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Palynofacies characteristics and palynological source rock assessment of the Cretaceous sediments of the northern Orange Basin (Kudu 9A-2 and 9A-3 boreholes)

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A sequence of five palynofacies types characterised by diagnostic palynomaceral assemblages defines five depositional environments within the Cretaceous sediments of the northern portion of the Orange Basin. Near the base of the sequence below seismic horizon P2, presence of a "p-wafer" palynofacies implies buoyant inertinite shards (palynowafers) were transported basinwards by bottom currents and settled from suspension in a low-energy, offshore environment. Occurrence of a mixed dysaerobic palynofacies between horizons P2 and PI indicates intermittent formation of semi-amorphous organic matter (with some wet gas-prone hydrocarbon source potential) during quiescent, mildly anaerobic periods, with accumulation of structured terrestrial organic material under more oxygenated bottom-water conditions. Within the overlying sequence between horizons PI and P, a xenomorphic palynofacies provides evidence of anaerobic conditions necessary for generation and preservation of large amounts of amorphous organic matter, resulting in the formation of a sapropelic, oil- to wet gas-prone source rock sequence during the Aptian. Subsequently, a low rate of sedimentation within an oxygenated water column during the Albian and Cenomanian produced an assemblage of sorted, blade-shaped humic debris described as a p-wafer/tracheid palynofacies between horizons P and N. Well-preserved, poorly-sorted phytoclasts form a tracheal/exinitic palynofacies within the Upper Cretaceous interval above horizon N, indicative of rapid sedimentation. Optical assessment of spore colouration indicates that the source rocks below horizon P are thermally post-mature within the dry gas phase. Above horizon K4, an abundance of dinoflagellate genera indicative of marine regressive conditions (*Dinogymnium*, *Andalusiella* and *Palaeocystodinium*) together with abundant *Azolla* megaspores and *Pediastrum* coenobia, suggest a relatively nearshore, deltaic environment of deposition with freshwater influence. The presence of reworked striate bisaccates of Permo-Triassic age above horizon P indicates post-Aptian erosion of Upper Ecca or Beaufort Group sediments formerly existing to the west of their present outcrop positions. Recycled Lower and Upper Cretaceous miospores were derived from an uplifted basin margin during the Senonian. The occurrence of *Phelodinium boloniense*, *Andalusiella polymorpha* and *Andalusiella mauthei* within the Campanian to Maastrichtian interval above horizon N is the first record of a Malloy peridiniacean suite south of the Walvis ridge.

Introduction

Qualitative assessments of organic matter type, palynomorph colour and visual percent abundance of detrital kerogen are often used in palynological investigations directed at appraisal of the hydrocarbon potential of source rock intervals and estimation of the degree of thermal maturity. Within the last decade many attempts have also been made to categorise the microscopic kerogen components in terms of the palynofacies concept (Batten, 1982). Palaeoenvironmental indices are determined from different palynofacies types using the degree of sorting of phytoclasts together with their different buoyancy characteristics and preservation potential (Fisher, 1980; Parry *et al.*, 1981; Habib, 1982; Whitaker, 1984; Thomas *et al.*, 1985; Boulter and Riddick, 1986; Tyson, 1987). In the following discussion, a palynofacies analysis and palynological source rock assessment is presented for two boreholes, Kudu 9A-2 and Kudu 9A-3, drilled in the northern portion of the Orange Basin (Fig. 1). The work represents a compilation of results contained within a report (Benson, 1988) on the Cretaceous palynology of the Kudu boreholes commissioned by the Namibian national petroleum exploration agency Swakor.

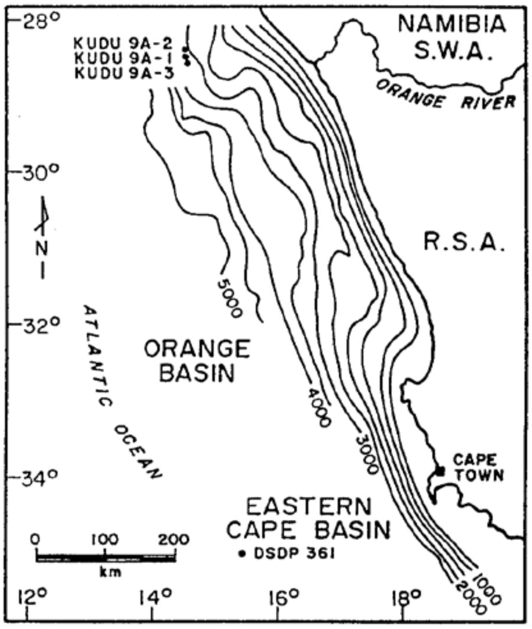

Fig. 1: Locality map of the boreholes studied in the northern Orange Basin and position of DSDP 361 in the eastern Cape Basin. Isopachs represent the interval between sea floor and seismic horizon P, contour interval 500 m (after Gerrard and Smith, 1984).

