Recent Exploration in the Timor-Leste Frontier

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SUMMARY

Onshore hydrocarbon exploration in Timor Leste has resumed after a 50-year gap from the last well by Timor Oil in 1972 to Timor Resources' recent drilling in the Suai Sub-Basin. Encouragement from the new wells is providing incentive to conduct further exploration, including targeting a deeper "sub-decollement" play, first proposed in the 1970s. The play concept depends on the model applied to explain crustal shortening during the continental collision that created Timor. There is debate over the mechanism and over the true nature of the metamorphic rocks outcropping north of the Suai Sub-Basin. Does the Lolotoi Metamorphic Complex (LMC) represent an allochthonous unit below which is an un-metamorphosed prospective section, or is it composed of uplifted Australian continental margin material? New data acquired by Timor Resources is used to update the regional model and present support for the former concept, which at the time of writing, is being tested by drilling.
The paper presents recently acquired seismic cross-sections, 2D gravity modelling results and data from the recent wells. The new data is used to support the concept that the LMC is the remanent of an allochthonous unit thrust from the north whose base is a major decollement. It is proposed that the allochthon sits above a complex of over-thrusted Australian Continental margin blocks including a deeper decollement that pre-dates the active decollement and associated accretionary wedge, visible today at the base of the Timor Trough. Building on work by previous authors, we show the rationale for a deep sub-decollement test in the Suai Sub-Basin of southern Timor Leste.

Key words: Timor Leste, Lolotoi Metamorphic Complex, Viqueque Basin, Suai Sub-Basin, Gravity Modelling

INTRODUCTION

Numerous oil and gas seeps in the southern half of Timor Leste have motivated several cycles of onshore hydrocarbon exploration dating from 1904, however a commercial discovery remains elusive. After a break of almost 50 years, (following the Indonesian occupation in 1975), exploration has resumed with the recent drilling of three wells in the Suai Sub-Basin, Figure 1. These wells are providing incentive for further exploration.

In this paper we discuss our recent activities and exploration approach. In the first part we show a regional structural model constrained by modern gravity data. The cross-section is used to demonstrate the regional setting of the Suai Sub-Basin, where our exploration activities are concentrated. In the second part we describe the results of our more localised geological mapping, seismic interpretation, and recent drilling results.

The main components of the underlying geological model are based on the work of numerous previous workers drawn to Timor because it is an active continental collision zone. The geological complexity and large volume of academic research has resulted in a broad spectrum of published concepts and models. There is broad agreement that compressional tectonics dominated during the initial collision of the Australian continent with the Indonesian Banda Arc, commencing during the early-mid Miocene. This led to a complex set of decollement planes and imbricate thrusts, which can be mapped in the hinterland of the Suai area with various levels of confidence. However, the exact relationship of the Australian continental sediments and Banda Arc associations are vigorously debated (Charlton 2001, 2004, 2009; Duffy 2013; Haig 2012, 2018; Harris 2006, 2011, Keep 2009, Standley & Harris 2009, Tate 2015)). In our model the Lolotoi Metamorphic complex represents an allochthonous block of Banda Arc material, (Figure 1), over-thrusted onto deformed Australian continental crust (ACC). This idea is generally consistent with most previous workers, (eg Standley & Harris 2009), however Charlton et al, (2021) argues that the Lolotoi Complex represents Australian continental basement underthrust beneath the collision complex and that the deeper seismic reflectors represent a mid-crustal detachment. We acknowledge the plausibility of this model but disagree with this hypothesis.

We propose a model based on 2D modelling of gravity data in which Timor developed as a result of movement on 3 main decollements starting with the Banda Arc subduction zone, and most recently along a decollement that emerges at the base of the Timor Trough, (Poynter et el 2013). We use seismic data and the recent drilling results to show how a localised snapshot of the Suai Sub-Basin fits into the big-picture model based on the gravity data.

