Understanding the structure, extent and potential source rocks of the syn-rift in Madagascar: integrating potential field and tectono-thermal geohistory modelling into seismic interpretation

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Summary

TGS completed a detailed integrated geophysical and geological evaluation of the hydrocarbon prospectivity of the western margin of Madagascar from the Cap St. Marie Basin in the south to the Ambilobe Basin in the north. The study was based on 49,000 km of multi-client 2D seismic data acquired in partnership with OMNIS, with 20,000 km thereof in partnership with BGP. Reprocessed data from seismic surveys acquired between 2001 and 2013 provided supplementary information.

Potential field data were acquired on all vintage and new seismic lines and fully compiled. Gravity and magnetic forward modelling, as well as basin temperature modelling, complement the seismic interpretation. Collectively, these various datasets provide valuable additional constraints regarding potential source rock deposition, periods where structural traps were created, and maximum extent of offshore syn-rift layers.

Introduction

Madagascar was originally part of the supercontinent of Gondwana. The Permo-Triassic Karoo phase of rifting along an existing zone of weakness between eastern Gondwana (Madagascar, India, Australia and Antarctica) and western Gondwana (Africa, Arabia and South America) failed during the Late Triassic. The location of rifting shifted west in the Early Jurassic, to the present-day continental margin of West Madagascar, resulting in the break-up of Gondwana in the Middle Jurassic (Geiger et al., 2004). Subsequently Madagascar together with India, Antarctica and Australia drifted southward along the Davie Fracture Zone (DFZ), a 1500 km long transform fault (Reeves, 2014; Reeves et al., 2015), and as a consequence ocean sea floor spreading started in the Somali and Mozambique Oceans.

Around 120 Ma, spreading in the Somali Ocean ceased and the spreading center relocated to the south, separating Antarctica from Madagascar and India. Extension between Madagascar and India commenced in the Aptian and subsequent break-up occurred in the Turonian (Reeves et al., 2015). The latter event is linked to the Marion hotspot and a major volcanic episode (Storey et al., 1995). The rifting and separation between Madagascar and India caused uplift of the eastern margin of Madagascar and renewed compressional tectonic activity in the basins on the western side of Madagascar and reactivated the DFZ.

The break-up of Gondwana created several major basins along the western margin of Madagascar: comprising the Cap St. Marie Basin in the south, the offshore Morondava Basin along the western margin of Madagascar, the Majunga Basin on the north-western margin and the Ambilobe Basin in the north (Fig.1).

