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Notes

Structural styles in the Papuan Fold Belt, Papua New Guinea: constraints from analogue modelling

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Abstract: Cross sections, seismic data and centrifuge analogue modelling reveal the structural styles in the oil-producing areas of the Papuan Fold Belt. They include inverted basement faults, detachment faults in the Jurassic section 1–2 km beneath the Neocomian Toro Sandstone reservoir, and tight, overturned folds in the reservoir sequence with stretched and boudinaged forelimbs, cut by break-thrusts. Additional features include highly variable thicknesses in the Cretaceous Ieru Formation, the regional seal sequence, including through-going detachments that isolate the overlying thick Miocene Darai Limestone. Centrifuge analogue modelling of intact, plane-layered strata determined that the mechanical stratigraphy and the thickness of weak beds above the lower décollement horizon exert the greatest control on the structural style. Large-offset thrust faults were only produced in models with pre-cut faults, generating early inversion and then large ramp anticlines, similar to those in the Kutubu Oilfield, which has reserves of >350 million barrels. It is suggested that the Kutubu Oilfield trend was underlain by a large normal fault and that, by analogy with the Vulcan Sub-basin, oil-rich source rocks may be confined to the hanging wall or north side of this fault. Oil would have been generated and expelled during thin-skinned deformation.

The aim of this paper is to describe the structural style of hydrocarbon traps in the Papuan Fold Belt (Fig. 1), particularly the thin-skinned structures, and to relate the structures to mechanical stratigraphy through physical, centrifuge analogue modelling. Structural interpretation has incorporated data from the many wells that have been drilled, from surface mapping and from 2D seismic and other geophysical surveys. However, the jungle-covered mountains in Papua New Guinea (PNG) severely hamper geological mapping and result in poor quality seismic data, so there remains much ambiguity in the structural interpretations. The ambiguity is greatest in the deeper, undrilled, parts of the structure and in the sheared forelimbs, both areas that are being investigated for additional hydrocarbon potential. In order to constrain the structural interpretation and hence assess this potential, physical scaled-modelling was carried out in a centrifuge using horizontal layers of plasticine and silicone putty to reflect the mechanical stratigraphy of the main beds. The models are generic rather than designed to replicate specific structures, but by varying the thickness and competence of the individual beds it was possible to obtain a very good fit to the known structures.

Oil and gas exploration commenced in PNG in the late 1920s, drilling shallow wells on seeps near major rivers on the Fly Platform. Exploration in the fold belt commenced in the 1950s on the accessible mountains, resulting in significant gas discoveries such as Barikewa in 1958 and Juha in 1983. Commercial oil was discovered in the Iagifu–Hedinia (Kutubu) anticlines in 1985 (Bradey *et al.* 2008) followed by nearby discoveries at Agogo, SE Mananda, Moran and Gobe, which have collectively been on production since 1992. Initial recoverable reserves in the known fields were well over 500 million barrels of low viscosity oil. The giant Hides gas field (Johnstone & Emmett 2000), with over 5 trillion cubic feet (TCF) reserves, was discovered in 1986 and will be the core of the gas development project planned in the near future. This project, combined with new technologies, has opened the door to a renewed phase of exploration for deeper, more cryptic oil and gas plays (Hill *et al.* 2008).

Currently, over 250 wells and sidetracks have been drilled in the Papuan Fold Belt, and more than 3000 km of 2D seismic data have been acquired, generally of poor to moderate quality. There has been considerable surface geological

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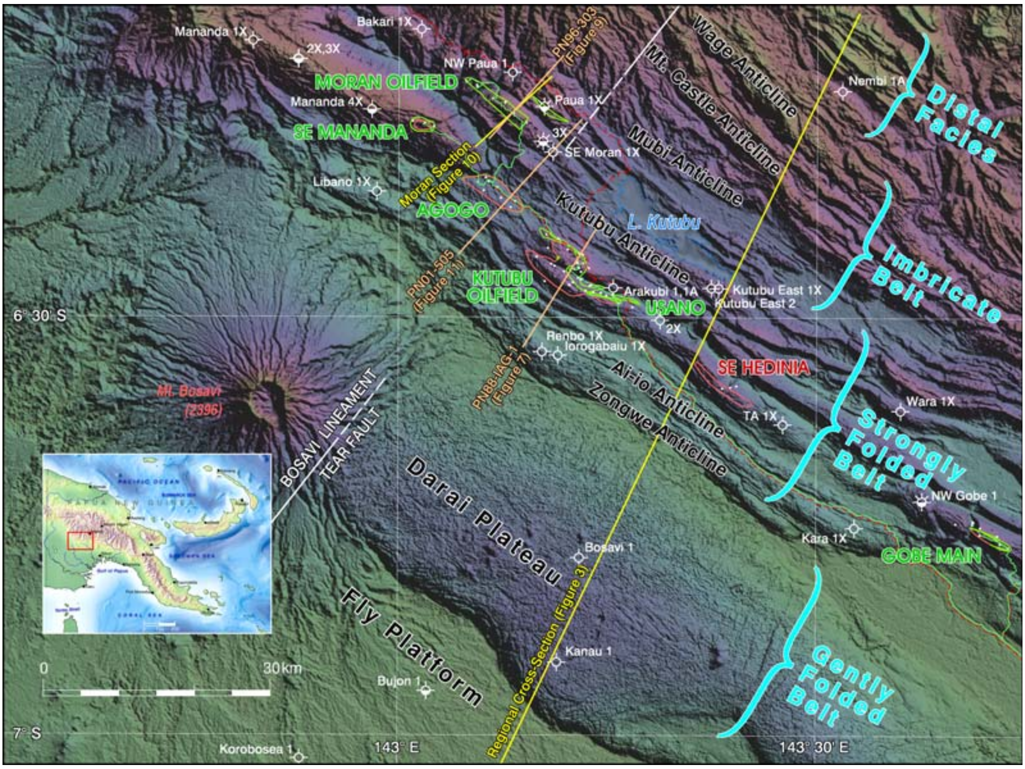


Fig. 1. Sun-shaded, digital elevation model showing the main features of the Papuan Fold Belt. The main structural belts are labelled, after APC (1961). The Darai Plateau is a very large asymmetric anticline overlying an inverted extensional fault that was active from Triassic to Miocene times. The structure is offset by a tear fault, the Bosavi Lineament, to underlie the mountain front in the NW part of the fold belt. All the producing oil and gas fields lie within the Strongly Folded Belt. Key wells are labelled and oil field and gas field outlines are shown in green and red, respectively. Wells within the fields are shown by white dots but, for clarity, are not labelled.

mapping, aided by $^{87}Sr/^{86}Sr$ isotope dating of the Miocene surface limestones (Hornafius & Denison 1993) and by analyses of synthetic aperture radar images. Structural interpretation has also been improved by the acquisition of regional and high-resolution aeromagnetic surveys, gravity surveys, and of earthquake seismic data. In this paper, a regional cross section is presented and two oil-producing structures and one breached structure are discussed, each of which has been drilled by numerous wells with dipmeter data, has been covered by widely spaced 2D seismic data and has good surface outcrop data. The structures are the Moran, Agogo and Paua anticlines (Fig. 1).

Tectonics, stratigraphy and structure of the Papuan Fold Belt

Tectonically, the island of New Guinea comprises the northern margin of the Australian continent that has undergone Miocene to Pliocene oblique convergence with the Pacific Plate resulting in collision with intervening microplates. The reader is referred to Hill & Hall (2003) for a recent discussion of PNG tectonics. The Papuan Fold Belt straddles the middle of the island and comprises precipitous mountains of heavily karstified Miocene limestone covered with dense equatorial jungle. The Fold Belt is made up of folded and thrust Mesozoic clastic rocks and Tertiary limestones and is bound to the south by the Fly Platform containing similar rocks, but undeformed. Compression in the fold belt occurred mainly in the Late Miocene and Pliocene (Hill & Raza 1999) directed roughly from NE to SW until the Middle Pliocene. Crowhurst *et al.* (1997) proposed that there was then a change to east–west compression in PNG, continuing to the present and resulting in increased strike-slip deformation.

The stratigraphy of the Papuan Fold Belt is summarized in Figure 2a and the simplified stratigraphy

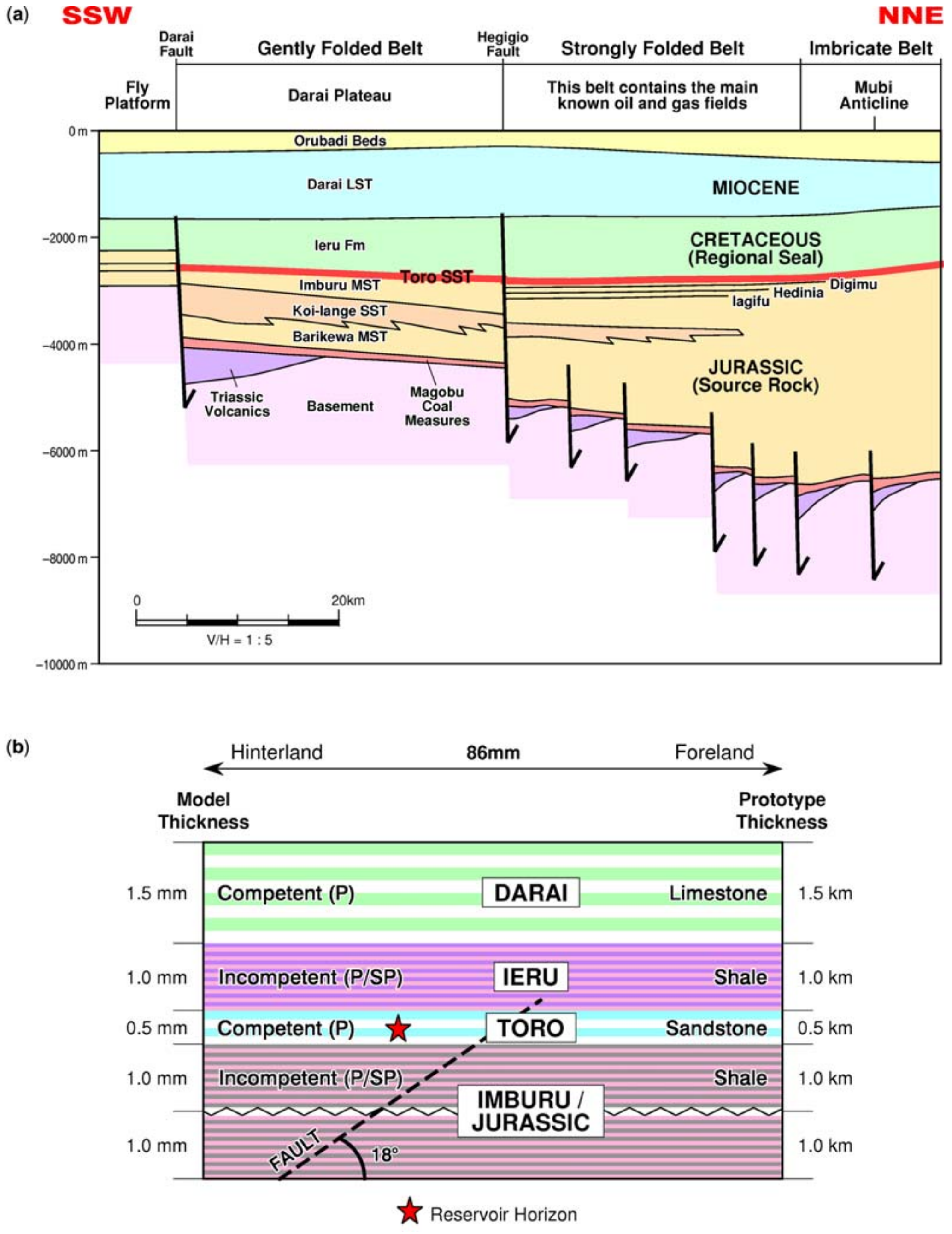


Fig. 2. Stratigraphy across the Papuan Fold Belt. (**a**) Simplified lithostratigraphic section (after Hill *et al.* 2000) flattened on the top Miocene. The Mesozoic section is dominantly mudstone, but contains the Upper Jurassic to Neocomian Iagifu, Hedinia, Digimu and Toro sandstone reservoirs. These are collectively modelled as Toro Sandstone. The Cretaceous Ieru Mudstone is the regional seal and is unconformably overlain by the thick Miocene Darai Limestone and Orubadi Marls. The Upper Triassic and Lower Jurassic syn-rift sequence is schematic on this section. (**b**) Stratigraphic column used for mechanical modelling in a centrifuge, showing the mechanical stratigraphy and real versus model thicknesses. P = plasticine, SP = silicone putty. 1 mm in the model is equivalent to 1 km in the prototype (see Table 1). In the later models, a thicker analogue Imburu sequence and pre-cut fault were used as shown.