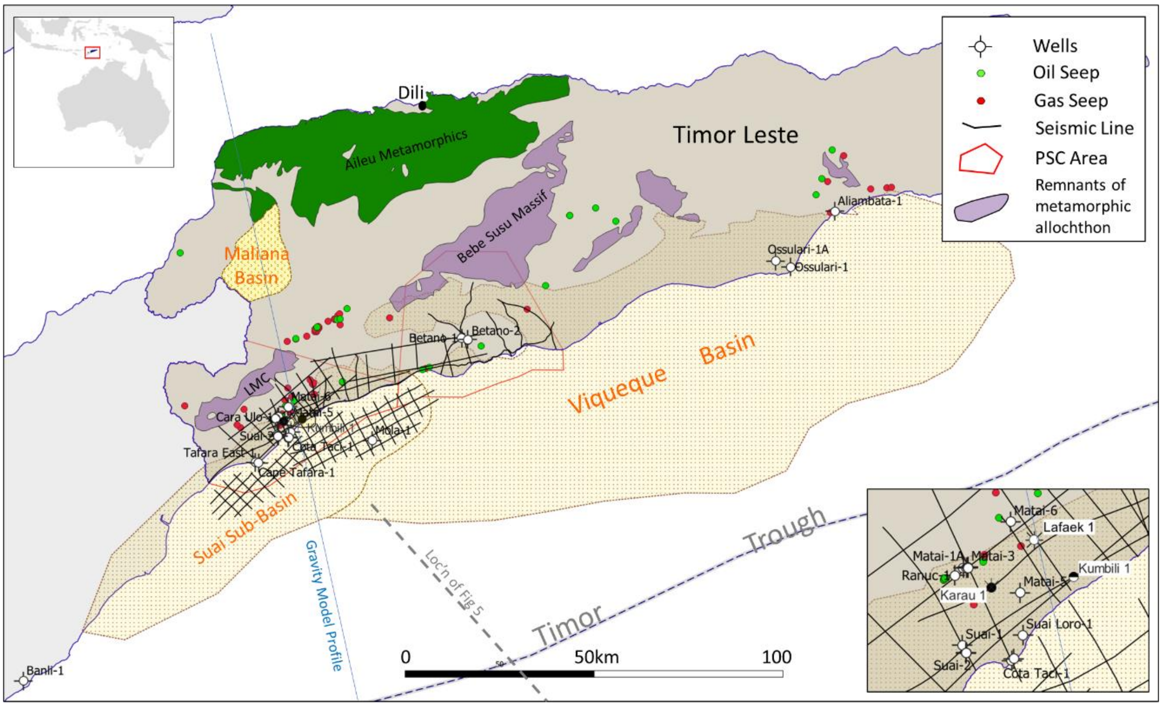

Figure 1. Location Map. Inset shows new well locations (white background) in onshore Suai Sub-Basin. LMC = Lolotoi Metamorphic Complex

We follow the stratigraphy described by Duffy et al (2017), Figure 2. Three mega-sequences are recognised plus a group of Allochthonous units that are associated with the Banda Arc. The oldest rocks make up the Gondwanan Megasequence over which lies the Australian Margin sequence. We refer to these combined sequences as Australian Continental Crust (ACC). The youngest rocks are those of the Syn-Orogenic sequence that comprise Plio-Pleistocene sediments eroded from the newly emergent Timor Island. Their provenance is a combination of uplifted ACC and allochthonous units of Banda terrain. The major unit of the Syn-Orogenic sequence is the Viqueque Formation which forms the basin on Timor's southern margin. Compression related movement was variously augmented by or intruded by soft sediments, which are recognised in outcrop as the Bobonaro Melange, a claystone unit widely recognised in Southern Timor Leste as tectonic melange, (Audley-Charles 1968, Harris 1998). On the chart it is shown as being coeval with the Jurassic Wai-Luli Formation with intrusive fingers into younger rocks. In our model, the melange is a mobile clay scooped up and over-thrusted within an earlier accretionary wedge that we propose developed south of the original oceanic subduction zone. This accretionary wedge has since been exhumed by the Timor uplift event. The currently active accretionary wedge in the Timor Trough provides a close analogy for the Bobonaro Melange, with mobile clay units (including mud diapirs), visible on marine seismic sections. There are numerous oil and gas seeps throughout Timor-Leste, particularly concentrated in the southern coastal areas, the oils average 32°API with the least biodegraded samples ranging from 34-45°API, Figure 1.

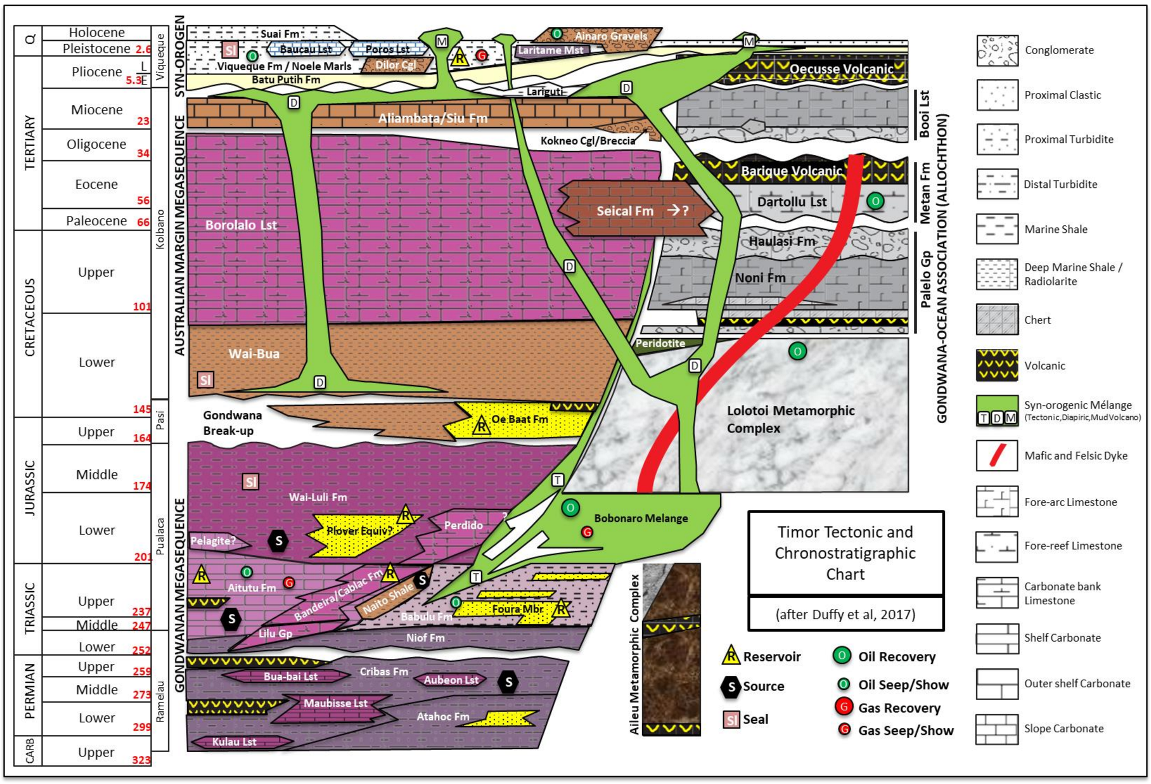

Figure 2. Chronostratigraphic chart

DATA

Most historical drilling data is provided from 21 wells drilled by Timor Oil Company between 1957 and 1972, the records are incomplete and limited by the technology of the day. Some early vintage digital seismic from 1968 to 1970 are available as scanned images. They do not generally image below the Viqueque Basin sequence however were useful constraints on some of the syn-orogenic faulting.

