RESERVOIR POTENTIAL OF THE SYN-RIFT SUCCESSION IN NORTHWEST PALAWAN, PHILIPPINES

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Abstract

This study focused on identifying depositional environments and their corresponding sedimentary facies to understand implications for reservoir potential in the NW Palawan Basin, Philippines. Rock physics relationships, well-based facies analysis, seismic facies analysis and mapping of depositional sequences identified sedimentary facies deposited as a result of interplay between different depositional settings. Depositional processes were controlled by tectonic activity, relative sea level change, subsidence and sedimentation. The facies change from an alluvial fan on the bounding fault margin that grade into marine facies in the basin axis and to a delta prograding into the basin from the flexural margin. Sedimentary facies change across the graben and reservoir distribution is limited by depositional setting. Reservoir quality in the Malajon-1 well was affected by both compaction and cementation to varying degrees. Potential hydrocarbon-bearing reservoirs of significant thickness and lateral extent were not penetrated by the Malajon-1 well. Reservoirs that appear to be more prospective are found mainly in channels and in deltas.

Keywords: syn-rift reservoirs, half-graben

1. Introduction

This study focuses on syn-rift sediments as potential reservoirs in a northeast-southwest trending half-graben northeast of the Camago-Malampaya Field in NW Palawan Basin, Philippines (Fig.1). The graben fill sediments are underexplored and very few wells have encountered sediments belonging to the syn-rift succesion. The Malajon-1 well drilled on an anticline in 1988 encountered gas shows in the syn-rift section but it is not known if there are good reservoirs rocks in the area. This syn-rift section was originally interpreted as metamorphics of Early Cretaceous to Jurassic and thought to be "economic basement". Later evaluations of well logs, biostratigraphic and geochemical data concluded that it is a sedimentary sequence of Middle-Late Eocene age belonging to the syn-rift sequence (A.Morado and J.Micu, personal communication). Recent biostratigraphic and geochemical analyses of cuttings in this section by Corelab (2014) confirm this finding and petrographic analysis in the study corroborates with this.

This study also aims to address the heterogeneity and complex stratigraphy expected in the half-graben by:

1. identifying sedimentary facies and determining their depositional environment and
2. evaluating the sedimentary facies for reservoir potential and predicting its distribution.

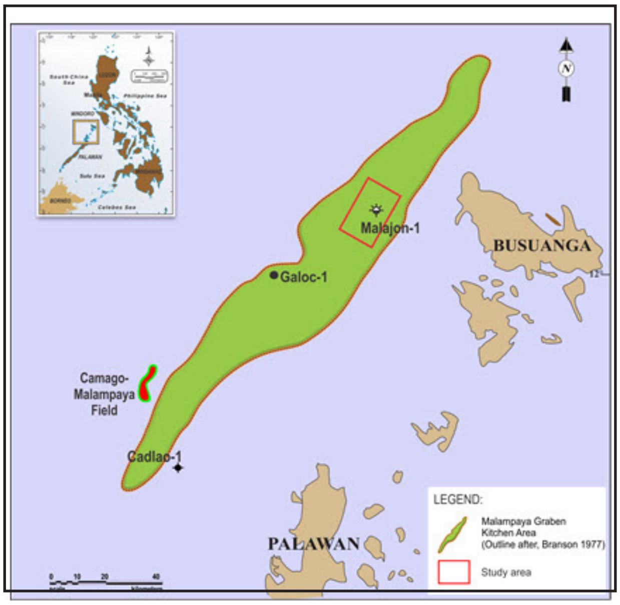

Figure 1. Location of the study area offshore Palawan Islands, Philippines.

2. Tectonic Setting and Stratigraphy

The NW Palawan Basin is located offshore Palawan, Philippines in water depths ranging from less than 100 m to more than 100 m to more than 1000 m. Whereas the rest of the Philippine archipelago is made up of oceanic crust, the North Palawan Block is of continental origin and is considered an integral part of Sundaland (Holloway,1982).The similarities in the tectonic and stratigraphic histories between the Northwest Palawan Block and the surrounding Southeast Asian Basins, particularly offshore Vietnam and southern China, suggest it was once contagious with mainland Asia (Williams, 1997). The stratigraphy of the basin, like all rift basins of Sundaland, is largely influenced by its tectonic development. The sediment type and depositional environments are directly of a basal fill (commonly fluvial), a middle related to the evolution of the basin. The tectonostra-tiraphic evolution of the basin can be classified into three (3) distinct phases and Figure 2 illustrates the general stratigraphy of the basin.

1. Pre-Rift (Cretaceous and older) is the period prior to the rifting of the South China Sea. The sequence is highly variable with Paleozoic and Mesozoic carbonates and clastics, igneous and metamorphic rocks having been encountered (Branson, 1997). The opening of the proto-South China Sea during the Early to Middle Cretaceous culminated the prerift stage.

2. Syn-rift (?Late Cretaceous t o early Oligocene) commenced with rifting on the southeastern Eurasian margin in the Late Cretaceous (Saldivar-Sali, 1986). There is limited penetration of the syn-rift; the published stratigraphic sequence is based mostly from nearby basins of Southeast Asia (Williams, et al, 1992a). The anticipated stratigraphy of the syn-rift sequences could vary considerably depending on the relative position to the graben, but typically it consists (lacustrine) source and upper fill units (fluvial to deltaic). These fill sequences can be fully continental, la custrine, a combination or fully marine as in the Chinese rift system (Williams, 1997). The NW Palawan Basin is currently interpreted to be located in a relatively distal setting such that rifting occurred in a predominantly marine environment (Branson, 1997). The syn-rift interval is further divided to

