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Understanding reservoir behaviour through an integrated geological and engineering study

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Abstract: In order to determine the character and behaviour of reservoir rocks, geological and engineering data need to be gathered, integrated and understood. This paper illustrates how a multi-disciplinary approach has been applied to a suite of sandstone reservoir rocks and how particular questions about reservoir behaviour were answered.

Samples were chosen for detailed study from a successful oil and gas producing well in the South East Asian region. Two differing formations were sampled, the lowermost of which was given a pessimistic prognosis based on V_{shale} and water saturation calculations. A program of Advanced Rock Properties tests and detailed sedimentological and petrographical analyses was carried out on the chosen samples. The study results showed that a large proportion of the clay encountered in the lowermost formation was contained within grains, rather than in the matrix as has been initially been assumed, explaining the better than expected reservoir performance.

INTRODUCTION

Authors such as Ebanks (1987) and Hearn *et al.* (1986) have demonstrated how geological reservoir characterisation can be used to build simulator models to predict reservoir behaviour. The objective of this paper is to illustrate how a multi-disciplinary approach to reservoir characterisation can be used to better understand and predict reservoir behaviour. In this study, engineering and geological analyses were performed on a group of samples taken from a successful oil and gas producing well in the South East Asian region.

The well in question contains two zones, both of which were cored and were later found to produce commercial quantities of oil. While the Upper Zone was clearly a good reservoir candidate, the Lower Zone had been given a pessimistic prognosis based on V_{shale} and subsequent water saturation calculations, which indicated that the zone was probably shaly and possibly water-producing.

To investigate this apparent anomaly, Routine and Advanced Rock Properties measurements were made on eight samples selected from the well. These measurements were porosity, permeability, grain density, capillary pressure, cation exchange capacity (C.E.C.) and electrical tests. In addition, petrographic analyses were performed on the same samples. These analyses were thin section, X-ray diffraction, scanning electron microscopy and Mineralog™ infra-red spectroscopy. A sedimentological study of lithofacies and depositional environments was performed on the cored intervals.

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SEDIMENTOLOGY

The reservoir is subdivided into two zones, an Upper and a Lower Zone. The two zones are separated by an impermeable interval of claystone, approximately 400 feet thick. The Upper Zone consists predominantly of fine to medium grained sandstones of a deltaic distributary channel system (Fig. 1). Sedimentary structures observed in the core include planar cross-bedding, minor argillaceous and carbonaceous laminae, and rare current ripples. These sandstones are clean, relatively uncompacted and exhibit excellent visible porosity.

The sediments of the Lower Zone are believed to have been deposited in a fluvial to lacustrine setting. They are dominated by very fine grained sandstone, with subordinate argillaceous siltstone and fine to medium grained sandstone (Fig. 1). The very fine grained sandstones appear to be relatively clean and porous when examined in the core and exhibit trough cross-bedding as well as more planar, horizontal laminae, minor carbonaceous laminae and intermittent burrowing traces. They are interpreted to represent crevasse-splay deposits. The presence of trough cross-bedding suggests deposition under a relatively high flow regime, possibly into a shallow lake. The fine to medium grained sandstones, located towards the base of the cored interval are similarly clean and porous, exhibiting both trough cross-bedding and planar cross-bedding. These were most likely deposited as sand bars of a fluvial channel. The argillaceous siltstones show intermittent traces of burrowing and root activity, and were probably deposited as overbank fines.

PETROPHYSICAL AND PETROGRAPHICAL ROCK PROPERTIES

Porosity–Permeability Relationships.

Reservoir quality is very good in the Upper Zone, but varies from poor to very good in the Lower Zone (Table 1). To gain a better understanding of porosity and permeability controls, a Reservoir Quality Index (RQI) was calculated and cross-plotted with various lithological parameters. RQI is analogous to Mean Hydraulic Radius (MHR) and can be used to provide an approximate value for the average pore radius of a rock (Amaefule *et al.*, 1988). This is a normalized porosity–permeability relationship, calculated in the following manner.

$$RQI = 0.0314*(K/\phi)^{1/2}$$

Where: RQI = Reservoir Quality Index, microns
K = Permeability, millidarcies
ϕ = Porosity, fraction

Permeability in the Upper Zone ranges from 952md to 4738md and helium injection porosity ranges from 30.1% to 36.8%. These data yield calculated RQI values of 1.76 to 3.56 microns, indicating very good to excellent reservoir quality. This is consistent with the low quantities of clays detected in the sample by X-ray diffraction and Mineralog™ analyses – clays make up less than 10 weight percent of the Upper Zone samples.

