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[EA]Constraining the Regional Slope of Western Papua New Guinea: A Study of Lithospheric Flexure*

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Abstract

This study presents 2D and 3D models of lithospheric flexure used to constrain the regional slope in an area covering western Papua New Guinea (PNG). Regional slope has a primary influence on the geometry and elevation of hydrocarbon-trapping structures. Structurally valid balanced and restored sections in the fold-thrust belt (FTB) require this gradient as an input to any restoration work.

The regional slope was assessed by modelling the lithospheric flexure along four 2D regional transects spaced across an area of approximately 300 km trending southwest-northeast. The input parameters consist of the load geometry, bulk densities of the load and mantle, and elastic thickness (Te). The flexure model was calibrated against regional depth structure basement maps and gravity profiles. The best fit model was a semi-infinite plate with variable Te along the transect.

A 3D flexure model was generated by using the same concepts and methodology of the 2D modelling. Te and orogenic load surfaces were generated by interpolating laterally between the 2D flexure models. The resultant 3D model showed a good correlation with the 2D flexure profiles.

This study revealed lateral variations in lithospheric strength properties along the PNG FTB. Moreover, this study links how these variations influence the structural style and the tectonic model in PNG.

Introduction

A defined regional slope forms the foundation of any valid structural model. In complex folded and thrusted stratigraphy such as the PNG FTB, the regional slope is difficult to define, yet is influential in modelling and defining structure geometries. Significant hydrocarbon resources are found within the PNG FTB, however the geometries of these structural hydrocarbon traps are one of the largest uncertainties. Constraining the regional slope is a first step in modelling and adds considerable value to hydrocarbon exploration and development in PNG.

The regional slope is typically determined from seismic reflector trends, however, in the PNG FTB, seismic coverage is sparse and consists of 2D data with poor resolution (Hill et al., 2004).

In the PNG FTB, determining the regional slope from standard methods such as subsurface seismic reflector trends, proves challenging due to:

- The poor-resolution of 2D seismic data, leading to incoherent mapping of the deepest horizon reflectors;
- Artifacts produced during the depth conversion of the over-thrust structures; and
- Uncertainty in velocities for depth conversion, especially with under-sampled lithologies such as shallow volcanic and volcano-clastics layers or locally varying velocity contrasts between karstified and unaltered Darai Limestone.

It is well-established that the regional slope is strongly associated with the architecture of lithospheric plate curvature (Watts, 2001). This study focused on modelling the lithospheric flexure produced by the orogenic load induced by tectonic plate collisions to constrain the regional slope in the western PNG FTB.

Methods

Four southwest-northeast trending 2D cross sections were modelled through the Papua New Guinea continent. Each model incorporated gravity, topography, and stratigraphic profiles (Figure 1). These section lines were traced along a previous flexure study by Haddad and Watts (1999) for comparison.

This study used and integrated two different software applications: Flex2D and Flex 3D by Cardozo (2009) and Toolbox for Analysis of Flexural Isostasy (TAFI) by Jha et al. (2017).

The input parameters required for the initial modelling of the sedimentary cover and basement were obtained from the review of 20 onshore wells throughout the area of interest. The average values for the lithosphere and mantle properties were obtained from Haddad and Watts (1999).

The load geometries were constructed as individual column composites of defined height and width, with average bulk density properties assigned to key stratigraphic layers and geobodies.

The 3D flexure model was constructed by kriging the 2D profiles forming lithospheric load and Te grid surfaces.

Results and Discussion

The lithospheric flexure map (Figure 2a) shows an overall northwest to southeast depth trend along the hinterland and deepening towards to southeast. The Te map (Figure 2b) shows a similar northwest-southeast trend and a gradual decrease in the base line from 40 km in Line 1 to 20 km in Line 4. Both results are in concurrence with trends found by Haddad and Watts (1999) with the additional benefit of spatial resolution through 3D modelling.

Bimodal Te results are consistent with previous models (e.g. Chen et al., 2013; Ji et al., 2017; McNutt et al., 1988; Tesauro et al., 2015) and have been attributed to both the thermal conditions and mechanical weakening of the lithosphere (Burov and Diament, 1995; Royden, 1996; Watts, 2001).

