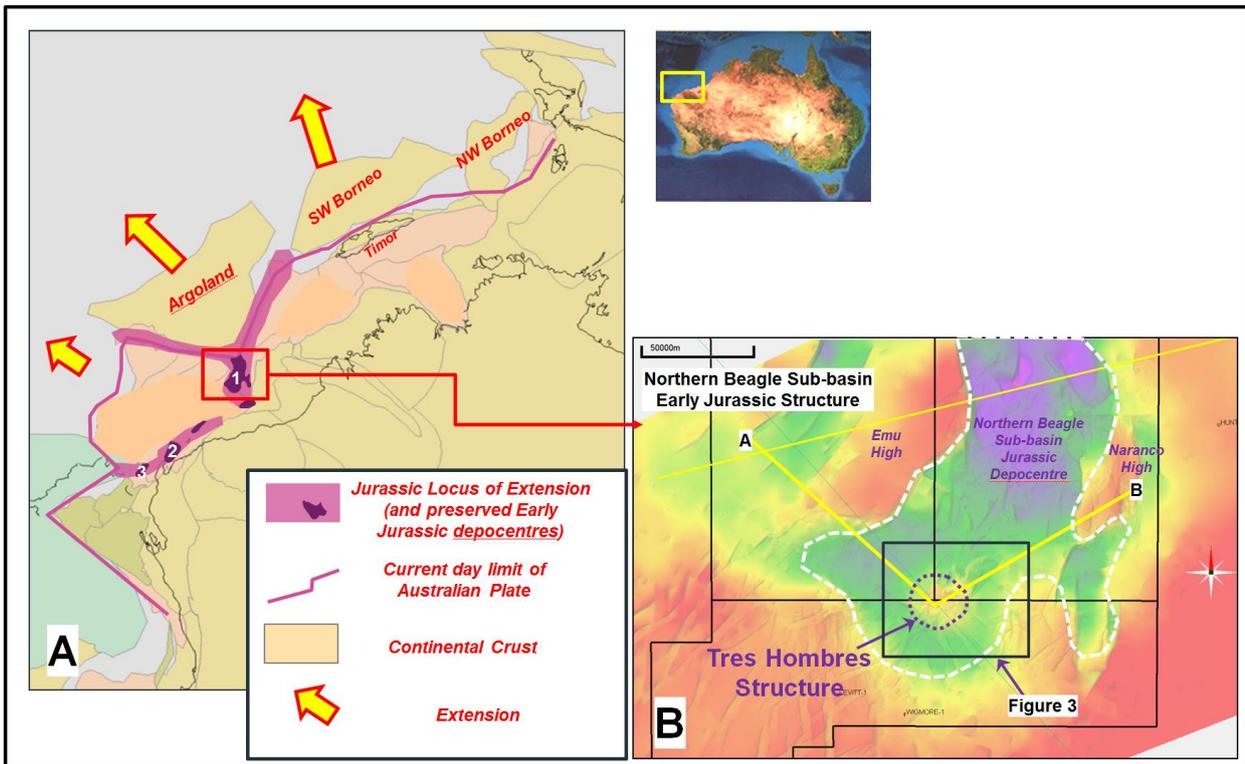


Figure 1. A. Paleogeographic reconstruction of Jurassic depocentres. 1 = Beagle Sub-basin, 2 = Barrow Sub-basin, 3 = Exmouth Sub-basin B. Structural architecture of the Northern Beagle Sub-basin and Tres Hombres. Line of section A-B is shown in Figure 2. Location of map shown in Figure 3 also shown.

The Palaeozoic-Mesozoic structural and stratigraphic framework of the Beagle Sub-basin is summarised in Figure 2. Of relevance to this study are the Permian–Jurassic intervals which are made up of three major megasequences: 1) a late Permian carbonate shelf sequence, 2) a thick succession of Triassic deltaic, marginal marine and fluvial sequences, and 3) Jurassic rift related marine-deltaic sequences. Late and post-Jurassic tectonism associated with crustal extension, seafloor spreading and rift flank uplift has resulted in erosion during the Callovian and Oxfordian, which is recorded by several major unconformities at the top of the Beagle Sub-basin Jurassic sequence.

