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Petrographic and diagenetic studies of the reservoir sandstone of the Malay Basin

CHU YUN SHING
Institute for Advanced Studies
University of Malaya

The reservoir properties of Late Oligocene - Miocene sandstones of the Malay Basin depend on primary depositional facies, mineralogical contents and burial diagenesis. Petrographic studies and classification show significant differences in the texture and mineralogical content of sandstones from different seismically defined groups, namely E, I, J and K. The oldest sandstones, group K, are braided stream deposits and contain mainly medium-grained sands. The group J sandstones deposited in a brackish- to shallow-marine environment, contain well sorted, fine- to medium-grained sands. The group E and I sandstones, which were deposited in estuarine environments, are fine- to very fine-grained and matrix rich.

The original mineral content of the sandstones has influenced the trend of post-depositional diagenetic changes. Higher primary porosity is generally present in the mature or clean sandstones. The loss of porosity in these sandstones commonly is due to quartz cementation and precipitation of authigenic clays. Mechanical compaction caused a major loss of initial primary porosity during shallow burial. Pressure dissolution of sandstone grains was mild, as deduced from cathodoluminescence studies, where the area of framework grain core contacts is minimal and interlocking grain boundaries are due to quartz overgrowths. The immature sandstones contain either high percentages of detrital clays or unstable rock fragments or both. Mechanical compaction caused the main diagenetic damages resulting in a major loss of intergranular porosity through deformation of ductile grains and subsequent formation of pseudo-matrix. Early loss of porosity and permeability retarded or inhibited further diagenesis. Thus, quartz overgrowths and cements are rare in these sandstones.

Secondary porosity generated by the dissolution of grains, especially feldspar grains, played an important role in contributing to total porosity. Investigations of grain and pore morphologies using the scanning electron microscope revealed a high percentage of micro-porosity preserved between the clay matrix and newly formed authigenic clays, especially kaolinite. Other diagenetic products are calcite and siderite cements with glauconite, chlorite and smectite being less common.

INTRODUCTION

The Malay Basin is located offshore of and parallel to the east coast of Peninsular Malaysia. It trends northwest-southeast and is about 480 km long and 200 km wide (Fig 1). Core samples were collected throughout the basin, but sample density is greatest in the south (Fig 2). The basin sedimentary fill thins to the south, with the older sandstones emplaced at shallower depth in the southern end of the basin (Fig 3). The samples were collected from four seismically defined units of Late Oligocene to Miocene age, groups K, J, I and E.

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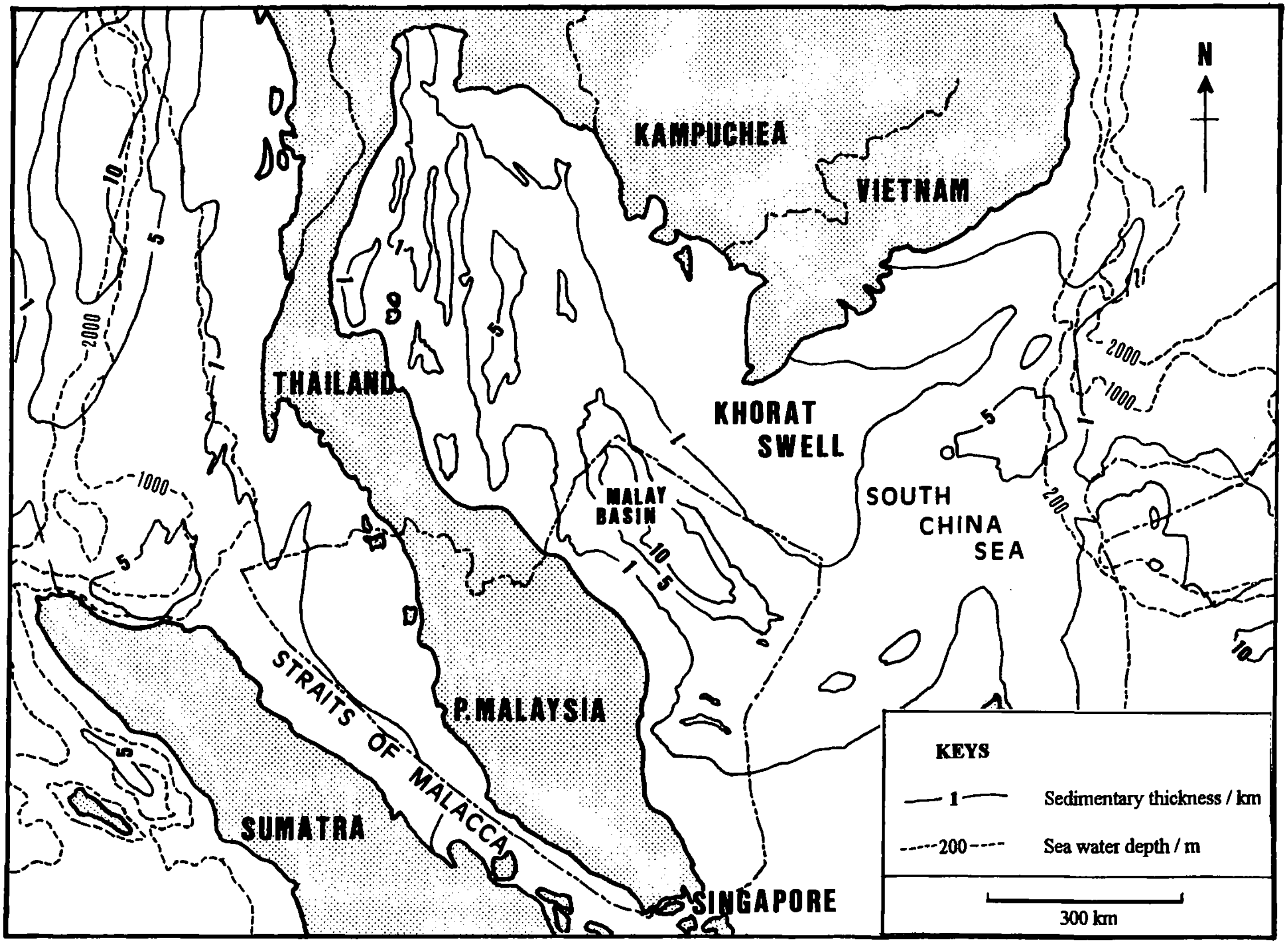


Figure 1: Location map of the Malay Basin.

