Structural Style in the Eastern Papuan Fold Belt, From Wells, Seismic, Maps and Modelling*

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Please see closely related article, Near-Field, Subthrust and Deep Reservoir Tests of the Kutubu Oil and Gas Fields, Papua New Guinea, Search and Discovery Article #20183 (2012). http://www.searchanddiscovery.com/documents/2012/20183hill/ndx_hill.pdf

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Abstract

Structural deformation in the PNG Fold belt involves reactivation of basement, detachment folds and out-of-sequence thin-skinned thrusts. In the Agogo area seismic data record a regional dip of ~10° to the NE in basement overlain by a thick syn-rift section. Immediately to the NE, reflection and earthquake seismic studies indicate that the Moran-Paua anticlines lie on a thrusted basement high. Geometric forward modelling, tied to wells, geology maps and poor seismic, suggests that they developed as detachment folds above a deep Jurassic décollement, but were decapitated and thrust along a shallow Jurassic décollement that cut-up through the forelimb of the folds. Each thrusted fold was oversteepened by the development of the next thrust, leaving the Moran oilfield with a 1 km hydrocarbon column. Thrusting of basement beneath Moran-Paua generated a large detachment fold at Agogo subsequently decapitated by shallower thrust faults, creating oilfields in both the gentle hangingwall and steep footwall-forelimb. The relative timing of basement thrusting and the overlying Moran-Paua deformation is uncertain. Along strike to the SE of Agogo, the Hedinia-Iagifu anticlines are similarly underlain by basement dipping at 5–10° and a thick-syn-rift section. Once again a large detachment fold was formed and decapitated on forethrusts and backthrusts creating the giant Kutubu oil and gas field in the hangingwall and a separate oil deposit in the steep footwall-forelimb. Analogue modelling suggests that the development of a large detachment fold at the site of an old normal fault is favoured by prior minor inversion of the fault. In contrast, further SE in the Usano area, seismic data indicate that basement dips shallowly NE in the foreland and may become sub-horizontal beneath the mountains. The Mesozoic stratigraphy appears to be thinner than at Agogo and Hedinia. At Usano, no large detachment fold structure is developed and the footwall is sheared out. Modelling suggests early inversion or thrusting of basement followed by shortening along Jurassic and top Cretaceous décollements. The latter facilitated the development of a duplex in the Mesozoic clastic section, including the main reservoir, and a separate duplex in the overlying Miocene carbonates. Thrusting along the Jurassic décollement decapitated the inversion fault which 'snowploughed' the adjacent Cretaceous mudstones causing oversteepening of the fault which created the Usano oilfield in the hangingwall.

Introduction

Exploration in fold and thrust belts is fundamentally different from most other geological provinces as the mountainous terrain makes acquisition of seismic data very expensive and the data are usually poor to moderate quality, at best. In contrast fold and thrust belts usually have excellent outcrop data and structures can be clearly imaged and interpreted on digital elevation models. Thus, compared to offshore provinces, the structures are better constrained at surface, but poorly constrained at depth. One way to help interpret the deep structure is to use analogue and numerical modelling, as discussed by Darnault et al., 2015 and Rey et al., 2015. Here, though, we focus on interpreting the deep structure by utilizing all the geological data from surface and wells tied to any available worthwhile seismic data, in order to construct representative cross-sections. These sections are then constrained by balancing and restoring them, but more importantly by forward-modelling to confirm that they are kinematically reasonable. We show how these techniques have been applied to the Papua New Guinea (PNG) fold belt to show varying structural style along strike.

The island of New Guinea is at the leading edge of the northward-moving Australian craton that has collided with island arc terranes in the Miocene to Pliocene creating an orogenic belt (Figure 1a; Hill and Hall 2003). The latter comprises accreted terranes, ophiolites, and igneous rocks of the Mobile Belt in the north and a Fold Belt to the south adjacent to the undeformed platform. The fold belt contains rich Cu-Au deposits and in PNG the frontal, SW, portion of the Fold Belt has large reserves of oil and gas. Hence there has been much exploration and production, but hampered by jungle-covered mountains and extensive karst topography with few roads. Critical to ongoing exploration and development is to understand the 3D geometry and evolution of the fold and thrust structures.

