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Petroleum Systems of the Eastern Indonesia Region

Guidance for Hydrocarbon Exploration in Eastern Indonesia

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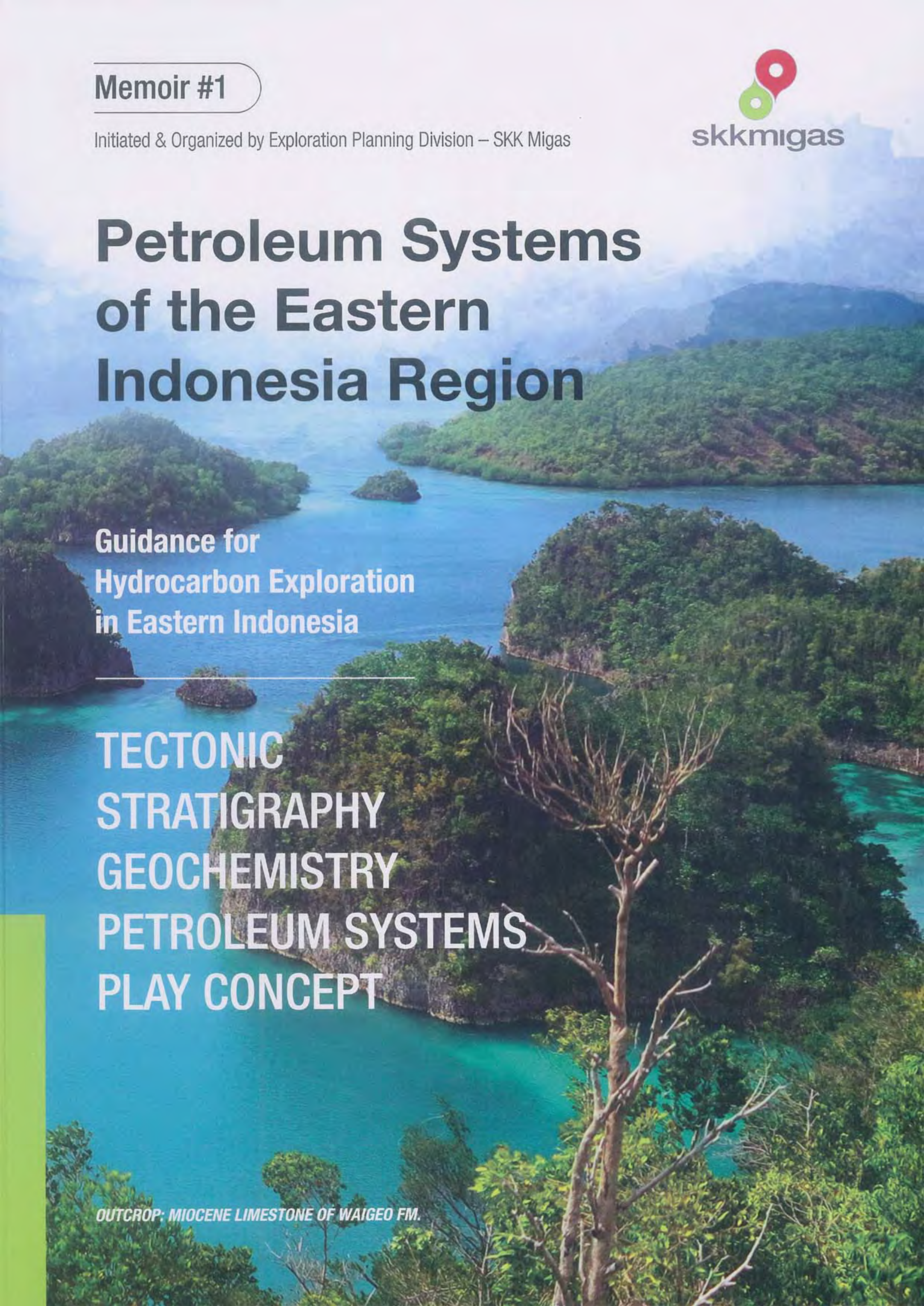

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MEMOIR #1

Petroleum Systems of The Eastern Indonesia Region

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A REVIEW OF MESOZOIC EXPLORATION PLAYS IN THE SOUTHERN PART OF ONSHORE EAST PAPUA, INDONESIA

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ABSTRACT

A summary is presented of the Mesozoic geology of the southern part of onshore East Papua, and its relationship with the Mesozoic petroleum system and geology of Papua New Guinea (PNG). The wells in the region of Papua Island (West Papua and Papua Provinces) were mainly drilled by Dutch during the colonial period until the late 1950s. However, a few wells have been drilled more recently (1990-2000) in the southern part of onshore East Papua, some of which encountered oil and gas in the Mesozoic objectives of the Early Cretaceous Woniwogi and Toro Sandstones, and the Late Jurassic LJ5 Kopai Sandstone.

Three distinct exploration plays are identified in the southern part of onshore East Papua: a Foldbelt Play, an Inversion Play, and a Foreland Play. The Foldbelt and Inversion plays have been drilled and encountered hydrocarbons, but so far without commercial success. However, these plays remain under-explored. Oil in the Cross Catalina-1 well (Foldbelt Play), and oil and gas in the Kau-2 well (Inversion Play) in the Mesozoic section have proven the presence of a working Mesozoic petroleum system. The Akimeugah and Kau-Strickland Basins are interpreted to provide source rock kitchens for Cross Catalina-1 and Kau-2 respectively. The Foreland Play has good potential for oil and gas exploration, but is effectively unexplored with an absence of seismic and well data. The lack of commercial discoveries in East Papua contrasts with the multiple condensate and gas accumulations discovered in the same play over the border in Papua New Guinea, indicating significant potential remains.

INTRODUCTION

The island of Papua (consisting of the Indonesian West Papua and Papua Provinces), and Papua New Guinea is often described as geometrically resembling a bird shape consisting of a "Bird's Head", a "Bird's Neck", a "Bird's Body", and a "Bird's Tail". The Papua Province region can be described as being located in the "Bird's Body" extending from the eastern end of "Bird's Neck" to the international boundary line between Indonesia and PNG in the east as shown in **Figure 1**. The region is a remote and inaccessible "frontier" area with large parts set in rugged mountainous terrain and virgin tropical forest. Consequently, there is a lack of infrastructure, and geophysical and geological data are sparse.

The eastern part of Papua Province geologically comprises (1) a northern Mobile Belt, (2) the Papua Fold and Thrust Belt in the center, and (3) a Stable Platform to the south. This paper focuses on the Fold and Thrust Belt and the Stable Platform. Exploration drilling results in the onshore West Papua or Bird's Head are included and briefly reviewed since the results were a trigger for the exploration activity in the southern part of onshore East Papua. The Mobile Belt is not addressed in detail in this paper, but in summary, is described as consisting of Tertiary volcanics and sediments with allochthonous terrane composed of ophiolites and high-grade metamorphic rocks (Nash et al., 1993). These rocks originate from island arcs and microcontinents accreted to the leading edge of the Australian plate during the Cenozoic (Mahoney et al., 2017).

Hydrocarbon exploration in West Papua began prior to 1950 when Nederlandsche Nieuw Guinea Petroleum Maatschappij (NNGPM) drilled several shallow wells on surface anticlines to evaluate the stratigraphy of the area. Most of the wells were dry with the exception of the Klamono-1 (1936) well in the Salawati Basin further to the west, and the Wasian-1 (1941) and Mogoi-1 (1941) wells in the Bintuni Basin. The Wasian and Mogoi Oil Fields have produced significant quantities of light oil (47.6° API gravity) and gas from the Late Miocene Kais carbonate from depths between 1000-3000 feet. The Klamono Oil Field produced asphaltic heavy oil (24° API) from very shallow depths of 370 feet, the oil having been altered by meteoric water and biodegradation.

In the post-1950 period, at least thirty exploration wells were drilled primarily to evaluate the Tertiary Kais carbonate reservoir in the Bird's Head area. The results were disappointing with the exception of the Kasim and Walio Oil Fields (Trend) discoveries in the Salawati Basin between 1972-1973. The Kais limestone Wiriagar-3 oil discovery in Bintuni Basin in 1981 was considered to be sourced by pre-Tertiary source rocks (Dolan and Hermany, 1988) and became the trigger of Mesozoic exploration in Papua Island including the Bird's Neck and Bird's Body. In December 1986, the Sebyar-1 well was drilled by Total in the Bintuni Basin to test the pre-Tertiary sedimentary section. Although the well failed to discover hydrocarbons it encountered mature source rocks in the pre-Tertiary section (Kartaadiputra and Samuel, 1988). Subsequently from 1992-1997 several large gas fields were discovered in the Middle-Late Jurassic gas sandstone reservoirs of the Kembelangan Group: Mogoi Deep, Wos, Wiriagar Deep, Vorwata, Roabiba, Ofaweri, and Ubadari (Casarta et al., 2004; Davis et al., 2006; and Yudhanto and Pasaribu, 2012). The total potential reserves of the fields are nearly 24 TCF (Marcou et al., 2004) and the fields are collectively being developed through the Tangguh LNG project. The Mesozoic-Paleozoic petroleum systems have been overwhelming gas-prone, some 80% of all hydrocarbons discovered to date in this region have comprised gas (Barber and Winterhalder, 2013).

To the east, in the southern part of onshore East Papua, very few exploration wells have been drilled and the area is considered under-explored. NNGPM drilled Aripoe-1 (1957), Merauke-1 (1957), and Jaosakor-1 (1958) to evaluate the stratigraphy of the region. The wells were dry, but as stratigraphic tests did not evaluate defined traps. The Aripoe-1 well reached a total depth of 5190 feet in the Paleozoic Kariem Formation. The Merauke-1 well reached a total depth of 4367 feet in Cambrian limestones. Jaosakor-1 encountered gas shows in the

Cretaceous Kembelangan and reached a total depth of 7330 feet in the Modio dolomite. The Kumbai Satu-1 well (Amoseas, 1980) targeted the Miocene Darai limestone but encountered only traces of gas, traces of oil were also encountered near the total depth of the well in the Cretaceous Piniya Formation. The Kuruwai-1 well (Amoseas, 1980) targeted Cretaceous sandstones, however, only dead oil was encountered in both the Woniwogi Sandstone and in the Brug Dolomite, **Figure 2**.

Exploration activity continued by Conoco in the southern part of onshore East Papua region in the 1990s to test the thrust belt and inversion plays in the Mesozoic-Paleozoic section. New exploration data were acquired. A total of 1241 km of 2D seismic lines of 1988, 1991, and 1995 vintages were shot, 12,500 km^2 of airborne magnetic and gravity acquired, and 19,163 km^2 of Synthetic Aperture Radar (SAR) were acquired in 1998 by Conoco. Seven wells were drilled: Noordwest-1 (1985), Sande-1 (1990), Cross Catalina-1 (1990), Digul-1 (1993), Kariem-1 (1997), Kau-1 (1997), and Kau-2 (1998). Results of these recent wells are crucial to establish the Mesozoic-Paleozoic stratigraphy and petroleum system components.

PRE-TERTIARY STRATIGRAPHY

The lithostratigraphic nomenclature in East Papua region was defined by the Irian Jaya Geological Mapping Project (IJGMP), a collaborative project between the Indonesian Geological Research and Development Centre (GRDC) and Australian Bureau of Mineral Resources (BMR) mapping program in the southwestern part of Bird's Body, Waghete-Omba area in the Akimeugah Basin in early 1980 (Panggabean and Hakim, 1986).

Stratigraphically, the oldest sedimentary section penetrated by wells is a pre-rift mega-sequence of the "Brug Dolomite", **Figure 2**. Based on structural reconstructions and outcrop mapping of the Brug in the Noordoost river, it is appropriate to equate the Brug to the Modio Dolomite (Granath and Argakoesoemah, 1989). The "Brug" Dolomite (Visser and Hermes, 1962 as cited by Pieters et al., 1983) is therefore equivalent to the "Modio" Dolomite described for the outcrops located in the southwestern part of Bird's Body, Waghete-Omba area. The age of the formation is Silurian to Early or Middle Devonian (Panggabean and Hakim, 1986) as indicated by the general aspect of a poorly preserved *Conodont* fauna (Pieters et al., 1983). The Brug in the Waghete consists of well bedded dolostone and dolomitic limestone with chert and pyrite nodules and siliciclastic sediments towards the top of the sequence. The Noordwest-1, Cross Catalina-1, Kumbai Satu-1 and Kuruwai-1 wells reached their total depths in the Brug Dolomite which was considered to be the "economic basement". However, hydrocarbon shows in the Brug Formation in the Noordwest-1 well indicate the potential for fracture or vug/palaeokarst porosity development in the deep carbonates (Kendrick and Hill, 2001). The formation is distributed extensively across the region and its thickness attains at least 3300 feet (Pieters et al., 1983).

Deeper and older basement rocks are the Precambrian Kariem and Awitagoh Formations, and the Cambrian-Devonian Tuaba, Kora, and Kemum Formations (Harahap, 2012). None of these basements have been penetrated by wells in the Papua region.

The Brug Formation grades into the overlying Mesozoic Kembelangan Group, with the Aifam Group largely absent in East Papua, **Figure 2**. Where present, the Aiduna Formation as part of the Aifam Group unconformably overlies the Brug as observed in the outcrops further to the west in the Waghete-Omba area. Lithologically, the formation consists of well bedded felspathic and micaceous fine- to coarse-grained lithic sandstones interbedded with carbonaceous shales and siltstones, minor fossiliferous biocalcarenites and polymict conglomerates, and coals. The Aiduna was probably deposited in paralic or fluvio-deltaic to very shallow (marginal) marine environments (Panggabean and Hakim, 1986; Harahap, 2012). The sandstones show high compaction and tight packing with estimated porosities ranging from 5-10% with a mean of 7%. Petrographically, most of the sandstones are characterized by well-developed quartz overgrowths that formed during early to late meso-diagenesis. The pore spaces have been cemented by authigenic silica and clay cement during diagenesis. However, there is a little secondary intergranular and intra-cement micropore texture due to dissolution of grain, cement and matrix during diagenetic events (Panggabean and Hakim, 1986). The formation age is assigned to Early Permian based on *Brachiopod* fauna (Archbold, 1991). The Aiduna Formation is interpreted to thicken southwest into the Akimeugah Basin suggesting that the area had a more active subsidence history than the eastern part of onshore East Papua or the Digul Arch area. In this basin (Waghete area) the maximum formation thickness is 3900 feet (Panggabean and Hakim, 1986; Harahap, 2012). The basin is thickest at the mountain front of the Papua FTB and thins towards the southwest where it on-laps onto the Arafura Platform offshore to the south of Papua Island.

The Triassic to Early Jurassic Tipuma Formation (Pigram and Panggabean, 1981) is not present in wells drilled in the eastern part of Papua, **Figure 2**. This formation is interpreted to have developed towards the west in the Akimeugah Basin. However, Hobson et al. (1997) suggested that the Triassic Tipuma Formation is absent along the onshore southern Bird's Body area over the foreland area with an exception in part of Papua FTB core structure. The Tipuma is proven absent in offshore wells South Oeta-1 (Amoco, 1986) and Kola-1 (Maxus, 1989), but was encountered by ASM-1X (Phillips, 1974).

The Tipuma Formation consists of red, maroon, green, grey to white feldspathic or tuffaceous lithic sandstone, minor red to grey micrite, arkose and polymict conglomerate, volcaniclastic sandstone and tuffs (Panggabean and Hakim, 1986). Reservoir quality is better than sandstones in the Aiduna Formation due to lack of quartz overgrowths with estimated porosities of 5-15%. The red color of the shales and lack of fossils indicated that the formation was deposited in a terrestrial, fluvial environment of the graben-fill (Kendrick et al., 1995). The Tipuma red beds marked the peak of the regressive cycle (Peck and Soulhol, 1986). The Triassic time corresponded to the culmination of a period of block faulting and uplift (Pigram and Panggabean, 1983 as cited by Peck and Soulhol, 1986).

The Kembelangan Group consisting of Kopai, Woniwogi, Piniya, and Ekmai Formations rest disconformably on the Tipuma Formation. Deposition of the Kembelangan began following a phase of Early Mesozoic rifting. The eustatic sea level curve shows that the most of the Jurassic/Cretaceous section is a major overall transgressive cycle which started in Early Jurassic following deposition of the Tipuma, and then became regressive during the Ekmai Formation deposition in Late Cretaceous, **Figure 3**.

The Kopai Formation is the basal unit of the Kembelangan Group. It is dated as Middle to Late Jurassic (Panggabean and Hakim, 1986) and has been penetrated by most of the recent wells in the Papua area, **Figure 2**. In the Akimeugah Basin, the formation consists of predominantly glauconite quartz sandstone interbedded with siltstone and calcareous mudstone and with minor micaceous sandstone ("greensand"), conglomerate, calcarenite and calcilutite. *Ammonites*, *Belemnites*, *Pelecypods*, and *Gastropods* are observed in this formation. Sedimentary structures include small scale cross-bedding, bioturbation and burrows, and ripple lamination. These sedimentary structures together with the presence of glauconite and large fossils, suggest that the formation was deposited in a restricted, shallow marine environment. The maximum formation thickness observed in outcrops is about 1000 feet (Panggabean and Hakim, 1986).

In the Early Cretaceous, the Woniwogi Formation was deposited conformably overlying the Kopai Formation in beach and near-shore inner shelf environments (Panggabean and Hakim, 1986). Outcrops in the Waghete area comprise well bedded to massive glauconitic orthoquartzite with minor siltstone and thinly bedded black calcareous mudstone near the top. The pore spaces have been filled by sparry and micritic calcite cement and clay minerals. Porosities range from 5-20% with an average of 10% and poor to fair permeability. Secondary porosity is prominent but marginal. The maximum thickness of the formation is 650 feet.

The Late Cretaceous Piniya Formation consists of predominantly grey to black calcareous claystones, minor muddy glauconitic quartz sandstone and muddy siltstone. The thickness of the formation is about 2600 feet. It was deposited in a shallow shelf setting during a maximum marine transgression.

The uppermost unit in the Kembelangan Group is the Late Cretaceous Ekmai Formation. The lithology is dominated by massive to thickly bedded glauconitic, calcareous quartz-arenite with some carbonaceous siltstones and thin claystones. The sandstone porosities are interpreted to range from 10-25%. Quartz overgrowths are present but are not well-developed, primary pores are more prominent and still preserved. The sediments were probably deposited in an inner shallow shelf marine environment. The maximum formation thickness is approximately 1300 feet.

EXPLORATION PLAYS AND PETROLEUM SYSTEM

There are three main hydrocarbon exploration plays in the southern part of onshore East Papua region: (1) the Foldbelt Play in the center along the Papua FTB, (2) the Inversion Play in the Digul Arch, and (3) the Foreland Play in the south, **Figure 4.** All of the exploration plays in this proven hydrocarbon province remain under-explored.

The primary reservoirs objectives are the Early Cretaceous Woniwogi and Toro Sandstones, and Late Jurassic (LJ5) Kopai Sandstones which were deposited as a passive margin succession on the northern edge of the Australian continental plate. Trap formation of the Foldbelt Play was initiated in the Late Miocene, while the Inversion Play over the Digul Arch was formed in two phases in the Late Oligocene and Plio-Pleistocene. The Foreland Play was relatively stable through time although faults were locally affected by the tectonics and structural development in the thrust front area further to the north.

Basin modeling indicates that mature source rocks are present in shales of the Early Cretaceous and Late Jurassic in the Akimeugah and Kau-Strickland Basins which thereby form the main source kitchens. The Aiduna shales and coals also form potential source rocks, but are likely gas-prone, **Figure 5**. Kola-1 located in the western most of the Akimeugah Basin offshore had oil shows and tested minor gas in the Early Permian Aiduna Sandstones. Hydrocarbon migration to these plays is proven by the Cross Catalina-1 well for Akimeugah Basin, and the Kau wells for Kau-Strickland Basin in the east, **Figure 1**. These basins developed in the Early Mesozoic on a passive margin along the northern edge of the Australian craton. The outline of these two basins is interpreted to generally follow a gravity low. The Mesozoic section is thickest in the area near the frontal thrust belt and thins towards southwestwards to the Digul-Fly Platform.

The primary, regional top seal is provided by thick shales of the Late Cretaceous Piniya Formation together with intra-formational shales within the Early Cretaceous and Late Jurassic sections.

Further discussions of the petroleum system components are included in each exploration play below. A review of the exploration and development drilling results in PNG is also included as an important analogue and a motivation for exploration in the East Papua region.

THE FOLDBELT PLAY

This Foldbelt Play geologically extends from the northwest to southeast along the Papua Fold and Thrust Belt (Papua FTB) in the Bird's Body region as shown in **Figure 1**, and regionally extends across the Indonesia-PNG international border to the east and merges with the Papua New Guinea Fold and Thrust Belt (PNG FTB). The Papua FTB is up to 150 km wide and 700 km long with surface mountain peaks reaching elevations of 4-5 km.

The ~2000 km-long orogenic belt of Papua New Guinea, at the northern Australian margin, represents a classic example of arc-continent collision (Dewey and Bird, 1970). The orogen is centred on the New Guinea Fold Belt, which lies between a foreland basin on the Australian Stable Platform in the south, and accreted island-arc terranes, oceanic and continental fragments of the Mobile Belt in the north (Dow and Sukamto, 1984; Pigram and Davies, 1987; Pigram and Symonds, 1991; Hobson et al., 1997; Davies, 2012; Baldwin et al., 2012). Northward-dipping subduction gave way to collision in the Mid-Late Miocene, and shortening and south-directed thrusting within the Middle Jurassic to Paleogene passive margin sequence to form the central fold belt began in the Late Miocene-Pliocene (Hill and Gleadow, 1989; Weiland and Cloos 1996; Hill and Raza, 1999; Hill and Hall, 2003).

