The Mananda Anticline, Papua New Guinea: A Third Oil Discovery, Appraisal Programme and Deep Potential*

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Abstract

The Mananda Anticline is one of the larger structures in the Papuan Fold Belt at 40 km long, 15 km wide and up to 2000 m high. It is >20 km from the nearest road and airstrip, is deeply karstified, covered in equatorial jungle, and is regularly in the clouds. The stratigraphy comprises 1 km of Miocene limestone, above 1 km of Cretaceous shale seal overlying earliest Cretaceous Toro and Digimu sandstone reservoirs and inferred Jurassic source rocks. The size of the structure suggests basement inversion and hence deep sub-thrust plays, but wells to date have been confined to the hangingwall where they have encountered thin-skinned structures and transported old normal faults. Since 1971, nine wells had been drilled along the topographic crest, including the SE Mananda-1 oil and gas discovery in 1991. Between 2000 and 2005, six moderate-quality seismic lines were acquired as well as additional field data, including Sr isotope dating of the surface limestone. The seismic, surface dips, Sr dates, and structural dips in the Mananda 3X/4X wells all indicated that the structural crest was SE of the topographic crest. In 2010–11 the Mananda 5 well was drilled 1.5 km south of Mananda 3X and tested oil and gas in the Toro sandstone reservoirs, which were 400 mTVD higher than in Mananda-3 and probably separated by an old normal fault. The Mananda 6 well was drilled in 2013 as an appraisal well to the Mananda 5 discovery and discovered the third separate field on the Mananda Anticline, with 2 new oil columns intersected down dip of the Mananda 5 block discovery. In 2013/2014, the Mananda 7 appraisal well was planned to appraise the Mananda 6 discovery and de-risk the major structural, fault seal and compartmentalisation uncertainties. The resulting 5 boreholes, including 3 geological sidetracks, achieved the appraisal objectives and significantly increased knowledge of the trap geometry and structural evolution of the Mananda Anticline. The future of the Mananda Anticline remains bright with 3 discoveries to date, further untested hangingwall fairway prospects and potentially large sub-thrust, footwall targets. This paper will examine the exploration and appraisal phases of the Mananda Anticline, focusing on the geological and operational challenges faced in the 43 year history.

Introduction

The Mananda Anticline is one of the larger structures in the Papuan Fold Belt at 40 km long, 15 km wide and up to 2000 m high. It is over 20 km from the nearest road and airstrip, is deeply karstified, covered in equatorial jungle, and is regularly in the clouds. Despite its challenges, the structure has been the focus of hydrocarbon exploration for over 40 years. With a similar structural style and superior in size to the nearby Hides and Kutubu structures, the lure of hundreds of millions to billion barrel field size has attracted 7 exploration wells, over 250 km of *extreme* 2D seismic acquisition and several hundreds of kilometres of geological surveys. The future of the Mananda Anticline remains bright with 3 discoveries to date, further untested hangingwall fairway prospects and potentially large sub-thrust, footwall targets.

Regional Geological Background

The Papuan Fold Belt stratigraphy (Figure 1b) that is present at Mananda comprises of a highly karstified Miocene Darai Limestone at surface which is approximately 1 km thick. This limestone overlies an approximately 1 km thick Cretaceous shale, the Ieru Formation, which is the regional seal. The Ieru Formation includes a number of thin sandstone units within a predominantly silty shale package which overlies the early Cretaceous Toro and Digimu sandstone reservoirs. The Toro Sandstone is predominantly made up of nearshore-marine shoreface deposits comprising upper-shoreface, middle-shoreface, lower-shoreface, upper-offshore, and lower offshore depositional facies (Boyd et al., 2015). The Digimu Member comprises incised valley-fill estuarine mouth-bar and estuarine central-basin depositional facies and the inter-reservoir depositional facies are typically inner- and outer-shelf muds. These high-quality, shallow marine sandstones form the reservoir for the giant Kutubu oil and Hides gas fields. The deepest stratigraphy penetrated at Mananda is the late Jurassic Koi Iange sandstone. A deeper Jurassic source is inferred and has not been penetrated at Mananda.

Like many structures in the Papuan Fold Belt, the Mananda Anticline formed during Mio-Pliocene compression probably as a foreland-vergent fault-propagation fold overlying a deeper inversion structure. The size of the anticline suggests basement inversion and hence deep sub-thrust plays, but wells to date have been confined to the hangingwall where they have encountered thin-skinned structures. The Mananda structure is the most frontal anticline in the Papuan Highland thrust front and is adjacent to the mildly deformed foreland structural region (Figure 1c). It is situated along trend from the Kutubu Oil Field, and Hides Gas Field (Figure 1a).

Exploration History (1971 to 2006)

Mananda 1X (Figure 2), spudded by Australasian Petroleum Company Pty Ltd in September 1971, was the first well drilled on the Mananda Anticline. The well was poorly sited on the northwestern flank of the anticline, mainly due to a favourable proximity to a water source for drilling operations. Mananda 1X failed to reach the Toro reservoir target because it intersected a major thrust fault in the Alene Member and drilled into a repeat section of Darai Limestone. Mananda 1X demonstrated that thin-skinned overthrusting to the SW formed the Mananda structure.