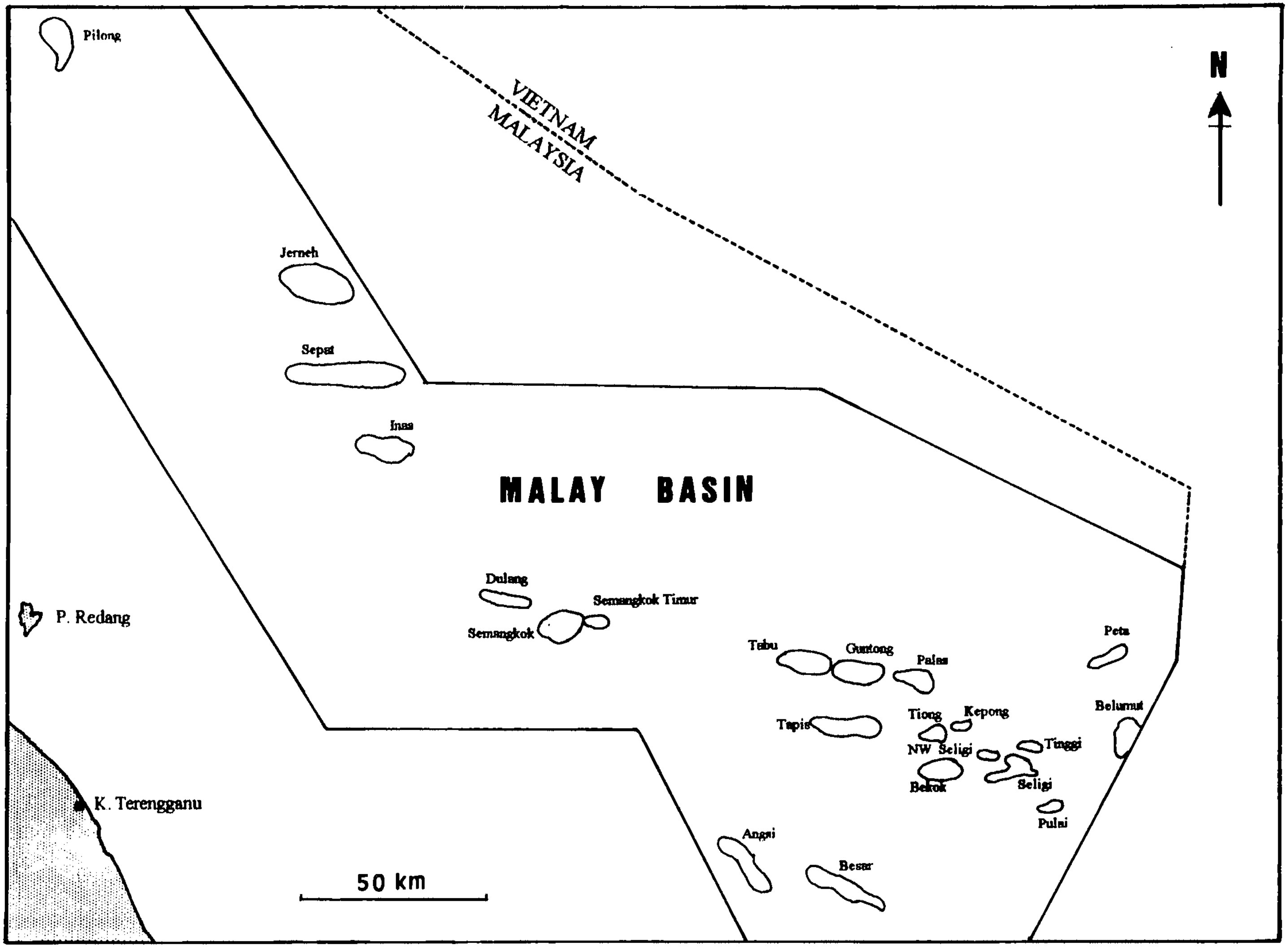


Figure 2: Location of fields sampled in this study.

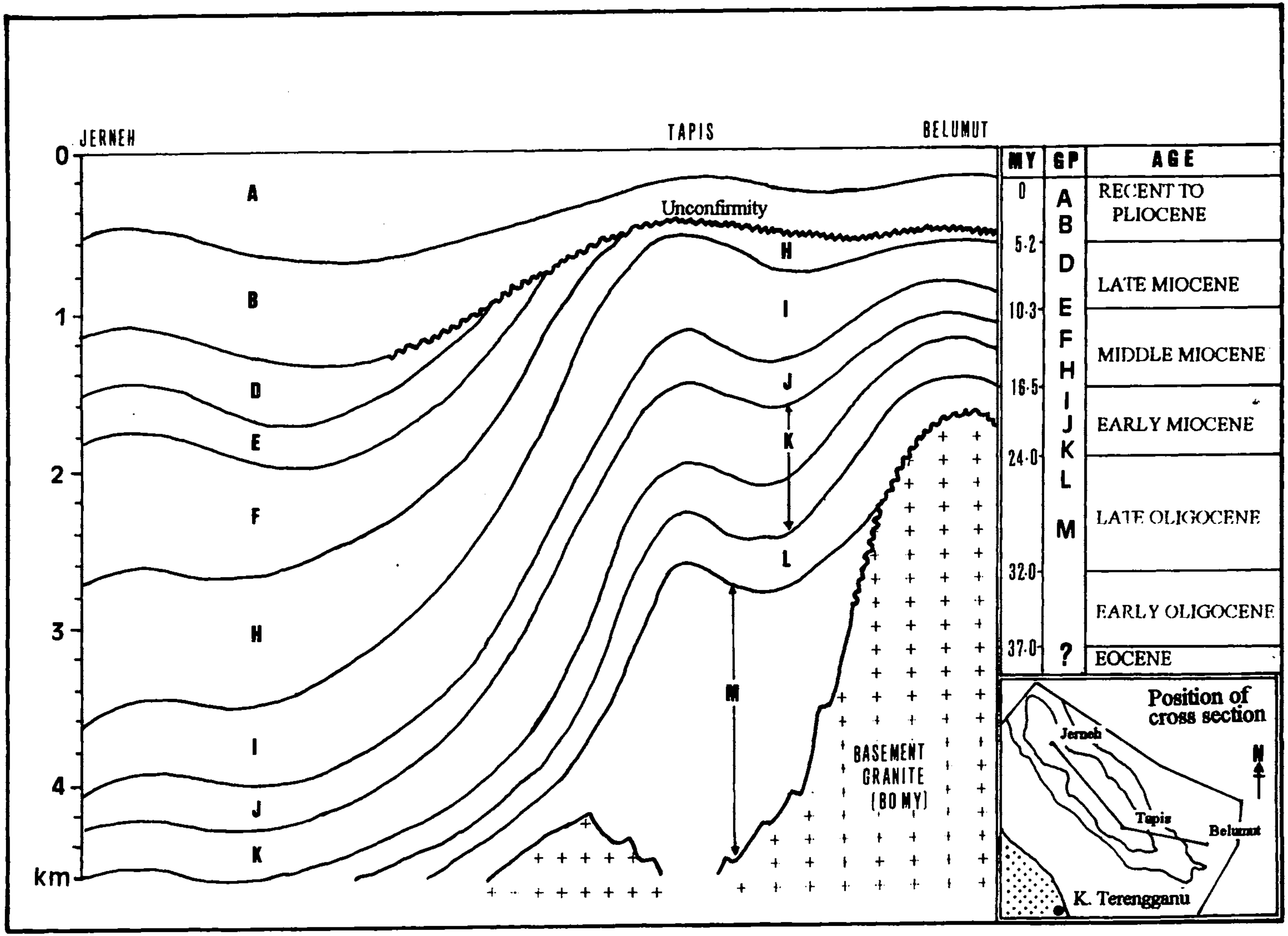


Figure 3: Malay Basin schematic stratigraphic cross section.

The petrographic study is based on 176 sets of point-counted data from 241 samples. The result revealed that the sandstones within each group are mineralogically similar. A more detailed study could be done by subdividing the petrographic results for each group according to sandstone units and sedimentary facies, but the current grouping serves the purpose of generalizing the mineralogical characteristics and diagenetic processes. These parameters can be used to interpret and predict the quality of a reservoir within a particular sandstone group.

Sandstones which differ mineralogically commonly experience different diagenetic processes and degrees of alteration (Surdam, MacGowan and Dunn, 1989). The Malay Basin sandstones have undergone substantial porosity reduction due to mechanical compaction during early burial. This initial porosity loss is similar to that of sandstones the Lower Cretaceous Travis Peak Formation, East Texas, where loss of porosity in the first 900m of burial is due to mechanical compaction (Dutton and Diggs 1992). With increased burial depth and time of burial, diagenesis may leach and dissolve unstable rock fragments and feldspar grains, thus enhancing secondary porosity. However, primary porosity can also be reduced by cementations. Chemical diagenesis in Malay Basin sandstones included detrital grain and clay alteration, authigenic clay precipitation, quartz cementation and carbonate cementation which increased with depth and time of burial. The porosity of a sandstone can be enhanced by dissolution of unstable framework grains and cements caused by the influx of fresh meteoric waters via unconformities due to tectonic uplift (Shanmugam, 1989 and 1990). Uplift and erosion exposed part of the Lower J and K sandstones at the southern end of the Malay Basin (Yap, 1990) and caused a recurrence in the generation of secondary porosity by dissolution of framework grains and cements in these sandstones, especially the K sandstones. Fine grained sandstones with low quartz content and abundant detrital clay matrix tend to lose their primary porosity owing to early mechanical compaction and have very little effective porosity preserved (Baillie, Tingate and Stuart, 1991). This is observed in numerous immature sandstones of both the E and I groups of the Malay Basin.

SEDIMENTOLOGY

Depositional Environments

The E, I, J and K sandstones are divided by seismic horizons and were deposited in different environments. The oldest sandstones, group K were deposited in a braided stream, fluvial environment (Nik Ramli, 1987, 1988a) during Late Oligocene to Early Miocene. The J sandstones were deposited during Early Miocene to Middle Miocene in brackish- to shallow-marine environments (Nik Ramli, 1986, 1988b). Groups E and I sandstones were deposited in estuarine environments during Early to Late Miocene (Hui and Pillar, 1988; Thambydurai, Mustapha,. Mueller and Dixon, 1988).

The provenances of these sandstones were primarily the Khorat Swell to the northeast and ancestral Peninsular Malaysia to the southwest of the Malay Basin. The source terrances are composed mainly of granite and metamorphic rocks.

Different depositional facies in each group was the major factor controlling the mineralogical content and textural characteristic of its sandstone units. The J sandstones, especially Upper J and Middle J sandstones, contain detritus derived from reworked sediments of the Lower J and K sandstones. A more complex change of mineralogical composition was encountered in the J sandstones compared to the Group E, I and K sandstones.