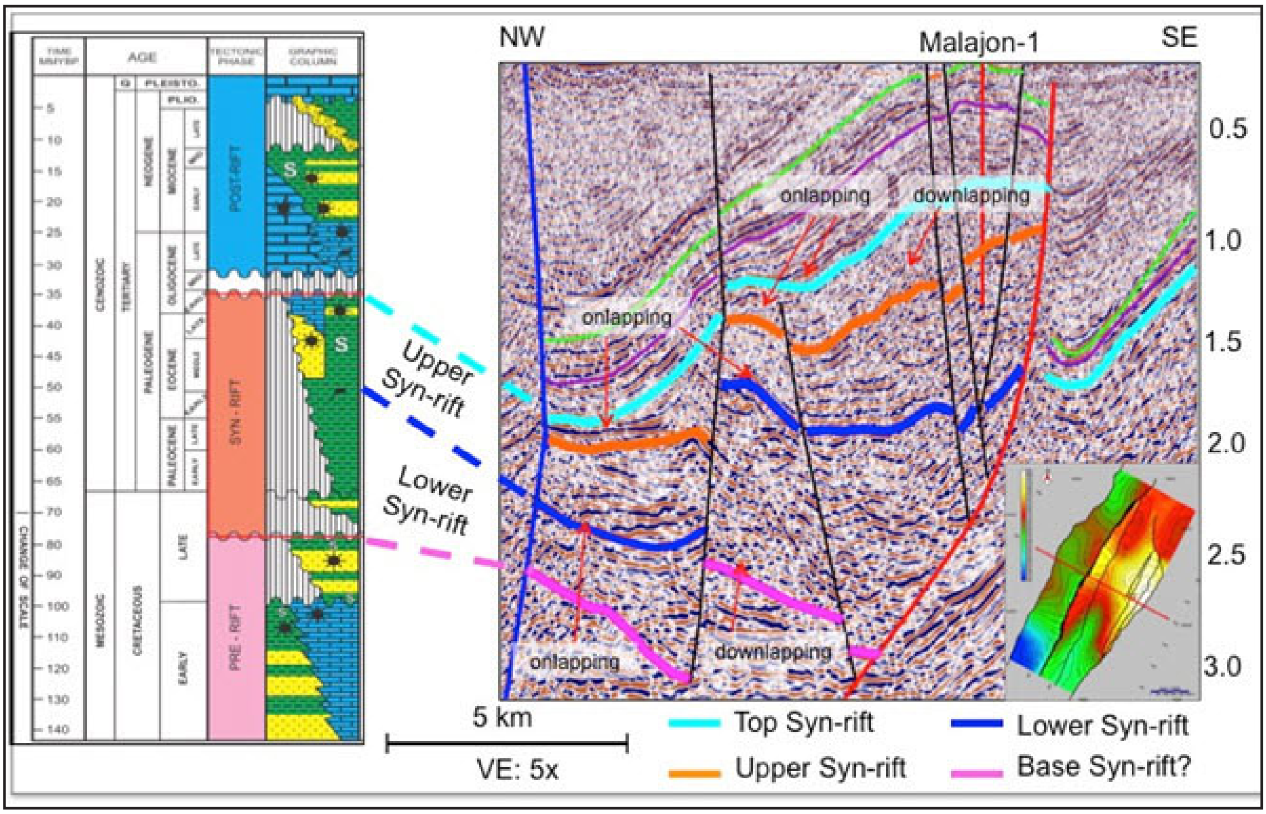

Figure 2. The generalized stratigraphy of the NW Palawan Basin and a seismic section at the well showing the horizons mapped as sequence boundaries in the syn-rift.

two stages albeit with ages older than most basins in Sundaland. The basin comprised of Early Syn-rift (?Late Cretaceous to middle Eocene) and Late Syn-rift (middle Eocene to early Oligocene) sequences. The Early Syn-rift corresponds to the period of rift graben formation, followed by maximum subsidence with deposition. All Paleocene to Eocene sediments in the basin were deposited in environments ranging from outer sublittoral to paralic (Sales et al, 1997). The Late Syn-rift is characterized by a period of waning subsidence in the graben that was filled with paralic sediments (Doust, 2008)). In the study area, the Upper Syn-rift sequence is composed of an upper marly sequence referred locally as the Malajon Marl of early Oligocene to late Miocene age and characterized by the presence of common to abundant carbonaceous or organic material plus a lower conglomeratic interval called the Malajon Conglomeratic Group of middle to late Eocene age, which is marked by an unconformity.

4. In the Post-rift (late Oligocene to Pliocene), the South China Sea opened resulting in a southward drift of the North Palawan Block which is represented by the mid-Oligocene Unconformity(Holloway, 1982). The Early Post-rift (late Oligocene to middle Miocene) corresponds to a period of tectonic quiescence following marine transgression that covered the existing graben topography (Williams, 1997). Shallow marine carbonates of the Nido Limestone Formation were deposited in fault block crests and Pag-asa Formation fine-grained sandstones were deposited primarily in deeper marine conditions (Branson, 1997). The Late Post-rift (middle Miocene to Pliocene) is marked by Mid-Miocene Unconformity and refers to period of inversion and folding when North Palawan Block collided with the Philippine Mobile Belt (Holloway, 1981). The collision resulted in inverted structures and reactivated faults (Branson, 1997) that formed traps and initiated development of passive margin. The sediments deposited during the Late Post-rift are represented by the Matinloc (late Miocene to Pliocene) and Carcar formations (late Pliocene to Recent) (Sales,et al, 1997).

3. RESULTS

3.1 Sequence Stratigraphic and Sedimentary Facies Analysis

Petrographic analysis

In the petrographic analysis, pebble to cobble-sized conglomerates from sidewall core descriptions contains mostly lithic fragments. Quartz, feldspars and opaque iron oxide minerals are common and few accessory minerals and heavy minerals. Lithic fragments include chert, and fragments of igneous, metamorphic and sedimentary rocks. The quartz grains observed are monocrystalline and polycrystalline quartz and microcrystalline quartz in chert. The sediments are sub-angular to sub-rounded, poorly sorted with grain size ranging from medium sand to granules. Iron oxide cements (presumably hematite) are common and weathered to limonite and goethite, which are brown and translucent. Thin coatings of iron oxide cement are also visible around the grains (Fig.3A). The sandstones are interpreted as lithic sandstones composed predominantly of lithic grains comprised of quartz and feldspars and other rock fragments from sedimentary and igneous rocks and, a few calcite and opaque iron oxide minerals. The sandstones in the lower part of the succession are interpreted as arkosic sandstones based on the composition with lithic fragments composed mainly of quartz, subordinate feldspars, other types of rock fragments and a few opaque iron oxides (Fig.3B). The sandstones are sub-angular to sub-rounded, medium sand to granule-sized grains, and moderately sorted. Iron oxide cements are less pervasive in the sandstones compared to the conglomerates as they occur mostly as rims in grains and calcite cements as fills in the pores or rims of grains. The grain shape and sorting, indicates they are texturally immature and suggests provenance proximal to the basin.