The next well, Mananda 2S, spudded in May 1984 but failed to reach the reservoir target due to the limited mechanical capability of the slimhole rig. Mananda 3X, drilled by Niugini Gulf Oil from the same location as Mananda 2S, spudded one year later, in April 1985. Following mechanical difficulties, the well was sidetracked and Mananda 3XST1 (Figure 2) was drilled to a depth of 2621 mMD in the Imburu B Formation (Figure 1). Mananda 3XST1 encountered oil shows in the Toro and Digimu sandstones but flowed water with minor amounts of oil when drill stem tested. Petrophysical analysis indicate residual oil in the Toro and Digimu sandstones and structural dip data demonstrated the well was not crestal and that updip potential remained to the southwest.

Mananda 4X (Figure 2) was drilled to appraise the updip potential to the south of Mananda 3XST1. The well spudded in March 1990 and reached a depth of 3248 mMD in the Koi-Iange Formation. As in Mananda 3XST1, the Toro and Digimu sandstones contained residual oil and structural dip data indicated the well was still not crestal and indicated that updip potential remained to the southwest of Mananda 4X.

The South East Mananda (SEM) Field is located to the south east of Mananda 4X and was discovered by the SEM 1X (Figure 2) well drilled by Niugini Gulf Oil in 1991. This well was followed by SEM 2X in 1994 and SEM 3, 4, and 5 wells in 2006. The SEM Project came on stream in March 2006 and involved construction of a 470 m cable suspension bridge over the Hegigio Gorge to enable flow lines to tie back from SEM to the existing facilities.

The Mananda 3ST1 and Mananda 4X wells were drilled on the mapped topographic crest of the Darai Limestone covered anticline. However, the dip data at reservoir level indicated further updip potential towards the forelimb of the structure to the southwest. The application of Strontium isotope analysis (Hornafius and Denison, 1993) provided high frequency, accurate, and spatially dense age dating of the Miocene limestone surface samples and enabled detailed mapping of the surface geology which identified that the geological crest of the structure was on the southwestern forelimb (Figure 3), thus supporting an updip accumulation from the shows encountered in Mananda 3XST1 and Mananda 4X. In 2010, the Mananda 5 well discovered and tested oil in the updip attic play. This was the first discovery on the main Mananda Anticline structure since the first exploration well in 1971. A 2012 seismic survey was acquired to delineate the updip attic play. A summary of Mananda well details can be found in Table 1.

Mananda Discoveries

Mananda 5

Mananda 5 was designed to test the updip “Attic” potential to Mananda 3XST1 and Mananda 4X. The Toro Formation was intersected 568 m higher at Mananda 5 than at Mananda 3XST1, confirming the “Attic” play fairway. The target reservoir was intersected 300 m high to prognosis with but significant thinning of all stratigraphic units up to 30 percent (Figure 4). The conformable, thinned stratigraphy indicate Mananda 5 intersected the footwall of a preserved normal fault system with Mananda 3XST1 and Mananda 4 in the hangingwall. The well reached total depth in January 2011 and discovered and flowed oil from the Toro and Imburu A sandstones.

Following the success at Mananda 5 an 88 km 2D seismic survey and geological mapping program was acquired in 2012, including a strike line to tie in existing wells and seismic. The new data was interpreted and integrated with existing data to generate a number of new structural models for the Mananda anticline and define the location of the Mananda 6 appraisal well. A saddle between Mananda 5 and a Mananda 6 location could be interpreted, however interpretation confidence was low due to poor seismic definition and ambiguous surface geology data.

Mananda 6

Mananda 6, located approximately 5 km southeast of Mananda 5, was spudded in April 2013 targeting the Toro, Imburu A, and Digimu sandstones in the "Attic" play of the Mananda Anticline. The well reached TD in the Imuru B Formation and intersected two separate oil columns in the Toro A sandstone and in the Digimu and Imburu A sandstones. Pressure data indicated that the hydrocarbon columns intersected in Mananda 6 are not in communication with Mananda 5. Dipmeter data indicated Mananda 6 is located on a northwest plunging nose and suggest a saddle or fault separating the Mananda 6 culmination from that drilled by Mananda 5.

The true stratigraphic thicknesses of the Ieru Formation, Toro and Imburu Formations were almost identical to those intersected in Mananda 5. This indicates that the stratigraphic thinning is a characteristic of the attic play and that the hypothesized syn-depositional normal fault footwall block extends at least from Mananda 5 to Mananda 6 (Figure 4).

Prospect analysis of the Mananda 5 and Mananda 6 discoveries concluded that structural uncertainty was the most significant contributing factor to the volumetric uncertainty range. Specifically, the location of the modelled bounding normal fault that creates the attic play, backlimb steepness, and the presence of compartmentlising faults along the attic fairway. Therefore, an appraisal drilling program was designed to de-risk the major structural and geological uncertainties.

Mananda 7 Appraisal

Mananda 7, 7ST1, 7ST2, 7ST3, and 7ST4 were drilled as deviated appraisal wells to follow up the Mananda 6 discovery. The wells were drilled from the same well pad as the Mananda 6 discovery, which is 5 km to the southeast of the Mananda 5 discovery and 11 km to the northwest of the SE Mananda oilfield (Figure 5a).

