

Chemical and optical investigations into the hydrocarbon source potential and thermal maturity of the Kudu 9A-2 and 9A-3 boreholes

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Chemical and optical studies carried out on the Kudu 9A-2 and Kudu 9A-3 boreholes revealed that two major intervals of Aptian-Barremian source shales are present below 3800 m and are analogous to oil-prone source intervals in the offshore Bredasdorp basin south of Mossel Bay, South Africa. The intervals were originally wet gas- to oil-prone although, as a result of the high palaeotemperature gradient, they have reached an advanced level of maturation and presently retain only some dry gas potential. Burial history studies show that oil may have been expelled from the shales during the latest Cretaceous and earliest Tertiary and that immediately succeeding structural movements allowed oil to escape updip. Any remaining oil was cracked to gas and wet gas-prone kerogen converted to gas by additional maturation supplied during further burial. The hydrocarbons that were encountered in the reservoir sands in the boreholes were, however, essentially dry. It is therefore quite possible that some, or all, of the gas presently retained in the reservoir formed by the thermal breakdown of pre-existing oil. There is also a possibility that some oil and wet gas could have escaped from the trap and been trapped further updip.

Introduction

The Kudu 9A-2 and Kudu 9A-3 boreholes (Fig. 1), drilled during the last months of 1987 and the first months of 1988, were comprehensively studied in order to determine the source potential; the origin of the gas encountered near horizon P, the timing of reservoir filling and the possible presence of other hydrocarbons trapped in the vicinity.

Results of both chemical and optical studies are presented diagrammatically in this report and the final conclusions take account of all the data. All depths are in metres below kelly bushing. A complete listing of the data is given in the Soekor report to Swakor (Davies and van der Spuy, 1988).

Sampling procedure

Cuttings were collected for routine analyses at approximately 5-10 m intervals throughout the borehole. For the chemical study, the samples were washed where possible to remove all drilling mud and sieved to collect the non-caved rock chip fraction (250-1500 μ). Samples that could not be washed or sieved were primarily from the interval above the 13³/₈ inch casing, although throughout the well there were isolated intervals where the samples were too soft for washing. Using cuttings for analysis is subject to compromises that reduce their value in providing accurate information about specific data points, e.g. downhole caving, pre-bit washing and mud contamination. However, cores provide excellent control points because they supply large, uncontaminated samples (except where mud has affected the outside surfaces). Sidewall core (SWC) samples provide valuable control between the routine cuttings and more rare cores, although they are generally small and may contain injected mud.

Samples from the unwashed portion of Kudu 9A-2 were analysed at 30 m intervals; most of the remainder of the borehole was studied at 20 m intervals, whereas the sections of greatest interest were studied at 10 m

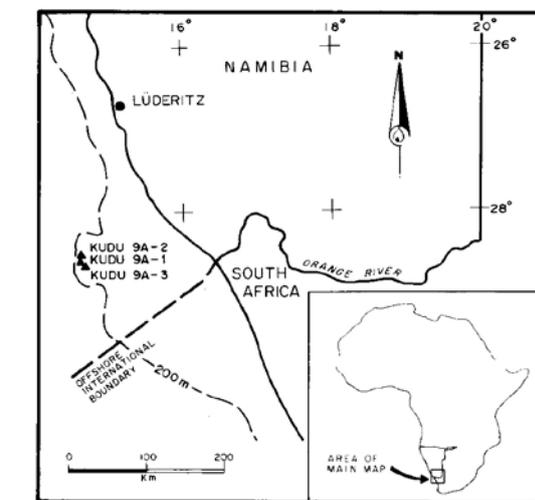


Fig. 1: Locality map - Kudu 9A boreholes, offshore Namibia.

intervals. This sampling program produced a total of 212 samples of cuttings. In addition to the cuttings, a number of SWC and core samples (46 and 21, respectively) were analysed in order to obtain accurate, *in situ*, data control points. Moreover, samples of drilling mud were collected every 100 m (a total of 40 samples) for analysis in order to provide an indication of the amount of mud contamination.

A total of 46 samples of cuttings, 5 SWC samples and 2 core samples were collected from just above horizon P to just below horizon P2 in Kudu 9A-3. The samples were chosen to provide confirmation of the source intervals and maturity determined from the Kudu 9A-2 data.

