Testing the Tertiary Basin Floor Fan Play in the Gulf of Papua, PNG*

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Abstract

The Gulf of Papua (GoP) is situated offshore of the southern coast of Papua New Guinea. Present-day morphology of the continental shelf consists of a broad platform that extends 180km outboard of the coast in shallow water of approximately 100m. The dominant litho-stratigraphy is the prograding Plio-Pleistocene delta-front deposits accommodated in the actively-growing Moresby Trough foreland basin and earlier Tertiary rift basins. Over the past four decades oil and gas exploration has focused on Mesozoic clastic and Miocene carbonate targets in the GoP. The extensions of the prolific, Mesozoic reservoirs of the Toro and Digimu Formations are limited as they progressively sub-crop the major, base-Tertiary unconformity, caused by the uplift and rifting at northern end of the Coral Sea. The Miocene carbonate play has previously been successfully tested by a number of small gas and gas/condensate discoveries made in isolated reefal build-ups, initially identified on 2D seismic data.

Exploration in the Plio-Pleistocene basin has been enhanced by the acquisition and processing of some 6500 km^2 of high-quality 3D seismic in 2010. These data have enabled the mapping and better understanding of the thick prograding section with good imaging of an interpreted turbidite sand fairway, feeder channels/canyons, and fan sheets.

Advanced seismic interpretation techniques have been adopted, including seismic attribute analysis, AVO analysis and simultaneous AVO inversion using true-amplitude processed, pre-stack seismic data. The interpretation supported the model of deep-water, turbidite deposition in the GoP with the likely presence of porous sandstone reservoirs in the form of turbidite fan sheets, consistent with gas-bearing sandstone reservoirs determined by rock physics analysis and forward models.

A three-well drilling campaign was carried out in 2013 to test this new play, targeting seismic amplitude anomalies which ranged in depth from 2300m to 3200m. In each of the wells, high-quality, quartz-rich, sandstone turbidites were intersected. Although similar in seismic character and AVO response, some of the reservoirs contained low-saturation ‘fizz gas’ whilst others accommodated higher-saturation, free gas or a

combination of the two. However, the discovery of gas at a number of levels has proved that an active and effective petroleum system exists within the Plio-Pleistocene clastic intervals of the GoP and has opened up a new play fairway.

Introduction

The Gulf of Papua (GoP) region in PNG is dominated by the Pliocene to present-day deltas of the Fly, Bamu, Turama, and Lakekamu Rivers. The deltas are infilling the actively-growing Moresby Trough foreland basin, and the present-day delta platform extends out to about 120m water depth. Major deltaic clinoforms with vertical relief of several hundreds of meters up to 1000m are seen on seismic, prograding towards the ESE, swinging towards SSE

Historically, exploration for hydrocarbon in the GoP has targeted Miocene reef structures, with a number of successes in the Pandora, Pasca, and Uramu discoveries. During the ‘carbonate play’ exploration drilling, numerous thin beds of good reservoir-quality sandstone beds were encountered in number of wells. Although only a few meters in thickness, these gave sufficient encouragement to investigate the petroleum system in the potential turbidite sand play.

Geological and Tectonic Setting

Recently, exploration activity was renewed with the acquisition of Fugro multi-client 3D seismic surveys to develop the new exploration concept of turbidite sand sheet ultimately leading to three-well drilling campaign completed in 2013 which targeted Plio-Pleistocene age sandstone sheets ranging in depth between 2300-3200 mSS (Figure 1).

The tectonic history of PNG was initiated during Late Triassic to Early Jurassic, Gondwanaland rifting and passive margin sedimentation which includes the main reservoirs Toro and Digimu of the PNG onshore oil and gas fields. Offshore, the Mesozoic litho-stratigraphy was uplifted and eroded in the end-Tertiary, Coral Sea rifting.

Widespread carbonate deposition during Late Oligocene-Miocene of the Mendi-Darai Formations covered much of the Papuan Basin as evident in the onshore Foreland platform, the Highlands, and in the near offshore area, overlain by the Pliocene-Pleistocene clastics of the Orubadi-Era beds.

Reef build-ups were common in the Lower and Middle Miocene on paleo-highs, including long-lived basement highs such as the Pasca-Pandora Ridge. These pinnacle reef structures have been the main focus of PNG exploration onshore and offshore with gas and condensate discoveries in Pasca, Pandora, Uramu, and most recently the Elk-Antelope thrusted-reef gas field.

A clastic margin has dominated from the Middle Miocene to present-day with a very high influx of sediments resulting from the uplift and erosion of the Papuan Fold Belt. The large clastic influx was initially infilling the actively growing Tertiary basin with prograding delta clinoforms with vertical relief of several hundreds of meters up to 1000 meters in an ESE direction. Present day topsets are in up to 100m of water, dropping to >1000 meters in the eastern part of the Gulf.

Stratigraphy and Reservoirs

The litho-stratigraphy in the offshore basin can be divided into three mega-sequences; i) the Mesozoic clastics of Triassic-Jurassic syn-rift and post-rift, limited to the near shore area and deeply eroded on the highs, ii) the Eocene-Miocene carbonate platform with reefal build-ups, and iii) the Late-Tertiary deltaic sequence, the focus of this paper. A schematic section of the GoP stratigraphy from NW to SE is shown below in Figure 2.

The Late Tertiary (Plio-Pleistocene) deltas prograde across the GoP from west to east. The clinoforms seen on seismic typically have relief of up to 700ms to 1000ms from top-set to toe-set, and commonly exhibit a mid-slope break where they onlap ridges and prograde beyond them. A paleogeography map for Late Pliocene time (2.4MA) shown in Figure 3 defines a NE-trending delta slope break and depicts sand accumulated in the shelf with potential low-stand slope and basin deposits.

