The geology and structural style of the Juha gas field, Papua New Guinea

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SUMMARY

The Juha Anticline in the jungle-covered highlands of Papua New Guinea was drilled by three crestal wells in the 1980's and discovered gas-condensate in a Lower Cretaceous clean quartz sandstone reservoir. The Juha-4 and Juha-5 wells drilled in 2007 further delineated the structure and defined a separate North Juha compartment. The Juha structure is 25 km long and up to 8 km wide and is traversed by a number of seismic lines, some of which are of moderate to good quality allowing the structure to be interpreted. Unlike most structures in PNG the seismic lines reveal the nature of the overlying Pliocene-Pleistocene sediment which help to define the depth of burial and timing of deformation. The wells and seismic data suggest that the Lower Cretaceous sandstone reservoir was buried by 1.5 km of Cretaceous shale, the regional seal, and 1.5 km of Miocene limestone as well as more than 1.6 km of Pliocene-Pleistocene sediment prior to uplift and erosion. To constrain the timing and style of extensional and compressional deformation, 25 2D seismic lines were interpreted aided by forward modelling of the structure. The seismic interpretation revealed basement-involved structures that were predominantly influenced by two major events, rifting in the Triassic-Jurassic and compression in the late Pliocene-Pleistocene. The deep structure remains uncertain, but gravity data indicate a very deep underlying graben a concept that has recently been investigated and validated by 3D analogue modelling. A key seismic section indicates inverted basement faults beneath Juha flattening upwards into a detachment horizon creating triangle zones in the Cretaceous mudstones such that the overlying Miocene Limestone in part deforms independently. The Juha Anticline is part of the PNGLNG project operated by ExxonMobil which commenced production in 2014, 32 years after drilling of the Juha-1 discovery.

Key words: Structure, triangle-zone, inversion, mountain-front, reflection-seismic.

INTRODUCTION

The structure of large mountain-front and foreland anticlines has received much attention, in part due to their significant potential as hydrocarbon traps (eg Vann *et al* 1986; Butler *et al* 2006). In particular, the timing is important, as modelling studies indicate that appropriately aligned pre-existing structures, such as old normal faults, can be reactivated to create large anticlines prior to thin-skinned deformation. These early-formed structures are then favourably placed for hydrocarbon charge. However, the nature of such reactivation is debated, in particular the significance of triangle zones and the amount of basement involvement in inversion structures. In Papua New Guinea (PNG), the large mountain front structures have been drilled since 1985 yielding significant reserves of oil and gas, such as in the Kutubu, Hides, Juha and P'nyang anticlines (Figure 1). From the point of view of understanding mountain front evolution, these anticlines have the advantage of having formed in the last 5 M.Y. with some structures still seismically active, although early reactivation has been suggested by some authors (eg Hill *et al* 2008, 2010). Importantly, there has been no overprint, such as by post-orogenic collapse.

Of the major anticlines, the Juha anticline is one of the least studied with relatively little information published, yet it is well defined by 5 wells, >16 good to poor-quality seismic lines, synthetic aperture radar images, geological maps and gravity data. Furthermore, the Juha anticline records the deformation of Pliocene to Pleistocene molasse sediments and exhibits interior unconformities that help to constrain the timing of development. The structure has previously been interpreted to be part of a thin-skinned duplex (Hobson 1986) or a basement-cored triangle zone (Hill, 1989), whilst 30 km along strike to the SE, the Hides anticline has been interpreted to be a large inverted normal fault involving basement reactivation (eg Cole *et al* 2000). More recently, Mahoney (2015) on a regional section suggested that the Juha structure formed as part of crustal-scale thrusting or inversion. The goal of this study was to define the structure of the Juha Anticline, to constrain its maximum burial and the timing and nature of its development. This was done by detailed interpretation of the seismic data and porosity analysis, which are reported here, leading to forward modelling of the depth-converted sections and comparison with analogue models. Here, one key seismic line is presented and discussed to illustrate the structural style. It is hoped that this detailed work will help to constrain models for mountain-front development.