Samples

A total of 155 samples were processed. These included 45 sidewall cores from 1550 m to 4408 m in Kudu 9A-3, 94 sidewall cores from 410 m to 4245 m in Kudu 9A-2, 16 samples of cuttings from 1000 m to 1750 m in Kudu 9A-2 and 16 samples from cores 1,2,3,4 and 6 in Kudu 9A-2. Using conventional palynological processing techniques, two organic concentrates were prepared from each sample - an unoxidised kerogen residue (for organic matter typing, visual estimation of thermal maturity and vitrinite reflectance studies) and an oxidised residue for biostratigraphy. Oxidised residues were sieved through a 10-micron nylon monofilament mesh to remove fines and to concentrate microplankton assemblages.

Display and interpretation of data

Composition of organic material and degree of thermal maturity were assessed for each kerogen slide using the qualitative technique outlined by McLachlan (1974). Palynological source rock assessment logs (Fig. 2) show the data derived from examination of the kerogen slides and consist of annotated panels and symbols for graphic display of the following information: (1) gamma-ray curve; (2) thermal maturity (displayed as a Soekor Spore Colour Code); (3) percentage composition of organic material; (4) palynofacies type; and (5) marine influence index (expressed as a phytoplankton ratio).

Seismic horizons and casing-shoe depths are plotted next to the gamma-ray curve. The occurrences of palynomorphs considered to be of palaeoenvironmental significance are plotted against palynofacies type (as "Index Palynomacerals") using keyed symbols. Tie-lines between each log are used to connect the boundaries between the main maturation limits observed in each of the boreholes. The alphanumeric codes inscribed within the circles positioned between each tie-line indicate the level of thermal maturity. Notes on depositional environments associated with each palynofacies type and calibratipn of spore colour alphanumeric codes with thermal maturation limits are presented in separate columns beneath the log display.

Optical assessment of organic material (viewed as microscopic particulate debris within strew-mounted kerogen slides) is dependent on the identification of different types of organic components or palynomacerals which may consist of structured palynomorphs, phytoclasts and unstructured organic matter. McLachlan (1974) adapted the palynomaceral classification scheme of Correia (1971) for use within Soekor as an interpretative aid in palynological source rock assessment. The results of this analysis are shown in Fig. 2 as a graphic log of the percentage abundance of Correia's palynomaceral groups with depth. The acronyms MOC, MOV, MOT and MOL appear as headings in a panel labelled "Kerogen Composition" and refer to Colloidal, Vegetal, Tracheal and Lignitic organic components, respectively.

As defined by Correia, colloidal organic components (MOC) include any amorphous organic aggregates or colloidal flocculant formed from the biochemical degradation of organic matter. Vegetal material (MOV) consists of palynomorphs (spores, pollen, phytoplankton, algae) and cuticle (equivalent to the coal macerals exinite and liptinite). The tracheal component (MOT) represents the gelified vascular tissues of terrestrial plants visible as translucent tracheids (some with bordered pits), scalariform vessel elements and structured opaque shards with translucent margins (equivalent to the coal maceral vitrinite). Lignitic material (MOL) consists of opaque, carbonised vascular tissues without translucent margins (equivalent to the coal maceral inertinite).

Shales with an abundant content of "amorphous" (colloidal/MOC) or "herbaceous" (vegetal/MOV) kerogen are generally indicative of oil-prone source rocks, while predominance of "woody" (tracheal/MOT) and "coaly" (lignitic/MOL) kerogen types produce gas-prone source rock intervals (Burgess, 1974).

Limitations of the study

No attempt is made to describe the microfloral assemblages in detail or to correlate the boreholes based on zonal assemblages of palynomorphs. Inter-regional correlation of the source rock sequence intersected below seismic horizon P in the Kudu boreholes with a coeval interval, Unit 7, also intersected in Deep Sea Drilling Project borehole DSDP 361 drilled in the eastern Cape Basin (Fig. I), is based on the microfaunal study of McMillan (1988). Palynological correlation with Aptian microplankton assemblages described from the Unit 7 sequence by Davey (1978) remains uncertain because the microflora recovered from below horizon P is poorly preserved and has low species diversity.

Palynological results

Composition of organic material

Detrital kerogen from the sediments of presumed Aptian age near the base of the sequence below horizon P consists of an alternation of lignitic debris (MOL) and amorphous organic matter (MOC). No structured algal remains of marine or lacustrine origin occur in association with the MOC. High visual percent abundance of MOC (50%) occurs within two intervals in Kudu 9A-2; between horizons P2 and P1 (4218 m - 4073 m) and in the overlying interval between horizons P I and P (3946 m - 3835 m). By contrast, MOC was not recorded in kerogen slides prepared from ditch cuttings below horizon P in the adjacent borehole, Kudu 9A-1. Chevron's palynological study (Kaska, 1974) of cuttings from the same interval also indicated absence of sapropelic debris. Evidently, poor hole condition in Kudu 9A-I below the casing shoe at 3557 m caused severe caving and downhole contamination of cuttings, masking any occurrence of abundant MOC below horizon P.

It is difficult to classify MOC occurring below horizon P using the descriptive morphological terms of Combaz (1980; i.e. clumped, clotted, granular, subcolloidal, flaky and spongy) as the onset of post-maturity has rendered the organic material opaque. The MOC consists of opaque, rounded aggregates with a clotted fabric of amorphous debris visible within a narrow, translucent margin around the edge of the grains. In contrast, semi-amorphous flakes of organic matter between horizons P2 and P1 consist of biodegraded phytoclasts (vascular tissues and cuticle) with some remnant structure still visible.