PETROGRAPHY

Methods

Conventional transmission light microscope (TL) was used to obtain the basic petrographic information. A total of 241 sandstone samples were obtained from the group E, I, J and K. Before sectioning, all samples were impregnated with epoxy containing blue dye in order to enhance visibility of sandstone porosity and prevent the clay from being washed away. Point counts of 176 thin sections were made at 250 counts per-slide for framework, matrix, cement composition and porosity. Point count analysis of grain size and sorting was obtained for 48 thin sections using a size interval of 1/2 phi (F). Cathodoluminescence microscopy (CL) was used to study the texture and quantities of detrital quartz core, quartz cement and silica cement. Other fine-grained minerals and micro-features were examined using scanning electron microscope (SEM). Clay minerals were analyzed using X-ray diffraction (XRD).

Framework Grains

The framework grains (FWG) average of approximately 60%, the remaining 40% is the intergranular volume (IGV). The E, I, J and K sandstones have an average framework of 59%, 59%, 63% and 62%, respectively (Table 1).

The E and I sandstones are mostly litharenite and feldspathic litharenite and have framework ratio of $Q_{71}F_9R_{20}$ and $Q_{69}F_8R_{23}$ (Q = quartz, F = feldspar, R = rock fragment), respectively (Fig. 4). For both E and I sandstones, quartz comprises 40.0% of the total sandstone composition. Nearly all quartz is monocrystalline with undulose extinction. Feldspar and rock fragments average 5% and 12% respectively. Feldspars are mostly untwinned K-feldspar and rock fragments are mainly of sediment rock fragments. Metamorphic rock fragments and volcanic rock fragments are generally rare. Compared to the J sandstones, the E and I sandstones have limited range of framework grains composition (Fig. 4).

The framework grains in the J sandstone comprise 55% to 70% of the total rock volume and quartz is the major component. The Middle J sandstones, J-30 and J-40 contain lower percentages of FWG (60%) compared to the J-20 sandstone (64%). The earlier have a higher detrital clay matrix which fills the IGV. The composition of FWG in the J-20 sandstone samples exhibits a range depending on the location and depth, for example, FWG in Seligi field is 55% whereas is 64% in Guntong field. The J sandstone is mostly sub-litharenite due to the low content of rock fragments and feldspar (Fig. 4), with an average framework ratio of $Q_{84}F_5R_{11}$. The types of quartz, feldspar and rock fragment are similar to that of the E and I sandstones.

Table 1: Average mineral and pore percentages of the E, I, J and K Sandstones, Malay Basin

Group	Qtz	Feld	Rfg	Ogn	FWG	Mtx	Cmt	Rep	Pore
E	40.8	4.9	11.2	2.0	**59.8**	13.1	13.3	0.0	14.7
I	39.4	4.7	12.9	2.3	**59.4**	15.5	13.4	0.0	11.7
J	50.4	3.3	6.5	2.6	**62.8**	14.3	12.9	0.1	9.9
K	41.0	4.3	13.0	3.5	**61.9**	11.4	15.4	0.1	11.2

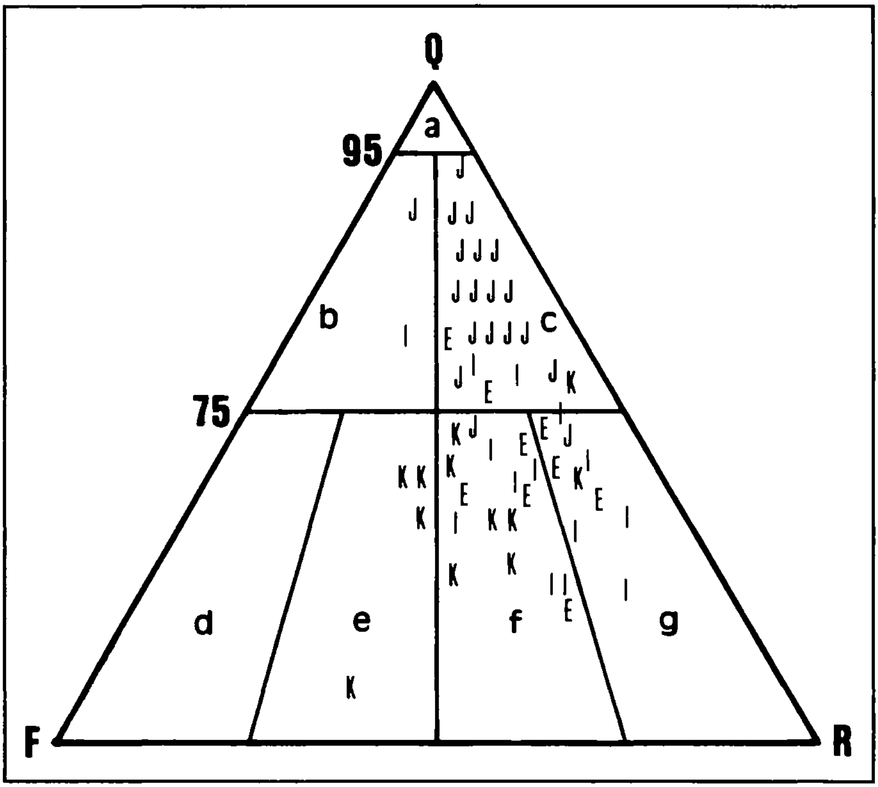


Figure 4: Malay Basin sandstones (E, I, J & K) framework components plotted on a Q-F-R diagram of Folk (1980). Compositional fields are: a=quartzarenite, b=subarkose, c=sublitharenite, d=arkose, e=lithic arkose, f=feldspathic litharenite, g=litharenite.

The K sandstone have an average framework ratio of $Q_{70}F_8R_{22}$, where they fall into the feldspathic litharenites. The quartz consists of both plutonic monocrystalline quartz and metamorphic polycrystalline quartz. The feldspar consists of a mixture of twinnwd and untwinned K-feldspar together with some plagioclase. Rock fragments are mostly sedimentary rock fragments but metamorphic and volcanic rock fragments are also present in significant amounts.