Background

The island of New Guinea comprises accreted volcanic arcs, ophiolites and igneous and metamorphic rocks in the Mobile Belt to the northeast, a central Fold Belt and a relatively undeformed platform to the southwest (Dow 1977; Hill & Hall 2003). The Juha anticline lies along the leading edge of the Fold Belt (Figure 1). Basement in PNG has been encountered in several foreland wells and is exposed in the mountains to the northeast of Juha where it comprises Triassic granites intruded into Late Permian to Early Triassic low-grade metamorphic terranes (eg Page 1976, Davies 1983). The margin was rifted in the Mid-Late Triassic and again in the Early Jurassic (Home *et al* 1990) and underwent a period of post-rift subsidence in the Late Jurassic to Early Cretaceous when shales with interbedded reservoir sandstones were deposited (Figure 2). Further subsidence led to flooding of the margin in the Early Cretaceous and widespread deposition of the Mudstone, the regional hydrocarbon seal.

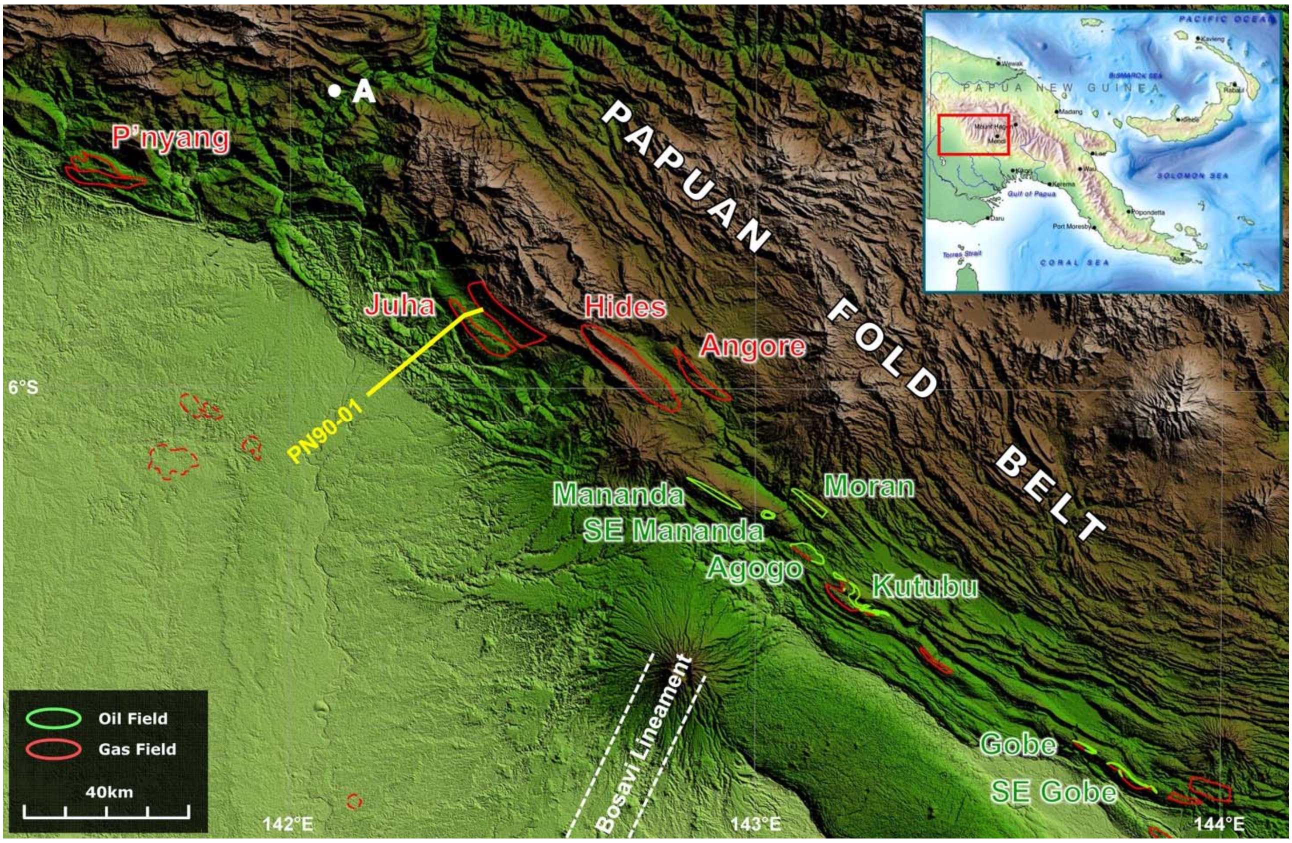

Figure 1 Location of the Juha Anticline in the frontal ranges of the Papuan Fold Belt, showing other oil and gas fields along strike. The PN90-01 seismic line is shown in Figure 3. 'A' refers to the outcrop of Triassic granite basement in the Strickland Gorge

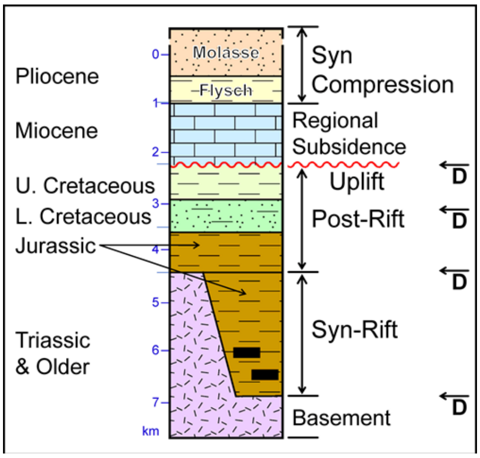

Figure 2 Sketch stratigraphic section for the Juha area showing approximate thicknesses of the main sequences and the main tectonic events. 'D' refers to known detachment horizons. Note that the colours on Figure 3 correspond to the sequences shown here.

Towards the end of the Early Cretaceous the eastern margin of the Australian continent was uplifted, (eg Muller *et al*, 2016) which caused a retreat of the shoreline in PNG and an erosional unconformity above the Upper Cretaceous beds. In the Eocene the Indo-Australian plate started moving rapidly to the north, associated with a transition from extension to compression in PNG and initial obduction of ophiolites (Davies and Jaques, 1984). However, deposition in the Fold Belt area did not resume until the Late Oligocene to Miocene when the margin was inundated allowing deposition of around 1-1.5 km of carbonates (Figure 2). Arc-continent collision and associated compression commenced in northern PNG in the Middle to Late Miocene and propagated south to create the Fold Belt in the Pliocene to Pleistocene. This caused deposition of flysch and overlying molasse sediments in a foreland basin setting (Figure 2).