Gulf of Papua Turbidite System

The Plio-Pleistocene in the GoP comprises a mud-rich delta where high influxes of fine-grained sediment eroded from the PNG Highlands mountain range enter the basin via the major river systems. Although dominated by fine-grained clastics, the provenance for the Gulf basin also includes areas of larger uplift and deeper erosion, such as the Kubor High metamorphic core complex. This area includes granites, granodiorites, and high grade quartzo-feldspathic gneisses, which shed quartzose clastics into the offshore basin.

The acquisition of a modern 6,500 km^2 of 3D seismic by Fugro Multi-client in 2010 was fundamental to the identification and maturation of a turbidite sandstone play. Amplitude-friendly seismic data processing was undertaken to preserve relative seismic amplitudes for lithology identification, hydrocarbon effects, and direct hydrocarbon indicators (DHI). Calibration of the seismic to existing well data showed that sands exhibit a soft response relative to the surrounding mudstones.

Morphologically, slope canyons were identified (Figure 4) including some large canyons up to 2km wide and 200m deep, incised into the underlying Miocene carbonate platform and slope. They provided the conduit to fluvial sediments deposited on the shelf to bypass the slope in some areas during a drop in sea level, potentially depositing reservoir sand facies on the intra-slope and at the base of slope in the deeper water. The interpreted sands feeders and sheets appear to migrate laterally and vertically (Figure 5).

Rock Physics, AVO Forward Modelling, Seismic AVO Inversion

To confirm and further evaluate the basin-floor fan prospects, a thorough reservoir-characterization evaluation was carried out, both in-house and by specialist contractors. The primary objectives of these studies were to predict lithologies, reservoir quality, and pore fluids by:

i. Carrying out a rock-physics study to calibrate the existing well data to the seismic data such that elastic properties observed at the wells could be used to interpret the elastic seismic inversion results

ii. Building AVO forward models to predict the reservoir properties responsible for the seismic AVO responses of the prospects.
iii. Generating AVO attributes from the seismic data
iv. Performing simultaneous seismic AVO inversion

A rock-physics analysis was firstly carried out to establish relationships between the petrophysical properties of the well logs with the acoustic parameters of the seismic data. Analogue sandstones intersected in the Pasca wells were used to calibrate the rock-physics models. Prior to carrying out the rock-physics workflow it was ensured that appropriate well log conditioning was carried out.

Forward AVO modelling was then conducted based on the resulting rock-physics model. A compaction trend was applied to account for the varying depth of each of the prospects. Wedge models were generated for sandstone reservoirs containing brine, gas and oil, and also combinations of the aforementioned (Figure 6). The models concluded that:

i. A brine filled reservoir should exhibit a Class I to Class II AVO response.
ii. An oil filled reservoir should exhibit a Class II AVO response
iii. A gas filled reservoir should exhibit a Class III AVO response

Characteristics of the AVO Anomalies

Each of the anomalies identified and thought to represent sandstones, are represented by amplitude events with consistent AVO anomaly signatures. Negative amplitudes at all offsets are believed to arise from a downward decrease in acoustic impedance across a lithologic boundary, a soft event. Near-offset amplitude is negative and only slightly above background. Amplitudes become increasingly negative with offset, consistent with a typical Class III AVO signature. The ratio of far offset to near offset amplitudes is generally between 2 and 3. Comparing real traces from angles stacks through the amplitude anomalies shows a good comparison to the modelled gas sand response (Figure 7).

AVO Attributes and Seismic AVO Inversion

Seismic AVO attributes were generated, as well as pre-stack, simultaneous AVO inversion to compute seismic elastic attributes. The AVO attributes provide a qualitative view of the AVO anomalies in the form of intercept and gradient, as well as various combinations of these two attributes (i.e. intercept*gradient product, AVA index, scaled Poissons ratio, etc.). Intercept-gradient plots were derived directly from the seismic amplitude varying with offset/angle of each of the seismic traces within the seismic anomalies to be compared to the AVO forward models to ascertain which reservoir properties best represent the anomalies.

AVO inversion provides a quantitative assessment of the anomaly which can be compared directly to well log measurements. The seismic elastic attributes computed in these studies were acoustic impedance, Vp/Vs ratio, Poissons ratio, density and band index which were ultimately used to infer lithologies and fluid properties. Acoustic impedance proved to be effective as a lithology indicator (low acoustic impedance for sandstones), whilst the VpVs and Poisson ratio is critical to determine the type of fluids occupying the pore spaces (brine, oil, or gas). As hydrocarbon-charged sandstones were modelled to be of low acoustic impedance and low Vp/Vs, these AVO inversion products proved critical in ranking which turbidite fans were to be drilled. An example showing the sequence of going from seismic amplitudes to elastics parameters is shown below in Figure 8.

Although the advanced forms of seismic interpretation described above are capable of determining the types of fluids contained in certain reservoirs, it is not capable of ascertaining saturations of these fluids. This means that the techniques may be able to infer that there is gas in a reservoir, but it is generally unable to distinguish high saturation gas (e.g., Sg of 80%) from low saturation ‘fizz gas’ (e.g. Sg of 10%).

Drilling Campaign

Three wells were drilled during 2013 using a semi-submersible drilling rig. All wells safely achieved pre-drill objectives, reaching the reservoirs ranging in depths from 2300mSS to 3200mSS. Initially a pilot hole was drilled to mitigate the potential shallow gas risk. Of the five seismic anomalies targeted, quartz-rich reservoir sands deposited in the form of deep water fans were intersected at each anomaly. The sandstone reservoirs proved to be of significant thicknesses, up to 55 meters. Two of the target levels contained high saturation gas, whilst the other three contained low saturation ‘*fizz gas*’.

The most significant discovery was located down dip from the crest in a combined structural/stratigraphic trap comprising a prominent seismic event with bright seismic amplitude of Late Pliocene age (Figure 9). The sand had deposited in elongated NNW-SSE orientation, controlled by the morphology of the underlying carbonate build-ups. The well has confirmed the presence of good-quality sand deep offshore with 55m gross sands penetrated with a high net/gross ratio. The sand has a gas saturation of approximately 50% Sg.