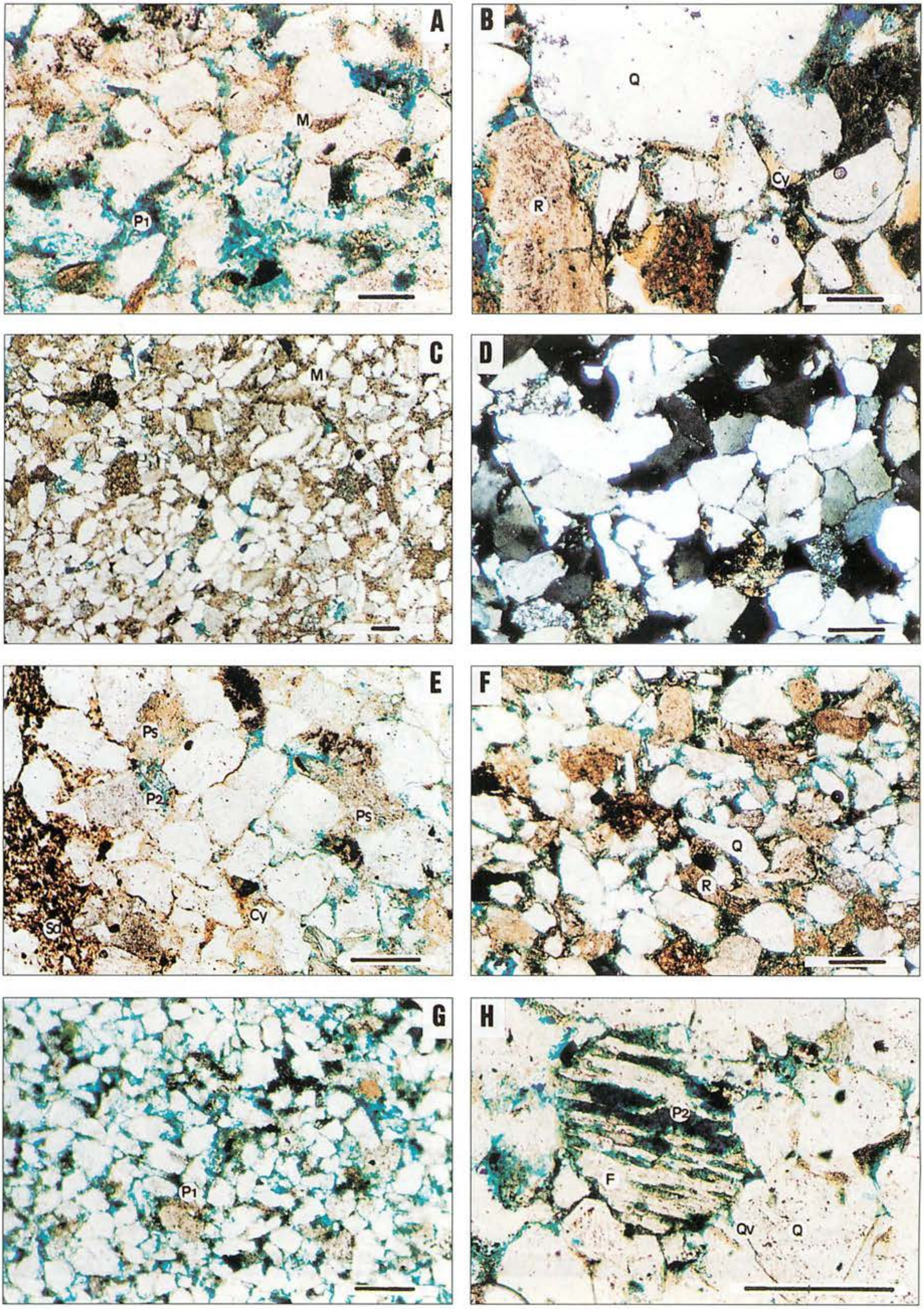
Matrix

In these four sandstones, the matrix content ranges from 4% to 40% of total rock volume and includes both detrital clay matrix and pseudo-matrix (formed by squashed clay clasts). The matrix content of the E and I sandstones primarily in the range of 8% to 18% although a few samples has as mush as 35%. Group J sandstones generally have 4% to 24% matrix but was 40% in a few samples. A majority of the J-20 sandstone samples have less than 10% matrix but the other sandstone units comprise 15% to 24% matrix. Along with detrital clay matrix and pseudo-matrix, clay matrix introduced by bioturbation is common in the J sandstones. The K sandstone has approximately 4% to 16% of matrix, which is detrital clay matrix and pseudo-matrix (Fig 5).

Cement and Replacement

Average cement content of these four sandstone groups ranges from 13% to 15% of total rock volume. Cements fill a minimum of 20% of the IGV. It is not uncommon for cements to fill 40% of the IGV and thus reduce primary macro-porosity by about one-half. Some samples were entirely cemented and no primary porosity is preserved. Major cement types are quartz, authigenic clays, siderite which occur in most samples and in significant quantities. Calcite and organic cements generally were found in small quantities. The SEM and CL studies showed that quartz cement occurred as subhedral overgrowths on detrital quartz grains and as fine-grained euhedral quartz (silica cement)(Fig 6). Clay minerals were identified using SEM and XRD. The four clay types listed in order of decreasing abundance are kaolinite, illite, chlorite and smectite (Fig 6).

Figure 5 : Transmitted light photomicrographs of the Malay Basin sandstones, bar scale = 0.2 mm. **(A)** Fine grained, moderately well sorted sandstone (Group J) with well preserved intergranular porosity (P1), and a small amount of detrital clay matrix (M). **(B)** Coarse grained, poorly sorted sandstone (Group K) with gravels of quartz (Q) and rock fragments (R). Pore-filling kaolinite (Cy) is abundant. (C) Very fine grained, moderately sorted sandstone (Group I) with abundant detrital clay matrix (M) and very little intergranular porosity. **(D)** Medium grained, very well sorted sub-litharenite (Group J) with almost only quartz grains. Extensive quartz overgrowths giving tight grain packing with long and sutured grain boundaries. **(E)** Moderately compacted sandstone (Group J). Some rock fragments squashed into pseudo-matrix (Ps). Grain outlines indistinct due to partial grain dissolution. Intergranular volume filled by authigenic clay (Cy) and siderite (Sd) cements. Secondary porosity (P2) generated by dissolution of the unstable grains. **(F)** Moderately compacted sandstone (Group I) with elongated grains of quartz (Q) and rock fragments (R). (G) Well sorted, clean sandstone (Group E) with minimal diagenetic compaction and cementation, preserving a large amount of intergranular primary porosity (P1). **(H)** A deeper buried sandstone (Group J) with secondary porosity (P2) formed by diagenetic leaching of unstable grains like feldspars (F). Quartz cementation (Qv) is widespread in this sandstone.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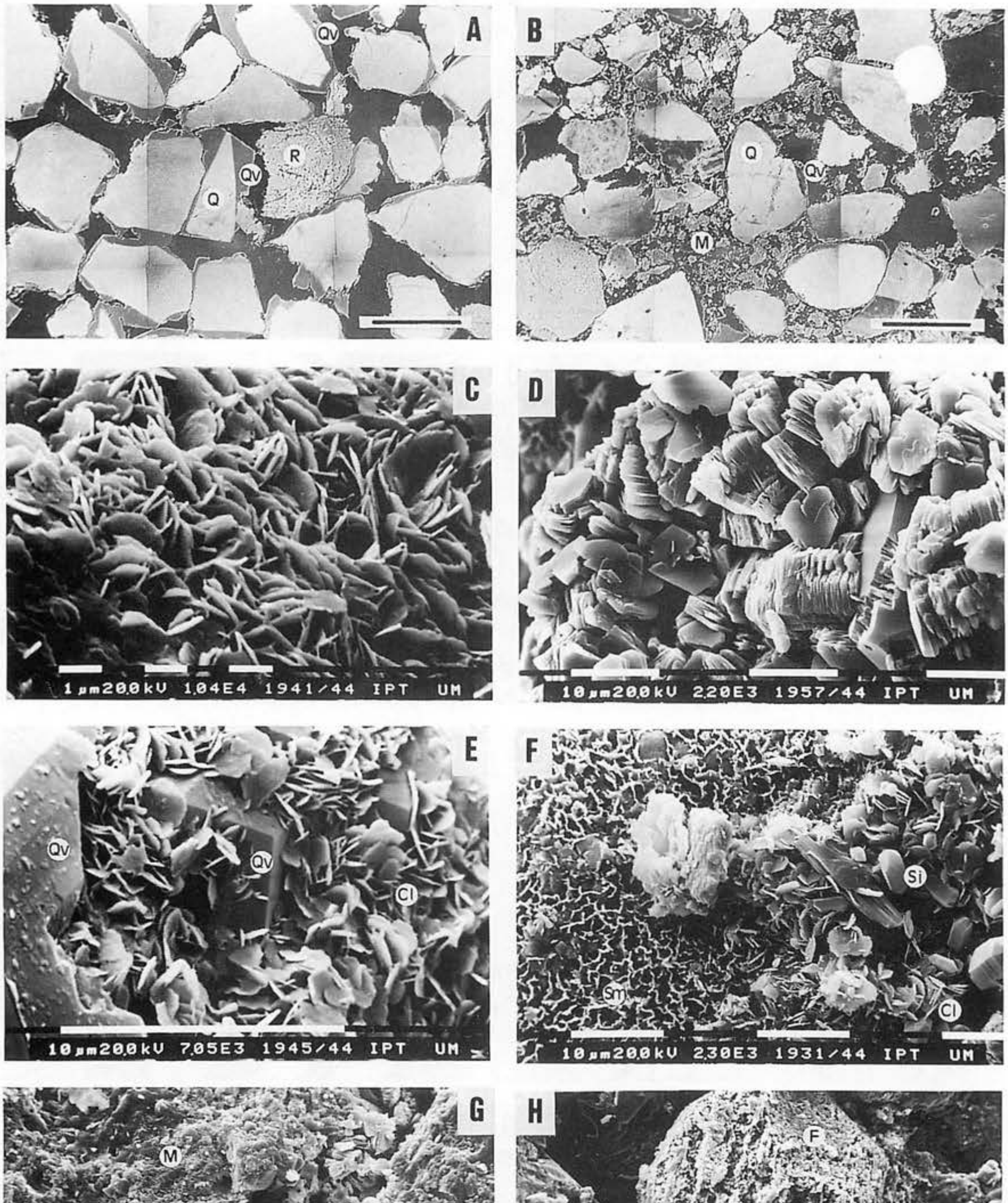
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In the E sandstones, the clay and quartz cements range from 2% to 7% and 2 to 9% of total rock volume respectively. The volume of these cements is slightly greater in the J and K sandstones compared to that of the E and I sandstones. The K sandstones have the highest amount of clay cement (6% to 10%); composed mainly of kaolinite.

Only minor amounts of replacement minerals are found in the Malay Basin sandstones. Feldspar grains were partially replaced by calcite cement and kaolinite but these comprise less than 1% of the total rock volume.