A total of 129 samples was collected for the optical study, 80 of which yielded slides with adequate amounts of kerogen suitable for organic petrographic examination. These included both kerogen concentrates from SWC samples and cores, as well as unprocessed core material. No cuttings were used due to the danger of contamination from mud and cavings.

Chemical analyses

All samples were dried at 35°C and then ground and sieved to collect the <math><150\ \mu\text{m}</math> fraction which comprised at least 95% of the original sample. The $150\ \mu\text{m}$ fraction consisted of individual sand grains as well as indurated silts and shales which usually react slowly to pyrolysis and give anomalously high temperature peaks. Each sample was subjected to three different analytical techniques to determine total organic carbon content (LECO), source potential and maturity (Rock Eval), and carbonate content (calcimetry).

Organic carbon

Samples used for total organic carbon (TOC) analyses (250 mg) were leached in hot 10% hydrochloric acid to remove the carbonates, washed to remove the chlorides and then pyrolysed in an oxidising atmosphere at temperatures in excess of 1000°C in a LECO carbon analyser. The resultant carbon dioxide was measured by a thermal conductivity detector and the quantity reported as percentage carbon relative to the rock mass. The instrument was calibrated frequently and quality control samples used routinely confirmed that the results have an error <math><5\%</math>.

Rock Eval

Rock Eval analyses, which were carried out on all samples, involved heating a small sample in an anoxic atmosphere to volatilise the free hydrocarbons at 250°C (S 1) and then pyrolyse the remaining kerogen within the temperature range $250\text{--}550^{\circ}\text{C}$. Products of the pyrolysis are newly generated oil and gas (S2) and, in the temperature range $250\text{--}390^{\circ}\text{C}$, oxygen-bearing compounds (S3).

The fourth parameter recorded was the temperature corresponding to the maximum of hydrocarbon generation during pyrolysis (Tmax). This parameter was used in evaluation of the maturation stage and as such comprised part of the palaeotemperature gradient calculation (Tissot and Welte, 1984). Spurious Tmax values were recorded in those samples which were affected by contaminants and also where the S2 peak was $0.2\ \text{kg/ton rock}$. These data points have therefore not been included in Fig. 2. The instrument was frequently calibrated against standard rock samples obtained from the Institut Francais du Petrole and the results showed an error of <math><5\%</math>. Moreover, quality control samples analysed against standards both locally and overseas were added to each sample batch in a manner similar to that used in the LECO procedure.

Calcimetry

Samples were immersed in warm hydrochloric acid in a sealed container and carbon dioxide was generated

by the reaction of carbonates with acid. The pressure gradient was recorded by a pressure transducer and the signal fed to a chart recorder. The rate of generation of carbon dioxide is related to the proportion of each type of carbonate in the sample and the content of calcite and dolomite is thus derived. Quality control and calibration samples were analysed at intervals in the same way as those used in the LECO and Rock Eval procedures.

Optical analysis

Core samples were slabbed and polished. Kerogen concentrates were produced from SWC samples using standard cold-acid palynological techniques (McLachlan and Fülöp, 1975). The concentrate was then mounted on perspex slides in cold-setting resin and polished.

The optical study involved measurement of vitrinite reflectance and observation of sporinite fluorescence for all samples, as well as maceral analyses over two intervals below horizon P which may have had source potential. Vitrinite reflectance and sporinite fluorescence can be directly correlated to organic maturity, while maceral studies supply an indication of source quality.

Vitrinite reflectance (VRO)

All vitrinite reflectance measurements quoted are mean, measured (in oil with a refractive index of 1.515) at random orientation using light of wavelength $546\ \text{nm}$. A standard Leitz MPV2 microscope was used and calibrated using a set of six glass standards with reflectances ranging from 0.299 to 1.672%.

An attempt was made to record a total of 50 readings from each sample to ensure accuracy in choosing the correct peak. Due to the nature of dispersed organic material and the small quantity of vitrinite in some samples, this was not always possible. Mostly, the number of readings was between 20 and 40. The vitrinite peak, regarded as being representative of the reflectance for a particular sample, was chosen taking quality of polish into account. Reworked vitrinite, which may form second and third populations with reflectances representative of previous burial histories, was often present. As all samples were either SWC or core samples, the problem of significant contamination by caving did not arise.

Sporinite fluorescence

All sporinite fluorescence was observed in reflected UV light using the standard Leitz high pressure mercury ultraviolet source attached to the microscope.

