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Petrography and porosity of the gas-bearing sandstones intersected by the Kudu 9A-2 and 9A-3 boreholes

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A petrographic study was carried out on boreholes Kudu 9A-2 and 9A-3. The gas-bearing reservoir target interval can be divided into a lower non-marine unit and an upper marine unit. The non-marine unit generally has very good reservoir characteristics with good secondary porosity after the leaching of calcite cement. The present porosity and permeability of these sandstones are determined by the distribution of silica cement, which in turn was controlled by the original carbonate and evaporite cementation of the sandstones. The marine unit comprises a shelly sandstone and a lithic sandstone facies, and has poor reservoir characteristics. Low initial permeabilities in the marine sandstones resulted in the limited passage of pore fluids, an almost closed system and therefore limited authigenesis. The shelly sandstones were pervasively cemented by calcite during shallow burial. Their interbedded nature and fine grain size inhibited dissolution of the calcite, effectively halting diagenesis at that time. The lithic sandstones underwent limited diagenesis and compaction of the ductile lithics resulted in the formation of abundant pseudomatrix. During burial, the alteration and breakdown of igneous clasts resulted in chlorite authigenesis, whereas quartz overgrowths developed where initial porosity was slightly better.

Introduction

The Kudu 9A gas-bearing structure lies approximately 125 km west of the Orange River mouth (Fig. 1). It has been drilled by the Kudu 9A-1 discovery well and further evaluated by two step-out wells, Kudu 9A-2 and Kudu 9A-3. The gas is reservoired in marine and non-marine sandstones, probably Barremian in age (McMillan, 1990), below seismic horizon P2 (Fig. 2). Significant differences in the quality and extent of the reservoir sandstones intersected by Kudu 9A-2 and Kudu 9A-3 are apparent from electric log (van Rijswijck and Steyn, 1988; Steyn 1988) and core analysis data (Vorster *et al.*, 1988). As a result of this difference in quality, Swakor commissioned a detailed petrographic study of this interval to describe lithologies from seismic horizon P2 to the base of the reservoir interval. The aims of this study were to describe in detail the reservoir quality of the sandstones, to interpret the paragenesis of the various sandstone units, and to explain, where possible, the factors influencing the distribution, preservation, enhancement and destruction of the porosity and permeability. The resulting report (Marot *et al.*, 1988) provides the basis for this paper.

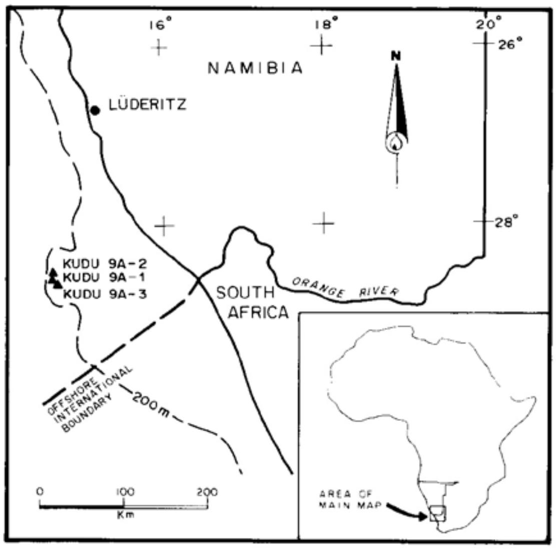

Fig. 1: Location of the Kudu 9A wells, offshore Namibia.

Lithostratigraphy

Boreholes Kudu 9A-2 and 9A-3 intersected 270 and 290 m, respectively, of the reservoir interval. The sequence comprises interbedded sandstone, limestone, volcaniclastic and basaltic lava beds (Wickens and McLachlan, 1990). The depositional environments range from aeolian dune deposits and terrestrial lava flows at the base to interbedded shallow-marine shelly sandstones and volcaniclastic tuffaceous sandstones towards the top of the reservoir interval. The top of the sequence comprises deep-marine claystones. The environments of deposition and facies are described in detail in Wickens and McLachlan (op. cit.).

Wickens and McLachlan (1990) interpret the non-marine sandstones as aeolian dune deposits. They are very well-sorted, well-rounded, fine- to medium-grained sandstones containing early anhydrite nodules and quartz cement.