Porosity

The porosities obtained by the point-counting method are generally 5% to 15% lower than those measured from core plugs (Fig 7). The difference is greater for sandstones that contain abundant detrital matrix and low primary intergranular porosity. The average point-counted porosity of the E sandstones is 15%, and is 13%, 10% and 11% in the I, J and K sandstones, respectively.

The porosities measured by point-counting are visible porosity which consists of primary intergranular porosity and well developed secondary intragranular porosity (Fig 5). Study of pore morphologies by SEM showed a significant amount of microporosity was preserved between detrital matrix grains and in the authigenic clay flakes (Fig 6). These porosities can contribute 3% to 5% porosity to a clean sandstone (less than 10% matrix) and 7 to 12% porosity to sandstones having more than 15% matrix. The amount of microporosity is the difference between point-count porosity volume and core porosity volume.

Figure 6 : Cathodoluminescence and scanning electron photomicrographs of the Malay Basin sandstones. **(A)** Medium grained, well sorted sub-litharenite (Group J), with mostly detrital quartz grains (Q) and contains abundant quartz overgrowths (Qv). Long, sutured grain boundaries are due to quartz overgrowths. Bar scale = 0.2 mm. **(B)** Sandstone (Group J) with high matrix content. Detrital quartz core (Q) is surrounded by matrix and minute quartz overgrowths (Qv). Bar scale = 0.2 mm. **(C)** Authigenic honeycomb chlorite coating grain surface of group J sandstone. Individual clay plates are attached perpendicularly to detrital sand grain. **(D)** Booklets of pore-filling kaolinite in porous sandstone (Group J). **(E)** Early chlorite cementation (Cl) in Group J sandstone which inhibited formation of quartz overgrowths (Qv). **(F)** Early authigenic smectite (Sm) as grain coating clay, followed by formation of chlorite (Cl) and silica (Si) cements as individual grains attached to it (Group J). Individual euhedral silica cement formed due to absence of detrital quartz as nuclear for the formation of quartz overgrowths. **(G)** Group K sandstone with abundant detrital clay matrix (M) and pore-filling kaolinite (K), remaining some intergranular primary porosity (P1). Microporosity (P3) is preserved between individual kaolinite clay flakes. **(H)** Partially leached feldspar grain (F) with some intragranular secondary porosity (P2) in Group J sandstone. Intergranular primary porosity (P1) is seen in the background of the photograph.

Grain Size and Other Physical Properties

The grain size measured using the transmission light microscope are within the range of gravel to silt (5.5F). Fine silt and detrital clay are lumped into matrix. Authigenic clay cement, quartz cements and porosity are excluded and the remaining constituents are normalized to 100%. The advantages of grain size analysis using the point-counting method compared to the sieve and hydrometer method are as follows; i) The original size of detritus is measured, ii) Detrital matrix and authigenic clays are separated into different categories.

The E, I and J sandstones are well to moderately well sorted sandstones and comprise very fine-grained, very fine- to fine-grained, and fine- to medium-grained sandstones, respectively (Fig 5). The K sandstones are modearately to moderately well sorted, medium grained sand, and commonly have gravels (3.0 to 5.0 mm).

Sandstone grains are commonly surrounded by matrix or cements and are in point contact. Quartzose such as the J-20 sandstones, tight and interlocking grain

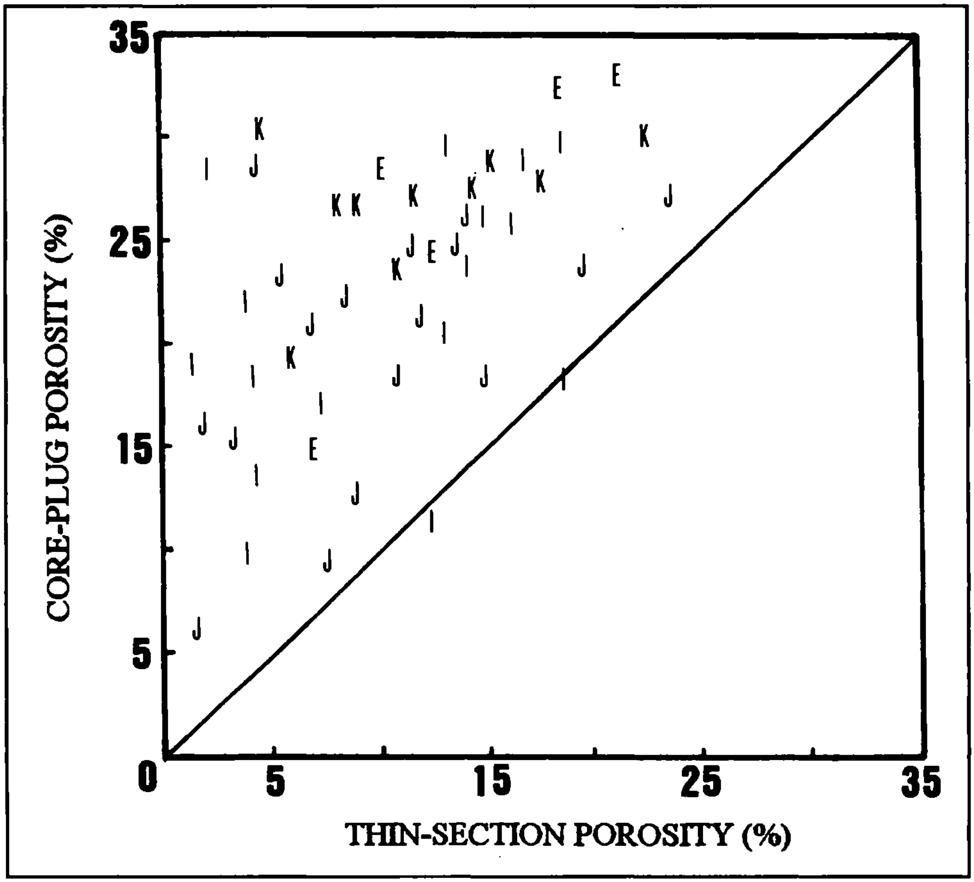

Figure 7: Porosity measurement performed on the plugsversus point-counted porosity. Plotting symbols identify sandstone groups. The diagonal line indicates 1:1 correlation.

and grain contacts are common and can be concavo-convex, sutured and relatively long (Fig 5). These features are the result of extensive quartz overgrowths and not pressure dissolution (Fig 6).

Preferred orientation of elongated sand grains was commonly observed in these sandstones. Laminated and interbedded sand and shale are common. Patches and laminations of detrital clay are also very common which made the identification of detrital clays possible. Detrital clay matrix introduced by bioturbation are abundant in most of the J sandstones especially in the J-30 and J-40 sandstones.

SANDSTONES DIAGENESIS

The three major mechanisms of diagenesis that caused the changes in rock volume and porosity in the Malay Basin sandstones are mechanical compaction, chemical dissolution and precipitation of authigenic cements. During shallow burial (<1000m), loss of porosity was mainly due to mechanical compaction by accumulation of sediments which increased the vertical stress (Jones and Addis, 1985; Rieke and Chilingarian, 1974; Bjorlykke, 1988). Assuming sandstone has 40% initial porosity, an estimated loss of 14-17% porosity was caused by the rearrangements of grains and a closer packing (Wilson and Sibley, 1978; Wilson and McBride, 1988). Further mechanical compaction can cause grain fracturing, ductile grain deformation (McBride, 1978, 1979) and pressure dissolution, which can result in an additional loss of approximately 12% of the porosity (Wilson and McBride, 1988). Cementation might cause another loss of 10-15% porosity.

Quartz and clay cements are the two major cements in the Malay Basin sandstones. An early clay cement coating on a detrital grain has the potential to retard the development of quartz overgrowths (Dewer and Ortoleva, 1991), but silica cement can still develop (Fig 6). The amount of quartz cement is controlled by the framework composition, residence time in the "silica mobility window" and the fluid composition, flow volume and pathways (McBride, 1989). Initial high porosities and permeabilities, combined with a relative abundance of detrital quartz as nucleation sites are a prerequisite to the formation of quartz overgrowths (Sullivan and McBride, 1991).

The Malay Basin sandstones generally have a quarter of their FWG composed of rocThe Malay Basin sandstones have approximately a quarter of their FWG composed of rock fragaments which consist of unstable grains such as clay clasts that are prone to ductile deformation. Mechanical compaction caused a closer grain packing due to grain rearrangement and deformation (Fig 5). Where effective compaction stress continued, these grains were further deformed and became pseudo-matrix. The effects of mechanical compaction reached a maximum at about 1000 to 1200m. Diagenesis at deeper burial proceeded with cementation, chemical dissolution and mineral or grain alterations. Dissolution of feldspar grains and unstable rock fragments are widespread, especially in the K sandstones (Fig 5 & 6). A significant amount of secondary porosity was generated by grain dissolution. The most common authigenic cements are quartz overgrowths, silica cements, clay cement and siderite. Less common cements are pyrite, calcite and glauconite. These cements are restricted to a few samples or in certain sandstone units; such as glauconite, is common in the J-20 and Middle J sandstones.