Maceral analyses

Maceral analyses were made by point counting and totals rounded to the nearest 5%. Each maceral type was determined by reference to standard reference works,

especially that of Falcon and Snyman (1986).

and 3650 m.

Results

Results are plotted in Figs 2, 3 and 4 and in Tables 1 and 2, and are interpreted below.

Maturation

Chemical

Gas data from cuttings (Soekor, 1989a,b) provided some information on maturity in the form of the wetness index $(C2-5)/(C1-5)\%$ plotted in Fig. 2. Interpretation of this has been done using the methods outlined in Tissot and Welte (1984) and references therein.

The first appearance of the higher homologues of methane marks the beginning of kerogen cracking and hydrocarbon generation. The main oil and wet gas windows (i.e. 80-160°C) are indicated by the wetness index being higher than 20% (Davies, 1979) over the approximate interval 2200-4100 m. The essentially dry gas recorded below the lower depth indicates that only methane has been generated and preserved in quantity.

The 3200-3400 m interval in Kudu 9A-3 has an anomalously low wetness index. The quantities of C2 + hydrocarbons are much lower than those in Kudu 9A-2, yet the methane contents are essentially the same. This may be a reflection of different absorption capacities rather than different maturities.

The Tmax data (Fig. 2) derived directly from the Rock Eval charts generally have an error of 3°C and are internally consistent. They have been interpreted following the guidelines in Espitalie *et al.* (1985). Since the organic material in most samples is clearly type III, i.e. woody and oxidised (S2/S3 ratios less than 2.5), the limits for the window in which oil generation from suitable source rocks is possible are Tmax 430-470°C, equivalent to a depth range of about 3600-3600 m.

The wet gas window (135-160°C), which is equivalent to a Tmax range of 470-490°C, is (by extrapolation) intersected between 3600 and 3950 m, whereas the dry gas window is present below 3950 m.

The interval 3830-3950 m and the samples from core 1 in Kudu 9A-2 have markedly lower Tmax values and, according to Espitalie *et al.* (1985), this may be due to the presence of better quality (i.e. more wet gas- and oil-prone) organic material in the kerogen. The data from the Kudu 9A-3 well do not, however, show consistently low Tmax values within the equivalent interval, although some do occur. A number of Tmax steps is evident, in particular at horizon L (830 m) where a significant Tmax step of 8°C is present, which may be related to uplift and erosion. Certainly, there is a significant time gap of about 25 Ma at that horizon (McMillan, 1988). Several smaller steps are also evident at 2000 m, 2600 m (coincident with horizon K4), 3500 m

Optical

Results of vitrinite reflectance measurements are presented in Fig. 2. A best-fit line, calculated using linear regression, projects to 0.26% VRO at the sea floor. This is in agreement with the expected value of close to 0.2% for uncoalified organic material (Dow and O'Connor, 1982). The best-fit line intersects the 1.35% reflectance line, which is approximately equivalent to a temperature of 135°C at 3700 m.

The wide scatter of points, evident at depths less than 1300 m, is associated with an abrupt increase in reflectance values. The scatter of points may be attributed to the various plant components forming vitrinite (Stach, 1982). The abrupt increase in reflectance at about 1200 m is known as the "first coalification jump", thought by some workers to coincide approximately with the start of oil generation, e.g. Teichmüller (1974). However, in this case it occurs some 300 m shallower than the reflectance value usually equated with the onset of oil generation.

A relatively featureless straight line from about 1300 m to 4000 m indicates a uniform increase in maturity with depth. There are no obvious steps in the maturation curve until about 2300 m. Here there is a slight increase in slope, possibly caused by a thermal event. This step could also be due to a change in depositional environment which may have affected reflectance. Microfaunas show a severe decrease in diversity at this point, implying an increase in water depth or a decrease in pH at the sea floor or both (McMillan, 1988).

A second abrupt increase in reflectance occurs at 4000 m, probably caused by a marked reduction in oxygen and the beginning of significant hydrogen release in the form of methane. This is believed to correspond approximately to the "death line" for oil generation (Teichmüller and Teichmüller, 1982). In this borehole it occurs at a reflectance close to 1.6%, which lends good support to this correlation.