Stratigraphy and Data

The Fold Belt stratigraphy is summarised in Figure 1b. The dominant outcrop in the Fold Belt is karstified Miocene Darai Limestone which has been mapped along many jungle traverses yielding well over 10,000 data points, each with dip/strike and dated by $^{87}Sr/^{86}Sr$ and micropaleontology. The resulting maps are a key data source. Over 250 wells have been drilled, usually to the Jurassic reservoirs, recording stratigraphy and dip data. Seismic data are very expensive to acquire and of poor to moderate quality (Figure 2) so are limited to 2D lines with 2-5 km spacing.

Structural Style

Previous studies of compressional deformation in the PNG Fold Belt (e.g. Hill et al., 2010) suggest that the structural style comprises: Mesozoic-Paleogene rifting in basement creating syn-rift growth sequences, inversion and/or thrusting of basement, detachment folds, thin-skinned thrusting along décollements in the Jurassic and near-top Cretaceous mudstones, and decapitation of inversion or detachment folds by out-of-sequence thrusts. At present, very large Miocene-Recent inversion structures are preserved in the foreland ahead of the leading edge of the Fold Belt, for instance the Darai Plateau on Figure 1a. This suggests that crustal-scale faulting occurred prior to thin-skinned deformation. This observation is important when interpreting complex fold-belt structures.

In the Agogo area seismic data record a steep regional dip of ~10° to the NE in basement overlain by a thick syn-rift section. Immediately to the NE, reflection and earthquake seismic studies indicate that the Moran-Paua anticlines lie on a basement high, here interpreted to be thrusted (Figure 3). Geometric forward modelling, tied to wells, geology maps, and poor seismic, suggests that Moran and Paua developed as detachment folds above a deep Jurassic décollement, but were then decapitated and thrust along a shallow Jurassic décollement that cut-up through the forelimb of the detachment folds. Each thrusted fold was oversteepened by the development of the next thrust, leaving the Moran oilfield with a 1 km hydrocarbon column. Thrusting of basement beneath Moran-Paua generated a large detachment fold at Agogo subsequently decapitated by shallower thrust faults, creating oilfields in both the gentle hangingwall and steep footwall-forelimb (Wightman 2015). The relative timing of basement thrusting and the Moran-Paua deformation is uncertain, but it is postulated that the basement thrusting was early such that the thin-skinned Moran-Paua shortening was out-of-sequence, at least in part.

Along strike to the SE of Agogo, the Hedinia-Iagifu anticlines are similarly underlain by basement dipping at 5-10° NE and a thick-syn-rift section. Once again a large detachment fold was formed that was subsequently decapitated on forethrusts and backthrusts creating the giant Kutubu oil and gas field in the hangingwall and a separate oil deposit in the steep footwall-forelimb (Figure 4). Analogue modelling suggests that the development of a large detachment fold at the site of an old normal fault in basement is favoured by prior minor inversion of the basement fault (Darnault et al., 2015).

Further SE in the Usano area, seismic data indicate that, in the foreland, the basement dips at ~10° NE towards the mountains (dip of 9° measured in the Toro at the base of the Usano-4 well) but may become sub-horizontal beneath the fold and thrust structures. The Mesozoic stratigraphic section, however, appears to be thinner than at Agogo and Hedinia. At Usano, no large detachment fold structure is developed and the recent Usano-4 well shows that the footwall is sheared out (Figure 5e).

Whilst this interpretation could be balanced and restored in a simple way, it did not reveal the kinematics of deformation. Thus a forward model was constructed starting with the known stratigraphic template and using the section in Figure 5a as a target. Many tens of iterations were required, but the eventual solution is shown in Figure 5b, Figure 5c, Figure 5d, and Figure 5e. The modelling suggests that early inversion or thrusting of basement was followed by shortening along Jurassic and top Cretaceous décollements. The latter facilitated the development of a duplex in the Mesozoic clastic section, including the main reservoir, and a separate duplex in the overlying Miocene carbonates. Thrusting along the Jurassic décollement decapitated the inversion fault which 'snowploughed' the adjacent Cretaceous mudstones causing oversteepening of the fault which created the Usano oilfield in the hangingwall (Figure 5).