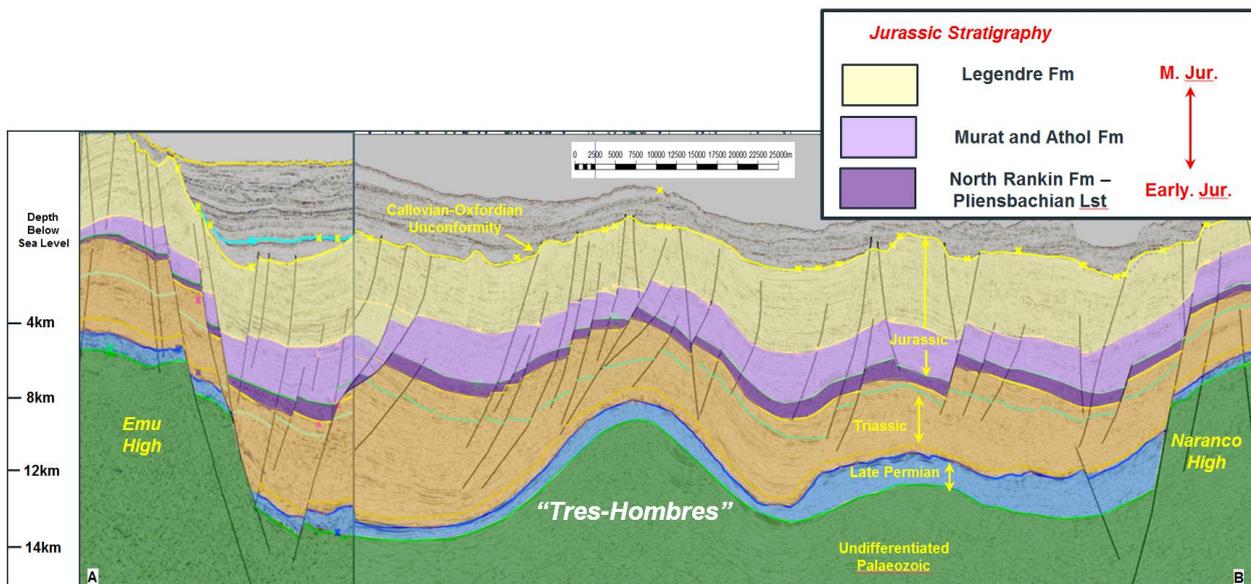


Figure 2: Structural and Stratigraphic Framework for the Northern Beagle Sub-basin – see Figure 1 for line of section

Seismic Data – Capreolus 3D Survey

The 22130km² Capreolus MC (Multiclient) 3D seismic survey was acquired by Polarcus during 2015 over the Northern Carnarvon Basin and covered the main Jurassic depocentre of the Northern Beagle Sub-basin (including Tres Hombres). The survey was acquired by the seismic vessels Polarcus Asima, Polarcus Amani and Polarcus Naila in 12 x 100m x 8100/9000m configurations, with 12.5m flip/flop shot interval and 12s record length. The survey is a modern broadband, depth processed, deep record 3D seismic survey providing excellent quality 3D imaging over an area previously only covered by relatively sparse regional 2D data.

THE TRES HOMBRES STRUCTURE

The Tres Hombres structure sits within the southern part of the Beagle depocentre (Figure 1A). It is a prominent mid-crustal feature that impinges on the late Permian, Triassic and Jurassic basin mega-sequences. Structure maps on Permian through Jurassic horizons show Tres Hombres to be >30km in diameter and have more than 5km of relief. The origin of the name Tres Hombres (“Three Men” in Spanish) although somewhat obscure, is probably due to the fact that it is one of three broadly similar structural features in the northern Carnarvon Basin, with the other two lying approximately 50km and 100km to the west (these other two are only imaged on regional 2D seismic lines). As we will show in this paper, detailed 3D imaging is vital to unravelling the detailed evolution and origin of these structures.

