Innovative 3-D Reservoir Characterization in the Papua New Guinea Fold Belt*

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Abstract

The primary reservoir units of the PNG Highlands include shoreface and incised-valley estuarine sandstone deposits within the Late Jurassic and Early Cretaceous Imburu and Toro Sandstone formations. Regional understanding of both the depositional environments in which these sands were deposited and their extent, is key to building accurate field-scale geological models. In the absence of good quality seismic data, this study uses various input data from 100–150 wells spread along 300 km of the fold belt to predict reservoir presence and quality. Data types include: core sedimentological interpretation, core analysis, well tops, and well logs to predict reservoir presence and quality. True Stratigraphic Thickness maps, Neural-Network based lithofacies logs, and normalised GR logs have subsequently been generated and used to produce a Regional 3D Petrel volume from which properties can be fed directly into field-scale models. Markov Chain, GR cut-offs, and Neural-Network based analysis on normalized GR have all been tested as a means to generate depositional facies for each reservoir unit. The result shows laterally and vertically extensive shoreface and incised-valley deposits that continue for 10's to 100's of kilometres along the fold belt. Numerous offset wells, and wells positioned off structure, help control the proximal-to-distal relationships and show an overall onshore-to-offshore trend from SW to NE with two main sediment inputs coming from the SE and the NW. Shorter range variability in the model is introduced by populating the depositional facies with lithofacies. Each lithofacies has been assessed in terms of rock quality using both qualitative and quantitative datasets including: routine core analysis, petrology, AFTA, and vitrinite reflectance data to populate the model with meaningful porosity and permeability values. Results show that the impact of burial history and rock composition is subtle but significant and gives insight as to the role the post-depositional history has played on the present regional properties distribution. The collective result of this study shows a consistent and common interpretation of the reservoir stratigraphy and properties between all of the PNG Highland Fields.

Introduction

The area of interest for this study covers the Papua New Guinea (PNG) Highlands Fold Belt from P'nyang Field in the North-West to Iehi Field in the South-East (Figure 1). The main sequences studied include the primary reservoir units: Iagifu, Hedinia, and Digimu members of the

Imburu Formation, and Toro Sandstone. Each of these units were subdivided into separate reservoir zones for modelling purposes (Figure 1).

The principal objective of this study was to build a regional-scale 3D Petrel model that incorporates a full understanding of key datasets from the primary reservoir units, the properties of which can then be either directly downloaded into or reproduced at the field scale.

In order to provide a pseudo-palaeogeographical reconstruction of the depositional settings, all wells have been flattened to a common datum, the regionally extensive Imburu A MFS. The unstructured flattened space (facies box) allowed the study of reciprocal relationships between geological formations, where subsidence rate is assumed constant and aggradational-progradational parasequences are mainly controlled by sediment supply and accommodation.

In the absence of high-quality seismic data, this study analyses all available full-core, petrology, and wireline-log datasets from 156 wells spread along 300 km of the PNG Highlands Fold Belt. The collective result shows a consistent and common interpretation of the reservoir stratigraphy and properties between all of the PNG Highlands Fold Belt fields, allowing for better prediction and understanding of reservoir quality and performance overall. The advantage of this methodology is that it is multidisciplinary and promotes better communication between geo-modellers and other disciplines, resulting in an improved alignment of ideas and ultimately better, and more internally consistent, field-scale geological models.

Reservoir Characterisation

A standard suite of analytical techniques have been used to help understand and characterise the type and distribution of sediments within the reservoir units, including conventional core interpretation, routine core analysis, well log interpretation and well correlation. The well correlation data provided the basis of regional true stratigraphic thickness (TST) maps.

Detailed sedimentological descriptions of conventional cores from over 40 wells, analysed within a rigid framework, provided a rigorous and consistent data set from which to extract sand-body architectural and reservoir-quality elements for the regional model. Each core was also described in terms of lithofacies and depositional facies (depofacies) and these, along with wireline logs, were used as the basis for populating both elements away from core control.