Comparing Figure 4a and Figure 5a of the Usano and Kutubu structures, respectively which are directly along strike from one another, it is apparent that the structural style is quite different. At Kutubu a large box-fold developed first and then was cut by thin-skinned structures. At Usano, there was initially a basement inversion or thrust with no significant fold. It seems likely that the cause was the original structure and stratigraphy. We suggest that under Kutubu there was originally a deep graben with a thick Jurassic syn-rift section that was squeezed into the detachment fold. In contrast the graben beneath Usano, if any, was much shallower.

Conclusions

Analysis of structural profiles through oil and gas fields of the Papuan Fold Belt indicates that the pre-existing configuration of basement played a significant role in the compressional deformation. It is postulated that areas with thick syn-rift section developed large detachment folds, probably enhanced by early basement inversion or thrusting. In areas with thinner syn-rift section, the folds were not developed and early basement thrusting/inversion resulted in a shear zone. In both areas, this deformation was followed by out-of-sequence thin-skinned thrusting that in part decapitated the early structures. Understanding these relationships is important in defining new hydrocarbon plays.

Acknowledgements

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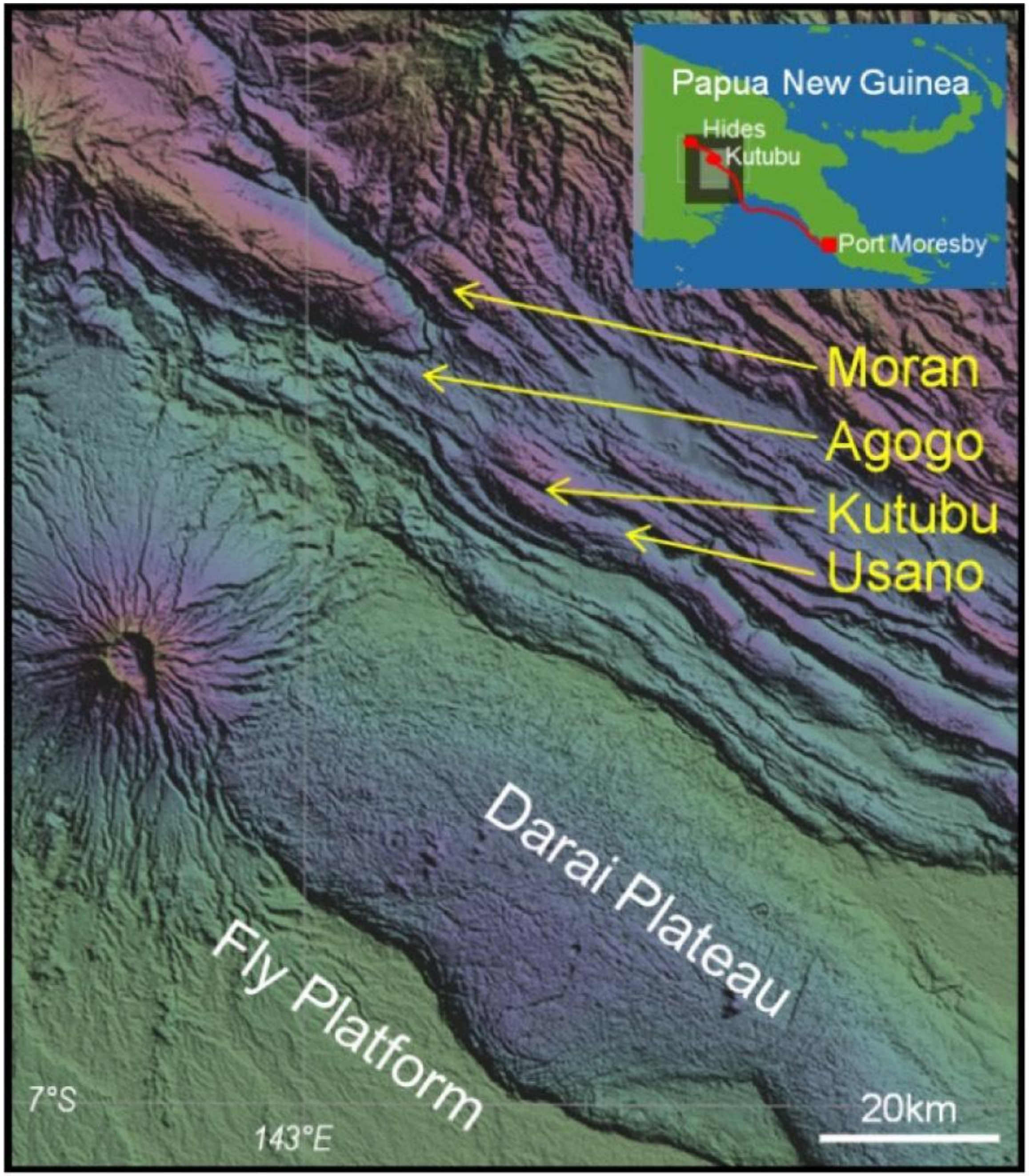