The marine interval comprises two main sandstone lithologies: 1) calcite-cemented shelly sandstones and 2) tuffaceous lithic sandstones. Where the calcite-cemented sandstones are interbedded with fossiliferous limestones, black shales and siltstones, they are fine-grained and are believed to have formed in a relatively low-energy shallow-marine or lagoonal environment. Coarser grained calcareous sandstones containing thicker walled shell fragments are interpreted as having been deposited in a higher energy, shallow-water environment.

The tuffaceous lithic sandstones are characterised by abundant igneous rock fragments, authigenic chlorite and quartz overgrowths. These sandstones are locally shelly and were probably also deposited in a shallow-marine environment.

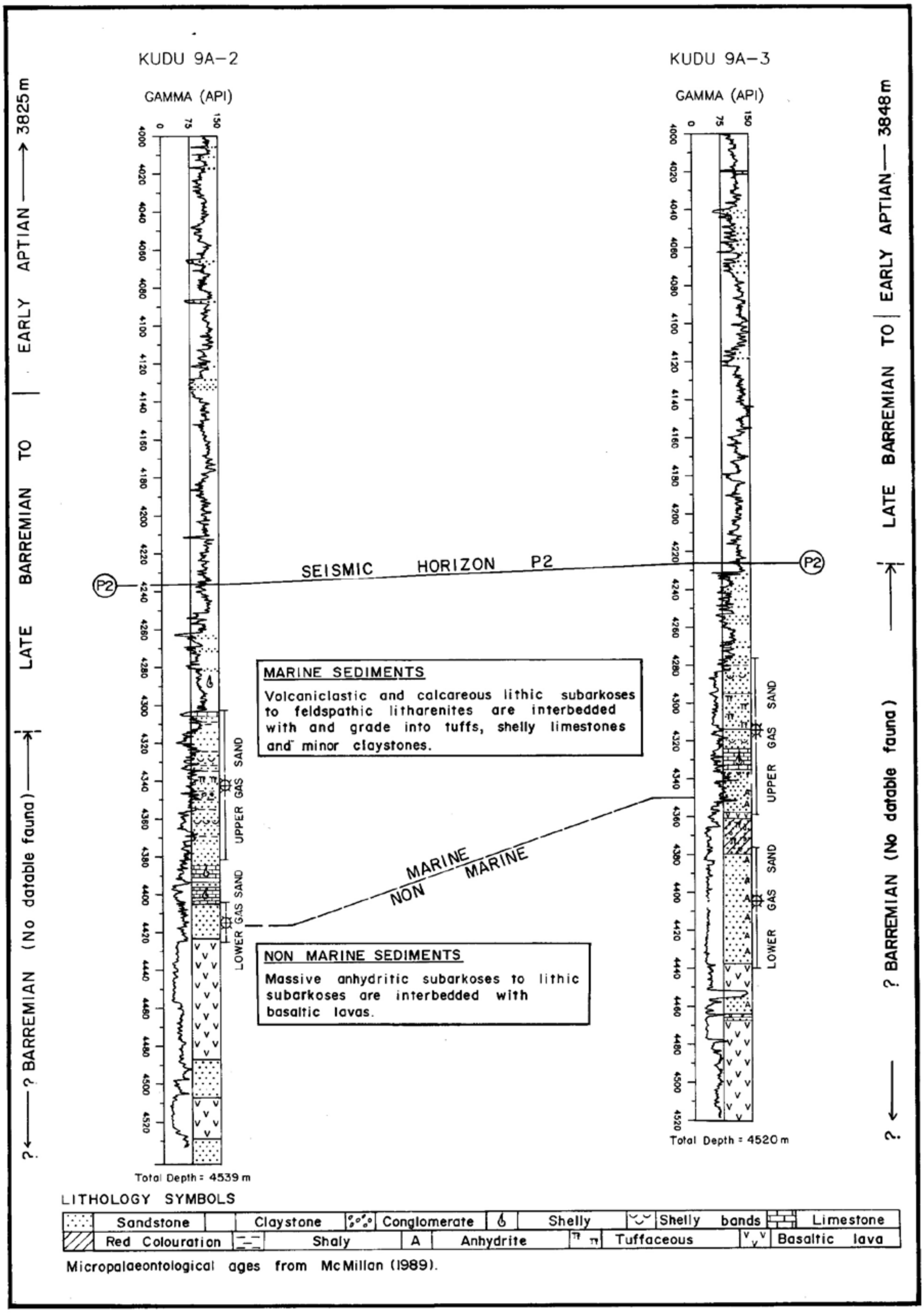

Fig. 2: Interpreted lithologies for the reservoir section of boreholes Kudu 9A-2 and Kudu 9A-3. All depths listed are in metres below kelly bushing.