Conclusions

A three-well drilling campaign was carried out in 2013 to test an interpreted basin-floor fan play in the Gulf of Papua. Numerous turbidite sand deposits were identified firstly in 2D seismic and later better-delineated by modern 3D seismic. Each of the basin floor fan prospects were mapped and had advanced seismic interpretation techniques applied to de-risk and rank each of them. The highly-ranked fans exhibited Class III AVO anomalies, consistent with gas-charged sand reservoirs and indicated by rock-physics and AVO forward models.

The three wells intersected the anticipated five seismic anomalies. All five contained good-quality, quartz-rich sands with good porosities and thicknesses, up to 55m. Two of the sand bodies comprised high-saturation gas, whilst the others also contained gas, however it was low-saturation ‘fizz gas’. The gas found in each of the reservoirs was biogenic, believed to have been sourced from the thick surrounding shales. One of the key risks of these prospects was the charge, i.e. the seismic technique’s inability to distinguish low saturation gas from high saturation gas.

The discovery of gas in the two of the five prospects drilled has proved an active petroleum system exists in the Gulf of Papua and has opened up a new Tertiary basin floor fan play fairway.

Acknowledgements

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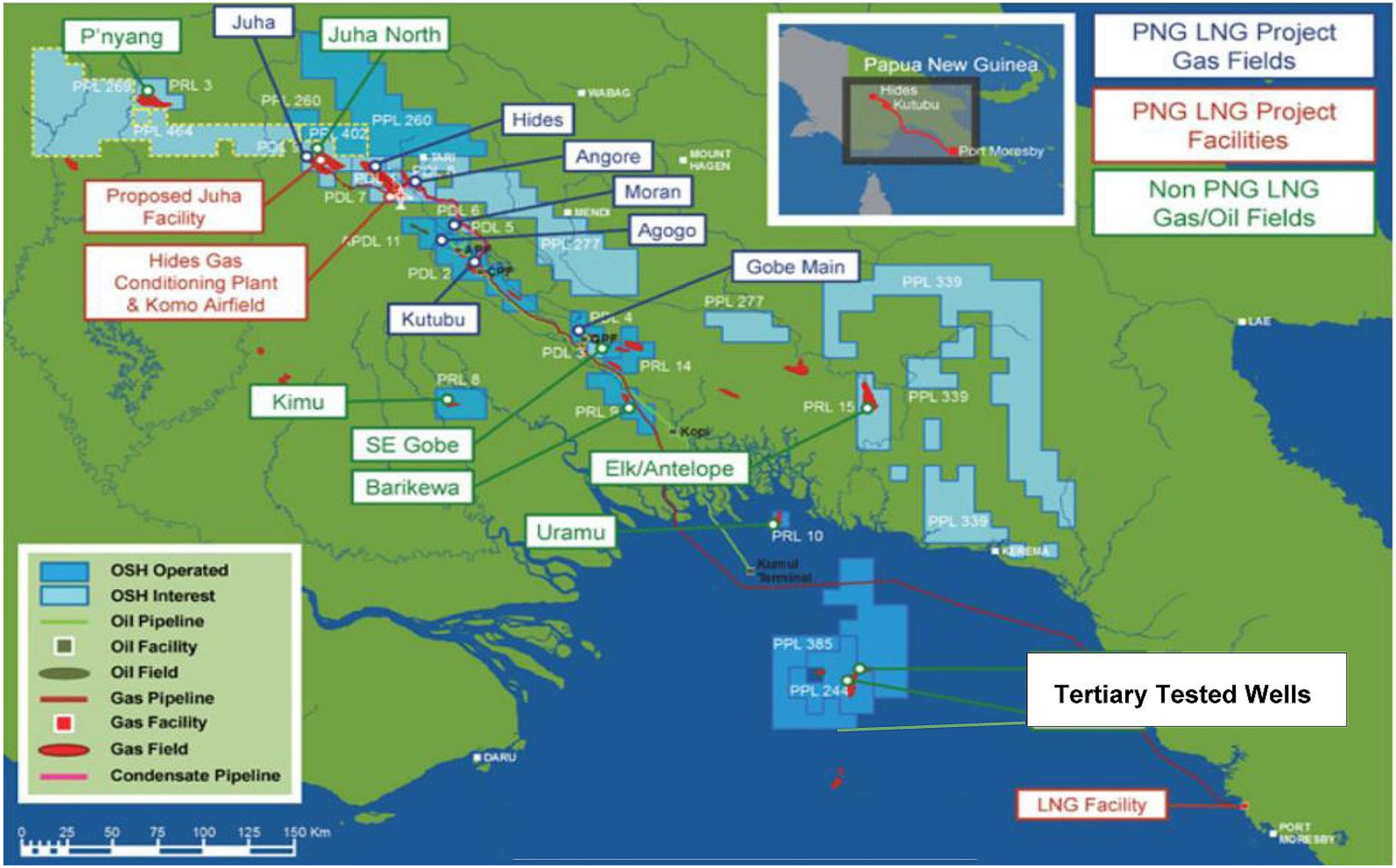

Figure 1. Location map for the offshore area of interest in the Gulf of Papua, PNG.