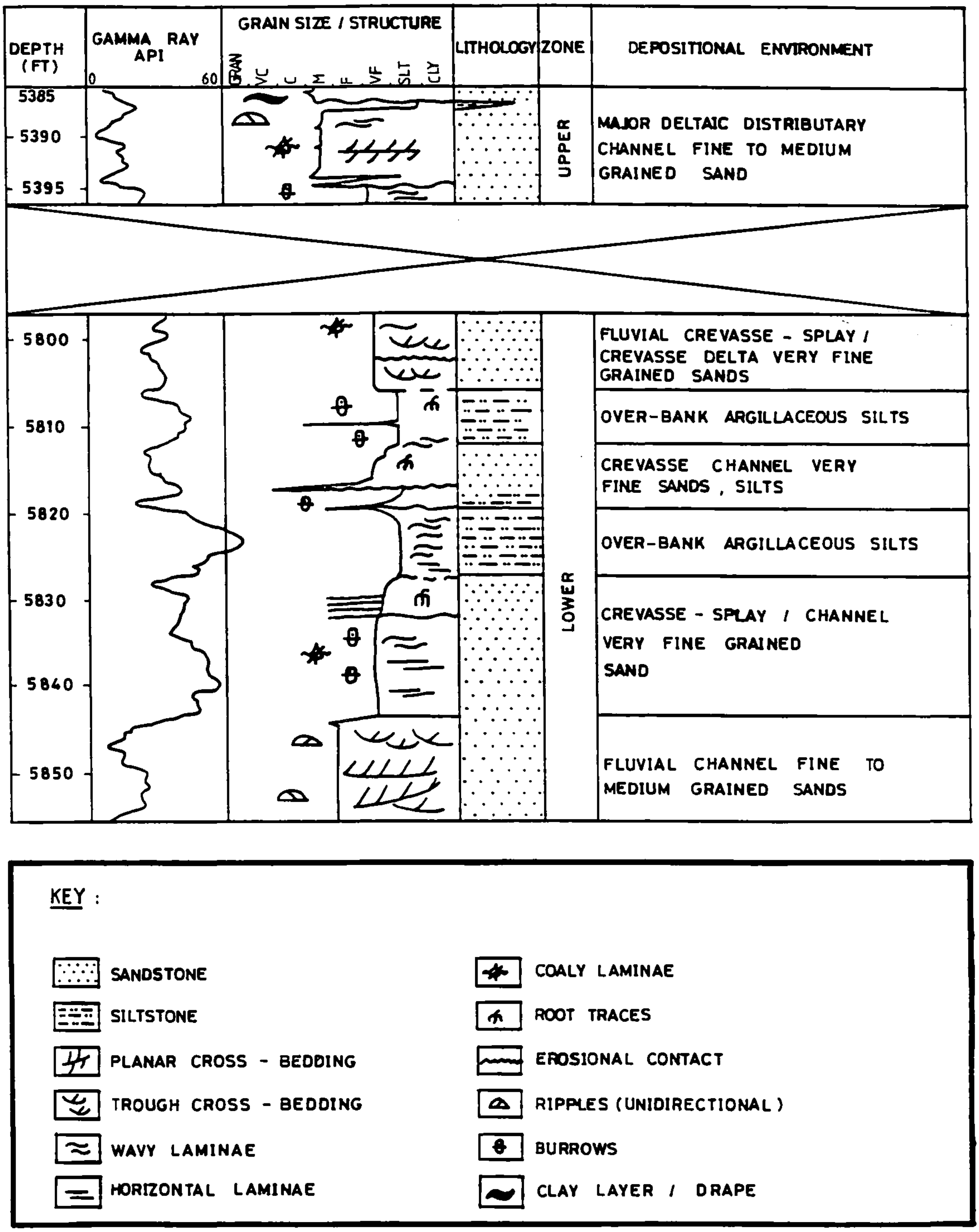


Figure 1: Lithological log of Upper and Lower Reservoir Zones

Table 1: Main lithological characteristics

ZONE	DEPTH (ft)	LITHOLOGY	GRAIN SIZE	Wt% CLAY	K∞ (md)	POR. (%)	RQI (micron)*
UPPER	5386	Sandstone	Fine-Medium	4.5	4738	36.8	3.56
	5390	Sandstone	Fine	5.0	1112	31.6	1.86
	5393	Sandstone	Fine	10.0	952	30.1	1.76
LOWER	5799	Sandstone	Very Fine	21.0	71	30.1	0.48
	5802	Siltstone	Coarse Silt	24.0	6.6	23.3	0.17
	5833	Sandstone	Very Fine	21.6	30.7	25.7	0.34
	5850	Sandstone	Fine-Medium	6.4	800	29.6	1.63
	5853	Sandstone	Fine-Medium	6.9	1097	28.6	1.94

Note: *RQI=0.0314√(K/ø), where K is permeability, md and ø is porosity, fraction

In the Lower Zone, permeability and helium injection porosity vary from 6.6md to 1097md and from 23.3% to 30.1% respectively, yielding RQI values of between 0.17 microns (poor quality) to 1.94 microns (very good quality). As expected, the fine to medium grained channel sandstones have the best reservoir quality (RQI of 1.63 and 1.94 microns) and contain only minor quantities of clay (6.4 to 6.9 weight percent clay). Also as expected is the poor quality of the overbank siltstone, with RQI of 0.17 and correspondingly high clay content (24.0 weight percent clay). The very fine grained crevasse-splay sandstones contain similar quantities of clay to the overbank siltstone (21.0 to 21.6 weight percent clay) but exhibit fair to good reservoir quality (RQI of 0.34 to 0.48 microns). It is these dominant very fine grained sandstones that are responsible for the apparent Lower Zone anomaly. High clay contents indicate high water saturations as calculated from logs, yet hydrocarbons can be produced on a commercial basis – as would be expected from the RQI values.

Thin section and modal point-count analyses reveal that the clay encountered in the samples occurs in three forms:

- dispersed authigenic and detrital clay matrix
- laminar detrital clay
- clay in grains ("structural" clay)

Structural clay is dominant in many of the samples examined (Table 2 and Table 3). Structural clay does not obstruct pore spaces – unless the samples are heavily compacted – but is indistinguishable from dispersed, pore-obstructing clay in X-ray diffraction, Mineralog™ and cation exchange capacity analyses, and in wireline logs.

