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Clay mineralogy in subsurface sandstones of Malaysia and the effects on petrophysical properties

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Abstract: Clay minerals are common constituents of the subsurface sandstones in Malaysia sedimentary basins. Kaolinite, illite, mixed-layer illite/smectite, chlorite, smectite, and mixed-layer chlorite/smectite have all been identified.

To date, petrophysical analyses of sandstone formations in the various basins indicate that clay content is the most prevalent control of porosity and permeability. Not only is the total amount of clay important but also the mineralogy, distribution, and morphology.

For reserve calculations, the ability to determine from wireline logs the total clay content in hydrocarbon-bearing reservoirs is very important. This ability often relies on the (sometimes erroneous) assumptions that the surrounding shales comprise clay only and that the sandstone formations contain clays of similar mineralogy and morphology to the surrounding shales.

Our investigations indicate that significant variation of clay mineralogy occurs, not only between basins but also within individual basins and within individual wells. This leads to significant variation of porosity, permeability, and wireline log response and demonstrates the need for a systematic study of clays during the exploration and development phases of a field.

INTRODUCTION

Clay minerals are common in the subsurface sandstones of Malaysia. This paper deals primarily with the clay mineralogy of these sandstones and the effects on petrophysical parameters.

The Malay basin, which is found off the east coast of West Malaysia, covers approximately 100,000 km^2 and is filled with up to 10,000 m of sediment (Ng, 1987). Fluvial, paralic, and marine terrigenous sediments occur within the basin.

Several basins occur within East Malaysia – Sabah and Sarawak. For the purpose of this paper, they are grouped together as the "basins of East Malaysia", though the Central Luconia Platform is not considered in this study. As in the Malay basin, there is a thick sequence of Tertiary fluvial, paralic, and marine terrigenous sediments.

The data presented in this paper were collected over a three year period as part of analytical tests performed on behalf of several oil companies in Malaysia. Data for over thirty wells were reviewed. As the data set is biased in areal extent, no

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presentation or interpretation of clay-type distribution is attempted. It can be shown, however, that the clays in the Malay basin and in the basins of East Malaysia vary significantly.

The clays vary in many aspects. There is a large range in the total clay content of the sandstones – from less than 10% to near 50%. Often there are differences in clay mineralogy between the clays in the sandstones and the clays of the adjacent shales/claystones. The clay mineralogy of the sandstones differs between basins, between wells within a given basin, and may vary with depth within a well. The distribution of these clays in the sandstones may be dispersed, laminated, or structural.

These variations, noted above, affect the porosity, permeability, and electrical properties of the sandstones. In addition, their effects on down-hole geophysical tools makes correct calculations of porosity, permeability, and water saturation difficult.

MALAY BASIN

The clay minerals found within the sandstones of the Malay basin are kaolinite, illite, mixed-layer illite/smectite, smectite, and chlorite (Table 1). All the clay-mineral types show a significant range in relative percentages, may have more than one type of distribution in the sandstones, and may be detrital or authigenic in origin. Each clay type is discussed separately below. Figure 1 is an X-ray diffractogram for the clay fraction from a typical sandstone.

Table 1: List of clay minerals identified in the Malay basin along with their range of abundance, origin, and distribution within the sediments.

Clays in the Malay Basin			
Clay	Relative %		Remarks
	Minimum	Maximum	
Illite	nil	70	D, A, P-F, I, S, P-B,P-L
Kaolinite	10	90	A, D, P-F, L, ?S
Chlorite	nil	9	D, P-F, L, rare (a, p-l)
Illite/smectite	5	30	D, A, P-F, L, P-L
Smectite	nil	70	D, A, P-L, L, P-F

D –detrital
A –authigenic
L –laminated
S –structural

P-F –pore filling
P-B –pore bridging
P-L –pore lining

Kaolinite

Kaolinite is a common clay mineral in the sandstones and shales. Figure 2 is a crossplot of the relative percentages of clay minerals (measured by XRD) versus total clay content (measured by Mineralog^{TM}) of sand and shale samples from a single-well. The sandstone samples have a significant scatter in relative percent kaolinite in the clay fraction. None the less, the maximum relative abundance of kaolinite shows a steady decline till around 35% to 40% total clay and then is relatively steady thereafter. The scatter of percent kaolinite in the cleaner sands is due to the mixing of authigenic clays with detrital clays plus variation in the authigenic clay production. The decrease in maximum kaolinite content represents both the increasing importance of detrital clays and less production of authigenic kaolinite. The data suggest that at 35% to 40% total clay, the detrital clay has occluded most effective porosity and prohibited significant kaolinite authigenesis.

In the detrital clays, which dominate beyond 40% total clay, kaolinite averages around 30 relative weight percent in this well. A value of 30% is high compared to what is seen in many other wells in the area. The relative abundance of kaolinite is generally between 10 to 20% of the detrital clay in the Malay basin.

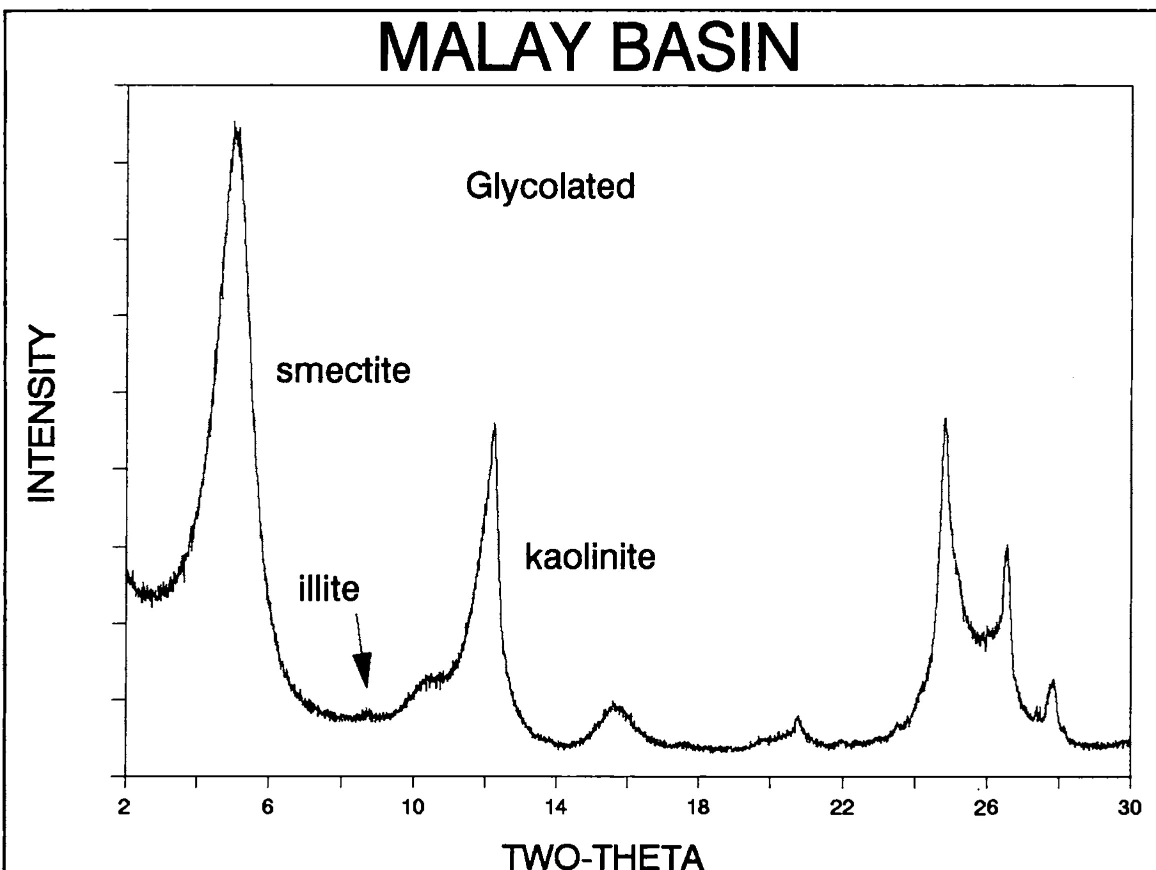

Figure 1: X-ray diffractogram of the clay fraction from a typical sandstone in the Malay basin.

Authigenic kaolinite formation is related to the dissolution of framework grains, many of which were K-feldspars. This is evident by kaolinite occurring within oversized pores (Fig. 3) or being proximal to partially dissolved grains.

In many cases as seen by scanning electron microscopy (SEM), kaolinite occurs in two distinct crystal sizes. There is a large (> 15 μm), fairly skeletal crystal (Fig. 5) and a smaller (< 5-7 μm) more compact crystal (Fig. 6). Hurst and Irwin (1982) related the size and morphology of kaolinite crystals to its formation. The larger crystals are envisaged to have formed during the flushing of meteoric waters through the sands. This typically occurs early during shallow burial of fluvial-deltaic sediments. In contrast, the smaller euhedral kaolinite crystals are interpreted to have occurred later when fluid flux is less and the temperature is higher.

The above interpretation appears to fit the authigenic kaolinite in the Malay basin. There is local evidence of the larger kaolinite crystals predating the smaller

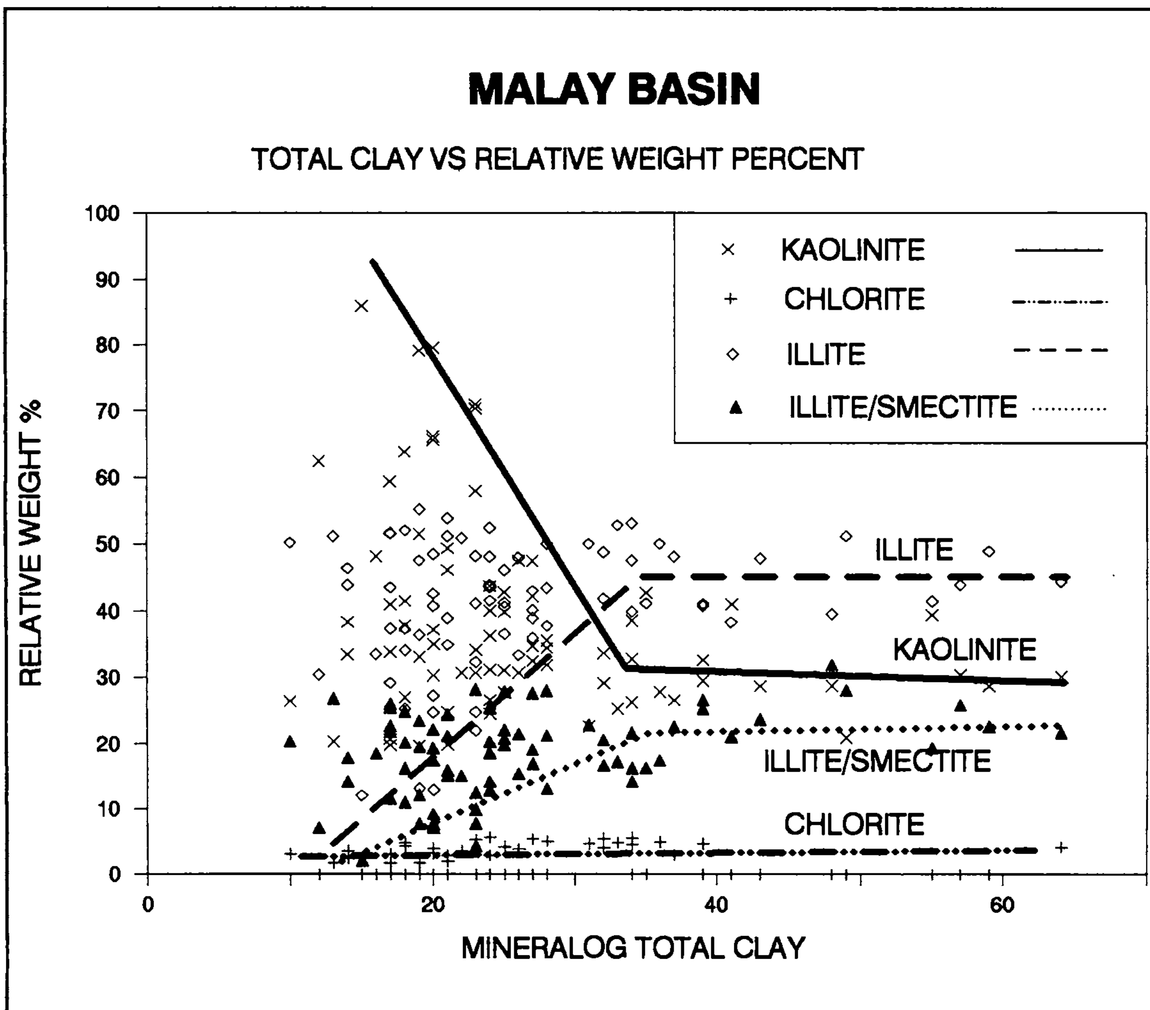

Figure 2: Crossplot of the relative clay percentages versus total clay.