It has been recognised globally that Te plays an important role in orogenic evolution (Arnaiz-Rodríguez and Audemard, 2014; Garcia et al., 2017; Ji et al., 2017). Moreover, the inherent strength of the lithosphere strongly influences the style and nature of upper crust shortening and deformation (Garcia et al., 2017).

The northwest-southeast trend of variable Te correlates with the spatial trend in structural style. Ollarves et al. (2019) showed that the thick-skinned structures are predominant in the western and central part of the area of investigation, these structures can be related to the relatively higher Te. In these areas, a higher Te influences the nature of lithospheric flexure, dictating a longer wavelength profile. This morphology is reflected in the general style of hydrocarbon trapping anticline structures. Conversely, the thin-skinned style characteristic of the eastern area (Ollarves et al., 2019) correlates with a lower Te. The anticline structures exhibit a shorter wavelength morphology similarly to their corresponding short wavelength, deep deflecting flexure profiles.

These two properties were used to generate a contour map (Figure 3) which reveals the variation of regional slope around the main hydrocarbon fields throughout the western PNG FTB.

Conclusion

While the results in flexure and Te trends are in concurrence with Haddad and Watts (1999), improvements are made in spatial resolution derived from the 3D flexure modelling. An improved Te map in the Western PNG area in conjunction with observed trends in structural style of hydrocarbon-trapping folds, supports the influence of lithospheric strength in the development of thick or think skinned deformation.

The bimodal trend of effective elastic thickness has been attributed to the influences of regional geothermal gradient, decoupling of the lithosphere and the combined model of mechanical weakening and thermal influx contributing to our understanding of the tectonic evolution of PNG.

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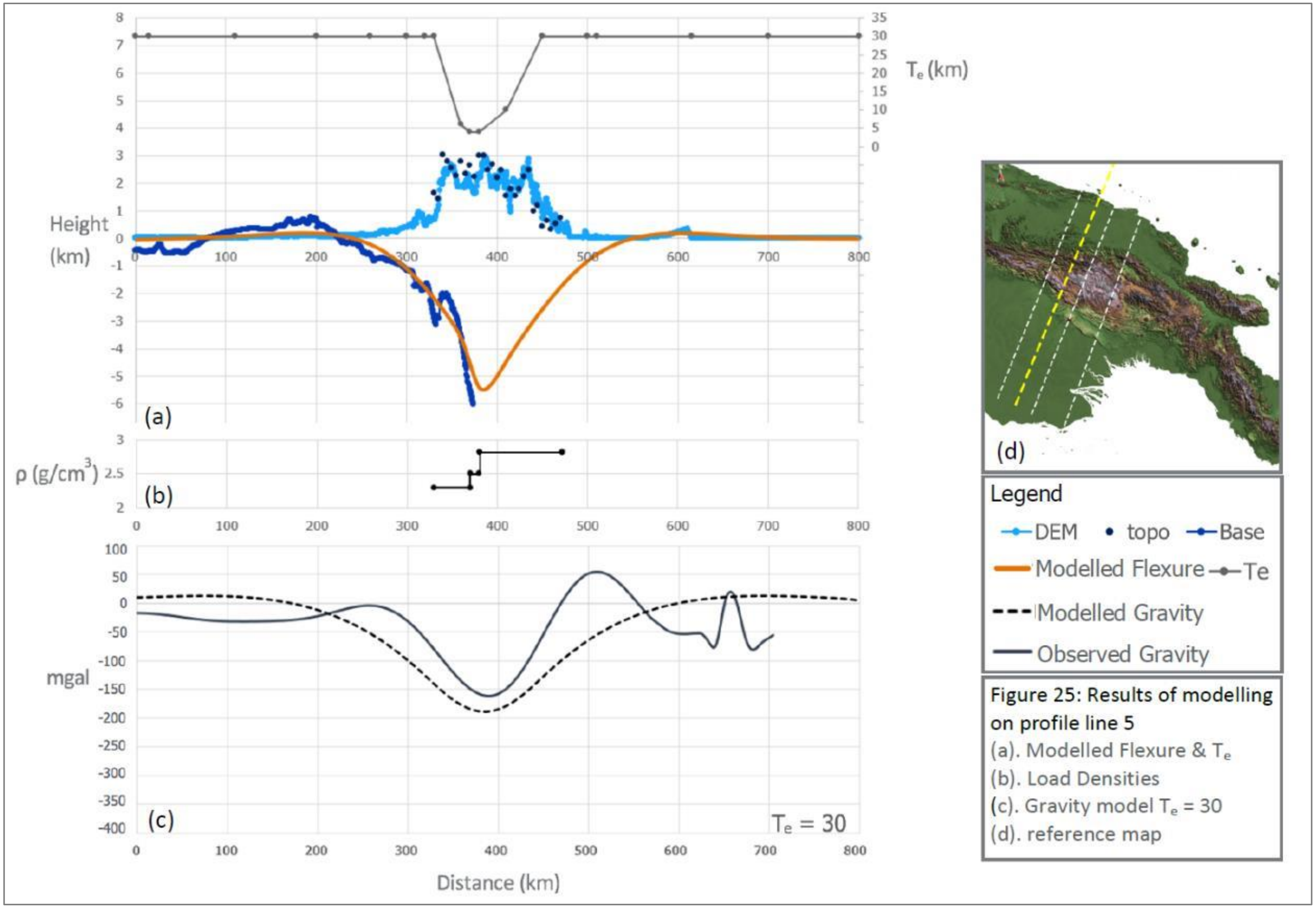