With only one vertical well penetration in the Mananda 6 block and poor quality seismic data, structural uncertainty regarding the size and shape of the Mananda 6 block and the potential existence of a gas cap were identified as primary uncertainties that required further appraisal. The Mananda 7 drilling program was designed to appraise these uncertainties. Firstly, a pilot hole would be drilled to the north of Mananda 6 to determine the structural geometry, and then the main hole would be drilled to target the crest of the structure to assess the presence of any gas cap and to become a potential future producer.

The pilot hole, Mananda 7, was proposed with a highly deviated trajectory to appraise the northern flank of the structure and assess the presence of a hypothesised old normal fault. Mananda 7 drill string became stuck in the Upper Ieru Formation and the well had to be mechanically sidetracked. Mananda 7ST1 drilled to an intra Alene marker encountering steeper than anticipated dips and formation tops deep to prognosis (Figure 5b). This combination of structural and stratigraphic data suggested that Mananda 7ST1 had drilled through the deformed section above a normal or backthrust fault at depth with potentially the development of a new unpenetrated compartment. Although initially planned as a pilot hole to retrieve structural data above the reservoir, based on these observations it was decided to attempt to penetrate the reservoir section. However, while pulling out of the hole to set casing, the drill string became stuck and the well had to be abandoned. It was decided not to re-drill the 7ST1 trajectory and to drill a well with that would directly prove the existence of the fault by drilling through it.

Mananda 7ST2 kicked off in the Upper Ieru Formation. The principle objectives of this borehole were to gather structural information to the southeast of Mananda 6, along the crest of the Mananda 6 block, and to look for further direct evidence of the fault that was inferred from Mananda 7ST1. Palynological and structural dip data confirmed that Mananda 7ST2 encountered a normal fault with missing section in the Bawia Member of the Ieru Formation. The well was drilled to the Alene target TD and structural information retrieved. The Toro reservoir was not penetrated at this location as it was decided to penetrate the new untested compartment on the other side of the normal fault, over 200 m updip of the Mananda 4X shows.

Mananda 7ST3 was drilled to test the prospectivity of a new block located to the north of Mananda 6 and potentially compartmentalised by the downthrown extensional fault intersected in Mananda 7ST2. The highly deviated well encountered the Juha and Alene members in both the footwall and downthrown hangingwall of the normal fault and drilled on through the Toro and Digimu reservoirs. Logs, pressures, and fluid samples confirmed the new block was not hydrocarbon bearing. After intersecting the normal fault twice, a dip, azimuth, and offset of the fault was able to be calculated confidently (Figure 5b and Figure 5c). The fault dipped approximately 70 deg to 15 deg (NNE) and displayed approximately 120 m normal offset.

Mananda 7ST4 was drilled with a trajectory to intersect the Toro and Digimu sandstones as a crestal future production well. Oil was confirmed in the Toro, Imburu A, and Upper Digimu sands. These were confirmed to have the same contacts and pressure regime as the Mananda 6 penetration. However, in the Lower Digimu sand lobe, a new oil column was intersected in a different pressure regime and with a projected oil water contact deeper than Mananda 6 contacts. Mananda 7ST4 intersected a small fault in the Alene Member which is attributed to compartmentalisation of the lower Digimu sand which established a new hydrocarbon bearing compartment. No gas cap was intersected. Mananda 7ST4 was plugged and suspended to maintain the option to use the well as a future producer. Mananda 7ST4 confirmed the presence of small, sub-seismic resolution compartmentalising faults in the Mananda 6 structure.

The Mananda 7 wells successfully achieved their pre-drill objectives, significantly reducing structural uncertainty on the size and shape of the Mananda 6 block and bounding normal fault presence, reducing the uncertainty regarding the presence of a gas cap and intersecting the Mananda 6 block crest in a future production location.

Mananda Structural Implications and Additional Prospectivity

The definitive well results from Mananda 7ST1, 7ST2, 7ST3, and 7ST4 have important implications for the structural style, structural history, and prospectivity of both the Mananda Anticline and surrounding fold belt structures. The northeast dipping normal fault that has been definitively intersected in Mananda 7ST2 and 7ST3 is interpreted to be a long-lived normal fault, propagating from basement prior to Mio-Pliocene thrusting where it was decapitated and carried in the thrust sheet. Thinning of the Mesozoic section across the fault from Mananda 3XST1 to Mananda 5 and Mananda 4X to Mananda 6 suggest that the fault was long lived and a syn-sedimentary growth fault. The topographic surface fault zone mapped by surface strontium data suggests late movement on this fault system, however the results of Mananda 7ST1 which drilled below the surface fault and above the deeper normal fault without intersecting any fault, suggest that the shallow faulting in the Darai Limestone is disconnected from the deeper normal fault system. It is interpreted that faults sole out in the shaley Ieru Formation and result from draping over the active fault in the Lower Ieru and deeper section.

The disappointing results of the wells that have intersected the downthrown hangingwall block reservoirs indicate that the long lived, episodic fault movement and reactivation is likely the reason why the giant Mananda Anticline is breached and not currently a billion barrel field, as its giant size would suggest. The combination of fault reactivation and a comparatively sandier Ieru Formation are likely to be combining factors in the breaching.