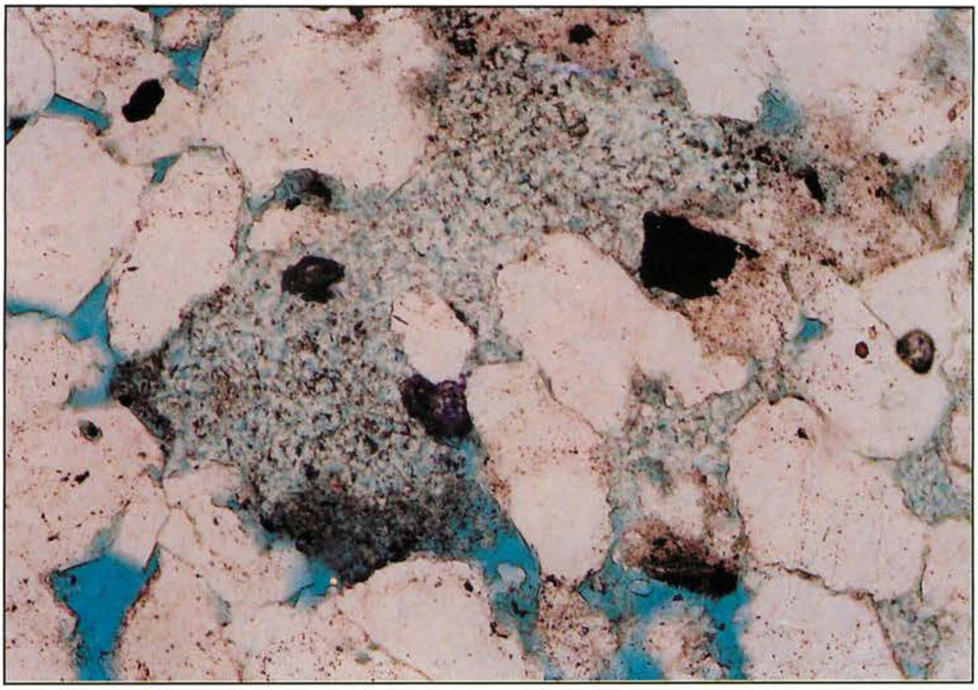

Figure 3: An oversized, secondary pore space being infilled with authigenic kaolinite (speckled milky area). Kaolinite within leached secondary porosity probably formed as replacement of feldspar crystals. Remnants ferroan dolomite is also shown (stained dark blue, high relief crystals). (125x, Plane polarized Light)

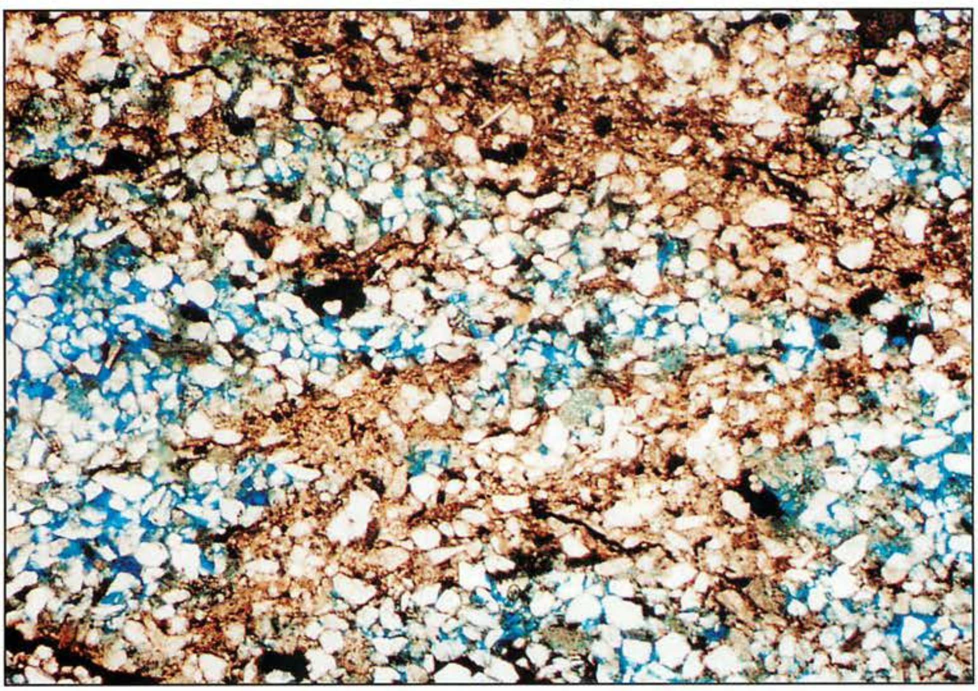

Figure 4: Original, laminated, detrital illitic clay shown here has been largely disrupted and dispersed by burrowing activity. (30x, Plane Polarized Light)

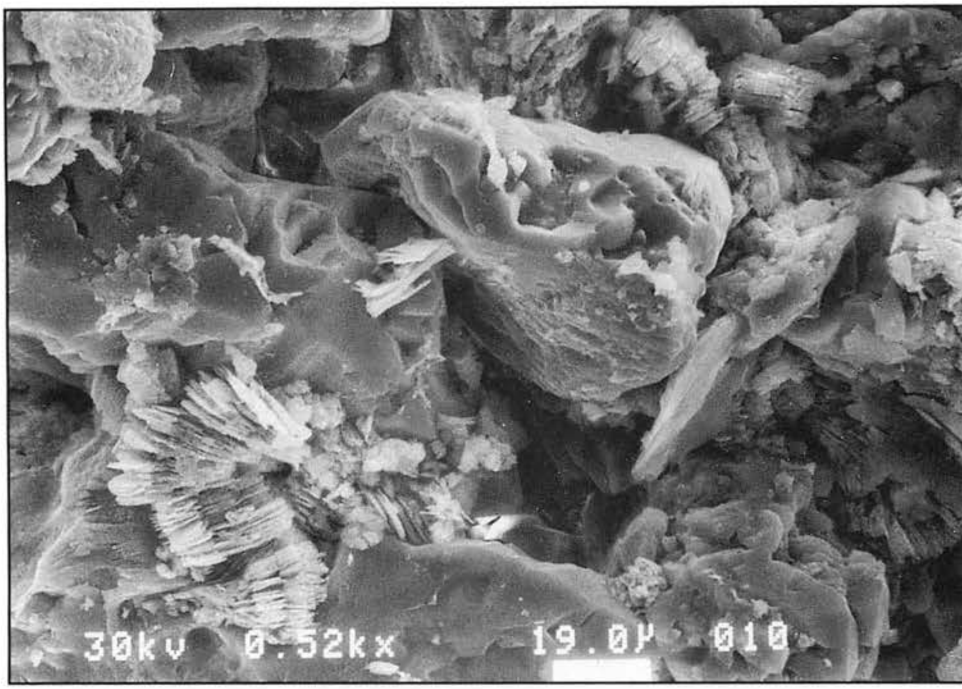

Figure 5: Relatively large skeletal, pore-filling kaolinite are shown sealing the pore-throats. Note that the diameter of the booklet is over 200 µm. Sample is from the Malay basin. Marker length — 19 µm.

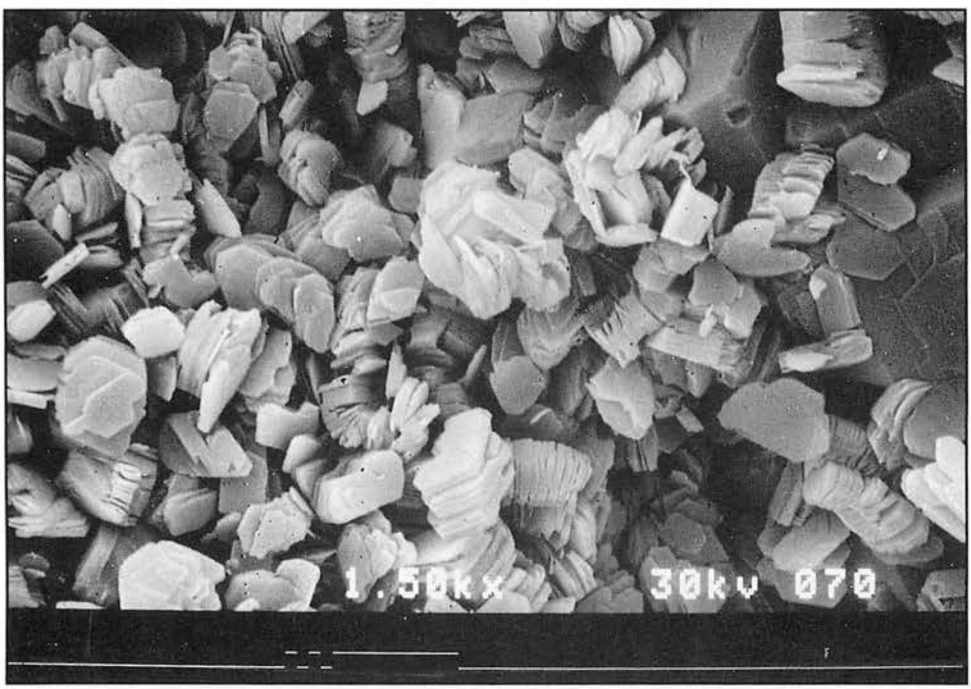

Figure 6: In contrast to Plate 1, the kaolinite booklets shown here are more compact, smaller (4 to 7 µm), and appears to be loosely attached. This sample is also from the Malay basin. Marker length — 10 µm.

ones. However, Hurst and Irwin (1982) find that the larger kaolinite is more typical of fluvial sandstones and the smaller kaolinite is more typical of marine sandstones, whereas in the Malay basin the smaller later kaolinite is common in fluvial and deltaic sediments and appears to be the prevalent type.

Illite

Illite is one of the major clay mineral types in the Malay basin. Its relative abundance in the cleaner sandstones is variable, but in the clay-rich sediments, illite averages 45% to 50% of the clay fraction (Fig. 2). The trend of minimum illite occurrence is a mirror image of maximum kaolinite occurrence. Illite increases in relative importance until around 35% total clay and remains roughly constant after that.

Illite is a significant component of the laminated detrital clays and the detrital clays that have been dispersed by bioturbation into the pore system of the sandstones (Fig. 4). Though illite is generally the prevalent mineral in detrital clays, an exception does occur. As will be discussed below, smectite may be the main clay mineral locally while illite occurs only in trace amounts.

In clean sandstones, the illitic (illite and low-expandable mixed-layered illite/smectite) clays are largely structural in distribution. These structural clays include micas, clay-replaced grains, and clay-rich sedimentary and metamorphic rock fragments. Illitic structural clays may range from 5 to 15% by weight of the sample.

Authigenic filamentous illite is also present in the Malay basin (Figs. 7 and 8). This clay has been found in samples below 2,000 m in two PSC (Production Sharing Contract) blocks, but does not occur in all wells which have penetrated that depth. Because the data base for deeper wells is small, little is known about the regional distribution of filamentous illite in the Malay basin.

Authigenic illite's apparent dependence on depth may be related to increasing temperature. In the few deeper wells for which analysis confirms filamentous illite, this illite increases in prominence from 2,000 m to 2,600 m. This suggest that its formation is depth/temperature related. The possibility of uplift and variations in geothermal gradient may cause variations in the depth at which filamentous illite occurs within the basin.

Mixed-layer clays

In the Malay basin, mixed-layer illite/smectite, like illite, appears to be of detrital origin in most cases. As is evident in Figure 2, the relation of illite/smectite to total clay is similar to that of illite, discussed above. The amount of mixed-layer illite/smectite is generally one-half to one-third the discrete illite. In claystones, illite/smectite averages around 20% of the clay fraction, by weight.

Authigenic illite/smectite is only locally present in minor amounts. Figure 9 shows the crenulated to blade morphology typical of this clay type in the Malay basin. The controls and timing of authigenic mixed-layer illite/smectite occurrence are unclear. When the clay appears to be neomorphosed (newly grown) its position

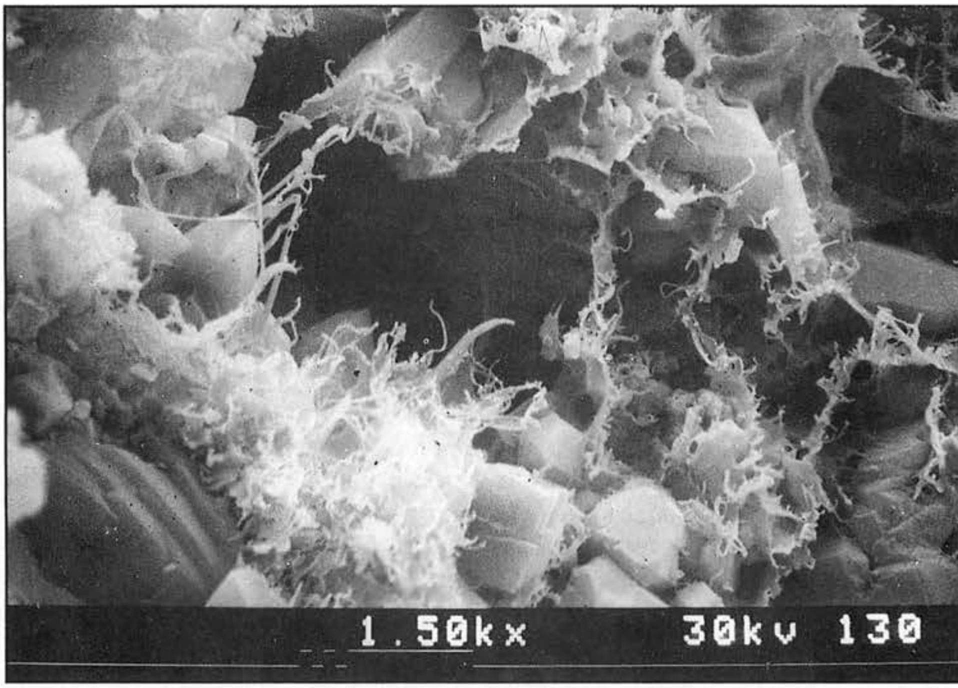

Figure 7: A detailed view of pore-bridging, filamentous illite from the Malay basin. Quartz overgrowths protruding into the pore space are likely to precede illite formation. Marker length — 10 μm.