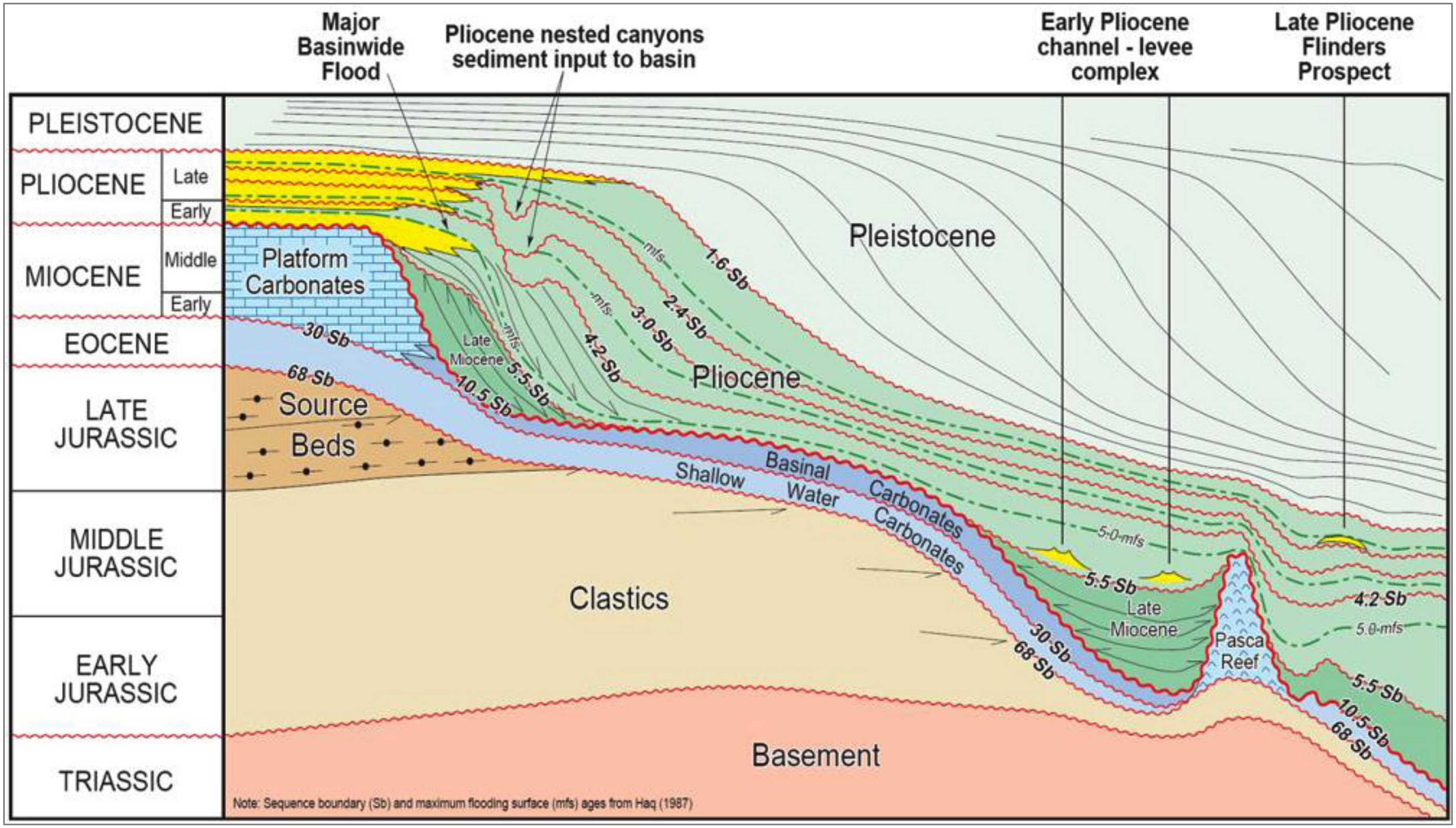

Figure 2. Conceptual diagram of the offshore GOP stratigraphy, from NW to SE, showing potential slope or basin-floor sands.