Lithofacies are rock units characterised by rock texture and composition, with grain size and sorting forming the primary discriminators. Lithofacies form the basic building blocks of vertical facies-sequence analysis that define depofacies and depositional settings. Lithofacies also provide a link between the fine-scale petrophysical properties of the rocks and the larger-scale sequence stratigraphic framework. Nine lithofacies make up the bulk of the rocks analysed in this study (Table 1). Lithofacies have been generated for the uncored intervals in all wells using a neural-network based workflow (detailed below).

The Iagifu and Hedinia members and Toro Sandstone are predominantly made up of nearshore-marine shoreface deposits comprising upper-shoreface, middle-shoreface, lower-shoreface, upper-offshore, and lower-offshore depositional facies. The Digimu Member and parts of the

Iagifu Member in the south-east region comprise incised valley-fill estuarine mouth-bar and estuarine central-basin depositional facies. The inter-reservoir depositional facies are typically inner- and outer-shelf muds.

Porosity and permeability, by lithofacies, were assessed using both qualitative and quantitative datasets including: routine core analysis, petrography, and burial history (AFTA, vitrinite reflectance and structural analysis). Because the sandstones of the Imburu and Toro formations are mostly quartzarenites with minor labile components, their diagenetic history was relatively simple and remarkably similar throughout the length of the fold belt. Reservoir quality degradation was primarily from authigenic quartz overgrowths formed in direct response to maximum burial depth and temperature (Tmax). Using the results of this analysis it was possible to explain and predict reservoir quality variations throughout the PNG Fold Belt in terms of local post-depositional history.

Log Normalisation and Neural Network

To populate lithofacies away from core control, this study utilised 29 wells that had both high-quality full-core interpretation and petrophysical-log data sets. The log suite was normalised, brine-filled and used as a training set for the artificial neural-network workflow, generating a Multi-Resolution Graph-based Clustering (MRGC) electrofacies model.

The modelled logs consisted of Gamma Ray, Neutron, Density, Compressional Acoustic Slowness, and Neutron-Density separation, and were trained using MRGC against a supervising log, namely the lithofacies description. The total of 129 possible lithofacies identified in core were condensed or combined into 44 key lithofacies from which 23 discrete electrofacies were identified, without significant reduction in the described geological facies (Figure 2).

A 10th nearest-neighbour artificial neural network was applied to the training dataset to propagate the electrofacies over the cored intervals and extended over the targeted reservoir intervals. An iterative reworking of the data was required where the modelled logs had been normalised to remove spurious data points believed to have influenced the training data model prior to acceptance.

Qualifying the appropriateness of the electrofacies model was validated by using a Similarity Threshold Model (STM) as a simple traffic light array, enabling the end user to quickly and efficiently see the appropriateness of the fit. For the model to be considered valid, an acceptance of >95% confidence was used with data plotting outside the 10th nearest neighbour barycentres, and rejected if <90% confidence was displayed. Propagation of the k-NN (number of nearest neighbours) lithofacies model was extended over wells without cores, with excellent results.

An additional layer of complexity was added to those final datasets where a quantifying flag was required to highlight facies that may have been incorrectly assigned, even though the mathematical solution on the k-NN STM model may have had high confidence. This flag was based on the mean of the STM array, and was assessed in an iterative process with the modelling geologist prior to incorporation in the final data set.

3D Static Modelling

The Imburu Formation and Toro Sandstone reservoir sequences were deposited in a very uniform depositional setting within the study area.

Nearshore and estuarine facies dominate, and the reservoir sandstones have very uniform rock textures and compositions. This uniformity permitted the reliable use of GR as a regional proxy for depositional facies. Using normalised GR, and analysing for both vertical and lateral trends, a 3D volume of GR was converted into a depofacies model for the entire Imburu and Toro formations using a straight cut-off methodology as a first-pass (Figure 3). The more statistically driven Hidden Markov Chain Model, using lithofacies from core as observations, was also used. Because of the non-uniqueness of the relationships, both techniques still required some level of hand editing after the first-pass conversion.