Sporinite fluorescence colours, observed under ultraviolet light, change progressively from green through yellow and orange to red with increasing maturity (van Gijssel, 1982). Fluorescence is finally extinguished at a vitrinite reflectance of close to 1.2% (Teichmüller and Teichmüller, 1982). From 915 m to 1943 m, the maturity indicated by fluorescence colours (Table 1) is far greater than that indicated by reflectance. This may be explained by the lack of a large primary sporinite population in these samples. The sporinite present may be reworked and therefore carry a maturity imprint from a previous burial history. Between 1943 and 3600 m, the profile becomes normal and fluorescence is essentially extinguished at 3600 m at a vitrinite reflectance of about 1.25%, close to the expected value of about 1.2% (Stach, 1982). There is no fluorescence detectable at depths greater than 3871.5 m. This supports the palaeo-

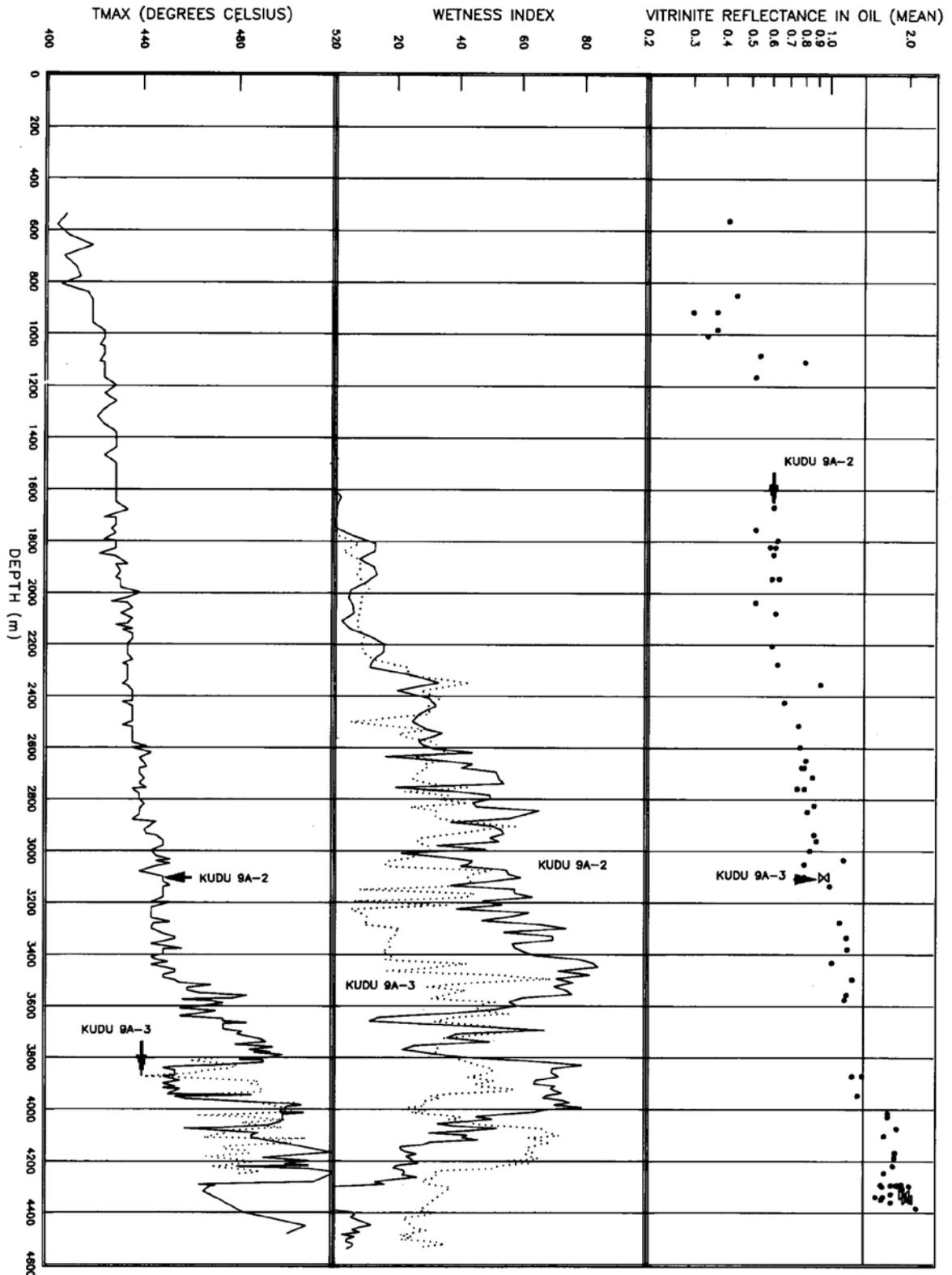


Fig. 2: Organic thermal maturity indices for the Kudu 9A-2 and 9A-3 boreholes: Tmax (°C), wetness index (% C2-5/C1-5) and vitrinite reflectance (%).