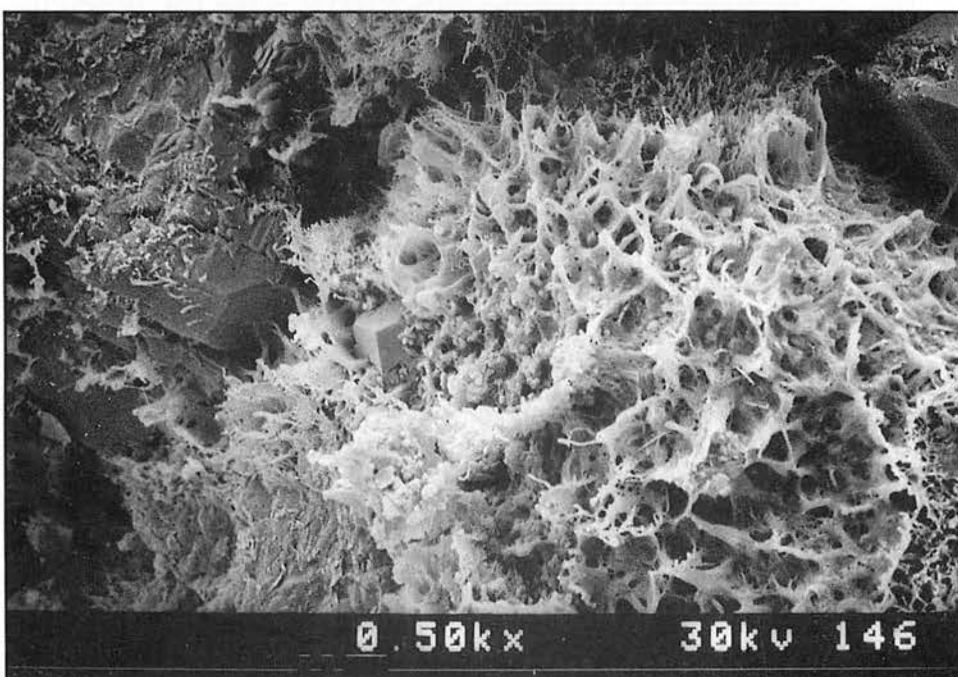

Figure 8: Morphology of illitic clay may varies from crenulated to fibrous. Porosity may not have been reduced significantly by illite formation, however, the permeability of this sandstone is reduced drastically. Marker length — 10 μm.

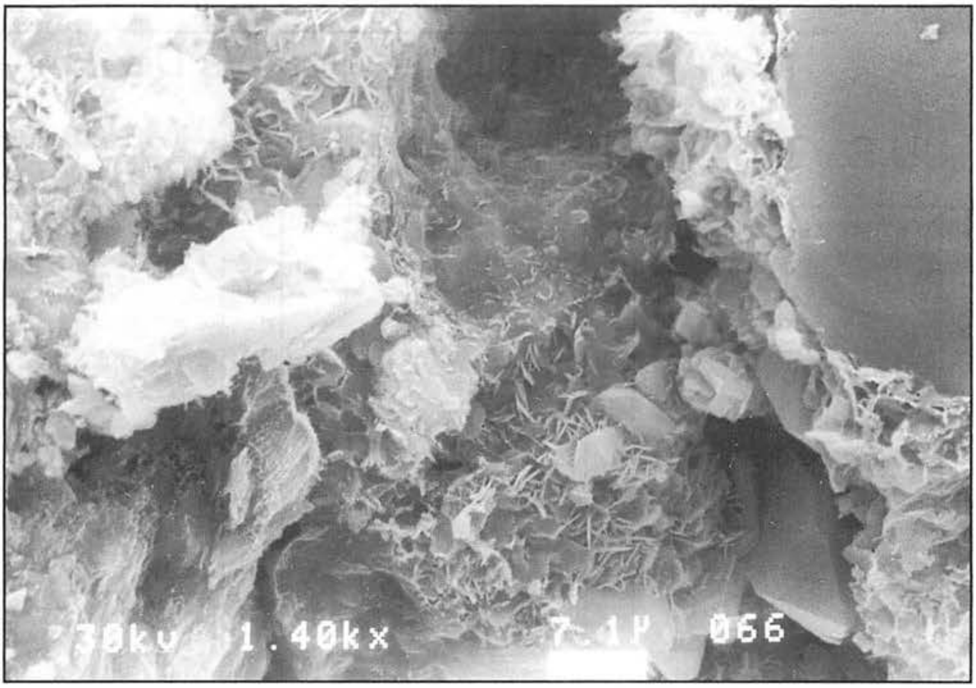

Figure 9: Intergranular pore (top right) is surrounded by grain-coating, crenulated illitic clay and uneven grain-coating rosette-like, authigenic chlorite (lower right). Marker length — 10 μm.

suggests an early diagenetic phase. In other cases, the crenulated illite/smectite appears to be recrystallized detrital clay, and if so it should be a relatively late occurrence.

An important parameter of mixed-layer clays are their expandability or smectite content. The mixed-layer illite/smectite clays, in many of the wells located in the Malay basin, contain minor smectite interlayers, circa 20% to 25%. A few wells contain mixed-layer illite/smectite with 40 to 60% smectite interlayers and discrete smectite has been observed in a couple of wells.

The mixed-layer clays of the Malay basin differ from those of the United State's Gulf Coast which decrease systematically in expandability with depth (Hower, *et al.*, 1976; Burst, 1969). In numerous wells, in at least three PM blocks, there is no significant change in expandability between the depths of 1,200 m and 2,500 m (Fig. 10). These wells consistently contain illitic mixed-layer clays with around 20% smectite interlayers. In a few other wells, from two PM blocks, the mixed-layer clays contained 40% to 60% smectite between the depths of 1,200 m to 3,500 m. No significant decrease in smectite content with depth occurred in these few wells either. In fact, in two wells the smectite content rapidly increased with depth (Fig. 10). In one well the change occurs between two samples only 15 meters apart. In these two wells, not only does the amount of smectite increases to around 100%, but the presence of discrete illite decreases to only trace to minor amounts. Unfortunately the locations for these wells are unknown, but it is known that the low-expandable and high-expandable mixed-layer clays occur in different fields.

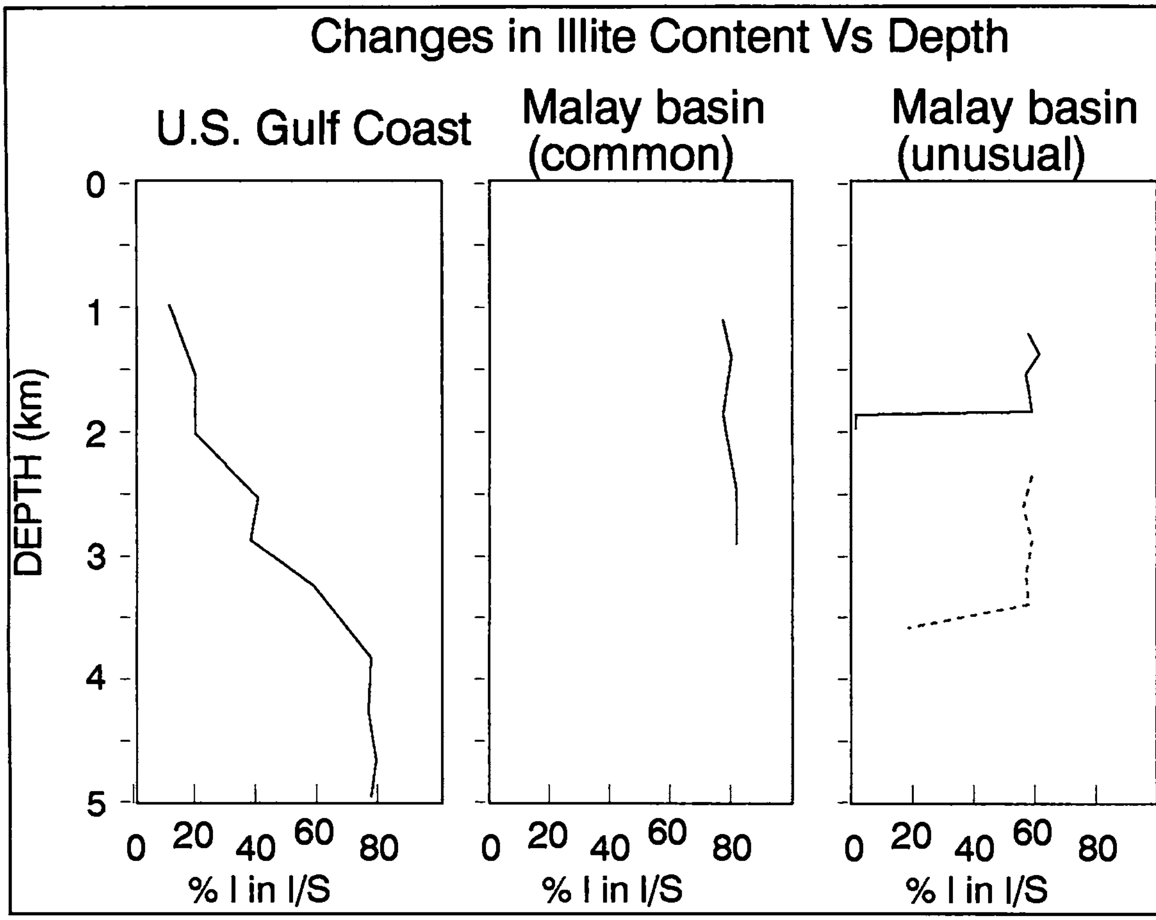

Figure 10: Changes of illite interlayers in mixed-layer clays, with depth, in the Malay basin in comparison with the normal trend found in the U.S. Gulf Coast (Hower *et al.*, 1976).

There are two interpretations of the noted areal variations in smectite content of the mixed-layer clays. One possible interpretation is that the different areas have experienced differing degrees of shale diagenesis. This may result from the areas having different geothermal gradients, having different amounts of burial and subsequent uplift, or having migrating fluids of differing chemistry (a corollary from Morton's, 1985, unorthodox opinion of punctuated illite/smectite diagenesis). No information that could confirm or disprove the above was collected for this paper.

A second interpretation is that there may be different sources and that the differing detrital clay composition reflects the sediment's provenance. A provenance with abundant shales and slates will result in detrital clays of similar composition, except in cases of severe and prolonged weathering. This is because the illitic clays of the bed rock are relatively stable during weathering. A granitic source will result in some degraded micas (illites) plus, depending on the extent of weathering, kaolinite and/or mixed-layer clays. A source with abundant volcanic or mafic igneous material would produce mainly smectitic (expandable mixed-layer illite/ smectite and smectite) clay except during extreme, prolonged weathering (Weaver, 1989; Chamley, 1989).

There are multiple source areas and source areas and source rock types for the Malay basin. The Khorat Swell and the Tenggol Arch are the probable sources from the northeast and southwest respectively (Ramli, 1988). Basement samples from within the Tenggol Arch include compacted argillaceous sandstones, granite, volcanic, argillite, and limestone (Ng, 1987). Ramli (1988) notes that the sediment source not only varies spatially but also varies temporally. It is possible, though not proven, that such variations in provenance could result in the variation of detrital clay found within the Malay basin.

Not only does provenance affect the detrital clays but it is a major control, along with paleoclimate and depositional environment, of authigenic clay type (Weaver, 1989). Provenance controls the authigenic clay mineralogy by controlling the original framework grain composition which is a major source of material for the authigenic clays.

Smectite

As mentioned above, smectite and very smectitic clays (> 60% smectite interlayers) occur rarely, but when they do, they may be the prevalent clay. Figure 15 is a thin section photomicrograph of an authigenic smectite that has occluded most of the effective porosity in the sandstone. In this sand the smectite commonly shows a grain-parallel habit, similar to Mathisen's (1984) stratified clay coats which he interprets to form from illuviation. Honeycombed and crenulated smectites also occur in lesser amounts. Identification of smectite is based on XRD (Fig. 11).