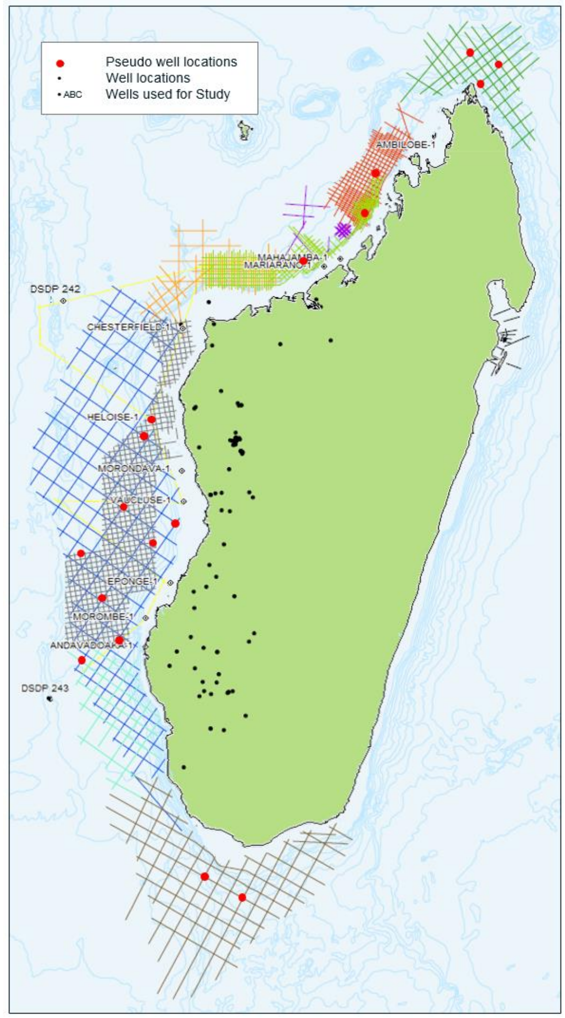

Figure 1: Madagascar – 2D surveys, pseudo well locations and available wells used in this study. The surveys (coloured lines) have been acquired in 2013 and 2014 and were complemented by the reprocessed surveys from 2001 and 2006.

Results from this study indicate that the onshore Permo-Triassic tectonic evolution of Madagascar had a much greater influence on the syn-rift and later rifting stages of the western offshore Madagascar basins with regards to structure, extent and trap systems than previously believed.

Method

Selected case studies illustrate how the limits of interpreting a detailed structural tectonic history within the syn-rift stages in seismic data were overcome by integrating subsurface crustal and tectono-thermal geohistory models. The results provide a more conclusive and robust interpretation.

Interpreted seismic horizons in depth are used as input for the gravity and magnetic forward modelled profiles of selected geological cross sections. However, to set up a complete geological model for the forward modelling further subsurface horizons – below the deepest interpreted horizon which is the acoustic basement – are needed.

A Top Lower Crust interpretation is required for the internal structure of thicker crustal sections, and a Moho is necessary to separate the crustal effects from the mantle response. For this purpose a spectral analysis using the Power Spectrum Method of Spector and Grant (1970) is performed on the gravity and magnetic data. Their method obtains the main mean depth estimates for the specified areas by correlating the regression of frequency clusters to mean surface depths.

During forward modelling (Talwani et al., 1959) the structure and rock properties of the initial geological cross section are adjusted until a satisfactory fit to the observed anomalies is achieved. Densities of the post-rift sediments are derived by converting seismic velocities after Gardner et al. (1974), and kept constant to separate out syn-rift structures, and to define the upper crustal boundary. The magnitude and depth of the source variations are constrained in more detail by wavelength separation modelling of the anomaly responses. The resulting crustal thicknesses and distributions are cross-checked against the thermal geohistory models.

Inputs into the geohistory modelling of pseudo wells are the stratigraphy (sequence stratigraphic interpretation tied to local wells), and lithology composition estimates (from seismic character). Available wells in the shelf areas were used to calibrate the 1D basin models. Bottom hole temperature (BHT) and vitrinite reflectance (VR) calibration in the crustal model involves thickness of the unstretched lithosphere (upper, lower crust and upper mantle) and its heat generation (HG). The lithology estimates, the BHT and the VR data can be used to calibrate the crustal HG using the predicted present-day temperature profile and predicted maturity profile. The crustal model is then applied to pseudo well simulations together with stretching events constrained by observed data, such as faulting on seismic profiles, and modelled data, such as crustal distribution in subsurface cross sections.

The simulations are then used to model the accommodation space at depocenters by considering sediment compaction and thinning of the crust. As a final check the resulting depths of the Moho and Lower Crust (at present time) are compared to the gravity and magnetic forward modelling results.

Source rock potential and expulsion timings are modelled using this dynamically thinning crustal model.

When the crustal thicknesses and tectonic implications match both the gravity modelling and the thermal modelling, the assumed and modelled structure and tectonic crustal model are considered reasonable and reliable.

Any required changes to the seismic interpretation are updated from the forward modelled horizons, which are constrained by the thermal modelling results.