TABLE 1: Sporinite fluorescence colours

Depth (m)	Fluorescence colour	Depth (m)	Fluorescence colour
0563.0	light yellow	1943.0	orange brown
0800.0	light yellow		bright yellow
0850.0	light yellow	2035.0	dark orange
0915.0	light orange		orange
0983.0	light orange	2205.0	dark orange
1008.0	reddish brown	2596.0	brown orange
1667.0	orange brown	2675.0	yellow
1753.0	light orange	2846.0	light yellow
1795.0	orange brown	3050.0	yellow
1821.0	orange	3275.0	dark orange brown
1850.0	orange brown	3835.0	
		3871.5	

geothermal gradient indicated by the reflectance data. The chemical and optical data from both these wells indicate an overall palaeotemperature gradient of 3.8°C/100 m to the base of the oil window (3650 m). Below that depth there is evidence that the heat flow was higher since the top of the dry gas phase is reached at 4000 m, an indication of a palaeotemperature gradient in excess of 4.0°C/100 m.

Quality and quantity of organic carbon

Chemical

The minimum quantity of organic carbon that a rock can contain and still be considered a potential source rock is 0.5%. However, experience from other wells both locally and internationally indicates that a cut-off of 1% is more realistic (Tissot and Welte, 1984). There are two intervals in the Kudu boreholes where the minimum requirement has been consistently exceeded, i.e. P-to-P1 and P1-to-P2 (Figs 3 and 4, Table 3). The minimum carbon content is not strictly applicable in highly mature rocks, i.e. in the dry gas window, as the rock may contain only residual quantities of organic material. However, over most intervals in these wells it is evident from the maceral study (Benson, 1988) and from pyrolysis parameters (S1 and S2/S3) that the organic matter was essentially woody. In addition, because this material has a high activation energy, very little loss of carbon occurred during burial through the oil and wet gas windows. Leythausen *et al.* (1980) showed that the proportion of generative organic material in type III Kerogen is about 12% and that generation occurs only at temperatures in excess of 160°C. Thus, the minimal carbon contents and the poor source quality are a reflection of the original organic matter, not the high maturity.

The upper source interval in Kudu 9A-2 has an average organic carbon content of 1.98% and an average S2/S3 ratio of 0.72 which Clementz *et al.* (1979) show to be indicative of dry gas potential. However, as the maturity level is very high, it is probable that the source quality and the organic carbon content were originally

much higher. The upper two SWC samples (3835 m and 3872 m) have S2/S3 ratios which are 1.47 and 2.01, respectively, and the Rock Eval charts show a narrow peak at 450°C which Soekor's unpublished studies have shown to be indicative of type II material. Espitalie *et al.* (1985) indicated this type of organic material as being up to 60% convertible to hydrocarbons during burial through the oil and wet gas windows.

The SWC samples also show relatively high S1 values which may suggest earlier oil generation. There are also four SWC samples in the interval 2935-3135 m in Kudu 9A-2 which have high S2/S3 ratios indicative of some wet gas potential. However, they have low S1 values and their organic carbon and S2 contents are no higher than in the surrounding samples. The S3 value in each case is much less than in the surrounding cuttings and the carbonate contents are also much less. As some carbonates dissociate in the temperature window used to trap the products of oxygenated pyrolysis (S3), a decrease in their content may appear to increase the source quality. Two of the logs recorded after drilling (Soekor, 1989a,b; Figs 3 and 4) also display features that are characteristic of potential source rocks, i.e. relatively high gamma radioactivity (110 API units) and relatively slow sonic velocity (75 µs/ft). In the absence of more detailed samples, these log characteristics can be used to define more precisely the upper and lower limits of this source rock.

It is therefore evident that, although there are no suitable samples to demarcate precise depths, the whole interval from 3830 to 3971 m certainly has some dry gas potential at present. Furthermore, this interval must have had at least wet gas to oil potential, if not oil potential, when immature. As the quantities of remnant organic material are still quite high, the original generative potential may have been significant.