It is evident that the smectite is an early diagenetic product. The smectite clay forms concurrently with some grain dissolution but predates most dissolution present in the samples. It predates the kaolinite, which is associated with late dissolution, and appears to preclude quartz cementation. The detrital clays, within the same depth region, are also predominately smectite.

Chlorite

Figure 9 shows a rare occurrence of authigenic chlorite in the Malay basin. In most cases the chlorite identified by XRD is believed to be detrital in origin. In the shales from one well, chlorite averages around 3% to 5% of the clay mineralogy. In Figure 2, chlorite appears to decrease to trace amounts at 40%. This is not commonly observed, and apparently, in this data set, the poor resolution between kaolinite and chlorite led to difficulties in quantifying chlorite at high total clay values.

BASIN OF EAST MALAYSIA

Kaolinite, illite, mixed-layer illite/smectite, chlorite, and mixed-layer chlorite/ smectite occur in the sandstones of East Malaysia (Table 2). Similar as to what is seen in the Malay basin, there is a significant range in relative percentages,

Table 2: List of clay minerals identified in the basin of East Malaysia along with their range of relative abundance, origin, and distribution within the sediments.

Clays in the East Malaysian Basin			
Clay	Relative %		Remarks
	Minimum	Maximum	
Illite	nil	50	D,? A, P-F, L, S
Kaolinite	2	70	A, D, P-F, L
Chlorite	5	70	A, D, P-L, L
Illite/smectite	?	?	?
Smectite	nil	66	A, P-L

D –detrital
A –authigenic
L –laminated
S –structural
P-F –pore filling
P-B –pore bridging
P-L –pore lining

distribution, and morphology of the above clay types. Figure 12 is an X-ray diffractogram of the clay fraction from a common sandstone.

Kaolinite

Kaolinite is a minor constituent in many of the marine sandstones, and increases in importance in paralic to non-marine sandstones. When observed in marine sandstones kaolinite morphology appears to be restricted to the smaller booklets, whereas in paralic sandstones, both the large skeletal booklets and the smaller compact booklets are observed (Fig. 13). The timing of most kaolinite precipitation appears to be moderately late, that is, it post-dates ferroan-carbonate cementation and grain dissolution.

Illite

Authigenic illite has been identified only once in samples from East Malaysia (Fig. 14). In most cases, the illite commonly identified by XRD is believed to be detrital in origin. The predominance of illite in the detrital clays is attributed to abundant illite in the source area. This clay often shows a dispersed habit due to bioturbation.

Mixed-layer illite/smectite

Mixed-layer illite/smectite mainly occurs as a detrital clay. Authigenic mixed-layer illite/smectite has been observed in the sandstones of East Malaysia (Fig 17). It never occurs as a major diagenetic phase, but may be slightly more common here than in the Malay basin.

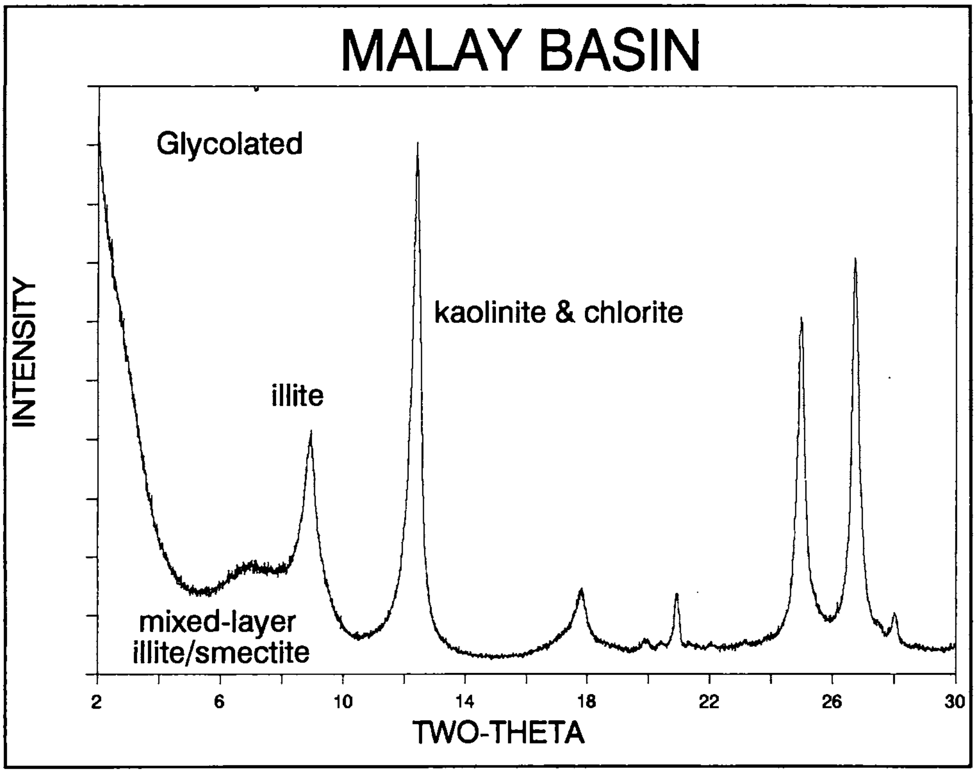

Figure 11: X-ray diffractogram of the clay fraction from a sandstone containing smectite and kaolinite as the main clay minerals.

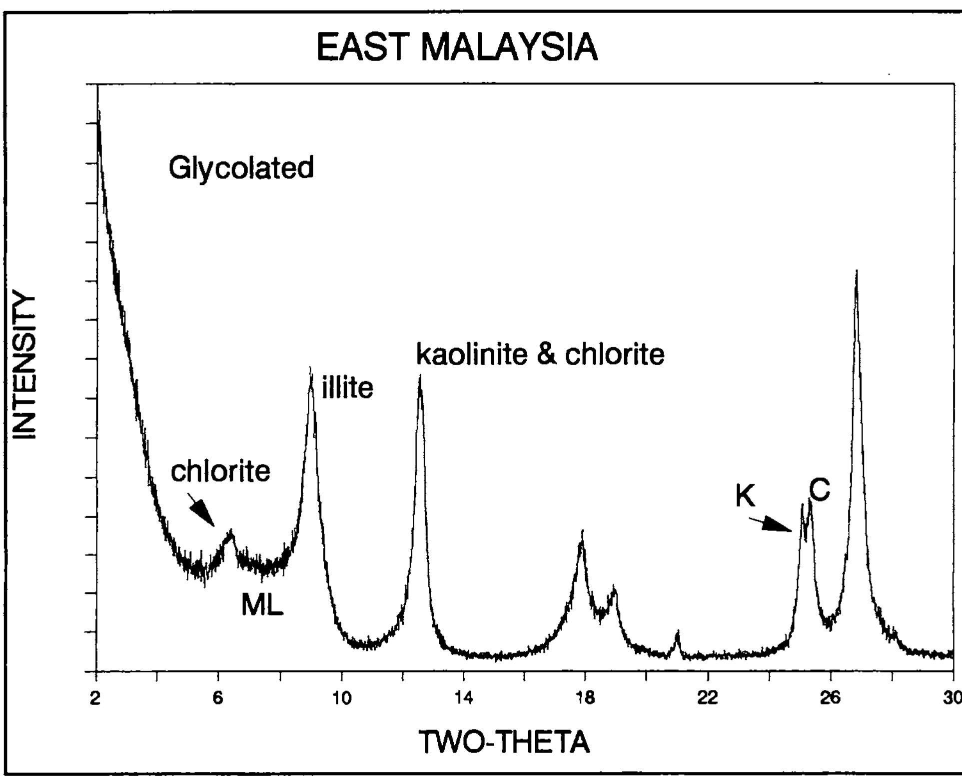

Figure 12: X-ray diffractogram of the clay fraction from a typical sandstone from an East Malaysian basin.

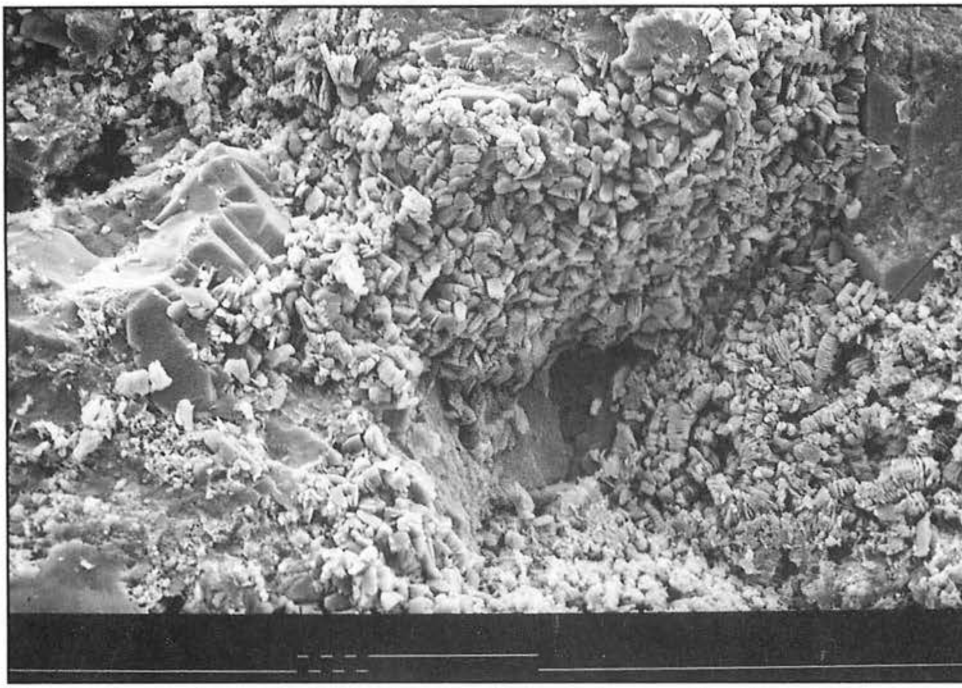

Figure 13: Authigenic kaolinite of varying sizes are shown in this photomicrograph. The larger booklets (lower right) appear more skeletal, whilst the smaller booklets are less skeletal and more compact (middle area). Marker length — 100 µm.

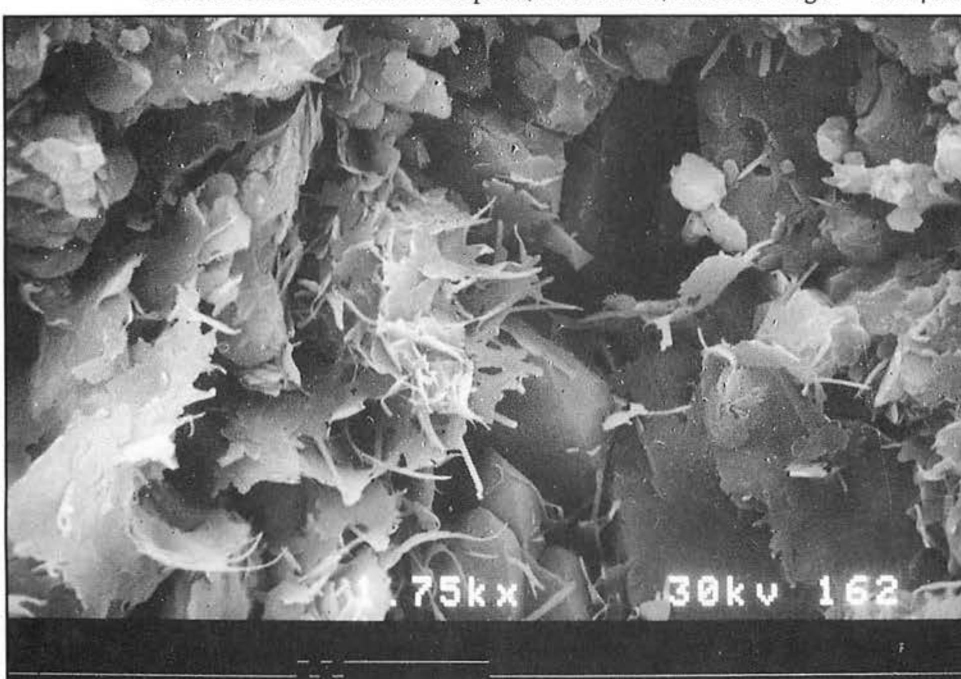

Figure 14: Filamentous illite is shown growing from platy illite, a phenomenon possibly attributed to recrystallization of pre-existing, platy illitic clay. This sample is from an East Malaysian basin taken at a depth greater than 2500 m. Marker length — 10 µm.