Mineral compositions and depth are the two major parameters which determined the diagenetic events of the sandstones. Most of the Malay Basin sandstones have undergone similar diagenetic processes, but in the more deeply burial sandstones, additional diagenetic processes and a greater degree of alteration were observed. The E and I sandstones have less complicated diagenetic histories because they have similar initial mineralogical contents and have undergone shorter burial periods at shallower depths. The variation in mineralogical content of the J sandstone has resulted in different diagenetic pathways although mechanical compaction was the major diagenetic process during early burial. The K sandstone also underwent a relatively complicated diagenetic processes due to its longer burial history. In the Early Miocene (deposition of middle J and J-20 sandstones), the K sandstone was exposed by uplift and erosion at the southern end of Malay Basin. A large amount of oversized secondary porosity developed by dissolution of unstable grains, matrix and cements. Quartz cementation and authigenic clay precipitation are well developed in K sandstones; possibly due to continuous fluid flow in these sandstones.

The younger sandstones, group E and I have undergone similar diagenetic processes due to their similar mineralogical content and relatively shallower depths of burial. Increasing depth reduced intergranular volume (IGV) and therefore reduced primary porosity. Mechanical compaction played an important role during early burial causing rearrangement of grains and deformation of ductile grains. Quartz cementation followed early burial, the degree of a quartz cementation increases with the age of the rock, the abundance of detrital quartz and the amount of quartz surfaces exposed in permeable intergranular pores. Authigenic clay, especially kaolinite and illite, are common. Illite formed mainly from the alteration and crystallization of detrital illite or clay matrix. It commonly occurs in sandstones with a moderate amount of detrital matrix. Kaolinite is abundant in porous sandstones, as well- developed pseudo-hexagonal clay flakes and booklets infilling the intergranular pore spaces. A sandstone with a moderate percentage of detrital matrix, feldspar and rock fragments has more secondary porosity caused by the dissolution of these materials compared to a clean quartzose sandstone or a matrix-rich sandstone. In the latest, the sandstone generally underwent an early loss of primary porosity due to mechanical compaction and inhibited or retarded other diagenetic events by its low permeability.

The J sandstone underwent a variety of diagenetic processes due to its wide range of mineralogical content. The clean, quartzose sandstones (particularly the J-20 sandstone) have approximate 5% to 12% quartz cement. Porosities preserved are mostly primary intergranular porosity and a small amount of secondary porosity from feldspar dissolution. These sandstones generally have 10% to 15% point-count porosity and have tight, interlocking grain boundaries due to extensive quartz cementation. For sandstones having 10% to 20% detrital matrix, mechanical compaction caused a major porosity loss. Diagenesis resulted in the precipitation of large amounts of various cements with siderite, quartz, silica, authigenic clays and calcite being most common. Secondary porosity and micro-porosity contribute a great portion (30-50%) of the total porosity in these sandstones. Numerous sandstone samples having less than 5% porosity due to early carbonate cementation or abundant detrital matrix during deposition. In general, authigenic clays including kaolinite, illite, chlorite and smectite are common in most of the J sandstones in addition to quartz overgrowths and silica cement.

The K sandstone has very well developed kaolinite clay flakes due to its larger initial intergranular pore spaces and longer time of burial. Authigenic clays are the major diagenetic products and they occupy 5 to 10% of the intergranular porosity. Quartz overgrowths occupy 2 to 5% of the total rock volume and are as much as 13% in numerous samples. Carbonate cement is in limited amounts except in a few samples which have approximately 30% calcite cement, with no remnant porosity. Secondary porosity created by dissolution of feldspar grains, unstable rock fragments, matrix and cement contributes significantly to total porosity (about 50%).

RESULTS

The petrographic analysis shows that a majority of these sandstone samples have distinct framework grain (FWG) compositions and intergranular volume (IGV) in each sandstone group. The IGV averages 41% in the E sandstones, 41% in the I sandstones, 37% in the J sandstones and 38% in the K sandstones. The decline of IGV from the younger to older sandstones is due to increasing depth of burial, which caused by closer grain packing through mechanical compaction. In another words, intergranular primary porosity was reduced due to the decrease in IGV. An increase in matrix volume (pseudo-matrix) and volume of authigenic cements with depth also significantly reduced porosity (Table 2). A slight increase in total porosity due to late stage diagenesis was achieved by dissolution of framework grains, matrix and cements.

Table 2: Porosity versus Petrographic Parameters

	Correlation Coefficient (r)			
Sandstone Group	E	I	J	K
Quartz Feldspar	-0.28 -0.14	-0.22 0.50 *	0.16 -0.13	-0.24 -0.04
Rock fragments	0.19	-0.08	-0.07	-0.07
Framework grains	-0.14	-0.01	0.15	-0.37 *
Matrix Cements	-0.16 -0.53 *	-0.64 * -0.52 *	-0.49 * -0.35 *	-0.53 * -0.36 *

* Significant at the 95% confidence level.

The quartz content in the framework composition of the E sandstones increases from southeast to northwest; from the Semangkok field to the Dulang and Jerneh fields. This coincides with an increase in depth from 1000m to 2000m. The framework content increases from 52% to 68% of total rock volume within this depth range (Correlation coefficent, r = -0.61, at 95% significant level) (Table 2). Matrix content and porosity in the E sandstones decline from 18% to 9% and 17% to 12% respectively within this depth range. Matrix content in E sandstones shows a decreasing trend from south to north possibly due to depositional facies. Porosity in E sandstones decreases as cement content increases (r = -0.53, 95%). There is no significant correlation between porosity and matrix content (Fig 8). Loss of porosity in the E sandstones that having less matrix is due to closer packing of framework grains and greater degree of cementation; which coincide with increasing depth.

The I sandstones show no significant trends related to areal distribution or depth of burial in their framework composition, which ranges from 57% and 63%. Cement content, however, increases significantly from 10% to 21% over the depth range of 1200m to 2200m (Table 3). Porosities decline significantly with increasing depth (r = 0.36, 95%), but have a wide range. Two major controls on the porosity are the matrix and cement content. Porosity decreases at any given depth from 17% to 1% as matrix increases from 5% to 28% (r = -0.64, 95%). An increase in cement from 7% to 21% causes a significant reduction in porosity from 17% to 5% (r = -0.52, 95%) (Fig 9).

The J sandstones have the widest range of mineralogical composition compared to sandstones in the other three groups. The framework composition ranges from 55% to 75% within the depth range of 1300 to 2500m, with no significant correlation

Table 3: Petrographic Parameters versus Depth

	Correlation Coefficient (r)			
Sandstone Group	E	I	J	K
Quartz Feldspar	-0.73 * -0.25	-0.10 0.20	-0.24 * 0.38 *	-0.44 * 0.31 *
Rock fragments	0.46 *	-0.08	0.17	0.02
Framework grains	-0.61 *	-0.03	-0.13	-0.18
Matrix Cements	0.52 * 0.10	-0.12 -0.33 *	0.11 -0.19	-0.30 * -0.15
Porosity	0.30	0.36 *	0.17	0.51 *

* Significant at the 95% confidence level.