The lower potential source interval has an average organic carbon content of 1.61% and an average S2/S3 ratio of 0.34, both of which are lower than in the upper source interval. It is unlikely that this interval still possesses any source potential even though the log characteristics are similar to the upper interval. It may be that a proportion of the organic material had wet gas to oil potential even though the S2 peaks of the few SWC samples are not as narrow as in the upper interval. However, the proportion cannot have been high, as the S3 values, which should decline with increasing maturity, are much higher (1.37) than in the upper interval (1.01), indicating that the original kerogen had higher oxygen contents. Moreover, none of the samples exhibit the low temperature (450°C), narrow S2 peaks that are typical of type II organic material. The upper and lower limits of this interval can also be accurately delineated using a similar sonic log value of 75 µs/ft, namely 4102-4229 m.

In this interval, however, the gamma response is neither as consistent nor as elevated above background as the upper interval. This provides a further indication

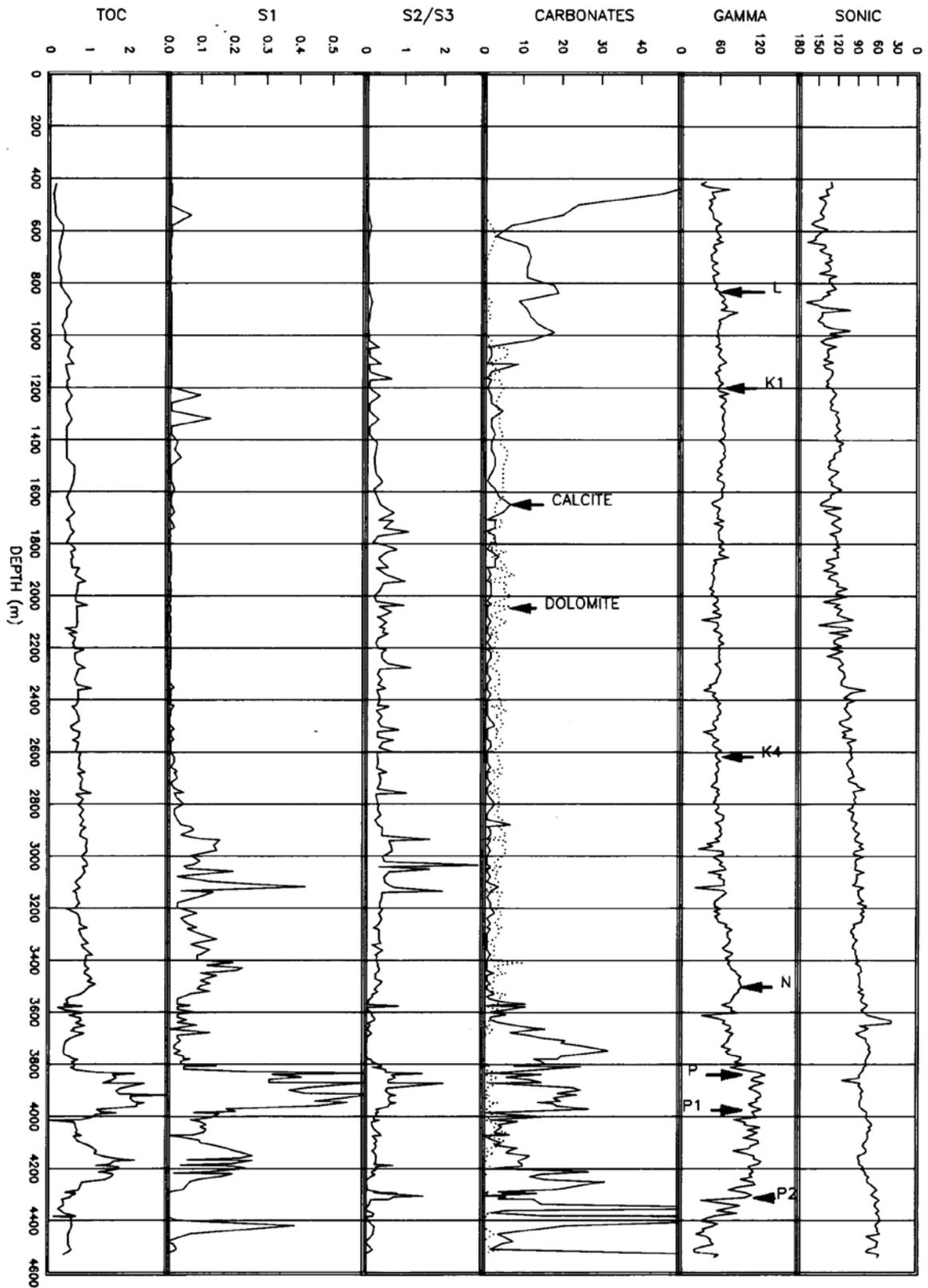


Fig. 3: Organic and log parameters for the Kudu 9A-2 borehole: TOC (mass %), S1 (kg/ton rock), S2/S3 (both S2 and S3 in kg/ton rock), carbonates (mass %), gamma (API units) and sonic ($\mu\text{s}/\text{ft}$).