In 2016, an integrated airborne geophysical survey was initiated by ANPM over the entire onshore extent of Timor Leste. Gravity data was acquired on a line spacing of 1200m (azimuth = 165deg) with orthogonal tie lines spaced at 6000m. The data were processed using a correction density of 2.4 gm/cc to generate a complete bouguer anomaly grid. These data were a vital constraint used to extrapolate surface mapping into the sub-surface. The airborne data was subsequently combined with satellite gravity from the Scripps Institution of Oceanography, 2014 to yield a merged gravity map extending from the Wetar Strait north of Timor to south of the Timor Trough, Figure 3. 2D profiles were extracted from this grid and used for upper-crust scale modelling to generate a regional cross-section through Timor Leste.

The remaining data is from Timor Resources' exploration program for two permits awarded in mid-2017 (PSC TL-OT-17-08 & PSC TL-OT-17-09). Extensive geological surveying was conducted with JV partner TIMOR GAP along with reprocessing of the Pertamina 1994 dynamite survey using common-offset multi-focusing technology, (Bucknill et al, 2019). This was followed by acquisition of 327 km of 60-fold 2D Vibroseis data in 2018 and 2019. The same processing techniques were applied to the Fafulu surveys allowing the three surveys to form the backbone of a revised interpretation over the Suai Sub-Basin, Figure 1. As a result, three new wells were drilled. The results from Karau-1 (2021) and Kumbili-1 (2022) along with preliminary results from Lafaek-1 (spudded Oct 2022, in progress at time of writing) have been integrated into the pre-drill interpretation. leading to a better-defined understanding of the regional tectonics, local structure, and nature of deposition in southern onshore Timor-Leste.

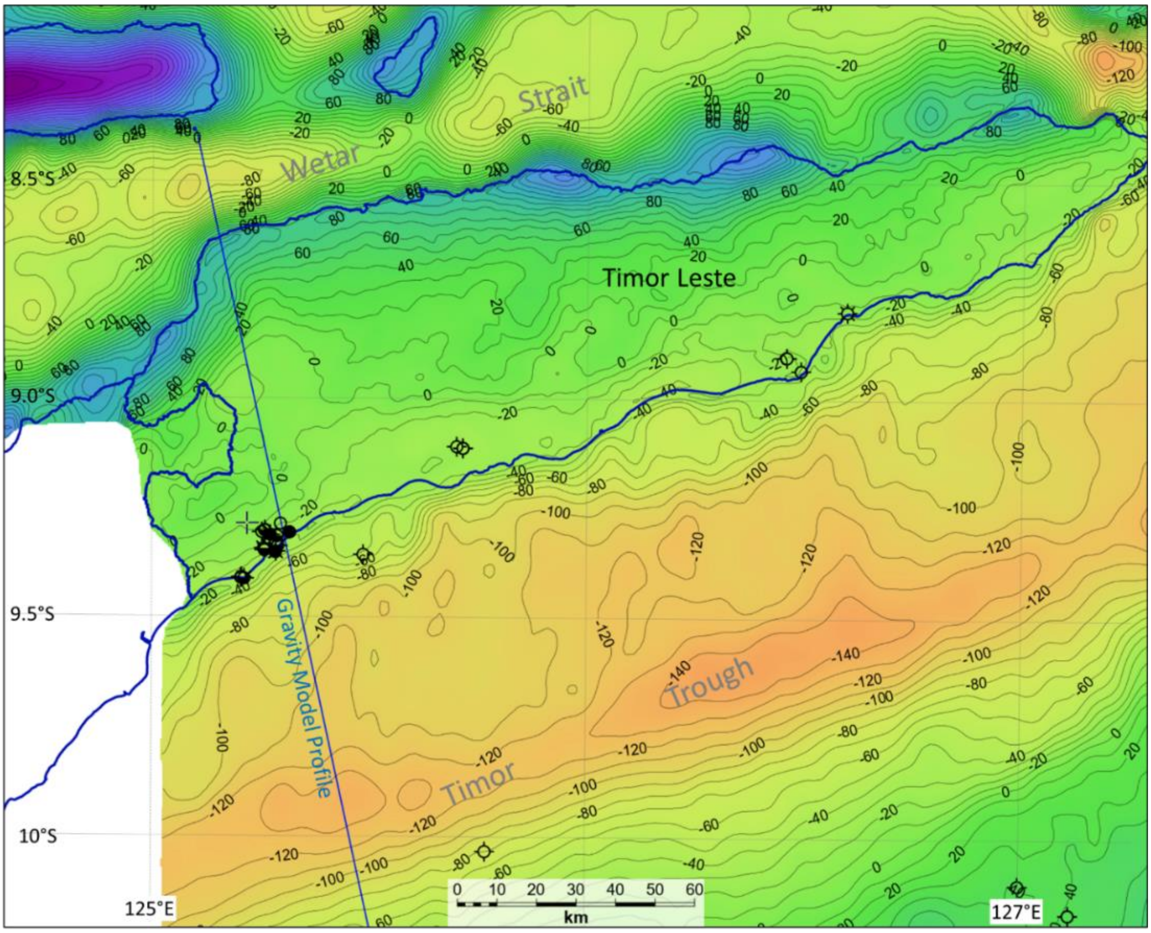

Figure 3. Bouguer Gravity Map from merged airborne and satellite data. Contour Interval = 10mgal