used in centrifuge analogue modelling (discussed later) is shown in Figure 2b. Beneath the Fly Platform and the fold belt, 'basement' comprises Upper Palaeozoic rocks, mainly Permian, that were deformed in the Early Triassic New England Orogeny and intruded by Middle Triassic granites (Van Wyck & Williams 2002; Crowhurst *et al.* 2004). The sequence was deeply eroded and the granites were exposed at that time. In the Late Triassic and Early to Middle Jurassic, the area was subject to extension and rifting (Home *et al.* 1990), depositing the syn-rift Kana Volcanics, Magobu Coal Measures and Barikewa Mudstone, the latter two being probable source rocks (Fig. 2a). Regional Late Jurassic subsidence flooded the margin allowing deposition of the Imburu Formation, Toro, Digimu, Iagifu and Hedinia sandstone reservoirs and the Cretaceous Ieru Formation seal. In distal facies of the northeastern Fold Belt, both the Imburu and Ieru mudstones are hydrocarbon source rocks. During the latest Cretaceous to Paleocene, southern PNG was uplifted, probably associated with northern Tasman and Coral Sea rifting. Subsequent erosion stripped some Upper Cretaceous sediments in the fold belt and Fly Platform area and deposition did not resume until Late Oligocene flooding allowed widespread deposition of Miocene shallow marine carbonates, the Darai Limestone (Fig. 2a). Carbonate deposition was halted by the Late Miocene onset of compressional deformation, which was also responsible for generation and migration of most hydrocarbons.

Structural models of the Fold Belt

APC (1961) divided the Papuan Fold Belt into three NW–SE-trending belts, illustrated in the regional section shown in Figure 3 (discussed below). In the SW was the 'Gently Folded Belt', including the giant but low relief Darai anticline, 40 km wide and 100 km long. Structures in this belt are generally considered to be inverted basement structures (e.g. Hobson 1986; Hill 1991). The second belt, *c.* 30 km wide, commenced NE of the Darai anticline and comprised the 'Strongly Folded Belt'. All the hydrocarbons to date have been found in this belt and its structural style is addressed in this paper. The area further to the NE was classified as the 'Imbricate Zone' and consists of thrust repeats of Miocene limestone and uppermost Cretaceous shales, which are recorded in outcrop. This area is not considered here, but was analysed by Hill *et al.* (2000) and is currently being explored by oil companies.

As little was known about the Papuan Fold Belt, early structural models followed those from better-studied fold belts in North America and Europe, for instance fault-propagation folds (Smith 1965), imbricate thrusts (Findlay 1974; Jenkins 1974), duplexes (Hobson 1986) and fault-bend folds (Hill 1991). It was only with the detailed analysis of individual anticlines following the drilling of several wells that it was found that the structures comprised detached folds with overturned and/or thrusted forelimbs (Lamerson 1990; Eisenberg 1993; Franklin & Livingston 1996). Regional sections continued to show underlying basement thrusts or basement inversion structures (Buchanan & Warburton 1996; Thornton *et al.* 1996; Cole *et al.* 2000). Drilling and seismic acquisition over the Moran and Paua anticlines indicated break-thrust structures with strongly sheared forelimbs (Davis *et al.* 2000; Lingrey 2000). Recently, Hill *et al.* (2008) and Bradey *et al.* (2008) used seismic and potential field data to confirm along-strike partition of the fold belt into zones with differing basement involvement.

To interpret and model the structure of the Papuan Fold Belt, it is important to know or infer the pre-compression configuration of the margin. For instance, was it a relatively undeformed ramp as beneath parts of the Canadian Rocky Mountains (e.g. Bally *et al.* 1966) or a highly faulted margin with abrupt thickness changes as recorded in parts of nearby Indonesia (e.g. Chambers *et al.* 2004)? Cooper *et al.* (1996) interpreted two regional seismic sections across the Timor Sea, a margin along strike to PNG with a similar Mesozoic history. There they found that the major basin-bounding fault abuts the stable Londonderry High, and that two large faults bound the Jurassic Swan Graben, but otherwise the Mesozoic section gradually thickens seaward over a distance of 180 km (Fig. 4). They also noted a significant offset of structures across the Paqualin transfer zone (e.g. Woods 1992). Cooper *et al.* (1996) proposed that this area is a good structural and stratigraphic analogue for the Papuan Fold Belt prior to thrusting.

Fig. 3. (*Continued*) Regional cross section over the Papuan Fold Belt based on projected well data, surface geology and, in part, on poor to fair quality seismic data. The seismic data were most useful in defining regional dip and elevation of basement and occasionally the dip and shape of the base of the Darai Limestone. The bulk of the section results from structural interpretation of well and surface data. The lowermost section, at half-scale, shows a restoration of the Gently Folded and Strongly Folded Belts such that the shortening has not yet propagated over the hypothetical graben containing source rocks. See Figure 1 for location and text for detailed discussion.

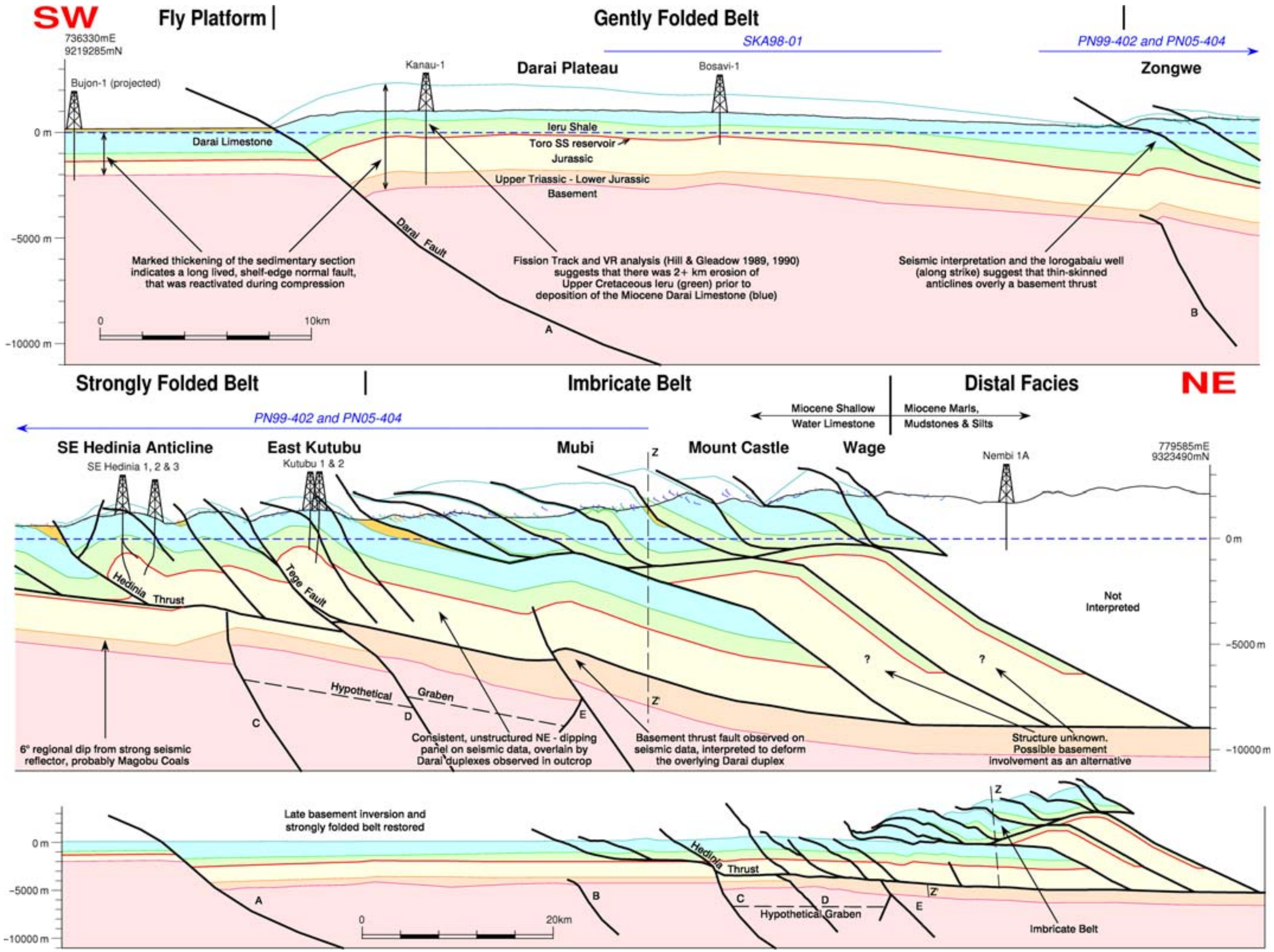

SW
Fly Platform
Gently Folded Belt
736330mE
9219285mN
SKA98-01
PN99-402 and PN05-404
Kanau-1
Darai Plateau
Bosavi-1
Zongwe
Bujon-1 (projected)
0 m
Ieru Shale
Darai Limestone
Toro SS reservoir
Jurassic
Upper Triassic - Lower Jurassic
Basement
-5000 m
Darai Fault
Marked thickening of the sedimentary section indicates a long lived, shelf-edge normal fault, that was reactivated during compression
Fission Track and VR analysis (Hill & Gleadow 1989, 1990) suggests that there was 2+ km erosion of Upper Cretaceous Ieru (green) prior to deposition of the Miocene Darai Limestone (blue)
Seismic interpretation and the Iorogabaiu well (along strike) suggest that thin-skinned anticlines overly a basement thrust
0
10km
-10000 m
A
B
Strongly Folded Belt
Imbricate Belt
Distal Facies
NE
Miocene Shallow Water Limestone
Miocene Marls, Mudstones & Silts
PN99-402 and PN05-404
SE Hedinia Anticline
SE Hedinia 1, 2 & 3
East Kutubu
Kutubu 1 & 2
Mubi
Z
Mount Castle
Wage
Nembi 1A
779585mE
9323490mN
0 m
Hedinia Thrust
Tege Fault
Not Interpreted
-5000 m
?
?
Hypothetical Graben
C
D
E
Z'
6° regional dip from strong seismic reflector, probably Magobu Coals
Consistent, unstructured NE - dipping panel on seismic data, overlain by Darai duplexes observed in outcrop
Basement thrust fault observed on seismic data, interpreted to deform the overlying Darai duplex
Structure unknown. Possible basement involvement as an alternative
-10000 m
Late basement inversion and strongly folded belt restored
0 m
-5000 m
-10000 m
A
B
0
20km
Hedinia Thrust
C
D
Hypothetical Graben
E
Z
Z'
Imbricate Belt

Fig. 3.