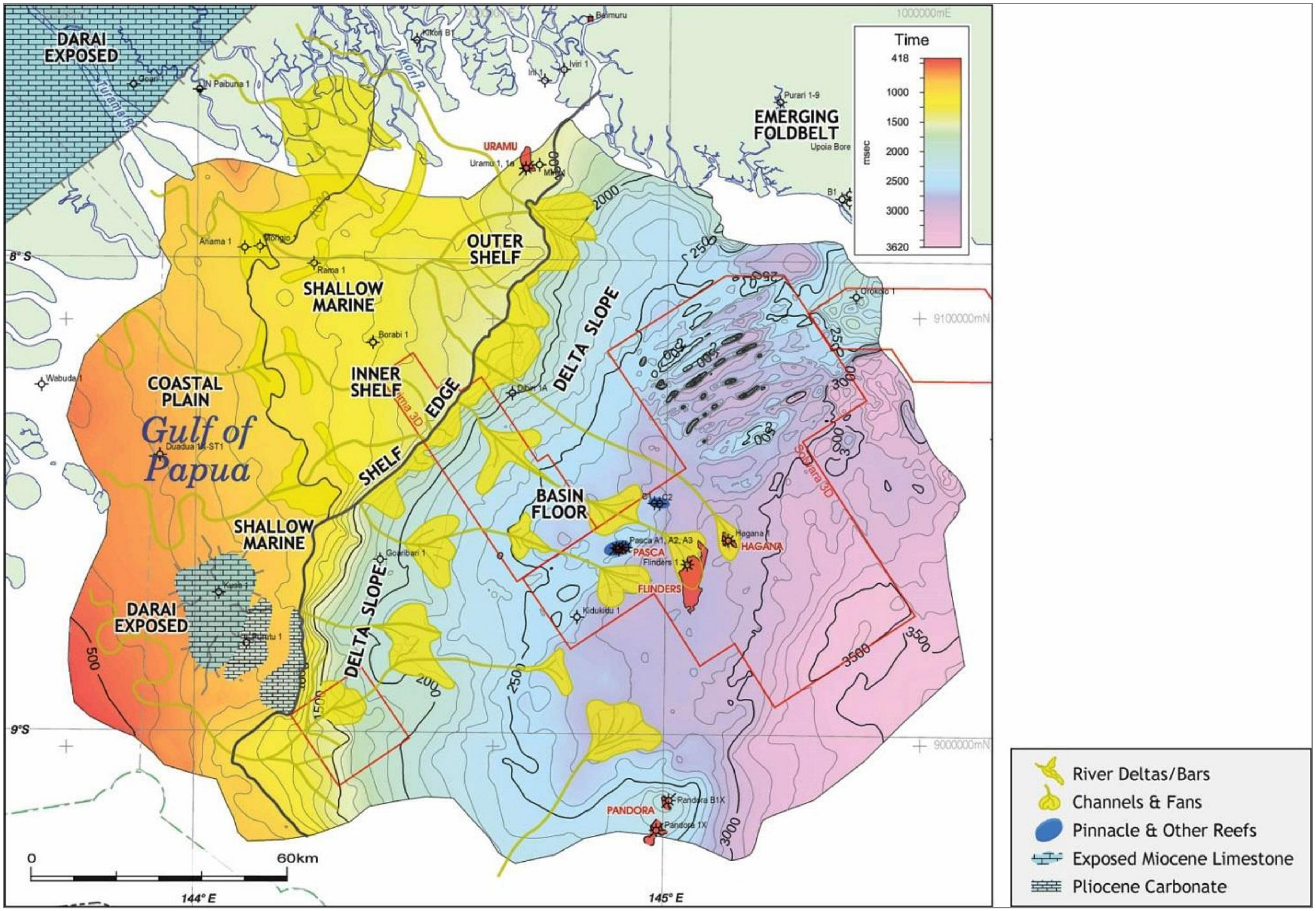

Figure 3. Paleogeography map of the Upper Pliocene - 2.4MA. The transport of sand can be seen coming in from the onshore in the west to deposit as fans in the Gulf of Papua depo-center. The 3D seismic surveys are represented by the red polygons.

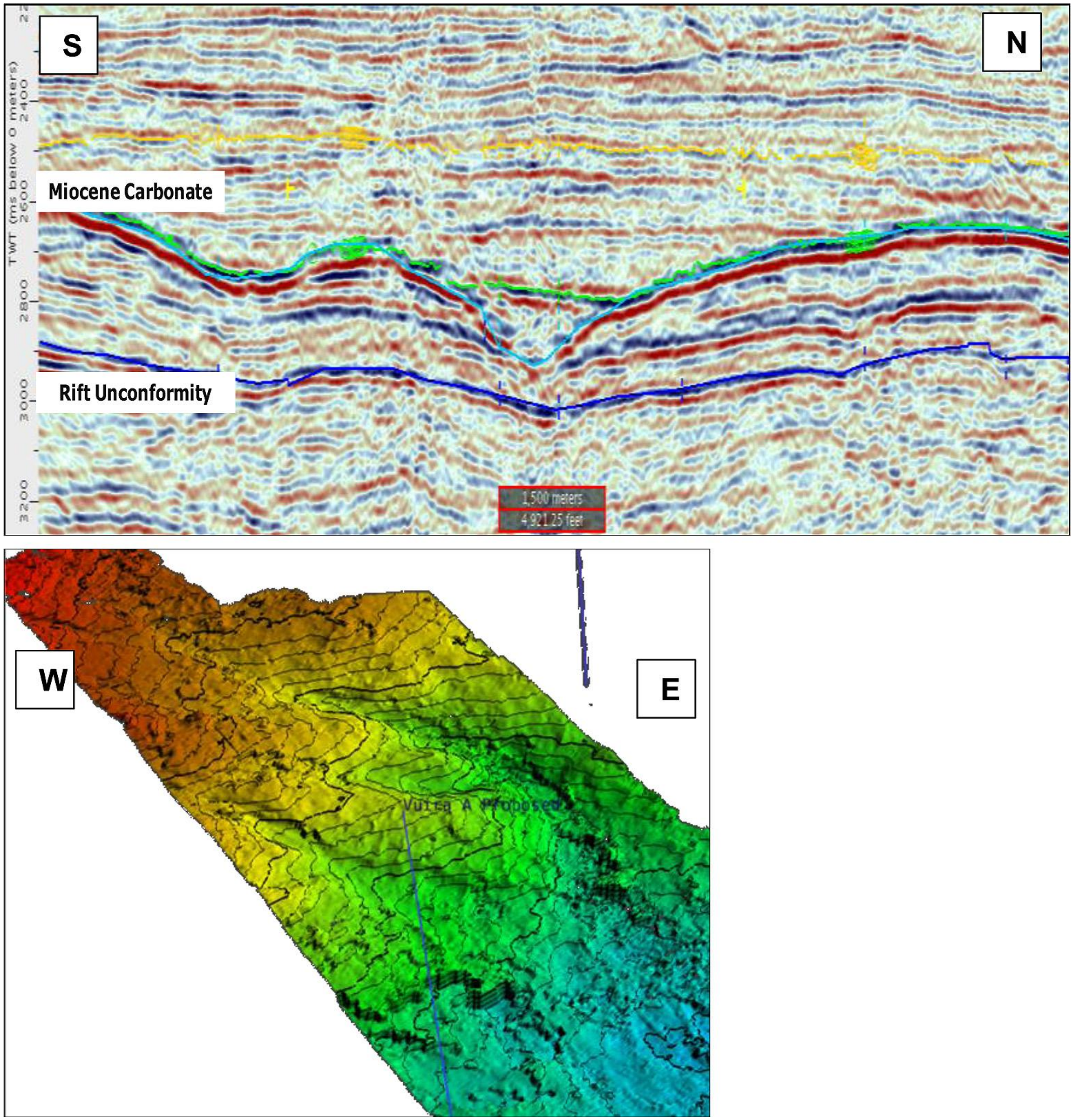

Figure 4. Erosional channel/canyon in carbonate slope (top). Mapped carbonate slope surface showing the sand feeder system from the west to east (bottom).