Working at the regional scale, the results demonstrate lateral and vertical continuity of nearshore and incised valley-fill deposits for 10’s to 100’s of kilometres along the fold belt. Numerous offset wells, and wells positioned off structure, help control the proximal-to-distal relationships. They show an overall onshore-to-offshore trend from SW to NE, with two main sediment inputs, one in the southeast and the other in the northwest. Prograding and retrograding relationships can also be seen on a scale not always visible at the field scale.

Lithofacies, which are key to the fundamental rock properties of porosity, permeability and hydrocarbon saturation, are populated within the depofacies model using the standard Petrel hierarchical methodology. Lithofacies do not have an inherent architecture, at least not at a mappable scale, but can be recognised in wireline logs and are predictable within the assigned sedimentological framework. They can therefore, be distributed in 3D space within the geological model.

The relationship between lithofacies and rock quality (porosity, permeability, and saturation) was assessed for all Imburu and Toro reservoir sandstones using an extensive conventional core dataset comprising routine core analyses, petrography and diagenetic studies (thin sections, XRD, and SEM/EDS) and basin modelling. Variations in grain texture (size and sorting), microporosity, —diagenetic impact” (including quartz overgrowth, carbonate and cements), Tmax, and porosity have been correlated to permeability and regional trends. The results show that Tmax has a measureable impact on reservoir quality with an increasing temperature trend as you move from Gobe Field in the southeast to Juha Field in the northwest (Figure 4). Most obvious is the impact Tmax has on the S_1 lithofacies in Juha Field, where elevated temperatures (probably burial related) have significantly reduced rock quality in that field. The clear advantage of assessing reservoir poro-perm properties with an integrated and regional approach is the enhanced ability to predict reservoir quality within a consistent geological framework, and at the same time recognise local anomalies.

Results and Conclusion

The lack of high-quality seismic data, and the resulting high degree of structural uncertainty in this highly compressional terrain of the PNG Highlands Fold Belt, necessitates new and innovative ways by which to build accurate, field-scale geological models. Aided by a significant number of wells with good core coverage, and using a standard suite of analytical techniques to help understand and characterise the type and distribution of sediments within the reservoir units, the principle objective of this study has been achieved — a regional-scale 3D Petrel model. In addition, properties from this model can then be either directly downloaded into or reproduced at the field scale. Using this extensive regional dataset lends itself to a new and multidisciplinary approach involving field and reservoir geologists, sedimentologists, petrographers, petrophysicists, and structural and basin analysts, in order to derive better field models with vastly improved predictive capabilities.