The core of the Papua FTB is interpreted to contain a complex thin-skinned thrust belt consisting of stacked thrust sheets containing Paleozoic to Late Tertiary sections. The Papua FTB and its extension across the international boundary into the PNG FTB has been interpreted to have initiated as early as the Oligocene (Nash et al., 1993; Martin-Monge et al., 2017), whilst Pigram and Davies (1987) and Kaufman et al. (1997) believed that the orogen was initiated in Middle-Late Oligocene. **Figure 6** shows a schematic (unbalanced) cross-section applicable to the Papua FTB (Granath and Argakoesoemah, 1989). **Figure 7** shows a north-south dip seismic line interpretation near the Noordwest-1 well illustrating the data quality degradation with increasing structural complexity.

Fold and thrust structures provide trap types for the Foldbelt Play. The external leading edge thrust sheets retain Mesozoic Kembelangan Group sediments while the imbricated internal thrust sheets are severely uplifted with the Mesozoic section eroded and older sections observed in the outcrops, mostly the Paleozoic Aifam Group. The basal detachment surface is interpreted to be in the Kembelangan Group. The Papua FTB structures developed following the southern progression of the thrust wedge with major thrusting towards the foreland (Granath and Argakoesoemah, 1989). The disturbed belt of this frontal structure in the south is covered by Quaternary terrace deposits which have various degrees of folding and thrusting as seen in SAR imagery and seismic lines.

Umbach and Klepacki (1994) interpreted several seismic lines across Papua FTB in the area further to the west showing the presence of back-thrust and active triangle zone development to explain a lack of thrusting at the leading thrust, **Figure 8**. In contrast, based on geochronology and cross-cutting relations, Kendrick and Hill (2001) and Hill et al. (2004) illustrated a regional cross-section of Papua FTB comparable to those in PNG, **Figure 9**, involving both thin-skinned and thick-skinned basement thrusting. The thin-skinned thrust is structurally the highest and overlies the thick-skinned thrust system. The basement is faulted by the thick-skinned system to produce basement related structural styles.

An alternative interpretation (Hobson et al., 1997) suggests that the thin-skinned model may not be appropriate for the Papua FTB. The steep rises in regional elevations indicate that the structural elevation is built by displacement along steepening downwards (steeply inclined faults) rather than shallowing downwards faults. The high-angle reverse faults involved incompetent basement in the deformation in which shortening through duplexing has been minimal (Nash et al., 1993).

There is a transition of structural styles along the west-east Papua FTB from thin-skinned in the west to thick-skinned deformation over the Digul Arch in the east where basement cored structures become evident. A fault system zone in the area of Baliem Valley crosscuts the thrust belt and appears to extend southwards becoming the Akimeugah Basin boundary to the east (Granath and Argakoesoemah, 1989; McConachie et al., 2000). This foreland basin is the southwestern extensional structure of the preserved Paleozoic and Mesozoic sections present along the Papua FTB.

The thick-skinned deformation observed in the Digul Arch continues further to the east to the Muller Anticline in PNG (Valenti, 1992). Structural deformation in the PNG FTB involves reactivation of basement, detachment folds, and out-of-sequence thin-skinned thrusts (Hill et al., 2015). The stacked thrust sheets in the PNG FTB are simpler than those shown in the model for the western part of the Papua FTB, **Figure 10** shows an example at the Agogo Field. The structural evolution of the fold and thrust systems forming the Hedinia, Iagifu, and Juha Gas Fields in PNG is shown in **Figures 11-12**. These reconstructions are based on seismic interpretation of data across the PNG FTB. Folding is structurally dominant, as the deformation increases, the folds become tighter, overturned limbs develop, and are finally cut by reverse faults.

Structural modeling and reconstruction of oil and gas fields in PNG suggest that the earliest stage of the basement structures were extensional fault footwalls or half-grabens (Buchanan and Warburton, 1996; Hill et al., 2004) formed in Middle-Late Jurassic times when the productive Barikewa and Imburu source rocks were deposited, **Figure 12**. The extensional fault traps were modified by the inversion and compression tectonics becoming thrusted hangingwall anticlinal traps where hydrocarbon re-migrated from the early formed traps in the sub-thrust footwall to the hangingwall anticlines (Buchanan and Warburton, 1996), **Figure 13.** The sub-thrust trap shown in **Figures 10-13**, could develop to be an overturned footwall trap. After successful drilling in the hangingwall anticlines, the overturned forelimb structures in the sub-thrust are also prospective as proven by wells in the Kutubu oil and gas fields (Hill et al., 2012), and in the Mananda structure (Keenan and Hill, 2015).

The nearest PNG gas field to East Papua, the P'nyang Field, **Figure 1**, is also interpreted as being a basement-involved compressional anticline, **Figures 14-15**. The P'nyang-1X well (Esso, 1990) encountered granodioritic basement rocks dated Latest Triassic-Early Jurassic age (Valenti, 1992; Valenti, 1993). The depth structure map of the top Toro Sandstone and the southwest-northeast geological cross-section of the P'nyang Field suggests that the trap is a simple thrusted-fold structural closure with the faults cutting through to the surface and detaching in the igneous basement rock. Valenti (1993) showed steeper thrust faults than those proposed by Eisenberg (1996). The P'nyang-2X well penetrated a massive

450-foot gross thickness of gas bearing Toro Sandstone reservoir with underlying thinner secondary sandstones reservoirs of Digimu and P'nyang Sandstones, **Figure 16**. The estimated resources (2C) of P'nyang Field are 3.5 TCF and 35-40 MMBC (Valenti, 1993; Emmett, 2017a). The Papuan Basin has about 550 MMBO, 10 TCF developed reserves, and 8 TCF undeveloped resources (Oil Search, 2008).

Four wells were drilled by Conoco to test the play in the Indonesian East Papua FTB (Noordwest-1, Sande-1, Cross Catalina-1 and Kariem-1). The primary reservoir target was the Early Cretaceous Woniwogi Sandstone. The Toro and Late Jurassic LJ5 Kopai Sandstones are not present due to pinch-out to the west and on-lap onto Digul-Fly Platform, **Figure 2**. It should be noted that the sandstone encountered below the Woniwogi Sandstone in Cross Catalina-1 was dated as Middle Jurassic in age. Preliminary paleogeographic reconstructions for the Early Cretaceous and Late Jurassic show the Digul-Fly Platform as the sediment provenances for the Toro and LJ5 Kopai Sandstones with southwest-northeast direction of deposition. Granath and Hermeston (1993) interpreted a Valanginian regional unconformity in East Papua and western PNG, **Figure 3**. In the Cross Catalina area the unconformity separated the Middle Jurassic part of the Kopai Formation from the Early Cretaceous Woniwogi Sandstones, thus eroding the Toro and LJ5 Kopai Sandstones. Noordwest-1 is interpreted to have been drilled off-structure, and no petrophysical logs were obtained in the Woniwogi section. Sande-1 did not reach the Woniwogi Sandstone due to drilling problems. Hence, the only valid Woniwogi Sandstone structural tests in this play were at Cross Catalina-1 and Kuruwai-1, **Figure 17**.

Wireline logs of the Woniwogi sandstones in the Cross Catalina-1 well show a massive and blocky profile with sharp-base suggesting channelized facies. A shallower, thin, fine-grained facies exhibits a fining-upward log motif. Conventional cores cut in Cross Catalina-1 show massive sandstones with planar and low angle cross-bedding suggesting high energy shallow marine, open shelf environment, **Figure 18**. Based on petrographic analysis, the sandstones are predominantly monocrystalline quartz with a high degree of maturity (well-rounded). Other components are well-rounded glauconite pellets, feldspar and skeletal grains. The sandstones are fine- to medium-grained and moderately sorted. The quartz grains have been modified by silica overgrowth cements. This silica cementation was the dominant diagenetic phase. Core porosity has an average of 7% while permeability ranges from 1 to 89 mD, with the majority less than 10 mD. Cross Catalina-1 is classified as non-commercial discovery as some bleeding light oil was observed from the Woniwogi conventional cores at surface. However, no flow was observed in the DST due to low reservoir pressure and generally low porosity and permeability caused by the extensive silicification of the reservoir (Kendrick and Hill, 2000).

In Kuruwai-1, the sandstones are thinner (net = 50 feet), and show both blocky and coarsening upward sequences suggesting shallow marine channel with sand-bars. The Woniwogi Sandstone is probably thicker in the sub-thrust of the Papua FTB and Akimeugah Basin to the southwest as observed in outcrops in the Waghete area (Panggabean and Hakin, 1986), and it may also have served as the carrier bed for hydrocarbon to migrate from the basin into the traps in the Papua FTB. However, the sandstone may be absent further towards the western flank of Akimeugah Basin as indicated by the South Oeta-1 well (Amoco, 1986) drilled offshore as shown by Kendrick et al. (1995); Hill and Hall (2003); Hill et al. (2012), **Figure 1**.

The Early Cretaceous Toro Sandstone in the center of PNG FTB has similar reservoir quality to the Woniwogi Sandstone in Papua FTB. The gross thickness of the Woniwogi Sandstone in Cross Catalina-1 well is about 260 feet with a net thickness of 170 feet. The Hides-1 (Esso, 1987) well encountered thick, gas bearing Toro Sandstone with a gross thickness of almost 650 feet. Porosity is generally low with a range of 7-16 % and an average of 11 %. Permeabilities are generally less than 100 mD. The Hides-4 well (1997) reached a total depth of 10,926 feet encountered a 450-foot interval of the combined Early Cretaceous Toro and Digimu Sandstones. A DST in the Toro Sandstone at around 10,000 feet flowed 12.9 MMSCFD and 446 BOPD. The Hides wells proved a connected lateral structure for a distance of over 12.6 km and a gas column height of 4068 feet. The Hides gas resources (2C) are in excess of 5.3 TCF (Oil Search, 1998 and 2008). Juha-1 (Esso, 1983) penetrated a relatively thin Toro Sandstone of approximately 100 feet thick with an average porosity of 7 %. At Agogo-1 (Oil Search, 1989) the main reservoir is the Digimu Sandstone with a similar thickness of around 100 feet and average porosity of 15%.

At the Noordwest-1well location on the northeastern margin of Akimeugah Basin, the basin modeling maturity profile shows the oil generation window of Ro = 0.7% occurred in the Early Cretaceous Piniya Formation. The Cross Catalina samples are immature with a maximum Ro of 0.4% in the Late Jurassic-Early Cretaceous section. The low geothermal gradient of 0.9°F/100 feet and low heat flow requires deeper buried mature Jurassic source rocks to generate oil. These are modeled to exist in the Akimeugah Basin which forms the source rock kitchen. It is believed that hydrocarbons migrated from in the Akimeugah Basin into the Foldbelt Play along the Papua FTB, proving the presence of active Mesozoic petroleum system as demonstrated by oil in Cross Catalina-1. The Cross Catalina oil composition indicates that the oil source facies has a terrestrial origin similar to those in PNG, **Figure 19**. In the central PNG FTB, the hydrocarbons are sourced from marine clay-rich sources with abundant terrestrially-derived organic matter deposited under oxic conditions. These oils show similarities with Westralian-sourced oils from the Australian Northwest Shelf (Martin-Monge et al., 2017).

NOTE ON LORENTZ NATIONAL PARK:

Lorentz National Park is located in the central part of the Akimeugah Basin and extends to the north into the southern part of the Papua FTB. The outline is shown and marked in blue, **Figure 1**. Some hydrocarbon exploration prospects in the western part of the Cross Catalina-1 discovery are located within the Lorentz National Park area.

The park was defined as a continuous, intact ecological transect from snow-capped mountains to a tropical marine environment, including extensive lowland wetland. It was established as a national park by the Indonesian Ministry of Forestry Decree No.154/KPTS-II/1997. The UNESCO World Heritage Committee decided to inscribe the park during the convention concerning the protection of the World Cultural and Natural Heritage in Marocco in 1999.

Geographically, the total property covers an area of around 2.35 million hectares and features the Puncak Jaya or Carstensz Pyramid, the highest summit in Southeast Asia with the height of 4,884 m. It is the largest world heritage property in SE Asia and one of the largest terrestrial world heritage properties in the world (Meyers, 2014).

THE INVERSION PLAY

The Inversion exploration play is mainly located in the Digul Arch area immediately south of the Papua FTB near the border with PNG. Inversion structures formed as a result of Tertiary compression and transpression of faulted blocks in the foreland basin, **Figures 1 and 4**. The Digul uplift is interpreted to have occurred in two phases, firstly during the Late Oligocene and subsequently the Plio-Pleistocene continuing to present day. This reactivation of the basement faults resulted in variably remobilized fault-throws and the development of the detachment folds above the basement, **Figures 11-12**. This basement-involved, thick-skinned deformation is postulated to have occurred prior to the thin-skinned tectonics to the west.

The core of the Digul Arch is interpreted to contain Paleozoic or older sediments, **Figure 20**. The Mesozoic and Tertiary sections are present on the flank of Digul-Fly Platform and thicken into the depocenter of Kau-Strickland Basin in the north-northeast where the Kau wells are located. The main reservoir targets of the play are the Early Cretaceous Woniwogi Sandstone, Early Createaceous Toro Sandstone, and Late Jurassic LJ5 Kopai Sandstone. In the Digul area, the Early Cretaceous Woniwogi Sandstone was penetrated by Kuruwai-1, Kariem-1, Digul-1 and the two Kau wells as shown in **Figure 17**. The detailed petrographic analysis of the Woniwogi Sandstone in the Kau-1 well shows that the sandstones are fine-grained quartz-arenites, moderately sorted with abundant pelletal glauconite. Quartz overgrowths are well-developed on most of the quartz grains. Based on thin sections, the sandstone has visible porosity of 4-8%, **Figure 21**, with log porosity of 9-11% in the Kau wells. Lithostratigraphic correlations of individual Woniwogi Sandstones are not definitive as the sandstones were likely deposited in the shallow marine environments with multiple distinct channels, **Figure 17**. Blocky and fining-upward sandstones with sharp bases are indicative of channels, and the stacked thin coarsening-upward cycles suggests prograding shoreface facies. The reservoir gross thicknesses ranges from 120-210 feet, with net thicknesses of 50-90 feet.

The Woniwogi Sandstone is present from the western part of the Papua FTB (Cross Catalina area) eastwards to the Digul Arch, but it is absent to the east in PNG, **Figure 22**. It is dated as Valanginian and lies stratigraphically slightly above the Toro

Sandstone. Granath et al. (1992), and Granath and Hermeston (1993) assigned the Woniwogi Sandstone to be Late Valanginian-Barremian and is time equivalent to the Alene Sandstone of the Ieru Formation in western PNG. The Early Cretaceous Toro Sandstone is well-developed in PNG and extends to the west to the Digul Arch area. The Toro Sandstone was encountered by Digul-1 and the two Kau wells, but is absent in Kuruwai-1, Kariem-1, and other wells immediately to the west, **Figures 22 and 23**.

The coarsening upwards cycles of the Toro sequences are consistent with the prograding sequences of the Early Cretaceous Gondwana passive margin. This is part of the Middle Jurassic to Early Cretaceous Gondwana syn-rift megasequence deposited in a passive margin setting on a relatively stable marine shelf which progressively deepened towards the northeast (Bidgood eat al., 2015). The blocky sandstones with sharp bases indicate deposition of large channels, **Figure 24.**

Distribution of the Early Cretaceous Woniwogi and Toro Sandstones is laterally variable across the region, though both remain well-developed in the Digul Arch area. The lateral variability is attributed to sea level fluctuations along the Early Cretaceous Australian continental passive margin. The Toro Sandstone was deposited in a regressive shallow marine sand complex in the western part of PNG and the Digul Arch, while the Woniwogi Sandstone was deposited in the southern part of Bird's Body area during a transgressive phase prior to the deposition of the Piniya Formation (Granath and Hermeston, 1993). The Woniwogi Sandstone grades to the Alene Sandstone and a shaley facies eastwards towards western PNG, and merges into the Ieru Formation shale, **Figure 22.**

The Toro Sandstone is petrographically described as a quartz arenite, moderately well sorted, and glauconitic. Thin sections show cements dominated by well-developed quartz overgrowths, however, they have visible inter-granular porosity ranging from 15 to 19%, **Figure 25**. Gross thickness ranges between 150-180 feet with a net-sand thickness range of 15 to 90 feet. The core porosity measured from core plugs is generally good 10-15 % with an average of 13 % and > 100 mD permeability. The average log porosity is 8 %. Hence, the reservoir quality of the Toro is significantly better than that in the Woniwogi.

In PNG, palynology indicates the Toro Sandstone was deposited on a shallow marine shelf. It is dated as Berriasian (earliest Early Cretaceous, Bidgood et al., 2015) which is the same age, but stratigraphically above the Digimu Sandstone which is also productive. The Toro Formation consists of at least three sub-units (Bidgood et al., 2015). The Iagifu, Hedinia, and P'nyang Sandstones are part of the Upper Imburu Formation, but are stratigraphically older than the Digimu, and therefore they are assigned to Tithonian, **Figure 26.**

Top seal for the Toro Sandstone is provided by the regionally extensive thick shales of the Ieru Formation in PNG, while the Woniwogi Sandstone is widely capped by thick Piniya shales in the Digul Arch and to the west, **Figures 2, 3, and 26.**

Another important reservoir objective in the Inversion Play is the Late Jurassic LJ5 Kopai Sandstone of the Kopai Formation which is productive in the southern part of onshore East Papua region. The Kariem-1, Digul-1, and Kau-2 wells penetrated the sandstone as shown in **Figure 27.** The section is predominantly composed of claystones, siltstones, and quartzose sandstones with rare lithic and feldspar grains and common siliceous cement. Further to the east, the sandstones are correlated to the Iagifu, Hedinia, and P'nyang Sandstones in PNG, therefore the age of LJ5 Kopai is assigned as Tithonian. In general, the sandstone shows coarsening upward sequences indicating shallow marine depositional environments prograding northeast to PNG. Although the net sandstone penetrated in Kau-2 is thin (3-5 feet thick), it flowed 55 BOPD and 242 MSCFD with a condensate-to-gas ratio (CGR) estimated to be 160-298 BBLS/MMSCF. The condensate has API gravity of 47.5°.

The Kariem-1 well encountered oil and gas shows in the LJ5 Kopai Sandstone. The gross thickness ranges 200-220 feet with net thickness of 50-100 feet. The reservoir is relatively thin and poor to fair quality. The average porosity measured from core plugs is 6 % with permeabilities of 0.1-2 mD. The log porosity is around 10 % with permeability <5 to 70 mD. The conventional core is shown in **Figure 28.** The core slab of the sandstone is highly bioturbated indicating it was deposited in a shallow marine environment. The well is interpreted to have been drilled off the structural crest on a complex, faulted closure. The 2D seismic data used to map the structure is relatively poor quality.

It is interpreted that hydrocarbons migrated to the Digul Arch structures from a mature source rock kitchen in the Kau-Strickland Basin located to the southeast. The source rock maturity profile in the kitchen area suggests that the Middle-Late Jurassic Kopai source rocks entered the oil window of Ro = 0.7% in the Early-Late Cretaceous, and the main gas generation of Ro > 1.3% occurred in the Pliocene. Basin modeling indicates the type II/III Middle-Late Jurassic source rocks in the Digul Arch (Kau-1 well) reached oil maturity (Ro = 0.7%) in the Early-Middle Miocene. The Late Jurassic shales generally have fair to good TOC of 0.8 – 2.7 % with an average of 1.15 %.

In contrast, the Early Cretaceous interval in Kau-2 comprises an argillaceous unit generally exhibiting good organic richness at the base with TOC ranges of 0.64 - 2.28 %, but pyrolysis analyses suggest poor potential for generating oil (HI < 100 mgHC/g TOC). Bitumen extraction data, compositional results, and fluorescence observations have indicated oil staining throughout the Early Cretaceous and Late Jurassic intervals. Biomarker results for selected samples imply derivation from a distinctly aquatic source rock facies dominated by algae with relatively subordinate higher plant contributions.

In PNG, the Cretaceous section is primarily gas prone or non-source rock quality and the Jurassic section is of marginal source quality containing a mix of Type II and III kerogen (Kaufman et al., 1997). The gravity of unaltered oils and seeps in the PNG FTB are 40-45° degree API suggesting very thermally mature oils. Biomarker data indicates the Iagifu-Hedinia oils are generated by the Jurassic

Imburu mature shales. Two periods of hydrocarbon generation are documented: a Late Cretaceous phase in the center of the basin, and a later Miocene phase continuing until present day (Kaufman et al., 1997).

Top seal is provided by the regional, thick Piniya shales and/or the intra-formational shales of the Late Jurassic and Early Cretaceous.

THE FORELAND PLAY

The Foreland Play is located south of the Digul Arch, in the Akimeugah and Kau-Strickland foreland basins south of the Papua FTB, **Figures 1 and 4**. The play is structurally simple but poorly explored. Seismic and well data in the region are sparse and effectively absent over large areas of the play, **Figure 29**, making it difficult to assess prospectivity. The Mesozoic section is absent in the Aripoe-1 well marking a southerly limit to the play where Pre-Tertiary sediments thin and pinch-out towards the southwest and onlap onto the Digul-Fly Platform. The area is an aseismic stable platform forming a topography low. Seismic interpretation suggests that the Digul-Fly Platform was the sedimentary provenance for the Kau-Strickland Basin to the north-northeast. The Akimeugah Basin is an area of exploration interest, however, in some areas Mesozoic and Paleozoic sediments have been partially eroded, for example in the Waghete area (Panggabean and Hakim, 1986).

The play has a comparable stratigraphy to the Foldbelt and Inversion Plays, but in contrast, is only subtlety deformed. There are various trap styles including: low relief Woniwogi and Toro Sandstones closures formed by drapes over of basement highs, Woniwogi and Toro stratigraphic pinch-outs onto Paleozoic on the basin margins, Paleozoic sub-crop traps, tilted fault blocks, and Tertiary reefal carbonates buildups on basement highs, **Figure 30**. Stratigraphic traps in the Foreland Play may also have formed along northwest-southeast oriented paleo-shoreline of the Woniwogi and Toro Sandstones during transgressive and lowstand stages following the development of the Mesozoic basins (Bidgood et al., 2015) during rifting of the Gondwana margin in Late Triassic-Early Jurassic (Cooper et al., 2012).