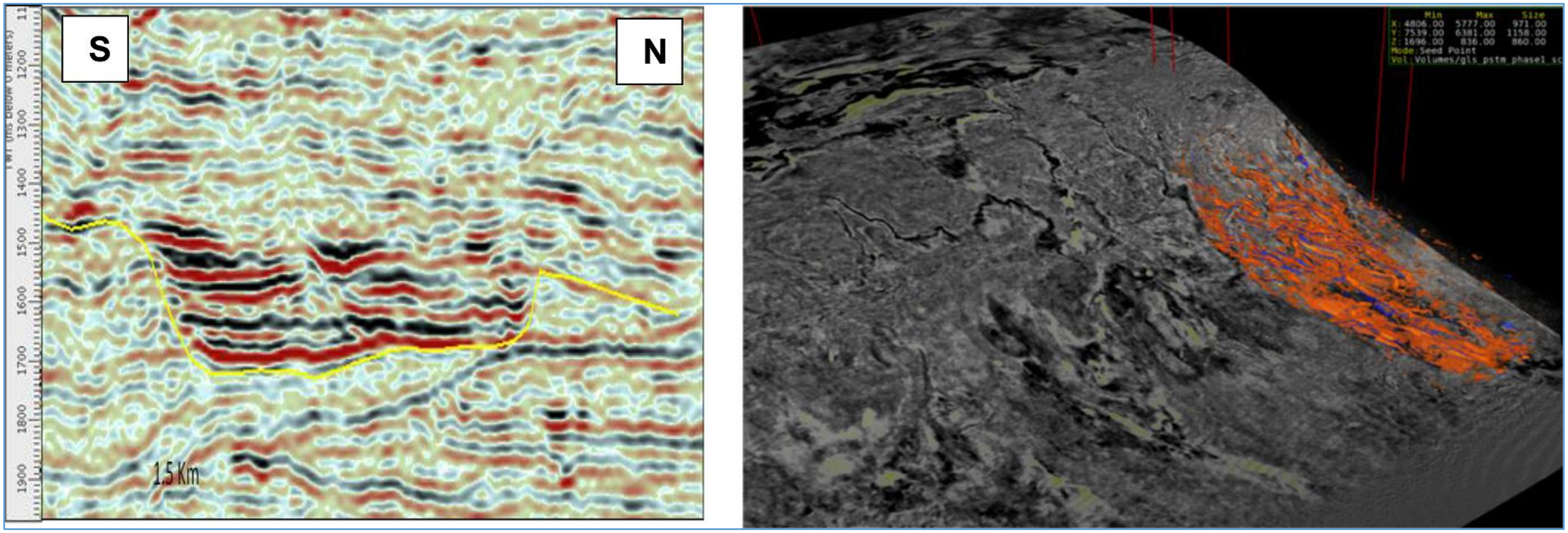

Figure 5. Pleistocene channel-fill sands. Seismic section (left) and amplitude geobody on a Pleistocene slope (right).

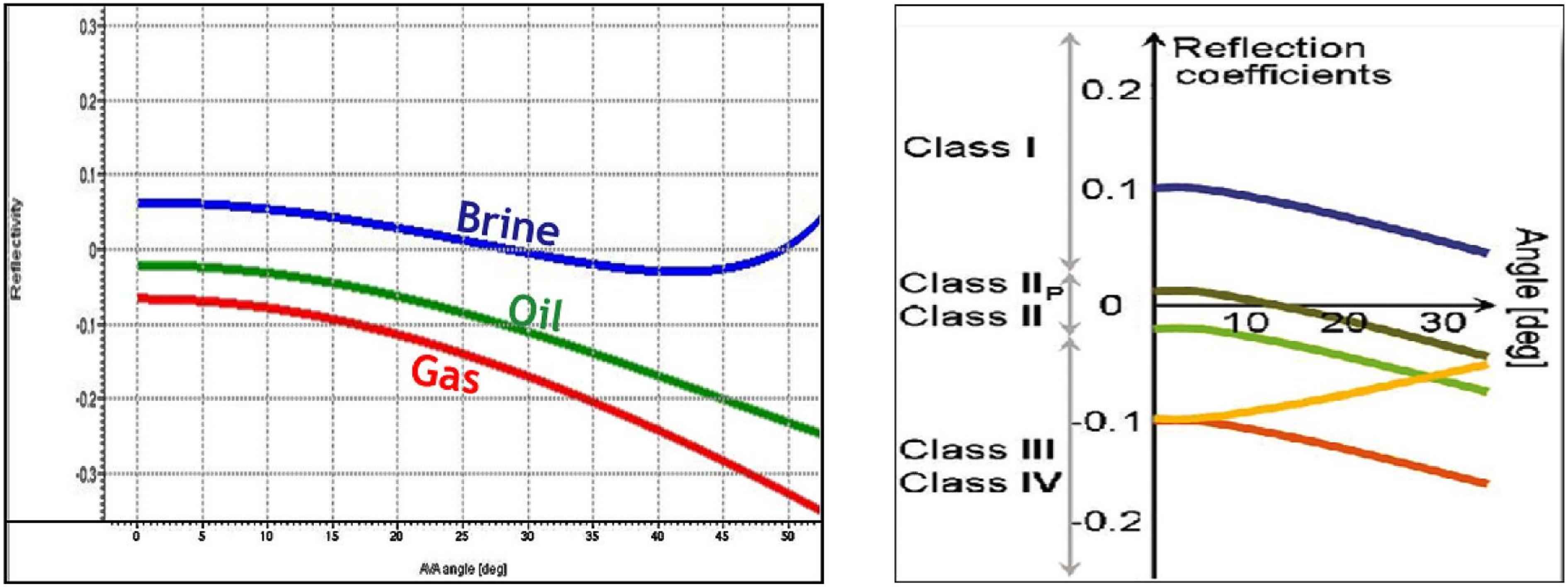

Figure 6. Forward AVO models were constructed based on the rock physics model, fluid substitution, and compaction trend for the 3 different fluid scenarios: brine, oil, and gas (left). Oil scenario is a Class II AVO response, and gas is a Class III AVO response.