Rock physics relationship analysis

A plot of velocity with depth shows effect of compaction up to about (2170m) and decreased velocity below this depth, which

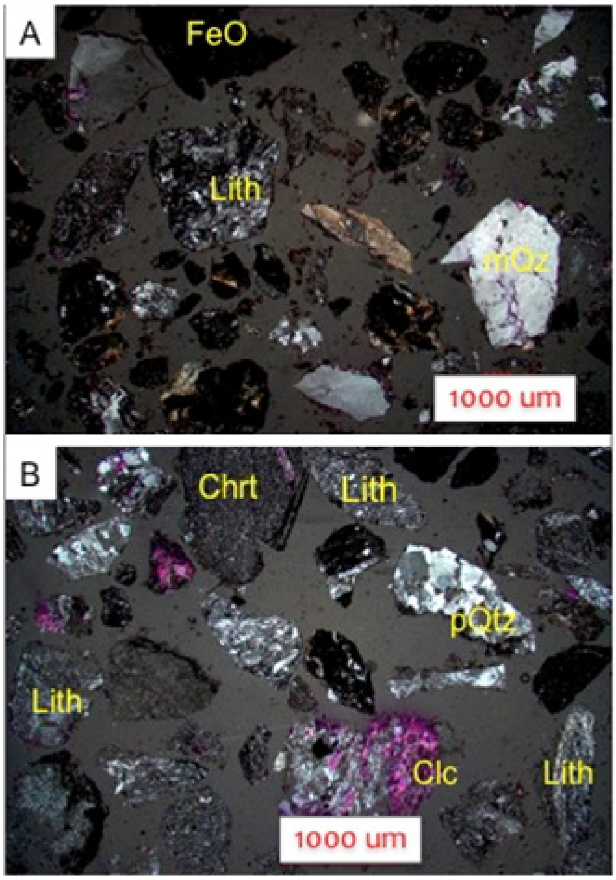

Figure 3. Thin sections of a conglomerate (A) and an arkosic sandstone (B) showing pervasive cementation in conglomerates than in sandstones

could be due to gas effect. The gas-bearing lithologies have low densities, which result to low acoustic impedance whereas the conglomerates have high velocities and high densities, consequently high acoustic impedance. A cross plot of gamma ray versus acoustic impedance colorcode by Sw per succession generally has a separation between sand and shale but there is excessive overlap, therefore a cross plot to differentiate shale from sand was extracted in the four thick sands that are at least 20 m thick, that could be potential reservoirs and definable in the seismic. Sands 1 and 4 are distinguished from shale with a GR cut-offs of 70 and 85API, respectively. It was difficult to differentiate Sand 2 but there is astrong impedance contrast between overlying stacked thin gas-bearing sands with the underlying Sand 2 conglomerate (Fig.4A). With a GR cut-off of 70API, there is an impedance contrast between the high impedance overlying shale with the low impedance gas-bearing sand in Sand 3 (Fig.4B). These impedance contrasts are observed as high amplitudes at the well location (Fig.4C).

Sands 1 and 2 are conglomerates that grade to sandstone as observed in thin section, GR, Vp and density values. The high velocity and high density in conglomerates are likely due to reduced porosity and permeability from cementation. The subangular to subrounded, poorly sorted grains indicate textural immaturity. The sediment is also minerallogically immature containing feldspars and rock fragments though it is mainly quartz. Immature sediments also are prone to porosity loss due to compaction. The cementation observed in the sandstones below the conglomerate is not as pervasive as in the conglomerates; as a result the sandstones have lower velocities and densities. Cementation and compaction causes lomerates to be hard, which explains the no observed negative separation in density and neutron porosity in Sands 1 and 2 because the conglomerates have very low porosity and permeability even though, gas was indicated by the Total Gas and resistivities.

Sands 3 and 4 are arkosic sandstones from petrographic analysis. Velocity and density are mainly affected by compaction and cements are very rare. The velocity and density of Sand 3 is lowered due to the gas effect. Conversely, Sand 4, has high velocity and density and does not have negative separation in density and neutron porosity, although gas peaks are recorded from this interval and intermediate and deep resistivities also have separation. This suggests that this sandstone is more compacted than Sand 3.

Porosity decreased with depth, with total porosity generally less than 25% in the syn-rift. The syn-rift section is highly fractured and almost no observed primary porosity that porosity could only be due to secondary porosity from fractures. Mudlog shows these fractures to be gas-filled. almost no observed primary porosity that porosity could only be due to secondary porosity from fractures. Mudlog shows these fractures to be gas-filled.

Depositional environment at Malajon-1 well and nearby wells

It is interpreted that the lower conglomeratic interval was deposited in a late to middle Eocene marine environment with strong terrestrial influence and this is observed in the well data. The sediments probably were deposited on an escarpment margin along the main bounding fault of the half-graben. Sedimentation in the axis of the basin at the hanging wall includes very coarse sediments from debris fall and sediment fans from the horst. The section encountered by the Malajon-1 well is interpreted to be an alluvial fan interbedded with transgressive marine sediments. The thickening and coarsening upward trend observed in the logs indicate a prograding sequence that was deposited in the basin when the active fan was prograding or outbuilding. Thin section descriptions of poorly sorted sediment with coarse grain sizes and muddy matrix conglomerates and sandstones indicate debris flow-dominated fans but fine-grained sediments interpreted as shaly sands, interbedded sands and shales, silty shales and shales from the well-based facies analysis could be from braided stream deposits. The transgressive sequences of fining upward cycles denote a rise in sea level that resulted to the deposition of marine shales. The generally low foraminifera in the section could be due to sea level fall or high sedimentation rate.