The Foreland Play extends into PNG immediately across the international border where the play has been more extensively explored and significant condensate and gas discoveries have been made such as Stanley, Elevala, Tingu, Ketu, Ubuntu, Puk Puk, Douglas, Koko, Kimu, **Figure 31**. The exploratory technical success rate for this play in PNG is about 33 % which is comparable to the success rate in the PNG Foldbelt Play of almost 40 %.

The nearest western foreland gas and condensate fields in PNG are the Stanley-Elevala/Tingu-Ketu-Ubuntu structural complex, **Figure 32**. Combined estimated resources (2C) are 60-70 MMBC and 2-2.5 TCF (Horizon Oil Limited, 2017; Emmett, 2017a&b). The Elevala-Ketu structure holds 58% of the overall resources in the western foreland while Stanley Field has another 19 % (Emmett, 2017b).

In the Stanley Gas Field of PNG, the productive reservoirs are the Toro and

Kimu Sandstones with a combined total gross reservoir thickness of about 394 feet and net pay of about 315 feet (Horizon Oil Limited, 2014). The Stanley-5 (Horizon Oil, 2014) production well reached a total depth of 11,172 feet and flowed 68 MMSCFD with associated condensate through a 122"/64" choke (Horizon Oil Limited, 2015). In the Stanley Gas Field, the Toro Sandstone reservoir has an average porosity of 15% and good permeability. The trap is a large inversion anticline formed during the Oligocene. It is believed that the source rocks are Late Jurassic shales of the Imburu Formation which have TOCs of 1-3%, and the Mesozoic shale sequences in the Muller and Kubor kitchens to the southeast which have maturity level of Ro = 1.5-4%. Hydrocarbon generation initiated in the Cenomanian with peak generation in the Late Miocene. The kerogen is generally of mixed terrestrial materials.

A cluster of fields consisting of Elevala, Ketu, Ubuntu and Tingu is situated about 70 km southeast of the Stanley field. The productive reservoir in this complex, the Elevala Sandstone, is poorly developed in the Stanley area where the Toro and Kimu Sandstones are the productive reservoirs. Top seal is provided by the Valanginian shales of the Alene Member. Seismic data shows the Elevala trap is a differential compactional drape over basement highs. The structure is a simple fault-block with relative small fault offsets. Thickness of the Elevala reservoir sand in Elevala-1 is approximately 160 feet. The Elevala sandstone exhibits coarsening upwards, a blocky middle section, and then has a fining upward section to the top of the reservoir. It was deposited immediately above the Toro and is dated as Valanginian, similar in the age to the Woniwogi Sandstone in the Papua FTB. At the Elevala Field, reservoir depths are about 10,200 feet. Elevala-1 (Horizon Oil, 1990) flowed at a rate of 11.9 MMSCFD and 634 barrels per day of 54° API condensate from the Elevala Sandstone (Carnarvon Petroleum, 2001; Horizon Oil Limited, 2012a). Elevala-2 confirmed a gross gas/condensate interval of 59 feet in the Elevala Sandstone. The Elevala Field's gas column height of greater than 165 feet implying that the Elevala structure is full to spill point (Horizon Oil Limited, 2012b). The average condensate-gas ratio in Elevala-1 is 65 barrels/MMSCF. The Ketu-2 well (Horizon Oil, 2012) flowed at the rate of 35-40 MMSCFD with a condensate-gas ratio (CGR) of 50-60 barrels/MMSCF. The Tingu-1 well (2013) flowed 48 MMSCFD with CGR of 50-60 barrels/MMSCF similar to Elevala gas (Horizon Oil Limited, 2014), and penetrated basement at 10,614 feet. The productive Elevala sandstone reservoir is at approximately 2.5 seconds two-way time on seismic data, the Kimu Sandstone is about 100-150 msec immediately below the Elevala Sandstone (equivalent to the Toro Sandstone) and is in vertical communication.

There are three active source rocks in Papua New Guinea: (a) Triassic lacustrine source rocks, (b) Jurassic mixed marine-terrestrial source rocks of the Imburu Formation, and (c) Late Cretaceous to younger terrestrial source rocks (Krawczynski, 2015). The oils discovered in the foreland are geochemically distinct from the Jurassic-sourced oils that are predominant in the PNG FTB (Martin-Monge et al., 2017). Several wells show evidences of algal-dominated source rocks and others are effectively sourced from carbonate-influenced lithologies.

DISCUSSION

It is important to note that there are many similarities between the geology of the southern part of onshore East Papua and the western part of PNG, however, whereas there have been many significant discoveries in the PNG sector, success has been minor in the East Papua region.

Possible explanations include:

(1) The overall lack of geological and geophysical data in onshore East Papua. Poor infrastructure, complex logistics, rugged terrain, and dense virgin tropical forest have contributed to high-costs of seismic data acquisition and hence limited data, **Figure 29**. In contrast there is less rugged terrain in the PNG FTB, **Figure 33**, hence the geophysical and geological data is denser and exploration significantly more mature.

(2) Several new oil and gas seepages were discovered during recent seismic acquisitions and geological fieldwork operations in the southern part of onshore East Papua region. These findings have added new information important to establish the extent of the active Mesozoic petroleum system in the area, **Figure 1**. This establishes that there are multiple oil and gas seepages in the onshore East Papua. Seeps were an important consideration in PNG, where exploration was stimulated circa 1911 with the recognition of oil seeps in the Papuan Basin (Hebberger, 1992).

(3) Balanced cross-sections across the thrust belt area are constructed based on sparse seismic control, and, where seismic data is available, seismic imaging in the Papua FTB is often poor and the interpretation ambiguous. The interpretation of thick, stacked, and complex thrust sheets of the thin-skinned deformation structure is therefore very uncertain within the thrust belt core of the external and internal thrust sheets. An alternative interpretation should be considered by applying the proven geo-seismic cross-section model for PNG FTB as an analogue. Hence, establishment of the structure and stratigraphy within the thrust belt core for well prognoses and prospect definition is high risk. In contrast, there is significantly denser coverage of seismic lines in the PNG FTB providing good control for balanced-cross section reconstruction.

(4) The WNW-ESE thin-skinned deformation trend in the western part of the Papua FTB progressively grades eastwards to thick-skinned styles in the Digul Arch. This basement involved structural style extends to the PNG FTB with development of less complex thrust sheets, **Figures 14-15, 20, and 36**. Less structural complexity in a thrust belt is generally preferable for hydrocarbon exploration.

(5) As some of the Paleozoic section outcrops at surface in the internal thrust sheets, there is increased risk of breaching and water flushing in the thrust segments where prospective Mesozoic rocks are preserved. The external thrust sheets where the Mesozoic shales of the Jurassic and

Cretaceous could remain preserved are lower risk, **Figure 6**. However, sand on sand juxtaposition of reservoirs in the Mesozoic section could be present in the area of external thrust sheets and cause hydrocarbon to leak into the Tertiary section.

(6) In the southern part of onshore East Papua, the Foreland Play is considered to be more attractive for oil and gas exploration than the Foldbelt or Inversion Plays. The Foldbelt Play has high risk, with complex traps situated in remote mountainous terrains which are expensive to explore and difficult to image. The Inversion Play contains smaller traps which could be heavily faulted and fragmented which increases risk and development costs. The Foreland Play has simpler structural traps which could be better constrained by future seismic programs. Seismic-to-seismic and seismic-to-well correlations are easier and more reliable in the Foreland Play. The primary risk in the Foreland Play is related to uncertainties in the presence of the petroleum system elements as reservoirs and source rock shales onlap or pinch-out onto the basement highs and source rocks may become immature. For reference, the Foreland Play in PNG, where significant gas and condensate reserves have been discovered, has a high success rate of around 33% .

(7) The unexplored Akimeugah Basin is attractive for exploration due to the large area of the basin and its geologic setting in an area proven to be the generative kitchen for oil present in the Cross Catalina-1 well.

(8) Significant areas of the East Papua Foreland and Fold Belt Plays lie within the Lorentz National Park and are therefore out of bounds for oil and gas exploration, **Figure 1**.

(9) The presence of proven hydrocarbon accumulations of the Early Cretaceous Woniwogi and Toro Sandstones, and Late Jurassic LJ5 Kopai Sandstone in the Digul Arch area should encourage exploration of the Inversion and Foreland Plays to the south-southwest as far as the Aripoe-1 well and to the west as far as South Oeta-1 well where the Mesozoic section is absent. The Kau-Strickland Basin in the southeast is believed to be the only effective kitchen to source hydrocarbon into the western part of both PNG Foldbelt and Foreland Plays and Inversion Play in the Digul Arch, **Figure 1**.

CONCLUSIONS AND RECOMMENDATIONS

(1) Although the provinces of West Papua and Papua are located in a remote area with lack of infrastructure facilities, the regions are one of the most attractive remaining under-explored areas for hydrocarbon exploration in Eastern Indonesia. Large oil, gas and condensate fields have been discovered in the West Papua Bird's Head in the Tangguh complex, and in adjacent PNG whereas only minor discoveries have been made in the East Papua Bird's Body where the Mesozoic section is similar. Further exploration work should be conducted in this part of Bird's Body area especially in the context of two proven oil and gas

generative kitchens: the Akimeugah Basin in the west and the Kau-Strickland Basin in the east. A working Mesozoic petroleum system in the southern part of onshore East Papua is proven active by bleeding oil in the conventional cores at the surface in Cross Catalina-1, and tested oil and gas in the Kau-2 wells.

(2) Three exploration plays are present in the onshore East Papua: the Foldbelt Play, the Inversion Play, and the Foreland Play, but none of these have been sufficiently evaluated by exploration drilling. The first two plays have been proven by sub-commercial discoveries at Cross Catalina-1 and Kau-2 respectively. The Foreland Play is considered most attractive geologically, but there is lack of sufficient geophysical and geological data currently available. Large condensate and gas fields have been discovered in this play nearby in western Papua New Guinea. Naturally, the geology of western PNG does not change across the political boundary and is very similar to that in East Papua and the Mesozoic petroleum system components have also proven extended into East Papua region. New geophysical and geological data acquisitions are required to evaluate the extension of this play from PNG to the East Papua region.

(3) Improved PSC's term and conditions are required and crucial to attract investors to explore this remote area. Furthermore, improved infrastructures and facilities would further stimulate interest in exploration by reducing costs and improving hydrocarbon prospect economics and commerciality.

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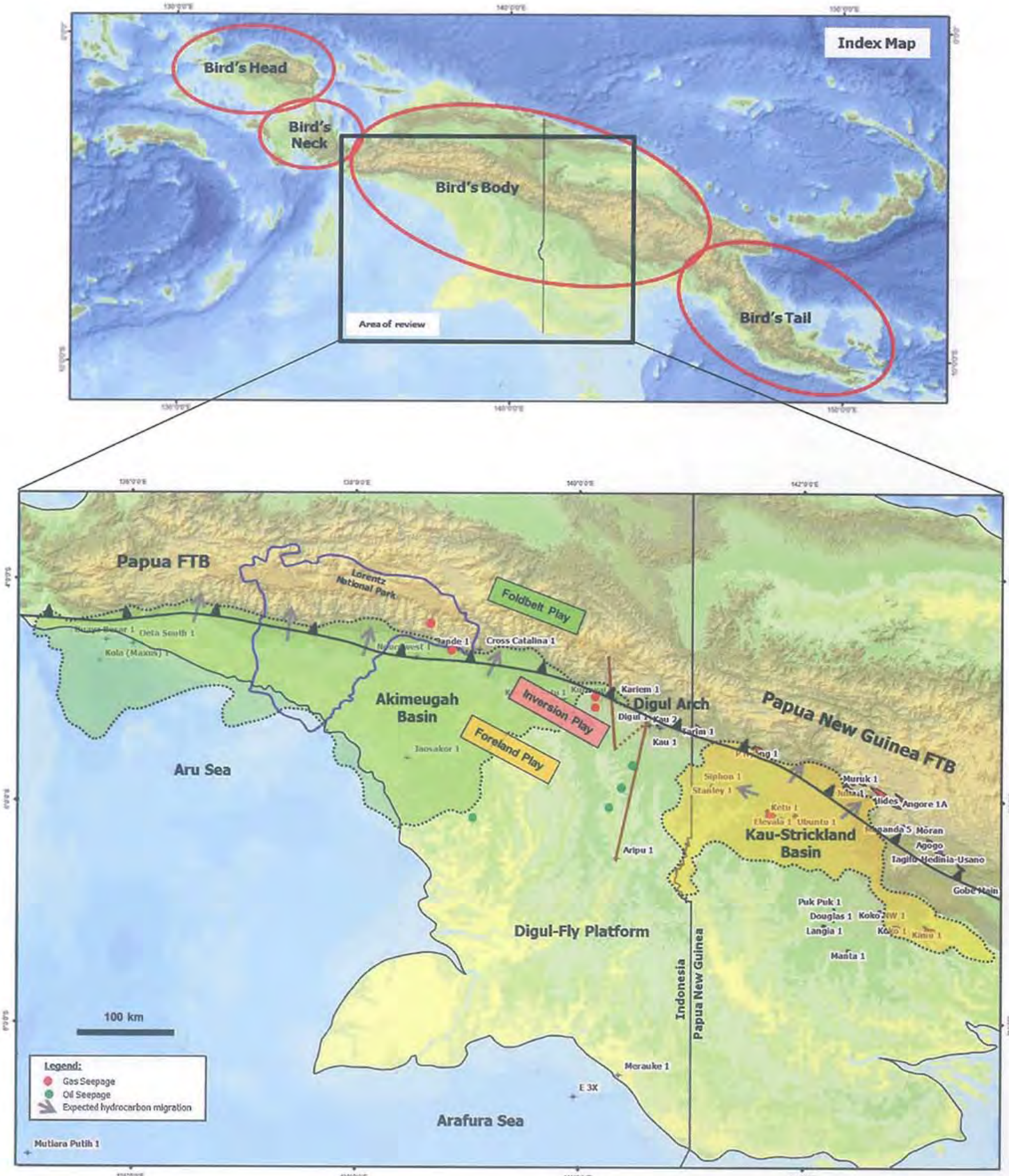


Figure 1. Exploration plays in the southern part of onshore East Papua region consisting of (1) Foldbelt Exploration Play in the center of Bird's Body, (2) Inversion Exploration Play in the Digul Arch, and (3) Foreland Exploration Play in the south. The Akimeugah and Kau-Strickland Basins are productive sedimentary basins sourcing hydrocarbon to the plays shown by black dotted lines. Blue solid line is outline of Lorentz National Park. FTB= Fold and Thrust Belt. Brown solid and dotted lines are geological cross-section showing all the exploration plays.

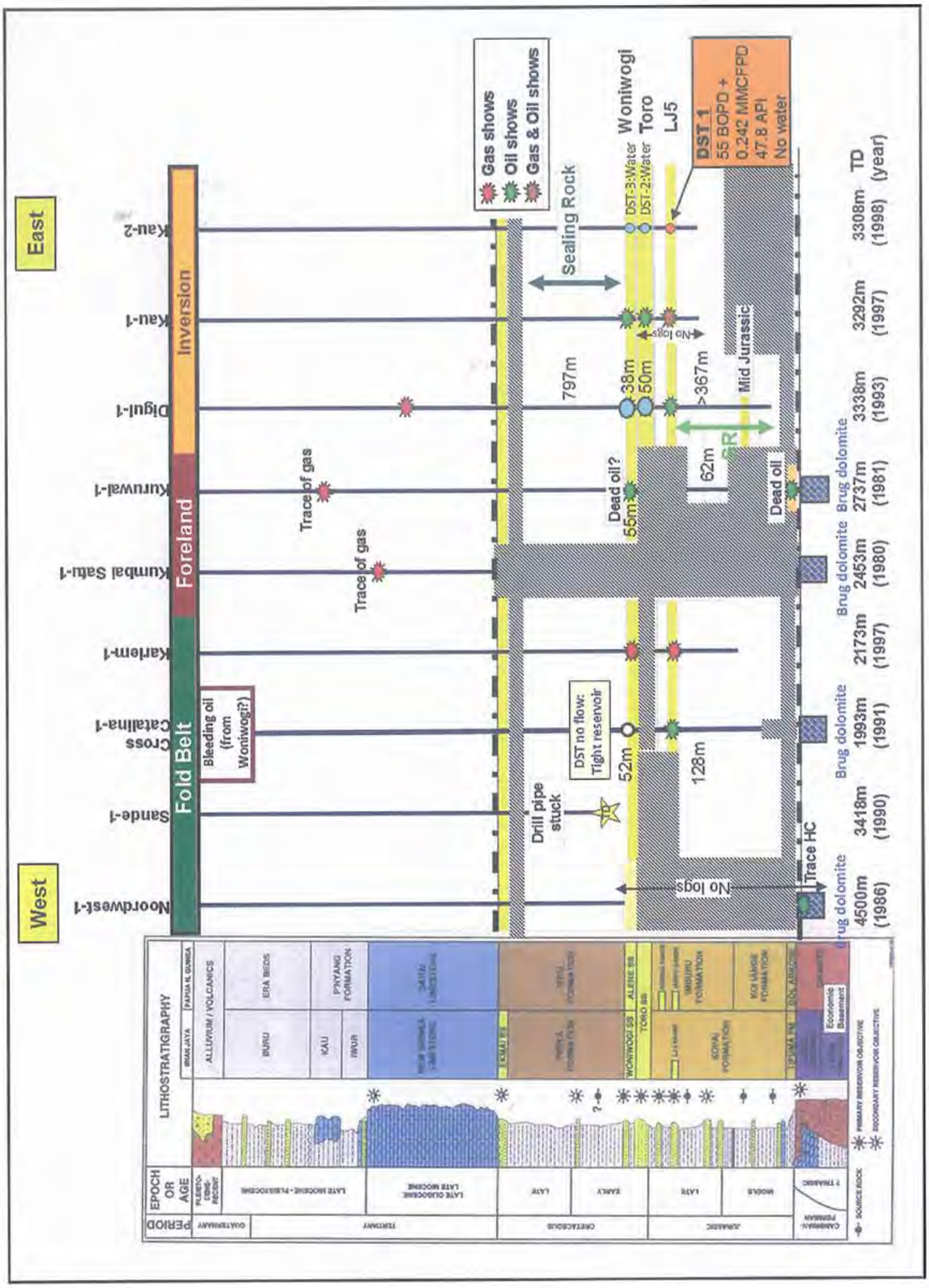
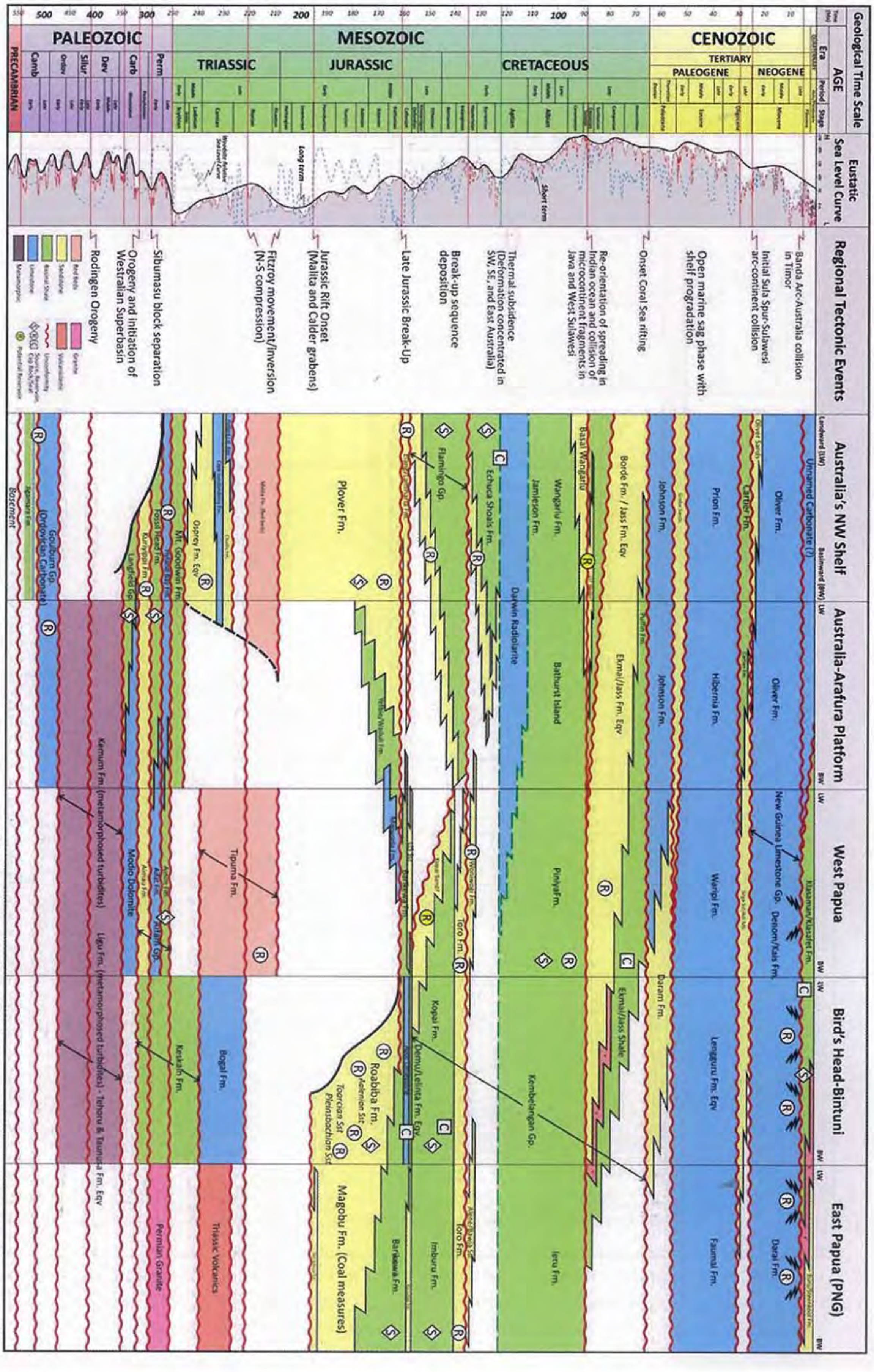


Figure 2. Stick diagram correlation of the current exploration wells in the southern part of onshore East Papua and generalized pre-Tertiary stratigraphy of Papua region (ConocoPhillips Warim Ltd., 2015).