However, on a positive note, the attic forming normal fault and thinned Ieru overburden give substantial updip prospectivity at reservoir level. This has been successfully tested with discoveries at Mananda 5, Mananda 6 and there are yet to be drilled four way dip closures on trend, along the attic fairway. This footwall thinning also makes a potential new play in other structures along strike with similar faults that have been identified in near crestal locations.

Finally, there remains an untested deep potential beneath the major thrust fault a deep footwall or forelimb structure. A number of structural styles are possible and interpretable from seismic and structural modelling. The prospectivity of such a play is further supported by the analogue Agogo Field (Figure 6) which has successfully proven and produced oil from a sub-thrust vertical forelimb structure. Agogo is 10 km from the Mananda Anticline and is the next structure along the thrust front to the southeast. Therefore, prospectivity exists for a large sub-thrust structure, given the size of the overall topography of the Mananda structure.

Conclusion

Exploration and appraisal drilling of the Mananda Anticline has successfully discovered 3 oil fields and uncovered structural and stratigraphic characteristics that are crucial to understanding the successes and failures of these wells. These learnings are critical for future exploration and appraisal drilling at Mananda and in structural analogues along the foldbelt.

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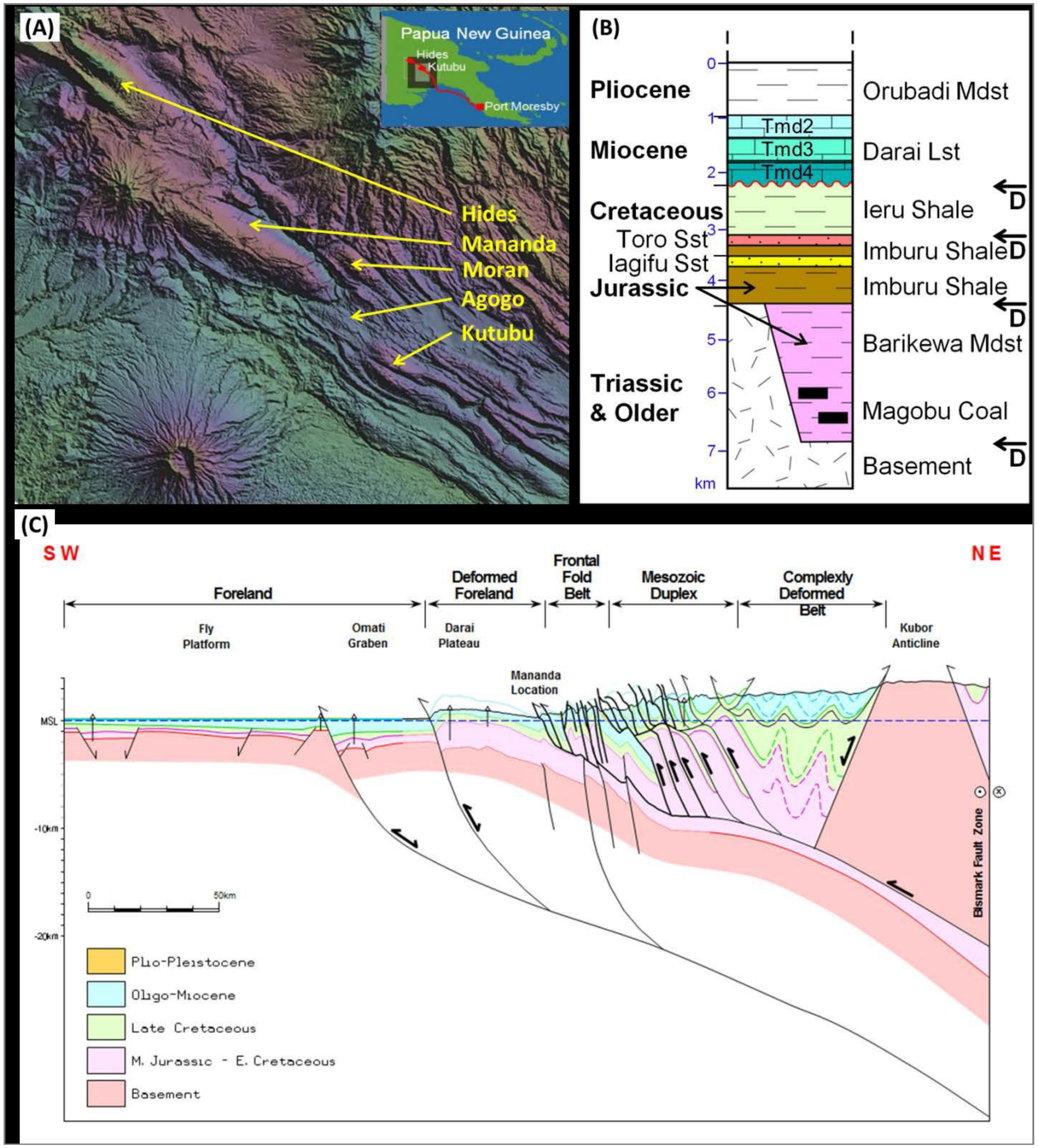

Figure 1. (a) Regional location map with surrounding fields. (b) Simplified stratigraphic column for the Papuan Fold Belt. (c) Schematic regional cross section of Papua New Guinea showing the location of the relative Mananda Anticline.