REGIONAL MODEL

Many authors have proposed theoretical cross-sections demonstrating Timor's underling structure. The new gravity data provides a means to add some quantitative detail to these models that also assists our exploration objectives. A profile was extracted from the merged gravity map and used to generate a 2D structural model. Profile Grav-1, Figure 4, demonstrates the strong gravity gradient increasing from south to north. The profile crosses the Maliana Basin which generates a local low gravity response, as well as the Suai Sub-Basin on the south coast of Timor Leste. On the northern margin of Timor, the gravity values reach a maximum that is a characteristic along the length of the island. The underlying structure, modelled down to 15km is based on various models including those of Hall & Wilson, 2000, Harris 1991 & 2003, Duffy 2012 Ota & Kaneko, 2010 and Audley-Charles 2011. The essential underlying elements of these models are:

- Australian continental crust (ACC) being subducted below present day Timor
- Over-thrusting of ACC along northward dipping decollements in a break forward sequence from the NW to SE, with the Timor Trough being the present day thrust front where the ACC begins subduction
- Obducted oceanic crustal material from the Banda Arc is thrust over the top of the northern most ACC

In our model deformation is interpreted to have been controlled by 3 major deformation planes designated: Banda Decollement, Timor Decollement, and Timor Trough Decollement. Other published models generally have numerous thrust planes and or theoretical stacks of thrust sheets. Undoubtedly there is much more localised faulting than shown in our coarse model which was built to support our exploration plays and help de-risk locations chosen for exploration drilling. However, we believe it is a plausible framework from which to incorporate more detail as additional data becomes available.

We note several limitations of the gravity modelling. Not only is it non-unique, it is difficult to incorporate all density changes which influence a given profile. While the model provides a plausible match to the recorded data, it does not include material below 15km. There are likely to be long period density changes down to the mantle that would impact the recorded gravity. Densities were derived from a combination of averaged log values and measurements of outcrop samples. These are regarded as realistic for the upper sections of the model, but the densities for deeper layers were based on theoretical values. The model should be viewed with these limitations in mind.

The location and depth of the Timor Trough Decollement is derived from offshore seismic data which clearly demonstrates where the ACC begins to be subducted beneath Timor. The deformation zone associated with the accretionary wedge above the decollement terminates in the base of the trough, Figure 5. Poynter et al 2013 documented this accretionary wedge describing the thrust tectonics and mud diapirism that characterises the deformation. The other decollements are more speculative and are inferred from a combination of the regional surface geology (Audley-Charles 1968), and the gravity profile itself. Details on the southern coastal margin are taken from the seismic interpretation of the Suai Sub-Basin area. Normal faulting controlling the Maliana Basin relies on work of Benincasa (2015), for the pull-apart model which explains how strike-slip movement facilitated the basin formation. Out of plane mass movement has occurred that is not strictly in the 2D model. The shape of the gravity profile north of the Maliana Basin gives a strong clue that there is a thick section of preserved high-density rocks whose base must dip to the north to match the gravity profile. We interpret this section as being Banda Arc terrain effectively obducted over the northern edge of the ACC. We include the Aileu Metamorphic rocks outcropping on the northern margin of Timor Leste as part of this unit, (Figure 1).

We believe that our model is consistent with the timeline for the collision proposed by Keep and Haig, (2010), whose work is based on foraminiferal assemblages. Their stages are repeated here for reference:

1. 9.8 Ma: Initial collision of Timor plateau (Australian continental terrace/plateau) with outer Banda Arc
2. 9.8–5.5 Ma: Phase of crustal shortening and loading
3. 5.5–4.5 Ma: Tectonic quiet interval due to locking of the subduction system
4. 4.5–3.1 Ma: Uplift & initial emergence of Timor due to subducting slab detachment and isostatic rebound
5. Post 3.1 Ma: Additional uplift and late extension

The "Banda Decollement" is the dormant equivalent of the Banda Arc subduction zone still active further west along the Java Trench. From 9.8Ma the phase of initial collision and subsequent crustal shortening would coincide with development of the "Timor Decollement" and the transport of Banda Terrain material over the top of the buoyant ACC. As proposed by Standley & Harris 2009, this gave rise to the Lolotoi Metamorphic complex which now sits as an allochthonous sheet over the Gondwana terrain of central Timor Leste, (Figure 1). As movement on that subduction plane ceased (or slowed dramatically), movement on the Timor decollement zone would cause overriding of Australian continental crustal material onto itself. A new trench would have developed to the south of the now dormant Banda Trench. with an accretionary wedge causing localised folding, thrusting and soft sediment deformation. We suggest that this older accretionary wedge is the source of the Bobonaro Melange, which comprises a mixture of clays caught up in the intense deformation near the emergence point of the decollement.

This in turn gave way to a third major decollement further south again which remains active today at the base of the Timor Trough, (Figure 5). In our gravity model we call this the Timor Trough Decollement. At about the time that the Timor Trough decollement developed it corresponded with the widespread uplift of Timor Island (stage 4 of Keep and Haig) who suggest it coincided with break-off of the oceanic crust originally attached to northern Australia. Evidence from marine fauna suggest paleo bathymetric depths near the centre of Timor Leste were up to 2.5km, (Haig 2012), implying more than 4km of uplift, after allowing for the current topographic elevation.

The cessation of movement on the Timorese part of the Banda subduction zone and subsequent shortening on the Timor and Timor Trough decollements, explains the southward offset of the bathometric low at the eastern end of the Java Trench where it swings south to join the Timor Trough.

The next section examines the geology and structure of the Suai Sub-Basin, its relationship to the regional model and the "sub-thrust" play concept, which targets the section below the "Timor Decollement".