Figure 1. Line 2 profile. (a) Modelled flexure profile showing lateral variation of Te (dark grey), topography (light blue), calculated elevation for the pillars, interpreted basement from seismic lines shifted (dark blue), flexure response (orange); (b) load density profile; (c) Gravity model assuming a constant Te = 30 km; (d) Reference map, line 2 shown in a yellow line.

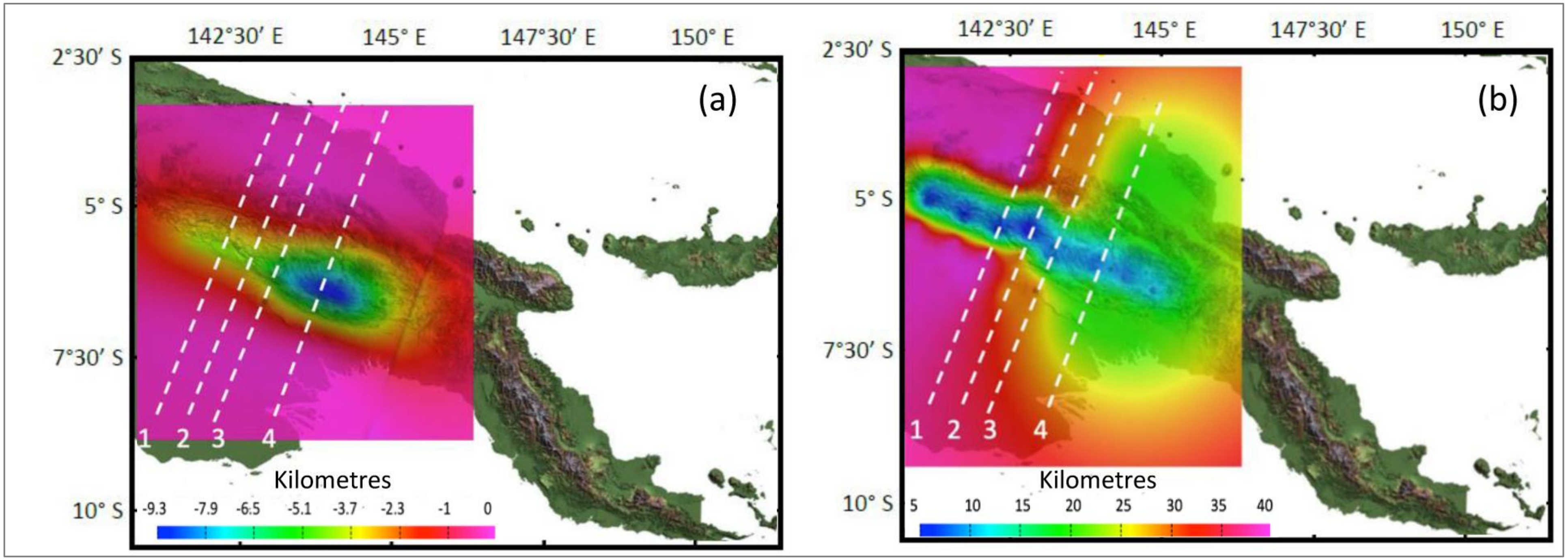

Figure 2. Digital elevation model and location of 2D transects overlaid by (a) Map of 3D regional lithospheric flexure. (b) Map of 3D elastic thickness (Te). The FTB hinterlands are shown as brown colours on the base map, with the low-lying foreland terrains shown as green in the base map.