Petrography and porosity of the gas-bearing sandstones

Sandstone petrology

Composition

Non-marine

The aeolian sandstones of the non-marine unit are fine- to medium-grained, with well-sorted and well-rounded grains (Fig. 6d). The massive aeolian sandstones are subarkosic to lithic subarkosic (Fig. 3; McBride, 1963). Higher in the succession, there is a greater volcaniclastic/tuffaceous lithic component and the sandstones plot as feldspathic litharenites ("transitional sandstones").

Early anhydrite nodules are a characteristic component of the non-marine sandstones (Fig. 7c). Calcite is rare, but it is believed that the existing porosity is secondary, resulting from the leaching of a previously more extensive calcite cement. Quartz overgrowths are variably distributed throughout the sandstones (Figs 6c and 7d), and comprise the main porosity-reducing cement. Authigenic chlorite occurs as pore linings throughout the sandstones (Figs 7d, 7e and 7f). The amount of chlorite increases with proximity to the lava flows.

Marine

1) The volcaniclastic lithic sandstones plot as feldspathic litharenites to litharenites (Fig. 3), and are generally very fine- to fine-grained and well-sorted. Less commonly, they are medium- to coarse-grained and moderately sorted. The lithic component is made up of basaltic igneous and tuffaceous clasts which are believed to have been sourced from penecontemporaneous volcanic activity. In the marine sandstones of both Kudu 9A-2 and 9A-3, the amount of feldspar is fairly constant (10 to 25%) whereas the lithic component varies from 10 to 50% (Fig. 3). This wide variation in the amount of rock fragments is believed to reflect pulses of volcaniclastic debris input into the depositional environment. The predominant cement is in the form of quartz overgrowths, with abundant authigenic chlorite occurring as grain rims, grain alteration products and pore fill (Figs 6a and 7a). The prolific chlorite authigenesis is related to the abundant igneous material associated with the marine sandstones and the interbedded lavas. The alteration of this igneous material has resulted in the release of high concentrations of iron