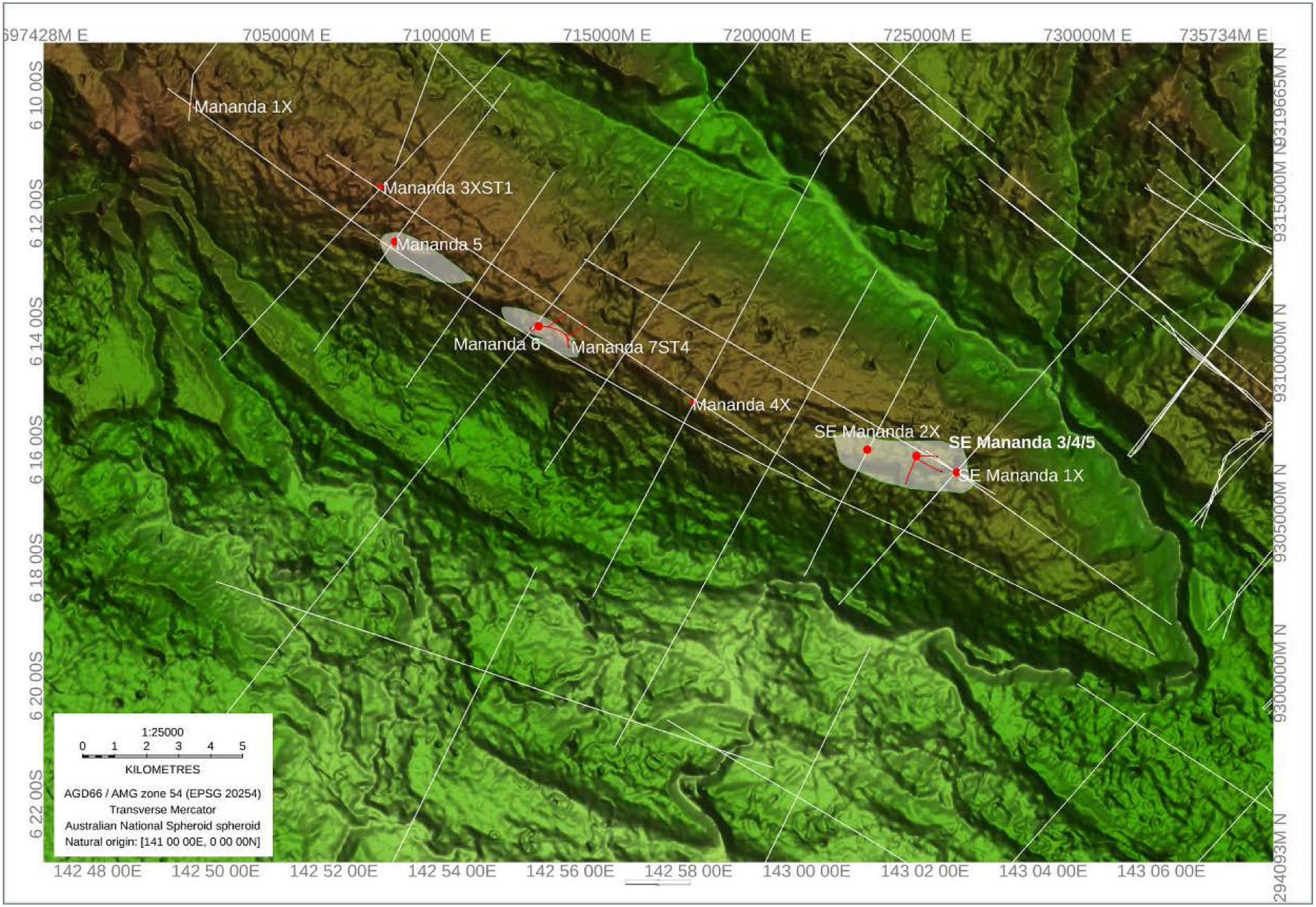

Figure 2. Mananda seismic and wells basemap with digital terrain model.