Structural Observations

Structural complexities are evident within the Jurassic and Triassic intervals in the area around Tres Hombres and suggest a more complicated structural evolution than that of a simple extensional rift system. The structural fabric of the Jurassic section is illustrated in Figure 3, which shows a time-slice view of discontinuities within the 3D seismic data over the area which highlight fault trends. These show that the simple overall rift architecture seen at the regional scale gives way to a more complex pattern of faulting, with a NE trend and a secondary NNW trend observed suggesting the presence of a deeper control on faulting.

Seismic lines through the area also reveal details of the architecture and history of faulting in the area. For example, there is clearly a detachment level just above the Permian Carbonates upon which faults within the Triassic and Jurassic sole out. Furthermore, it is of interest to note that the spectacular Permian carbonate shelf edges, which in places have >2km of primary depositional relief on them, appear to act as a focus for overlying faulting. Shallower faulting within the overlying Triassic and Jurassic clearly originates at the level of the Permian carbonate shelf edges – the interface between the hard, lithified Permian limestones and overlying early Triassic shale prone section acting as a mechanical discordance upon which later faulting nucleates.

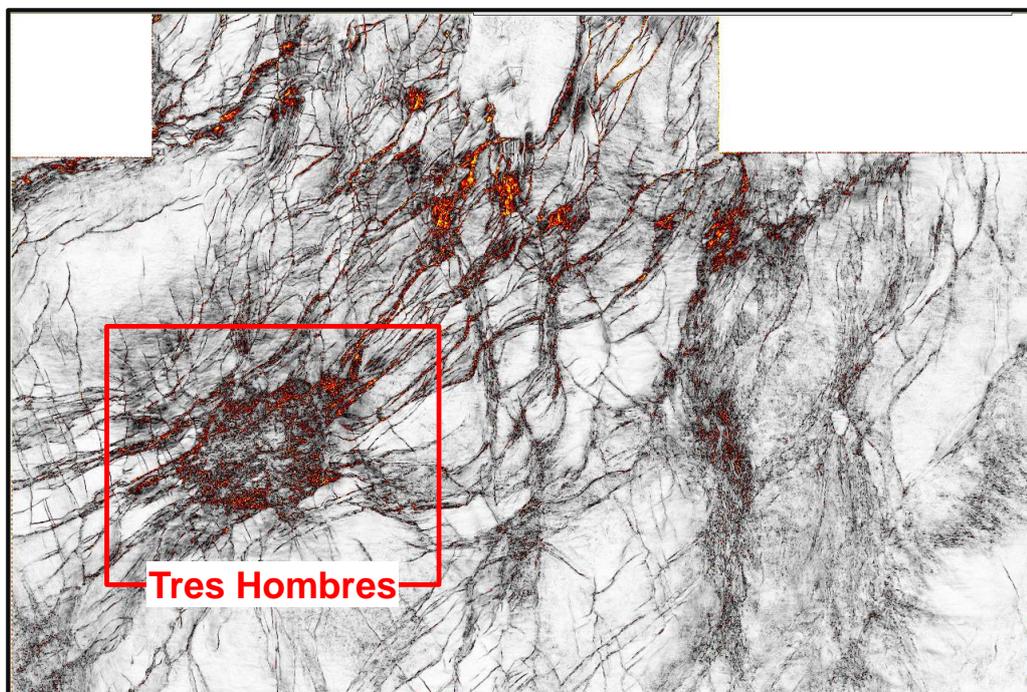


Figure 3: Structural grain at the Jurassic level over the Beagle Sub-basin. Timeslice is a discontinuity (variance) attribute generated from the Capreolus MC3D survey at Jurassic levels (actual level shown in profile view in Figure 4C). Area of map shown in Figure 1.