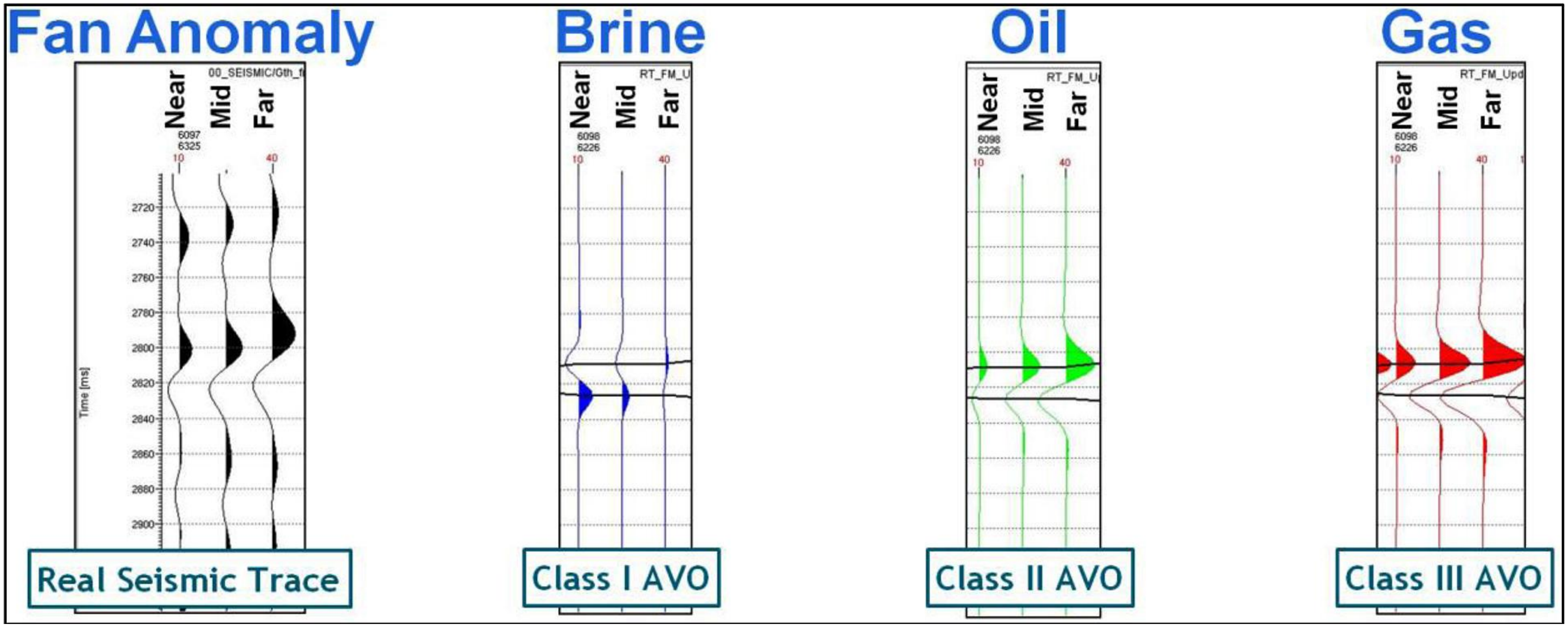

Figure 7. Comparison of actual seismic angle stack amplitudes (near, mid, far) with the modelled responses of brine, oil, and gas reservoirs. It can be seen that the real seismic AVO response is most similar to the modeled gas response.