METHOD

The overall aim of the study is to define the structural evolution of the Juha Anticline and here we illustrate this using one seismic line. As part of the project, twenty-five seismic lines (Table 1) were interpreted and tied to the wells (Table 2). Additional data included geological maps of the area and a digital elevation model (DEM) icombined with a Synthetic Aperture Radar (SAR) image that were used for topographic analysis and to help delineate the surface geology (Table 3). The structure was determined by detailed observations of the seismic which are recorded in the section below. Subsequent work of forward modelling and section balancing is beyond the scope of this paper and will be reported elsewhere.

OBSERVATIONS FROM SEISMIC

Regional seismic dip-line PN90-01, reprocessed in 1996, joined to the 81-03-24 line, illustrates the typical structural features seen in the Juha area (Figure 3). It traverses the flat stratigraphic sequence of the foreland, intersecting the Cecilia Anticline, Wai Asi Syncline, Wai Asi Anticline, Liddle Syncline and continues up to the northeast reaching the Juha structure where it intersects the Juha 3ST1 well. The Juha structure is a flat topped monocline with approximately 3.5km of structural relief and 7.5km wide at its north end. The southern limb of the Juha structure dips at approximately 11º (Figure 3 A) and is consistent with outcrop readings taken to the west of the line (Davies and Norvick, 1974). Where visible on the seismic, the underlying horizons appear to follow the same general trend. Moving south, the line shows reasonable good quality data over Liddle Syncline to the Wai Asi Anticline. Between CDP 550 to 650 at the Wai Asi Syncline, the data is extremely poor, most likely a product of Pliocene bedsat surface or the result of a significant fault shadow. The well-imaged Cecilia Anticline has a calculated back-limb dip of 18º (Figure 3 B), which compares with 15º - 20º dips recorded in the field (Davies & Norvick, 1974).