Within Albian and Cenomanian sediments between horizons P and N, the kerogen is dominated by lignitic

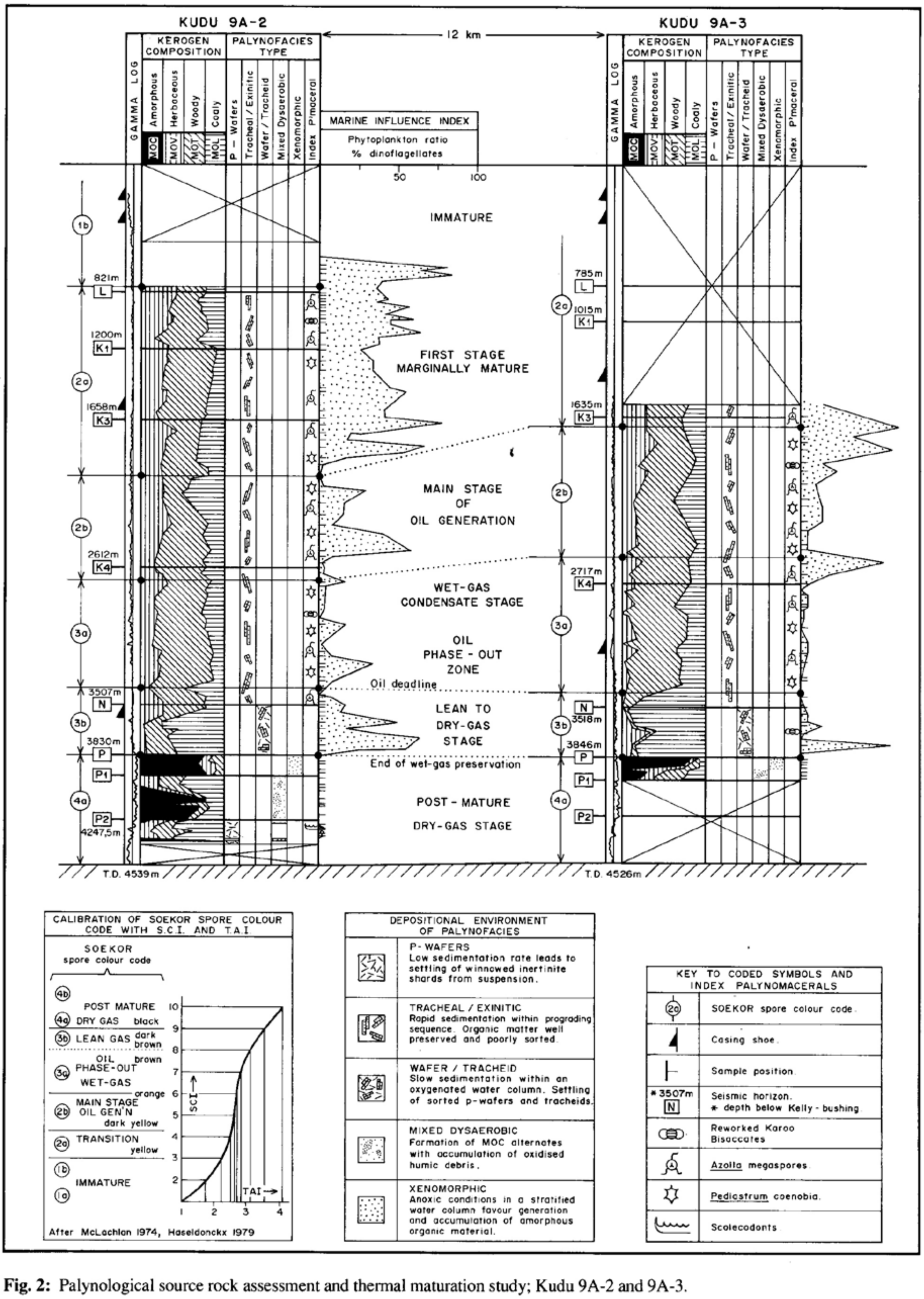

Fig. 2: Palynological source rock assessment and thermal maturation study; Kudu 9A-2 and 9A-3.

debris (MOL) with relatively small amounts of translucent tracheid (MOT). Terrestrial palynomorphs appear to be biodegraded and are not very abundant. Dinoflagellates are relatively common, diverse and well preserved. Three samples contain small amounts (< 10%) of clumped MaC with a granular texture similar in appearance to that found in a single sample at 4387.56 m, within core 6, below horizon P2 in Kudu 9A-2.

Kerogen from within the Late Cretaceous sequence encompassed by horizons' Nand L consists of a varied assortment of structured humic debris (MOT), inertinite shards (MOL) and cuticle. A diverse microfloral assemblage is developed in most samples. At intervals, high phytoplankton ratios were recorded (up to 80% of total palynomorphs).