(Adapted from Faulkner & McInerney, 2003; and McConachie et al., 2000)

Figure 3. Regional Eastern Indonesia Chronostratigraphy showing correlation of stratigraphy of Papua region and surrounding area (ConocoPhillips Warim Ltd., 2015).

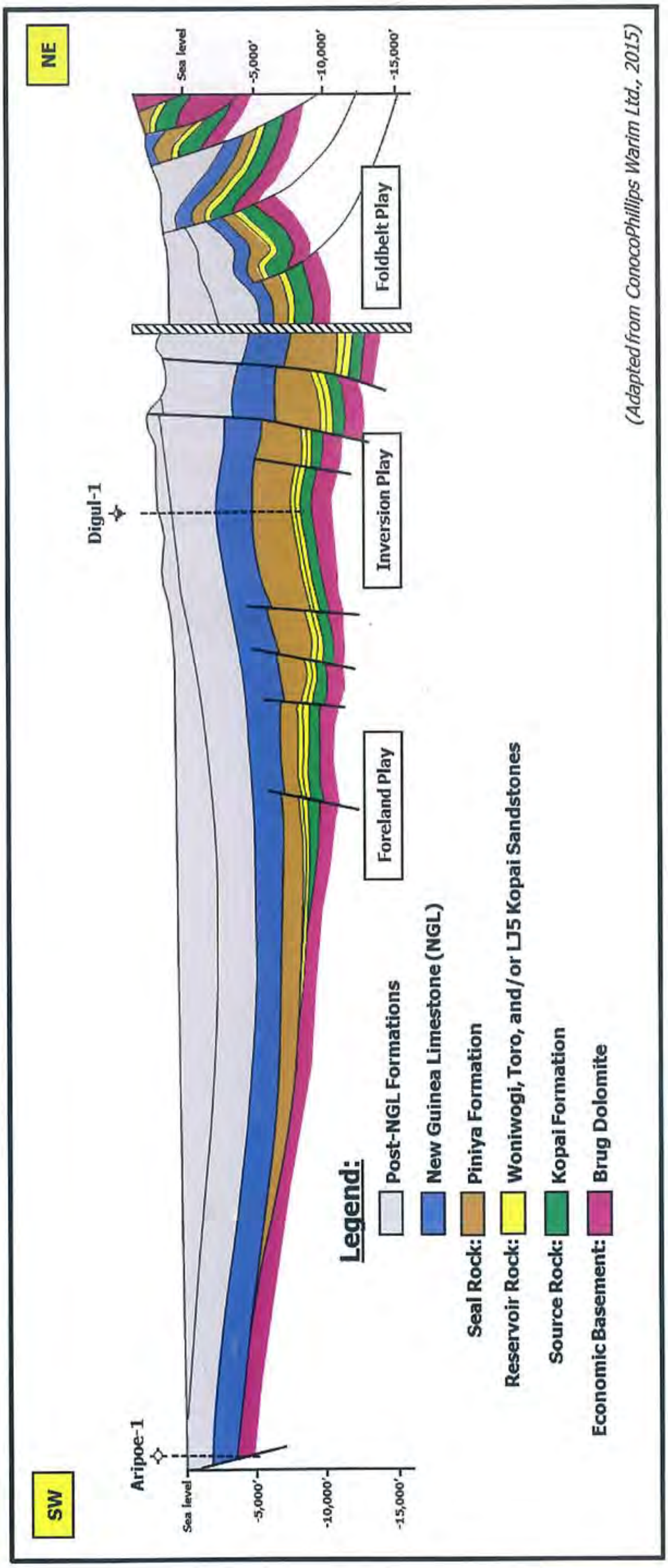


Figure 4. Exploration plays in the southern part of onshore East Papua. Geological interpretation across Digul-Fly Platform – Akimeugah Foreland Basin in the southwest and Papua Fold and Thrust Belt in the northeast (ConocoPhillips Warim Ltd.,2015). Position of the cross-section is shown in Figure 1.

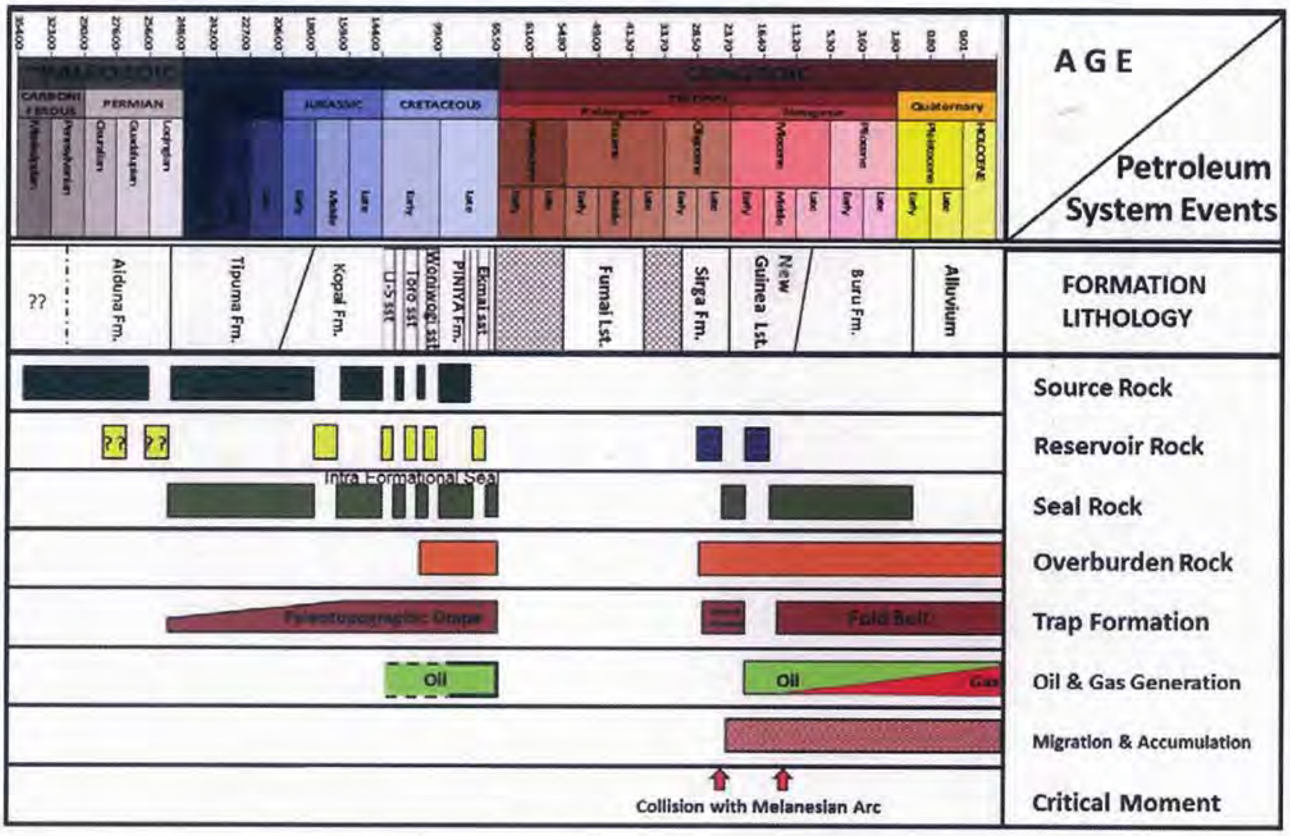


Figure 5. Petroleum system chart of the southern part of onshore East Papua region. The Paleogene unconformity is recognized from the seismic and biostratigraphy interpretation (ConocoPhillips Warim Ltd., 2015).

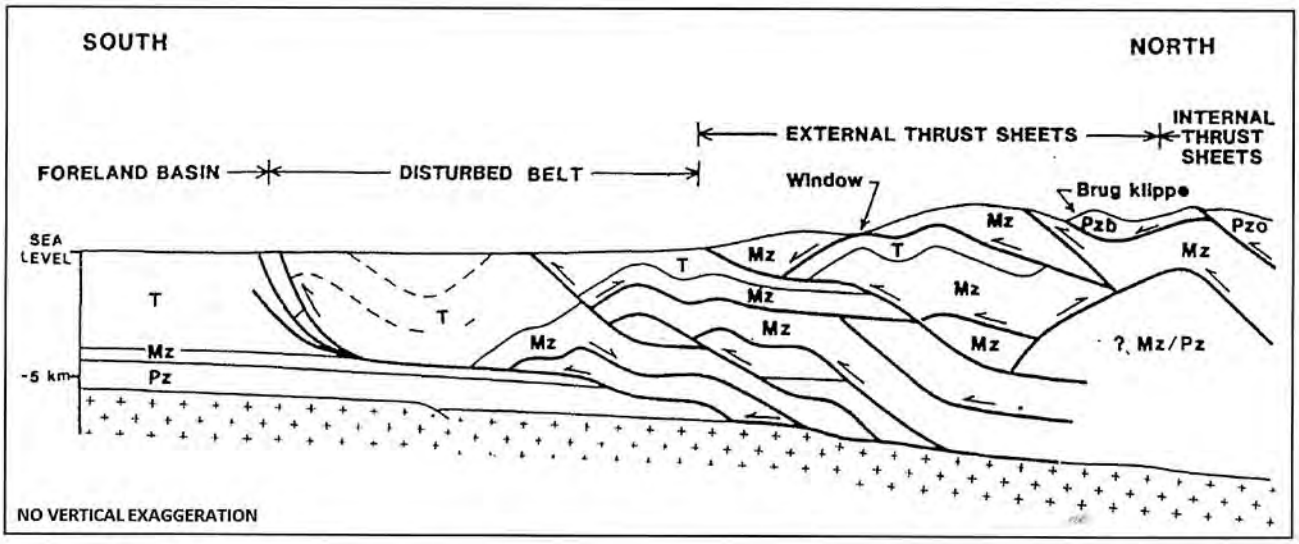


Figure 6. Generalized and unbalanced structural cross-section across the thin-skinned style of the Papua FTB after integrating geological fieldwork, and Synthetic Aperture Radar (Granath and Argakoesoemah, 1989). Pz= Paleozoic undivided, Pzo= Paleozoic Ordovisian, Pzb= Paleozoic BrugFm., Mz= Mesozoic undivided, and T= Tertiary undivided.

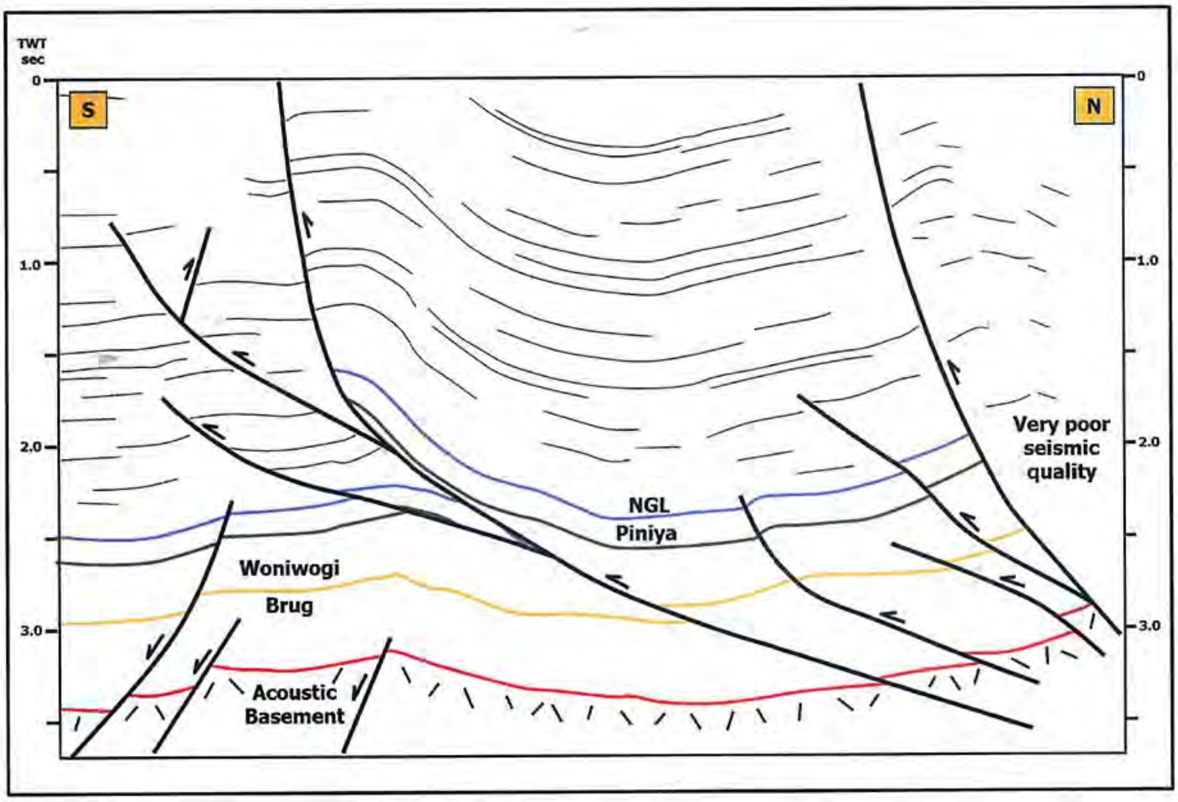


Figure 7. Seismic line interpretation over Papua FTB near the Noordwest-1 well. Note relatively good imaging over leading thrust in the disturbed zone, imaging is significantly degraded where imbricated thrust sheets stack in the external thrust sheets to the north.

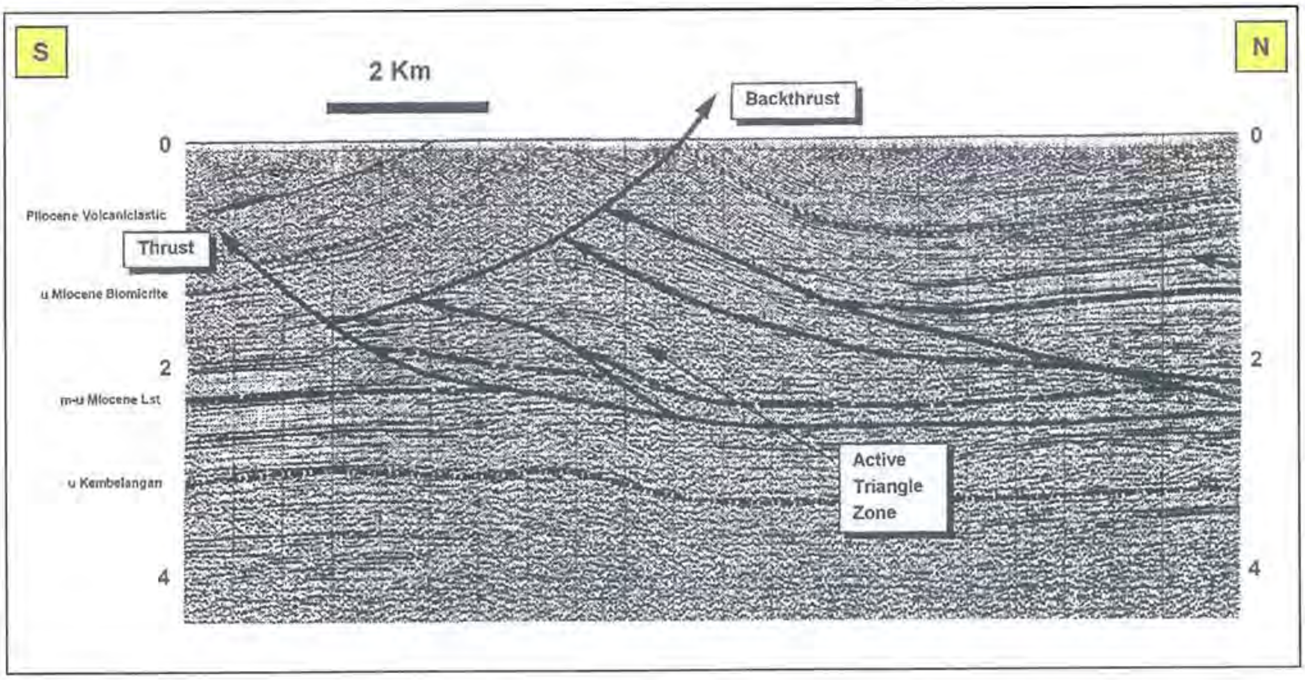


Figure 8. Seismic line interpretation over the western part of Papua FTB showing the presence of back-thrust and triangle zone (Umbach and Klepacki, 1994).

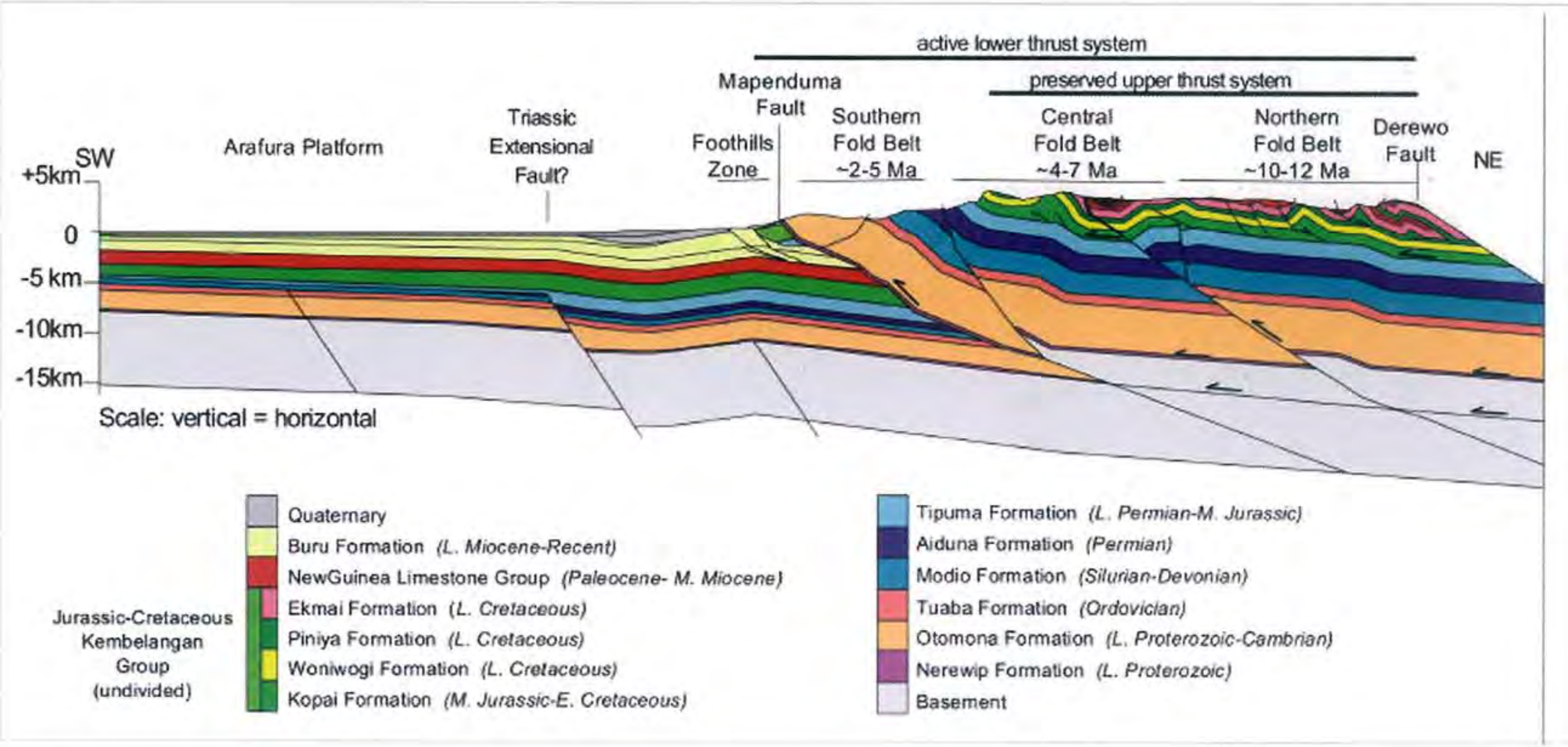


Figure 9. A regional cross-section showing the involvement of both thin-skinned and thick-skinned structural development (Kendrick and Hill, 2001; Hill et al., 2004)

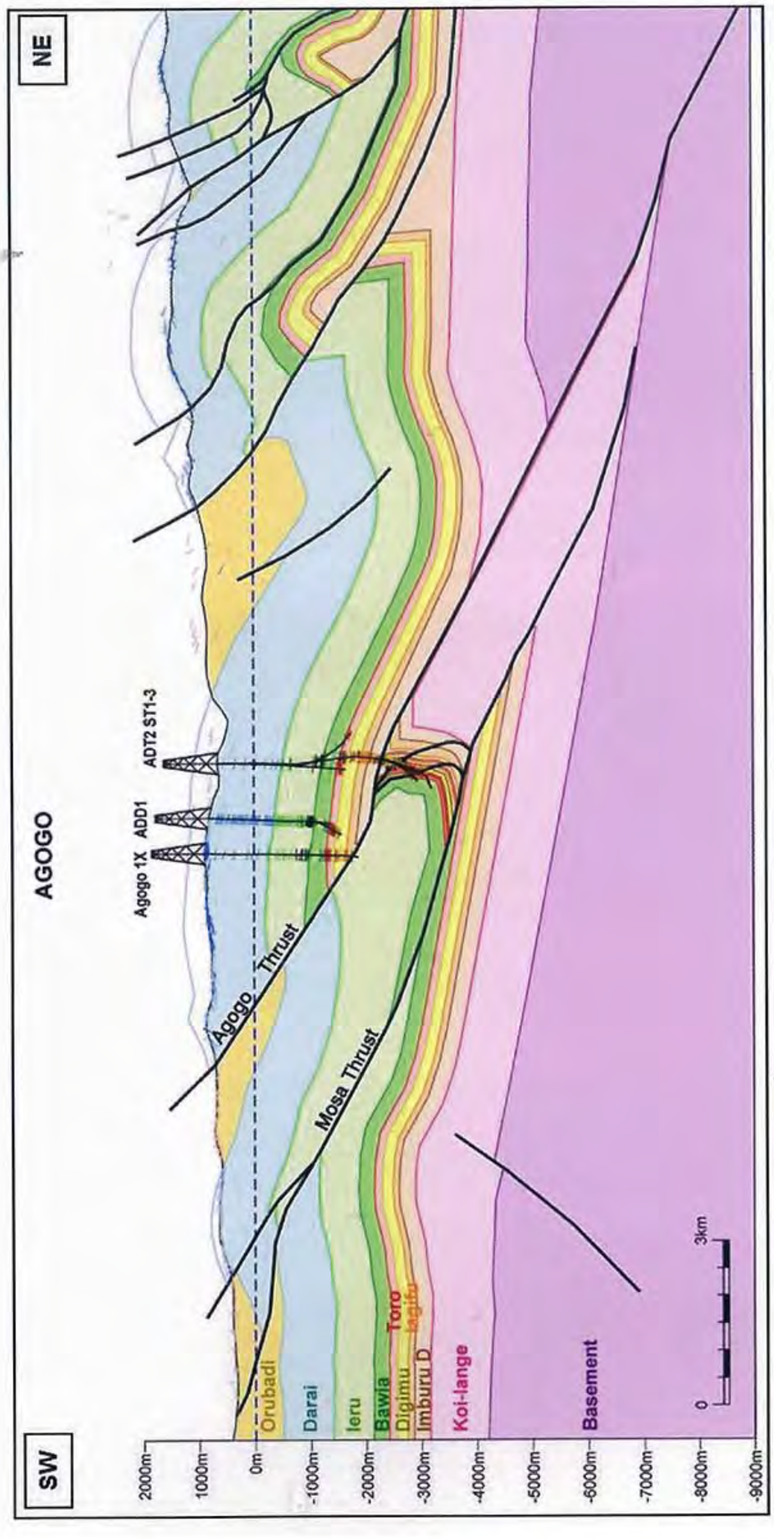


Figure 10. SW-NE geoseismic cross section of the Papua New Guinea FTB across the Agogo Structure (Parish, 2016).