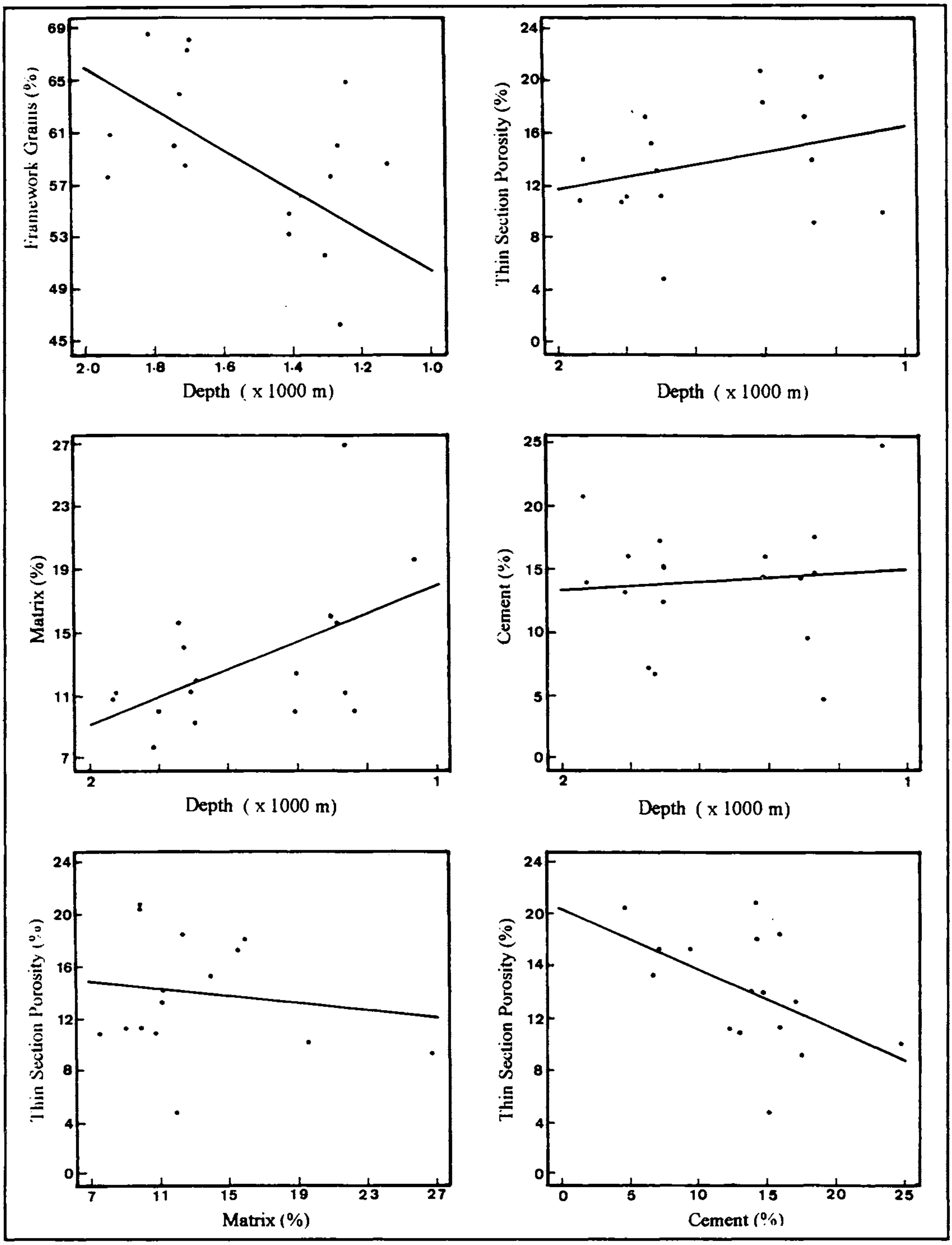

Figure 8: Plot of petrographic parameters from point-counted samples with depth and porosity of the E Sandstone. The lines represent linear regression between two parameters.

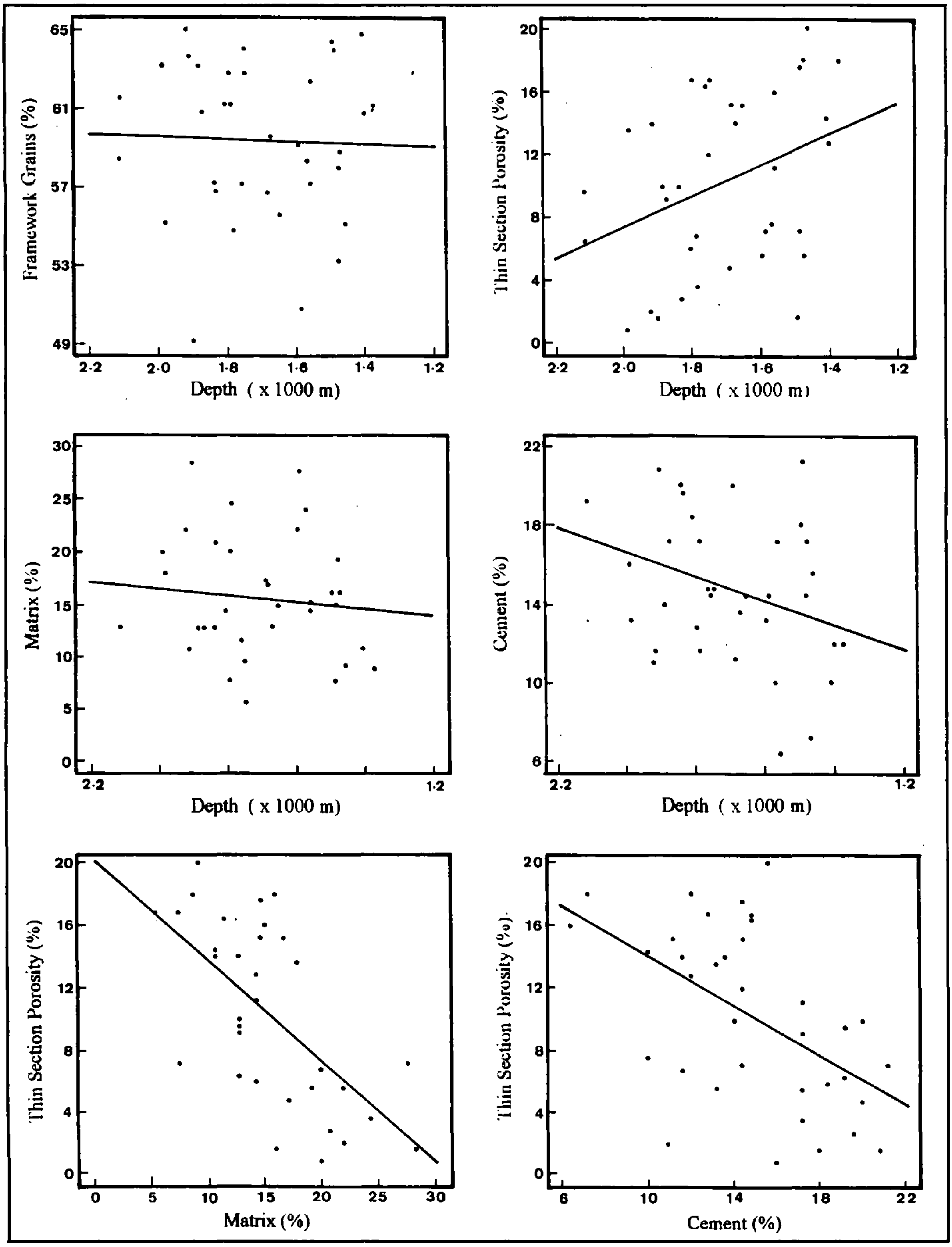

Figure 9: Plot of petrographic parameters from point-counted samples with depth and porosity of the I Sandstone. The lines represent linear regression between two parameters.

between composition and depth of burial. In terms of correlation with depth; a slight, but significant, increase in quartz content (r = -0.24, 95%) and decrease in feldspar content (r = 0.38, 95%) is observed. The porosity ranges from 0% to 18%. There is no significant correlation with depth although there is a slight decrease in the range of porosity with increasing depth. The porosity is controlled mainly by the matrix and cement content. Although the data are scattered, a trend clearly shows porosity declining from 12% to 4% as the matrix content increases from 3% to 30% (r = -0.49, 95%) (Fig 10).

Although samples of K sandstones are from depths of 1000m to 2200m, most samples are from depths of 1200m to 1600m. The framework composition is between 57% and 67% and displays no significant correlation or trend with depth. A slight increase in matrix with increasing depth from 10% to 16% within the depth of 1200m to 2200m (r = -0.30, 95%) is observed. Porosity declines from 12% to 4% within the same depth range (r = 0.51, 95%). Similar to the I and J sandstones, K sandstones porosity is controlled by the amount of matrix and cement (r = -0.53 and r = -0.36 respectively, 95%) (Fig 11).

CONCLUSIONS

Original mineralogical composition, depositional facies and diagenesis are the three major controls on sandstone reservoir quality. Porosity decreases significantly with depth in sandstones of all four groups. The main controls on porosity are the sandstone mineralogy, abundance of matrix and authigenic cement. The E, I, J and K sandstones are significantly different, both mineralogically and texturally due to variation of depositional environment, sedimentary facies and provenance. The diagenetic events and the end products are primarily affected by the initial mineral composition but time and depth of burial also play a significant role. In order to predict the effective porosity of a sandstone, the range of its mineralogical content needs to be known, together with understanding the diagenetic events that the sandstone has undergone.