Table 2: Clay form and reservoir quality

ZONE	DEPTH (ft)	Wt% CLAY	CEC MEQ/100G	MAIN CLAY FORM	RQI (micron)*	VISIBILE POROSITY (%)
UPPER	5386	4.5	2.34	Structural	3.56	26
	5390	5.0	1.51	Dispersed	1.86	24
	5393	10.0	1.80	Structural	1.76	28
LOWER	5799	21.0	3.42	Structural	0.48	14
	5802	24.0	4.51	Structural/ Dispersed	0.17	3
	5833	21.6	1.48	Dispersed/ Structural	0.34	13
	5850	6.4	1.86	Dispersed	1.63	21
	5853	6.9	1.76	Dispersed	1.94	22

Table 3: Simplified point count data based on 250 counts – volume %

FORMATION		UPPER ZONE			LOWER ZONE			
Depth (ft)	5386	5390	5393	5799	5802	5833	5850	5853
Quartz	60	59	58	48	45	48	59	62
Feldspar	5	5	2	3	4	6	9	5
Lithics/Accessories	3	5	3	3	10	10	4	4
Clay in Grains	3	2	5	18	18	7	1	2
Dispersed Clay	1	2	3	8	13	10	3	4
Laminar Clay	0	0	1	2	1	4	0	0
Cement/Replacive	1	3	1	4	6	2	3	2
Visible Porosity	27	24	27	14	3	13	21	21

Plots of total clay content against permeability (Fig. 2) and helium injection porosity (Fig. 3) show some scatter, but do reveal a broad, inversely proportional relationship between the amount of clay present and reservoir quality. On closer inspection, it appears that some of the more argillaceous samples may possess better porosity and permeability than predicted by V_{shale} estimates. A similar relationship is shown by a plot of total clay content against RQI (Fig. 7).

However, by plotting values of dispersed, pore-filling clay obtained by thin section point-count analysis against RQI, a very clear, straight line relationship is seen (Fig. 5). When structural and laminar clay volume is plotted against RQI, there is a considerable amount of scatter in the data (Fig. 6). These observations show that the principal control on reservoir quality is the quantity of clay dispersed throughout the pore network, which is not necessarily the total amount of clay encountered in the rock. Interestingly, point-counted values of visible porosity in thin section agree well with RQI data (Fig. 4), indicating that visible porosity is a good indicator of reservoir quality.

Capillarity and Pore Networks

Capillary pressure curves from the Upper Zone's fine to medium grained deltaic channel sandstone exhibit low threshold entry pressures and low residual water saturations of 10% (Fig. 8). This is due to the large, unobstructed pore network revealed by the thin section (Fig. 8) and scanning electron microscopy photomicrographs (Fig. 12).

In the Lower Zone, capillary characteristics are very different. The capillary pressure curve from the dominant very fine grained crevasse-splay sandstone (Fig. 9) exhibits a fairly high threshold entry pressure of 4psi – indicating smaller pore/pore throat sizes– and a high residual water saturation of 69%. Note the much smaller grain size and pore sizes evident in the thin section (Fig. 9) and scanning electron photomicrographs (Fig. 13), compared to the Upper Zone sandstone (Figs. 8 and 12). The high water saturation is consistent with high water saturation values calculated from log analysis. The reasons hydrocarbons are produced from the Lower Zone are:

- the high clay content allows a high water saturation to be bound in immobile form.
- because clays occur in structural rather than dispersed form, the flow capacity of the sandstone is unimpeded, even though pore and pore throat sizes may be small.

Not surprisingly, the overbank siltstone shows a much higher threshold entry pressure of 9psi and very high residual water saturation at 93% (Fig. 10). The high residual water saturations associated with the crevasse-splay sandstones and overbank siltstones explain the initial pessimistic prognosis for the Lower Zone from wireline log analysis.