Stratigraphic architecture

In the graben, where the stratigraphy is complex and the reflectors rarely extend beyond the individual half- grabens, the syn-rift section was mapped and subdivided to an Upper Syn-rift and a Lower Syn-rift based on unconformities. The Top Syn-rift which was mapped at the top of the marly sequence called Malajon Marl (Fig.2). This marly sequence is interpreted to be the upper section of the Upper Syn-rift. The Upper Syn-rift is defined byanother prominent unconformity that corresponds to the Top of the Malajon Conglomeratic Group (Fig.3). This unconformity was recognized in the dip meter survey, and is marked by decrease in nannofossils and microfossils and an abrupt increase in vitrinite reflectance, separating the upper marginally mature to mid mature from lower late mature sequence. The unconformity is also characterized by bright amplitudes and reflectors belonging to the Malajon Marl onlap on this unconformity (Fig.2). The Lower Syn-rift is defined by an erosional surface where there is a prominent channel in the graben. The reflectors of the Upper Syn-rift downlap this unconformity.

Seismic facies analysis

Depositional facies in the syn-rift section are highly variable as manifested by the differing seismic facies. The observed l ateral and vertical facies change is expected in syn-rift depositional facies. In the Malajon-1 area, bounded by the main bounding fault to the east, the seismic reflection configuration is hummocky prograding clinoforms that show irregular, discontinuous subparallel reflection segments and non-systematic reflection terminations with variable amplitudes in the Upper Syn-rift sequence (Fig 5). The Upper Syn-rift sequence (discussed from here and forward) refers to the section below the Malajon Marl. The pattern grades laterally into larger, better-defined clinoforms. The reflection pattern becomes more high amplitude, laterally continuous and parallel into the axis of the basin (Fig.5). To the west,another facies becomes apparent with a tangential oblique prograding clinoform pattern (Fig.5). The relatively steeply dipping strata appear to terminate updip by toplap or to a nearly flat upper surface or to the unconformity of the top of the Upper Syn-rift and downdip by downlap against the lower surface of the facies or terminate abruptly onto Lower Syn-rift. These prograding clinoforms have decreasing amplitudes from west to east. Depositional dips of the clinoforms are at slope 2-3 degrees. The highly discontinuous with bright lens-shaped reflectors are observed in the erosional surface of the Lower Syn-rift. In the Lower Syn-rift sequence, the reflectors become more parallel in the main bounding fault (Fig.6) that grade to another facies of parallel reflectors in the axis of the basin (Fig.6). In the flexural margin, prograding clinoforms, which are larger than those in the Upper Syn-rift, are observed (Fig 6).

3.2 Depositional Facies and Sediment Distribution

Seismic mapping of depositional sequences

The three facies recognized on seismic in the Upper Syn-rift sequence were deposited at the same time but at varying rates. The facies deposited at the main bounding fault has a fan shape in plan view and a convex shape in cross section. This facies is interpreted to be an alluvial fan consisting of prograding and transgressive sequences that were building into the fault parallel to the main bounding fault The reflection configuration of the middle facies at the apex of the basin indicates relatively uniform deposition in a subsiding basin. The marine facies also interfingers with the prograding facie interpreted to have been deposited in a deltaic environment. The delta is lobe-shaped in plan view and wedge-shaped in cross section. The oblique prograding pattern entails depositional conditions of both relatively high sediment supply, little basin subsidence and little to no sea level rise, allowing rapid basin infill and sediment bypass. This delta is interpreted to be a Gilbert type of delta with parallel topsets, steeply dipping foresets of 10-15 degrees and gently dipping bottomsets of 3-5 degrees (Fig.5.).

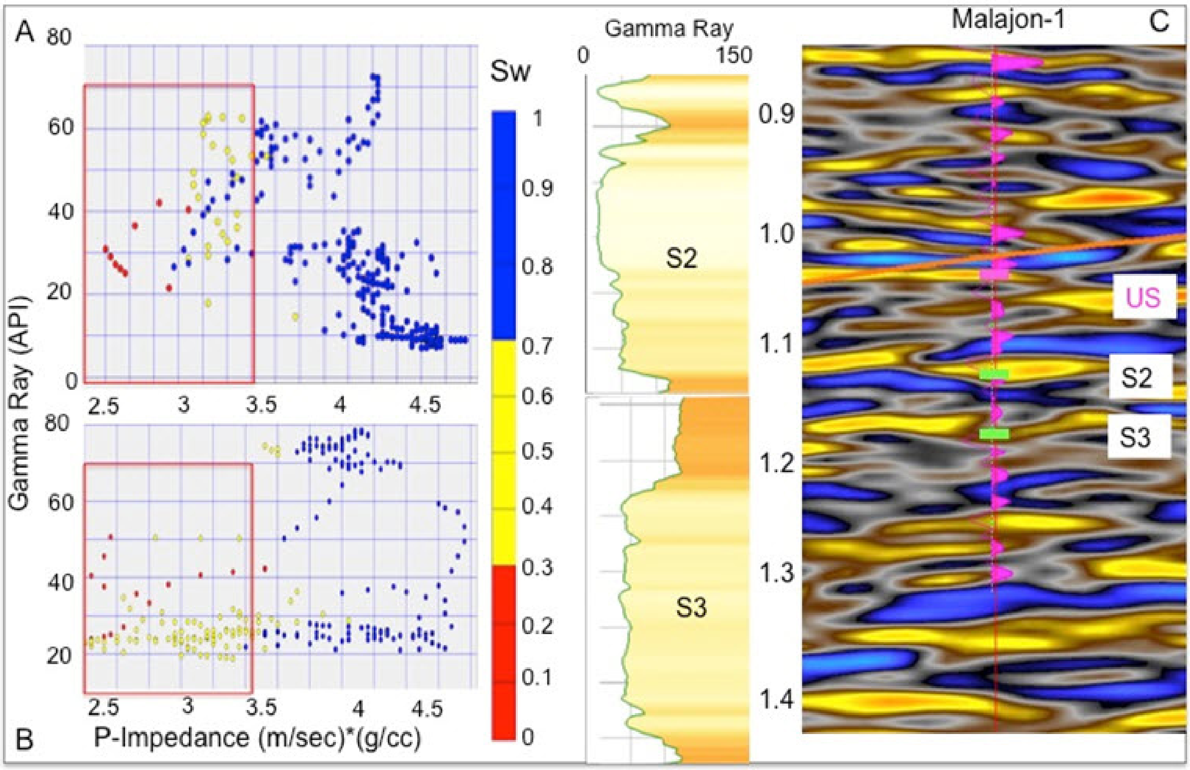

Figure 4. Plot of GR versus P-impedance color code by Sw shows gas-bearing sand can be differentiated from the conglomerates below it (A) and high impedance shale can be separated from the from low impedance gas-bearing sands. The impedance contrasts show as high amplitude response at the well (C)

sshallow water. The transgressive sequence denotes a change in relative sea level that marine sediments. The alluvial fan is observed to interfinger with the facies at the axis of the basin, which was deposited in a marine environment as channel fills, probably from submarine channels or pelagic sediments. Channels are controlled by