It is evident that a major change in composition of the organic matter occurs at the level of horizon N, reflecting a regional change in depositional setting. Detrital kerogen below horizon N is characterised by well-sorted, poorly preserved phytoclasts, alternately dominated by high proportions of blade-shaped inertinite and clusters of MOC, while the kerogen above horizon N consists of poorly-sorted phytoclasts, well-preserved vascular tissues, abundant palynomorphs and a low proportion of inertinite shards.

Palynofacies

Fluctuations in the visual percent dominance of various palynomaceral groups observed within the strew-mounted kerogen residues produce variations in "palynofacies" (Combaz, 1964, 1980). Using this concept, a succession of five palaeoenvironments characterised by different levels of oxygenation and sedimentation rate are inferred from five palynofacies types occurring within Cretaceous sediments of the Kudu boreholes.

Three palynofacies occur below horizon P as follows:

(1) An association of palynomaceral assemblages dominated by blade-shaped inertinite shards or "palynowafers" (Whitaker, 1984) within the sampled portions of the cored interval below horizon P2 is best described as a palynowafer (or "p-wafer") palynofacies, similar to phytoclast assemblages recorded by Boulter and Riddick (1986) from hemipelagic shales within submarine fan lobes and channel complexes. Presumably vigorous current activity within a nearshore environment was necessary for initial winnowing and selective sorting of the detrital kerogen, resulting in suspension of the inertinite shards which have buoyancy characteristics similar to those of charcoal. Subsequent to entrainment within a turbulent water column, the buoyant palynowafers were transported by marine currents in an offshore direction and progressively settled from suspension where sedimentation rates and current activity were minimal.

(2) In contrast, overlying sediments between horizons P2 and P1 contain a variety of palynomacerals consisting of corroded palynomorphs, biodegraded semi-amorphous terrestrial debris, MOC and palynowafers. Thomas *et al.* (1985) described a similar assemblage from the marine Heather Formation (Viking Graben, North Sea) as a "mixed dysaerobic" palynofacies where variable conditions for the generation and preservation of MOC within dysaerobic bottom waters resulted from fluctuation in the stability and nutrient status of a stratified water column. Analogous "dysaerobic conditions" (Tyson, 1987, p. 53) were developed between horizons P2 and PI in Kudu 9A-2 where the water column varied from aerobic to mildly anaerobic. Degradation of humic tissues and cuticle occurred during deposition of the lower portion of the interval between horizon P2 and 4102 m under mildly anaerobic conditions, indicated by incomplete bacterial reworking of some phytoclasts (forming semi-amorphous clumps of MOC with remnant structure preserved) and presence of a benthonic microfauna (McMillan, 1988). Bottom-water conditions subsequently became more oxygenated and unfavourable for formation and preservation of anaerobic bacterial decomposition products, allowing accumulation of structured humic debris observed between 4102 m and horizon P1. Presence of abundant palynowafers indicates a low-energy environment with low rates of sedimentation conducive to settling of buoyant inertinite particles. Organic detritus in the topmost sediment layers was continually exposed to an aerobic bacterial oxidation zone because of the low sedimentation rate, resulting in altered woody tissues typical of a "micrinitic" palynofacies (Habib, 1982, p. 116).

(3) Detrital kerogen between horizons P1 and P resembles the "shredded xenomorphic" palynofacies of Habib (1982) and consists predominantly of clumps of amorphous organic matter with ragged margins formed by decomposition and complete bacterial reworking of organic debris in subaquatic muds under anaerobic conditions, typical of a "sapropel" (Tyson, 1987, p. 56). Presence of anoxic bottom waters is also apparent from the absence of benthonic microfauna (McMillan, 1988). Limited influx of terrestrial phytoclast material is indicated by the presence of "p-wafers" in some samples.

Of note is the occurrence of a high visual percent abundance of MOC (80%) at 4387.56m in core 6 of Kudu 9A-2, indicating localised development of dysaerobic conditions below horizon P2 where a mildly anaerobic water column was sufficient for preservation of biodegraded organic debris. The MOC may have formed by decomposition of organic matter within lagoonal sediments of the carbonate sequence in core 6, resulting from anaerobic conditions established around decomposing organic matter present within fine carbonate mud (Tissot and Welte, 1984, p. 77).

The association of palynomacerals recorded between horizons P and N is described as a wafer/tracheid palynofacies to imply high visual percent abundance of bladeshaped inertinite ("p-wafers") and translucent tracheids. Dinoflagellates are abundant and well preserved while the miospore microflora is composed mostly of corroded specimens of *Classopollis* pollen. Selective sorting of the phytoclasts indicates prolonged transport from the source area to a relatively distal site resulting in winnowing of less buoyant humic debris with oxidation and degradation of terrestrial palynomorphs. Habib (1979, p. 458) suggested that *Classopollis* pollen is more easily transported by marine currents because of its generally small size and spheroidal shape. Occurrence of small amounts of MOC implies localised development of dysaerobic conditions when terrestrial input was diminished and conditions within the water column became mildly anaerobic.