The Miocene Limestone is clearly defined on this line and has been drilled at the Cecilia 1 well along strike (Figure 3). North of CDP 1171 the limestone crops out (Figure 3 A) and therefore a visible reflector marking the top is not defined on the seismic. The limestone in the crest of the Juha Anticline is elevated 1.4 seconds above regional limestone in the foreland at the southwest end of the line. Stratigraphically, the seismic reveals a 1.6 second limestone to basement sequence (Figure 3 C) in the southwest, compared to approximately 4 seconds at the northeast end of the line under Juha (Figure 3 D). The bulk of this thickening occurs in the Jurassic section and is here attributed to Jurassic extensional faults and syn-rift growth (Figures 2 and 3).

The transparent section above the top Miocene Limestone, correlates to a flysch sequence (marine mudstones and marls), mapped at surface between CDP 1077 – 1171 CDP (Figure 3 E). It is interesting to note the transition between the Miocene shallow water carbonates, and the overlying flysch, which formed in a deeper marine depositional environment. This change in depositional environment is attributed to the onset of orogenesis causing subsidence at Juha and inundation by mudstones, with little deformation. The overlying well-bedded molasse beds have a strong reflective signature and crop out to the southwest of CDP 1071 (Figure 3 F). It is important to note that the flysch and molasse beds are parallel to the underlying Miocene reflectors in the core of the syncline as opposed to onlapping against the anticline. This indicates that all the beds were deposited prior to deformation.

The Cecilia and Wai Asi Anticlines are tight and narrow structures that require a shallow detachment in contrast to the Juha structure that is a broad open large monocline that suggests a deep detachment. It is interesting to note that under the Juha structure the limestone reflectors are continuous and there is minimal shortening, yet there is a substantial structure at Juha. A distinct fault crops out at surface at CDP 400 (Figure 3 G) and is drilled 25 km along strike at the Cecilia 1 well. The Miocene Limestone in the Cecilia Anticline, has considerable offset across the Cecilia Fault of ~0.6 seconds TWT (Figure 3 G) with smaller offset of the Wai-Asi anticline (Figure 3 I). However, beneath the Liddle syncline there is no offset of the Miocene and Cretaceous beds and minimal offset of the Cretaceous beds at Juha (Figure 3 H). This indicates that the underlying fault creating the Juha Anticline must connect to the Cecilia and Wai-Asi anticlines at a deeper level than the Cretaceous, here interpreted to link through the Jurassic sediments. At Figure 3 M, a uniform panel dipping to the southwest which continues into the foreland is observed. This panel of dips together with the poorly imaged horizontal beds in the Jurassic beds below suggests a triangle zone (Figure 3 N). The divergent beds at O on Figure 3, are similarly interpreted such that triangle zone faults link the Jurassic to the Miocene section through the Cretaceous beds.

The elevation of the top Miocene Limestone in the Wai Asi and Liddle Synclines (Figure 3 J & K) is ~0.3 seconds TWT above the regional top Limestone in the foreland (Figure 3 L). The uplift of these beds relative to regional occurs even though the underlying beds appear to be parallel and roughly horizontal. This suggests that the thrust-faults underlying the synclines are parallel to bedding, but it is also possible that the very large extensional fault at N on Figure 3 has been mildly inverted. This is important in the evolution and hydrocarbon charge for Juha. However, care is required in the interpretation of this region as the slow velocities in the Pliocene molasse sequence in the foreland are replaced by higher velocities in the Cecilia and Wai Asi Anticlines, resulting in pull-up of the underlying structure at Cretaceous level, so that they would be pushed down on a depth section.

Within the Juha anticline which was formerly a deep graben, the Early Cretaceous reservoir sands were buried by approximately 2.6 seconds TWT of Late Cretaceous, Miocene and Pleistocene sediment as seen across the seismic section. This equates to 4.5~5 km of sediment in total. However, the average porosity of the reservoir sands is 8%. Using the Sclater and Christie (1980) modelled relationship between compaction and porosity in clean quartz sandstones, a maximum burial of up to 7km is indicated, suggesting that the molasse beds may have been up to 2 km thicker prior to uplift and erosion.