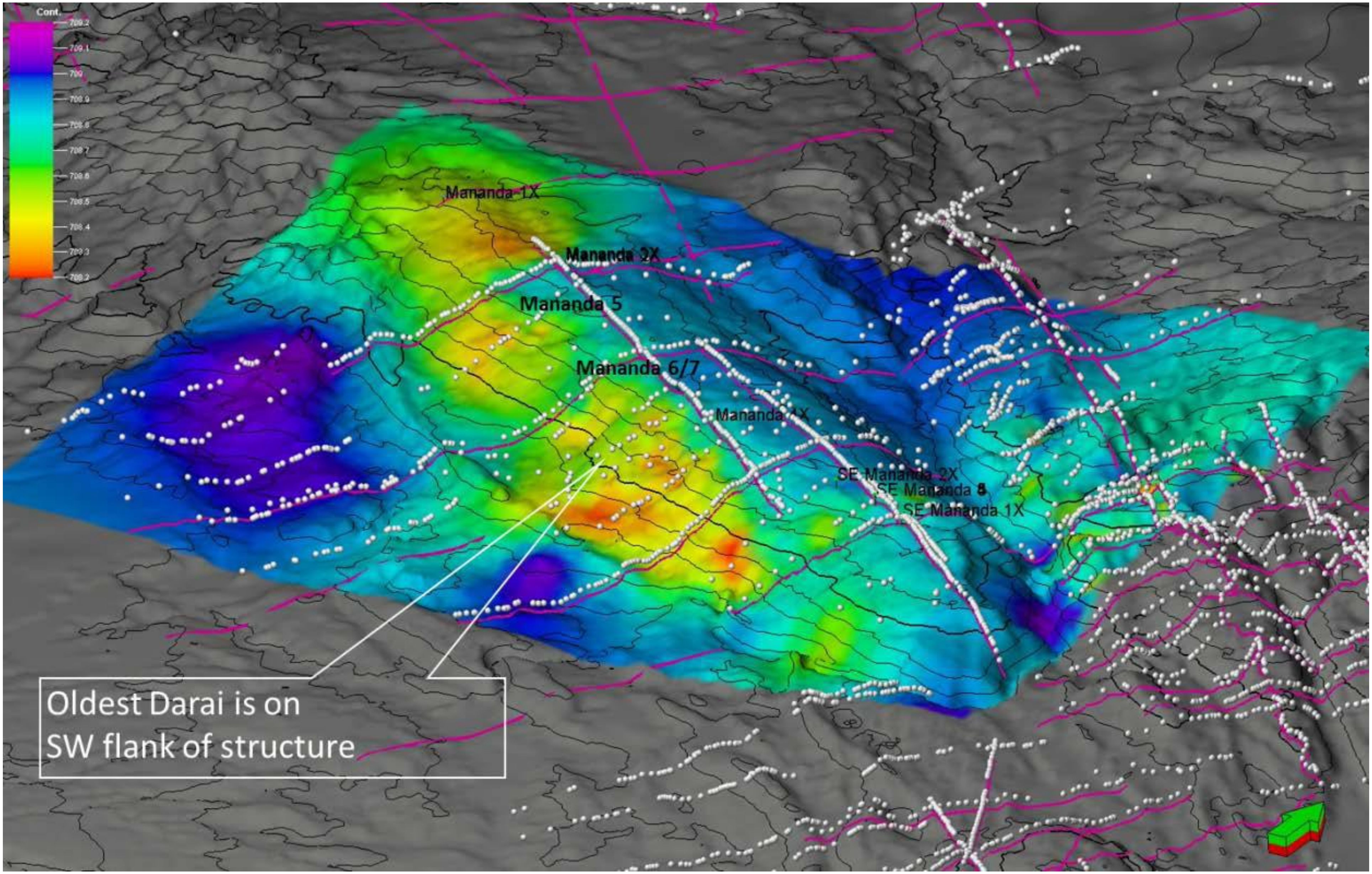

Figure 3. Darai Limestone strontium age overlaying the digital terrain model indicating the oldest stratigraphy and geologic crest is on the southwestern flank.