The sequence above horizon N consists of a poorly-sorted mixture of well-preserved phytoclasts with equidimensional and rectangular shaped tracheids and vitrinite shards, fragments of cuticle, abundant dinoflagellates and miospores (many of them reworked). Using the terminology of Habib (1982, p. 116), the palynomaceral assemblage is described as a tracheal/exinitic palynofacies to imply high visual percent abundance of unsorted vascular tissues and palynomorphs. As pro deltaic processes contribute to very high rates of sedimentation (Habib, op. cit., p. 115) the unsorted nature of the detrital kerogen suggests that organic debris was dumped within a sequence of rapidly prograding delta fronts. Peak phytoplankton ratios, shown as sharp inflections on the marine influence curves (Fig. 2), may indicate intermittent flooding of a shallow prograding shelf during marine transgressive phases, resulting in suppression of progradation at delta fronts, reduced terrestrial input and lower rates of sedimentation within an oxygenated nutrient-rich water column supporting a large phytoplankton population.

The abundance of *Azolla* megaspores (produced by an extant group of Hydropterid water ferns) and chlorophycean algal colonies (Pediastrum coenobia) within the interval between horizons N and L indicates proximity to riverine backwater environments with many lakes and ponds. The association of marine microplankton and abundant freshwater derived palynomorphs implies that the latter were originally deposited in a floodplain setting and underwent subsequent transport and redeposition under offshore marine conditions as part of the detrital kerogen content of sediments in distributary channels.

Thermal maturity

The extent of carbonisation of spores and pollen within unoxidised kerogen preparations was used to visually estimate thermal maturity using the qualitative technique outlined by McLachlan (1974). Soekor Spore Colour Codes (“1a” to “4b”) indicating different levels of thermal alteration are calibrated against the Thermal Alteration Index (TAI) scale (Staplin, 1969) and the Robertson Research Spore Colour Index (SCI) (Haseldonckx, 1979) in the “Notes” column of Fig. 2.

Spore Colour Codes for the Kudu boreholes plotted in Fig. 2 range from ”1b” to a maximum of ”4a” and fall within the immature to post-mature phases of the hydrocarbon metamorphic facies described by Staplin (op. cit.).

Abundant reworked palynomorphs with different thermal histories occur between horizons Nand L, creating problems for qualitative assessment of the maturation trend. This is apparent from Chevron’s thermal maturation study (Kaska, 1974) of the same interval in Kudu 9A-1, where a wide scatter of TAI values was recorded for each sample. A plot of these TAI values versus depth revealed an enigmatic reversal of maturation trend between horizons K3 and K4 inconsistent with the thermal gradient derived from vitrinite reflectance studies of the adjacent Kudu 9A-2 borehole (Davies and van der Spuy, 1988).

The occurrence of opaque MOC, indicative of State of Preservation Index 4 on Correia’s (1971) S.P.I. scale, and Spore Colour Codes of “4a” below horizon P demonstrate onset of post-maturity beyond the bottom limit of the oil window within the dry gas phase. The visual assessment of post-mature organic matter is confirmed by the absence of liptinite/exinite fluorescence (Davies and van der Spuy, 1988).

Maturation limits for the two boreholes Kudu 9A-2 and Kudu 9A-3 are summarised as follows:

(i) below horizon P, kerogen is post-mature within the dry gas stage; (ii) mature kerogen between horizons P and N is within the lean to dry gas stage in the lower portion of the oil phase-out zone; (iii) between horizons Nand K4, kerogen is mature within the wet gas/condensate stage in the upper portion of the oil phase-out zone; (iv) main-stage of oil-generation and release occurs between horizons K4 and K3; (v) marginally mature kerogen within the transition zone to full maturity occurs between horizons K3 and L.

The palaeo- top of the main-stage of oil generation occurs approximately 600 m higher than that indicated by the present-day main-stage limit for type III kerogen.

Hydrocarbon potential of source rock interval

Dow and O‘Connor (1982, p. 154) provide the following useful guide for qualitative assessment of the hydrocarbon potential of shales based on visual percent abundances of palynomacerals:

(1) Mature kerogen with less than 35 visual percent of oil-prone kerogen (i.e. MOC and MOY) will yield dry gas, while oil-prone source rocks usually contain over 65 visual percent of these palynomacerals.

(2) In general, mature shales with intermediate percent-ages of MOC and MOY will expel condensate and wet gas.

(3) Mature kerogen with high visual percentages of MOL has very low hydrocarbon yield and may be considered as barren of source potential.

Using these percent abundance values as an interpretative guide, reference to the log of kerogen composition plotted in Fig. 2 shows that the main hydrocarbon potential in the Kudu boreholes was developed within the post-mature shales between horizons P2 and P, where significant proportions of MOC (amorphous organic material) are present as follows:

(a) Kudu 9A-2; between horizons P1 and P: 75 to 80% MOC; lower two-thirds of interval between horizons P2 and P1: 60 to 75% semi-amorphous MOC;

(b) Kudu 9A-3; top half of interval between horizons P1 and P: 75 to 80% MOC.

However, since biodegradation of a diverse range of organic materials of different origins forms different kerogen types, determination of the original composition of the MOC below horizon P is required before its actual hydrocarbon potential can be assessed (Tissot & Welte, 1984, p. 158). The MOC does not appear to have formed from Type I oil-prone kerogen as both lacustrine and marine algae are absent. Nevertheless, it may consist of the bacterial degradation products of either lipid-rich marine phytoplankton or terrestrial humic debris, the original morphological features of which are no longer preserved.