RESULTS

Using reasonable velocities to calculate thicknesses from the TWT measurements, the observations reported above allow the development of the following geological history for the Juha Anticline. In the Late Permian to Early Triassic, the PNG margin was subjected to compressional deformation as also recorded in eastern Australia in the New England orogeny (eg Crowhurst *et al* 2004). In the Juha area this was manifested by the intrusion of Triassic granites recorded in the basement outcrops of the Strickland Gorge 55 km to the northeast of the Juha Anticline (Figure 1, Page 1976, Davies 1983). The mountains were eroded in the Middle Triassic, exposing the granites as the current basement. In the Late Triassic to Middle Jurassic the PNG margin underwent rifting (eg Home *et al* 1990) which in the Juha area created significant basin-bounding faults with Middle Jurassic to Upper Triassic section only ~600m thick on the stable platform to the southwest, but over 7 kms thick in the trough beneath the Juha Anticline to the northeast. These large extensional faults acted as buttresses to the subsequent compressional deformation and largely controlled the development of the mountain-front structures.

The PNG margin underwent flexural subsidence in the Late Jurassic through the Early Cretaceous, allowing flooding of the continent and widespread deposition of sands and muds in a fining- and deepening-upwards sequence (eg Home *et al* 1990). This was manifested as a 400-600m thick post-rift sequence across the Juha area (Figures 2 and 3). Uplift of the eastern margin of Gondwana commencing around 105 Ma (eg Muller *et al* 2016) caused gradual retreat of the sea in the Late Cretaceous in the Juha area and ultimate exposure of the sediments creating an erosional unconformity above the ~1000-1400m thick Upper Cretaceous beds at Juha. The margin did not drop below sea level again until the Late Oligocene to Early Miocene when widespread Miocene carbonates were deposited which are 1300-1600m thick at Juha.

The onset of compression in PNG is marked by the ~350m thick Pliocene flysch beds that stifled ongoing reef development and by the overlying molasse beds that are at least 1500m thick, both of which are conformable with the underlying Miocene carbonates. This indicates that at this time the Juha area was part of a foreland basin sequence to growing mountains to the northeast. The Early Cretaceous sandstone reservoirs were buried by at least 5 km and possibly up to 7 km of sediment prior to deformation and uplift in the Pleistocene. Interpretation of the seismic data indicates that the Juha Graben was inverted, probably on steep faults but that the main fault flattened into a near bedding-parallel detachment within the Jurassic section. This created the Juha Anticline as a large fault-bend fold with relatively little shortening and no major faults cutting the Cretaceous to Miocene section. However, minor thrusts and backthrusts within the Mesozoic section created the crestal structure containing the Juha gasfield. The Jurassic detachment fault propagated to the southwest across the Cecilia half-graben and 'encountered' basement in the footwall of the Cecilia normal fault so cut up section to the Cretaceous beds (Figure 3). There it continued as a backthrust creating a triangle zone that is suggested on the seismic data by divergent bedding. Two splays kicked-off the backthrust and cut up through the Miocene-Pliocene beds creating the Cecilia and Wai-Asi anticlines (Figure 3).

CONCLUSIONS

The structural and stratigraphic analysis reveals that the Juha mountain-front structure is neither simple nor a single structural style. It incorporated deep-seated inversion to build the large, flat-topped Juha anticline with relatively little shortening and a fault-bend-fold geometry along its leading edge. To the southwest, this passes into triangle zones in the Cretaceous section that link the shortening to thrust splays that cut through the overlying Miocene carbonates and Pliocene foreland basin sequences. An issue to consider is that the deepest burial was in the Pliocene which was probably the time of gas-generation. This was prior to the compressional deformation in the Pleistocene so timing of hydrocarbon charge is a problem. Potentially, the Juha anticline was mildly inverted during deposition of the molasse sequence creating a trap. This is consistent with mild early inversion in the Kutubu and Usano structures along strike in the Papuan Fold belt inferred by Hill *et al* (2010, 2015).