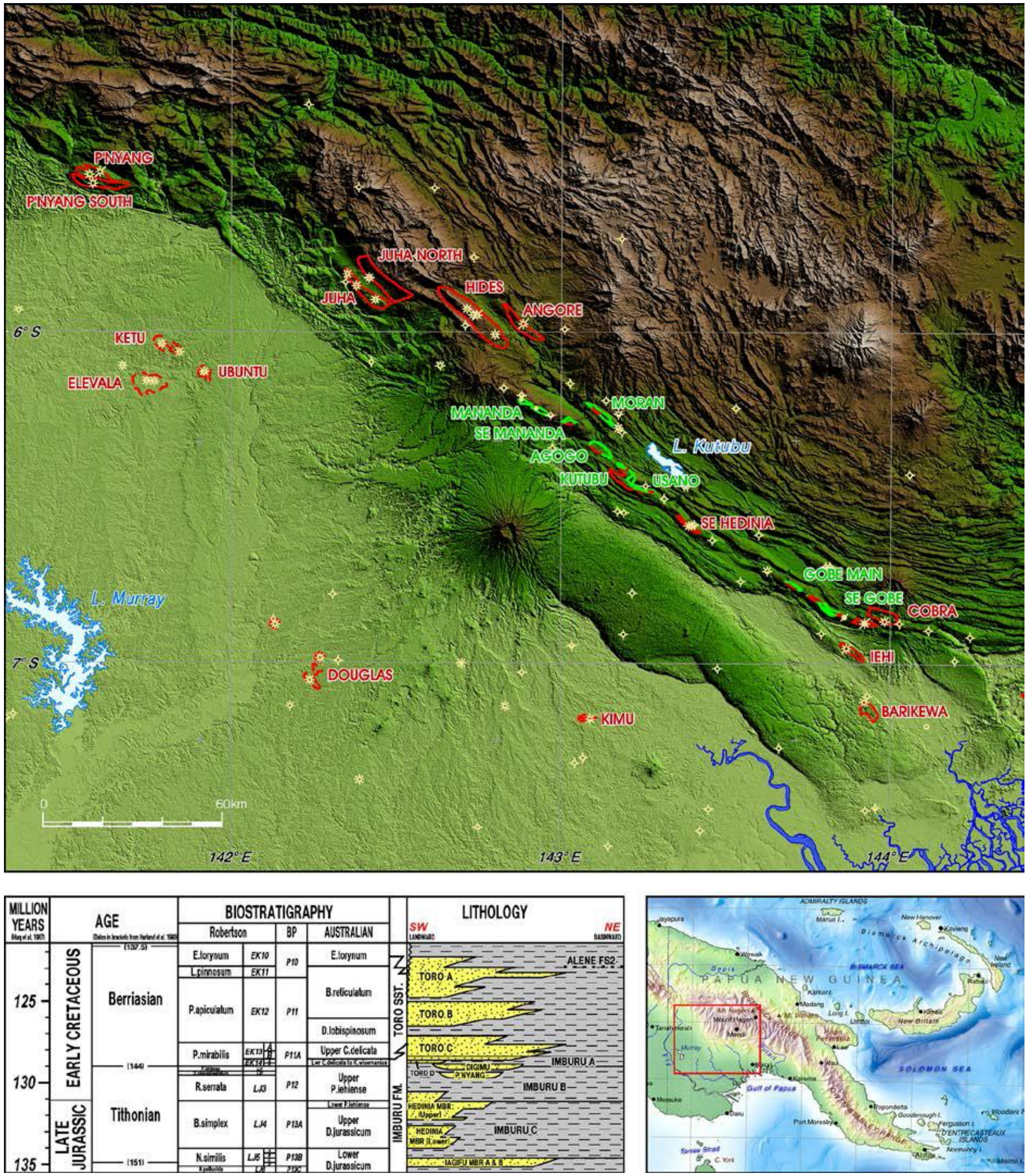


Figure 1. Location, study area and reservoir stratigraphy.