Tissot & Welte (1984, p. 503) mention that it is not possible to discriminate between hydrogen-poor and hydrogen-rich amorphous organic matter using optical kerogen-typing techniques, stressing that Rock Eval pyrolysis and fluorescence spectral techniques should be used to quantitatively differentiate oil-prone from gas-prone amorphous kerogens. On the other hand, use of these quantitative techniques in assessment of pre-horizon P MOC is limited as fluorescence spectra and Rock Eval results are influenced by the onset of post-maturity (Davies and van der Spuy, 1988).

Pocock (1982) demonstrated that aerobic biodegradation of humic material produces yellow-orange coloured MOC with a granular texture, while reducing conditions within lipid-rich marine sediments form highly degraded grey-black MOC with a platy texture. However, assessment of MOC occurring below horizon P using Pocock's criteria is not possible as the original colour and fabric of the organic material has been so modified by thermal maturation that it IS now opaque.

MOC developed within the Aptian Unit 7 sapropelic claystones of DSDP 361 in the eastern Cape Basin (Fig. 2) is coeval with that occurring below horizon P in the Kudu boreholes. It is well preserved and thermally immature. Herbin *et al.* (1987) determined the hydrocarbon potential of the claystones using the Rock Eval pyrolysis method. Access to kerogen slides of Unit 7 MOC prepared by McLachlan and Pieterse (1978) permitted an assessment of the degree of morphological similarity (and perhaps hydrocarbon potential) to that of MOC below horizon P.

Thompson and Dembicki (1986) related four textural types of MOC to hydrocarbon generating potential based on geochemical analysis of the amorphous material. Photo-micrographs of Thompson and Dembicki's oil-prone Type A closely compare with that of Unit 7 MOC, while their gas-prone Type C is comparable to that of MOC below horizon P in the Kudu wells. Reference to Thompson and Dembicki's (op. cit.) description of textural differences between Types A and C makes such a distinction uncertain as the morphological terms used apply to *both* forms of MOC from within Unit 7 and below horizon P. (Type A amorphous kerogens are described as "chunky, compact masses with weak, polygonal, mottled, interconnected network textures" while those of Type C form "dense clumps with granular, fragmented or globular texture").

Colour and granularity of the MOC in Unit 7 indicates a terrestrial derivation by decomposition of Type III kerogens in a non-reducing environment (Pocock, 1982). However, Batten (1983) found that textural classification of MOC provides an unreliable guide to derivation of structureless organic matter as both marine and non-marine amorphous debris may appear in a finely divided state and/or as aggregated masses with a spongy, granular, clotted or lumpy appearance - all of which are developed within Unit 7 MOC. Quantitative Rock Eval pyrolysis data provides an alternative assessment. Herbin *et al.* (1987) show that the Unit 7 sequence is rich in aquatic organic matter (up to 18% TOC) interbedded with turbidite layers rich in terrigenous particles (3-25% TOC). The Hydrogen Index reaches 700 mg HC/g TOC indicating Type II kerogen. The petroleum potential of the sediments is very good and ranges from 30 to 150 kg - HC/t of rock. As some degree of morphological similarity exists between MOC from Unit 7 and that developed below horizon P, the Rock Eval pyrolysis data for Unit 7 sapropels may indicate that at least some of the post-mature MOC within the sequence below horizon P in Kudu 9A-2 and 9A-3 once had similar hydrocarbon potential (i.e. oil- to wet gas-prone). The occurrence of biodegraded humic and cuticular debris between horizons P2 and P I in Kudu 9 A- 2 demonstrates a more wet gas-prone source potential, as suggested from the geochemical data (Davies and van der Spuy, 1988).

The dark grey shales present in association with limestones throughout the cored section down to core 6 in Kudu 9A-2 (4394 m) have a poor generating potential. Only in core 6 are there shales which yield MOC and it is unlikely they represent a significant source of hydrocarbons from below horizon P2, particularly as the geochemical analyses (Davies and van der Spuy, 1988) indicate a low organic carbon content for the interval.

Discussion of results

Palaeoenvironments within sequence below horizon N

The association of dinoflagellates and palynowafers within the cored sequence below horizon P2 is interpreted to represent offshore deposition of sorted detrital kerogen following reworking of coastal plain sediments during a marine incursion. Vigorous sorting by high-energy bottom currents winnowed the detrital kerogen, depositing heavier traction load components nearer the shoreface while buoyant inertinite shards (palynowafers) were carried basinwards as suspended load. Presumably low-energy and minimal current activity at the sea floor within the distal portions of this transgressive sequence allowed palynowafer debris to settle from suspension. Presence of scolecodonts (the jaw apparatus of polychaete worms) within cores 6 and 4 below horizon P2 in Kudu 9A-2 may indicate relatively nearshore conditions, as they are generally found between tide-levels and in shallow waters of less than 40 m where the bottom sediments consist of sand admixed with considerable mud containing decaying organic matter (Shrock and Twenhofel, 1953, p. 509).