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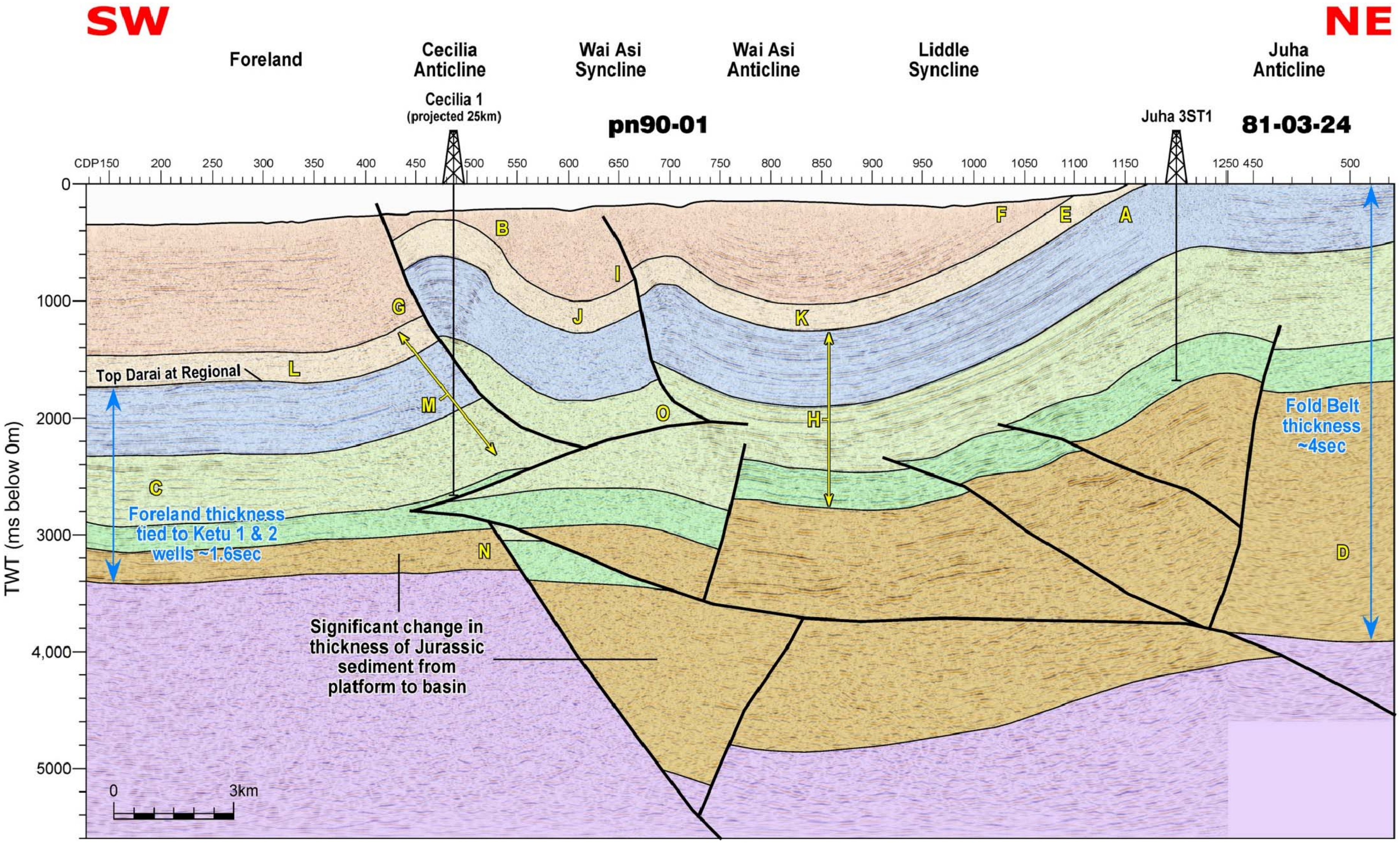

Figure 3 Seismic line PN90-01 joined to 81-03-24 across the Cecilia, Wai Asi and Juha Anticlines. The location of the line is shown on Figure 1 and the colours correspond to the units shown on Figure 2.