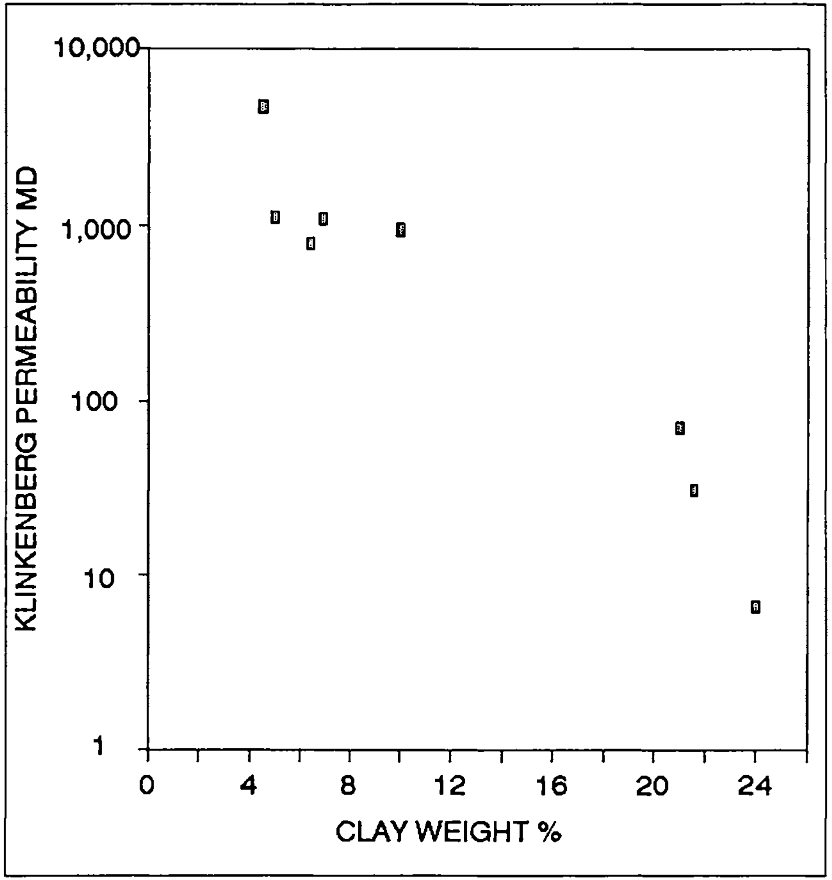


Figure 2: Effect of clay on permeability

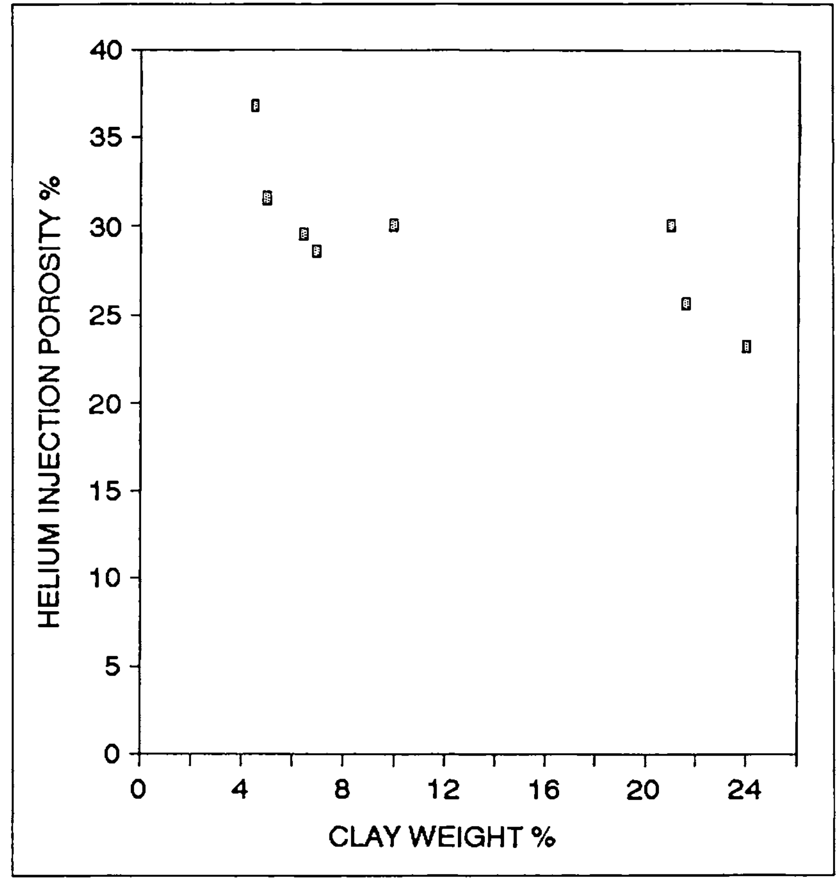


Figure 3: Effect of clay on porosity

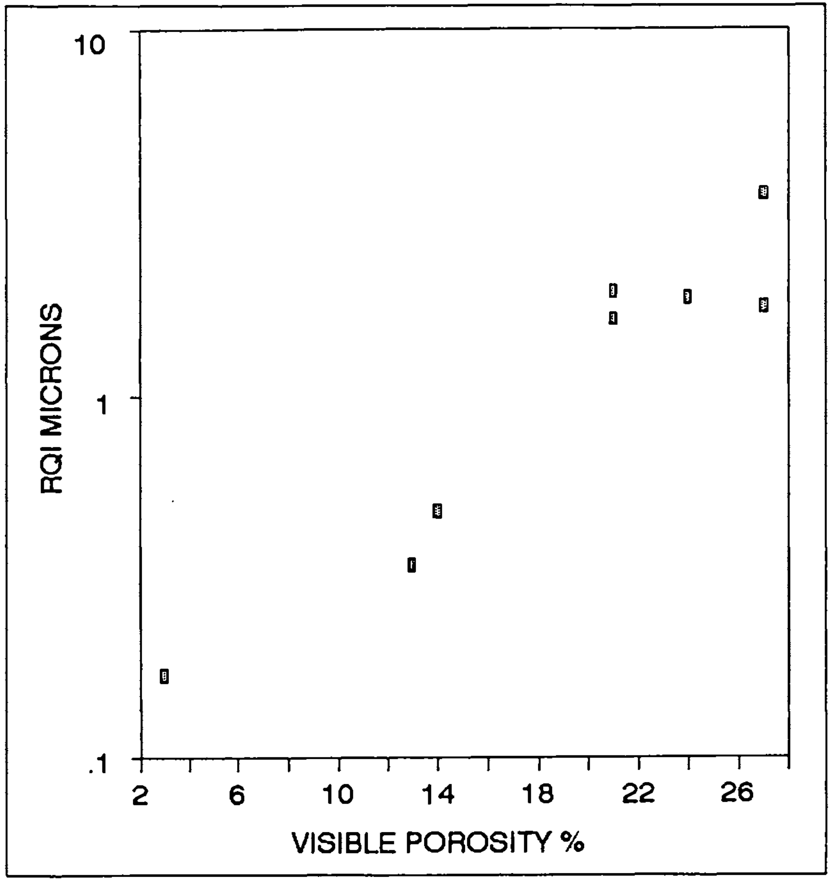