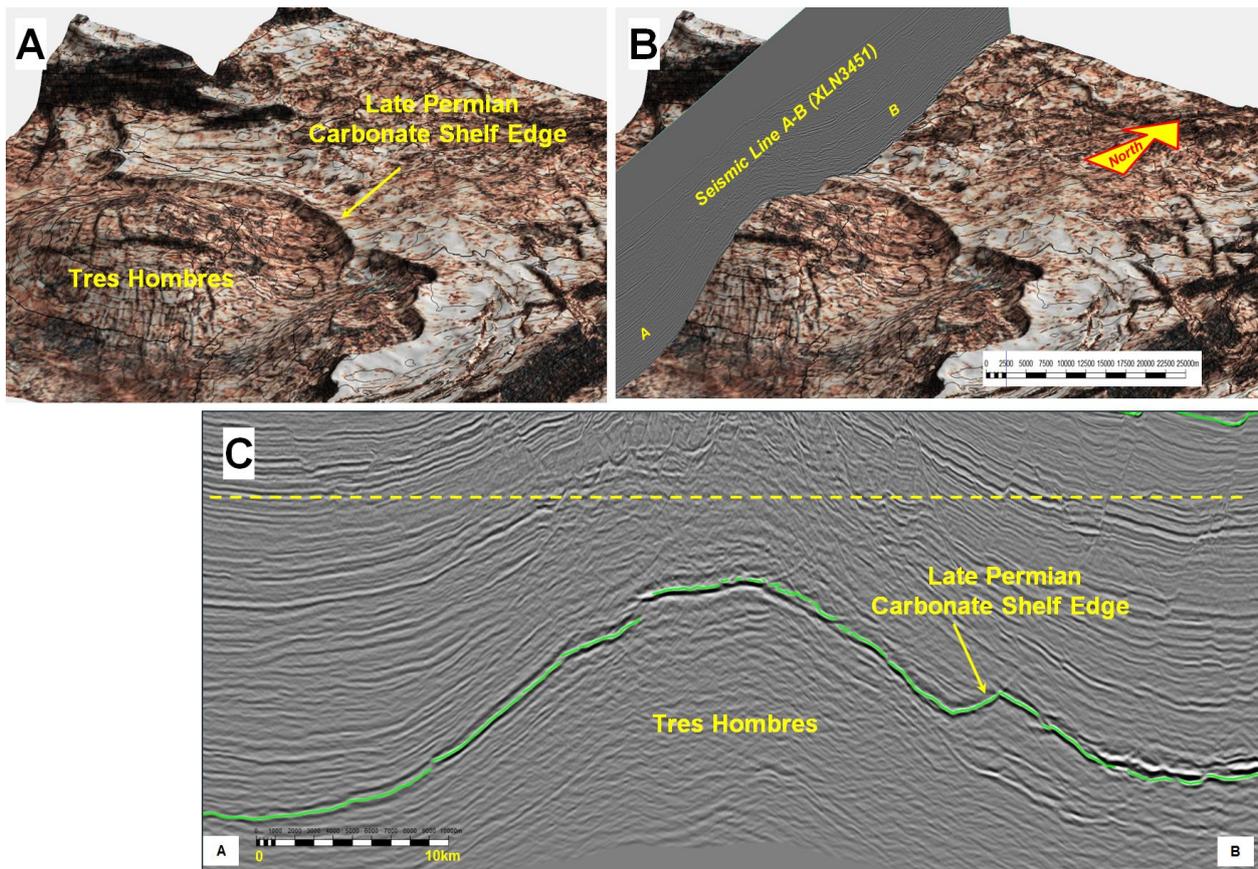


Figure 4. A. 3D perspective view looking north over the late Permian P75 horizon (green horizon shown in C). Surface is draped with a spectral decomposition colour-blended attribute map, which highlights stratigraphic and structural details, such as the spectacular late Permian carbonate shelf geometries. B. 3D view of seismic Line XL3451 from the Capreolus 3D. C) Seismic line XL3451 showing profile view of Tres Hombres. Note the seismic expression of the Permian carbonate shelf. Horizontal dashed line shows the time-slice level at which the variance map in Figure 3 has been extracted on. Refer to text for discussions.