Figure 1a. Location of the Moran, Agogo, Kutubu, and Usano anticlines along the leading edge of the Fold Belt in PNG. The Darai Plateau is a crustal scale inversion ahead (SW) of the Fold Belt.

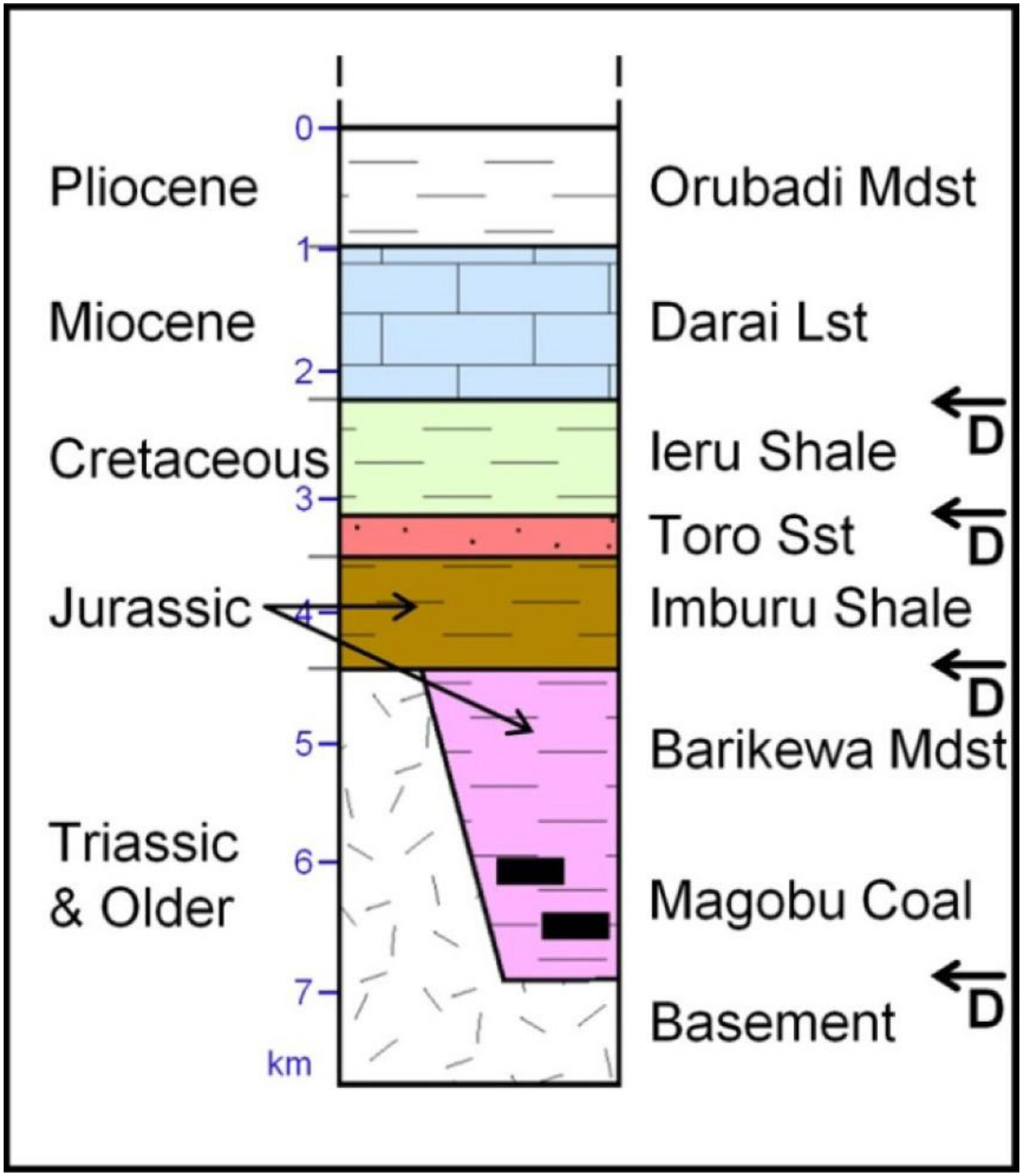

Figure 1b. Simplified stratigraphy for the Papuan Fold Belt. The source rock is Jurassic, the Toro is the reservoir, and the Ieru is the regional seal. D = décollement.