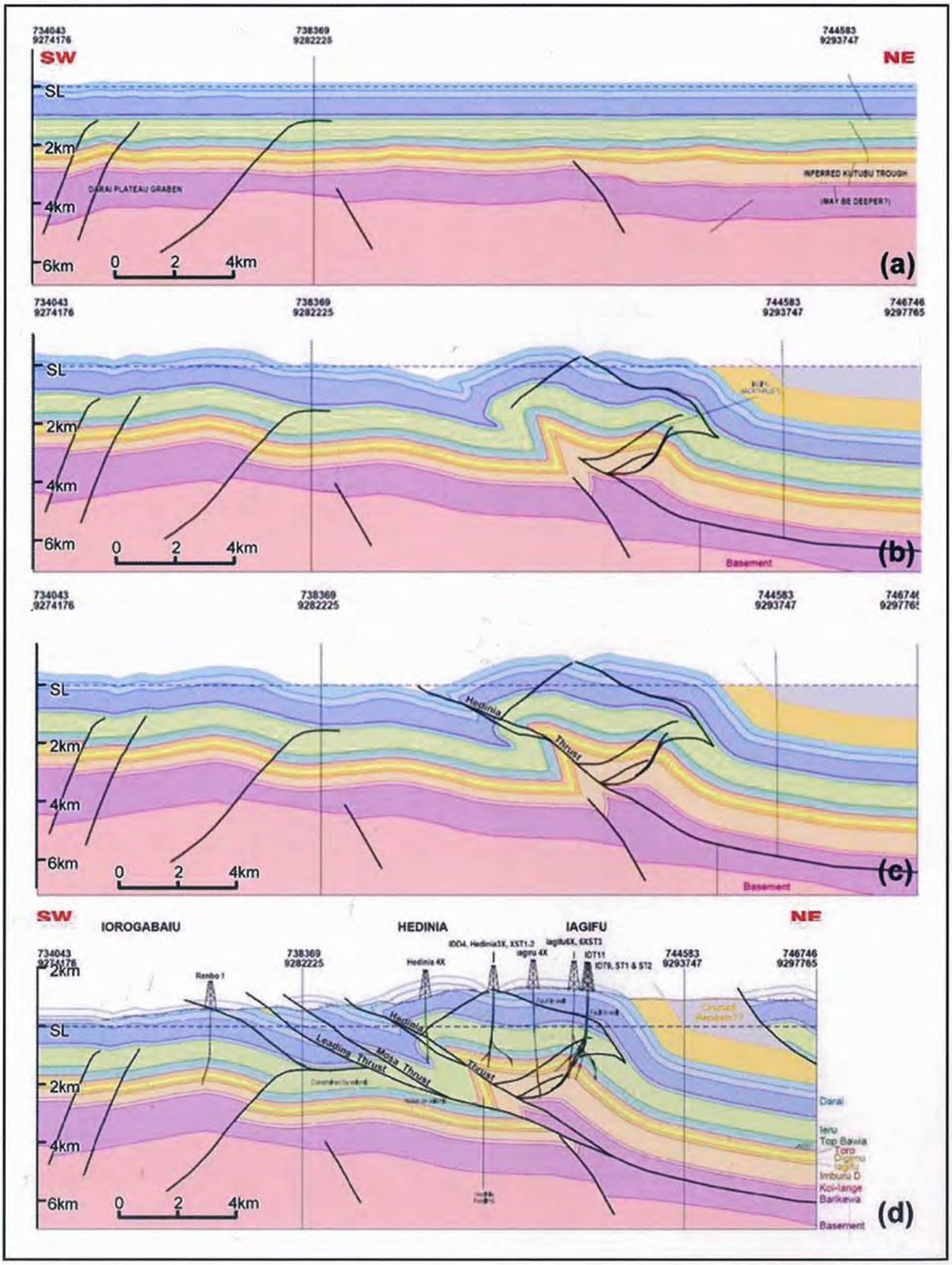


Figure 11. Development of the Kutubu structure showing Hedinia and Iagifu anticlines (Hill et al., 2015).

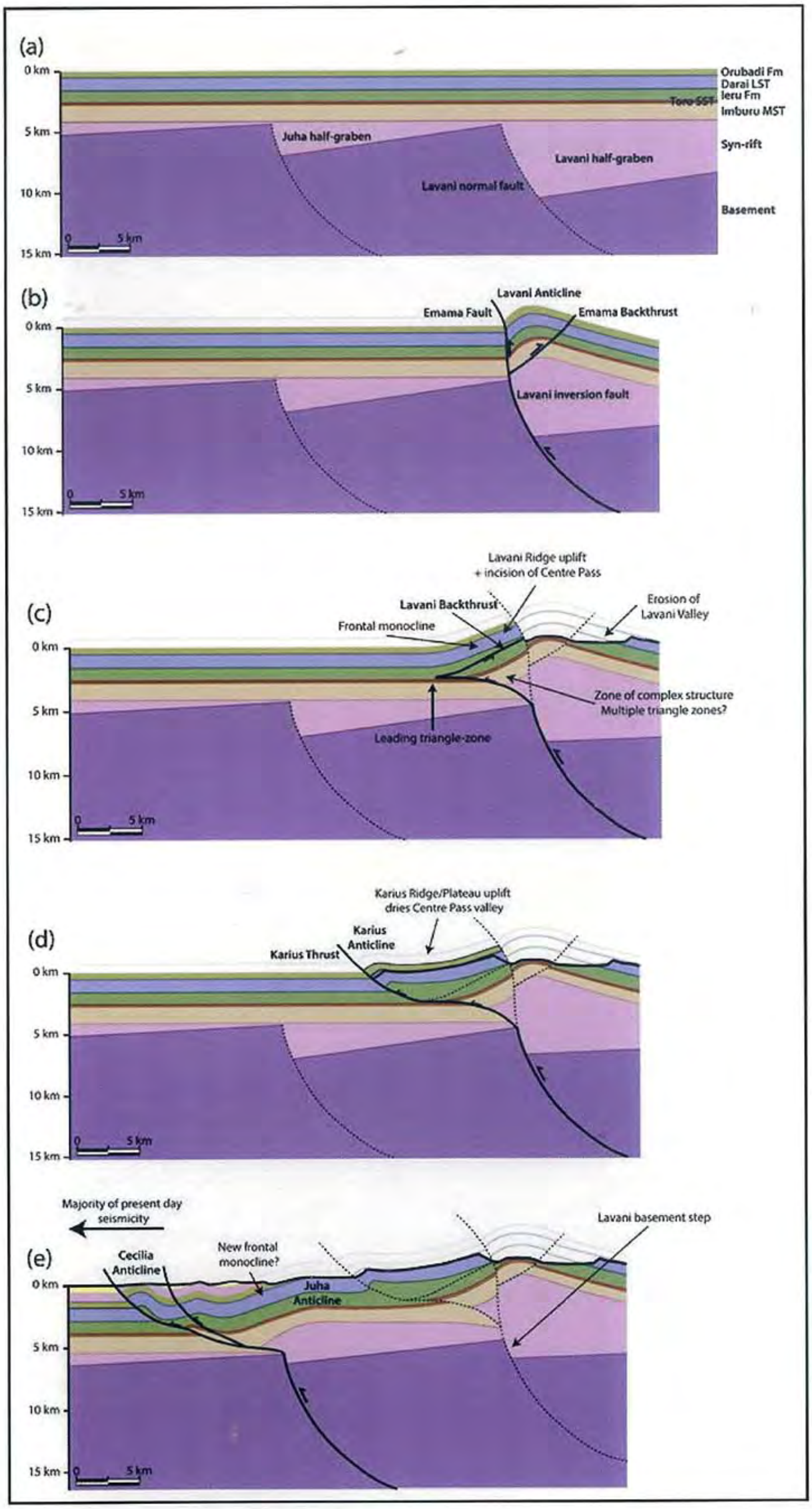


Figure 12. Strutural development of the Greater Juha area (Mahoney et al., 2017).

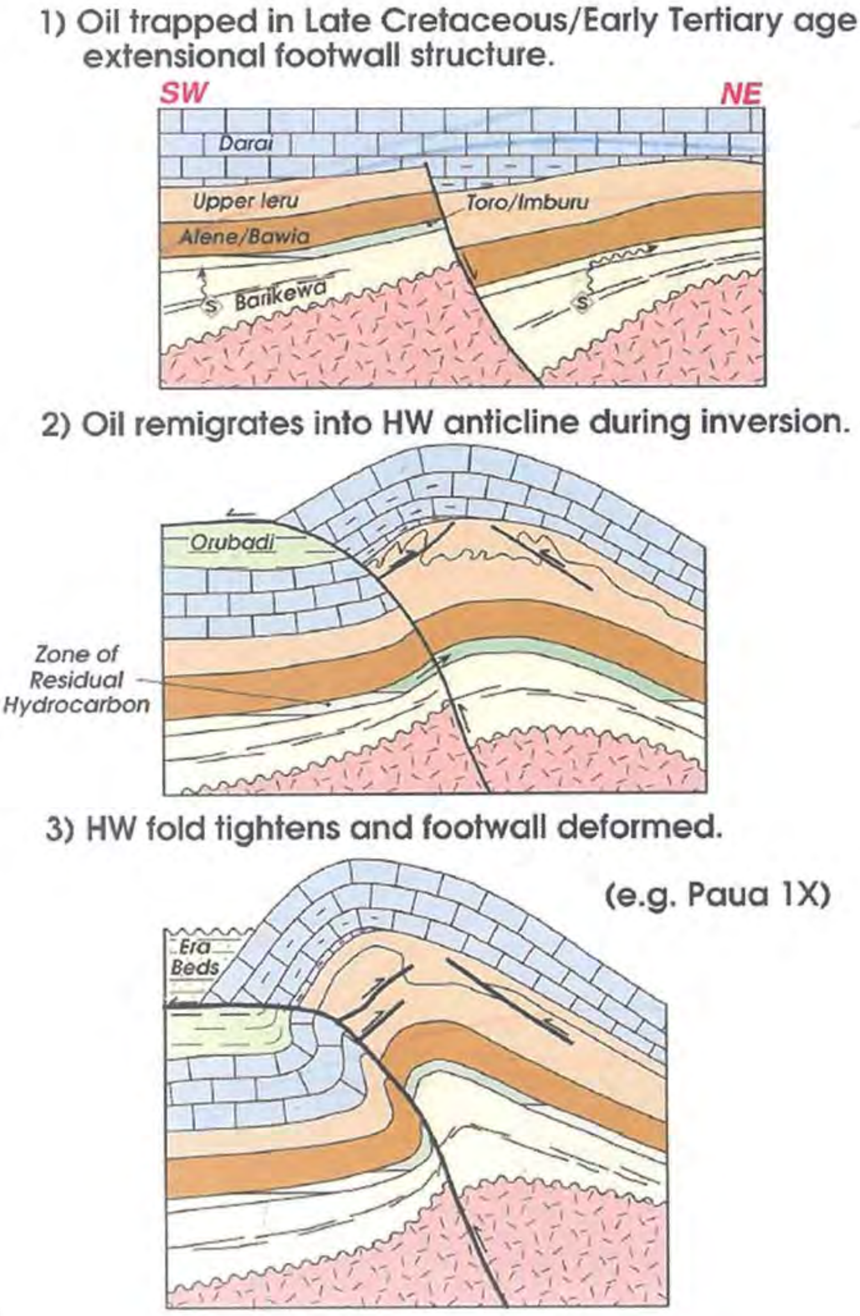


Figure 13. Structural modeling and reconstruction showing hydrocarbon re-migration from the extensional footwall trap into hangingwall thrust anticline during inversion and compressional tectonics (Buchanan and Warburton, 1996).

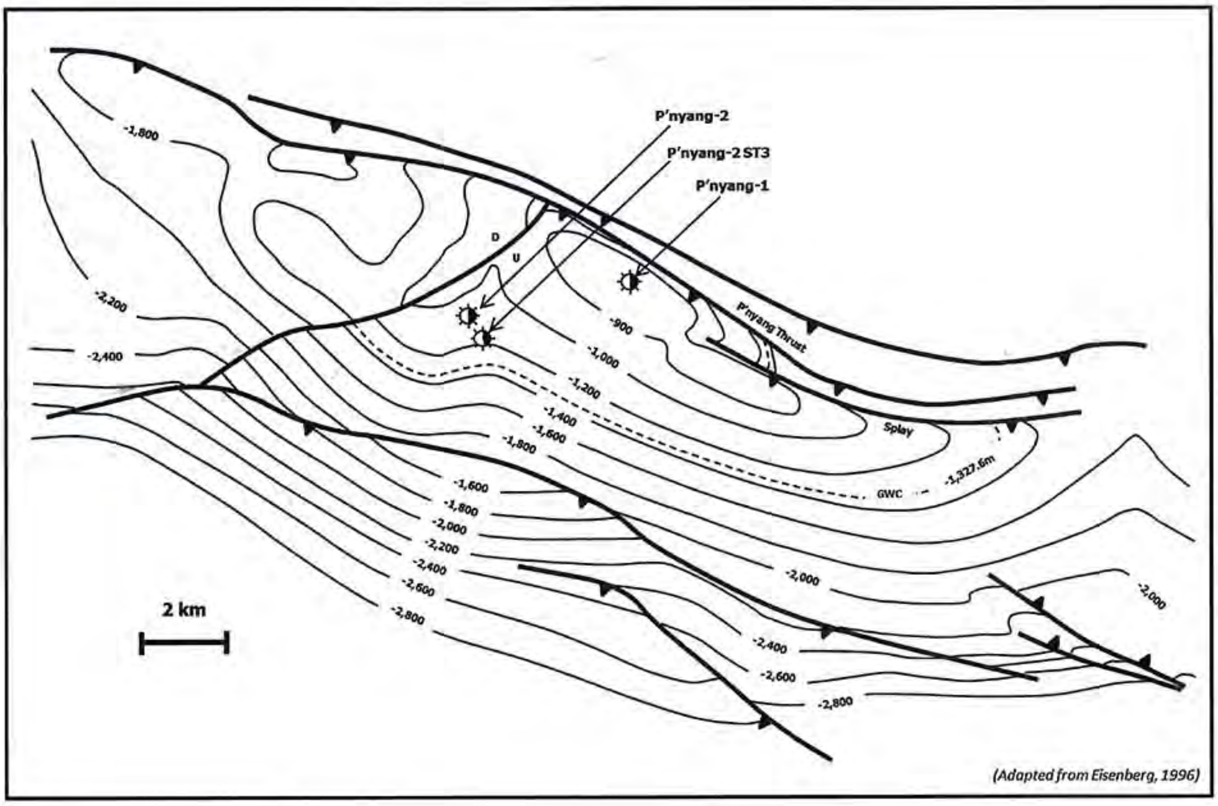


Figure 14. Top Toro Sandstone depth structural map of P'nyang Gas Field (Eisenberg, 1996).

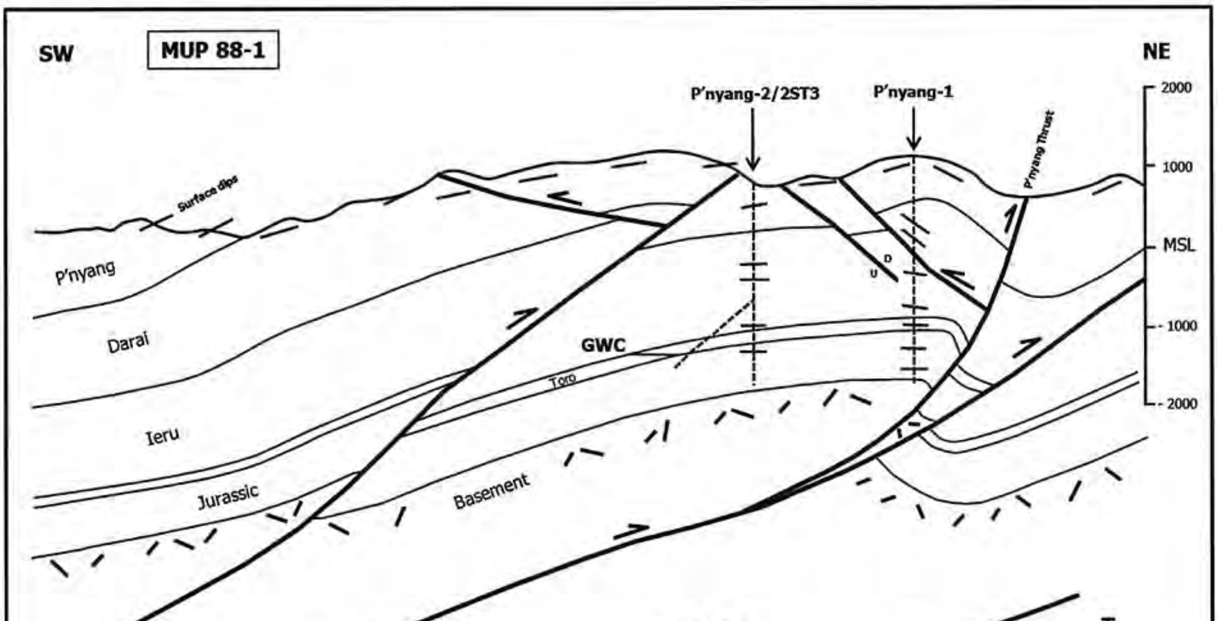


Figure 15. Southwest-northeast geological cross-section showing the presence of basement involved structural style and total depth of the P'nyang wells (Eisenberg, 1996).