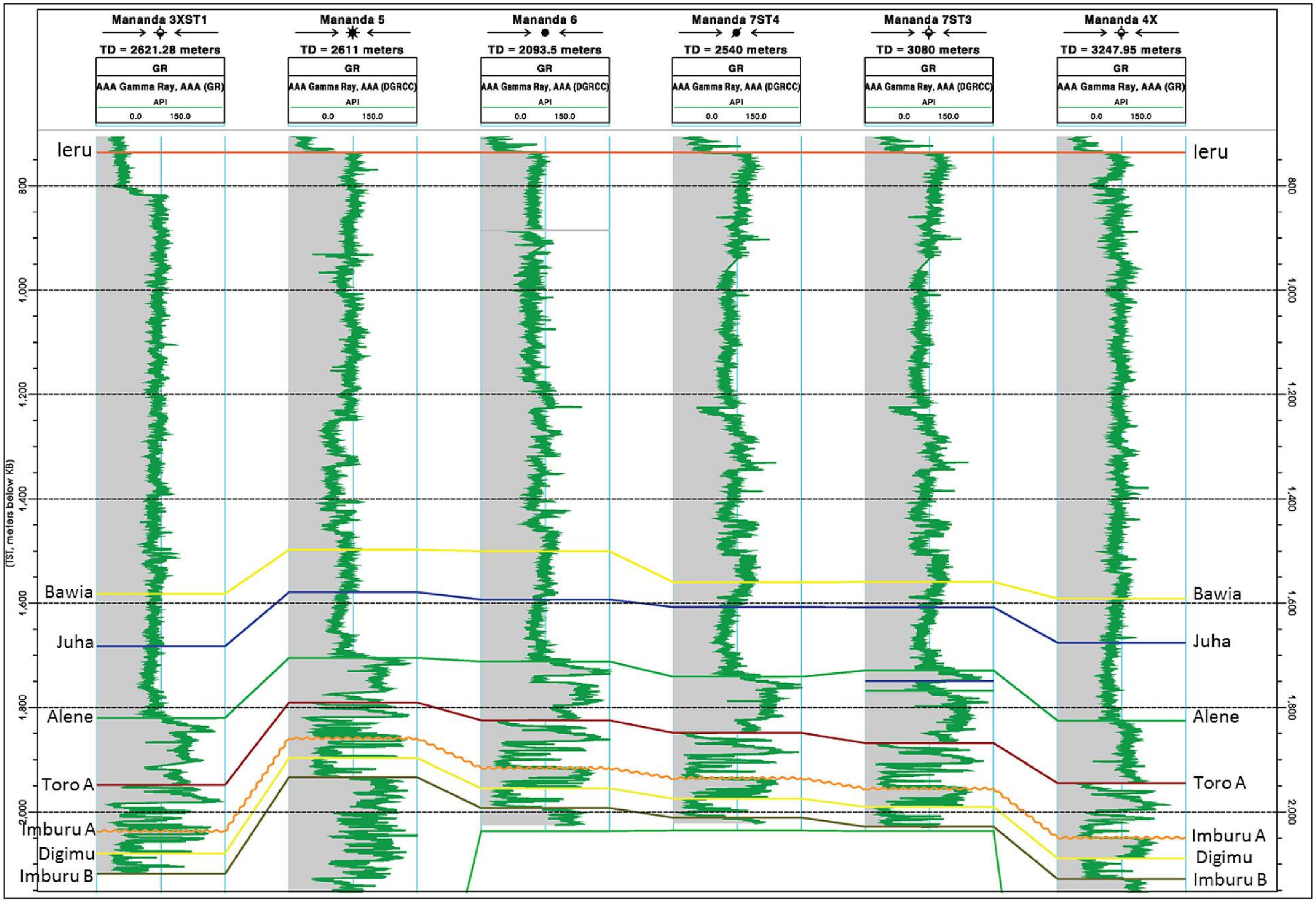

Figure 4. True stratigraphic thickness (TST) correlation of Mananda wells datummed on top Ieru Formation. The correlation illustrates the increased thickness of hangingwall penetrations (Mananda 3XST1, Mananda 4X) in comparison to footwall penetrations (Mananda 5, Mananda 6). Note Man 3XST1 Top Ieru log character is suppressed by casing.

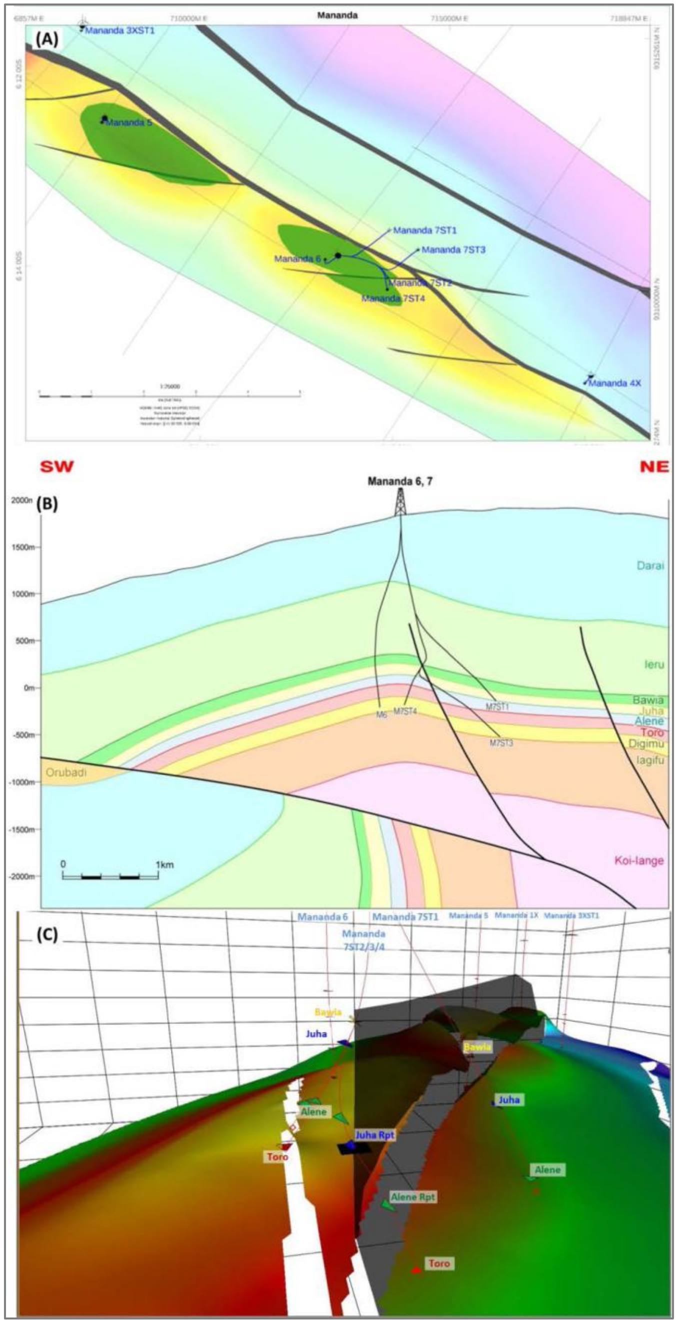

Figure 5. Mananda 7 (a) Map, (b) cross section, (c) 3D model visualisation (Toro depth surface).