Figure 4: RQI against visible porosity relationship

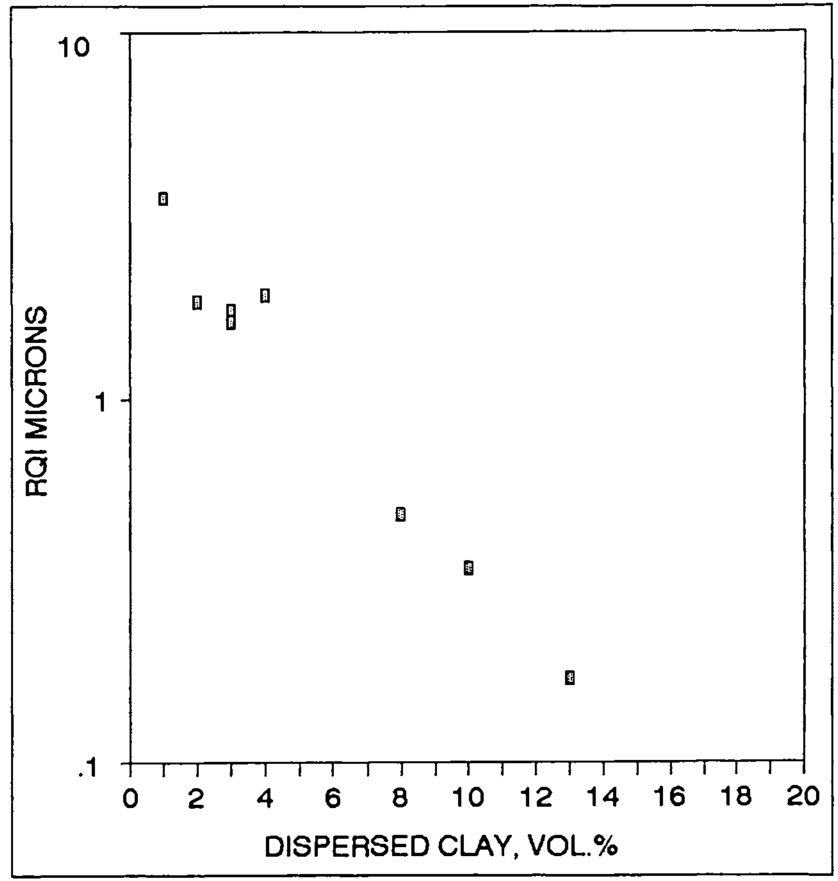


Figure 5: RQI against dispersed clay volume

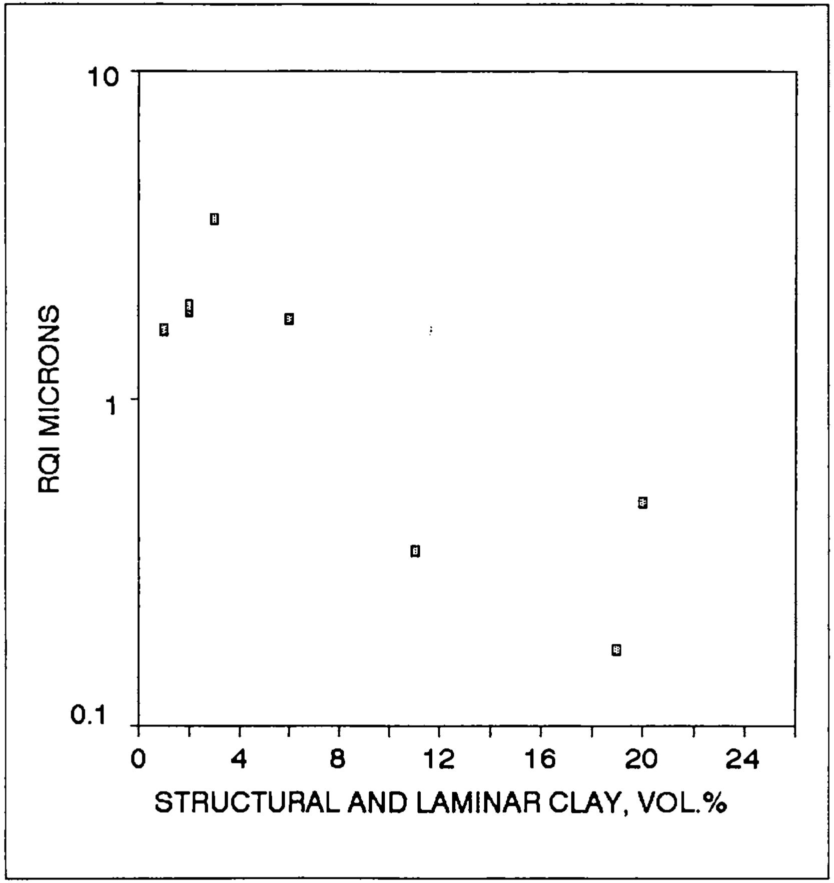


Figure 6: RQI against structural and laminar clay