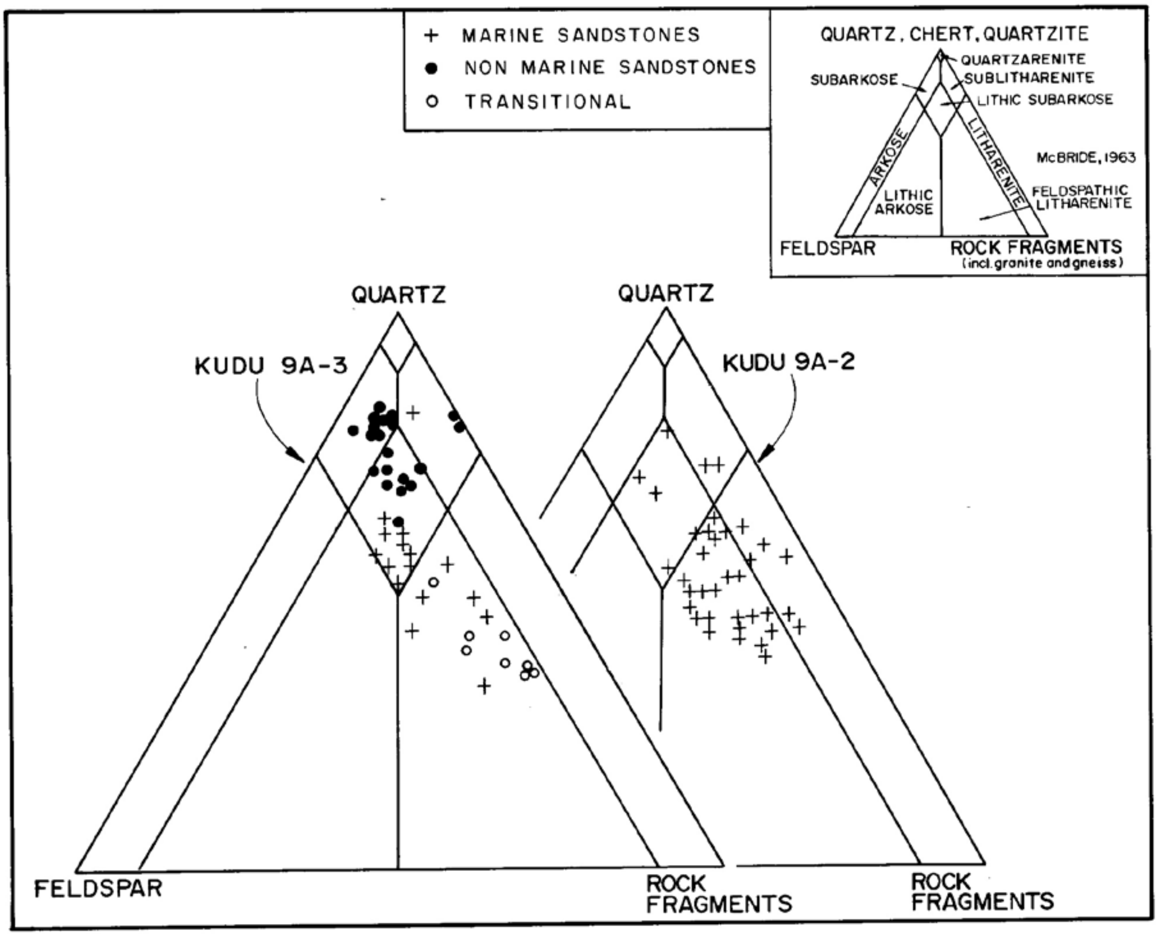

Fig. 3: Variations in framework grain composition of the marine and non-marine sandstones in Kudu 9A-2and Kudu 9A-3.

and magnesium into the pore fluids so that the greatest abundances of chlorite occur in the volcaniclastic lithic sandstones and those adjacent to the lavas and tuffs. Compaction of the ductile grains (chloritised basaltic clasts and tuffaceous fragments) has resulted in the formation of pseudomatrix which, together with abundant detrital illitic clays (Fig. 6b), further lowered the porosity and permeability.

2) The shelly sandstones are classified on the basis of their framework grains as lithic subarkoses (Fig. 3.) They are moderately to poorly sorted, fine- to coarse-grained rocks, and pebbly in places. They have extremely poor reservoir quality due mainly to the abundance of poikilo-topic calcite cement (Fig. 7b). The calcite is believed to be an early phase which protected the sandstones from compactional effects and resulted in a "floating grain" texture for most of these sandstones. Locally these sandstones grade into fossiliferous limestones.

Diagenesis

Two distinctly different regimes of diagenesis and reservoir quality are apparent over the interval studied, coinciding with the marine and non-marine sandstones. The reservoir quality is closely linked to the different diagenetic histories of the sandstones.

Non-marine

Early (shallow) burial

This was a very active period of diagenesis and was controlled by the relative positions of the depositional surface and the water table. At times when the water table was exposed as an interdune area, evaporation resulted in the precipitation of nodular anhydrite and 'poikilotopic calcite, forming tightly cemented bands at the interdune surface (Lupe and Ahlbrandt, 1979). During periods of lower water-table level, no evaporation occurred and the sandstones were progressively buried to below the water table without anhydrite or calcite development. Extensive quartz overgrowths developed in the porous, uncemented sandstones, as rare overgrowths and, in other areas, as pervasive pore-filling cement. The extent of quartz overgrowth devel-opment was regulated by the distribution of calcite cement and porosity (Fig. 4). Evidence for the early precipitation of these cements is apparent in the resultant "floating grain" texture.

Middle burial

The middle stage of diagenesis is considered to have been relatively quiescent in the tightly cemented sandstones where the early cements preserved the sandstones against the effects of compaction and further cementation. Quartz overgrowth development and minor chlorite authigenesis occurred in the remaining porosity. Partial and, in places, total replacement of silicates (predominantly feldspars) by calcite occurred, resulting in corroded margins of grains and enlarged areas of cement.

Late (deep) burial

The most important event in this stage was the dissolution of the calcite cement and the formation of secondary porosity. The evidence for the porosity being secondary includes corroded grain margins, skeletal feldspars and over-sized pores. The cause of the dissolution is not known but could be related to the formation of carboxylic acids during the maturation of organic matter in nearby shales (Surdam *et al.*, 1989). If this is the mechanism, it is believed that the amount of carboxylic acid exceeded the carbonate and the result was the removal of all carbonate and Al^{3+} from the system. This could explain the absence of carbonate as well as the dissolution textures in the aluminosilicates (Surdam *et al.*, 1989).