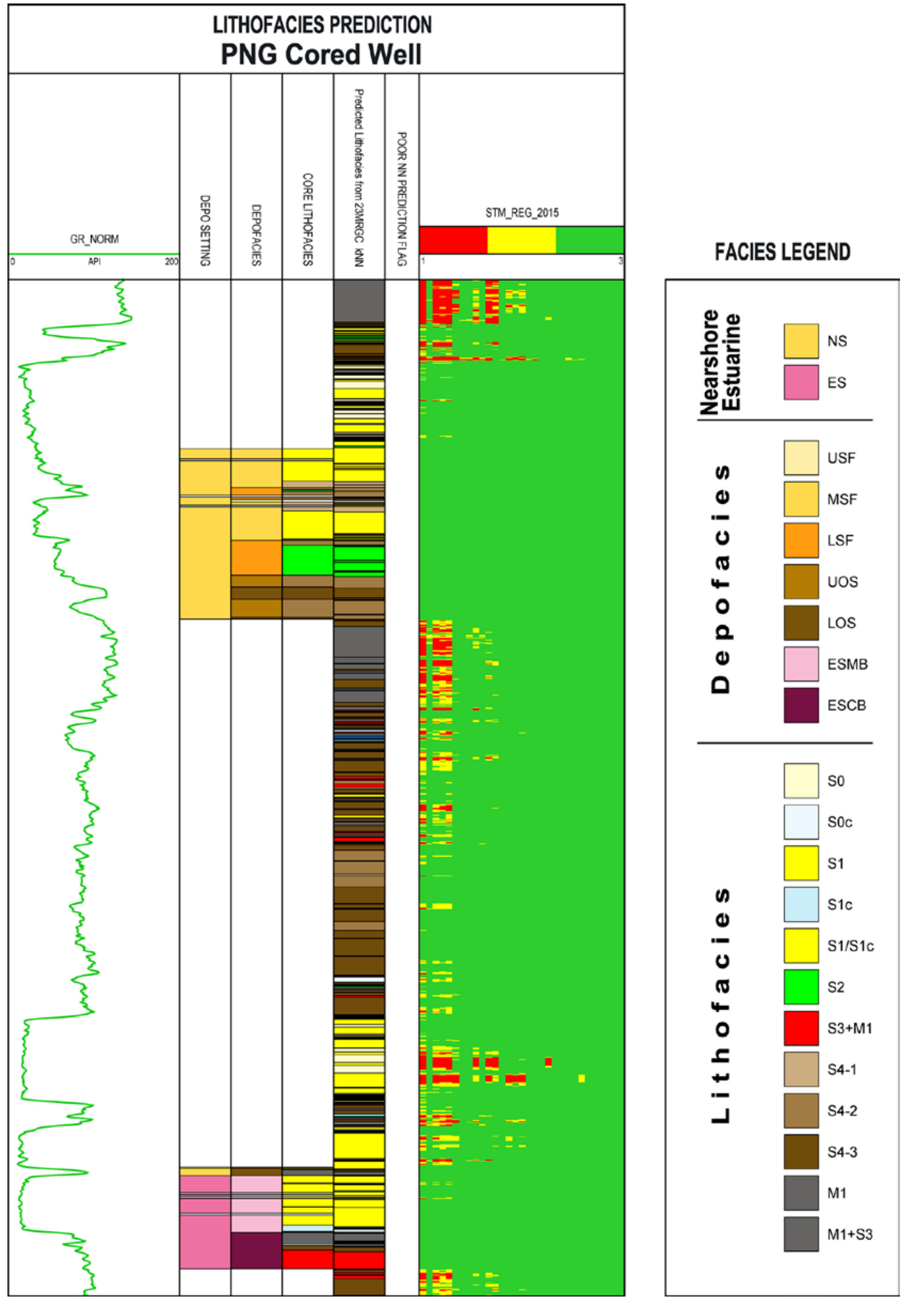


Figure 2. Core interpreted depositional setting, depofacies and lithofacies against normalised GR and MRGC predicted lithofacies from neural network workflow (track no.5). STM traffic light array: Green >95% confidence, yellow >90%<95% and red <90% confidence in result.

