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Complex fold and thrust belt structural styles: Examples from the Greater Juha area of the Papuan Fold and Thrust Belt, Papua New Guinea

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A B S T R A C T

The remote and inhospitable Papuan Fold Belt in Papua New Guinea is one of the youngest yet least well-documented fold and thrust belts on Earth. Within the frontal Greater Juha area we have carried out >100 km of geological traverses and associated analyses that have added significantly to the contemporary geological and geophysical dataset. Our structural analysis provides evidence of major inversion, detachment and triangle zone faults within the uplifted Eastern Muller Ranges. We have used the dataset to develop a quasi-3D model for the Greater Juha area, with associated cross-sections revealing that the exposed Cenozoic Darai Limestone is well-constrained with very low shortening of 12.6–21.4% yet structures are elevated up to 7 km above regional. We suggest the inversion of pre-existing rift architecture is the primary influence on the evolution of the area and that structures link to the surface via triangle zones and detachment faults within the incompetent Mesozoic passive-margin sedimentary sequence underlying competent Darai Limestone. Arc-normal oriented structures, dominantly oblique dextral, up-to-the-southeast, are pervasive across a range of scales and are here interpreted to relate at depth to weakened pre-existing basement cross-structures. It is proposed that Palaeozoic basement fabric controlled the structural framework of the basin during Early Mesozoic rifting forming regional-scale accommodation zones and related local-scale transfer structures that are now expressed as regional-scale arc-normal lineaments and local-scale arc-normal structures, respectively. Transfer structures, including complexly breached relay ramps, utilise northeast-southwest striking weaknesses associated with the basement fabric, as a mechanism for accommodating displacement along major northwest-southeast striking normal faults. These structures have subsequently been inverted to form arc-normal oriented zones of tear faulting that accommodate laterally variable displacement along inversion faults and connected thrust structures.

1. Introduction

Globally, there has been significant effort to document structural styles within fold and thrust belts, revealing often complex relationships between basin evolution and the subsequent style of deformation during compression. Early basin extensional architecture and mechanical stratigraphy appear to be key controls on the subsequent evolution of both thick- and thin-skinned compressional deformation. But modern rift and rifted-margin structural analogues show that extensional architecture is often remarkably complex (e.g., East African Rift: Morley et al., 1990; Chorowicz, 2005; North West Shelf, Australia: Longley et al., 2002; Frankowicz and McClay, 2010) and a wide range of factors impact inversion geometry and style (e.g., Buchanan and Buchanan, 1995; Bonini et al., 2012). Additionally, compression may occur in the presence of an evolving stress field associated with far- and near-field tectonism (e.g., Saintot and Angelier, 2002) or syn-tectonic sedimentation (e.g., Storti and McClay, 1995). For these reasons the relative influence of extension-related architecture and compression-related influences can be difficult to demonstrate, particularly where robust constraints on subsurface geometry are absent.

The Papuan Fold Belt (PFB) of Papua New Guinea (PNG) is

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located on the northern margin of the Australian plate (Fig. 1a) and has significant demonstrated mineral and hydrocarbon wealth. Yet the PFB remains poorly understood geologically, due largely to its isolation and its complex tectonic history. As such, it has the potential to provide significant new insights into our understanding of fold belts globally.

Over the past few decades, the accessibility and affordability of aviation-based exploration as well as new specialized methods of data acquisition (e.g., Hornafius and Denison, 1993; Hill et al., 1996a) have significantly improved our understanding of the local-scale structure of the PFB. Indeed the PFB is currently being actively explored for hydrocarbons and minerals involving drilling and the acquisition of widely-spaced 2D seismic data which substantially constrain geologic models. Moreover, recent and ongoing tectonism in the PFB means that present day convergence vectors (e.g., Wallace et al., 2004; Koulali et al., 2015; Stanaway and Noonan, 2015), earthquake solutions (e.g., Abers and McCaffrey, 1988; Ekström et al., 2012) and contemporary landforms can aid structural and tectonic models.

Significant variations in structural style have been recognised across the PFB, often related to pre-compression margin architecture (e.g., Hill, 1991; Buchanan and Warburton, 1996; Hill et al., 2010). However the majority of studies are based on cross-sections and do not explain how along-strike structural variations are accommodated. In particular, our understanding of the structure of the PFB decreases significantly to the west of the extensively explored hydrocarbon-bearing frontal structures in the Kutubu Fold and Thrust Belt (KFTB) (Fig. 1b). The remote neighbouring North West Fold and Thrust Belt (NWFTB) is characterised by a contrasting set of structural styles to that of the KFTB. Most obviously, it is characterised by comparatively higher surface elevations and broader structural wavelengths (Fig. 1b). Within the NWFTB region, the Greater Juha area (Fig. 1c) is contiguous with the PFB frontal hydrocarbon trend and is thus a highly prospective area undergoing active exploration. Indeed, the Juha Anticline and the Hides Anticline, 30 km further east, are both large gasfields (Fig. 1c).