Chlorite development occurred after the removal of the calcite and therefore lines the secondary pores and does not encapsulate the grains. Earlier minor chlorite authigenesis is related to early burial and can be seen to enclose grains and itself be enclosed by silica cement, with which it was penecontemporaneous. The final intensive chlorite phase, however, lined all secondary pores and inhibited the further development of quartz overgrowths by isolating the necessary nucleii, thereby

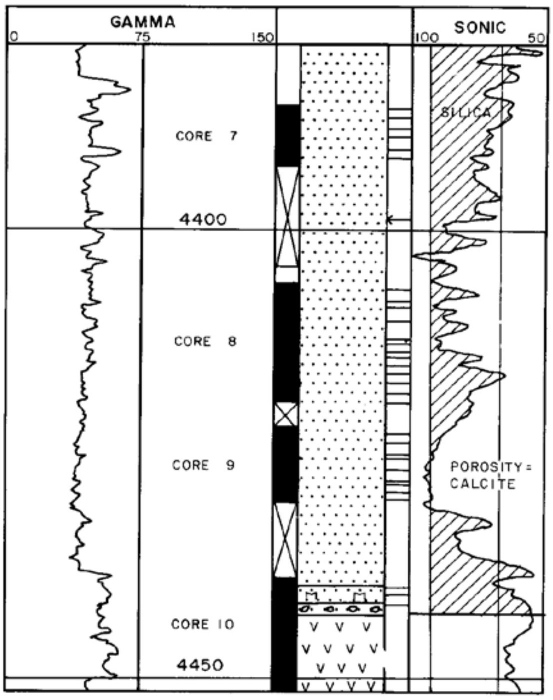

Fig. 4: Sonic log indicating the present-day distribution of quartz cement (crosshatched) in the aeolian sandstones. Quartz overgrowths developed in porous sandstones where there was no calcite developed. When this early cement was leached out, zones of good, well-connected secondary porosity were formed, currently alternating with tight quartz-cemented zones.

preserving the porosity of the sandstones.

The final event was the migration of gas into the sandstones and the confinement of mineral diagenesis to the thin water films surrounding grains, effectively ending all but very localised diagenesis.

Marine sandstones

The diagenesis of-the marine sandstones was relatively simple. Low initial permeabilities resulted from the fine grain size, abundant detrital clay in the lithic sandstones and cement in the shelly sandstones. This inhibited the passage of pore fluids through the sandstones, with the result that diagenesis occurred in an almost closed system.

The shelly sandstones were extensively cemented by early calcite which was never removed. Subsequent limited replacement of silicate and some recrystallisation of the shells and micrite occurred, but diagenesis was effectively halted by the calcite cementation.

The presence of abundant igneous material within and interbedded with the lithic sandstones gave rise to the formation of abundant authigenic chlorite, both as pore fill and as grain rims. These sandstones were highly susceptible to the effects of compaction, resulting in the deformation of the ductile tuffaceous and chloritised basaltic clasts to form pseudomatrix, and hence further destruction of the porosity and permeability.

Porosity and reservoir potential

The porosity and permeability values of the marine and non-marine sandstones are markedly dissimilar. In the marine sandstones, porosities range from I to 13% and permeabilities from 0.1 to 0.23 mD (Vorster *et al.*, 1988). The values are so low that permeability - porosity plots are meaningless. Slight improvements in porosity occur in the volcaniclastic lithic sandstones but the permeability remains very poor. Thin section and SEM studies reveal that these slightly higher porosity values relate to microporosity associated with the abundance of authigenic clay in the volcani-clastic lithic sandstones. The main causes of porosity destruction in the volcaniclastic sandstones are compactive deformation of the lithic clasts and authigenic quartz overgrowths. Permeability was seriously impaired by these same factors and also by the pervasive authigenic chlorite. In the calcite-cemented sandstones, it is the poikilotopic calcite which has totally destroyed porosity and permeability.

The non-marine sandstones are characterised by good to very good reservoir quality. The porosities range in value from 1 to 20% and the permeabilities from 0.1 to 767 mD (Vorster *et al.*, 1988). Where permeability values are extremely good, invasion by drilling mud (confirmed by EDS studies) has resulted in caking on the chlorite rims (Fig. 7f).