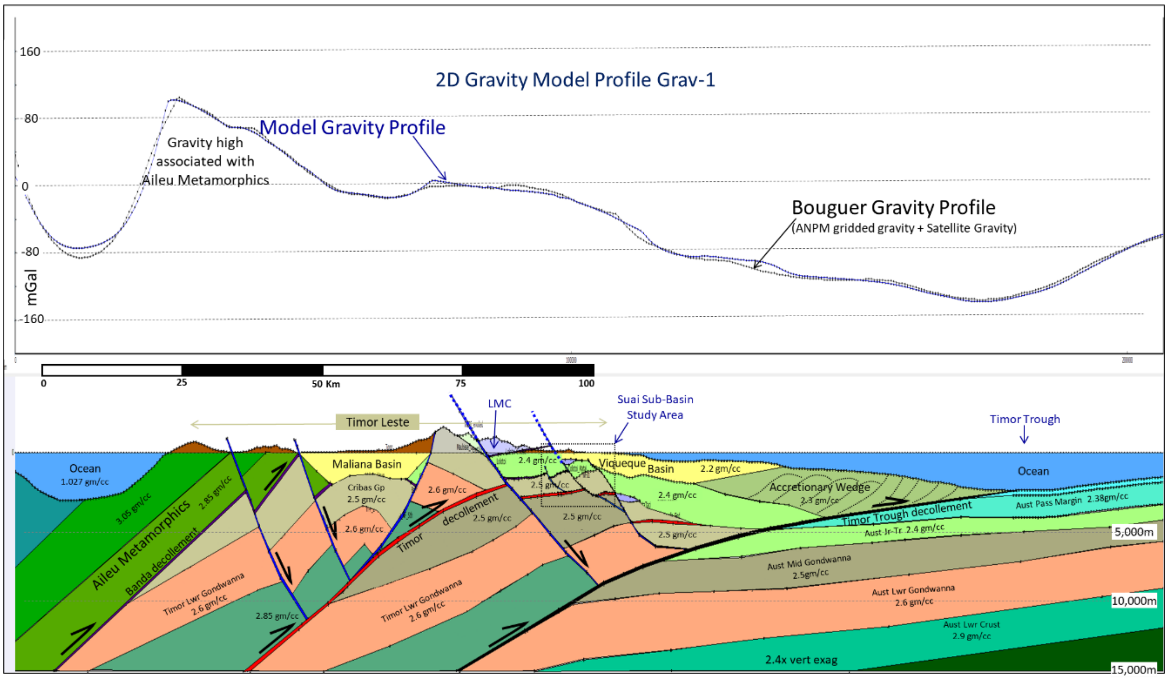

Figure 4. Bouguer Anomaly Gravity profile and sub-surface model for traverse shown in Figures 1 and 2. LMC: Lolotoi Metamorphic complex Vertical exaggeration: 2.4

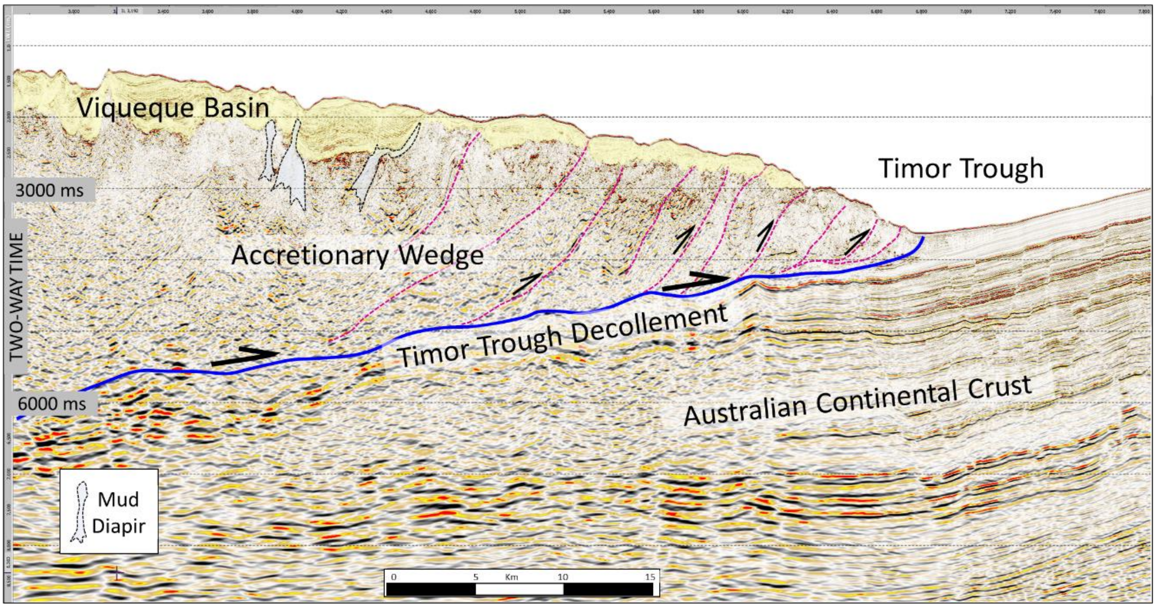

Figure 5. Timor Trough Decollement imaged by seismic data south of the Suai Sub-Basin. It shows the highly faulted accretionary wedge developing over the relative undeformed Australian Continental succession.