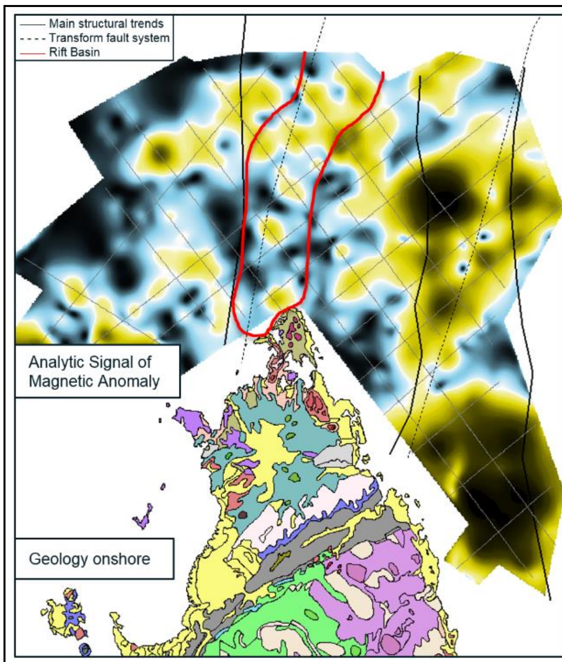

Figure 2: Ambilobe area – Magnetic Analytic Signal with main tectonic trends and Geology onshore (Purdy & MacGregor, 2003). The main structural trends offshore (solid black) align with the trends of the two major transform fault zones (dashed black). The geological trend marked in between the faults is regionally correlated to the strikes found onshore: the trend of the outcrop which is crossing the tip of Madagascar (grey) changes trend direction into the fault offshore.

Examples

Traps, source rocks and plays of Cretaceous and Neocene ages were calibrated with available well data for Madagascar (Fig. 1) and can mostly be mapped confidently in the post-rift sediments in all offshore basins. However, the Jurassic syn-rift sequence boundaries and structures are not always imaged clearly enough on the seismic data to be confidently mapped across all surveys. This is sometimes due to steep fault planes that interfere with the imaging, or Upper Cretaceous igneous intrusives and extrusives that mask the seismic reflections at greater depth.

The Karoo sequence in Madagascar is a proven onshore source rock. The presence and viability of the layer as an offshore source rock was tested with basin temperature models by implementing, excluding and varying its thickness and depth in several pseudo well locations. The results of this study indicate that the Permo-Triassic syn-rift layer is present in the Ambilobe area, Majunga Basin, and on the Morondava shelf and slope towards the Jurassic rift basin. It may not be present in West Morondava Basin further offshore and the Cap St. Marie area. Forward modelling of potential field data in conjunction with thermal modelling suggests that the additionally interpreted Permo-Triassic sequence is possibly below the depth window where it would be a viable source rock for the offshore basins. However, by integrating the modelling results with the seismic interpretation, it can be inferred that the pre-existing Karoo rift topography controlled Jurassic syn-rift deposition, and reactivation of the Karoo faults created further accommodation for siliciclastic syn-rift deposits.