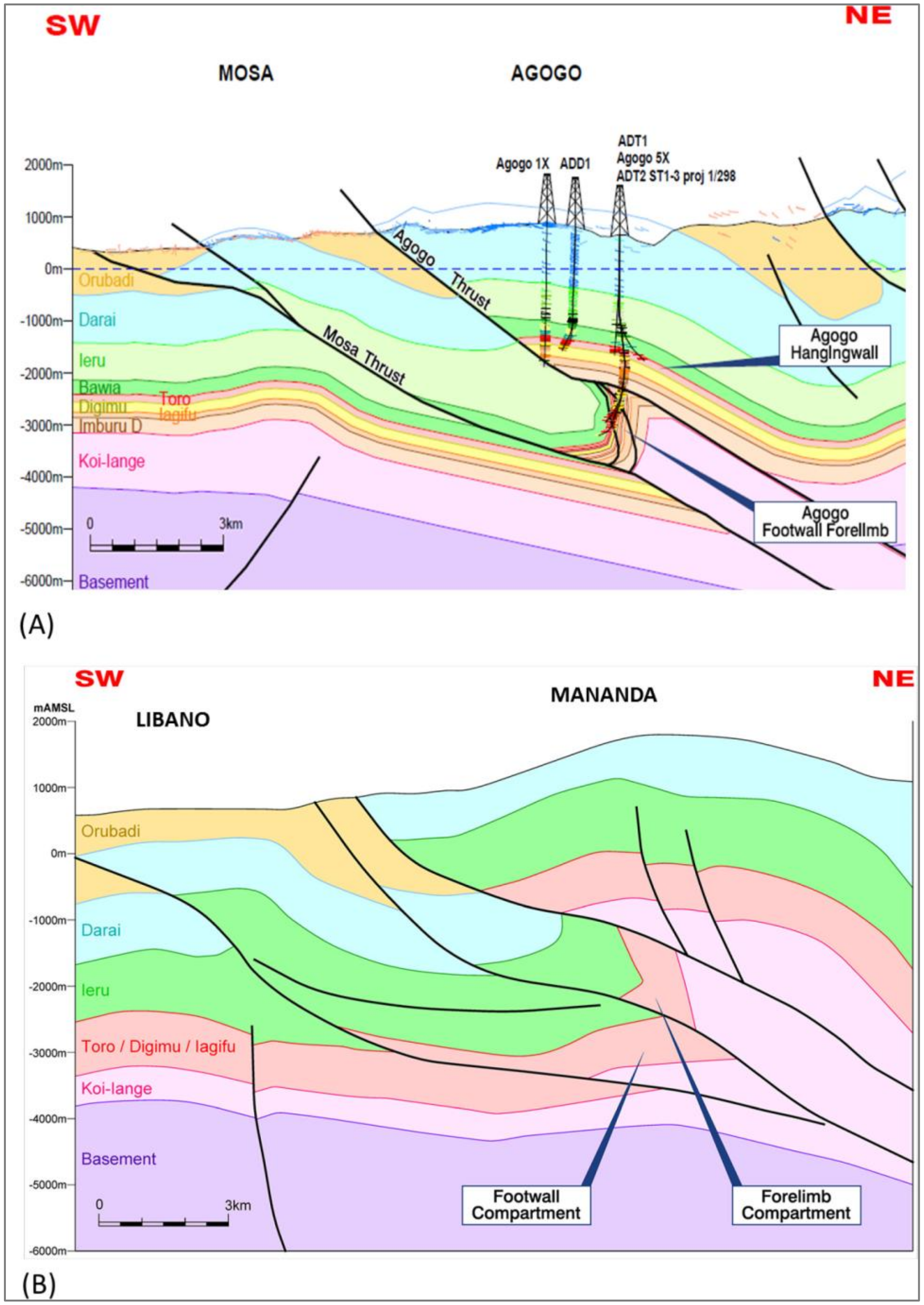

Figure 6. (a) Structural cross section of the Agogo Field showing successful forelimb wells. (b) Cross section of the Mananda Anticline showing the interpreted footwall and forelimb compartments similar to the nearby Agogo analogue.

Well Name	Year	Company	Status	Comment
Mananda 1X	1979	Australasian Petroleum Company	Dry Hole	Failed to reach reservoir. Drilled major thrust repeat.
Mananda 2S	1984	Niugini Gulf Oil	Dry Hole	Mechanically failed to reach reservoir
Mananda 3X/ST1	1985	Niugini Gulf Oil	Dry Hole with shows in Toro/Digimu.	Recovered small amount of oil/water on DST. Off structure, updip to the SE.
Mananda 4X	1990	Chevron Niugini	Dry hole with shows in Toro/Digimu.	Off structure. Updip to the SW
SE Mananda 1X	1991	Chevron Niugini	Oil and gas discovery.	73m HC column discovered in the Toro sandstones
SE Mananda 2X	1994	Chevron Niugini	Appraisal well	Drilled 2.8km NW of SEM 1X
SE Mananda 3/4/5	2006	Papuan Oil Search	Appraisal/Development wells	
Mananda 5	2010	Papuan Oil Search	Oil Discovery in Toro and Imburu A.	Updip test of Mananda 3XST1 and 4X.
Mananda 6	2013	Papuan Oil Search	Oil discovery in Toro, Imburu A and Digimu.	Updip test of Mananda 5. Discovered new accumulation.
Mananda 7	2014	Papuan Oil Search	Appraisal wells	

Table 1. Summary of well results on the Mananda Ridge.