In the Lower Syn-rift, environment of deposition can only be inferred from sediments of Paleocene-Middle Eocene of nearby wells Ga loc-1 and Cadlao-1 where the biostratigraphic analysis indicates a marine depositional setting. The sediments at the escarpment margin have more parallel reflectors than in the Upper Syn-rift sequence, implying a relatively uniform sediment supply in a relatively uniform subsiding basin (Fig.6). This alluvial fan with a fan-shape in plan view and convex in cross section. There is high rate of sedimentation from terrestrial input coming from the east due to the large-scale delta prograding from the flexural margin into the basin in a slope of 2-3 degrees (Fig.6) This implies high accommodation space and a low subsidence rate in the basin that results to extensive basin infill from both the east and the west. Much of the accommodation space was probably created prior to deposition.

The Upper Syn-rift sequence and the Lower Syn-rift sequence have the same depositional settings but the lateral and vertical extents of the facies were controlled by the rate of subsidence, sediment supply and relative rise in sea level. It appears that the Lower Syn-rift sequence was deposited in a condition where the rate of subsidence is lower than when the Upper Syn-rift. On the contrary, sea level seems to play a more important role in the Upper Syn-rift than in the Lower Syn-rift. The thickness of the Lower Syn-rift is greater than the Upper Syn-rift, implying high sediment supply in the early stage of the rifting.

Depositional Model

A simplified model from Leeder and Gawthorpe, 1987 illustrates a depositional model for the syn-rift where facies distributions are dependent on the slope and depth and there is an observed marked contrast in the depositional styles across the half-graben system (Fig.7).

Extension caused the hanging wall to detach from the footwall and form an asymmetrical basin above the footwall. Drainage systems systems transporting sediments tend to follow the axis of maximum subsidence Lateral transport systems deposit high gradient alluvial fans and low gradient deltas down the footwall and hanging wall slopes, respectively, normal to the strike of the main bounding fault. Subsequent deposition of alluvial fans decreased the gradient of the fan surface on the hanging wall,

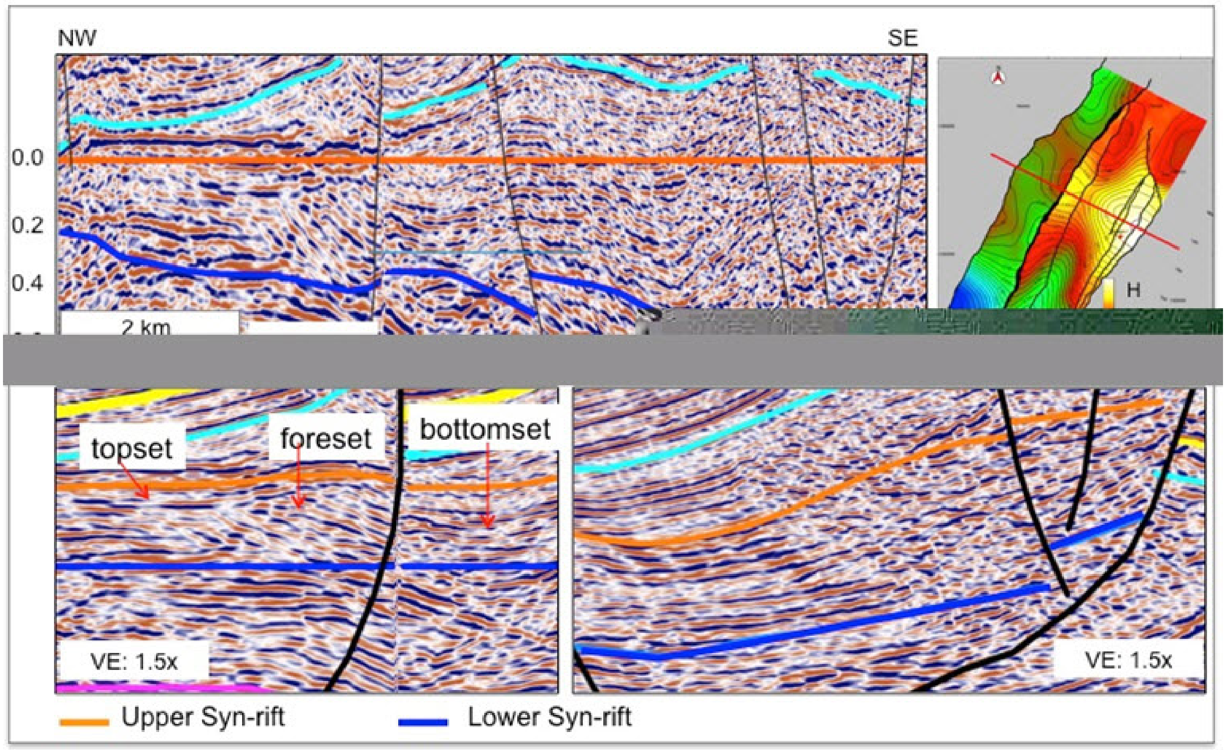

Figure 5. Facies identified from the seismic showing alluvial fan at the main bounding fault that interfingers with marine facies at the axis of the basin that interfingers with delta (Gilbert-type delta) prograding into the basin from the flexural margin.