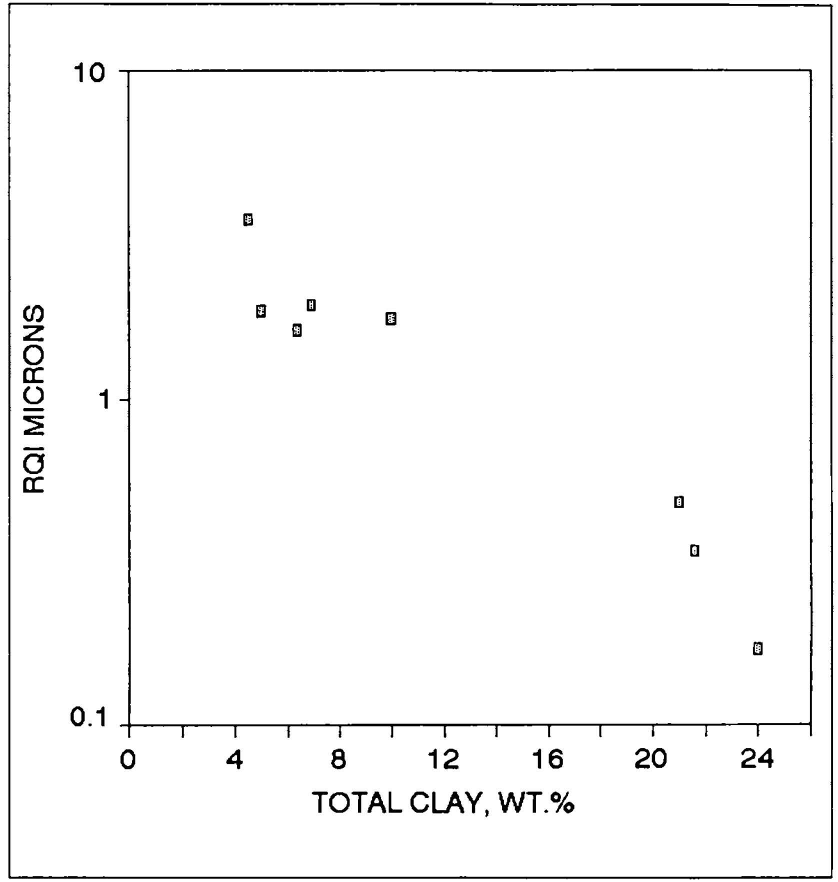


Figure 7: RQI against total clay

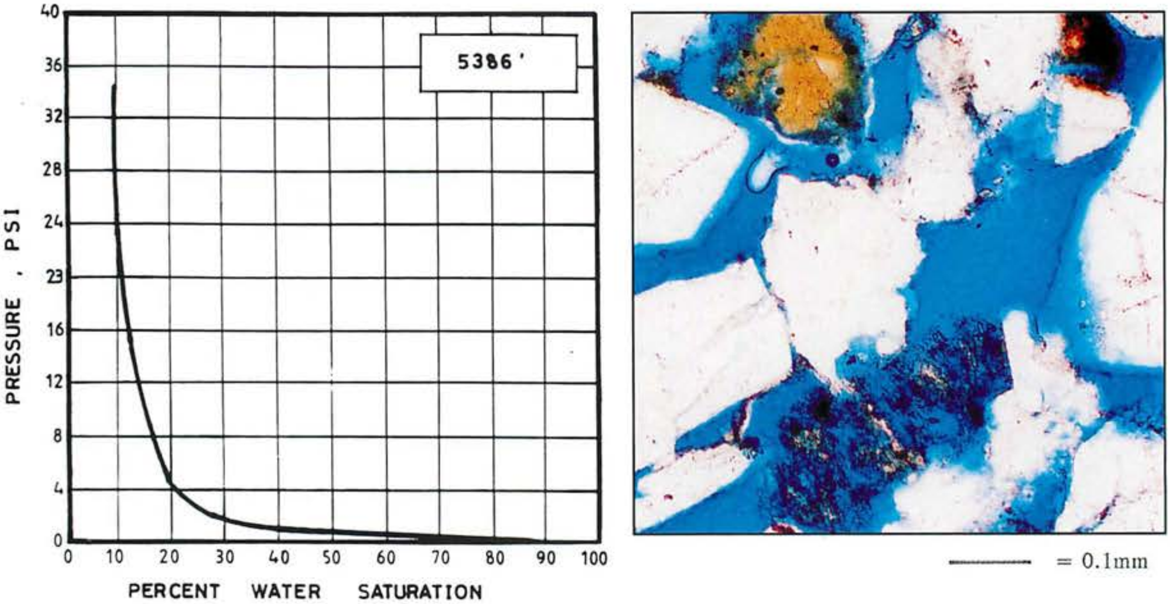


Figure 8: Capillary pressure curve and thin section photomicrograph, 5386 feet.