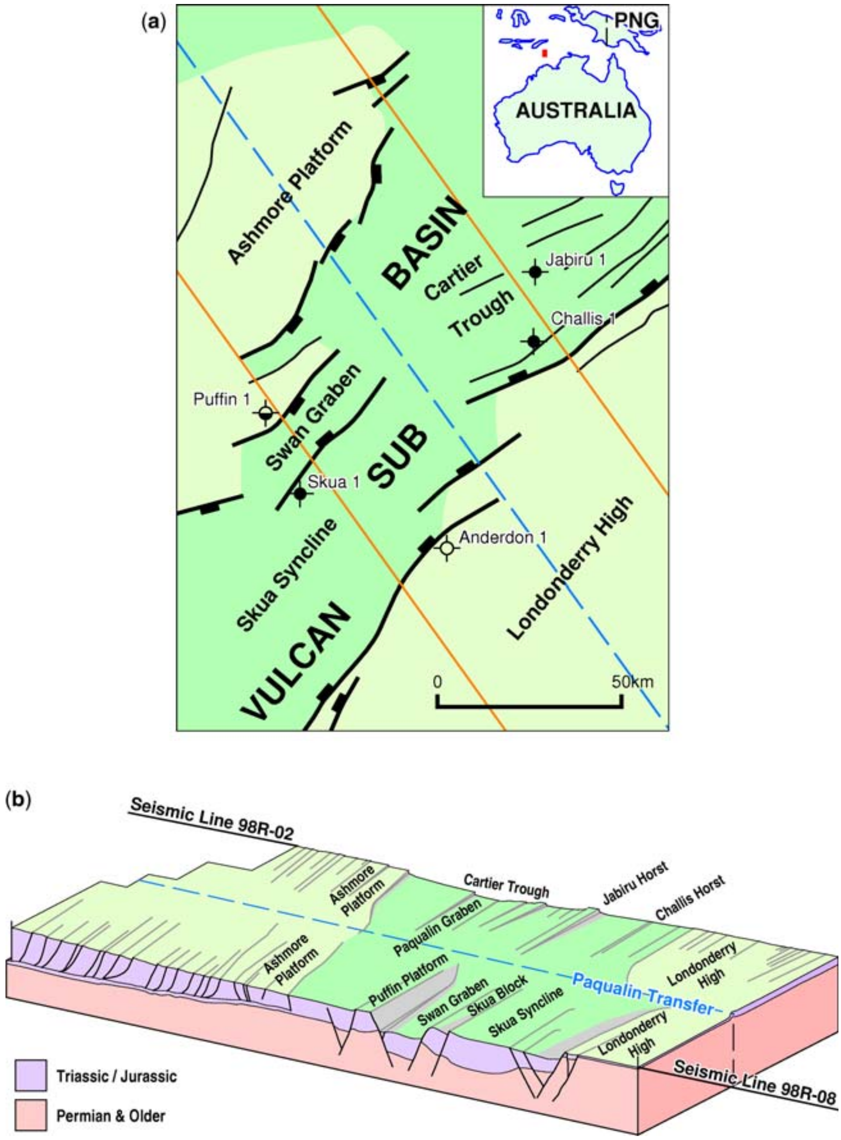


Fig. 4. (**a**) Location map of regional seismic lines across the Vulcan Sub-Basin in the Timor Sea, along strike to PNG. Cooper *et al.* (1996) inferred that this area was a good analogue to the pre-deformation stratigraphy and structure of the Papuan Fold Belt. Jabiru, Challis and Skua are oilfields, each with recoverable reserves of 50–150 million barrels. (**b**) Block diagram of the top Callovian in the Vulcan Sub-Basin showing the Upper Jurassic rift geometry, after Cooper *et al.* (1996). Note the large growth fault adjacent to the Londonderry High similar to the Darai Fault in PNG (Fig. 3). Oil source rock is largely restricted to the syn-rift fill in the Swan and Paqualin grabens (Kennard *et al.* 1999) and may be similarly restricted in PNG.

Regional structure of the Papuan Fold Belt

A regional cross section was constructed in 2DMove from the foreland across the Darai Plateau, the Strongly Folded Belt and the Imbricate Belt (Fig. 3). The section was drawn to honour all stratigraphy and dips from outcrop and ten boreholes in addition to synthetic aperture radar images and limited potential field data. It was constructed along or close to seismic lines, particularly the semi-regional line PN05-404 (shown in Hill *et al.* 2008)

across the Fold Belt. In general seismic data quality was moderate, ranging from poor to occasionally good. Migrated seismic lines were used for all interpretations, although regularly checked against those with stack and wave-equation processing. The interpreted horizons were imported into GXII and vertically depth stretched using laterally varying interval velocities for each of the main stratigraphic units. The resulting depth horizons were then imported into 2DMove and were used to guide the form of structures. Due to the moderate quality of the seismic data, they were not relied upon in detail to construct the cross sections. The top and base of the Darai Limestone were usually reasonably imaged so the underlying structure was interpreted by projecting down using known stratigraphic thicknesses.

The section was incrementally restored using 2DMove to help validate the interpretation and show the likely structural evolution. Due to the complexity of the structures, several methods were used in restoration. Late-stage basement inversion structures were restored using a tri-shear algorithm that accommodated local changes in thickness of the overlying sediments. The tri-shear algorithm was a good approximation to the deformation for the Mesozoic section, but not for the competent Darai Limestone, that required separate, fault-parallel flow restoration. Relatively simple fault-bend fold structures were restored using fault-parallel flow algorithms. More complex structures, such as the overturned SE Hedinia and Moran anticlines, had late break-thrusts restored by fault-parallel flow, were partially unfolded using a flexural slip unfolding algorithm, and then again restored using fault-parallel flow. Usually a small degree of area balancing was required for the core of the structures. The regional section was restored incrementally in six stages, but only one is shown in Figure 3, illustrating restoration of the Gently Folded and Strongly Folded Belts.

Fly Platform and Gently Folded Belt

The thickness of sediments above basement within the Darai Plateau is more than double that of the adjacent Fly Platform (4800 m v. 2200 m) indicating inversion of a previously extensional growth fault (Fig. 3). The extensional fault was probably a major basin-bounding fault, as the sedimentary thickness to the north remains at 4–6 km. The growth appears to be continuous through geological time, suggesting a relatively stable platform to the south, similar to the Londonderry High of Cooper *et al.* (1996; Fig. 4). Offset of the Darai Limestone and continuing earthquake activity suggest that Darai Plateau inversion was Pleistocene to Recent. However, a component of Late Miocene inversion cannot be ruled out.

There is clearly a significant unconformity between the Cenomanian upper Ieru Formation and the Late Oligocene basal Darai Limestone. Apatite fission track analyses (e.g. Hill & Gleadow 1989, 1990) combined with vitrinite reflectance profiles in the Kanau-1 well indicate >2 km erosion of the uppermost Ieru Formation beneath the Darai Plateau, but <1 km erosion beneath the foreland, prior to Darai Limestone deposition. This suggests that in the Early Tertiary the old normal fault was inverted and that the hanging wall was eroded prior to regional Oligo-Miocene subsidence.

Although they appear to have structural closure, neither the Kanau-1 nor the Bosavi-1 wells drilled on the Darai Plateau recovered hydrocarbons. This is thought to be due to lack of charge. It is notable on the cross section that the Toro Sandstone reservoir in both wells is near sea-level. To the SW, the Toro Sandstone almost abuts the basal Darai Limestone across the Darai Fault. It is considered likely that along strike the Toro connects to the basal Darai Limestone and hence is in pressure communication with the foreland, consistent with the low pressures recorded in the Kanau-1 well.

Strongly Folded Belt

Where the gently NE-dipping limb of the giant Darai Plateau meets the frontal fold belt structures, such as Zongwe (Figs 1 & 3), strong linear reflectors were observed on seismic at *c.* 3 s (see Fig. 9 in Hill *et al.* 2008). These are interpreted to be Magobu Coal Measures overlying basement. Using the depth conversion methods outlined above, these reflectors record a consistent dip of *c.* 6° for over 12 km to the NE beneath the Strongly Folded Belt suggesting a planar, relatively undeformed Jurassic sequence above basement such that the overlying Zongwe, Ai-io and SE Hedinia structures are detached within the sedimentary section (Fig. 3). The Zongwe anticline is interpreted to be the leading edge of the thin-skinned thrusting, in that there is a Darai Limestone repeat at surface along a fault detached within the Ieru Formation. This is thought to be underlain by a reactivated basement thrust creating a large gentle fold in the Toro reservoir. The evidence for the basement thrust from seismic data is equivocal as the data quality in that area is poor. However, on the synthetic aperture radar image (Fig. 1), the Zongwe and Ai-io anticlines together can be interpreted as a 3–5 km wide asymmetric structure that resembles a mini Darai Plateau.

The SE Hedinia anticline has been drilled by three wells and the detachment is inferred to be near the top of the Koi-Iange section. The SE Hedinia wells show that the anticline is tight, probably with an overturned forelimb, or with a forelimb sheared out by thrust faulting. Both are typical

structural styles along strike. Due to the steep dips, the core of the structure is not effectively imaged on seismic data. Between SE Hedinia and Kutubu East (Figs 1 & 3), there is a consistent SW-dipping panel from basement through to the basal Darai Limestone indicating uplift of basement to the NE on a significant basement fault. Based on seismic interpretation and section balancing, the basement faulting is interpreted to deform the top Koi-Iange Formation detachment so that at least some of the basement faulting occurred after the overlying thin-skinned deformation.

The Kutubu East anticline was drilled by two wells, which encountered minor gas and very high pressures, as opposed to normal to low pressures in the Strongly Folded Belt to the SW. The conundrum of having a breached structure that preserves very high pressures is currently being investigated, but it clearly shows a sealing fault underlying the Kutubu East anticline. Regionally, this fault separates the high pressure belt to the NE from the adjacent SE Hedinia Gasfield and Kutubu Oilfield to the SW.

Imbricate Belt

Over a distance of 10 km to the NE of the Kutubu East anticline, interpretation of the seismic data (Hill *et al.* 2008) indicates a planar, gently NE-dipping panel of strata from basement to top Darai Limestone. Geological maps show that this panel is overlain by thrust repeats of Darai Limestone and thin upper Ieru Formation, the start of a major Darai duplex that crops out over a band that is 24 km wide from Lake Kutubu to the Wage anticline. Beneath the mapped Mubi anticline the step-up in basement, inferred from seismic data, appears to fold the overlying Darai Limestone duplex, so the basement thrusting occurred after the thin-skinned deformation.

The Darai Limestone duplex exposed at surface represents considerable shortening in the Darai Limestone and upper Ieru Formation. Below, or to the NE, this must be balanced by equivalent shortening in the lower Ieru Formation to Koi-Iange Formation. On the cross section, this has been represented as a simple duplex forming the Mount Castle and Wage anticlines. However, numerous other interpretations are possible, including basement involvement. A recently acquired regional seismic line across these structures may resolve the subsurface geometry.

Centrifuge analogue modelling

Background

In order to create a more accurate representation of the subsurface structure of the Papuan Fold Belt, and to improve exploration success, scaled physical analogue models were employed. These centrifuge models simulate mechanical stratigraphy and can help determine which factors control the deformation and thus predict the structural style, the deformation sequence and the geometry of hydrocarbon traps. Dixon (1996) showed that when a pre-existing dip-slip fault was inserted into the model to simulate an old basement or extensional fault, it was reactivated early in the deformational history, prior to thin-skinned deformation. Recent centrifuge modelling of facies changes and reefs within fold and thrust belts, such as the Canadian Rocky Mountains, clearly demonstrated that mechanical stratigraphy not only affected the structural style, but also the sequence of structural deformation (Dixon 2004). This modelling also demonstrated how the strength of the basal décollement surface influences the style of deformation. A décollement of moderate strength produces foreland-verging folds in weak, basinal facies and thrusts in competent platform facies. A weaker basal detachment promotes upright folding in the basin facies and forethrusts and backthrusts associated with upright buckling on the platform (Dixon 2004).