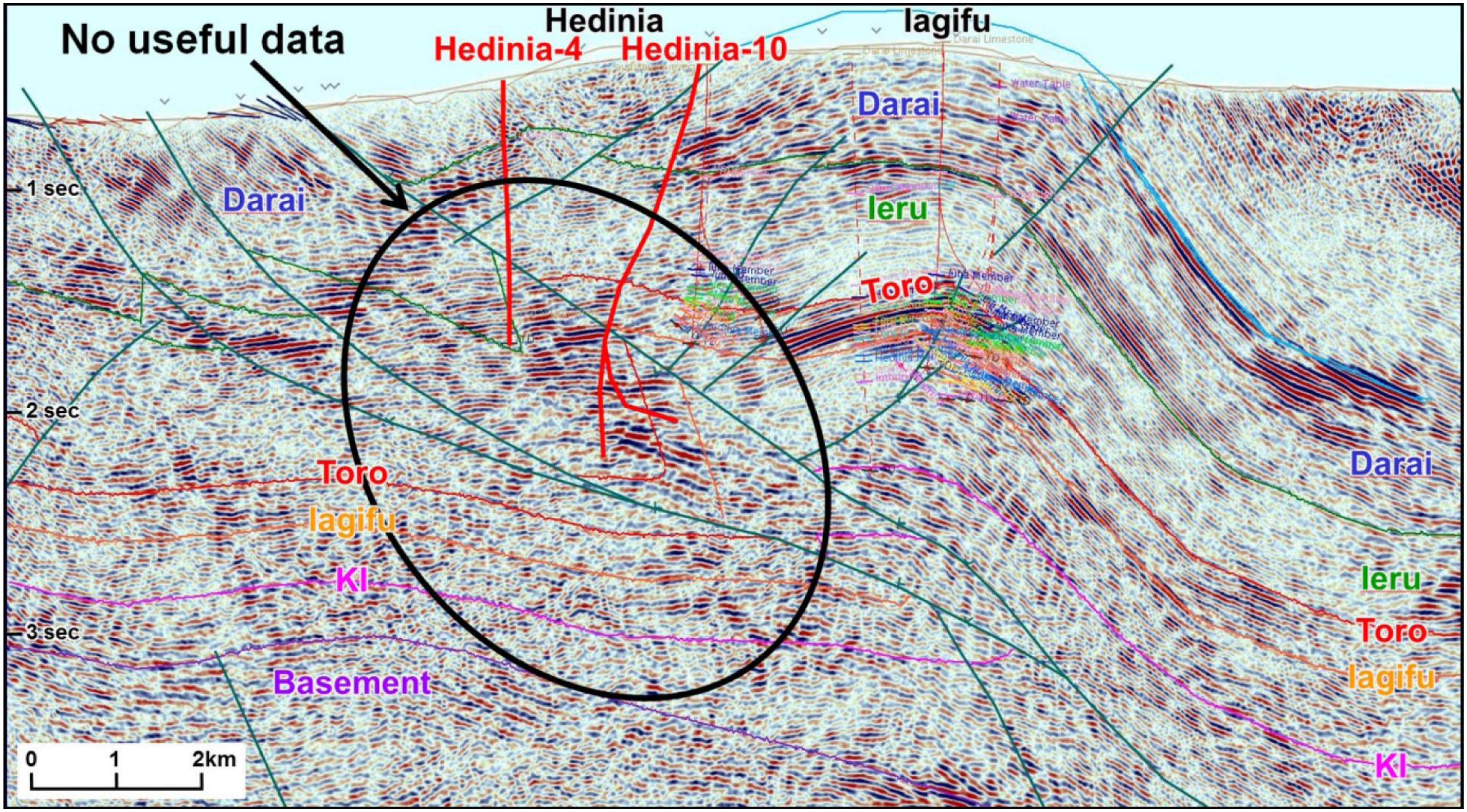

Figure 2. Seismic line across the Hedinia and Iagifu anticlines of the Kutubu oil- and gas-field. Note the regional dip in basement is reasonably clear, but the steeply overturned beds in the forelimb in the Hedinia-4 and -10 wells are not imaged on the seismic, marked by the area of ‘no useful data’. The structure is fundamentally a box-fold with thrusts cutting through the forelimb.