SUAI SUB-BASIN INTERPRETATION

The Suai Sub-Basin interpretation focusses on the area where most historical drilling and seismic data has been acquired, Figure 1. The equivalent interval on the regional cross section is highlighted in Figure 4. Seismic interpretation and mapping have focussed on the following:

1. Identifying and correlating extensional faults associated with the uplift and syn-orogenic processes
2. Correlating and mapping several intra Viqueque Formation reflectors for assessing Intra Viqueque plays
3. Identifying an event within the earlier accretionary wedge for assessing plays in this section (Intra ACC)
4. Mapping the "Timor Decollement" horizon to define a deep sub-decollement play

2D seismic imaging, especially in the onshore data is adequate in the syn-orogenic section where the Plio-Pleistocene aged Viqueque Formation is well imaged along with the extensional faults associated with the uplift and collapse into the developing Timor Trough. Figure 6 shows an example from the most recent seismic acquisition in 2018. Syn-orogenic faults are the normal faults in black and generally throw down to the south. Typical normal fault lengths are 8-10 km with some major faults such as NF-14, (Figure 7) over 20km long. Viqueque Basin reflectors may be readily correlated and mapped within this section which is gently folded suggesting that it has undergone mild compression during late Pleistocene or Holocene. In the Suai Sub-Basin, the Viqueque formation onlaps and pinches out at about 6 km inland from the coast. The new exploration well, Karau 1, was designed to test this pinch-out and a roll-over mapped in the underlying ACC section.

Below the Viqueque Basin, earlier compressional tectonics are demonstrated by thrust faults shown in maroon, which dissect the ACC section. Imaging of the ACC section is moderate to poor because the deformation intensity creates complex geometries which scatters the seismic energy. An intra ACC event was correlated and mapped based on seismic character. It formed the primary target for the second new well, Kumbili 1, Figure 7. The well targeted a local high within the intra-ACC event. It is evident from the seismic section that there is considerable extensional collapse and thickening of the syn-orogenic section around the Kumbili block. Although it is now highly dissected by normal faults, the structure was probably an original high block created by movement on the Timor Decollement. We interpret that the subsequent syn-orogenic extensional faulting has augmented this pre-existing structure.

The Timor Decollement was also interpreted in the seismic data and used to constrain the regional gravity model described earlier. The decollement surface is mapped to form a broad local high north of Kumbili 1 and is currently being tested by the drilling of Lafaek 1. This well will examine the concept that less deformed ACC rocks (sub-decollement), lie below the deformed ACC section, Figure 6 and 7. Uncertainty caused by poor seismic imaging and velocity control means that other technology such as borehole imaging is critical to assess the drilling results.

The Timor Decollement event is slightly deeper than the blue event mapped by Charlton et al 2021, who regarded the surface as the top of uplifted and metamorphosed Australian continental basement which they equate to outcropping rocks north of the Suai Sub-Basin mapped by Audley Charles (1968) as the Lolotoi Metamorphic complex, (Figure 1). In our regional model, the Lolotoi Metamorphic Complex, is an allochthonous unit comprising Banda Arc associated rocks that have been thrust over the ACC. Our model requires much less uplift than Charlton et al but has similarities in so far as the rocks interpreted below our Timor Decollement (and below Charlton's blue horizon) are both Australian continental material. The biggest question perhaps is the extent to which those rocks are metamorphosed. Some evidence pertaining to this question has been provided by results of Karau 1 and Kumbili 1.

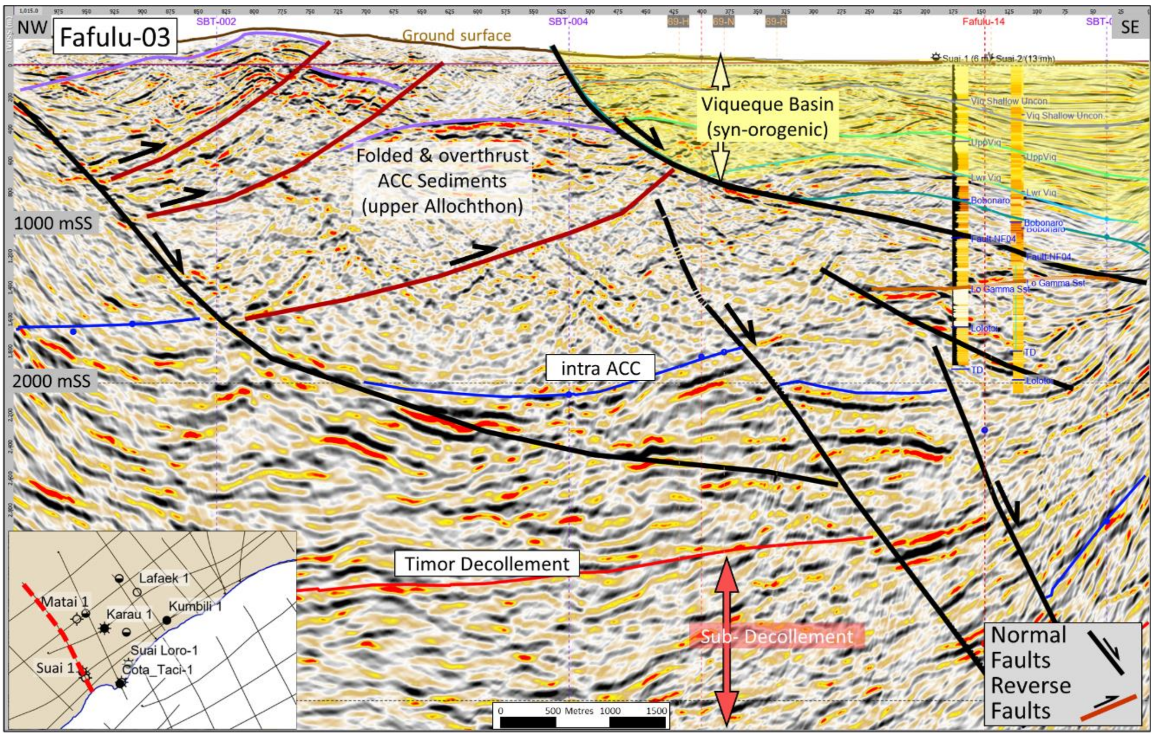

Figure 6. Seismic Line Fafulu-03. Syn-Orogenic Faults are black & Accretionary Wedge Faults are maroon.