Dixon (1996) applied generic analogue models to the Papuan Fold Belt, and showed detached or loosely linked structures in competent beds, depending upon the relative strength of the intervening weak layer. He illustrated the potential for complete detachment between the reservoir and near-surface structures. He also showed that pre-existing faults in a ‘basement’ analogue are reactivated early in the deformation and remain as important features. However, the amount of reactivation varied inversely with the dip of the pre-existing fault such that reactivation was barely noticeable if the initial pre-existing fault was steeper than about 45°. Dixon’s (1996) pre-existing faults extended through the analogue Mesozoic section, with growth in the competent reservoir analogue, but not in the underlying weak Jurassic syn-rift section. Dixon (1996) also discussed the limitations of the modelling. He pointed out that it cannot simulate variables such as geothermal gradient, pore-fluid pressure and syntectonic erosion. Furthermore, the modelled stratigraphic sequence rests on a rigid baseplate that is not involved in the deformation.

PNG model parameters

The centrifuge experiments were performed in the Experimental Tectonics Laboratory at Queen’s University, Canada. The centrifuge modelling technique used is discussed in detail by Dixon & Summers (1985), Dixon & Tirrul (1991), Liu & Dixon (1991) and Dixon & Liu (1992). The centrifuge employed in these experiments (Fig. 5) can

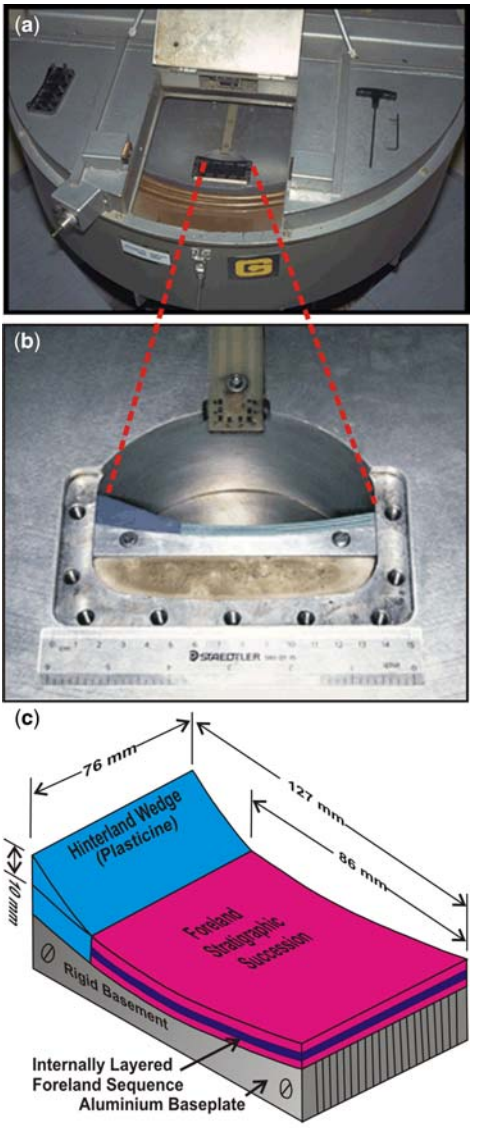


Fig. 5. Centrifuge modelling. (**a**) An oblique view of the centrifuge used for analogue modelling, showing the location of the chamber within the centrifuge rotor. (**b**) Close-up of the centrifuge rotor, indicating how the model fits into the chamber. (**c**) Schematic diagram of the initial model configuration. The rigid base plate represents the basement of the model, and consists of aluminium plates. Shortening of the foreland stratigraphic succession is caused by the gravitational collapse of the hinterland wedge.

subject the model to a centripetal acceleration up to 20 000 g, such that it simulates the Earth's gravity. All experiments were subjected to an acceleration of 4000 g (where $1\ g = 9.8\ m/s^2$, normal Earth gravity). Each model underwent two to four deformation stages, each stage lasting for five minutes at the maximum acceleration of 4000 g, with an additional seven minutes for the acceleration and deceleration of the centrifuge. The models were photographed in plan view and cross section after each stage. Table 1 outlines the model scaling ratios used, after Liu & Dixon (1991).

The models were constructed of plasticine modelling clay and silicone putty, with internally layered units of differing mechanical strengths. These materials exhibit a contrast in their competencies and are suitable analogue materials for the different rock types in the Papuan Fold Belt (Dixon & Summers 1985). In the models, the plasticine represents competent units such as limestone and sandstone, and a combination of silicone putty and plasticine represents incompetent units such as shale. The strength of a mechanical unit can be altered by changing the ratio of plasticine to silicone putty, with an increase in plasticine corresponding to an increase in strength.

Building on Dixon's (1996) work, the models presented here were designed to specifically simulate the known stratigraphy (Fig. 2). From a mechanical point of view, this comprises the strong Miocene Darai Limestone; the weak Cretaceous Ieru Formation, intermediate strength Upper Jurassic Iagifu, Hedinia, Digimu and lowermost Cretaceous Toro sands (here collectively termed Toro) and the weak Jurassic clastic sequence, mainly Imburu Formation (Fig. 2b). The thicknesses and competencies of the layers were varied in each model to demonstrate how different mechanical stratigraphies, and different combinations of pre-existing faults, control the overall structural style of the fold belt (Table 2). Importantly, the thickness and strength of the Jurassic syn-rift section was varied to see if it resulted in different structural styles. If a characteristic style could be attributed to a specific syn-rift thickness, it may be possible to predict the location of old normal faults in the Papuan Fold Belt by analysing structural style.

The initial Papuan Fold Belt modelling focused on changes within the overall mechanical stratigraphy, the strength and thickness of the lower detachment horizon and the competency of the Ieru Formation. Further centrifuge experiments incorporated previous modelling work by Dixon (1995) and Dixon *et al.* (1996), that show how primary extensional faults can disrupt the typical deformation sequence of fold and thrust belts. The models created for these experiments contained a pre-cut fault in the lower unit. The fault was cut at an angle of 18° dipping to the hinterland. This very low angle was used as steeper dipping faults were found to exhibit less reactivation and then lock up (Dixon 1995, 1996; Dixon *et al.* 1996).

Table 1. *Model scaling ratios used for this study, after Liu & Dixon (1991)*

Quantity	Ratio (model: prototype)	Equivalence (model = prototype)
Length	$l_r = 1.0 \times 10^{-6}$	1 mm = 1 km
Specific Gravity (mass)	$\rho_r = 0.6$	1.60 = 2.67 (bulk value of stratigraphic column)
Time (strain rate)	$t_r = 1.0 \times 10^{-10}$	10^{-3} s^{-1} = 10^{-13} s^{-1} (for example)
Acceleration	$a_r = 4.0 \times 10^3$	4000 g = 1 g
Stress	$\sigma_r = \rho_r\, l_r\, a_r = 2.4 \times 10^{-3}$	Calculated from other ratios

Table 2. *Construction details for plane-layered models KL10, 12, 17 and 19 and for pre-cut fault models 20 and 22*

Model	Prototype unit	Construction materials	Number of internal laminae	Total unit thickness (mm)	P:SP thickness ratio	Total model thickness
KL10	Darai	P	8	1.5	1:0	4 mm
	Ieru	P/SP	16	1.0	1:1	
	Toro	P	4	0.5	1:0	
	Imburu	P/SP	16	1.0	1:0	
KL12	Darai	P	8	1.5	1:0	5 mm
	Ieru	P/SP	16	1.0	1:1	
	Toro	P	4	0.5	1:0	
	Imburu	P/SP	32	2.0	1:0	
KL17	Darai	P	8	1.5	1:0	5 mm
	Ieru	P/SP	16	1.0	2:1	
	Toro	P	4	0.5	1:0	
	Imburu	P/SP	32	2.0	1:0	
KL19	Darai	P	8	1.5	1:0	5 mm
	Ieru	P/SP	16	1.0	2:1	
	Toro	P	4	0.5	1:0	
	Imburu	P/SP	32	2.0	2:1	
	Darai	P	8	1.5	1:0	
KL20	Ieru	P/SP	16	1.0	2:1	5 mm
KL22	Toro	P	4	0.5	1:0	
	Imburu	P/SP	32	2.0	1:0	

Abbreviations: P, plasticine, SP, silicone putty.

Vaseline petroleum jelly was applied to the fault surface to prevent the hanging wall and footwall from re-adhering after being cut. The initial model configurations for these experiments are shown in Figure 2 and Table 2. Regrettably, the seismic data in PNG were not of adequate quality in the basement, typically at 3–6 s two-way time (twt), to determine the dip of faults to compare with the model (see discussion).

Plane layer, mechanical stratigraphy modelling

The initial model had a relatively thin basal unit, simulating *c.* 1 km of Jurassic section as observed beneath parts of the Fly Platform (Fig. 3). Foreland-verging imbricate duplex structures developed as thrusting initiated early during deformation and only low-amplitude folds were able to form prior to the development of break-thrusts (Fig. 6a, KL10). Two décollement surfaces exist within the Imburu and Ieru analogues, creating differential shortening and thrust spacing between the competent units.

The second model shows an increase in the thickness of the basal unit from 1.0 mm to 2.0 mm, simulating *c.* 2 km of Jurassic section above rigid basement, as observed beneath the Darai Plateau (Fig. 3). This modification decreased the amount of foreland vergence and created more upright structures (Fig. 6b, KL12). There was an increase in folding versus thrusting, with increased fold amplitude in both the Toro and the Darai analogue units. The décollement horizon within the Ieru analogue was not active consistently throughout deformation, allowing regions of both harmonic and disharmonic deformation to develop.

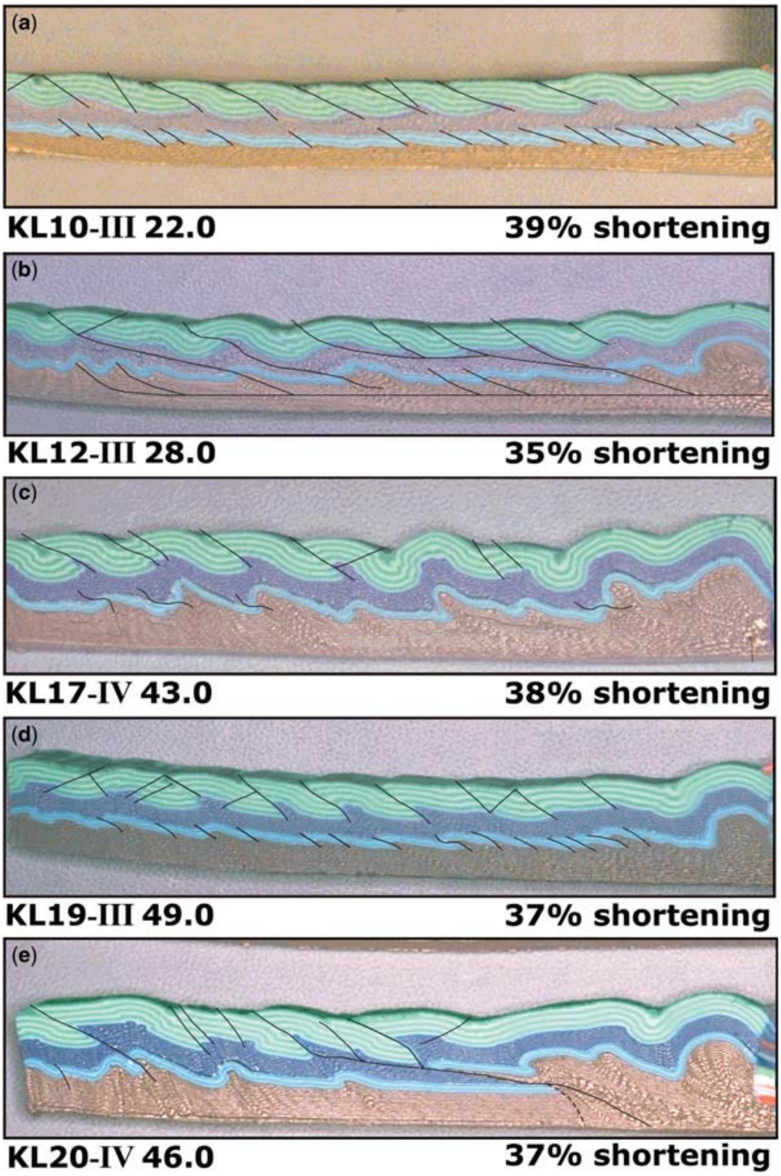


Fig. 6. Centrifuge analogue modelling of intact, plane-layered strata with initial conditions as shown in Figures 2 and 5 and Table 2. Note the variation in structural style as the thickness and relative mechanical stratigraphy are varied. Observed faults have been highlighted with thin black lines. Model (**a**) has a 1-mm thick Imburu analogue as opposed to 2 mm for models (**b**) to (e). In model (**c**) the mechanical strength of the Ieru is increased and in model (**d**) the mechanical strength of the Imburu is increased. Model (**e**) has a pre-cut fault dipping at 18° from the base Imburu to the base Darai analogue. See text for discussion.