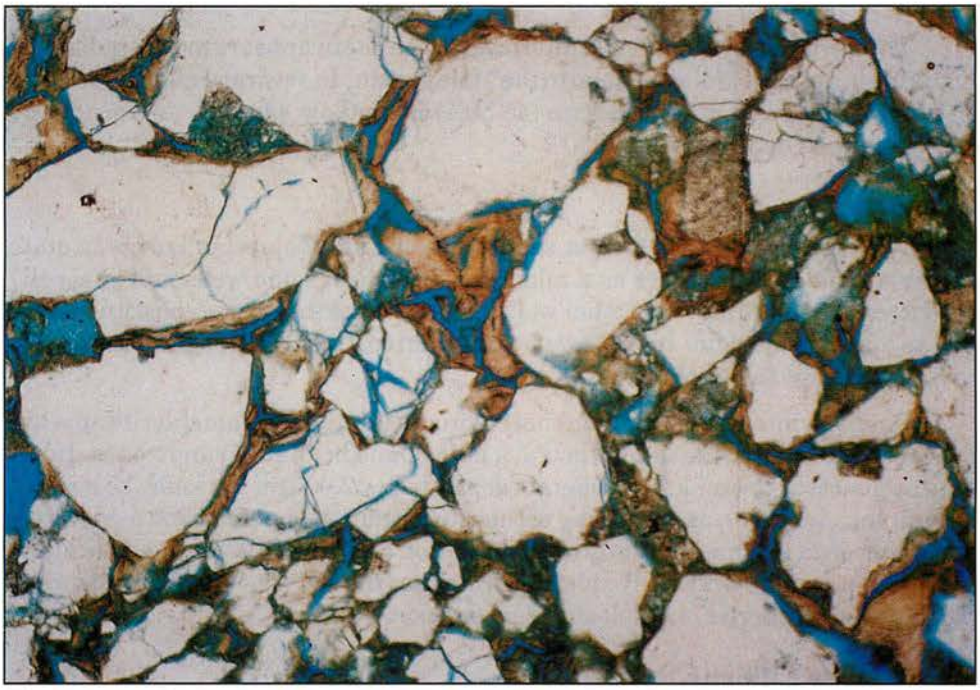

Figure 15: Uniform distributed, authigenic, pore-lining to pore-filling smectitic clay (brownish clay) partially occluding effective pore spaces. Samples is form a sidewall core derived from the Malay basin. (25x, Plane Polarized Light)

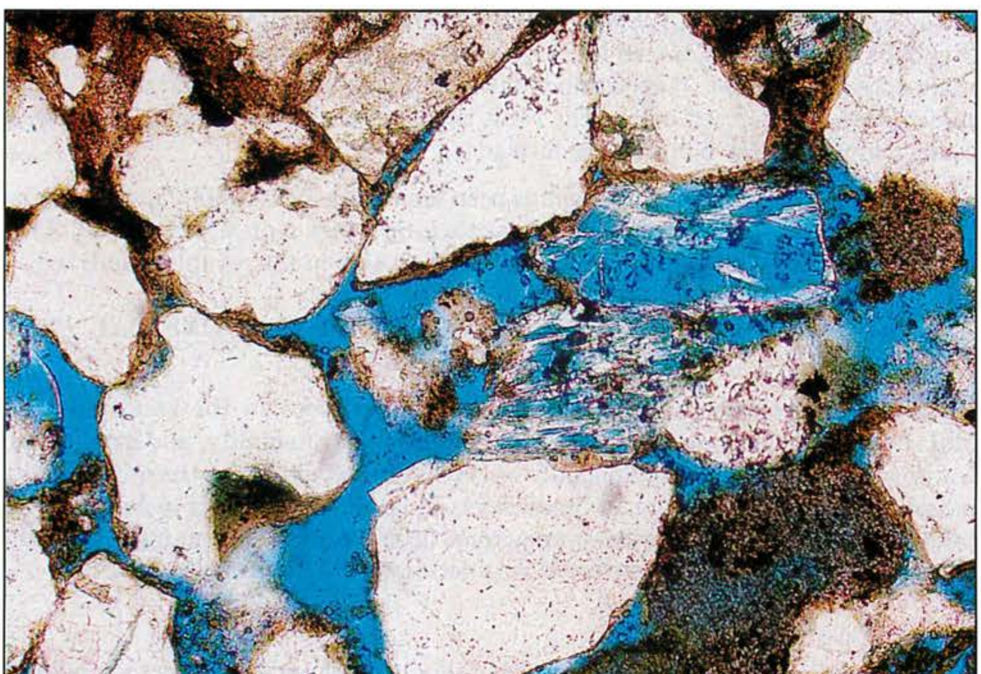

Figure 16: Common, grain-coating chloritic clay is shown in this sample taken from an East Malaysian basin. This clay type is considered to have precipitated relatively early in the diagenitic history as it is documented to be included within quartz overgrowths (lower middle grain). Extensively leached feldspar is also documented (middle right). (130x, Plane Polarized Light)

The variation of expandable interlayers with depth appears more predictable in the basins of East Malaysia than in the Malay basin. In several wells, the amount of smectite interlayers is moderate (45-50%) in shallow samples and gradually decreases with depth to around 30%.

Chlorite

The occurrence of chlorite in sandstones of East Malaysian basins is quite variable (Table 2). It occurs as a minor constituent in some wells and generally restricted to detrital clays. In other wells, chlorite is the major clay constituent and has an authigenic origin. In these wells, it is grain coating (Fig. 16) and shows edge-to-face and rosette morphologies (Fig. 18).

Based on interpreted depositional environments, authigenic chlorite appears to be restricted to marine sands, though it is not found in all such sandstones. It has only been noted in samples of moderate depth, below 2,000 m. This may be a result of sampling, however, as the timing of chlorite formation appears to be moderately early – prior to late quartz overgrowth formation and grain dissolution. Locally it may be concurrent with early siderite formation, though elsewhere it appears to postdate early siderite and dolomite cementation.

Mixed-layer Chlorite/Smectite

To date, mixed-layer chlorite/smectite has been noted in only one area, however in this area it is locally a major constituent (Table 2) and occurs in several wells. This chlorite/smectite has an authigenic origin, as noted by its crenulated to honey-combed morphology (Fig. 19). Identification of this clay was based on XRD (Fig. 20). Like chlorite, mixed-layer chlorite/smectite appears to be a moderately early diagenetic phase. It is postulated that in this area, chlorite and mixed-layer chlorite/smectite formed during the same time and that the local pore chemistry controlled which clay mineral was formed.

Mixed-layer chlorite/smectite has been found only below 2,000 metres. It is therefore unknown if the amount of smectite interlayers reduce with burial. The amount of smectite interlayers ranges from 35 to 40% in the samples analyzed.

EFFECTS OF CLAY MINERALOGY ON PETROPHYSICAL PARAMETERS

As discussed above, clay minerals commonly occur in the sandstones of Malaysia. Many rock properties including porosity, permeability, and irreducible water saturation are affected not only be clay content, but also by the mineralogy, morphology, and distribution of these clays. In addition, standard techniques for calculating the above properties from wireline logs are affected, making it difficult to calculate true values. Some basic considerations are discussed below.

V_{shale} - V_{clay}

Any discussions on the effects of clay should start with how clay is typically "measured" in the industry. The parameter "V_{shale}" is commonly calculated in the

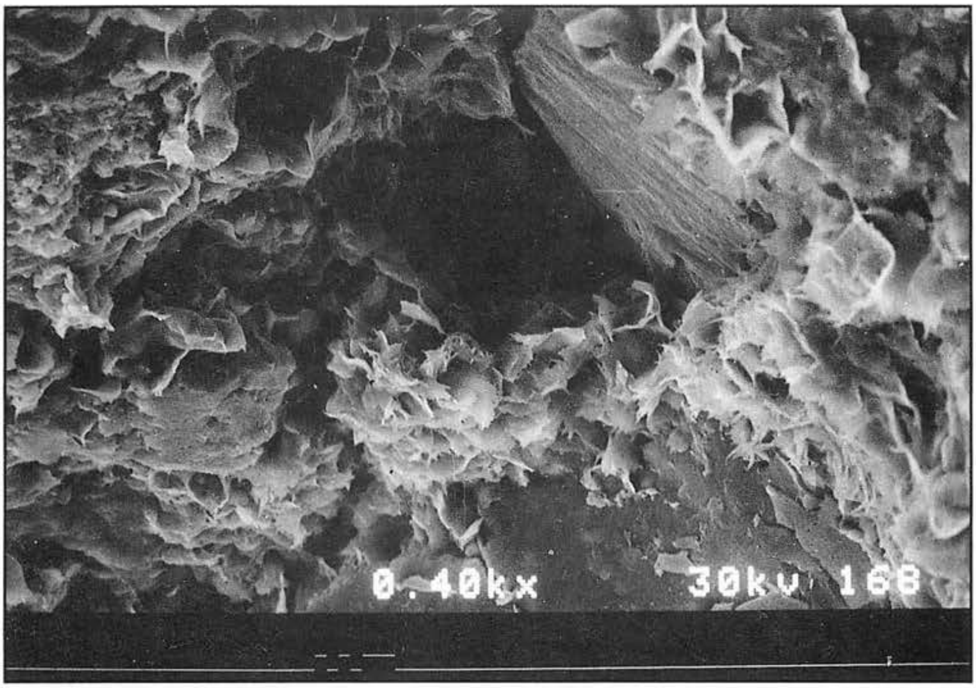

Figure 17: Mixed-layer illite-smectite clays, with a combination of crenulated to slightly filamentous morphology. These clays are seen partially occluding pore space and choking pore-throats. Marker length — 10 μm.

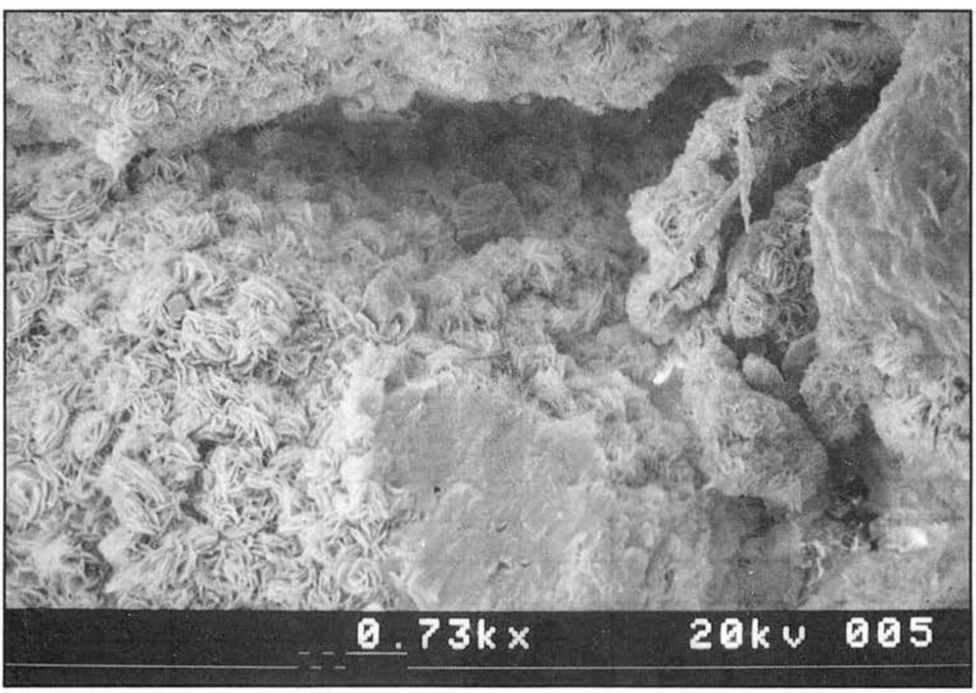

Figure 18: Well crystalline, authigenic, grain-coating chlorite rosettes. Pore-throats are severely restricted by pore-lining chloritic clay. Sample is from an East Malaysian basin. Marker length — 10 μm.

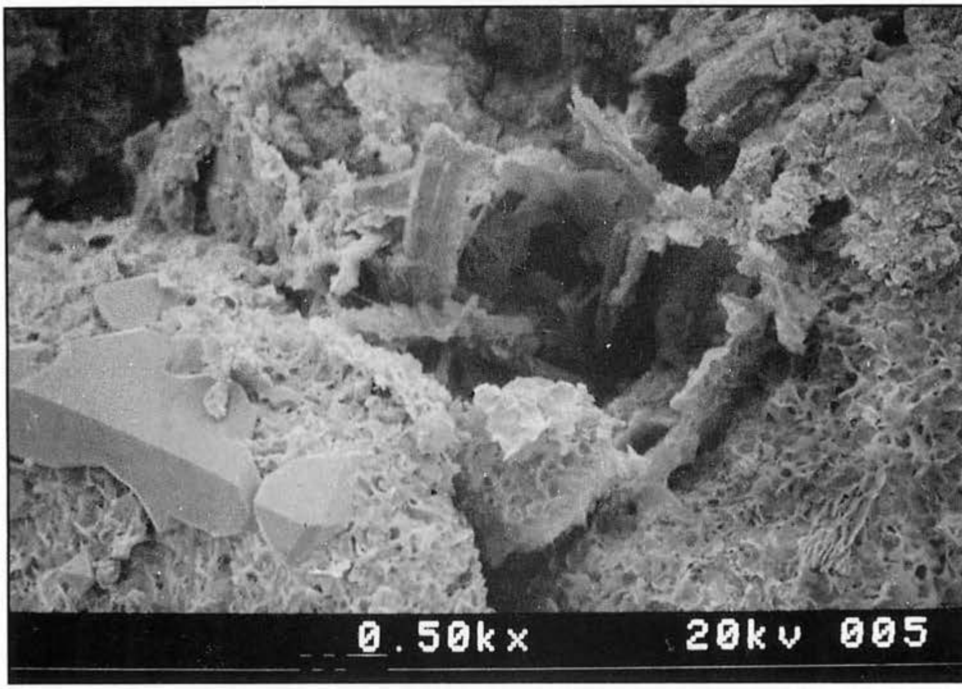

Figure 19: Moderate to well crystalline, grain-coating clay to pore-lining mixed-layer chlorite/smectite clay with crenulated to honeycombed morphology. An extensively leached feldspar grain is also shown (middle right). Marker length — 10 μm.