Timing Constraints

The Permian carbonate shelf geometries are spectacularly imaged on the Capreolus 3D seismic data. They form intricate arcuate-shaped shelf edge geometries that trend broadly from the NW to the SE (Figure 4A). While discussions on the origins and significance of these Permian carbonates are beyond the scope of this paper, they have been explored in recent stratigraphic investigations (Paschke, et al 2018) and are significant in the context of this paper in that they provide an important constraint on the timing of the Tres Hombres structure. Seismic profiles across the Tres Hombres Dome (Figure 4B and 4C) suggest that the Permian carbonate shelf edges predate the evolution of the structure, with shelf edges observed on the flanks of the present-day dome. Presumably carbonate shelf edges would not have grown on the flanks of any evolving emergent structure – if anything they would have been expected to have formed on the crest of such a feature. So an older limit for the onset of growth of Tres Hombres can be put at the earliest Triassic. Further constraints on timing can be gained from thickness maps in the Jurassic and Triassic sections. These show that the Tres Hombres structure was active from the latest Triassic through the Jurassic, with clear thinning over the crest within these intervals. The onset of growth of Tres Hombres began therefore somewhere during the middle-late Triassic. This timing raises questions regarding the origins and mechanisms of emplacement for the Tres Hombres structure.

Potential Origins and Mechanisms for Emplacement of Tres Hombres

Several mechanisms for the emplacement and origin of the Tres Hombres feature have been considered and include:

1. Basement cored structural inversion (compressional model). The large scale of the structure and relief associated with it could conceivably be due to compressional processes – either via a deep-seated thrust fault or reactivation of an early

normal fault. This model is hard to demonstrate with any mapped faults within the deep pre-Permian intervals as the seismic character below Tres Hombres is rather transparent. There are other problems however with this model, not the least of which is that the Triassic – Jurassic tectonic setting in the Carnarvon Basin was one of overall extension. Some compressional structures and related unconformities are seen onshore in the Fitzroy Trough of the Canning Basin (Kennard et al, 1994) however these are probably associated with space problems generated during tectonic events within inboard, intra-cratonic settings. Furthermore, it is difficult to reconcile the circular, dome-like geometry of Tres Hombres with any fault-related mechanisms – any hangingwall fold would invariably be elongate in a direction orthogonal to compression.

2. Diapiric salt-related model. This model arises from some gross superficial similarities in morphology to large scale salt diapirs observed within other basin settings, specifically the Gulf of Mexico. In addition there are salt sequences documented within the early Palaeozoic of NW Australia (Kennard et al, 1994). Notwithstanding that this model has some significant problems in terms of scale and timing, it was kept as a working hypothesis during early phases of this investigation.
3. Magmatic intrusion model. Given the overall extensional tectonic regime, another plausible model is that Tres Hombres is related to thermal effects associated with rifting; i.e. a large diapiric intrusion that evolved through the latest Triassic and Jurassic.

Each of these models has implications for lithologies expected within the core of the structure. For example, a compressional fault related structure might be expected to display the same lithologies as those in surrounding rocks – ie. presumably involving a core of metasedimentary pre-Permian basement rocks. A salt-cored diapiric structure on the other hand would clearly have markedly different lithologies within the core of the structure, as would a large scale intrusive batholith. One obvious way to discriminate between these models is via the use of potential fields data and gravity and magnetic modelling.