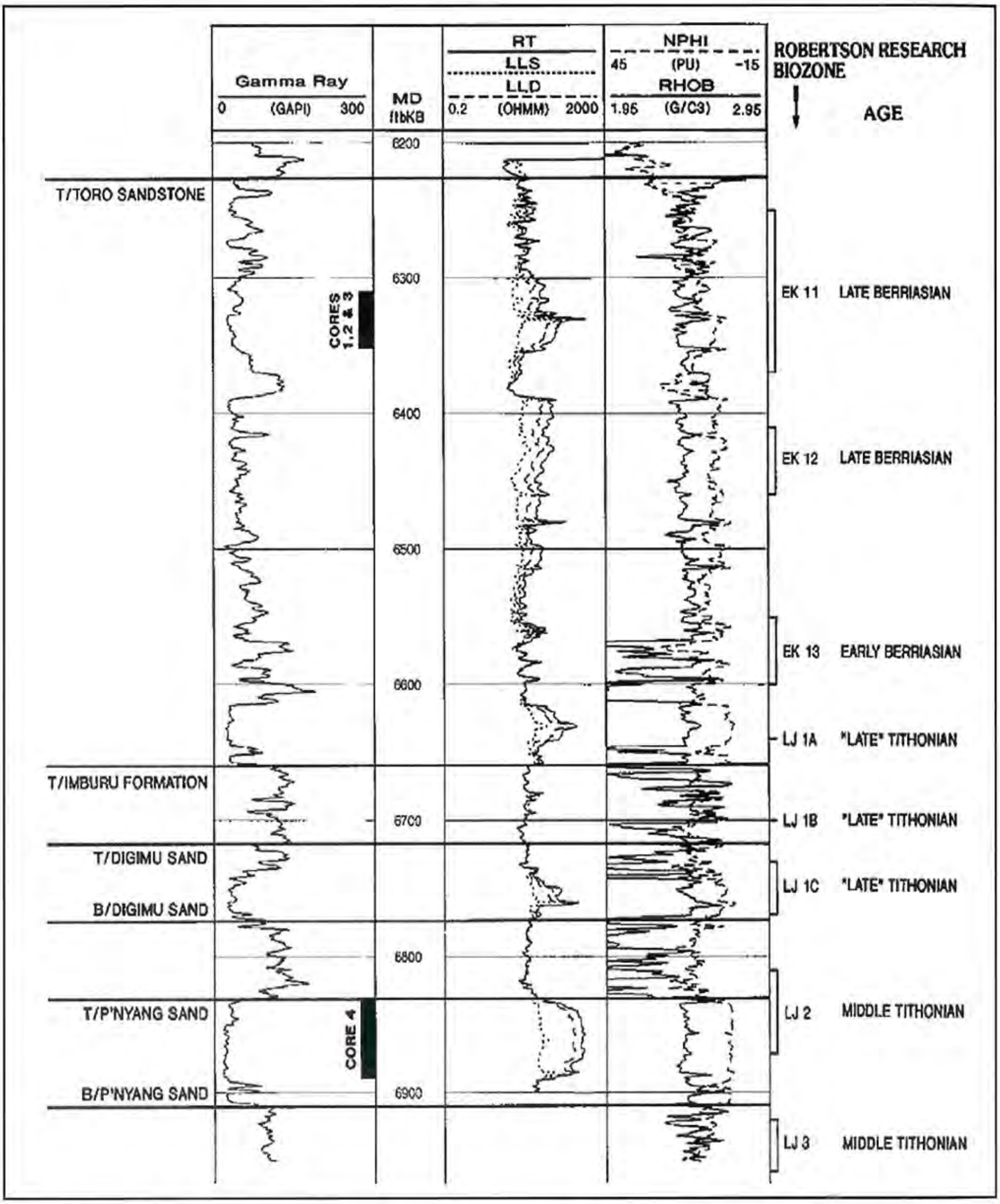


Figure 16. Wireline logs of P'nyang-2X well (Valenti, 1993). Gross thickness of the Toro Sandstone is about 450 feet. Additional sandstone reservoir potential immediately underlies the Toro. Cross-over of neutron and density logs indicates the presence of gas.

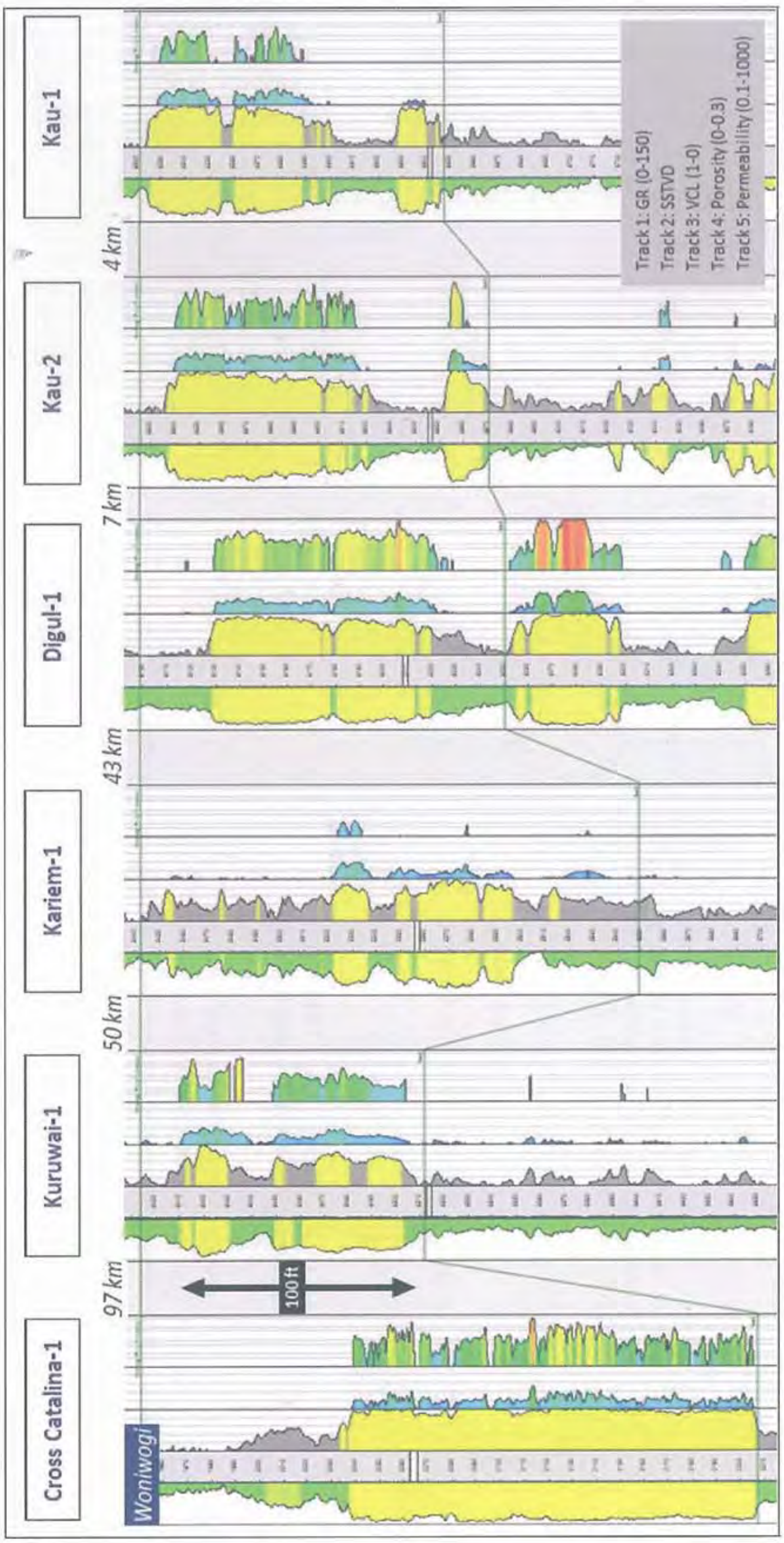


Figure 17. Wireline log correlation of the Woniwogi Sandstone encountered by wells in the Foldbelt and Inversion Plays. Note: The sandstones are marked in yellow while siltstones and shales are marked in green (ConocoPhillips Warim Ltd., 2015).

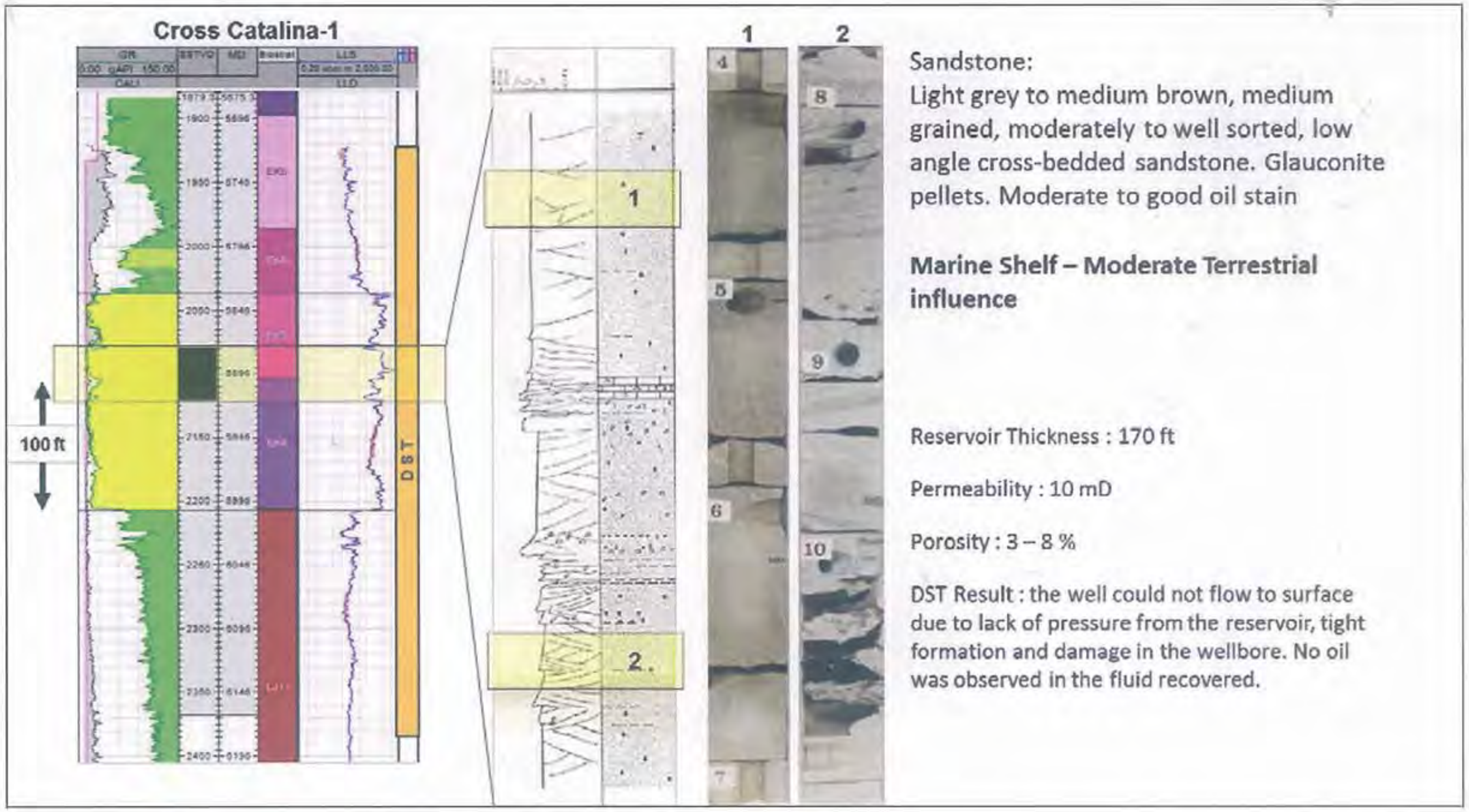


Figure 18. Wireline logs and conventional core of the Woniwogi Sandstone cut in Cross Catalina-1. Massive and blocky cross-bedding with sharp base of channels have been described. The sandstone was likely deposited in an open shallow marine environment with terrestrial influence (ConocoPhillips Warim Ltd., 2015).

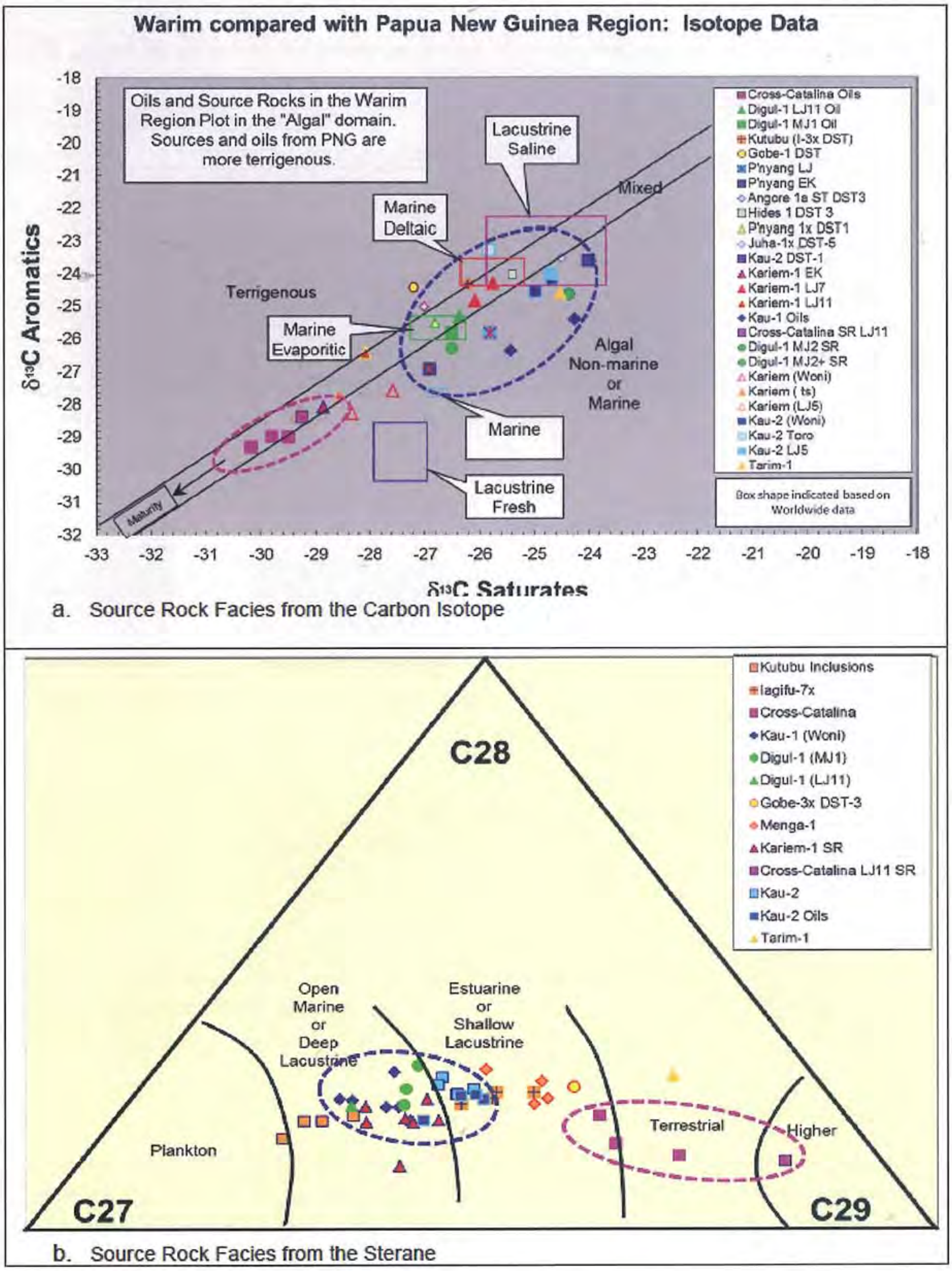


Figure 19. Source rock facies from carbon isotope and sterane of some wells drilled in the southern part of onshore East Papua region, and western part of PNG (ConocoPhillips Warim Ltd., 2015).

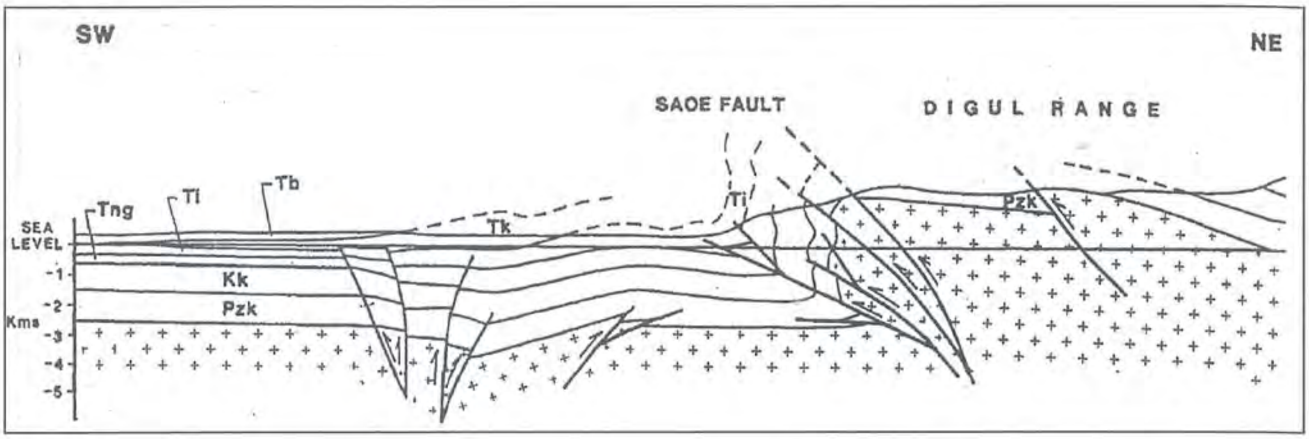


Figure 20. Generalized geological cross-section over the Digual Arch (Range) area showing the presence of thick-skinned deformation (Granath and Argakoesoemah., 1989). Tb= Birim Fm, Tk= Kau Ls, Ti= Iwur Fm, Tng= New Guinea Limestone Group, Kk= Kembelangan Group undivided, Pzk= Kariem Fm.

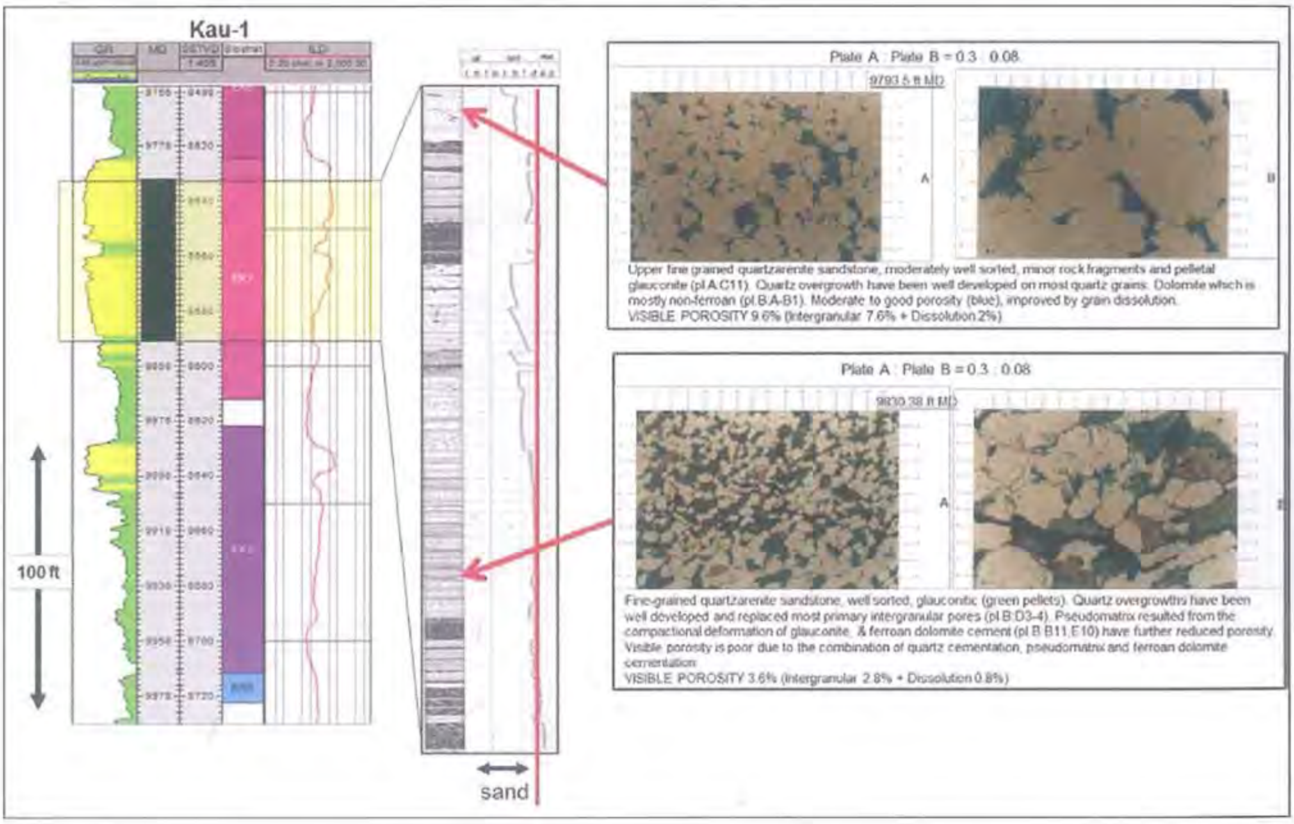


Figure 21. Wireline logs and conventional cores of the Woniwogi Sandstone cut in Kau-1 well in the Digul Arch area. The log shows blocky with sharp base, and thin coarsening upward sequences. Petrographic results indicate that the sandstones are tight caused by the development of quartz overgrowths (ConocoPhillips Warim Ltd., 2015).