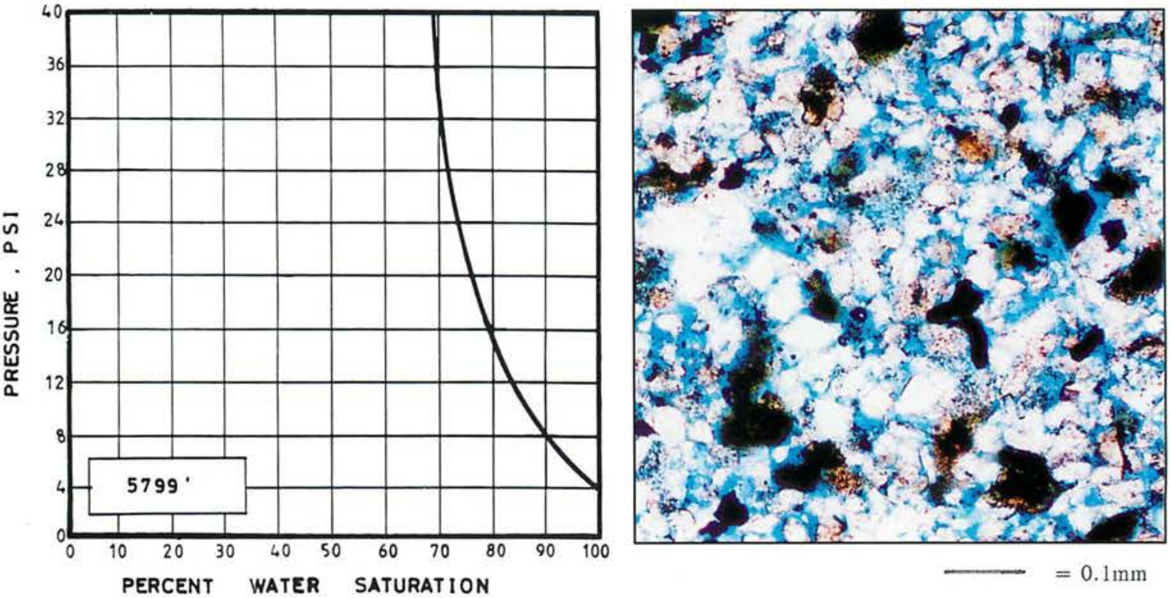


Figure 9: Capillary pressure curve and thin section photomicrograph, 5799 feet.

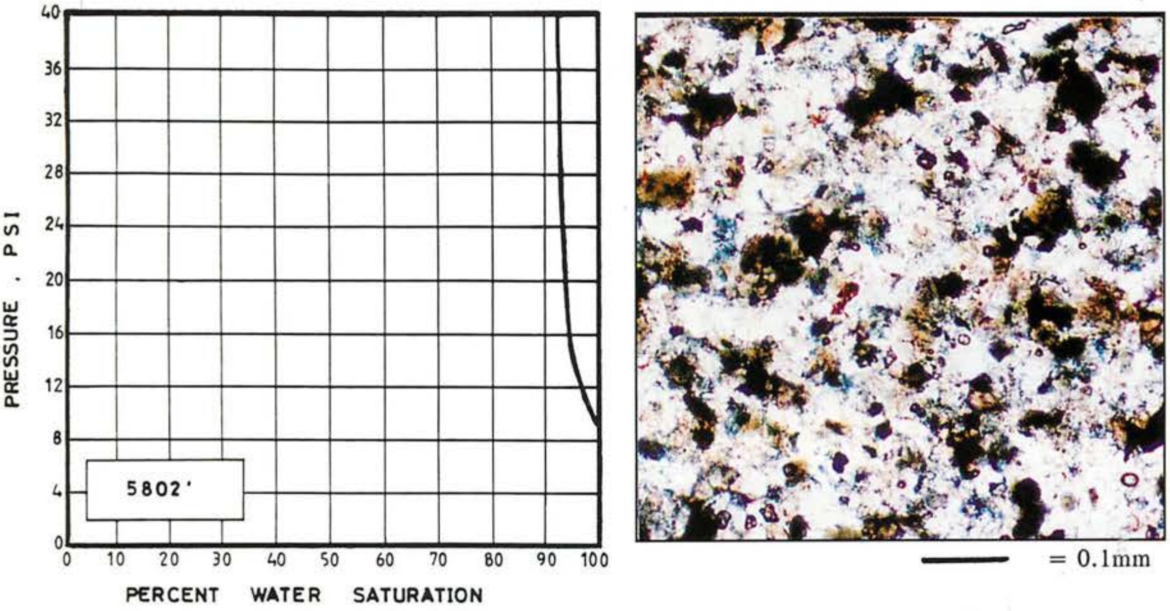


Figure 10: Capillary pressure curve and thin section photomicrograph, 5802 feet.