Here, new geological field observations together with legacy data have been used to construct cross-sections and a detailed geological map to document and understand structural styles within the Greater Juha area of the NWFTB. Our contemporary dataset reveals a complex interplay of pre-compression rift architecture, mechanical stratigraphy and compressive stresses on the spatio-temporal evolution of the Greater Juha area.

2. Geological setting

The geological evolution of New Guinea is complex and much-debated, with a number of key tectonic events having had significant influence on the rock record. At present, the island of New Guinea comprises three major tectonic provinces (after Hill and Hall, 2003): (1) the Stable Platform to the south, (2) the Mobile Belt to the north and (3) the central New Guinea Fold Belt (NGFB) (Fig. 1a). The Stable Platform is the northern edge of the relatively undeformed Australian continent while the Mobile Belt comprises island arcs and microcontinents accreted to the leading edge of the Australian plate during the Cenozoic (e.g., Hill and Raza, 1999). The NGFB separates the Stable Platform and Mobile Belt and formed predominantly within sediments of the Australian continental margin during the Late Miocene to Pliocene (Hill and Gleadow, 1989).

2.1. Tectonic and stratigraphic framework

The rock record of New Guinea (Fig. 2) reveals a complex geological evolution for the northern margin of the Australian continent, which is summarised briefly here. Further details and tectonic history reconstructions for New Guinea are given in Pigram and Symonds (1991), Hill and Raza (1999), Hill and Hall (2003) and Baldwin et al. (2012) and for SE Asia by Hall (1996, 1997, 2002, 2012), Metcalfe (2002) and Zahirovic et al. (2014, 2016).

Limited basement outcrop and well intersections suggest Late Permian and Early Triassic metasediments and volcanics, and Middle to Late Triassic granites underlie most of the PFB and the Stable Platform within PNG (Fig. 1b). The overlying Mesozoic stratigraphic sequence was subsequently attributed to the tectonic stages of rift-drift sequences and facilitated early ideas for Early Mesozoic rifting on the New Guinea margin (e.g., Pigram and Panggabean, 1984). Northwest-southeast and WNW-ESE oriented grabens filled with Early Mesozoic syn-rift sediments (Fig. 2) and associated normal faults have been suspected to underlie the PFB (e.g., Hill, 1991) and have been identified across adjacent foreland regions (e.g., Home et al., 1990; Kawagle and Meyers, 1996; Schofield, 2000). The cessation of rifting in the Middle Jurassic was recorded throughout the Papuan Basin as a thick, widespread post-rift sequence dominated by fine-grained clastic sediments including the Jurassic-aged Imburu mudstone and Cretaceous-aged Ieru Formation (Fig. 2). During the early post-rift phase a number of prograding sandstone sequences were deposited, including the Early Cretaceous Toro Sandstone and Middle to Late Jurassic Koi Iange Sandstone (Fig. 2). Several of these sandstones host the main hydrocarbon reserves in the PFB. The Late Cretaceous to Palaeogene history of the Papuan Basin is largely unknown with a prominent top Ieru unconformity located across most of southern PNG (Fig. 2). Subsequent subsidence during the Late Oligocene to Early Miocene accommodated the deposition of 1–2 km of Darai Limestone (Fig. 2) in southern New Guinea, building the Cenozoic platform.

Compression within the Mobile Belt began during the Middle to Late Miocene (12–14 Ma) and within the NGFB in the Late Miocene to Pliocene (5-4 Ma) (Hill and Gleadow, 1989; Hill and Raza, 1999). The dominant orientation for compression-related structures throughout the PFB reflects northeast-southwest compression, with an increasingly large sinistral strike-slip component recognised northwards in the Mobile Belt (e.g., Pigott et al., 1985; Crowhurst et al., 1997), related to east-west compressive stresses from the ongoing collision with the Finisterre Arc terrane (Hill and Raza, 1999). Contemporary seismicity suggests the PFB is still undergoing compressive deformation with focal mechanisms suggesting northeast-southwest directed convergence (Ekström et al., 2012). In fact, GPS plate velocities suggest that the PFB may be accommodating up to 15 mm of convergence between the New Guinea Highlands (Mobile Belt) and Australian plate (Stable Platform) annually (Wallace et al., 2004; Koulali et al., 2015; Stanaway and Noonan, 2015).

In the Late Miocene, crustal flexure associated with plate collision and Mobile Belt uplift resulted in the formation of foreland basins to the south and southwest of the Papuan Highlands (e.g., Davies, 1983). This prompted the deposition of variably thick Late Miocene to present, shallow marine to non-marine syn-tectonic sediments. The onset of Late Miocene uplift is recorded by the deposition of calcareous clastics and reworked limestone fragments in the Orubadi Formation (Fig. 2) (Home et al., 1990). In the Pliocene, the progression of uplift and erosion in the highlands, along with contemporary volcanism, contributed to the deposition of the thick non-marine Era and Strickland Formations in the southwest of the PFB (Fig. 2) (Davies, 1983; Home et al., 1990).

Prominent stratovolcanoes and associated intrusions throughout PNG are, in general, poorly understood. Potassium-argon (K-Ar) data suggests that volcanism in the Papuan Highlands had begun by at least the Middle Miocene (Page, 1976). However, the majority of the prominent stratovolcanoes and