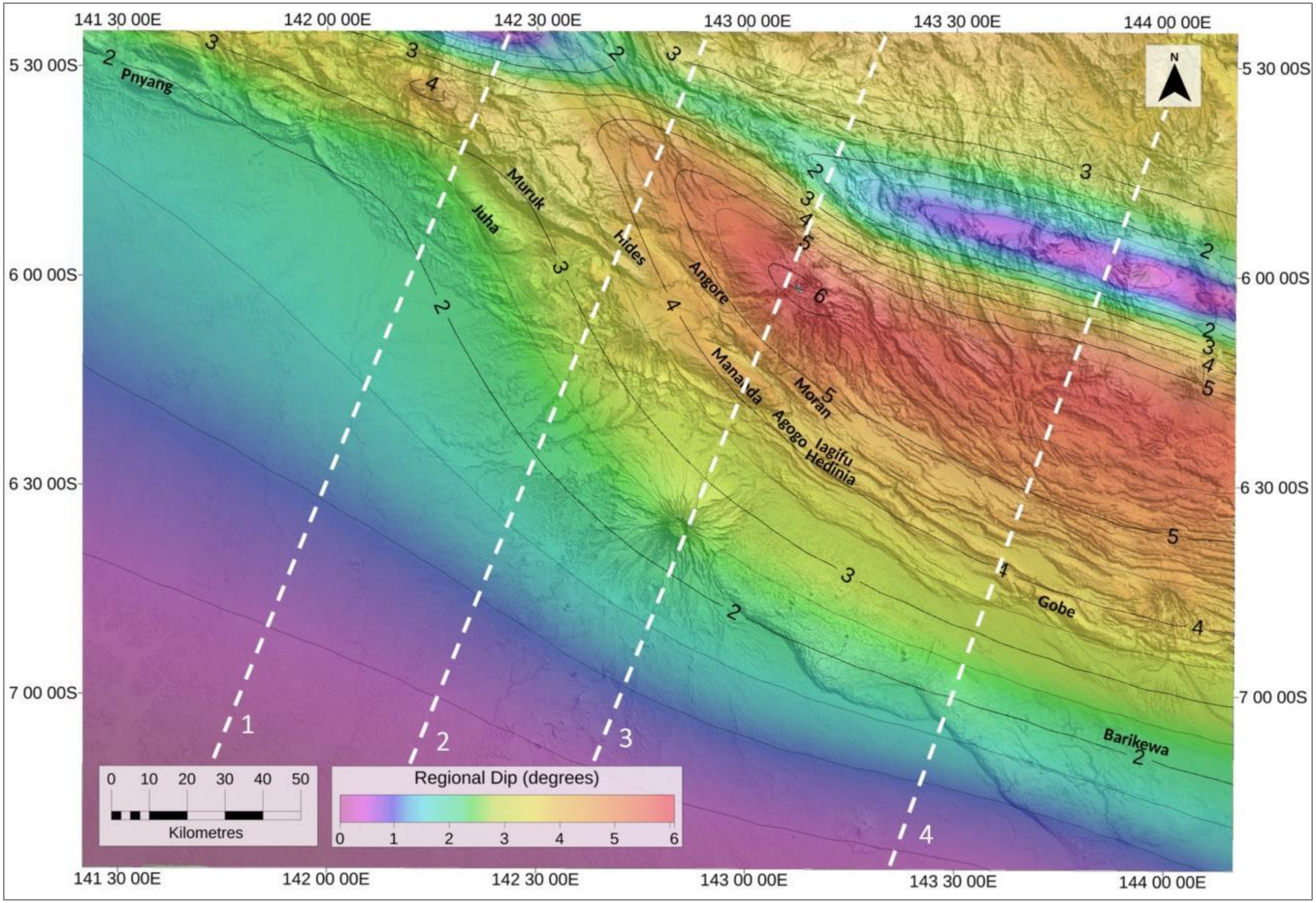

Figure 3. Slope map and contours of the lithospheric flexure due to loading.