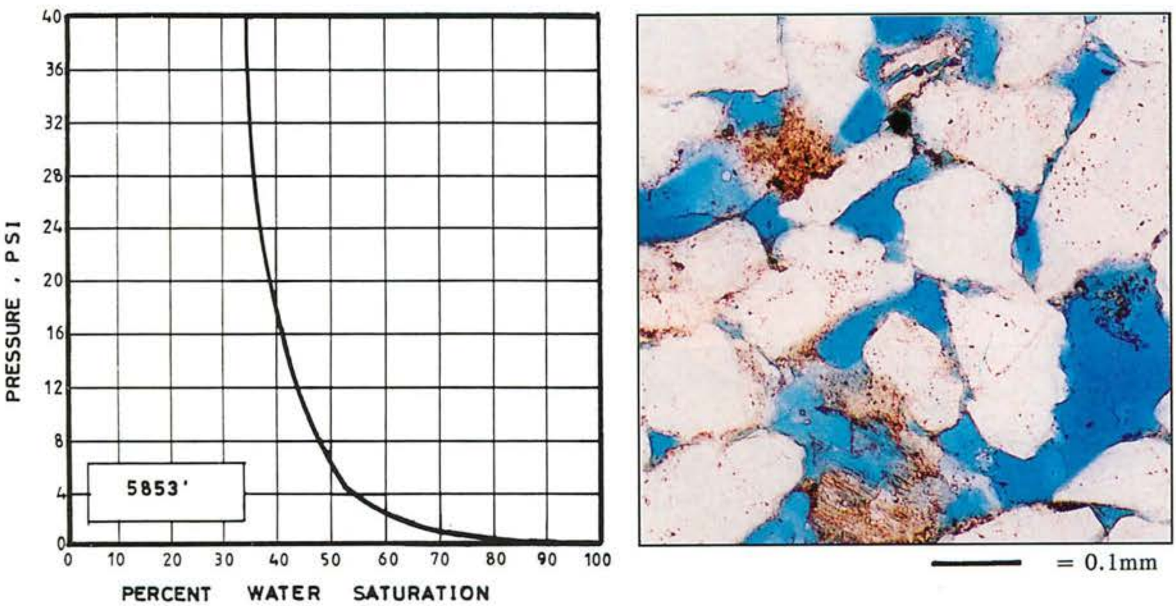
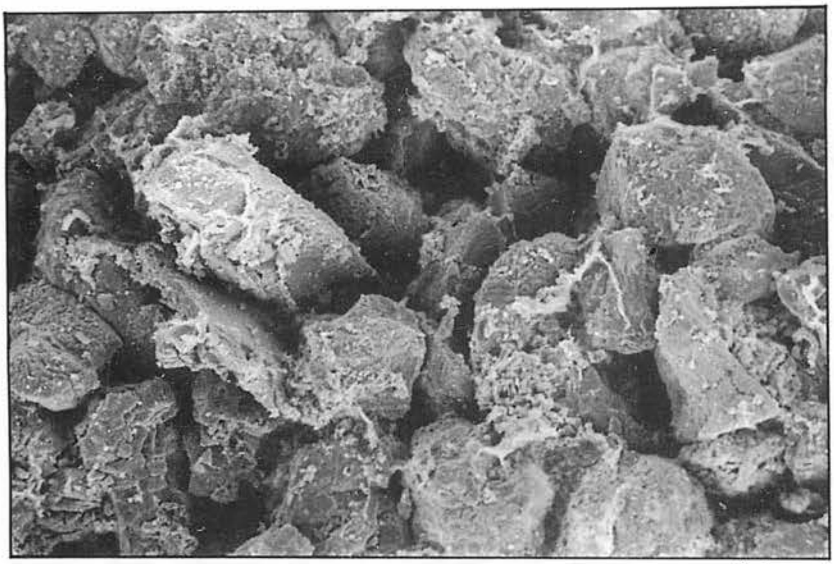
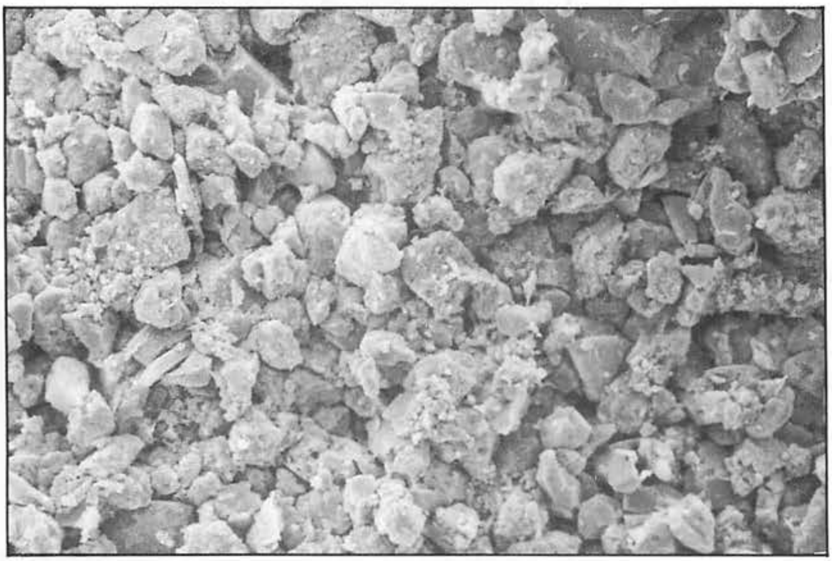


Figure 11: Capillary pressure curve and thin section photomicrograph, 5853 feet.



= 0.1mm

Figure 12: Scanning electron micrograph, Upper Zone– fine to medium grained distributary channel sandstone



= 0.05mm

Figure 13: Scanning electron micrograph, Lower Zone– very fine grained crevasse-splay sandstone

= 0.1mm

Figure 14: Scanning electron micrograph, Lower Zone– medium grained fluvial channel sandstone

The fine to medium grained fluvial channel sandstone exhibits low threshold entry pressures, but has high residual water saturation of 35% (Fig. 11). Thin section (Fig. 11) and scanning electron photomicrographs (Fig. 14) indicate that pores and pore throats are relatively large and open. The relatively high water saturation is probably due to the mainly dispersed nature of the clays in the pore network, contrasting with the mainly structural clays of the deltaic channel sandstones in the Upper Zone.

CONCLUSIONS

1. Capillary pressure data confirmed log estimates of high water saturations in the Lower Zone.
2. Commercial quantities of hydrocarbon were nevertheless produced from the Lower Zone because the large amounts of structural clay present hold the high water saturation as an immobile phase.
3. Visible porosity values obtained from thin section point-counts were found to be a valid guide to reservoir quality.
4. Percentages of dispersed clay provided a more clear-cut guide to reservoir quality than values of total clay, structural clay and laminar clay content.
5. Both detailed geological and engineering data were needed to explain the anomalous behaviour of the Lower Zone reservoir.

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