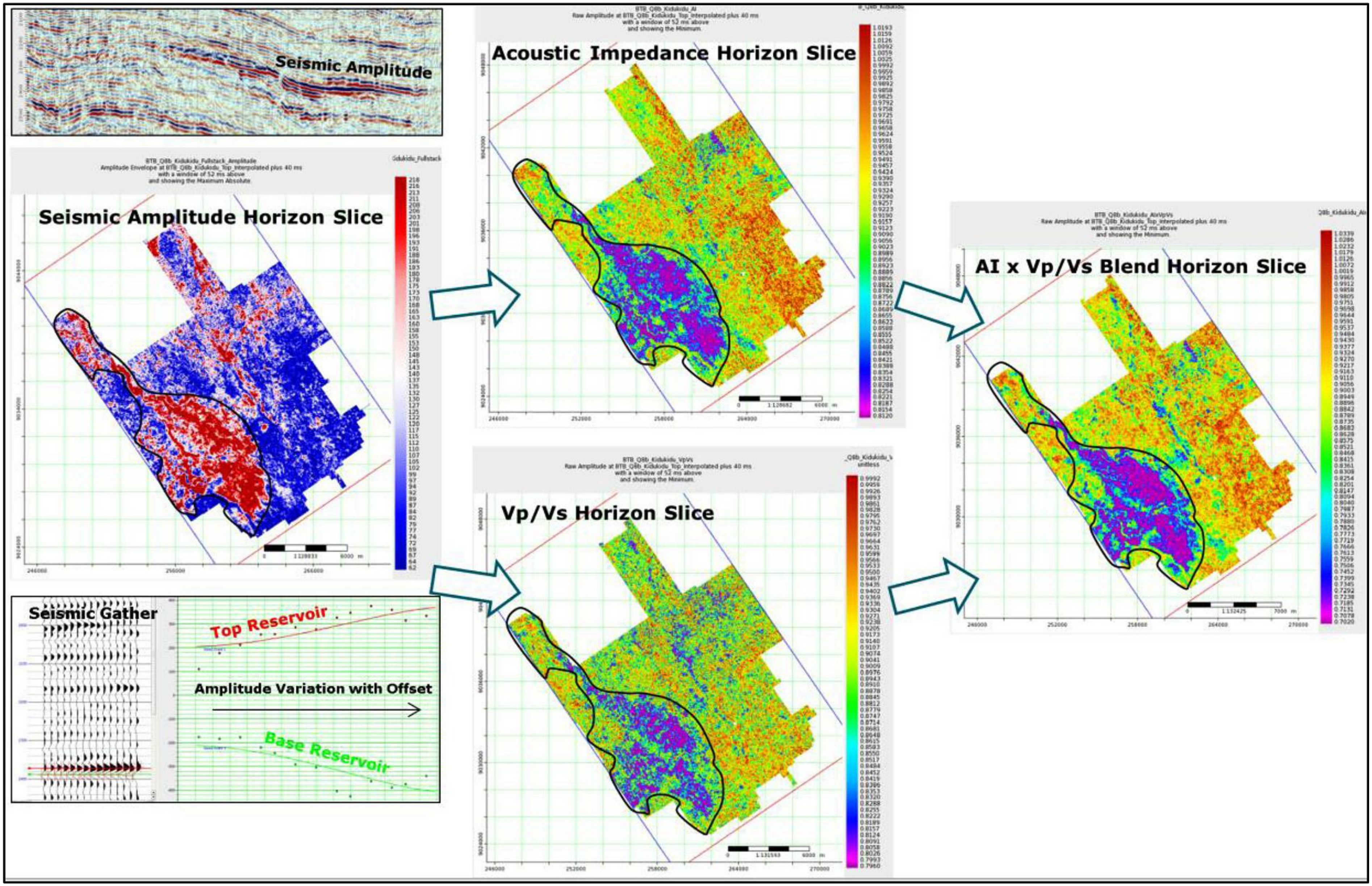

Figure 8. From seismic amplitudes (left) to elastic properties (acoustic impedance and vp/vs) (center). Where there is a location of common low acoustic impedance and low vp/vs (right), there is a high probability of a gas charged reservoir.

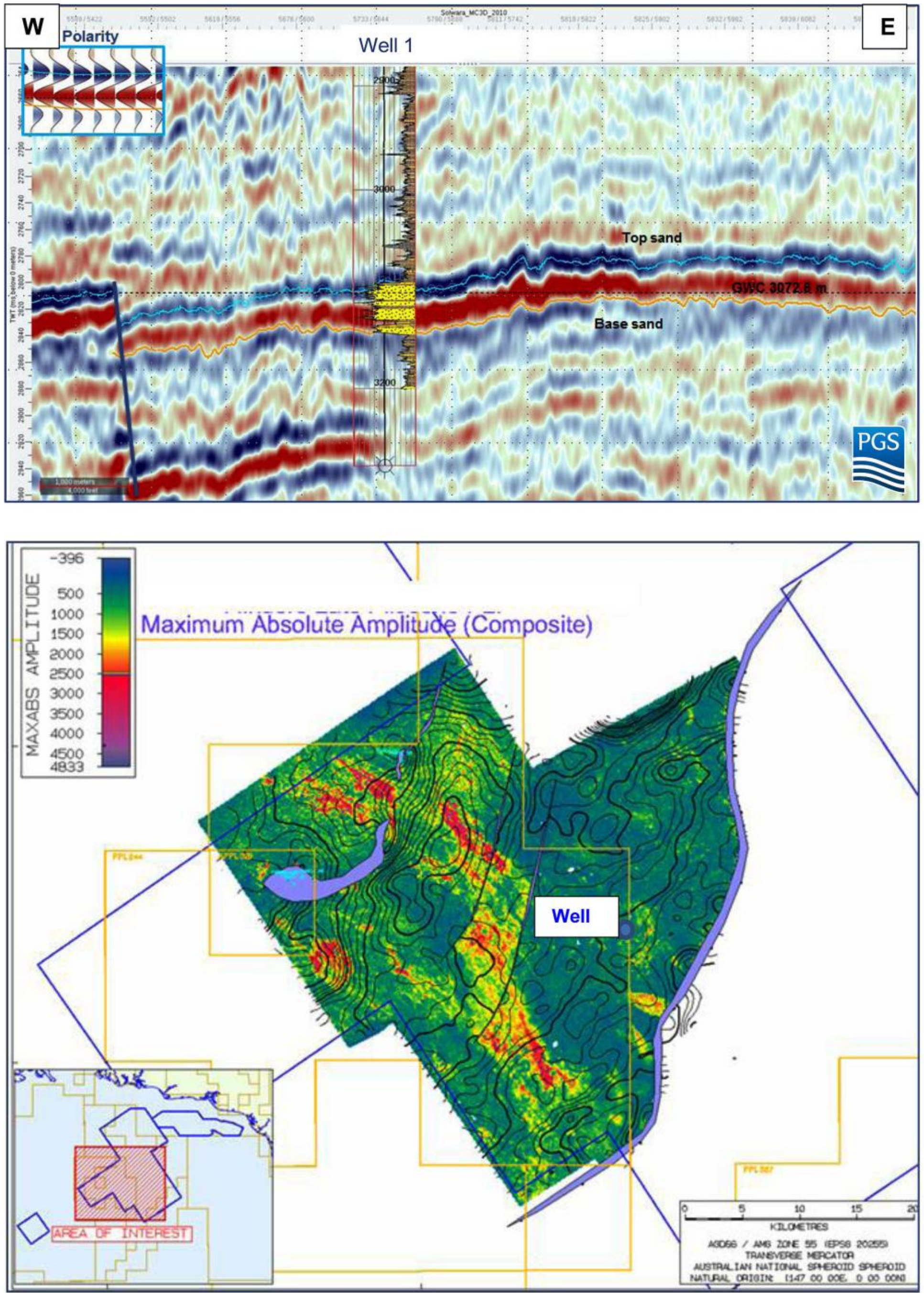

Figure 9. Drilled turbidite sand sheet. Seismic section with lithology log overlaid (top), and a maximum seismic amplitude horizon slice (bottom).