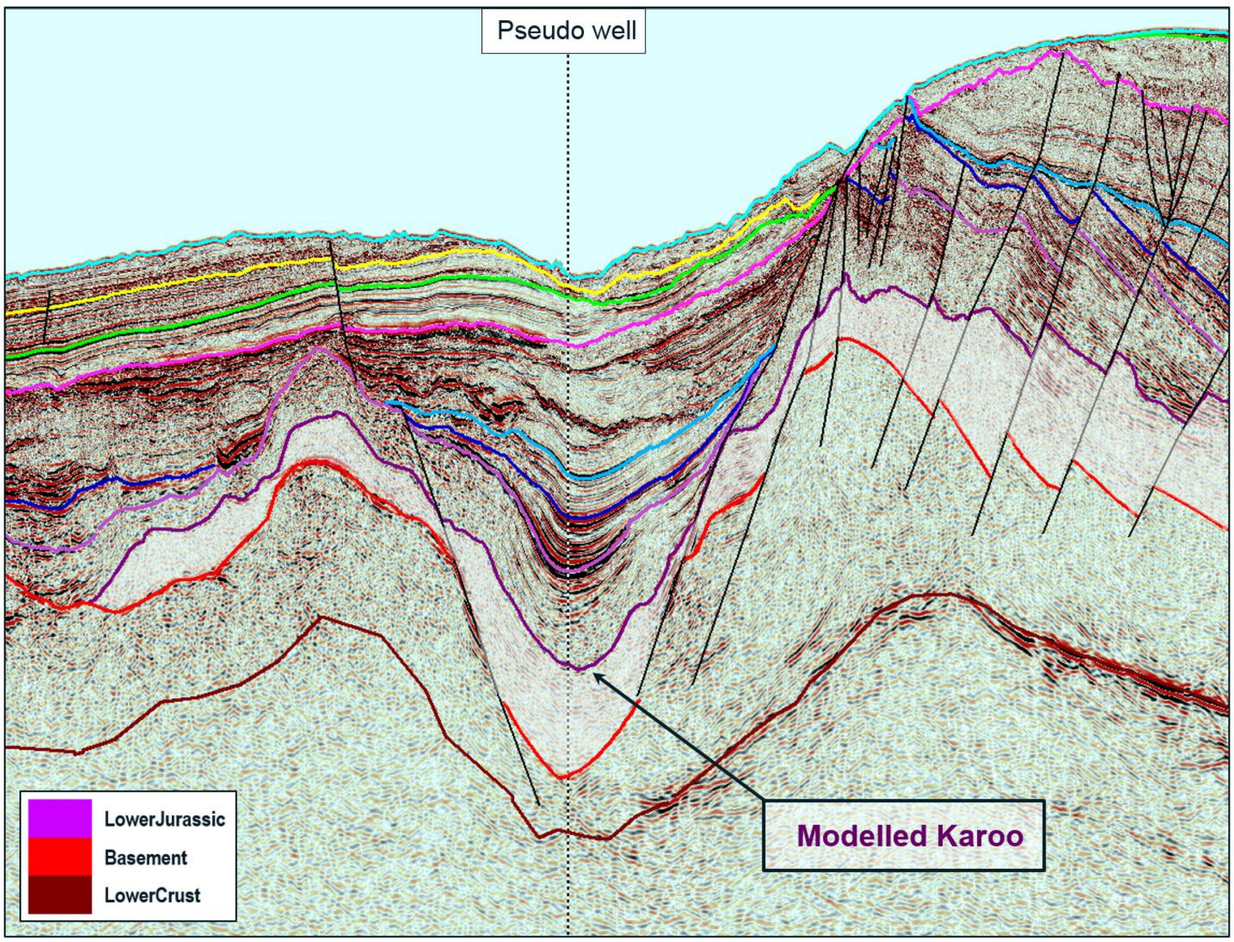

Figure 3: Ambilobe area – Seismic section in TWT with depocentre of modelled Pseudo well. The seismic interpretation on TWT (lower crust is model driven) shows the additionally modelled Karoo in purple. This section illustrates that the prominent faults that limit the deep rift basin would only show half of the displacement of the syn-rift layers if the Permo-Triassic sequence was not present.

In the Ambilobe area the seismic interpretation of the basement in the main rift basin in the west and the crustal high in the centre (Fig. 2), did not correlate well with the crustal model. An alternative deeper basement structure has been determined, which suggests the previous interpretation marked the base of the Jurassic and coincides with the top of the Karoo sequence. This allows the interpretation of an additional rifting event in the deep central (N-S) rift basin which adds a sediment layer to the depocentre model (Fig. 3). The presence of the offshore Permo-Triassic syn-rift layer in Ambilobe was not evident in the seismic interpretation. Hence, this suggests that this syn-rift sequence extends further offshore than previously believed.