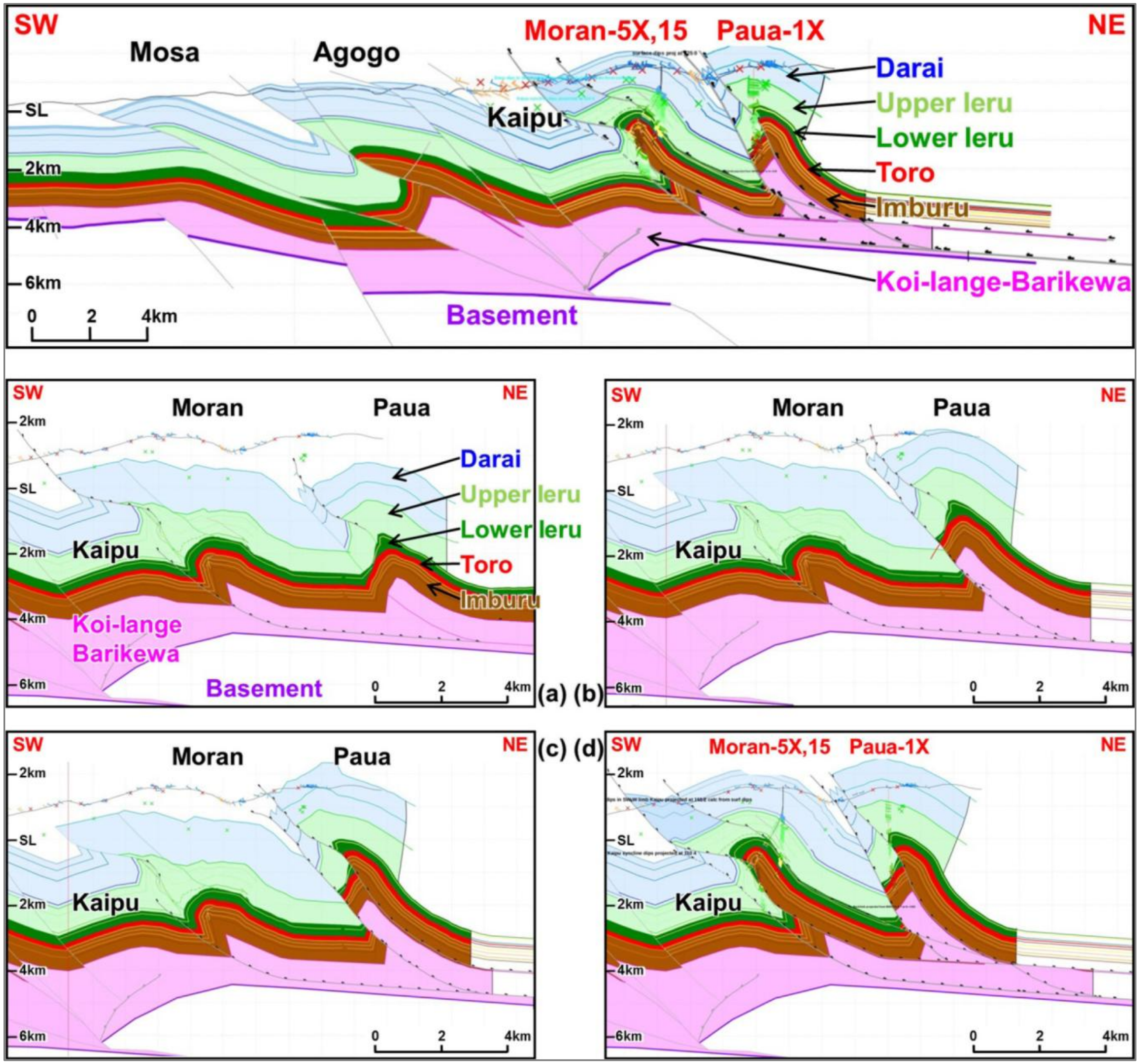

Figure 3. Top- A semi-regional section across Agogo and Moran-Paua showing ~10° basement dip SW of Agogo, basement thrusting beneath Moran-Paua, and faulted detachment folds at both Agogo and Moran-Paua. A-b-c-d - Geometric forward modelling of the Moran-Paua structures showing a) the initial development of detachment folds above a deep Jurassic décollement, b) thrusting along the deep décollement through the forelimb of Paua, c) thrusting of Paua on a shallow Jurassic décollement, d) thrusting along a shallow Jurassic décollement through the forelimb of Moran, which also decapitates Paua.