Table 3: Properties of selected mineral and fluids.

	Density	Neutron Porosity	K (wt%)	Th (ppm)	CEC (meq/100g)
Illite	2.53–2.65	24–30	3.2–5.8	6–22	10–40
Kaolonite	2.60	36–37	0–1.5	18–26	3–15
Chlorite	2.7–3.3	51–52	0		10–40
Smectite	2.12–2.53	24–44	0–0.6	10–24	80–150
Muscovite	2.83	20	7.9–9.8	6–22	
Quartz	2.65	–2			
K-Feldspar	2.54–2.57		10.9–16		
Water	1–1.2	60–100			
Oil	0.7–0.9	60			

logging industry. It is often used synonymously with V_{clay}(Worthington, 1985) even though theoretically and practically the two are not the same parameter (Heslop, 1974). The shaly sand model in Figure 7 defines the terms V_{shale} and V_{clay} as used in this paper.

V_{clay} may be defined as the percent (by volume) of clay minerals in a measured unit of rock. Two types of V_{clay} are discussed in the literature. One type is $V_{clay(wet)}$, which includes bound water, and the other type is $V_{clay(dry)}$, which is only the volume of the clay solid. As defined above, V_{clay} is impossible to measure and is difficult to calculate.

V_{shale} may be defined as the percent (by volume) of "shale" in a measured unit of rock. In practice, V_{shale} would include clay minerals, non-clay minerals and water-filled pores containing both bound water and capillary water. This is because the most clay-rich shale (termed $V_{shale_{max}}$ in this paper), as identified by wire-line logs, is chosen as representing 100% V_{shale}. The assumption that 100% V_{shale} equals 100% V_{clay} is erroneous because, as seen in Malaysia, clay mineral content in shales and claystones rarely reach as high as 70% by weight (measured by XRD and Mineralog™).

The inclusion of clay-associated capillary water in V_{shale} does differ from some authors (Poupon *et al.*, 1970). It is included here because capillary water is important to a wells productivity (Bos, 1982; Zemanek, 1989) and because the capillary water is highly variable in clays (Hurst and Archer, 1986; Nadeau and Hurst, 1991).

Traditional V_{clay} – actually V_{shale} – calculation (Poupon and Gaymard, 1970; Poupon *et al.*, 1970) is based on the use of several "clay indicators" and choosing the lowest calculated value of V_{clay}. The clay indicators include resistivity, SP, gamma-ray, and combinations of sonic, density, and neutron-porosity logs. Gamma-ray logs and neutron-density crossplots appear to be the preferred traditional indicators. The basic technique is to find a 100% wet-clay log response and a clay-free sandstone log response, and assume a near linear variation with V_{clay} between the two values. Several problems occur with this technique. Firstly the wireline logs respond to other factors besides clay (e.g. framework minerals, porosity, gas saturation, etc.) (Poupon and Gaymard, 1970). Secondly, there are no 100% wet clays in nature and clay-free sandstones are almost equally rare (this paper). Thirdly, the responses of the above logs not only depend on the total clay amount in the rock, but also depend on the mineral composition of the clay (Fertl, 1983). As shown above, clay mineralogy is variable in Malaysia.

Discussion of the first problem is beyond the scope of this paper.

The second problem may be overcome if the V_{clay} was independently determined at several points. From this one could develop a V_{clay}– log response relation, assuming constant relative clay mineralogy. However, laboratory techniques, such as XRD and Mineralog™ do not measure clay volumes but rather clay weights. V_{clay} may be calculated by making assumptions above clay densities and independently measuring the porosity of the sample.

The third problem, changing clay mineralogy, is very difficult to correct for by using traditional logs. The traditional method compares the log response in the sands to the log response of $V_{shale_{max}}$. As log response is clay type dependent, not just total clay dependent, this technique will only work if the clays in the sands are similar to those in the shales. As discussed above, there are commonly major differences. Table 3 lists important variables for the different clay mineral types. As can be seen there are large variations in specific radioactivity (potassium and thorium content), density, neutron porosity, and cation exchange capacity (CEC). These affect gamma-ray, density and sonic, neutron, and resistivity logs respectively. SP, resistivity, and sonic logs are also affected by the distribution of the clays.

The advent of modern spectral-gamma tools allows not only V_{clay} calculations but also allows clay typing (Rukhovets and Fertl, 1982; Fertl, 1983; Herron, 1986). However, difficulties due to the natural variability within a particular clay-mineral group and the general difficulties in analyzing multicomponent systems may lead to errors (Hurst, 1990; Humphreys and Lott, 1990). It is proposed here that clay mineral identification from spectral-gamma logs may allow for accurate V_{clay} calculations but need calibration with laboratory measurements for each area.

Porosity

A major control on porosity is total clay content. It is important to differentiate total porosity from effective porosity. Figure 21 defines several porosity terms and the type of porosity being measured by different tools. Total porosity may be defined as the portion of bulk volume not occupied by solids. Total porosity includes both movable fluids and immobile water. Effective porosity, as defined here, includes only those pores of large size through which fluids may move. The difference between total porosity and effective porosity is the amount of bound water and the amount of capillary water. Bound water is largely a function of the electrical properties of the clays and may be related to clay mineralogy. Capillary water is largely related to microporosity which is generally affected by clay morphology.

Some authors include the small pores containing capillary water as part of effective porosity (Juhasz, 1979). In this paper these small pores are not included with effective porosity because at irreducible water saturation "all pores below a constant size are blocked by the wetting phase" (Holmes *et al.*, 1971). It should be noted that as defined here, effective porosity would also be a function of wettability and fluid type – whether gas or oil – as well as pore-size distribution.

Visible porosity– measured in thin section is equivalent to effective porosity in many cases (Helsop, 1975). Figure 22 shows the relationship between humidity-dried helium porosity and visible porosity from one well in the Malay basin. In this well, visible porosity and therefore effective porosity are basically zero at around 12% helium porosity. Total porosity would be equivalent to humidity-dried helium porosity, in this case, as the samples contain low-expandable clays and therefore bound water is minimal. It is implied that there is around 12% capillary water in the silty shales. Figure 23 shows the relationship between total clay (wt%) with helium porosity for the above mentioned well. Note that 12% porosity equates to

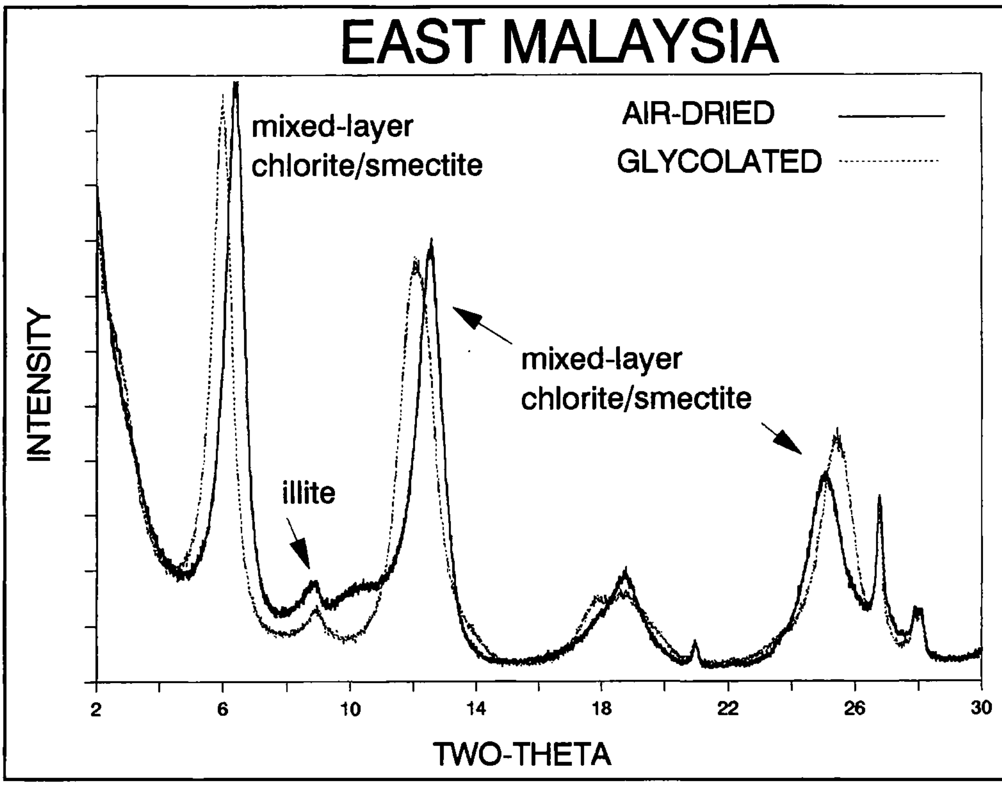

Figure 20: X-ray diffractogram of the clay fraction from a sandstone containing primarily mixed-layer chlorite/smectite.

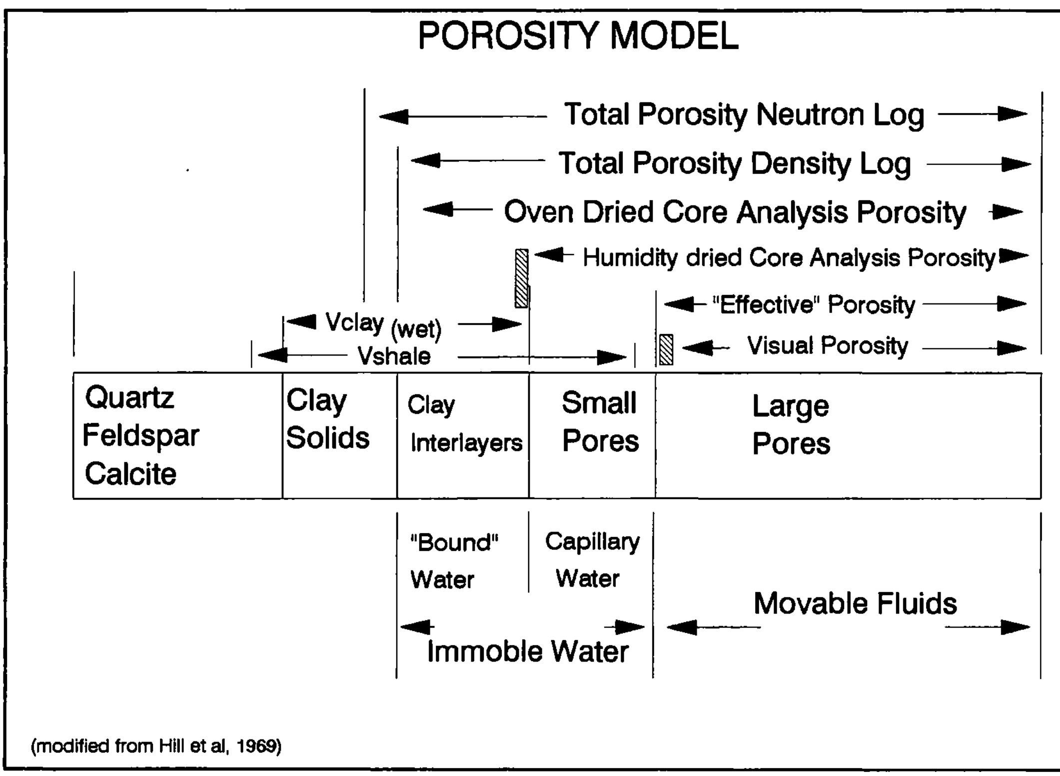

Figure 21: A porosity modelfor a clay-bearing sandstone. Note that no relative volumes are suggested by the sizes of the blocks in this diagram (modified from Hill *et al.*, 1969).

around 40% total clay. 40% total clay equates to a permeability of around 0.1mD (Fig. 24) which confirms that the porosity is largely ineffective. Figure 25 and Figure 26 show the porosity and permeability relationships with total clay for a well in East Malaysia. Similar trends can be seen in these figures though the exact numbers vary and reflect the higher degree of compaction in this deeper well.