In contrast to these findings in the north of Madagascar, the absence or presence of the Karoo sequence in the Cap St. Marie area in the south has up to now always been unknown. Although gravity and magnetic modelling identified continental crust throughout the majority of the area, it seems the presence of a Permo-Triassic sequence is not required to accommodate the rift basin depth, or required for the tectonic extension to match the crustal thinning. Consequently, only Jurassic and younger syn-rift layers were interpreted, and as such, it is possible that this section is thicker in the Cap St. Marie area than in other areas.

In the Majunga area, the Karoo layer is a pronounced reflector that was identified on the seismic section in addition to the Jurassic and basement horizons, but only occurred locally at the north-eastern shelf edge (blue polygon, Fig. 4) The pseudo well models at 3 selected depocentres (Fig. 1 and Fig. 4) indicate that a Permo-Triassic sequence with an extensional component is necessary to accommodate the present-day subsidence and comply with the burial history. The local seismic interpretation of the top of Karoo, however, only identifies the syn-rift layer in one of these locations. Hence, the previous seismic interpretation was revised. Since the pseudo wells are 1D models at a single location, the gravity and magnetic subsurface models guided the revisions of the seismic interpretation, and determined the extent of the Karoo (Fig. 4). The results of this integrated study are of particular interest in the Majunga area. Here, the Permo-Triassic syn-rift structures, such as anticlines and fault-related closures, serve as additional traps and control for the Jurassic syn-rift deposits, which are the source rocks that have been modelled to be viable for the offshore basin petroleum system.

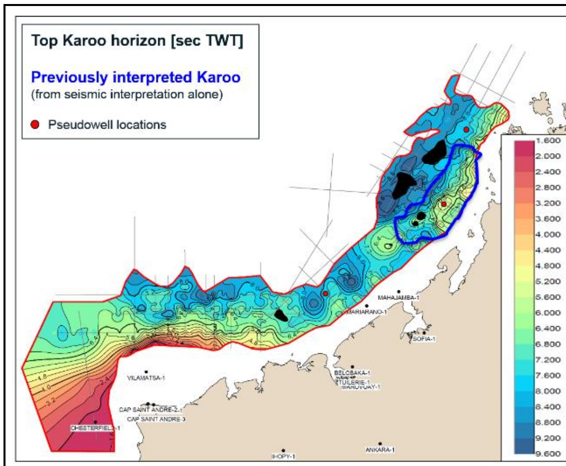

Figure 4: Majunga Basin – Top Karoo extent before (blue polygon) and after (grid) the integrated modelling study. The pseudo well models showed that another rifting event is necessary for the crustal model to work with the well data of the calibrations and the seismic sequence interpretation of the depocentre. The additional syn-rift layer was introduced into the subsurface cross section models. The grid surface shown is a seismic interpretation guided by the gravity and magnetic forward modelled horizon from several profiles evenly distributed over the area.

Conclusions

Potential field and thermal modelling integrated with the seismic interpretation more confidently constrain the extent of the petroleum plays and improved understanding of the potential hydrocarbon prospectivity offshore Madagascar. Gravity and magnetic forward modelling in conjunction with the 1D thermal modelling was applied to revise and constrain the depositional areas, extent, and thickness of the Permo-Triassic syn-rift layers for the Madagascar margin. This sequence is a proven source rock onshore. Its viability as a source rock in the offshore basins was not studied previously and poorly understood (e.g. Rusk, Bertagne & Associates, 2003) . The findings of this study significantly improve the understanding of the presence and extent of the Karoo offshore Madagascar. We illustrate that the presence of this syn-rift sequence in the Deepwater Ambilobe and Majunga Basins would have been overlooked with a pure seismic interpretation study. In contrast to previous understanding, we infer that the Karoo rift structure largely controlled Jurassic syn-rift deposition, and reactivation of Karoo faults during the Jurassic rift phase created further accommodation and structural traps.

Acknowledgements

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EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2016 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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