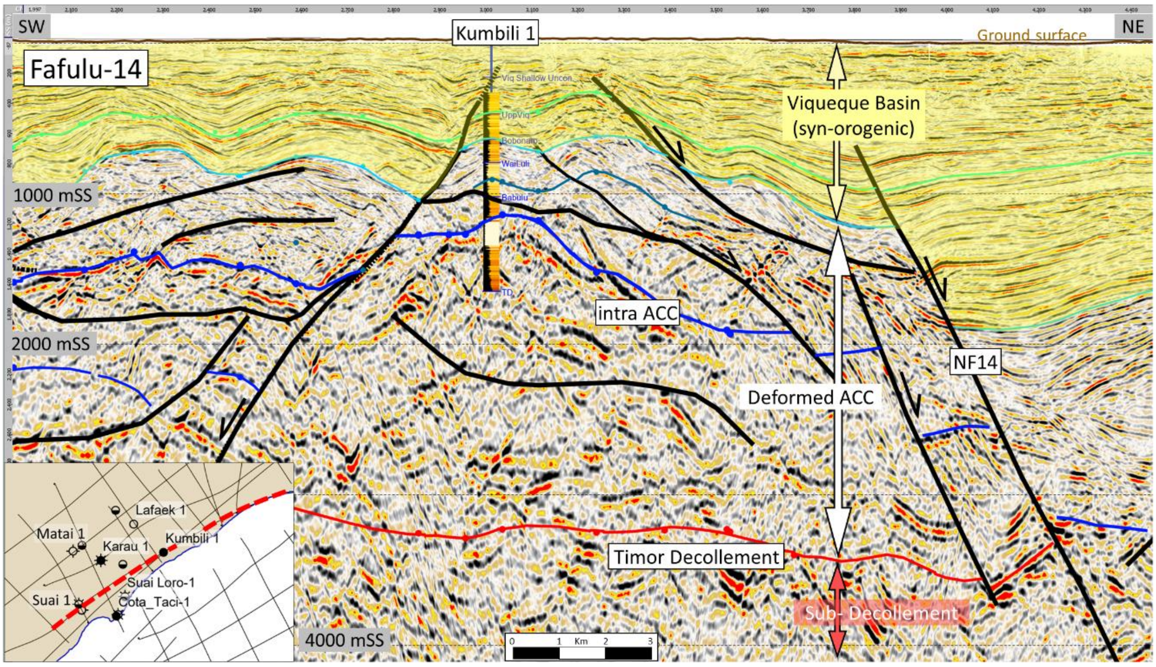

Figure 7. Seismic Line Fafulu-14 which approximately follows the coastline. The Kumbili high block is evident with a thickening syn-orogenic section on either side. The ACC section suffers poor imaging due to scattering of seismic energy caused by complex deformation of this interval.

WELL RESULTS

Three wells, Karau-1, Kumbili-1 and Lafaek-1 were drilled by Timor Resources in 2021/2022. These wells were the first phase of a drilling campaign designed to test a number of prospects and play types, including a sub-decollement target.

Pre-drill prognoses recognised uncertainty in seismic mapping and alternative interpretations were included for each well. In each case the intersected depths of mapped seismic horizons were within uncertainty and the primary or alternative interpretation realised. Pressure prediction modelling based on the historical data proved to be erroneous as overpressure was encountered at shallower levels than predicted. We interpret the likely cause as inadequate de-watering of accretionary wedge sediments that were exhumed rapidly during the syn-orogenic phase.

Karau-1 reached TD at 660mMDRT in Triassic carbonates and clastics with intervening Bobonaro clay, oil (43.5-46°API) and condensate (54.6-55.6°API) samples were recovered from four levels. Due to the shallow total depth (TD) there is limited direct support for a sub-thrust play other than noting that the maturity and pressure of these hydrocarbons is indicative of a much deeper generation than their present depth. The oil recoveries were in the secondary objective at the edge of mapped closure, with the crest to the west of the well location. This new information explains why five shallow water wells previously drilled in the vicinity of Karau 1 intersected an oil layer on water in Suai/Viqueque formation aquifers.

Kumbili-1 reached TD at 1670mMDRT, having penetrated a Viqueque section and then Bobonaro clay with intervening intervals of various ages before entering a late Triassic section (39.8°API oil recovered) with Bobonaro clay diminishing with depth, and reaching TD in meta-sediments. The well is planned to be re-entered for DST testing in 2023.

Lafaek-1 was designed to test the sub-decollement play beneath the Timor Decollement and was in progress at the time of writing.

A wireline FMI image log was acquired in Karau-1 and Kumbili-1, with a total run length of 1674m from Viqueque synorogenic sediments through to metamorphosed sediments. At the time of writing, it remains unclear as to whether the metasediments are associated with Banda Terrain material, or are composed of ACC material. The Viqueque interval structural dip correlated with seismic and comprised a dominantly sand-conglomerate section with interbedded mudstone. The Bobonaro mélange contained competent carbonate and clastic intervals that whilst internally layered were highly variable in dip and azimuth. This deformation style, with current maximum stress direction NNE-SSW, between the competent limestone and sandstones within ductile clay and mudstone is as commonly observed in surface outcrop (Fig. 8). This style of deformation is consistent with that expected to form within an accretionary wedge.