There are other clay-related factors which control total and effective porosity. One important factor is clay distribution (Thomas and Stieber, 1975; Juhasz, 1981). Figure 27 is a simple model illustrating how the relation between V_{shale} (from $V_{shale_{max}}$) and total porosity varies depending on the three main modes of clay distribution - dispersed, laminated, and structural. There is a sharp decrease in total porosity with dispersed clay until the intergranular pores are filled at around 40% V_{shale}. At this point effective porosity would be zero. Interlaminated clay-rich shales and clay-free sands show a less rapid drop in total porosity with clay content. In addition, effective porosity would only become zero at 100% V_{shale} in this case. Total porosity may actually increase with increasing structural clay, however there would be no change in effective porosity.

For there to be a good porosity$_{(total)}$ – V_{clay} correlation, there must be no significant variation in clay distribution. In the two examples shown above, more scatter is apparent in the samples from the Malay basin. In this sample set both laminated and dispersed clays occurred, as well as structural clays in minor amounts, which apparently causes the observed scatter. For there to be a good porosity $_{(effective)}$ – V_{clay} correlation, there must be no significant variation in relative clay mineralogy and clay morphology (i.e. clay-bound water and capillary water). Where the clays are highly variable, the effect of each clay type on porosity must be considered individually.

Figure 28 shows the effect clay distribution has on a typical neutron-density cross-plot. The shaded area shows where most "typical data" plot (Poupon *et al.*, 1970). For there to be a good relationship between clay distribution and clay amount with the neutron-density crossplot it is important that there is not significant variation in clay mineralogy.

A special problem occurs during detailed reservoir description when the same clay mineral has two or more types of morphology with differing capillary water. In general, the morphologies of authigenic clays (be it the kaolinite booklets, the chlorite rosettes, or the crenulated to honey-combed mixed-layer clays) differ significantly from the platy morphology of equivalent detrital clays and would contain differing amounts of associated capillary water. Where the occurrence of authigenic clays may be correlated with total clay content and relative clay mineralogy, and in Malaysia there does appear to be such a correlation, then the measurement of V_{clay} and clay types may allow for correction of effective porosity with varying clay morphology.

Electrical Properties

Two electrical parameters, formation factor and resistivity index, are of major concern of the petrophysicist. These parameters are required for calculation of

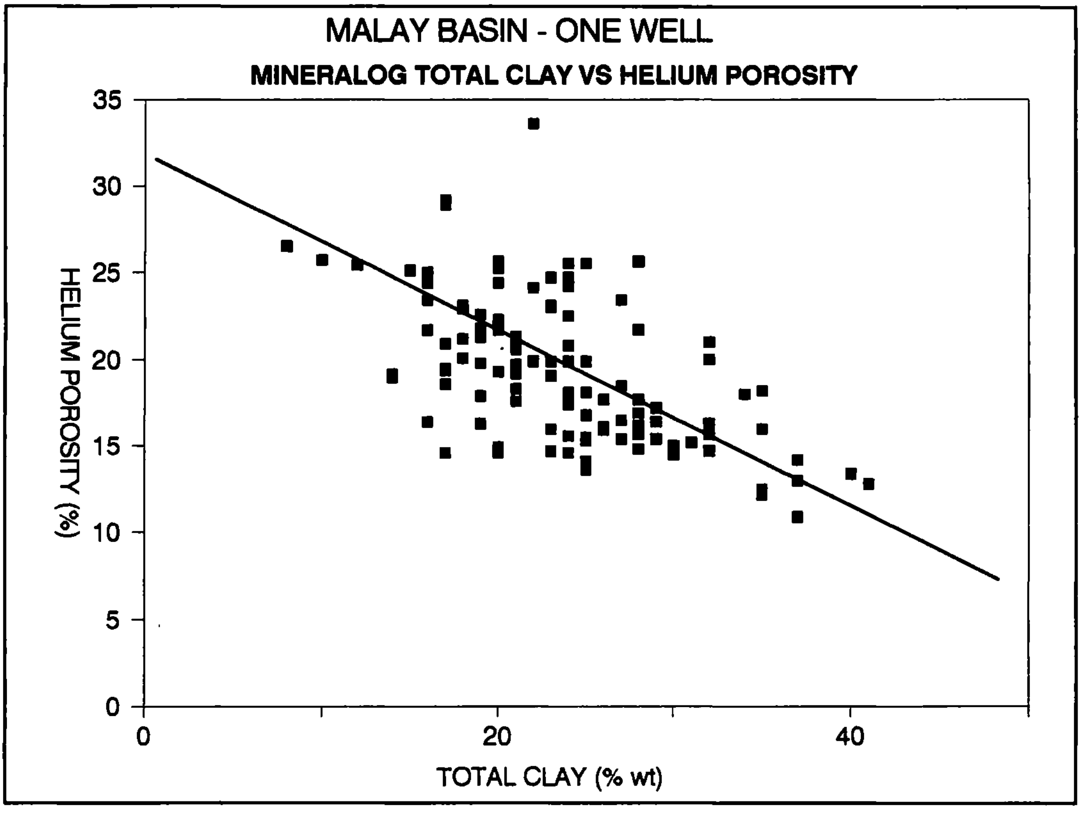

Figure 22: A crossplot of visible porosity, as measured in thin section by a 250 point count, with helium porosity.

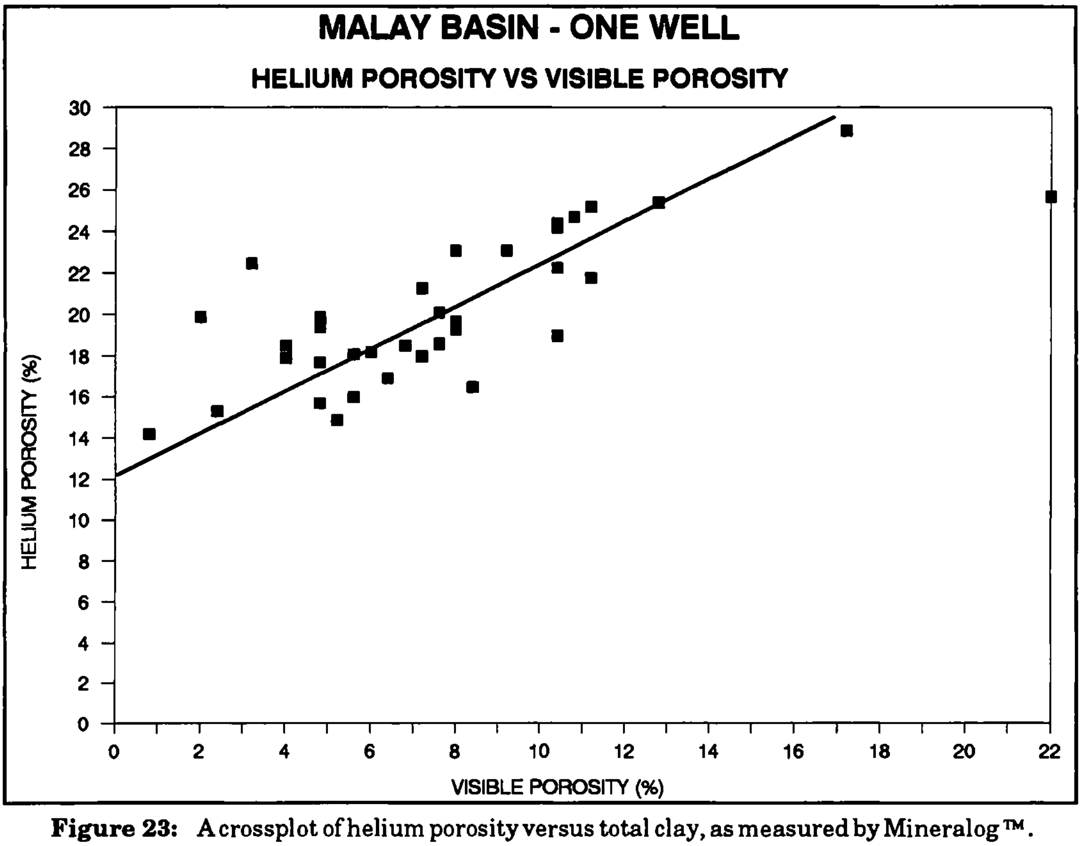

Figure 23: A crossplot of helium porosity versus total clay, as measured by Mineralog™.

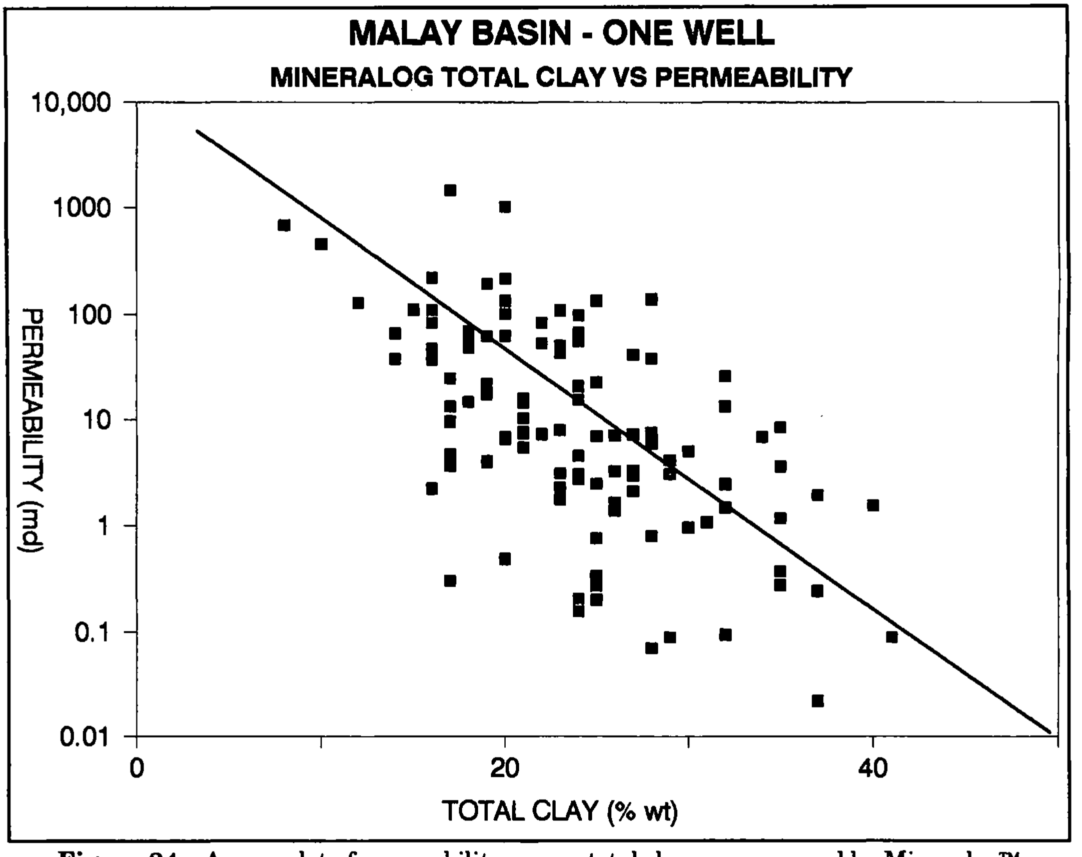

Figure 24: A crossplot of permeability versus total clay, as measured by Mineralog™.

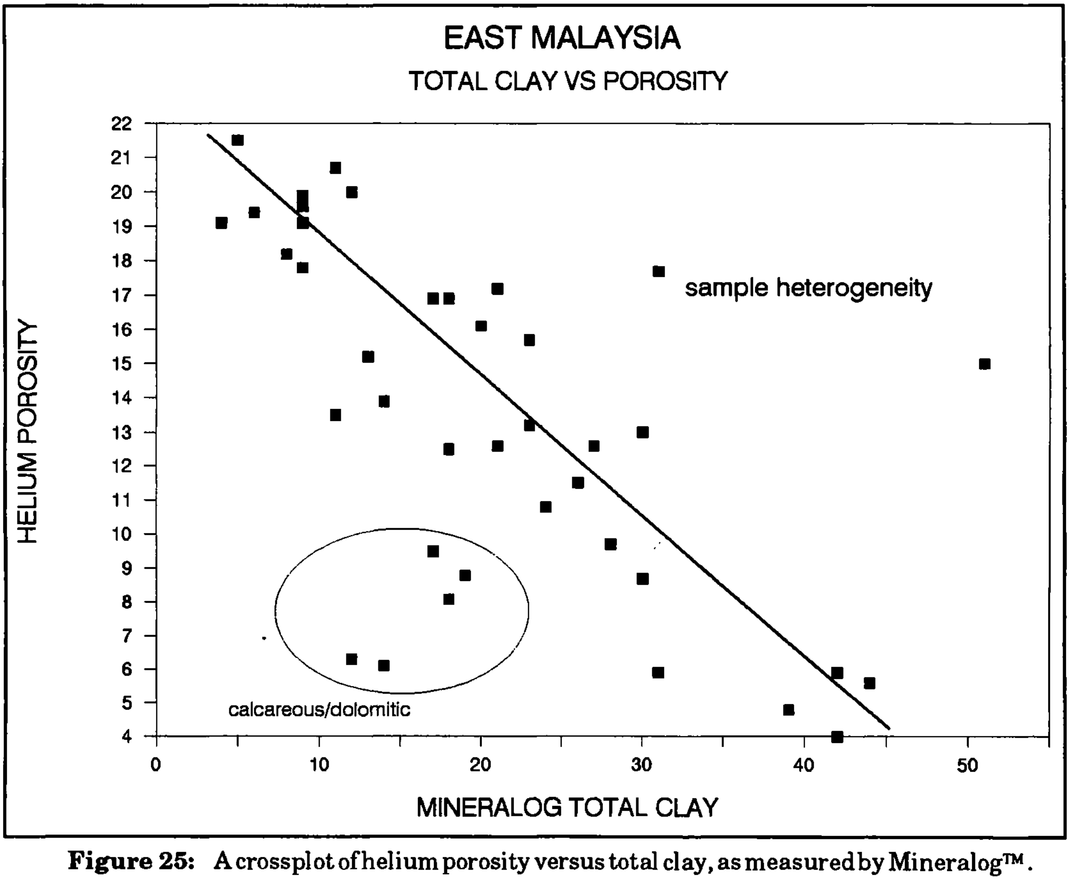

Figure 25: A crossplot of helium porosity versus total clay, as measured by Mineralog™.