The third model incorporates an increase in the mechanical strength of the Ieru analogue, creating a mechanical linkage between the overlying Darai and underlying Toro competent units (Fig. 6c, KL17). By forcing the linkage of the competent units, the upper three units act as a single beam deforming above a weak, relatively thick, décollement horizon. The upright, fold-dominated structures are harmonic between the competent units, with surface structures situated directly above the

structures at depth. However, in detail it can be seen that the Toro analogue is dominated by tight folding, the Ieru analogue manifests substantial changes in thickness and the Darai analogue records both open folding and thrust faulting. The Ieru analogue acts as a local or diffuse detachment zone connecting the folds and minor faults in the Toro analogue to the faults in the Darai analogue. The structural style is very similar to that recorded in the Moran and Usano structures (Franklin & Livingston 1996; Davis *et al.* 2000; Lingrey 2000) and is discussed further below.

The fourth model includes an increase in the mechanical strength of the Jurassic Imburu analogue (Fig. 6d, KL19). This strong lower décollement horizon produced a thrust-dominated structural style, containing duplexes with foreland vergence. Upright structures did not develop due to the enhanced foreland vergence. Early developed folds had very low amplitude, and thrusts developed early in the deformation. A significant second décollement surface developed within the Ieru analogue, allowing the structures between the Darai and Toro analogues to become laterally displaced from each other.

Varying the mechanical stratigraphy used in the fold and thrust modelling of plane-layered strata resulted in four different structural styles (Fig. 6a–d). The structural style that most resembles that recorded in the Papuan Fold Belt is shown in Figure 6c, perhaps with elements from Figure 6d. Thus the modelling suggests the presence of a relatively thick and weak Jurassic section and a slightly more competent Ieru section. The models are discussed further below when compared to cross sections of the Papuan Fold Belt.

Modelling of pre-existing faults

Recently acquired and/or reprocessed seismic data across the Kutubu Oilfield suggest a low-angle thrust fault with 4–8 km of displacement in that area of the Papuan Fold Belt (Bradey *et al.* 2008), as illustrated in Figure 7. The Kutubu seismic line (Fig. 7) also shows an unusual 'double-hump' structure in the hanging wall with the Toro Sandstone and Darai Limestone both gently folded, except in the forelimb where overturned Darai was encountered at the base of one well. The structure has been confirmed by 43 wells drilled over the field (Bradey *et al.* 2008). The double-hump structure in part results from thrust displacement over a series of ramps and flats, but it requires a relatively large thrust displacement. No such large-offset thrust or double-humped anticline was recorded in the plane-layered models presented above. It has

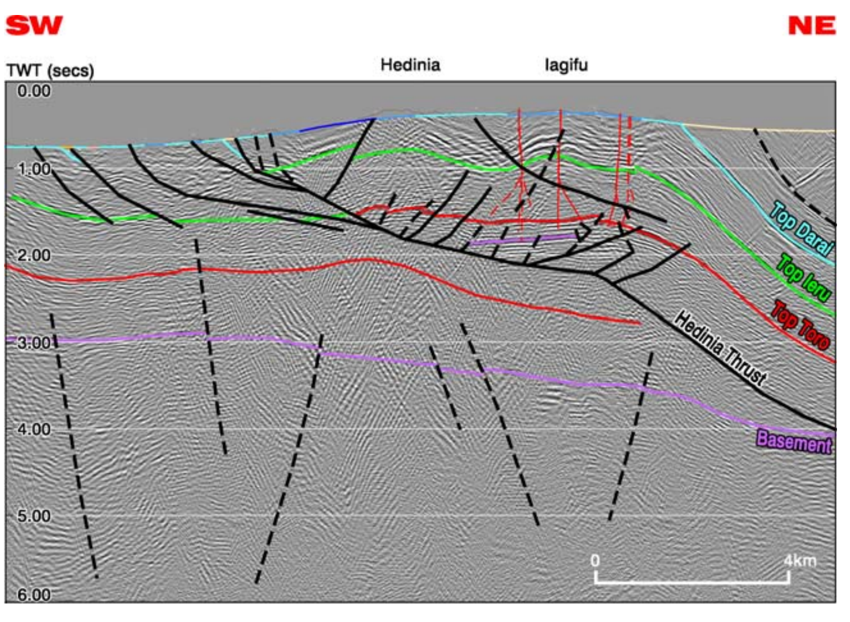


Fig. 7. Seismic line PN88-IAG-1 across the Iagifu and Hedinia anticlines that comprise the Kutubu Oilfield. See Figure 1 for location. Note the inferred relatively large offset of the Toro and two-humped nature of the Toro anticline, similar to that in Figure 6e. Note also the required internal deformation within the Ieru in the anticline cores, as shown by tighter folds in the Darai than in the Toro.

long been suspected that Jurassic extensional faults were a controlling factor in the structural evolution in the Papuan Fold Belt (e.g. Buchanan & Warburton 1996) and that the Kutubu Oilfield is underlain by a Jurassic normal fault that may have been reactivated. These concepts were tested by models that included one or two faults cut into the pre-deformation model, each of which was lubricated by Vaseline petroleum jelly smeared along the fault surface. In order to obtain the large thrust offset, the faults were pre-cut at 18° to bedding and lubricated as steeper pre-cut faults tend to lock up during deformation (Dixon 1996).

A model was run with a single pre-cut fault from the base of the Imburu analogue to the base of the Darai analogue (Fig. 6e, KL20). The stratigraphy used was the same as that in Figure 6c (Table 2). The pre-cut fault was reactivated early in the deformation and accommodates much of the shortening. The dip of the pre-cut fault evolved to become steep as it passed through the break in the Toro analogue, shallow as it continued through the incompetent Ieru analogue, and steeper again where it propagated through the Darai analogue to the surface of the model. Much of the shortening was channelled to the incompetent Ieru unit, creating laterally displaced structures between the Darai and Toro analogues. A second large fault with a shallower dip developed in the Darai analogue on the foreland side of the reactivated fault. The slip on the pre-cut fault at Toro level is roughly equal to the sum of the slip on these two Darai faults indicating that the pre-cut fault splays upwards, linking to both faults. Furthermore, some of the displacement was channelled towards the foreland along the Ieru décollement, creating greater shortening and a different structural style within the Darai analogue than in the Toro analogue. The differential shortening laterally displaced the Darai analogue further towards the foreland with respect to the structures that developed in the Toro analogue.

This model bears a strong resemblance to the structure of parts of the Kutubu Oilfield (Fig. 7) and to that shown in the SE Hedinia area on the regional cross section (Fig. 3). In particular, the model shows a two-humped Toro anticline in the hanging wall of the pre-cut fault, as seen in the Kutubu anticline and large displacement along the fault. Further, the model shows a detachment in the Ieru, with splays cutting through the Darai towards the foreland of the Toro structure, as recorded in the Zongwe and Ai-io structures on the regional section (Fig. 3).

To test the possibility of multiple normal faults beneath the Papuan Fold Belt, two faults were pre-cut in the model, each penetrating from the base Imburu to half way through the Ieru analogue unit. Displacement along the pre-cut faults was simultaneous within the resolution of the experiment, each with equivalent shortening that was channelled to both competent units (Fig. 8). The region between the two pre-cut faults acquired the least amount of deformation, creating a large zone of uplift where the panel between the faults was transported up the frontal fault towards the foreland. Initial thrusting along the pre-cut fault can be seen after only 5% total shortening (Fig. 8a). At 16% total shortening, the faults remain as the dominant feature of the model (Fig. 8b), but as deformation progresses to 44% shortening, younger fold–thrust structures develop independent of the reactivated faults (Fig. 8c). Importantly in these models, the pre-cut faults were reactivated first creating anticlines akin to inversion structures and the fold and thrust structures formed subsequently. If true in the Papuan Fold Belt, it would have important implications for migration and charge of structures (see discussion).

Comparing the model shown in Figure 8c with the regional cross section (Fig. 3) it is apparent that there are some broad similarities. Perhaps the structure above the leading pre-cut fault is equivalent to the broad SE Hedinia–Kutubu East culmination, in other words the Strongly Folded Belt. The long hinterland-dipping limb above the pre-cut fault in the model is very similar to that interpreted on seismic data (Hill *et al.* 2008) used to construct the regional cross section. Similarly, the structure above the more hinterland pre-cut fault in the model could equate to the broad culmination defined by the Mount Castle and Wage structures on the regional section. If this comparison is valid, then it suggests that the two culminations may be associated with pre-existing faults, perhaps Jurassic extensional faults.

Structural style from well and seismic data

The Moran anticline

The Moran anticline was first drilled in September 1996 and was found to contain an 800 m oil column in Digimu and Toro sandstone reservoirs. Davis *et al.* (2000) stated that 'the Moran structure is a narrow, elongate SW-vergent fault-bounded anticline with a moderate to steeply dipping (30°–50°) backlimb and an overturned near vertical forelimb'. Davis *et al.* (2000) and Lingrey (2000) presented cross sections through the Moran 1X, 2X, 1XST and 2XST wells, two of which drilled through the hanging wall across the thrust and tagged the footwall. The sections indicated that the structure was folded first then a break-thrust broke