The increase in abundance of MOC between horizons P2 and P may reflect slow subsidence of the depositional site into deeper, poorly-oxygenated water. However, the corresponding phytoplankton curve indicates that the sampled portions of this interval are devoid of dinoflagellate cysts and acritarchs. In comparison, diverse dinoflagellate assemblages (up to 30 species in one sample), acritarchs and algal cysts are associated with MOC in turbidites of Unit 7, DSDP 361, deposited within a deep-water anoxic environment (Jacquin and De Graciansky, 1988; Magniez-Jannin and Muller, 1987). This negative evidence suggests a depositional site closer to shore for the sequence between horizons P2 and P.

As microfaunal assemblages (McMillan, 1988) within the sediments between horizons P2 and P indicate a deep-marine environment (i.e. base of continental slope), a number of suggestions are listed below to explain the apparent absence of dinoflagellate cysts:

(1) Dinoflagellates may have encysted within the photic zone and settled down to an anaerobic sea floor where conditions were favourable for bacterial degradation of the microplankton cell membranes and formation of MOC, a mechanism proposed by Raynaud *et al.* (1989) to explain the presence of lamellar structures and bacteria as main components of the amorphous organic matter in source rocks. If this occurred, it is difficult to explain the presence of well-preserved dinocysts within the deep-water sapropelic claystones of Unit 7, DSDP 361, recorded by Davey (1978) and McLachlan and Pieterse (1978).

(2) Planktonic dinoflagellates living within the photic zone of the open ocean at the Kudu depositional site may not have encysted to produce fossilisable remains on the sea floor.

(3) Turbid coastal waters may have inhibited photosynthetic productivity within the euphotic zone, creating an unfavourable environment for phytoplankton.

(4) During deposition of the sequence below horizon P within a restricted basin, inflow of substantial freshwater may have prevented dinoflagellates from colonising the water column because of the reduced salinity of the surface waters. Supporting evidence for this is provided by the occurrence of *Braarudosphaera* species in Kudu 9A-1 (Polugar, 1974) below horizon P, as concentrations of this coccolith in modem and ancient sediments are most common in coastal water of low salinity (Bukry, 1974).

The change at horizon P from a restricted anoxic basin with a xenomorphic palynofacies to an oxygenated pwafer/tracheid palynofacies with abundant and diverse microplankton is correlated with development of an open-ocean connection between the Atlantic and Indian Oceans. Palynological assemblages at DSDP sites within the South Atlantic intersecting Aptian sapropelic claystones (Cape Basin DSDP 361; Falkland Plateau DSDP 330,327) also record a deepening marine environment, with development of open-oceanic circulation in the Albian after an initial restricted basin stage during the Aptian (Jacquin, 1987; Jacquin and De Graciansky, 1988).

Phytoplankton abundance

The phytoplankton curves generally display decreasing phytoplankton ratios with depth (Fig. 2). Below horizon P, microplankton are poorly represented, occurring only in the cored sequence. A sudden increase occurs between horizons P and N where rapid expansion in phytoplankton abundance and conspicuous short-lived dominance of *Kiokansium polypes* (Cookson and Eisenack, 1962) suggests a significant increase in marine organic productivity.

The abundance of *Spiniferites* and other chorate dinoflagellate cyst genera between horizons P and N may be facies controlled, similar to dinocyst assemblages in the Palaeocene of southeast England where dominance of *Spiniferites* is interpreted as being indicative of an open-marine environment (Downie *et al.*, 1971).

Above horizon N, rapid fluctuations occur in the abundance and diversity of microplankton cysts. High visual percentages of dinoflagellates occur within samples in the vicinity of horizons K4, K3 and K, characterised by an abundance of *Dinogymnium* spp. and the peridinioid cysts *Palaeocystodinium* and *Andalusiella*. These high phytoplankton ratios do not necessarily imply deposition under open-marine conditions in a shelf environment as the ecological tolerances of the dinocyst genera (listed below) imply regressive nearshore conditions.

(1) Dominance of *Dinogymnium thecae*, together with low phytoplankton species diversity, suggests estuarine conditions with salinity fluctuations (May, 1980). The corrugate structure of *Dinogymnium* tests evidently acted to prevent damage caused by cell-volume change during rapid fluctuations in salinity within estuarine environments (May, 1977).

(2) May (1980) and Schrank (1984) show that microplankton assemblages dominated by *Palaeocystod-*

inium and *Andalusiella* are typical of marine regressive phases.

(3) Davies *et al.* (1982) used dominance of peridiniacean cysts as an indicator of epicontinental nearshore environments.

Reworked palynomorphs and sediment provenance

Reworking of palynomorphs occurs when a sedimentary rock undergoes erosion and its first-cycle palynomorph contents are subjected to a second cycle of renewed transportation and deposition. The relative stratigraphic age and thermal maturity of the reworked palynomorphs provide clues as to the provenance of the sediments and the burial history of the source areas. In general, palynomorphs are most likely to be found reworked in sediments which are the product of very rapid erosion with subsequent rapid transport and deposition under non-oxidising conditions (Muir, 1967).