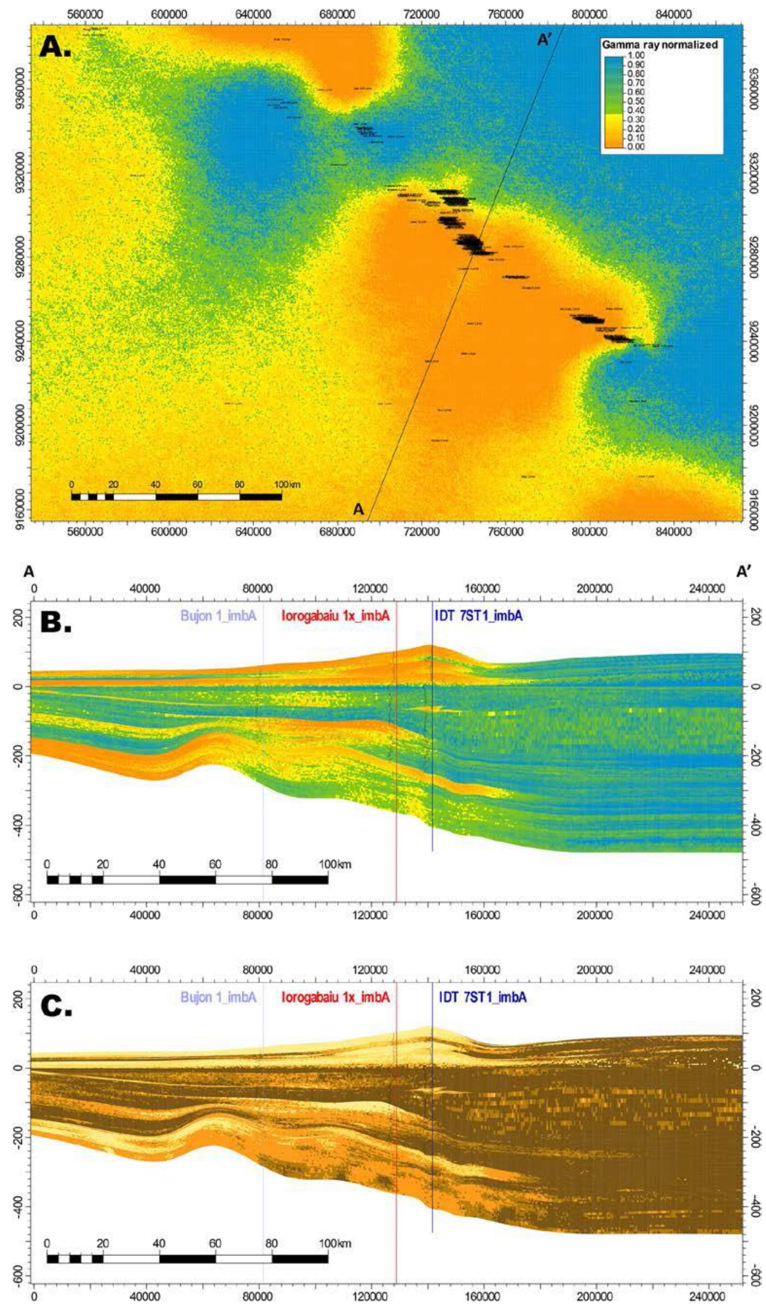
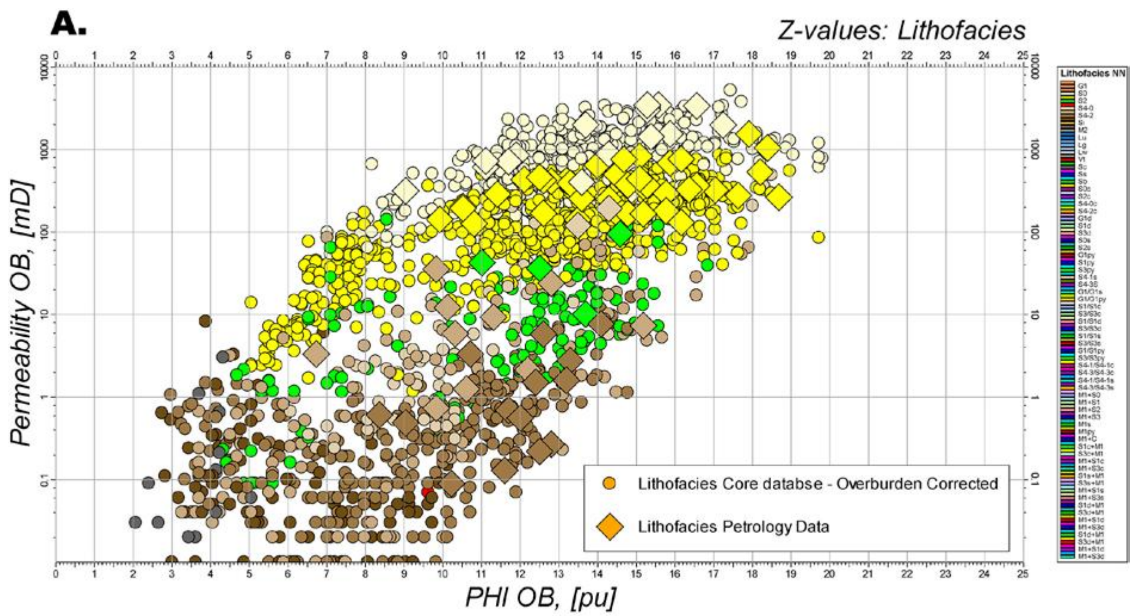


Figure 3. A) Normalised GR map at Toro level. B) Cross-section (A-A') of normalised GR and C) first pass conversion of normalised GR into depofacies.