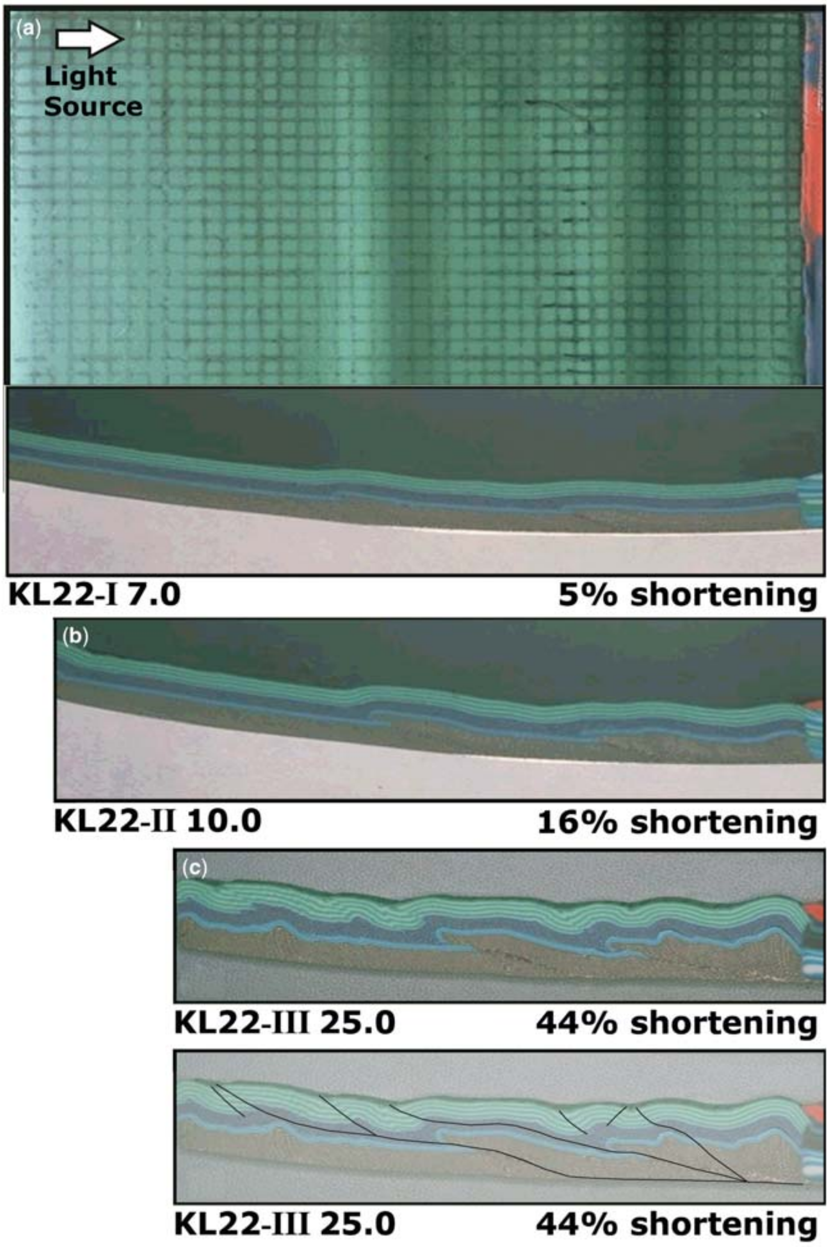


Fig. 8. Centrifuge analogue modelling of plane-layered strata with two faults pre-cut from the base Imburu to middle Ieru as shown in Fig. 2b. Initial conditions are recorded in Table 2 and Fig. 2. Note that the pre-cut faults are reactivated first making large anticlines (a and b) and the thin-skinned deformation encroaches at higher degrees of shortening (c). See text for discussion.

through the stretched, faulted and boudinaged fore-limb. The structure is strongly compartmentalised (Hill *et al.* 2008), with a fault across the centre separating an 800 m oil column to the west from an equivalent higher-pressure water column at the same elevation to the east (shown by the abrupt eastern edge of the field boundary on Fig. 1). Here, we present two seismic lines across the Moran anticline and adjacent structures and a cross section based on well data, surface dips and

seismic data and utilizing the centrifuge analogue modelling presented above.

Figure 9 shows uninterpreted and interpreted versions of recently reprocessed, migrated seismic line PN96–302 across the Moran anticline through the Moran 1X, 2X, 1XST and 2XST wells. The *c*. 5 km seismic line illustrates the difficulty in acquiring good quality data across this steep, mountainous, jungle-covered terrain with karstified limestone at surface. Data acquisition is exacerbated by crooked line paths, air-filled caverns, deep fissures, an irregular low velocity weathered zone and a velocity inversion from the Darai Limestone to the underlying Ieru Shale (Lingrey 2000). Seismic acquisition is also limited by the current cost of US$ 100 000/km, in part due to the necessity of helicopter-supported operations.

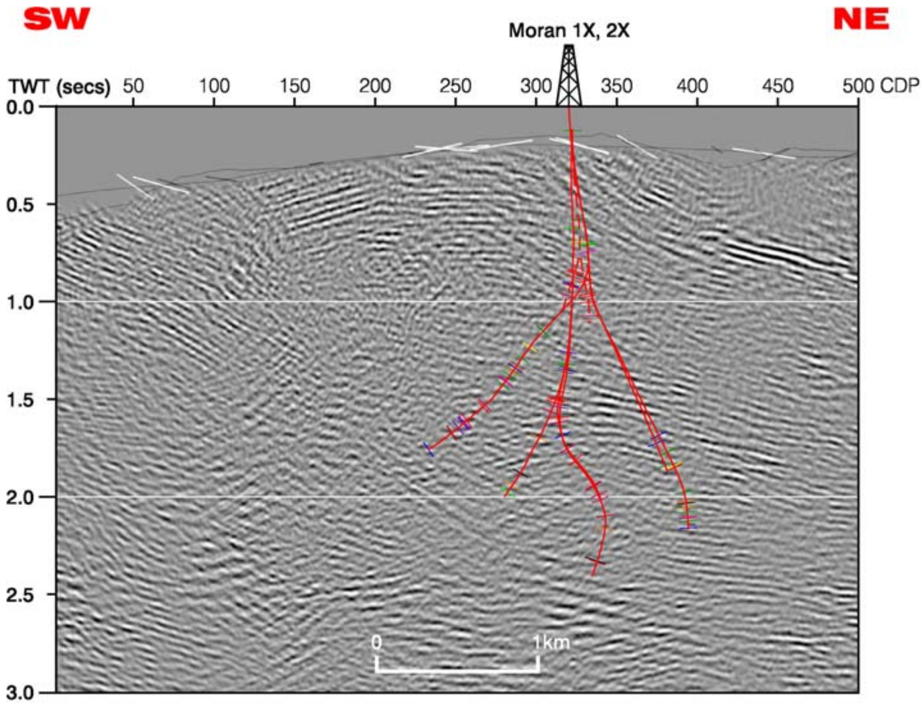
Although the seismic data quality is only poor to moderate, it is still useful in helping to interpret the structure when used in conjunction with surface geology. Indeed, now that the obvious surface anticlines in the Papuan Fold Belt have been drilled, such seismic data are vital in future exploration. On the uninterpreted section of Figure 9, the broad form of the strongly reflecting Darai Limestone can be seen, revealing the position of the Moran Thrust. The inclination of the backlimb can also be determined, both at surface and at depth, away from the core of the structure. It is also possible to infer a potential sub-thrust structure at Toro level, as shown, although this is not proven and relies in part on structural and modelling analogues. Unfortunately, below the Darai Limestone in the core of the structure, almost all of the reflectors are spurious, as shown from the interpretation post-drilling. The steep dips and probable small-scale internal faulting of the beds make imaging of the core of the structure almost impossible. In areas without well control, interpretation of the core relies on structural and analogue models.

Figure 10a shows a structural interpretation of the Moran and Paua anticlines as well as the NE limb of the large Mananda anticline that is imaged on the seismic line (Fig. 9). The Moran section is similar to those presented by Lingrey (2000) and Davis *et al.* (2000), except that the borehole dips have all been reprocessed, there are additional surface dips and the seismic data have been reprocessed. The Mananda part of the section is constrained by additional seismic lines and eight wells on the Mananda anticline along strike and the Paua structure is constrained by two wells projected onto the section. It should be noted that the number of dips shown is only a small sample of those used to construct the section and that the Mesozoic stratigraphic zonation is very fine, with many more horizons correlated than can be shown. Thus the hanging wall anticlines are well constrained.

The Middle Jurassic to basement portion of the section is largely unconstrained and schematic. A key part of the interpretation is the 'regional' level of the relatively undeformed Middle and Lower Jurassic section. Projecting those beds downdip from the foreland suggests that the top of the Middle Jurassic should be at *c*. 5 km subsea, consistent with the regional section (Fig. 3). However, interpretation of the seismic data suggests that the top of the Middle Jurassic is at 3–4 km subsea beneath Moran and modelling of earthquake seismic data in the area (Hill *et al.* 2008) indicates high velocity basement is at 6 km subsea. Therefore, reverse faults in basement have been inferred on the interpretation, as shown. These may be reactivated extensional faults, but this is unproven.

As can be seen from comparison of Figure 10a, b, there are strong similarities between the section interpretation and the centrifuge model shown in Figure 6c. Both sections show open folds in the Darai but tight to overturned folds in the Toro–Iagifu (reservoir) section, with large changes in thickness of the intervening Ieru Formation. Both show brittle faulting in the Darai, but more folding in the reservoir section. Furthermore, a detachment within the Ieru is manifested in both sections, connecting the faulting in the Darai above Moran to the thrust fault underlying the Paua anticline. Such structures may well have formed out-of-sequence as the Moran anticline developed in front of and below the Paua anticline.

A significant difference between the interpreted and analogue model sections (Fig. 10a, b) is the level of detachment beneath the reservoir. The Moran wells and a few other wells drilled to the fault in the Papuan Fold Belt, combined with the seismic data, strongly indicate a detachment in the Imburu Formation just above the Koi-Iange Formation, *c*. 800 m below the top of the Toro Sandstone. In contrast, in the analogue model the fundamental detachment is scaled to be 2.5 km below the top of the Toro. However, it should be noted that the level of detachment varies in the Papuan Fold Belt and that there is good evidence from seismic data (better quality than in Fig. 9) that the detachment is deeper, *c*. 1.5–2.0 km below the top Toro, in the core of the Mananda anticline, the core of the Kutubu Oilfield (Fig. 7) and the northeastern part of the regional section (Fig. 3). Another difference is the degree of thickness changes in the Ieru, which is considerably greater in the analogue model. It may be that the interpreted cross section underestimates Ieru thickness changes in the synclines; for instance the Darai keel between the Moran and Mananda



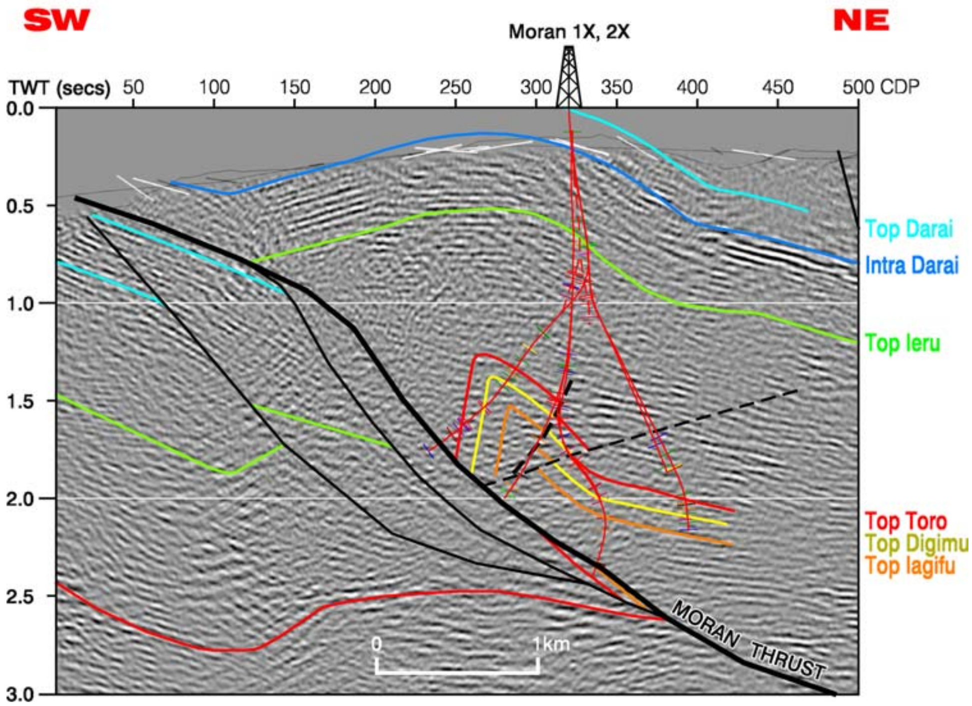


Fig. 9. Seismic line PN96-303 through the Moran-1 and Moran-2 wells, blank and interpreted. The well ticks are horizon tops, not dips. The data illustrate the limitations of seismic acquisition and interpretation in PNG. However, it is possible to infer the shape of the Darai Limestone, the location of the Moran Thrust and potential sub-thrust structures. See text for discussion.