In Fig. 4, the gamma ray curve over the non-marine sandstone in Kudu 9A-3 indicates a massive, uniform sandstone whereas the sonic log shows marked variations in porosity, which coincide well with the analysed porosity values (Vorster *et al.*, 1988). The thin section study indicates that the present porosity distribution is a function of the abundance of quartz cement and therefore a result of the complex early diagenetic history of the sandstone. Permeabilities show a relatively consistent correlation with porosities (Fig. 5) which indicates that quartz cement was also the dominant influence on permeability. There are, however, variations in permeability at each porosity value (Fig. 5). These variations are believed to be a function of the amount of chlorite present which, due to its large surface area to volume ratio and its position within the pore space, affects permeability more than porosity. The presence of chlorite is also significant in that it would create a problem if acid stimulation of the reservoir proved necessary. In the presence of hydrochloric acid, the high iron content would result in the precipitation of insoluble gels in the pores and a significant reduction in permeability.

Studies carried out by Soekor on sandstones elsewhere off southern Africa indicate that good porosity and permeability values at depths in excess of 4000 m are uncommon, and it is believed that the good reservoir quality in Kudu 9A-3 has been preserved by two mechanisms. Firstly, the protection of the potential porosity from the effects of compaction during burial by the poikilotopic calcite cementation and secondly, the

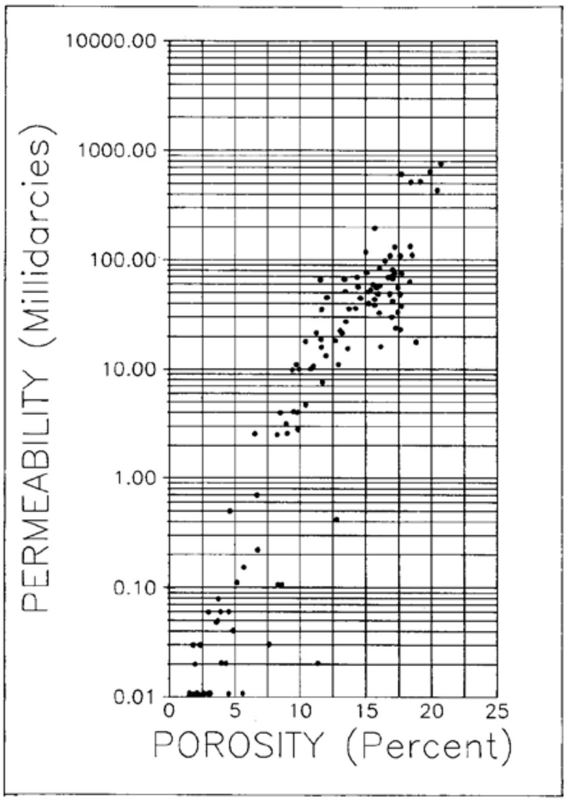

Fig. 5: Permeability values showing a direct relationship with porosity values in the aeolian sandstones.

preservation of secondary porosity by the development of chlorite rims which prevented further quartz cementation.

The thicker development of the non-marine sandstone in Kudu 9A-3 compared to Kudu 9A-2 is largely responsible for the better reservoir quality in 9A-3. Small intervals of well-developed secondary porosity and permeability are evident from the logs in the non-marine intervals of Kudu 9A-2 but, due to the smaller volumes of sandstone, the effect of the silica cementation during early diagenesis has been more deleterious.

Conclusions

Within the Kudu field the main cementing agents are poikilotopic calcite, quartz overgrowths and, in the non-marine sandstones, isolated anhydrite nodules. Chlorite is ubiquitous and results from the abundance of basic igneous material within the succession. The presence of chlorite should be considered in the event of stimulation of the reservoir.

It is clear that the preservation of good reservoir quality in the Kudu sandstones was a result of a complex interplay of diagenetic factors. Good reservoir quality is restricted to the aeolian sandstones which are best developed in Kudu 9A-3. Early calcite cement preserved the porosity against compaction and permanent cementation effects. This early cement was later leached at depth and formed interconnected secondary porosity. Bands of quartz cement provide some permeability barriers within what appears to be a massive, homogeneous sandstone.

The poor reservoir quality of the marine sandstones is a result of abundant calcite cement in the cleaner sand-

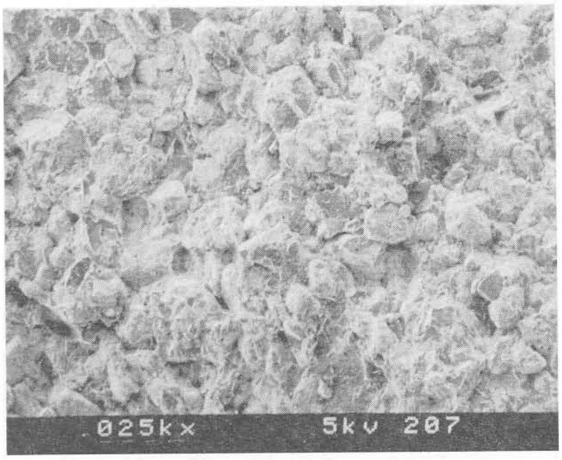

Fig. 6a: Marine sandstone from 4291.71 m: porosity = 6.5 % and permeability = 0.01 mD, with abundant quartz cement and authigenic chlorite as alteration of grains and pore fill.