Gravity and Magnetic Data

Onboard gravity and magnetic data were acquired over northern parts of the Capreolus MC 3D seismic survey. These data were processed by Edcon and have been used to investigate modes of emplacement for Tres Hombres. Analysis of the Bouguer corrected gravity and reduced to pole magnetic maps highlighted a deep, dense, magnetic anomaly in the location of Tres Hombres. Using local well control to constrain rock properties within the Mesozoic section, and seismic velocities (including regional refraction data) for deeper stratigraphy down to the Moho, a multi-layer 3D model was populated with expected densities and magnetic susceptibilities for a range of rock-types, ranging from igneous intrusives (mafic-intermediate-felsic), through to metasedimentary lithologies, as well as salt. Models were then used to generate synthetic magnetic and density signatures for the various emplacement scenarios for Tres Hombres, and compared to actual data. Using a value of 2.8g/cm^3 for density for the core of Tres Hombres, and a magnetic susceptibility of 0.04SI gives a very close match to the observed data and fitting anomaly strengths. These constraints immediately rule out any salt-related model, due to the low density and non-magnetic properties expected within most salt diapirs. Likewise, a metasedimentary core to Tres Hombres appears to be unlikely unless extremely high values of density and magnetic susceptibility are assumed. The requirement for dense, magnetic core for Tres Hombres appears to best match a model of an intrusive batholith with potential lithologies in the deep core of the structure ranging from intermediate-mafic.

DISCUSSION - ORIGINS OF THE TRES HOMBRES STRUCTURE

The most likely interpretation for the origin of the Tres Hombres structure is that it is a result of a thermal perturbation within the lower crust – potentially some sort of precursor event to Jurassic rifting (perhaps a result of upper mantle convective processes or plume activity). Partial melting of the lower crust during such an event would have resulted in diapiric magmatic intrusive activity within mid-crustal levels during the latest Triassic – Earliest Jurassic with the subsequent formation of the Tres Hombres batholith. Ongoing contemporaneous doming affected sedimentary architecture within the fill of the Northern Beagle Sub-basin; most notably with thinning within Late Triassic-Jurassic sequences above Tres Hombres. These crustal processes also likely exerted an influence on the distribution of clastic depositional systems during the Jurassic. The diapiric evolution of the Tres Hombres batholith appears to have stalled at mid crustal levels. There are no mapped intrusives (sills, dykes) in the area around Tres Hombres, nor are there any Jurassic volcanics or other near surface expressions of magmatic activity (calderas etc) in the area - again indicating that the Tres Hombres dome remained a deep-seated feature. Such large-scale deep rift-related thermal processes often progresses through to continental breakup and ocean floor spreading. In the case of the Beagle Sub-basin however, rift processes switched to areas outboard (north-westward) of Tres Hombres – presumably due to the migration of deep thermal (plume?) activity into those areas. Tres Hombres remained “frozen” in the Northern Beagle Sub-basin as a remnant batholith and since the Jurassic has acted as a rheological (hard) control on successive phases of subsidence (it still has an expression on the present day seafloor). In summary, the Tres Hombres dome is best described as a thermal remnant of the rifting process preserved within mid-crustal levels of the failed rift arm of the Northern Beagle Sub-basin.

ACKNOWLEDGMENTS

The authors acknowledge Polarcus for permission to use images from the Capreolus MC3D seismic survey.

REFERENCES

Belgarde, C., Manatschal, G., Kuznir, N., Scarselli, S., and Ruder, M., 2015. Rift Processes in the Westralian Superbasin, North West Shelf, Australia: Insights from 2D deep reflection seismic interpretation and potential fields modelling: APPEA Conference proceedings (extended abstract).

Heine, C., and Müller, R.D., 2005. Late Jurassic rifting along the Australian North West Shelf: margin geometry and spreading ridge configuration: *Australian Journal of Earth Sciences*, 52, 27-39

Kennard, J.M, Jackson, M.J., Romine, K.K., Shaw, R.D. and Southgate, P.N. Depositional Sequences and Associated Petroleum Systems of the Canning Basin, WA. *The Sedimentary Basins of WA*, 657-676.

Metcalf, I., 2011. Palaeozoic-Mesozoic History of SE Asia: In: Hall, R., Cottam, M., Wilson, M. (Eds.), *The SE Asian Gateway: History and Tectonics of Australia-Asia Collision*. Geological Society of London Special Publications, 355, 7-35