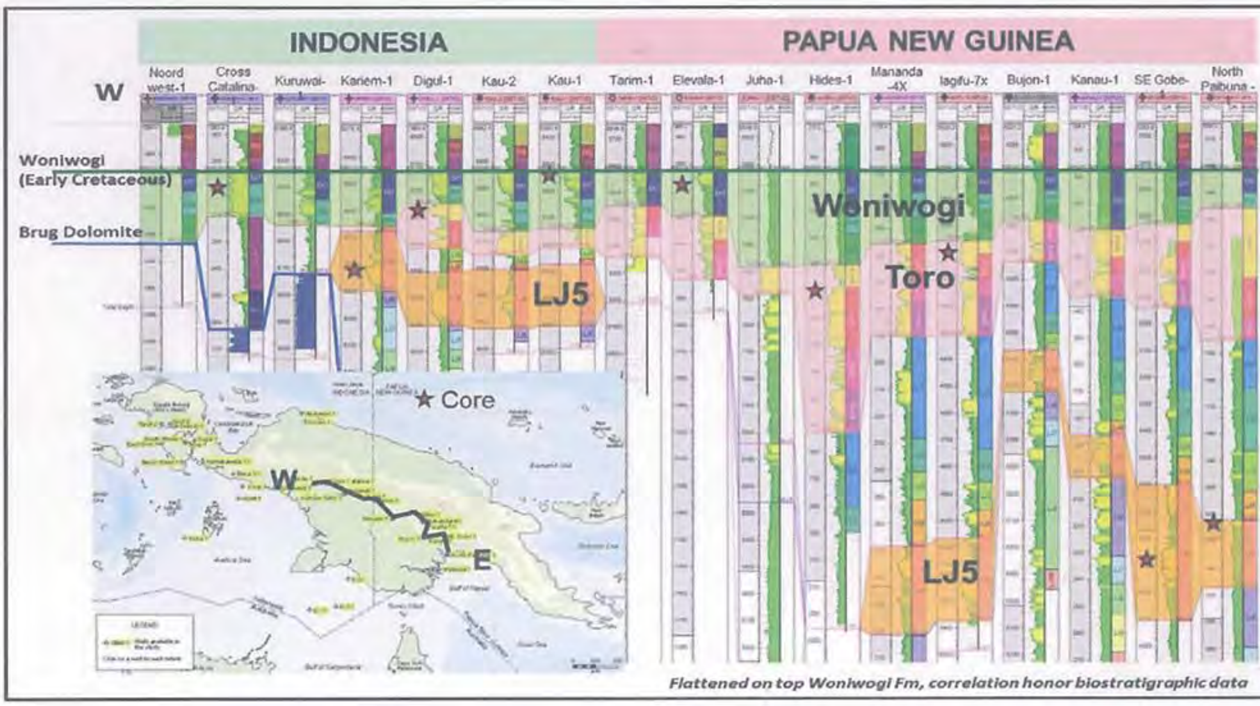


Figure 22. Correlation of lithostratigraphy of the Woniwogi and Toto Sandstones, and Late Jurassic (LJ5) Kopai Formation in the Digul area across PNG. The correlation is flattened on top of the Woniwogi Formation to honor biostratigraphic data (ConocoPhillips Warim Ltd., 2015).

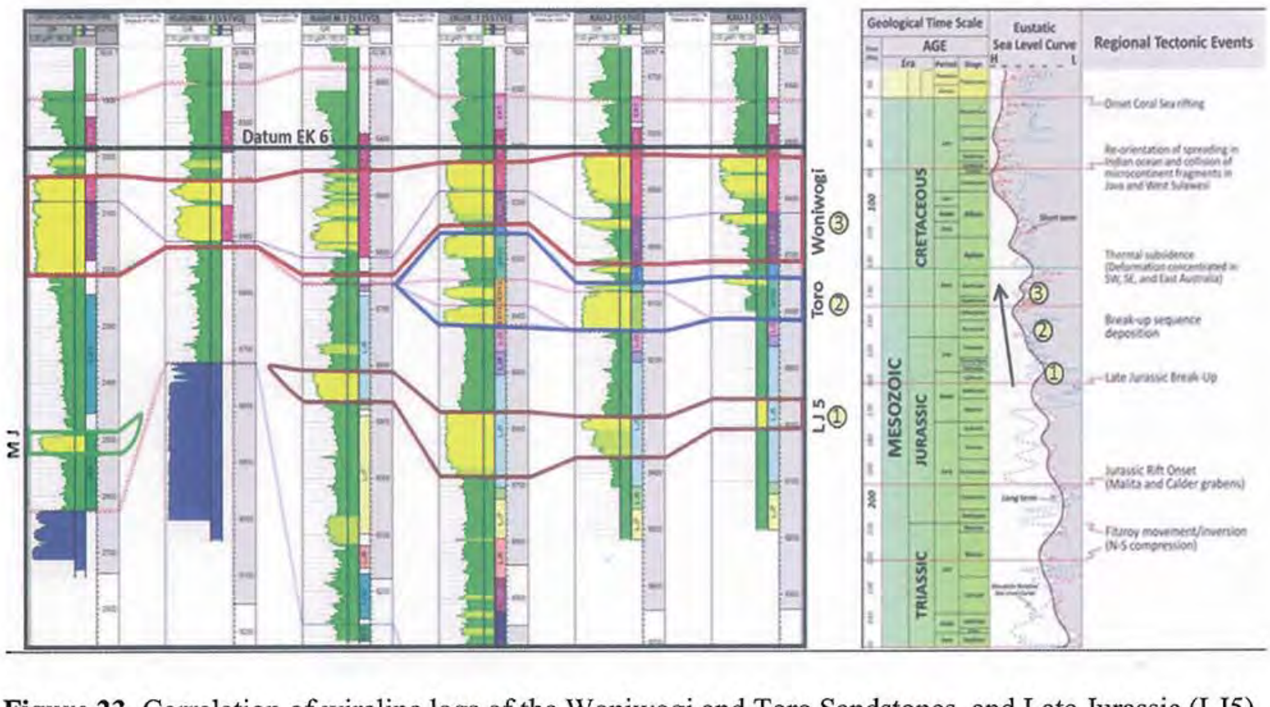


Figure 23. Correlation of wireline logs of the Woniwogi and Toro Sandstones, and Late Jurassic (LJ5) Kopai Formation (ConocoPhillips Warim Ltd., 2015). The Toro and LJ5 Sandstones are developed on the Digul Arch and across the border into PNG, but do not extend to the west to the Cross Catalina area (ConocoPhillips Warim Ltd., 2015).

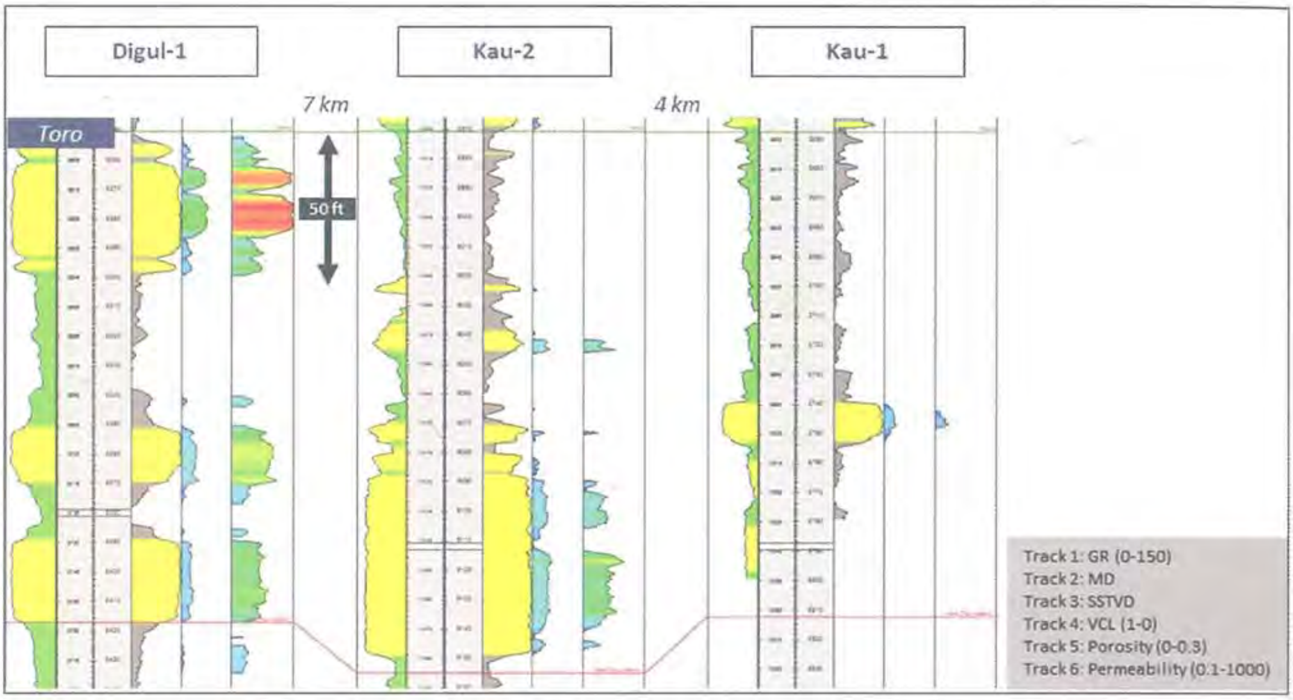


Figure 24. Lithostratigraphic correlation of the Toro Sandstone in the Digul-Kau area. The log shapes indicate multi channels. The coarsening upward log motifs suggest prograding shallow marine deposition (ConocoPhillips Warim Ltd., 2015).

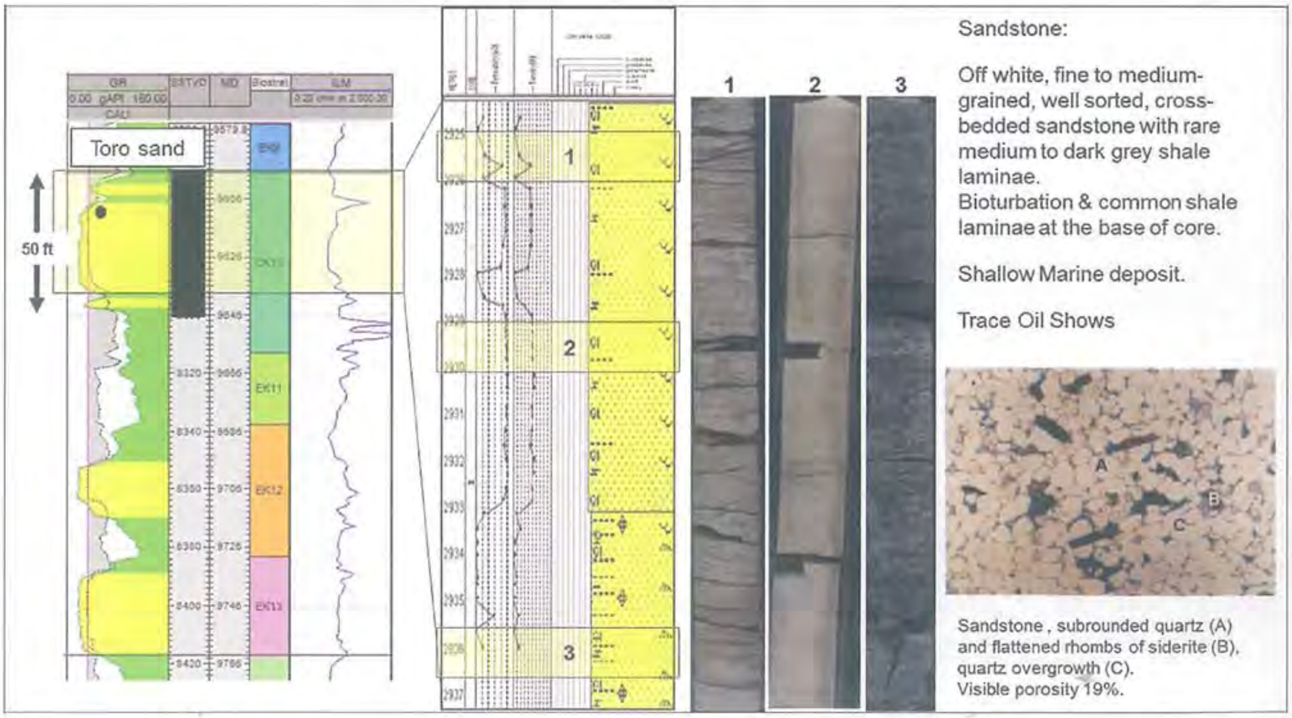


Figure 25. Conventional core description of the Toro Sandstone cut in Digul-1 well. The wireline logs show blocky shape indicating channels. The core description reported fine-to-medium grained, well-sorted sandstone with cross bedding, bioturbation, and common shale laminae at the base suggesting shallow marine sediments (ConocoPhillips Warim Ltd., 2015).

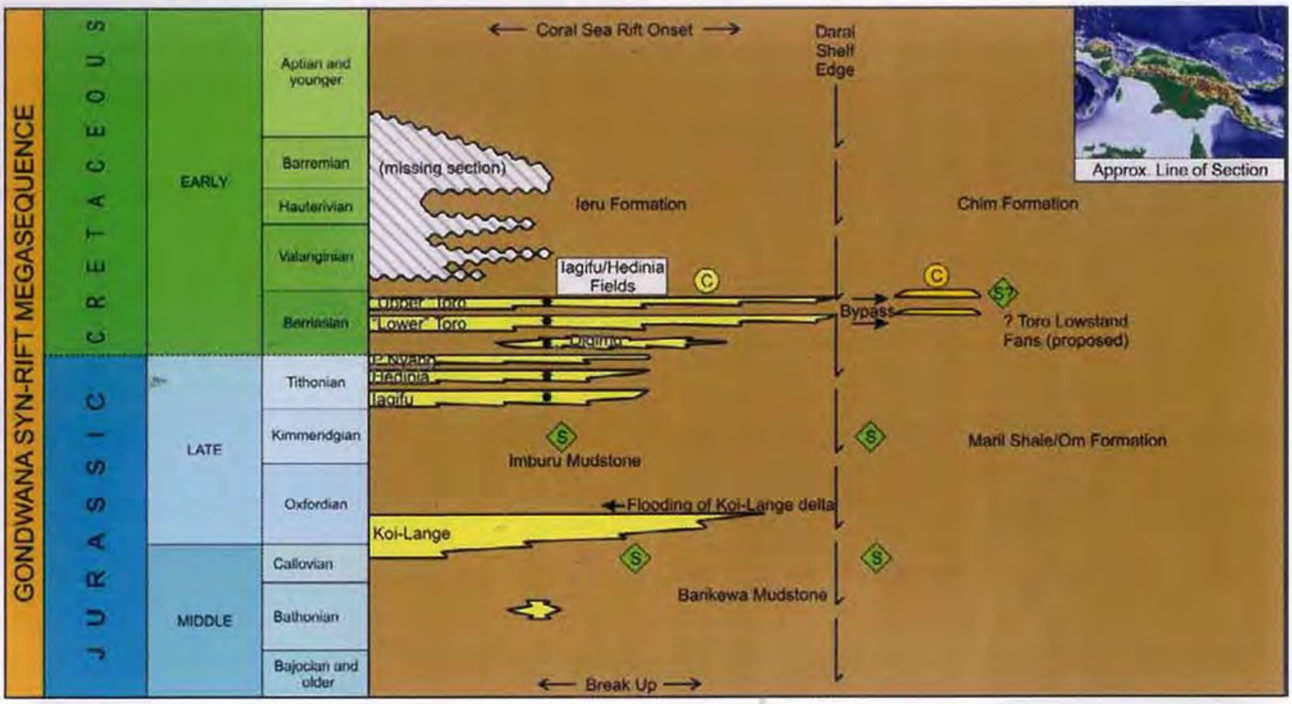


Figure 26. The Late Jurassic to Early Cretaceous general stratigraphy of PNG showing the stratigraphic position of the Toro Sandstone and other reservoirs relative to the overlying and underlying formations. The Ieru Formation forms a regional seal capping the reservoir objectives (Bidgood et al., 2015).

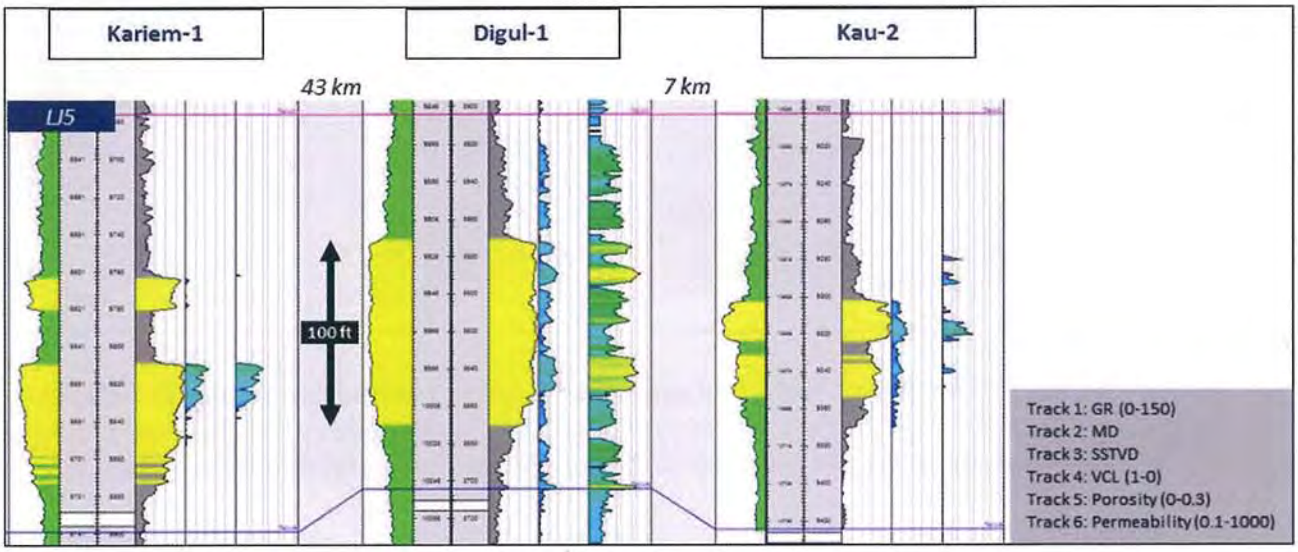


Figure 27. Wireline logs of the LJ5 Sandstone penetrated by Kariem-1, Digul-1, and Kau-2 wells. The logs show coarsening upward facies with occasional blocky and fining upward sections (ConocoPhillips Warim Ltd., 2015).

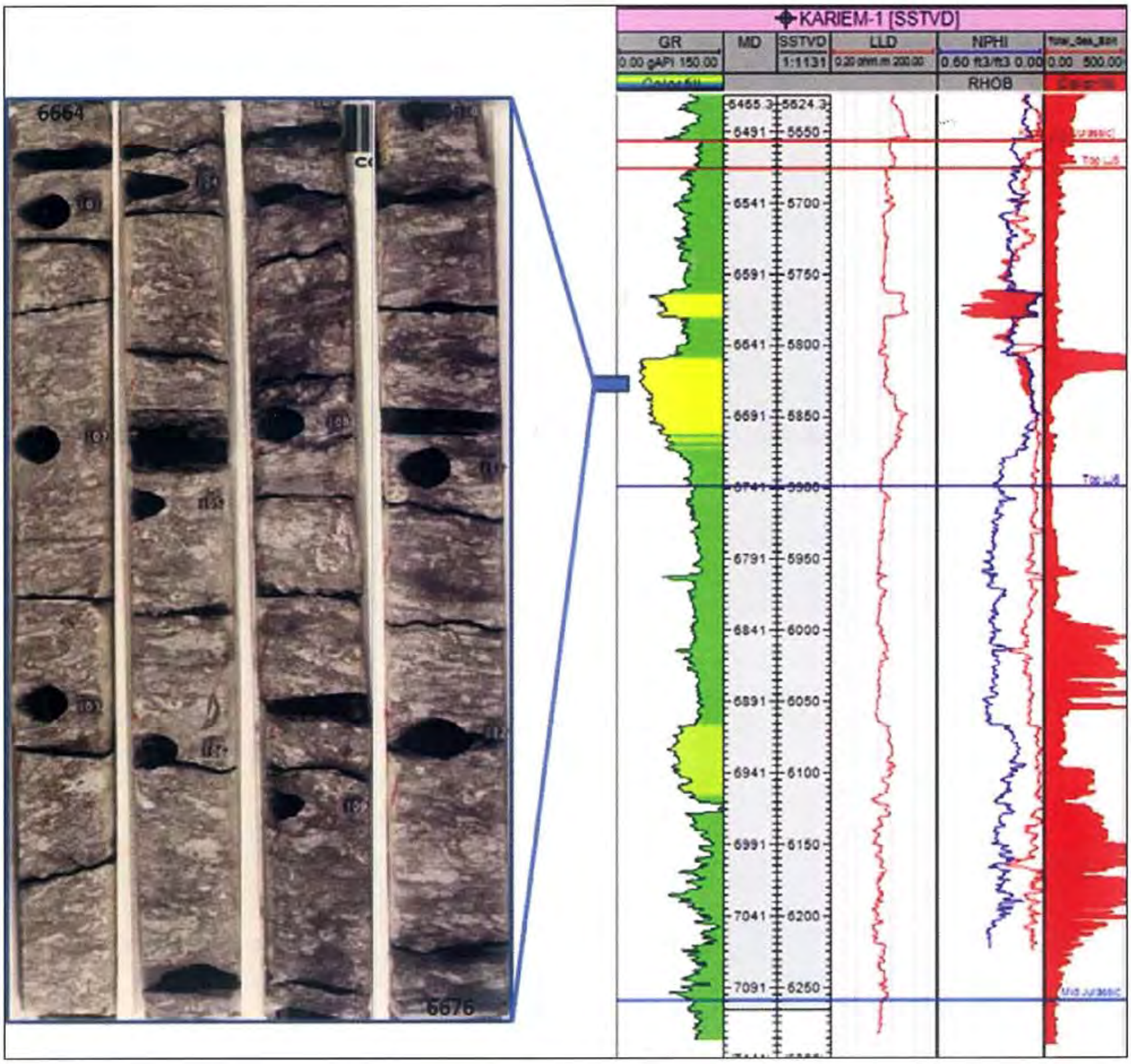


Figure 28. Core slab of LJ5 Sandstone in Kariem-1 well showing intensively bioturbated sedimentary structure (ConocoPhillips Warim Ltd., 2015). The cored interval indicates thin coarsening upward shallow marine sandstone beds with thick shales, probably of a shoreface facies.