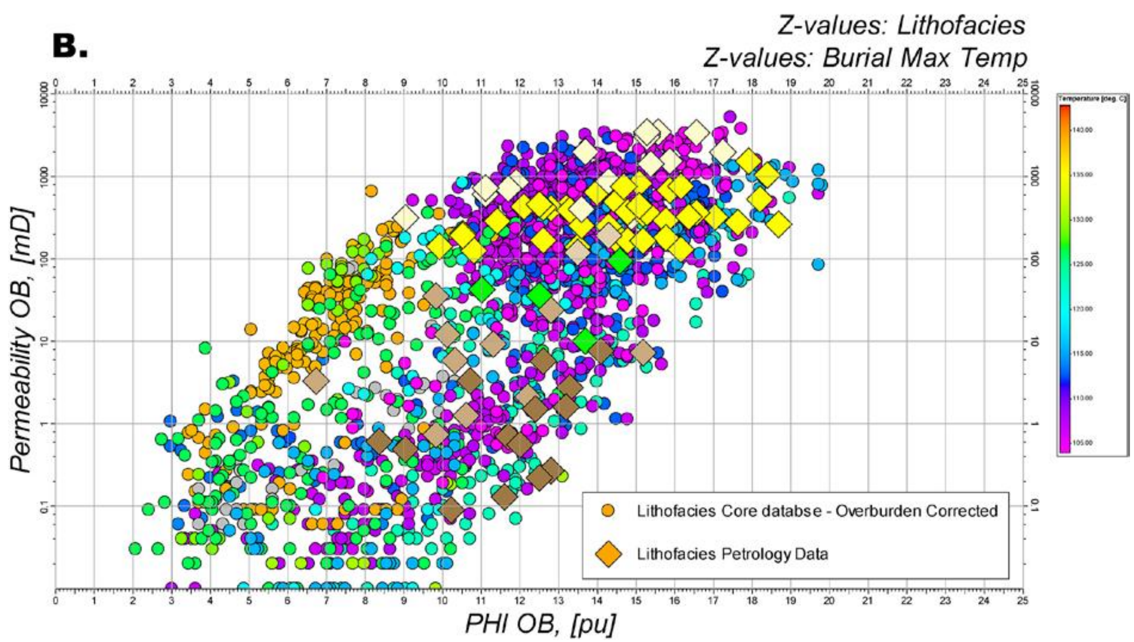


Figure 4. Overburden corrected core porosity and permeability cross-plot by A) lithofacies and B) temperature. Higher temperature Juha data points can be seen in orange, >135 deg. C. Lower temperatures associated with better quality rock.

	Nearshore						Estuary		
Depofacies	*USF*	*MSF*	*LSF*	*Offshore* UOS*	*Offshore* LOS*	*Inner Shelf*	*Mouth Bar*	*Central Basin*	*Margin/ Tidal Flat*
Pebble (vf) conglom (G_1)	○								
Unstrat coarse sst (S_0)	●	○					●		
Xbd or flat-bd med sst (S_1)	●	●					●		
Low-angle xbd fn sst (S_2)		○	●				○		
Ripple x-lam vf sst (S_3)			●	○					○
*Clayey sst (S_4)***	○	○	○	●	●	○	●	○	●
Mudstone (M_1)			○	○	●	●		●	●

● *Dominant lithofacies* ○ *associated lithofacies* ** Also referred to as Offshore Transition* *** Including $S_{4\text{-}0}$ $S_{4\text{-}1}$ $S_{4\text{-}2}$ & $S_{4\text{-}3}$*

Table 1. Assemblages of lithofacies, and their abundance, in the depositional facies of the nearshore and estuarine depositional environments which dominate in the Imburu and Toro formations of the PNG Fold Belt.