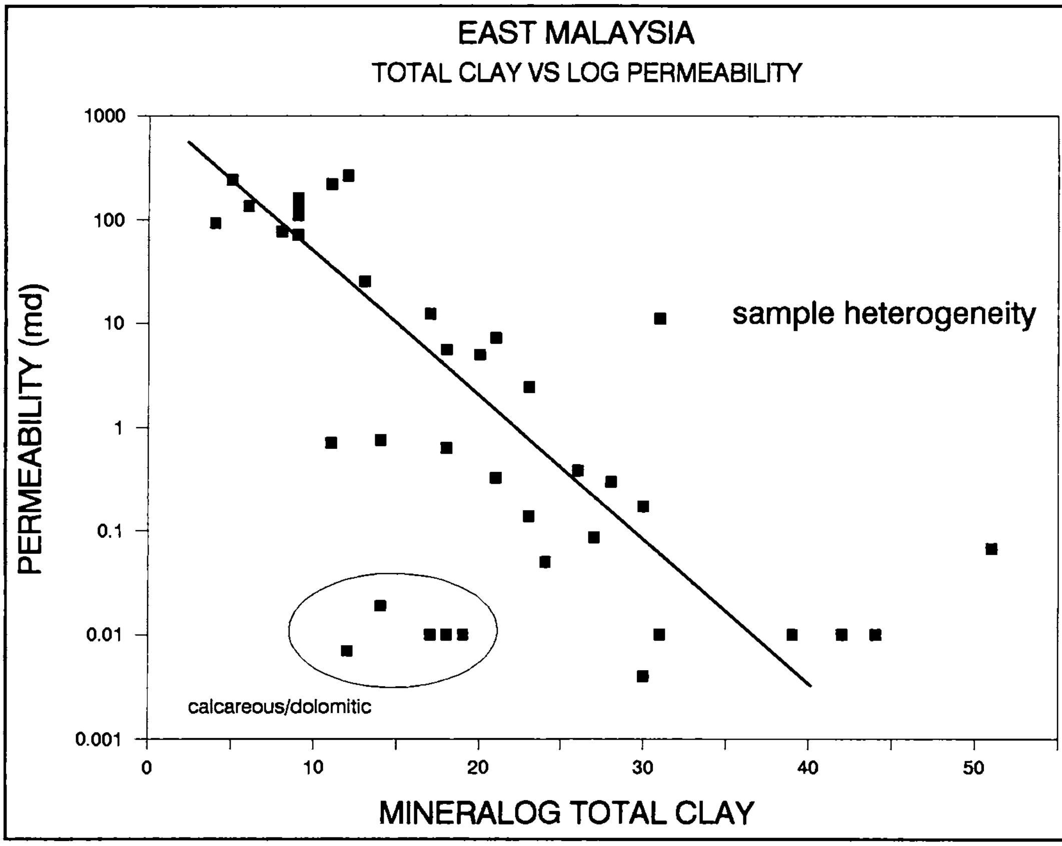

Figure 26: A crossplot of permeability versus total clay, as measured by Mineralog™.

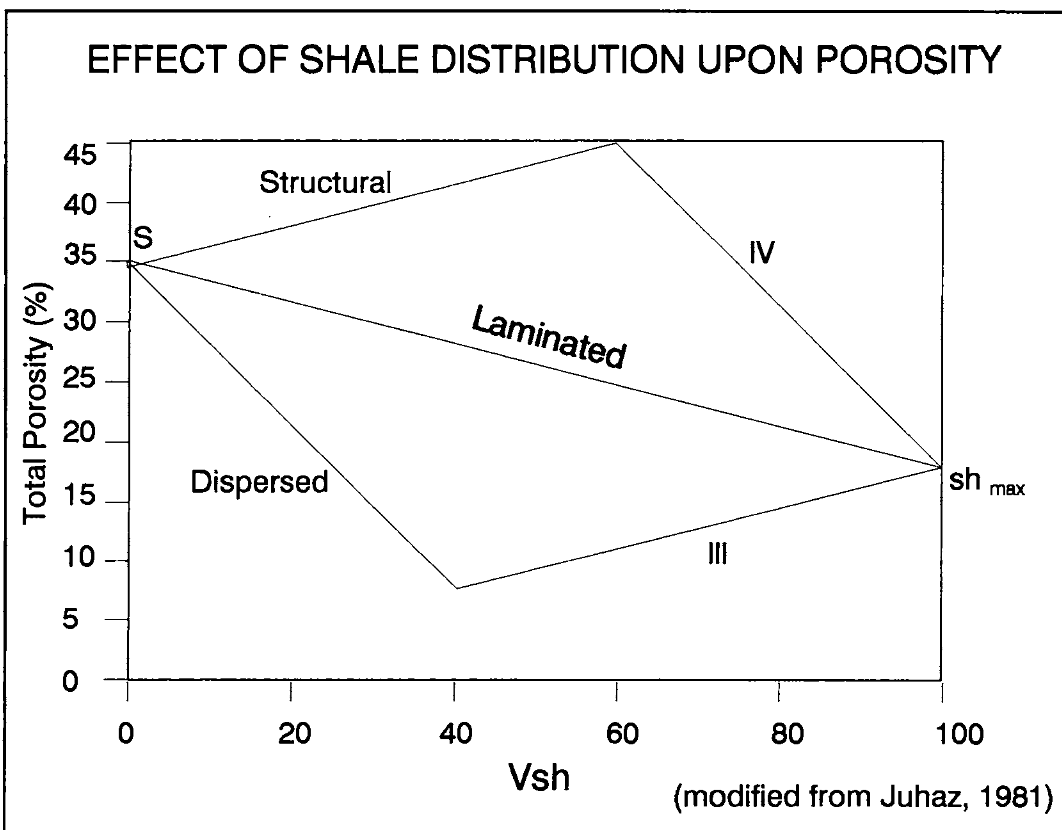

Figure 27: A generalized diagram showing the relationship between total porosity and Vshale for different type of shale distribution (modified from Juhaz, 1981).

water saturation (Sw) from wireline logs. Both are affected by the total clay content and the relative clay mineralogy in the sandstones.

There are more than 30 shaly sand models for calculating Sw in the literature. Worthington (1985) divides these into two main groups. Those dependent on log-derived V_{shale} and those based on "double-layer models". The V_{shale} models, to work properly, require that there be no significant variations in clay mineralogy – at least between high-CEC clays and low-CEC clays (refer to Table 3). The "double-layer" models would generally be preferred and are required in formations with variable clay mineralogy, as seen in some wells in East Malaysia. However, most models of this type require laboratory measurements, most importantly cation exchange capacity, on conventional core or rotary-sidewall core samples which are not always available. New "double-layer" shaly sand evaluation techniques, such as those proposed by Fertl (1987) attempts to overcome this sample limitation by equating CEC with clay mineralogy and clay volume as determined by spectral-

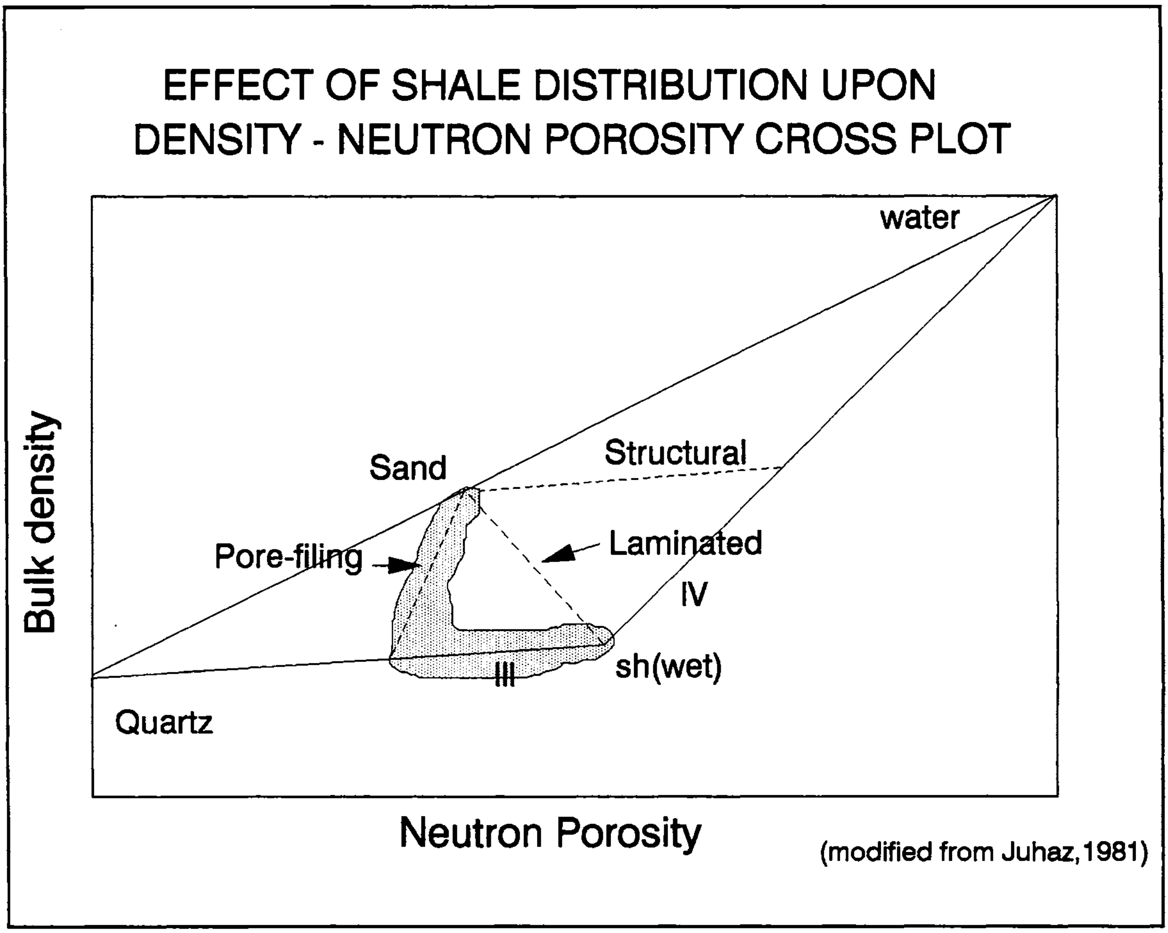

Figure 14: A generalized diagram showing how sediments with varying V_{shale} and different types of shale distribution would plot on a neutron-density crossplot. (dashed lines). The shaded area is where most data tend to plot (modified from Juhaz, 1981).

gamma tools. However, as Table 3 shows, there is a natural variability in CEC for each clay mineral. Therefore some calibration with subsurface samples is required for each area and possibly for each formation where complex lithologies occur.

SUMMARY

Clay minerals are an important constituent in the subsurface sandstones of Malaysia. The clays show significant variation in total content, origin, mineralogy, distribution, and morphology between samples. In general, detrital clays comprise mainly illite and mixed-layer illite/smectite with lesser chlorite and kaolinite. The authigenic clays comprise mainly kaolinite, chlorite, and mixed-layer chlorite/smectite with lesser authigenic illite and mixed-layer illite/smectite. Smectite occurs locally. Kaolinite is the main authigenic clay in the Malay basin except in two wells where smectite was prevalent over a restricted depth range. In East Malaysia kaolinite, chlorite, and mixed-layer chlorite/smectite are the main authigenic clays. Kaolinite is more commonly the prevalent authigenic clay in non-marine to paralic sediments, while authigenic chlorite and mixed-layer chlorite/smectite are apparently restricted to marine sands.

Petrophysical parameters, such as V_{shale}, porosity, permeability, and water saturation are affected by the occurrence of clay. Not only is total clay content important, but clay mineralogy, clay distribution, and clay morphology affect the above parameters and the analyst's ability to calculate them from wireline logs. V_{shale} calculations are affected by clay mineralogy. Measured and calculated porosity and permeability are affected by clay distribution and clay morphology. Calculated and true water saturations are affected by all the clay variables.

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