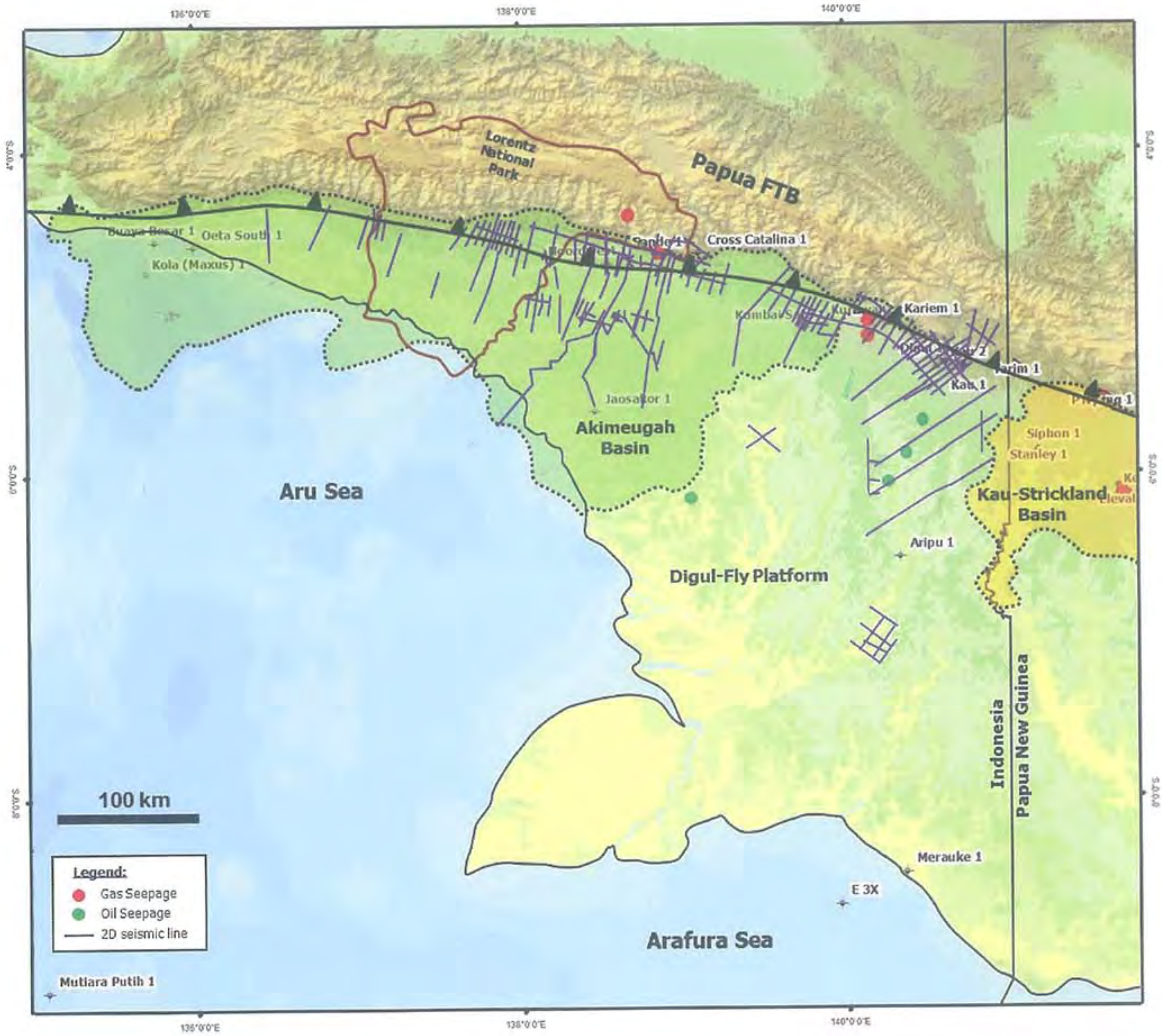


Figure 29. Seismic line coverage over the southern part of onshore East Papua. Thin-skinned thrust sheets are denoted by solid barbs. Black dotted lines are the Akimeugah and Kau-Strickland Basins. Solid blue line is the Lorentz National Park outline. Red and green dots are gas and oil seepages.

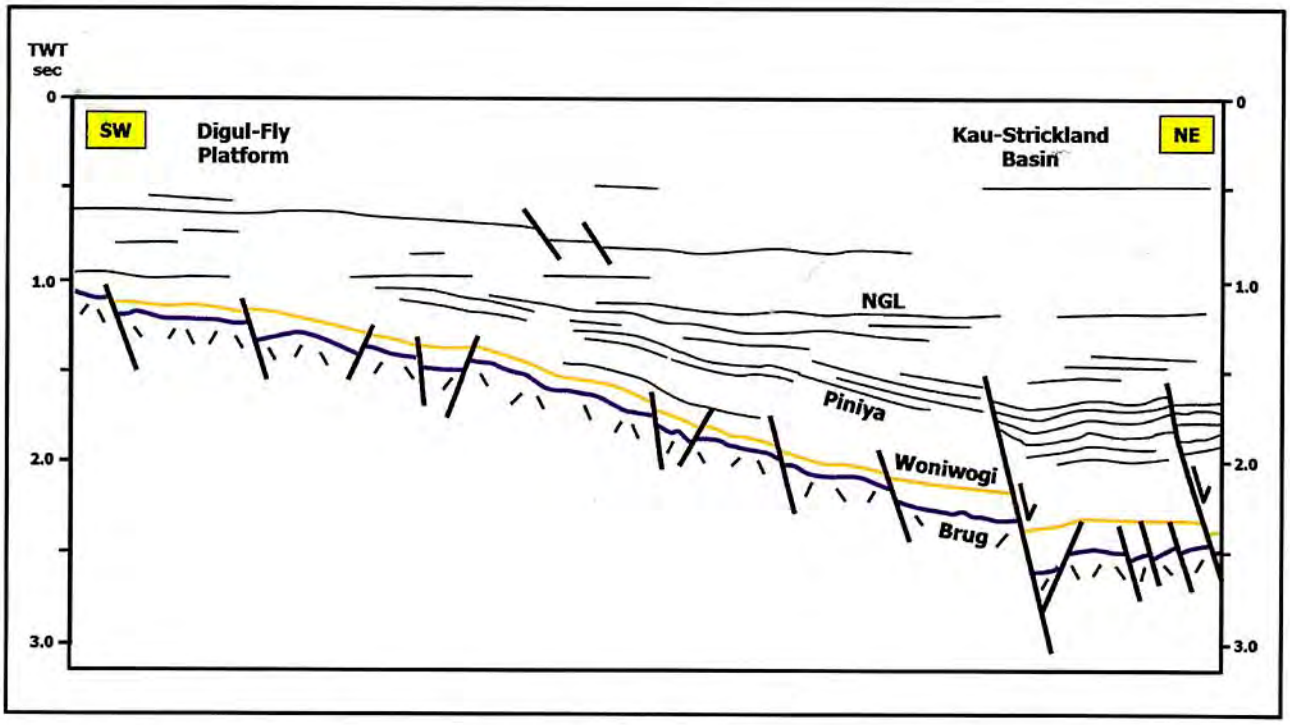


Figure 30. Seismic line interpretation over Foreland Basin. Note the Woniwogi pinch-out onto the Digul-Fly Platform to the southwest and drape over basement structures to the northeast. Also note a significant unconformity at the base of the New Guinea Limestone.

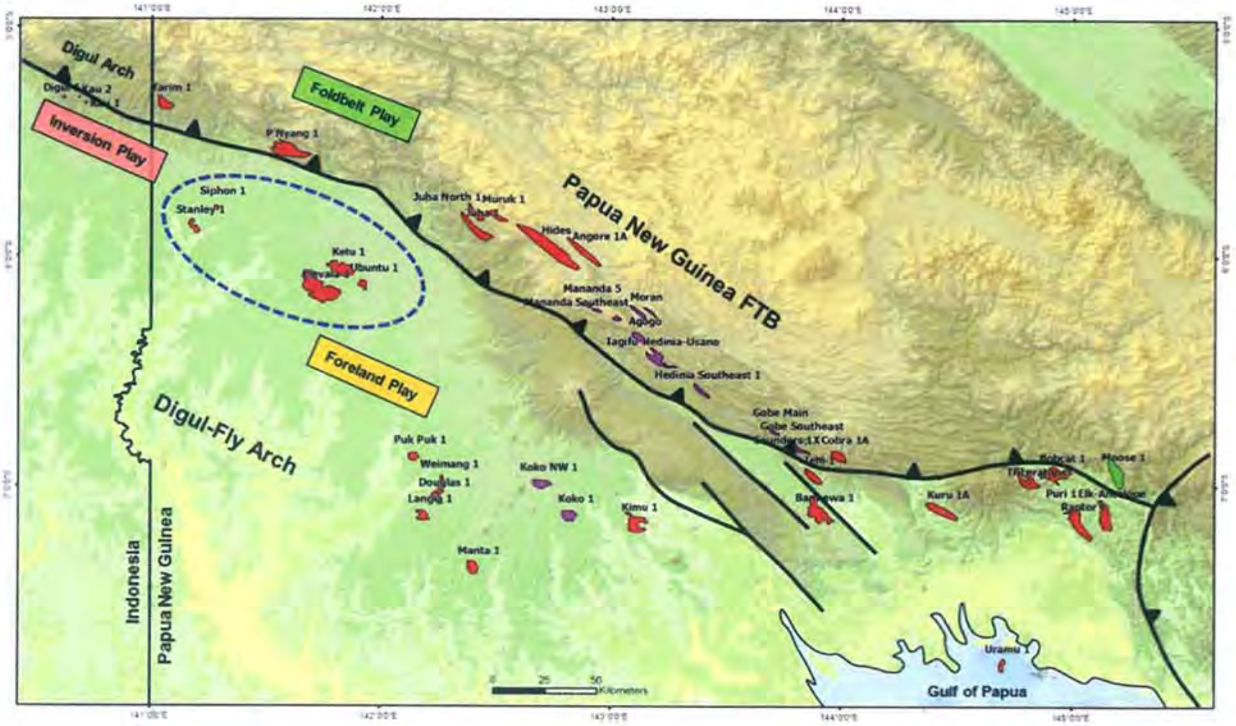


Figure 31. The nearest locations of the proven Foreland Play gas fields to the Indonesia-PNG border: Stanley, Ketu, Ubuntu, and Elevala marked by blue dashed circle. Red outline denotes gas field. Basement involved thrusting is denoted by solid barbs. Green outline is oil field. Purple outline denotes a field consisting of oil and gas.

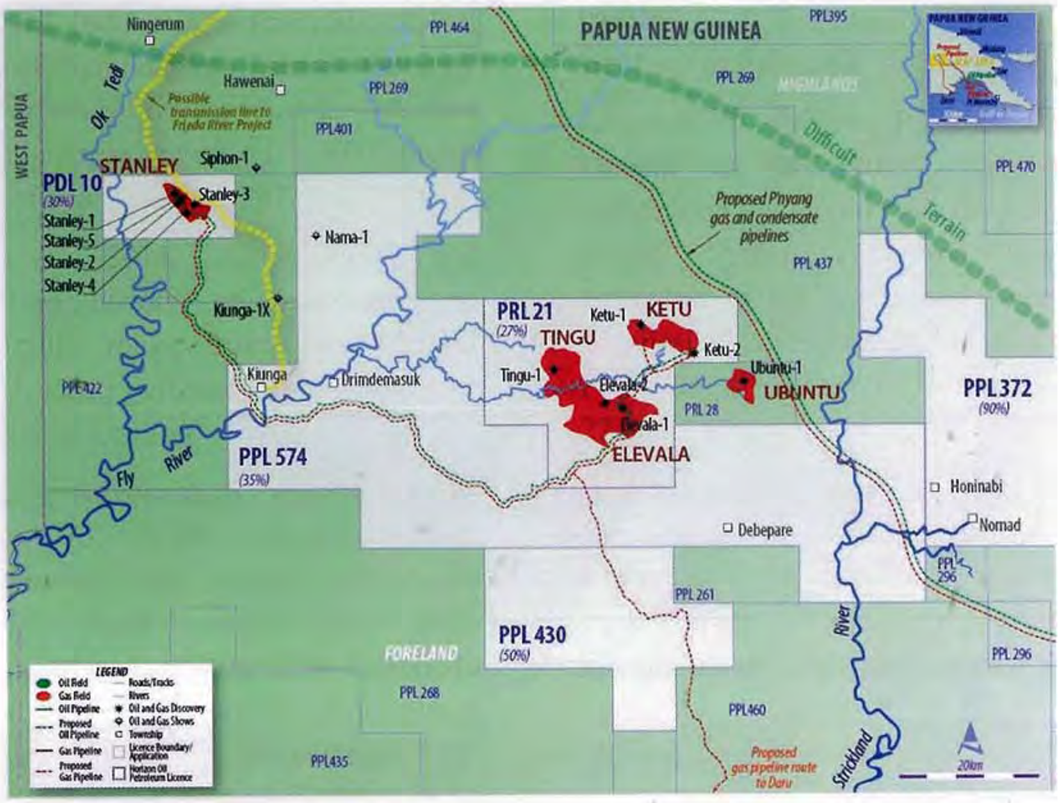


Figure 32. Stanley, Tingu, Elevala, Ketu, and Ubuntu Gas and Condensate Fields, nearby Foreland Gas Fields in PNG with their structures and well locations (Horizon Oil Limited, 2016).

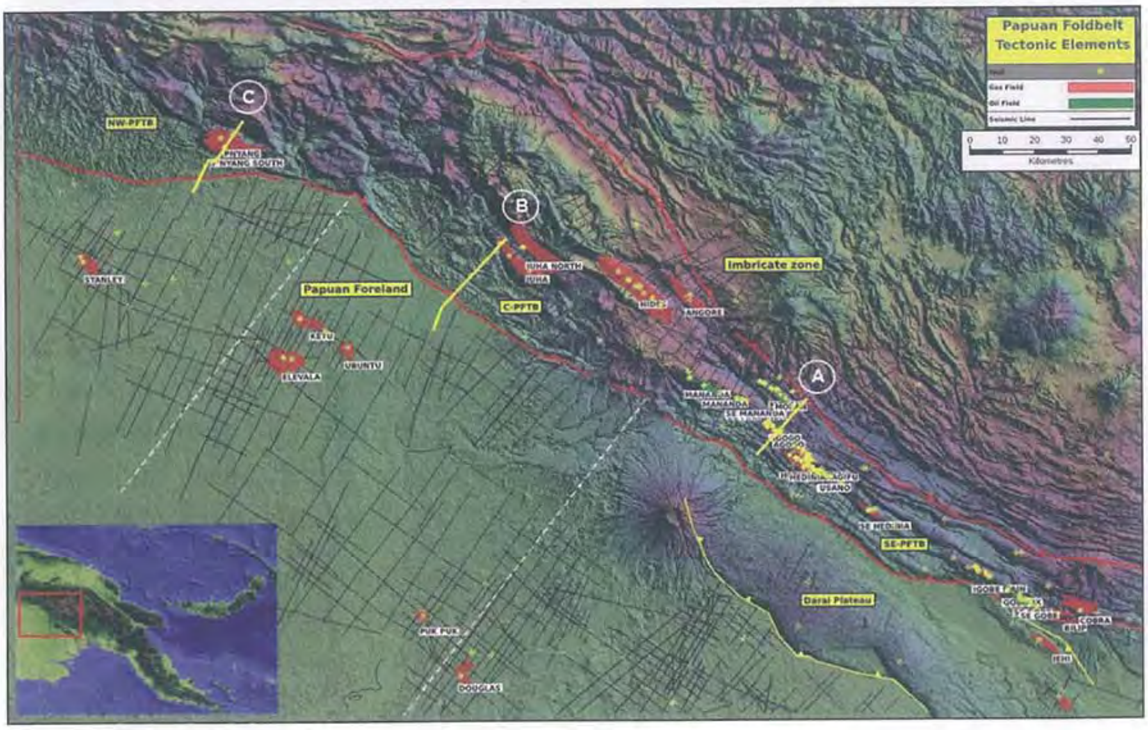


Figure 33. Seismic line coverage over the Papua New Guinea FTB and foreland basin (Parish, 2016).The yellow solid lines are the seismic interpretation across Agogo (A), Juha (B), and P'nyang (C) structures.

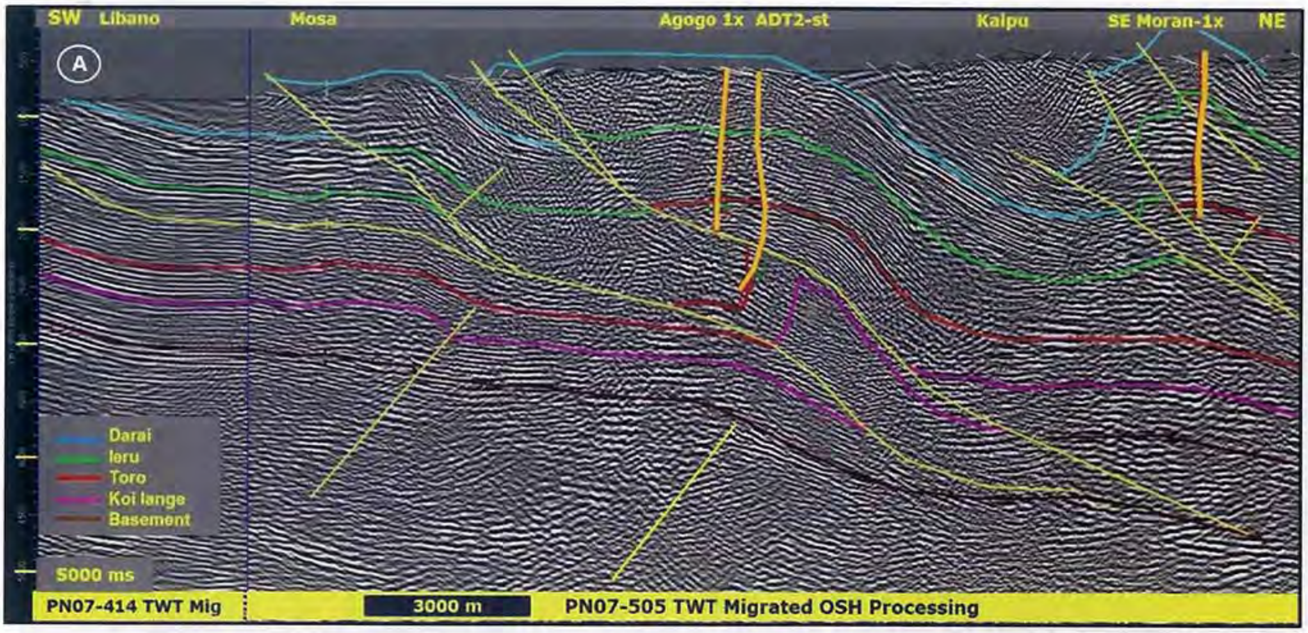


Figure 34. An interpretation of seismic line across Agogo and Moran structural closures (Parish, 2016).

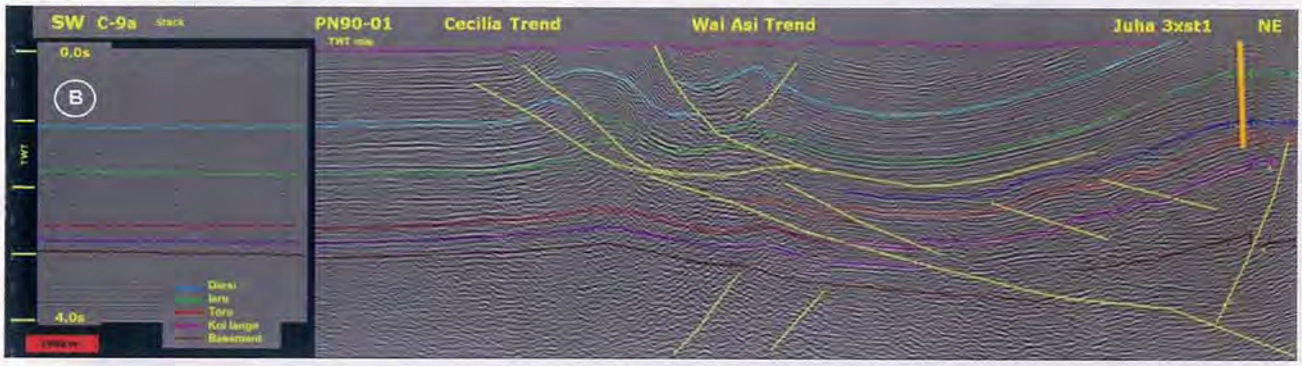


Figure 35. An interpretation of seismic line across Juha closure and Cecilia Trend (Parish, 2016).

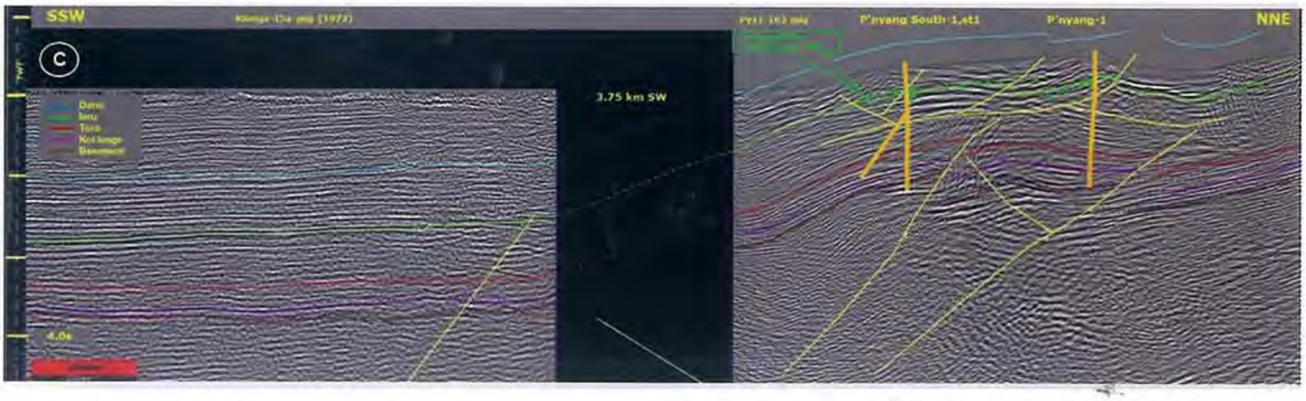


Figure 36. An interpretation of seismic line across P'nyang structural closure (Parish, 2016).