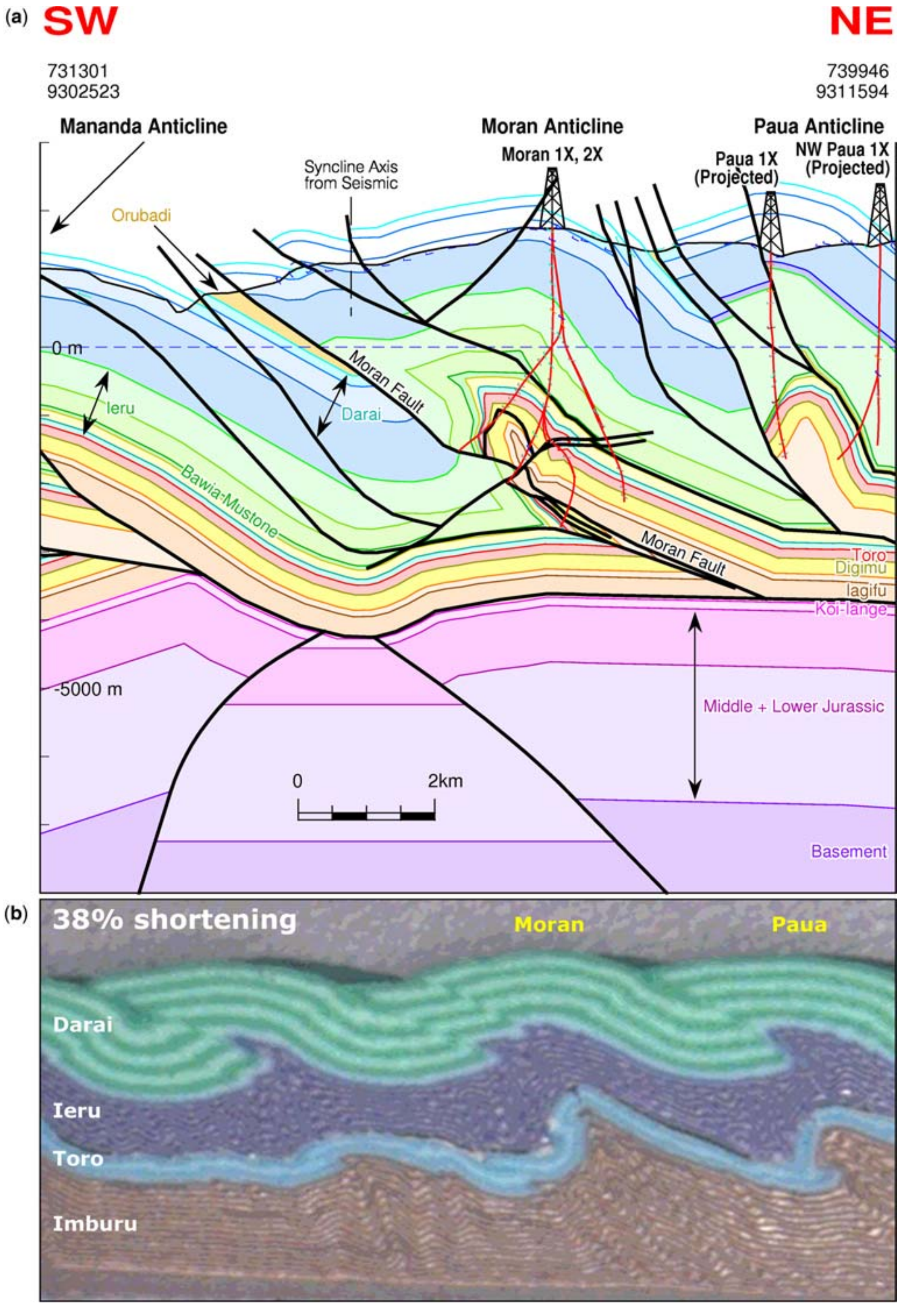


Fig. 10. (**a**) Structural cross section of the Moran and Paua anticlines based on detailed well dips and stratigraphy, surface mapping and seismic data. The well ticks are representative dips. This section has not been balanced. (**b**) Expanded view of the middle of Figure 6c showing a strong similarity between the interpreted section and the analogue model.

anticlines could be shallower, as it is only constrained by poor quality seismic data.

Detailed analysis of the Moran cross section (Fig. 10a) reveals several features that suggest a structural evolution (discussed later). In the core of the structure a low-angle, folded thrust fault was encountered at three locations in the boreholes, with *c*. 50–100 m offset. The wells that drilled the forelimbs of both the Moran and Paua structures found a relatively complete stratigraphic sequence, but 30–50% of the normal thickness and cut by faults. The Moran Fault was interpreted to comprise a zone of faults through these stretched beds and is itself offset by a backthrust encountered in three wells. Within the Ieru Formation, the Bawia Mudstone is a weak and mobile bed in which the thickness is highly variable, probably due to tectonism. This horizon is interpreted to be the main detachment horizon within the Ieru Formation as dips are highly variable above it with common thrust splays but dips below are relatively consistent. One further feature is the interpretation of ‘out-of-the-syncline’ thrust faults (Dahlstrom 1970), for which the main evidence is offsets and increased thickness of the Darai Limestone.

Combining those features suggests the following structural evolution:

(1) Minor low-angle thrust faults developed through parts of the structure.
(2) A fault-propagation fold developed with a stretched overturned forelimb, including folding of some of the existing low-angle thrusts.
(3) With continued shortening, the fold evolved into a break-thrust.
(4) The next structure towards the foreland, the Mananda anticline, was thrusted and folded, jacking up the existing structures and generating out-of-the-syncline thrusts and backthrusts due to the resultant space problems.

In terms of hydrocarbons, it seems likely that the 800 m oil column is preserved, in part, due to tight folding of the reservoir so that it is encased in mudstone of the Ieru Formation, the regional seal. The forethrusts and backthrusts have effectively made the crest of the anticline a pop-up structure that may have helped to isolate and preserve the hydrocarbon column. It is notable that the adjacent Paua structure encountered a residual oil column, minor gas and high pressures and that the same was true for the eastern half of the Moran anticline across an important tear fault (Hill *et al.* 2008). The Mananda structure to the southeastern preserved a small oil column at low pressure in an isolated crest at its SE end, the SE Mananda field (Fig. 1).

Moran–Agogo structure

Figure 11 shows *c*. 9 km of an interpreted version of a recently reprocessed, migrated seismic line PN07–505 across the Agogo Oilfield and the southeastern part of the Moran anticline. This SE part of the Moran structure tested water at high pressure instead of oil. Although imaging of the core of the Moran structure is still poor, probably due to

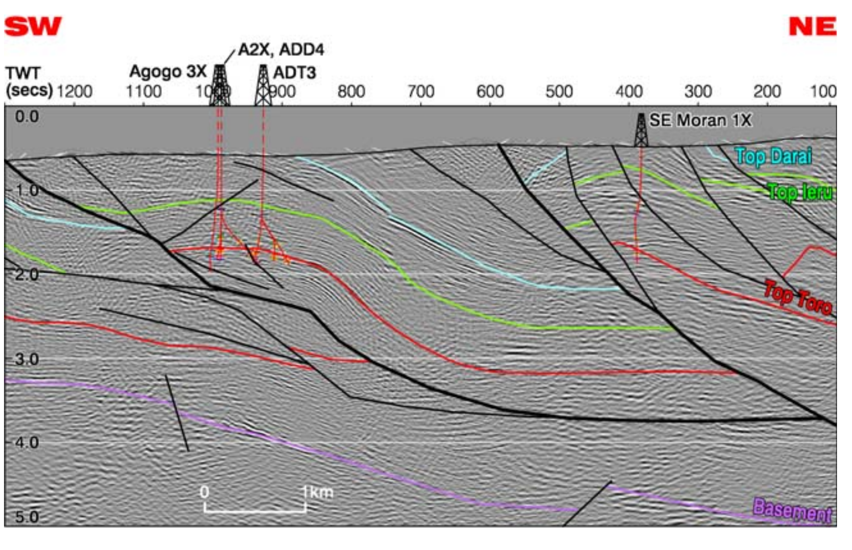


Fig. 11. Structural interpretation of seismic line PN07-505 across the Agogo oilfield and SE Moran anticline. See Figure 1 for location. The Agogo anticline, the adjacent syncline and even the underlying basement are relatively well imaged.

steep dips and faulting, the seismic and nearby Moran-3X well data (Fig. 1) suggest that the structure is a thrust ramp, with a less well developed forelimb than the oil bearing part of the structure shown on Figure 10. The SE Moran structure is perhaps more like the thrust Toro structure near the centre of Figure 6e than the folds with stretched forelimbs near the centre of Figure 6c.

The Agogo anticline is along strike, but slightly en echelon to the SE Mananda anticline, hence is further away from the Moran Thrust. Thus the syncline between the Moran and Agogo structures is preserved rather than faulted out as it was on Figures 9 and 10. In consequence, the Darai Limestone to Jurassic section is much better imaged, particularly within the Agogo structure. It is also possible to infer some underlying basement structure as shown on the section. It is notable that the structural style on this seismic line is not exactly like any of the centrifuge analogue models presented here. In particular, the consistent large thrust offset of Toro Sandstone and Darai Limestone differs from the models, but resembles the Toro offset near the centre of Figure 6e and towards the right hand side of Figure 8c.

Discussion

Centrifuge analogue modelling

The influence of mechanical stratigraphy upon structural style was demonstrated by the experiments presented here, as shown by the different structural styles in Figure 6. The thickness of the competent beds remained the same in these experiments, so the variations in structural style were due to subtle changes in the relative strength and thickness of the weaker layers. Thin alternating strong–weak–strong–weak layers with large competence contrasts resulted in imbricate thrusts in the strong layers with thrust spacing proportional to the bed thickness (Fig. 6a). The intervening weak layers acted as ductile detachments that accommodated the variable strain, so that thrusting in the strong layers was disharmonic, as previously recorded by Dixon (1996). Doubling the thickness of the lower weak layer above ‘basement’ profoundly changed the structural style with more buckle folds developing that were variably harmonic and disharmonic in the overlying competent units (Fig. 6b).

The basal weak layer above basement in PNG is the syn-rift sequence, so modelling thickness changes as in Figure 6a, b suggests how structural styles might change across a syn-rift growth fault. Unfortunately it was not possible to run a model with a step in basement. However, Dixon (2004) modelled lateral changes in mechanical stratigraphy to represent reef versus off-reef facies, showing abrupt changes in structural style at the boundary. The modelling presented here indicates that in PNG and elsewhere, the structural style would similarly change dramatically across an old extensional fault with thick, weak syn-rift strata on one side (Fig. 6b) and thin equivalent strata on the adjacent high (Fig. 6a). The large folds preferentially formed over the syn-rift strata (Fig. 6b) would be more prospective as hydrocarbon traps.

Slightly strengthening the upper weak layer in the models produced dominantly buckle folds in the middle competent layer, the Toro reservoir analogue, and thrusting in the upper, thick competent layer, the Darai analogue (Fig. 6c). These models were most like the known fold belt structures, such as in the Moran anticline. Significantly, the models were able to produce tight, overturned folds in the Toro reservoir section with break-thrusts through the attenuated forelimb as recorded in the Moran, Paua and SE Hedinia anticlines (this paper) and the Usano and Hedinia anticlines (e.g. Lamerson 1990; Franklin & Livingston 1996). Furthermore, the models recorded open folds in the more competent Darai and common faults cutting the Darai, many of which were splays from a Ieru detachment that rooted back to the previous Toro anticline, towards the interior of the fold belt. The models also recorded dramatic thickness changes within the Ieru as proven in many wells. The importance of the models is not in the area of known structures, but as an aid to interpretation in areas under exploration with little subsurface data and poor to moderate quality seismic data.