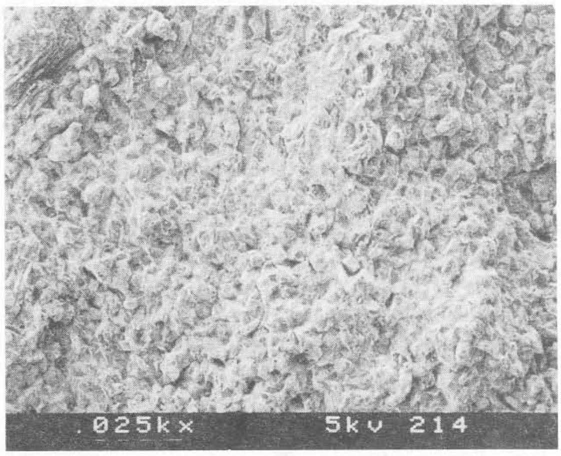

Fig. 6b: Marine sandstone from 4337.00 m: porosity = 2.4 % and permeability ≤ 0.01 mD. Low porosity and permeability are due to fine grain size and abundant detrital and authigenic clay.

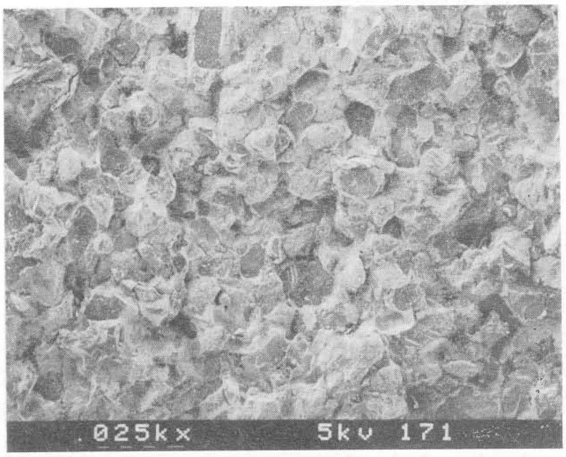

Fig. 6c: Aeolian sandstone from 4382.01 m: porosity = 12.7 % and permeability = 0.02 mD. Abundant quartz cement has occluded macroporosity. Microporosity is associated with authigenic chlorite, here seen encapsulating grains.

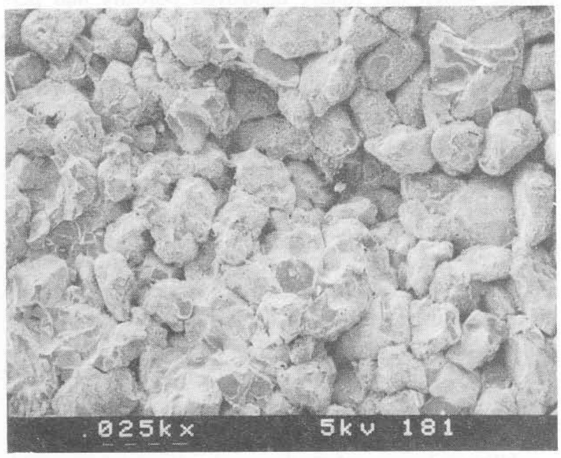

Fig. 6d: Aeolian sandstone from 4406.83 m: porosity = 19.7 % and permeability = 638 mD. Chlorite rims can be seen lining the secondary pores and inhibiting quartz overgrowth development.