REFERENCE TABLES

Line Name	Year	Length (km)	Survey	Energy Source	Datum	Rep vel m/s	Reprocessed
84-01-os08	1984	37.625	Juha 1984	Dynamite	800	3500	Yes
84-02-os08	1984	6.075	Juha 1984	Dynamite	800	3500	Yes
84-03-os08	1984	7.563	Juha 1984	Dynamite	800	3500	Yes
84-04-os08	1984	7.6	Juha 1984	Dynamite	800	3500	Yes
84-06-os08	1984	7.87	Juha 1984	Dynamite	800	3500	Yes
84-10-os08	1984	7.412	Juha 1984	Dynamite	800	3500	Yes
84-12-os08	1984	8.55	Juha 1984	Dynamite	800	3500	Yes
84-14-os08	1984	12.3	Juha 1984	Dynamite	800	3500	Yes
84-16-os08	1984	10.462	Juha 1984	Dynamite	800	3500	Yes
84-08-os08	1984	8.7	Juha 1984	Dynamite	800	3500	Yes
81-03-21-os08	1981	10.8	Juha 1981	Dynamite	800	3500	Yes
81-03-22-os08	1981	4.65	Juha 1981	Dynamite	800	3500	Yes
81-03-23-os08	1981	16.35	Juha 1981	Dynamite	800	3500	Yes
81-03-24-os08	1981	5.3	Juha 1981	Dynamite	800	3500	Yes
81-03-25-os08	1981	11.5	Juha 1981	Dynamite	800	3500	Yes
81-03-26-os08	1981	6.5	Juha 1981	Dynamite	800	3500	Yes
81-03-28-os08	1981	11.8	Juha 1981	Dynamite	800	3500	Yes
81-03-30-os08	1981	6.6	Juha 1981	Dynamite	800	3500	Yes
PN90-01-os96	**1990**	**32**	**Dodomoma**	**Dynamite**	**800**	**3500**	**Yes**
PN90-02-gd96	1990	27	Dodomoma	Dynamite	800	3500	Yes
PN92-04-gd96	1992	13.075	Liddle	Dynamite	800	3500	Yes
PN92-03-gd96	1992	9.5	Liddle	Dynamite	800	3500	Yes
PN91-01-gd96	1991	11.237	Nomad-Sisa	Dynamite	800	3500	Yes
BA07-01	2007	10.56	Baia River	Dynamite	800	3500	Yes
BA07-02	2007	12	Baia River	Dynamite	800	3500	Yes

Table 1 Seismic Dataset Summary with seismic line from Figure 3 highlighted

Well Name	Operator	Spud Date	TD (mMD)	Checkshot survey
Juha 1X	Niugini Gulf Oil Pty Ltd	23-Oct-82	3741.72	Yes - Schlumberger
Juha 2X	Niugini Gulf Oil Pty Ltd	13-Oct-83	3602.74	Yes
Juha 3X	Niugini Gulf Oil Pty Ltd	6-May-85	943.96	-
Juha 3X ST	Niugini Gulf Oil Pty Ltd	6-May-85	3422.60	Yes
Juha 4 ST	Oil Search Limited	24-Apr-07	3290.00	Yes
Juha 5	Oil Search Limited	23-Dec-06	3652.00	Yes
Baia 1	Niugini Gulf Oil Pty Ltd	6-Jan-86	2997.71	No
Cecilia 1	Texaco Overseas Petroleum Company	22-Apr-71	3765.80	No
Lavani 1	Amoco Papuan New Guinea Exploration	21-May-82	2986.43	No

Table 2 Well Dataset Summary

Data Type	Data Composition	Source	Vintage	Quantity
Seismic	2D digital data	OSL	1981 - 2007	25 lines
Well Data	WCR	OSL	1971 - 2007	7 Wells
	Check shot data	OSL		5 checkshot surveys
	Formation Tops	OSL	Current working set	
SAR	Digital Elevation Model	OSL	1987	1 image at 12m x 12m pixel resolution
Geological Maps	Digital Geological Maps	OSL	1997	4 culture files (images)

Table 3 Dataset Summary