Within the Upper Cretaceous sediments above horizon N, microfloral assemblages are notable in that they consist of reworked spores and pollen of more than one geological stage. Kaska (1974) noted this as a complicating factor in the biostratigraphic zonation of this interval in Kudu 9 A-I. Three assemblages of reworked palynomorphs occur between horizon N and L, namely:

(1) striate, diploxylonoid, haploxylonoid bisaccate pollen of Permo-Triassic age, Spore Colour Code "3a" (i.e. mature, bottom of oil-window);

(2) Lower Cretaceous (Neocomian-Albian) spores and pollen (e.g. *Balmeiopsis limbatus* (Balme, 1957), *Dictyotosporites complex* Cookson and Dettmann, 1958), Spore Colour Code "2b" (i.e. mature, middle of oil-window);

(3) Upper Cretaceous (Cenomanian-Santonian) spores and pollen (e.g. *Stoverisporites microverrucatus* Burger, 1975; *Cretacaeiporites scabratus* Hemgreen, 1973; *Bahiaporites reticularis* Regali *et al.*, 1974), Spore Colour Code "2a" (i.e. marginally mature, top of oil-window).

As indicated above, the assemblages of recycled palynomorphs have different spore colouration indices, implying that they have been derived from three sedimentary sequences with different burial histories. Lower and Upper Cretaceous sediments were relatively deeply buried prior to their recycling during the Senonian. Uplift, erosion and transport of these sediments into the basin was rapid as the reworked Cretaceous palynomorphs are well preserved, unlike the striate Permo-Triassic bisaccate grains which display corroded margins indicative of long distance transport. The sudden appearance of reworked Cretaceous palynomorphs at the level of horizon N, together with the sharp increase in abundance and diversity of phytoclasts, suggest a dramatic change in provenance.

Occurrence of reworked striate bisaccates within Unit 6 of DSDP 361 and between horizons P and L in the Kudu boreholes may indicate that Karoo-age basins began to act as source areas only during post-Aptian times. The thermal maturity of the striate bisaccates indicates that the source sediments, within one of the onshore Karoo basins of southern Africa, attained a level of maturation within the bottom of the oil-window. Examination of kerogen slides (I.R. McLachlan, pers. comm., 1988) prepared from some of the probable source localities within the Lower Permian Dwyka and Ecca Groups in the southern half of the Karoo Basin and southwestern parts of the Kalahari Karoo Basin, indi-cates the organic matter is carbonised and post-mature. Evidently, Karoo-age sediments eroded and redeposited within the Cretaceous interval above horizon P were derived from younger, less altered stratigraphic units (e.g. Upper Ecca or Beaufort groups) which once occurred at higher structural levels closer to the coast (McLachlan and Pieterse 1978).

Brief review of palynostratigraphy

Phelodinium boloniense (Riegel, 1974), *Andalusiella polymorpha* (Malloy, 1972) and *Andalusiella mauthei* Riegel, 1974 are the most common dinoflagellate cysts recorded above horizon N. They are typical members of the Campanian peridiniacean assemblage described as "the Malloy Suite" by Lentin and Williams (1980, p. 28) which may correspond to a subtropical or tropical water province. The Malloy peridiniacean suite is based on assemblages described from the Campanian of Spain, Senegal, Gabon, Brazil, Venezuela (Lentin and Williams, 1980, p. 22-23) and Egypt (Schrank, 1984b, p. 183-184). This occurrence provides the first record of the development of a Malloy Suite south of the Walvis Ridge. By way of contrast, existence of a more temperate palaeo latitudinal province to the south is suggested by occurrence of an austral counterpart to "the Williams Suite" (Lentin and Williams, 1980, p. 27) of peridiniacean dinoflagellate cysts in coeval sediments from the Rio Guanaco Formation in Argentina (Pothe de Baldis, 1986).

The distribution of *Nelsoniella aceras* Cookson and Eisenack, 1960 within the three Kudu boreholes is of stratigraphic significance. As the great majority of records for *Nelsoniella aceras* occur within Australia, some importance must be given to its inferred stratigraphic range spanning the latest Santonian to mid-Early Campanian in the most recent Australian Mesozoic palynological zonation scheme of Helby *et al.* (1987). In Kudu 9A-2, the apparent extinction point of *N. aceras* occurs at 2513 m, 100 m above horizon K4, implying that the overlying Cretaceous sequence below horizon L is no older than Campanian. This age assignment also matches that derived from the published stratigraphic ranges of peridinioid taxa within the Malloy Suite. A Senonian age is also suggested by the occurrence of abundant *Azolla* megaspores above and below the extinction point of *N. aceras* as *Azolla* massulae and glochidia first appear in the Campanian becoming abundant in Upper Campanian and Maastrichtian strata (Srivastava, 1980).

Sediments between horizons N and P contain microplankton cysts characteristic of Albian to Cenomanian sediments in Australia; in particular, *Litosphaeridium siphoniphorum* (Cookson and Eisenack, 1958), *Litosphaeridium arundum* (Eisenack and Cookson, 1960) and *Pseudoceratium ludbrookiae* (Cookson and Eisenack, 1958). No age-breakdown based on microplankton assemblages is possible for the interval between horizons P2 and P due to the apparent absence of dinoflagellate cysts. Poorly-preserved miospores and microplankton recovered from the cored interval below horizon P2 in Kudu 9 A -2 have Lower Cretaceous affinities.

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