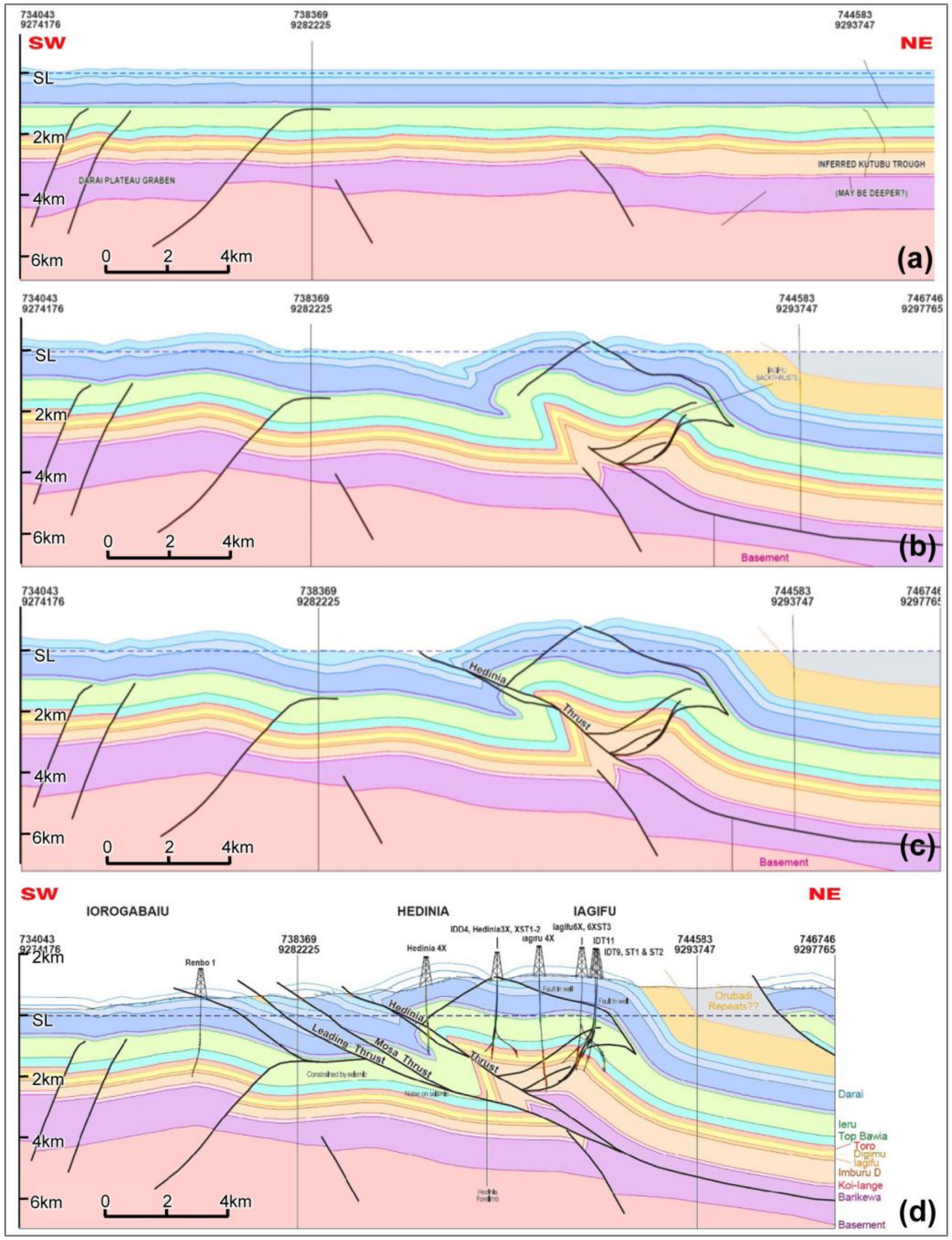

Figure 4. Evolution of the Kutubu structure comprising the Iagifu and Hedinia anticlines. Formation of a box-fold above an old normal fault (a, b) is followed by 'decapitation' thrust faults (c, d).

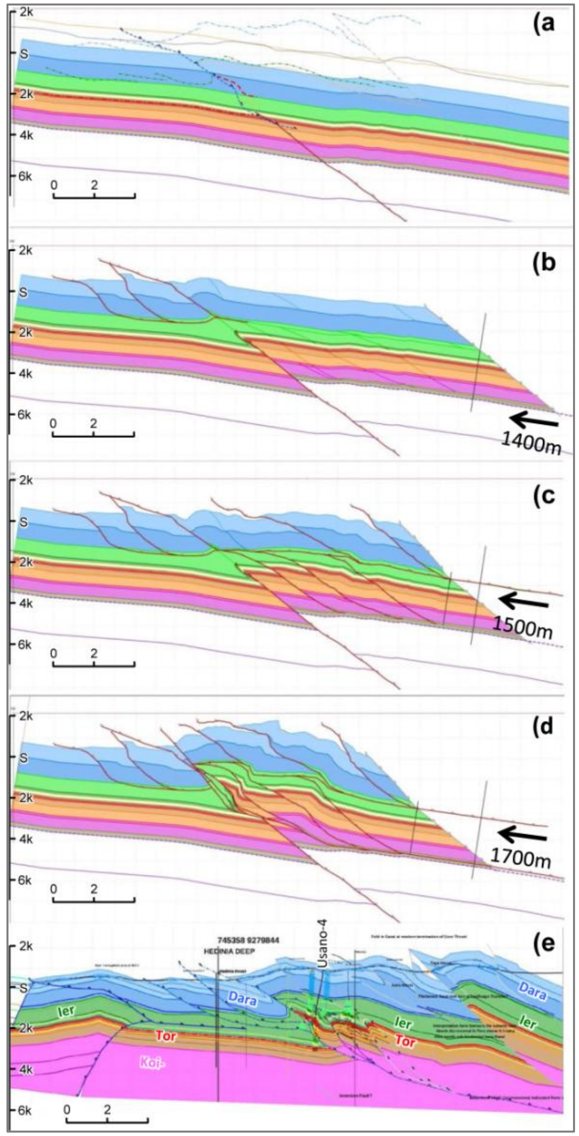

Figure 5. Forward modelling (a-d) of the structure at Usano (e) incorporating the results from the recently drilled Usano-4 well. a) Original template with target horizons shown dotted. b) 1400 m of shortening on a basement-involved fault, elevating regional. c) 1500 m of shortening on Mesozoic and Miocene duplexes separated by an Upper Ieru decollement. d) 1300 m of shortening first utilizing the previous inversion fault and then cutting through it, oversteepening the inversion fault as drilled in Usano-4. e) The post-drill section through the Usano-4 well for comparison.