When a lubricated pre-cut fault dipping at 18° through the Mesozoic analogue was introduced to the model (Figs 6e & 8) it was reactivated early in the deformation and recorded a large displacement. In the hanging wall an overturned fold was generated at the leading edge (Fig. 8). This large offset, particularly in the centre of Figure 8c, is similar to the structure interpreted within the Kutubu Oilfield, the largest oilfield in PNG (Fig. 7). The modelling did not otherwise produce faults with large offset. A comparison of Figure 6c and e shows the impact of the pre-cut faults in sections that otherwise had identical stratigraphy. With the exception of the pre-cut fault the structural style is the same. This suggests that a pre-existing fault or weakness was necessary to produce the Iagifu–Hedinia anticlines that contain the Kutubu Oilfield (Fig. 7).

It is debatable whether or not a pre-cut fault dipping at 18° can represent the effect of an old extensional fault, which would be expected to have a dip of 45–60°. Dixon (1996) modelled the reactivation of pre-cut faults, but found that with steeper pre-cut faults the amount of reactivation

decreased, such that there was minimal reactivation of faults dipping steeper than *c.* 45°. An important consideration is that Dixon's pre-cut faults did not have thicker, weak (syn-rift) beds in the hanging wall so did not simulate a Jurassic growth fault offsetting basement. However, Dixon's later experiments with an abrupt facies change from weak to strong beds across a vertical contact (Dixon 2004) did generate a fault with large offset at the contact, albeit at relatively high levels of shortening. Importantly these structures had an overturned fold in the hanging wall, as recorded by drilling at the leading edge of the Hedinia anticline in the Kutubu Oilfeld (Bradey *et al.* 2008). Combining the results from the models shown in Figure 6a, b with the pre-cut fault models and Dixon's (2004) facies change models, it seems very likely that an old extensional fault with a thick, weak syn-rift section would be reactivated early in the deformation as a thrust fault. Furthermore, this fault would propagate to have a large displacement compared to other faults in the area. The Hedinia Thrust beneath the Kutubu and SE Hedinia oil and gas fields (Figs 3 & 7) is probably such a fault.

PNG structural style and hydrocarbon prospectivity

In the introduction, the Timor Sea area was proposed as an analogue for the pre-deformation architecture of the Papuan Fold Belt (Fig. 4; Cooper *et al.* 1996). In order to assess hydrocarbon prospectivity, this concept is reviewed further here, incorporating the results from the structural sections and centrifuge modelling experiments. The Timor Sea lies between the Bonaparte Basin to the NE with gas reserves of 28 TCF and the Browse basin to the SW with gas reserves of 30 TCF (Australian Government 2007). Within the Timor Sea, the Vulcan Sub-basin (Fig. 4) contains a handful of medium-sized oilfields with total reserves of 357 million barrels (Longley *et al.* 2002), similar in size to those of the Papuan Fold Belt. Rifting to form the Vulcan Sub-basin occurred in Late Jurassic to Early Cretaceous times (Pattillo & Nicholls 1990) following Late Triassic to Mid Jurassic rifting in PNG (Home *et al.* 1990), as part of the same break-up of the north Australian margin (Veevers 2000). Kennard *et al.* (1999) concluded that oil generation and expulsion were restricted to Oxfordian–Kimmeridgian syn-rift source rocks principally within the Swan and Paqualin grabens and the deepest (SW) portion of the Cartier Trough (Fig. 4). Thus the oil source rock was focussed in local deep graben within an otherwise gas-prone area.

The regional cross section presented here (Fig. 3) illustrated a number of different structural styles across the Papuan Fold Belt, which can be related to features within the Vulcan Sub-basin. The section showed that the Darai Fault (Fig. 3) is an important basin-bounding fault across which there is significant growth in several stratigraphic units demonstrating long-lived extensional activity. This is akin to the major basin-bounding fault that abuts the Londonderry High such that the sediments beneath the Darai Plateau may be comparable to those in the Skua syncline (Fig. 4b). In PNG, the basin-bounding extensional fault is interpreted from seismic data to continue along much of the front of the Papuan Fold Belt, although occasionally offset across tear faults such as the Bosavi Lineament (Fig. 1). The Paqualin Transfer across the Vulcan Sub-basin (Fig. 4a; Woods 1992) is considered to be a basement-controlled feature that probably resembled the Bosavi Lineament prior to compressional deformation.

The Darai Fault was probably inverted in Early Tertiary times, was definitely inverted in Pliocene times and remains active, as indicated by compressional earthquakes. Importantly, the current basement inversion occurred prior to any thin-skinned deformation as the nearest thin-skinned structure is 40 km to the north (Fig. 3). This is consistent with the results of the centrifuge analogue modelling with a pre-cut fault (Fig. 8 and Dixon, 1996) in which the existing faults were reactivated in compression at low amounts of shortening prior to the onset of thin-skinned deformation. If inverted early in the deformation sequence, it would be reasonable to expect structures such as the Darai Plateau to trap any subsequent hydrocarbon charge, yet *all* wells in that area are dry with few oil shows. As the structures to the north are charged, there must be a barrier to migration between the Strongly Folded and Gently Folded Belts (Figs 1 & 3).

The Strongly Folded Belt contains all of the commercial oil reserves found in PNG, with large gas discoveries to the NW at Hides and to the SE in the Gulf of Papua. The belt is underlain by a large-offset thrust fault and has accompanying large hanging wall anticlines (Figs 3, 7 & 11) that appear to be less common elsewhere in the fold belt. The centrifuge analogue modelling suggests that a pre-existing weakness is required to generate such large-offset faults. It seems likely that, prior to compressional deformation, the Kutubu, Agogo and SE Hedinia oil and gas fields (Figs 1, 3, 7 & 11) were underlain by a significant normal fault, perhaps the southern bounding fault of a deep graben similar to the Swan Graben on Figure 4 (see hypothetical graben on Fig. 3). The graben could have been the source kitchen for all the oil and been responsible for the development of the

large-offset fault that created the Strongly Folded Belt, hence supplying both trap and charge. The significant normal fault may be the barrier to migration into the Gently Folded Belt structures to the SW.

Proposed structural evolution

Combining the structural observations from the cross sections presented and the analogue modelling the following structural evolution is suggested.

- The pre-compression architecture of the margin consisted of a stable platform in the south bounded by large Late Triassic to Mid Jurassic extensional faults with thick syn-rift sediments beneath the future Darai Plateau. Further north, beneath the future Strongly Folded Belt, a second major normal fault is inferred, bounding the area to the north that contained the main oil source rocks. This may have been a deep graben (Fig. 3).
- During early compressional deformation, in the Late Miocene, there was probably minor reactivation of basement faults as shown on Figure 8a, including the fault beneath the Strongly Folded Belt.
- Thin-skinned thrusting occurred along an Imburu detachment that was in some areas between the Iagifu and Koi-Iange sandstones (Fig. 10a) and in other areas below the Koi-Iange (Figs 3, 7 & 6c). The transition from one detachment level to another probably occurs across transfer zones that may be old basement faults similar to the Paqualin Transfer on Figure 4.
- In the Strongly Folded Belt, the inverted normal fault was reactivated as the Hedinia Thrust and accommodated 4–8 km of shortening, building the Iagifu and Hedinia anticlines that comprise the Kutubu Oilfield (Figs 1 & 7).
- As the thin-skinned structures propagated over the source kitchen beneath the Strongly Folded Belt, oil was generated and expelled.
- In areas such as Moran, a fault-propagation fold developed with a stretched overturned forelimb, including folding of some of the existing thin-skinned thrusts. This evolved into a break-thrust.
- Thrusting and folding of the next structure towards the foreland occurred, jacking up the existing structures and generating out-of-the-syncline thrusts and backthrusts due to the resultant space problems.
- As orogenesis propagated further towards the SW, inversion occurred creating the Darai Plateau and was probably accompanied by renewed basement reverse faulting beneath the fold belt, perhaps reactivating old extensional faults.

Future work

To determine the hydrocarbon prospectivity of the Papuan Fold Belt, understanding the structural style is vital and this paper attempts to address that issue. However, equally as important is understanding which faults seal and which faults leak and/or breach the structures. Furthermore, the timing of fault sealing with respect to hydrocarbon charge is important as fault seal parameters will change with the changing stress regime (e.g. Castillo *et al.* 2000). Crowhurst *et al.* (1997) argued that the compression direction was NE–SW in the Late Miocene, but changed to more E-W in the mid Pliocene. Such a stress rotation would have a significant effect on the sealing capabilities of faults, particularly cross-cutting faults. The importance of sealing or breaching faults is demonstrated by the Moran and Paua structures (Figs 1 & 10). The Moran oilfield resides in the NW half of the anticline where there is an 800 m oil column, separated by a sealing cross fault from the SE portion of the structure that tested water at elevated pressures. To the NE the Paua anticline encountered very high pressures, a residual oil column and minor gas and is thought to have been breached and then resealed. Clearly the dip-slip faults between Moran and Paua must seal, yet may previously have been open to allow hydrocarbon charge. Resolution of this issue is beyond the scope of this paper, but is the aim of ongoing studies.

Conclusions

(1) Centrifuge analogue modelling of intact, plane-layered strata determined that the mechanical stratigraphy and the thickness of weak strata above the lower décollement horizon exert the greatest control on the changing structural styles of the Papuan Fold Belt.
(2) The models most like known structures had a thick, incompetent Jurassic shale sequence, a competent Toro reservoir sequence, an intermediate competence Ieru sequence and a competent Darai sequence.
(3) These models produced tight overturned folds in the Toro, thickness changes and detachments in the Ieru and open folds and thrust faults in the Darai, all recorded in the Moran anticline.
(4) Centrifuge analogue modelling with pre-cut faults in the Mesozoic section produced early inversion anticlines as recorded in the Papuan Fold Belt by inversion of the Darai Fault.
(5) With continued shortening the pre-cut faults accommodated much of the shortening as large-offset thrust faults that did not otherwise occur in the models.

(6) The large-offset faults produced a 'double-hump' hanging wall similar to that in the Kutubu Oilfield, PNG's biggest oilfield with >350 million barrels original oil in place.
(7) The undeformed PNG margin probably comprised a small number of large basin-bounding or graben-bounding faults across which there was substantial growth in the stratigraphic section. Away from those faults the Mesozoic section probably thickened gradually towards the NE.
(8) The seismic data, structural sections and analogue modelling defined the important elements of the PNG structural style. These are:
   (a) Inverted basement faults.
   (b) Thin-skinned faults detached in the Imburu at various depths of 1–2 km below the top Toro.
   (c) Tight and overturned anticlines in the Toro with long, continuous, steep backlimbs and stretched and boudinaged forelimbs cut through by a zone of break-thrusts.
   (d) Highly variable thickness within the Ieru, with the major detachment within the incompetent Bawia Member. This detachment is often reactivated out-of-sequence as the next structure towards the foreland forms.
   (e) Open folds in the competent Darai Limestone, cut by numerous thrust faults linking back into the Ieru detachments.
   (f) Cross-cutting or tear faults in places linked to old basement faults. These faults often seal and compartmentalise the reservoirs. The transition from one detachment level to another probably occurs across these faults.
(9) Understanding the structural style is only the first step in determining the hydrocarbon prospectivity. The next, more difficult, step is to determine the hydrocarbon charge, fluid pressures and sealing and/or breaching nature of faults.

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