The outcropping Metamorphic Complexes (MC) within Timor-Leste have been attributed with a wide range of protolith ages in the literature. A synthesis of published data and additional new analysis was conducted by The University of Melbourne (Duffy 2021) with support from Timor Resources. From this work an approximate Permian age (possibly reset by metamorphism) was derived for the Aileu MC and Carboniferous to ?Lower Triassic (with a Palaeo-Proterozoic Anorthosite intrusion) for the LMC. A similar metamorphic complex in central Timor Leste, the Bebe Susu Massif, (Figure 1), is sparsely dated but is interpreted to comprise a complex of Pre-Permian, Cretaceous and Pre-Cretaceous metamorphics and volcaniclastics. In all cases these metamorphic rocks can be demonstrated to lie above rocks with Australian margin affiliations.

There are no known samples of metamorphic core or cuttings from the historical wells to compare with outcrop. Kumbili-1 collected cuttings samples in the metamorphic section which was comprised of metasediments. However, analysis of two organic metasediment samples near TD yielded VR of 4.55 and 3.71% of anthracite rank, which is lower than expected from the metamorphic grade of surface LMC in the type location. At this stage our conclusion is that the low-grade meta-sediments in the base of Kumbili 1 are not equivalent to rocks of the LMC. Our interpretation is that they represent partially subducted and now exhumed Australian crustal rocks of Gondwana affiliation.

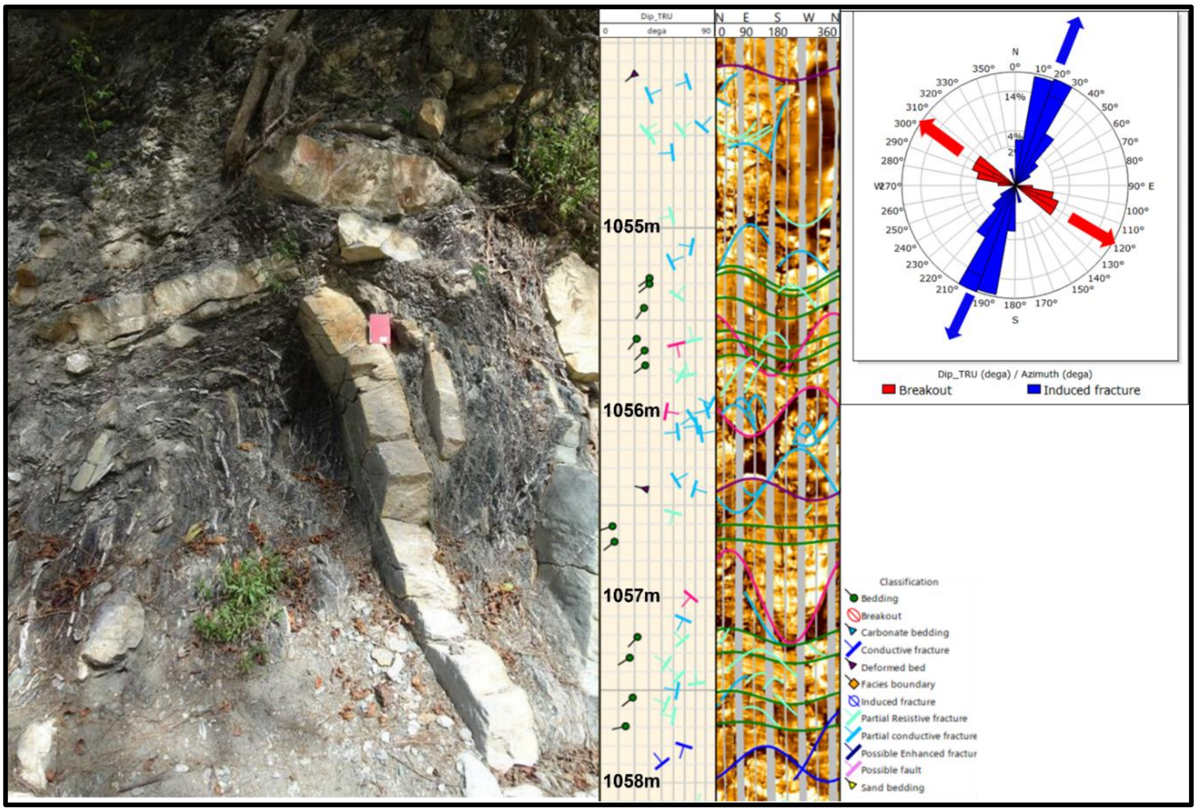

Figure 8. Structural Style and Stress Direction

CONCLUSIONS

The ideas presented demonstrate how new data and academic research have been integrated to develop an updated subsurface model allowing a reassessment of prospectivity in Timor Leste generally and more specifically in the Suai Sub-Basin with the identification of several prospective targets. The new well data has confirmed that a hydrocarbon system is active in southern Timor Leste. Oil recoveries confirm historical knowledge gained from oil and gas seeps and early drilling data. We have demonstrated that the early accretionary wedge interval is the source of hydrocarbons and have evidence that the underlying (over thrusted interval) is also hydrocarbon bearing. Low grade metamorphic rocks in the base of Kumbili 1 contained gas shows that hint at an even deeper source. Hence the drilling has added considerable new information that will assist ongoing exploration. However, given the complexity of the geology, many questions remain, including a definitive understanding of the nature and origin of metamorphic rocks in Timor Leste. Whilst recognising uncertainty our interpretation provides corroborating evidence for laterally extensive and relatively undeformed sub-decollement rocks with potential to be hydrocarbon targets.

ACKNOWLEDGMENTS

The authors thank Timor Resources for permission to publish this material and acknowledge Autoridade Nacional do Petróleo e Minerais (ANPM), Timor Leste, for permission to use the airborne gravity data.

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