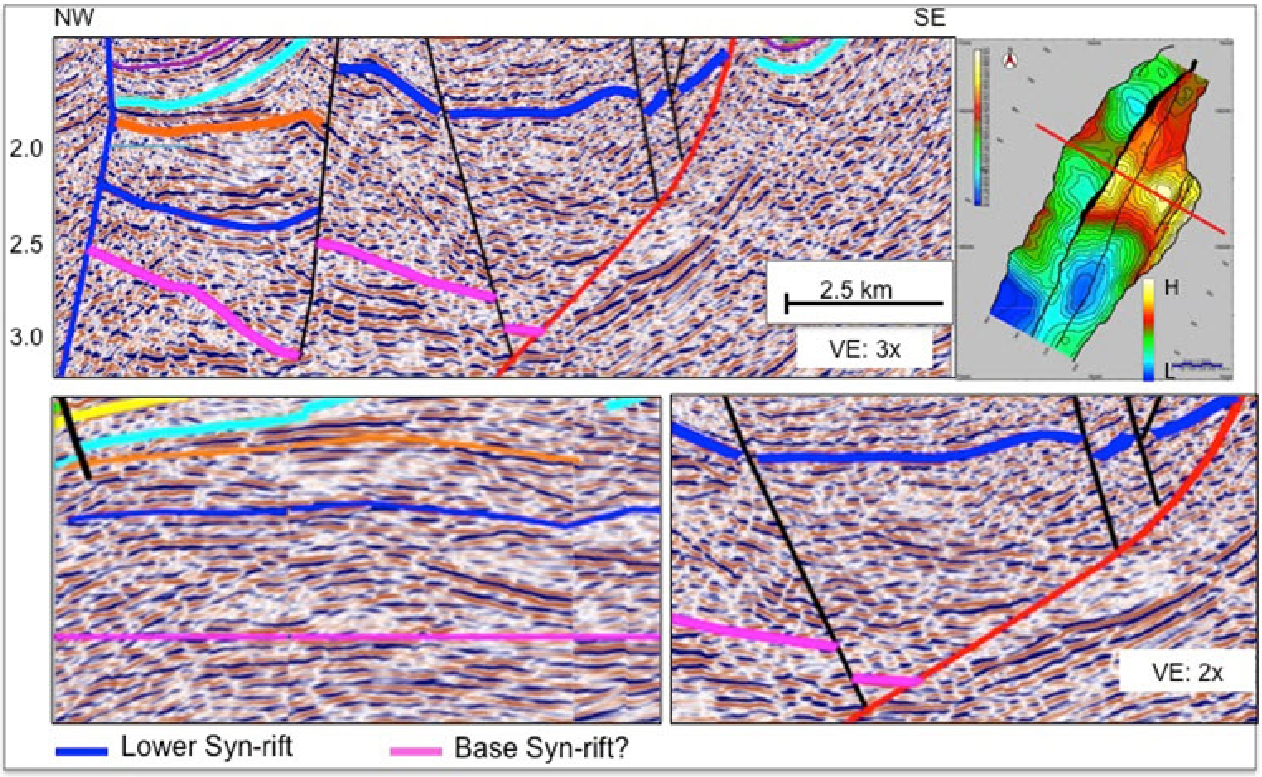

Figure 6 Facies identified from the seismic showing alluvial fan at main bounding fault that interfingers with marine facies at the axis of the basin that interfingers with the delta prograding into the basin from the flexural margin.

so that renewed sedimentation led to deposition of a new fan close to the fan apex which prograded gradually over the old fan segment causing a crude coarsening upward cycle to be developed. Towards the basin, the fans will prograde laterally over the distal portion of older fan surfaces forming offlap sequences. Axial transport systems deposited marine sediments via submarine channels parallel to the main bounding fault. The channels migrated preferentially to axis of maximum subsidence in response to fault-induced tilting. Uplift of the foot wall caused subsidence that resulted to marine transgression over the distal portion of the alluvial fans and the delta lobes.

Potential reservoir distribution

The RMS amplitude map of the Upper Syn-rift (Fig.7) extracted at a window of 50 msec has amplitude anomalies in the facies interpreted to be from submarine channels and facies interpreted to be from prograding delta. Very little amplitude anomaly was observed in the distal part of the alluvial fan. High anomalies in Spectral decomposition refer to either sands or shales that have high a amplitude response at tuning thickness and does not necessarily translate to sands, hence it should be tied to RMS maps. Spectral decomposition map in a frequency of 22.3 (Fig.8A) in the Upper Syn-rift matches with the RMS amplitude map distribution of potential gas-bearing sands. The syn-rift section has a tuning thickness of 50 m at a frequency of 22 Hz, therefore the anomalous values on the 22.3 Hz map are sands about 50 m thick that are mostly in the channels and in delta. The interpreted channel belt extends up to 2.5 km wide.

In the Lower Syn-rift, the RMS map extracted at 60 msec window displays high amplitude anomalies in facies interpreted to be delta and very little in the channels (Fig.9A). Also, the location of the high amplitude anomalies probably represents the delta front. This coincides with Spectral Decomposition map showing sand distribution (Fig 9B). The 17.2 Hz map has amplitude anomalies indicating sands thicker than 50 m in the Lower Syn-rift. The interpreted channel belt extends about 1 km