The three major diagenetic processes which reduced or altered the porosities are mechanical compaction, chemical dissolution and authigenic cementation. Mechanical compaction, which began soon after deposition, caused a major reduction in primary intergranular porosity in these sandstones. During deeper burial (>1000m), mainly quartz overgrowths and clay cementation reduced intergranular porosity. Chemical dissolution occurred during the same time and generated a substantial amount of secondary porosity especially in the feldspathic-litharenite sandstones. Most quartzose sandstones such as sub-litharenites retained much of their primary porosity during early diagenesis, but tended to lose their intergranular porosity by quartz overgrowths and clay precipitation. Regeneration of porosity (secondary porosity) in these sandstones is rare because the quartz framework grains are physically and chemically more stable. Poorly sorted sandstones and matrix-rich sandstones experienced an early loss of porosity by mechanical compaction due to burial. However, subsequent diagenesis including chemical dissolution and cementation was mild due to the early loss of porosity and permeability which inhibited the influx of rock-altering fluids such as meteoric waters.

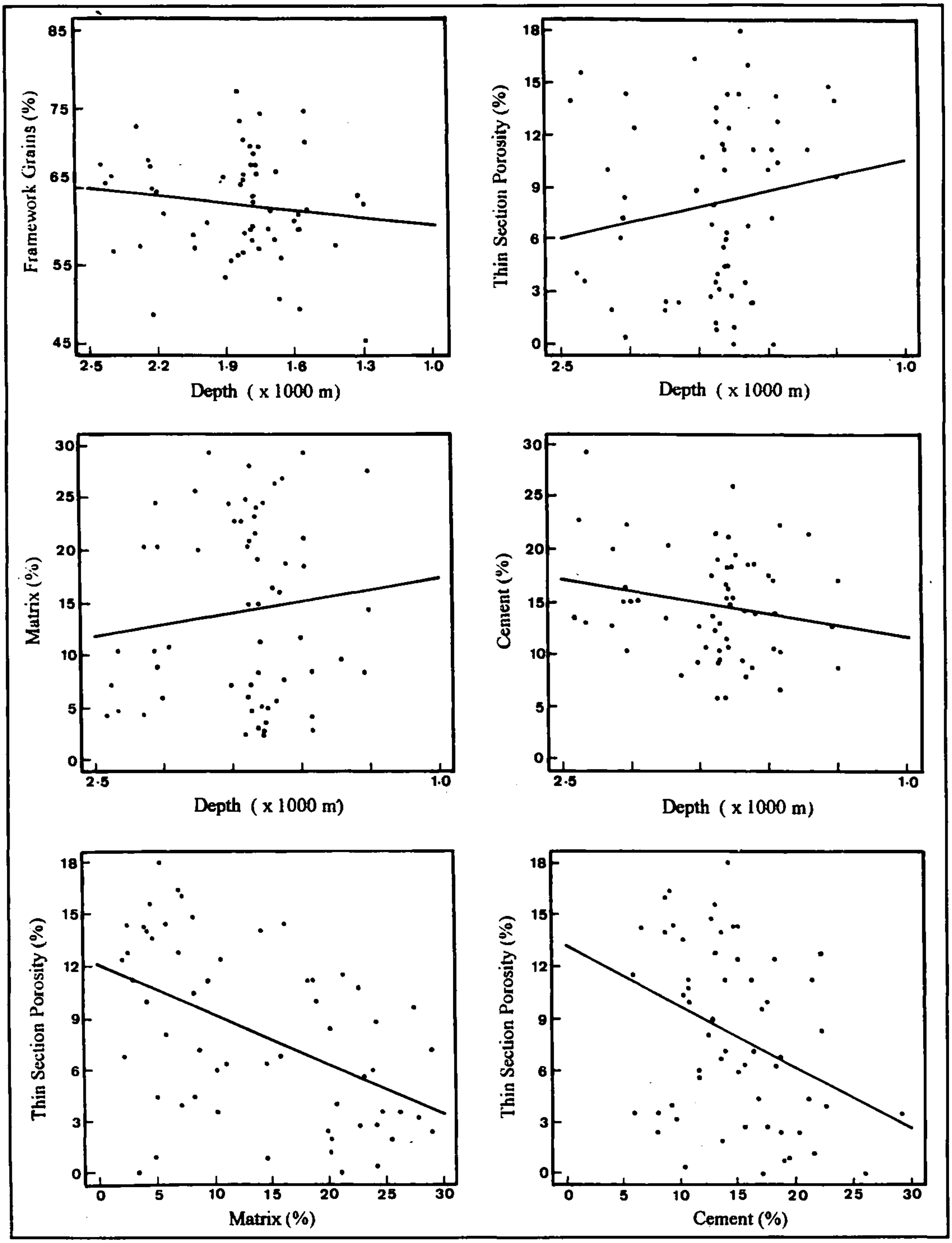

Figure 10: Plot of petrographic parameters from point-counted samples with depth and porosity of the J Sandstone. The lines represent linear regression between two parameters.

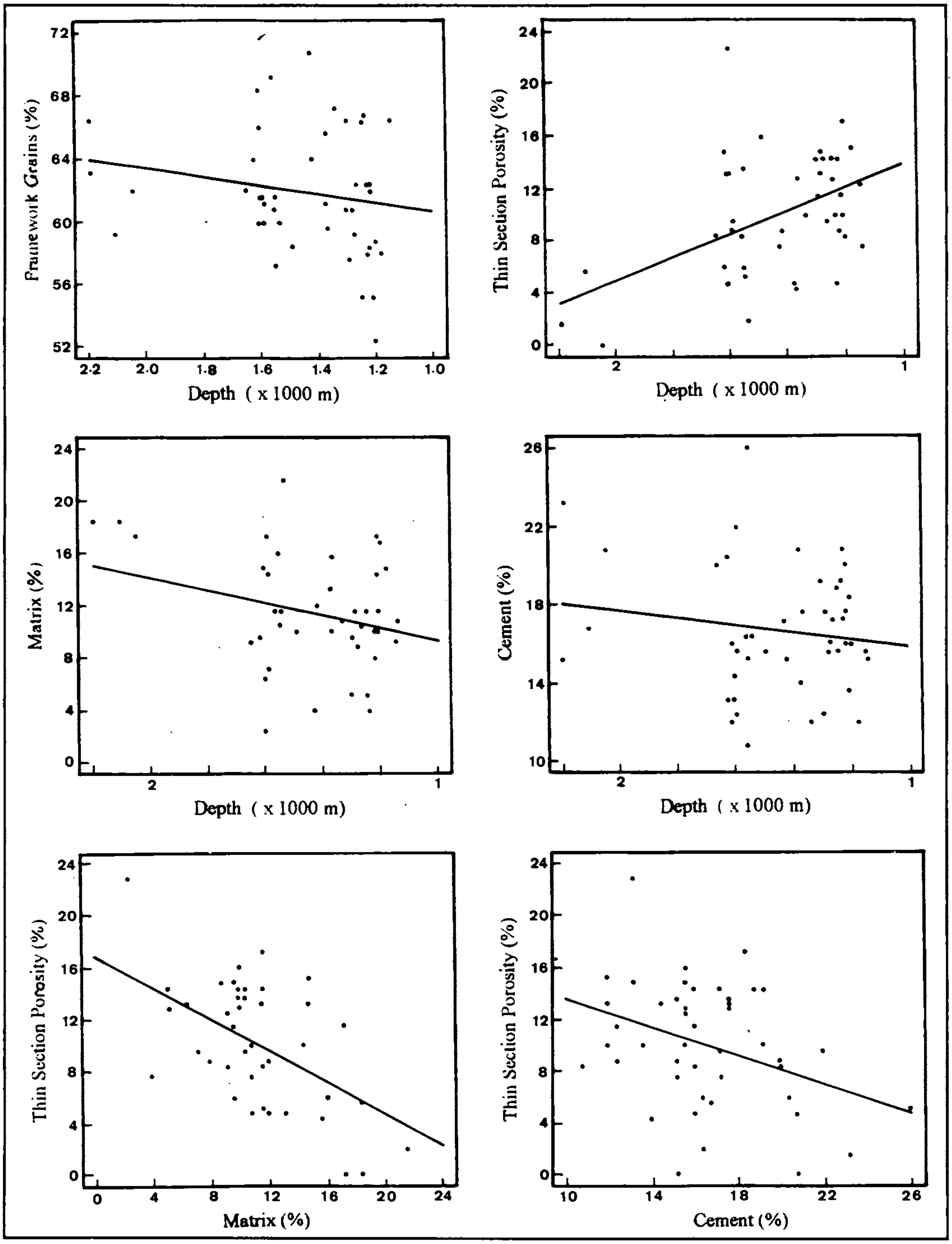

Figure 11: Plot of petrographic parameters from point-counted samples with depth and porosity of the K Sandstone. The lines represent linear regression between two parameters.

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