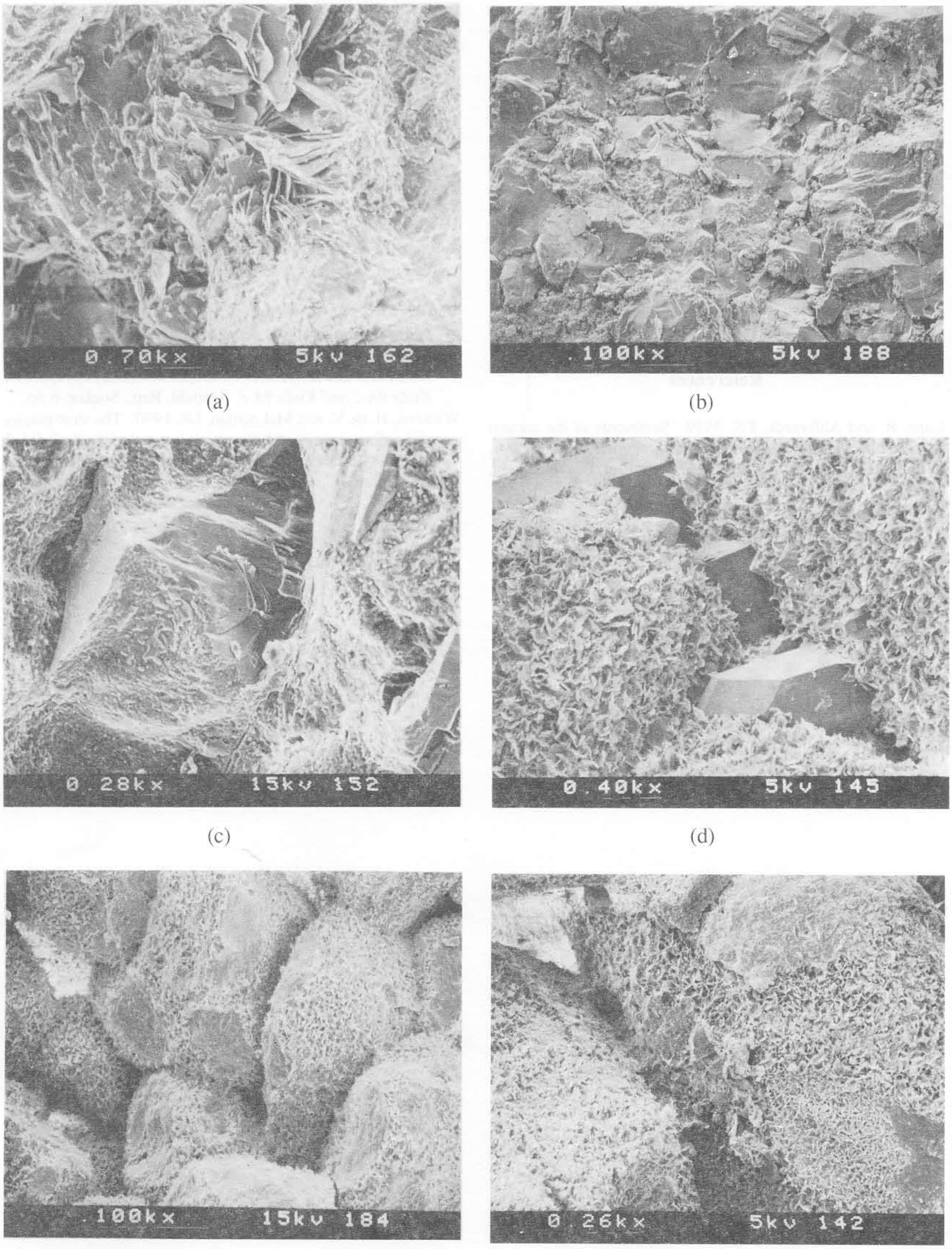

Fig. 7: Poor porosity and permeability values in the marine sandstones can be attributed to abundant authigenic chlorite: [(a) 4335.15 m, porosity = 4.0%; permeability = 0.01 mD] and calcite cement; [(b) 4314.64 m, porosity = 5.2%; permeability = 0.02 mD]. In the aeolian sandstones early anhydrite occurs as nodules (c) and there are varying amounts of quartz cement in the form of overgrowths (d). The development of chlorite pore linings (d, e, f) has, however, inhibited the amount of quartz overgrowth by isolating the nucleating grains. Note that the grain point contacts are devoid of chlorite (e). The extremely good permeability in the aeolian sandstones resulted, in places, in contamination by drilling mud, which can be seen caked over the chlorite rims (f).

stones, together with intense authigenesis of chlorite and quartz, and compaction in the ductile, volcaniclastic sandstones. The poor quality was compounded by the absence of secondary porosity development.

The better reservoir quality in Kudu 9A-3 compared to Kudu 9A-2 is due to the thicker development of the good quality reservoir aeolian sandstone within it, and the development and preservation of well-interconnected secondary porosity.

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