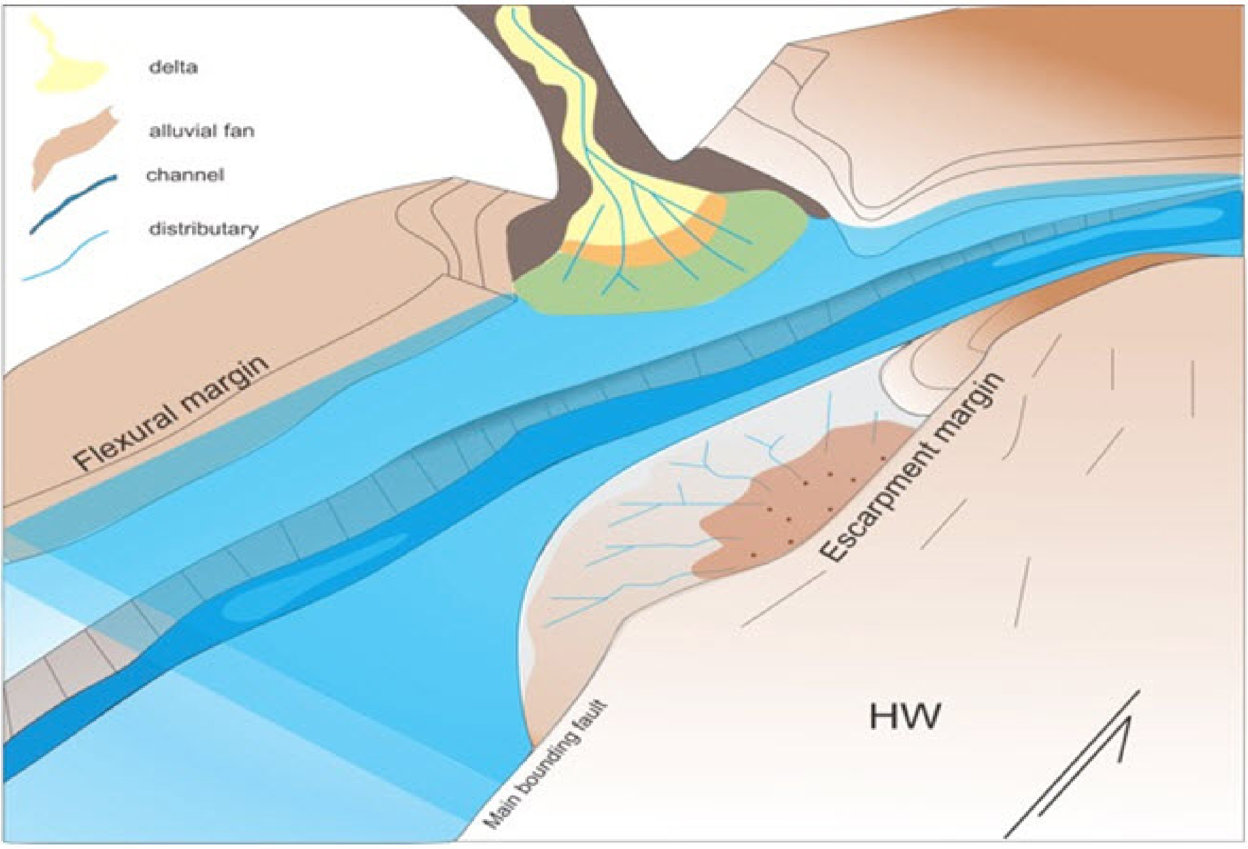

Figure 7. Depositional model for the syn-rift (modified from Leeder and Gawthrope, 1987).

wide, narrower than in the Upper Syn-rift.

4. Discussion

Implications in the Potential Reservoirs

The evolution of the half-graben in the area controlled the depositional environments and sedimentary facies. Tectonic activity is determined depositional processes, resulting in different depositional facies across the graben. This facies change has a profound impact to the distribution of potential reservoirs. The lateral and vertical extents of the facies indicates reservoir distribution is limited by depositional setting and does not extend across the graben

The reservoirs of the alluvial fan are both from debris and stream flow deposits. Results of petrographic analysis and rock physics have shown that these potential reservoirs specifically the conglomerates are compacted and cemented which has negative impact on its reservoir quality due to reduced porosity and permeability. There are less compacted and cemented sands in the Upper Syn-rift, which could be attributed to the fewer minerals in the sands that were precursors to cementation. There is also a distinct compaction trend affecting the sediments at up to 2100 m. Geochemical analysis indicates gas encountered in the Malajon-1 are migrated gas. It is likely that the gas migrated after cementation since gas formed in situ would have inhibited cementation.

Faulting in the syn-rift section is prevalent throughout its history, hence, porosities of these potential reservoirs are probably from fractures as the interval was described as highly fractured in the well report and mudlog record indicates fractures are gas-filled. On the contrary, reservoir mapping indicates distribution of potential reservoirs to be very limited which could be due to its lateral extent and thickness is not definable in the seismic.

In contrast, reservoir mapping indicates potential reservoirs away from the well from sedimentary facies of a prograding delta. Although, these potential reservoirs have not

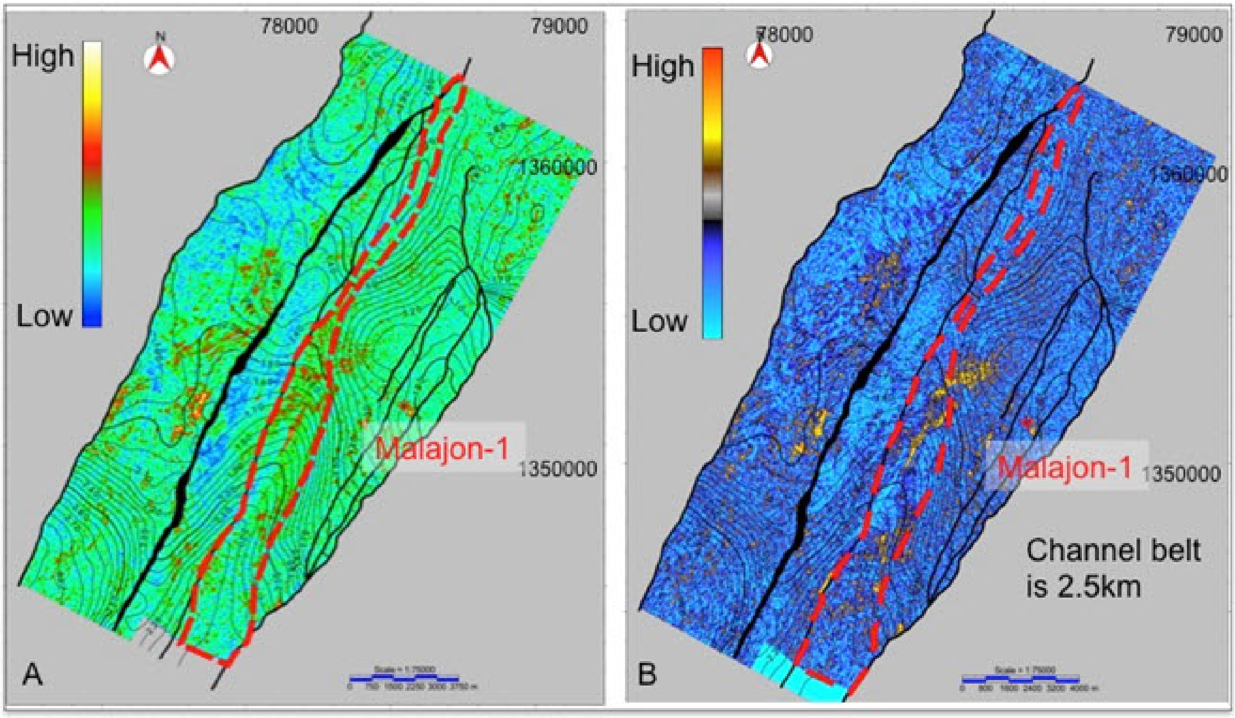

Figure 8. Potential reservoir distribution as shown by RMS (A) and Spectral Decomposition (B) with the red dashed line interpreted to be the channel belt in the Upper Syn-rift.

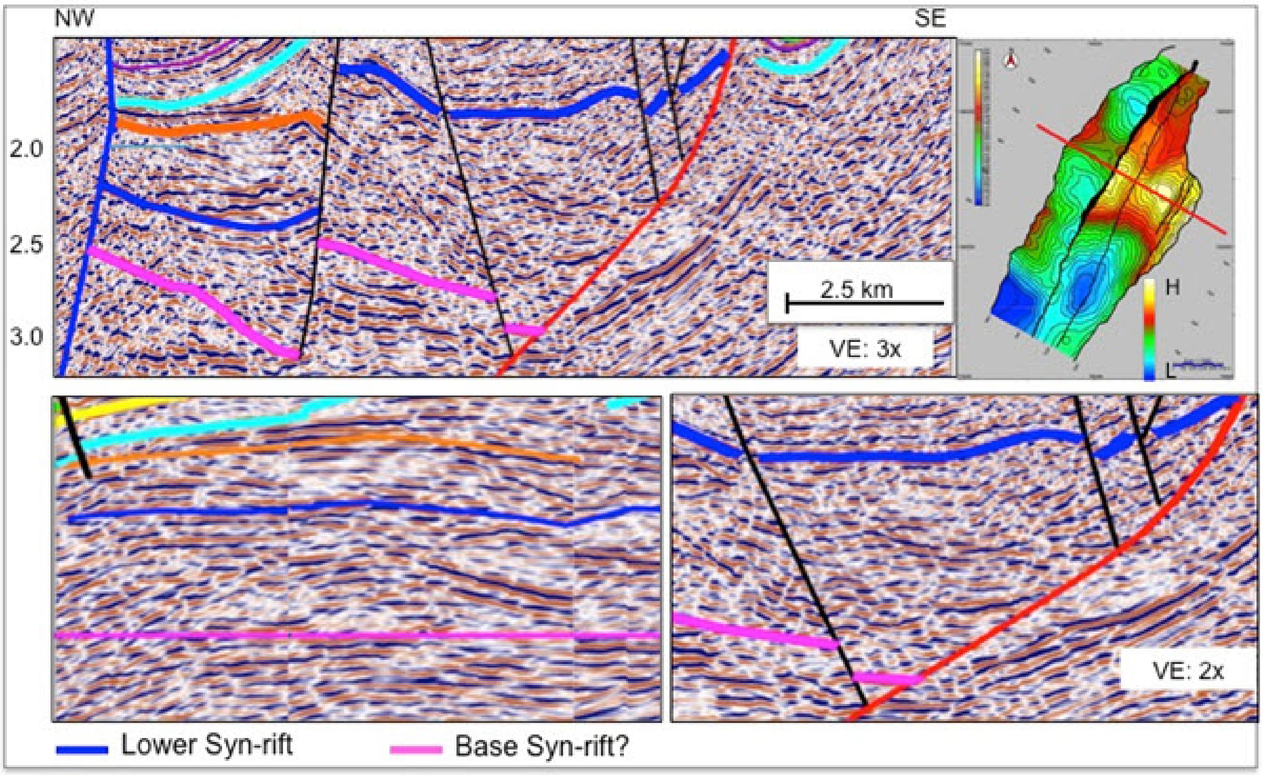

Figure 9. Potential reservoir distribution as shown by RMS (A) and Spectral Decomposition (B) with the red dashed line interpreted to be the channel belt in the Lower Syn-rift.

been penetrated in the well and not much can be said of its reservoir quality, the potential reservoirs are thicker and laterally extensive and could be more prospective than the reservoirs drilled by Malajon-1.

In the Lower Syn-rift where the sequence is generally thicker, mapping delineated reservoirs in a large-scale prograding delta which are laterally and vertically more extensive than in the Upper Syn-rift. Reservoir quality is not known but its potential appears to be more prospective than the alluvial fan.

Compaction has an effect on the reservoir quality of the syn-rift section but the effect of cementation is not known in the potential reservoirs deposited in channels and in deltas.

5. Conclusions

The study recognized the heterogeneity and complex stratigraphy in the half-graben with the sedimentary facies of different depositional environments identified in the area. The study also evaluated the reservoir potential of the sedimentary facies and their distribution. The conclusions that can be drawn from the study are as follows:

1. Petrographic analysis of ditch cuttings confirms the previous interpretation that the syn-rift section encountered by the Malajon-1 well is a sedimentary sequence rather than economic basement.
2. High amplitude response in the seismic is related to lithology and fluid contrasts.
3. The depositional facies vary across the half-graben. The facies identified for both Upper Syn-rift and the Lower Syn-rift sequences are deposited in a marine setting with terrestrial influence. Sedimentary facies are from alluvial fan, submarine channels/pelagic sediments and prograding delta.
4. Tectonic activity controlled depositional processes resulting in different depositional facies across the graben. Other factors that influence the lateral and vertical extents of the facies are sediment supply, relative sea level, accommodation space, sedimentation rate and subsidence rate.
5. Reservoirs encountered in the Malajon-1 well exhibit effects of compaction and cementation that impacted their porosity and permeability. The wet gas encountered in the well is migrated and not expelled in situ.
6. There is no significant gas-bearing reservoirs that are laterally and vertically extensive on the crest but down the flank which corresponds to the distal portion of alluvial fan and in channels. The more prospective reservoirs are found in facies interpreted to be deposited in a delta.

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