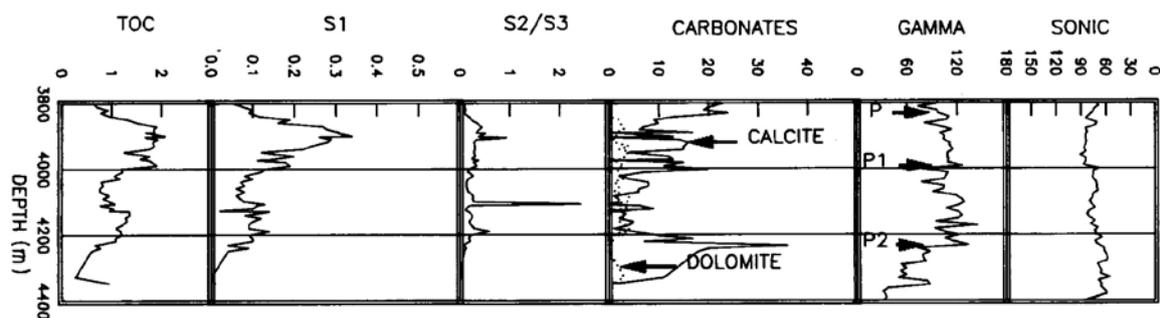


Fig. 4: Organic and log parameters for the Kudu 9A-3 borehole: TOC (mass %), S1 (kg/ton rock), S2/S3 (both S2 and S3 in kg/ton rock), carbonates (mass %), gamma (API units) and sonic ($\mu\text{s}/\text{ft}$).

that differences between the two source rocks existed, although this may be partly due to their different maturation levels (temperature difference between the upper and lower intervals of 6-15°C).

The cuttings- and ditch-gas data recorded during drilling also confirm differences in source quality. The upper interval has a high proportion (15-20%) of wet ditch-gas and considerable amounts (200-500 units) of the heaviest (C4 and C5) cuttings gas. The lower interval, by contrast, has only trace amounts of wet ditch-gas and the cuttings gas comprises essentially only C1-C3. The lower-remnant organic carbon content also suggests that the original potential could only be described as fair (Clementz *et al.*, 1979).

A further interval with a few low temperature (455-475°C) Rock Eval peaks was found in core 1 in Kudu 9A-2. This interval (4294-4303 m) also has the characteristic log responses for source rocks, although the Rock Eval data do not indicate any remnant source potential and the LECO recorded very low organic carbon values. It may be that this interval also had source potential which has been lost due to overmaturation.

Some of the cored intervals, especially below 4386.5 m, comprise almost exclusively carbonates. Analyses confirm that, although these limestones are very dark and contain some woody fragments, they and the adjacent shales have very small quantities of organic matter (average TOC <0.5%) and no source potential.

In Kudu 9A-3, the upper source interval (3846-3990 m) has an average organic carbon content of 1.75% which is more than 10% lower than in the equivalent stratigraphic interval in Kudu 9A-2. Moreover, the quality of the organic material is also lower: the S2/S3 ratio (0.32) is only 50% of that in Kudu 9A-2. A similar reduction in source quantity and quality occurs in the lower source interval of Kudu 9A-3, 4128-4158 m (and possibly also 4097-4112 m). The organic carbon contents (1.33%) and the S2/S3 ratio (0.01) are significantly lower than in the upper interval. Nevertheless, the low T_{max} temperatures suggest that both intervals originally had a higher potential. In addition, at least the upper interval could have been oil prone whereas the lower may have been only wet gas prone.

Optical

Maceral analyses were carried out on all polished kerogen slides over the two shaly intervals of interest, namely 3830 to 3971 m and 4102 to 4229 m. The intervals are regarded as potential source intervals by virtue of their sonic and gamma log responses. The results of these maceral analyses, which may be biased as the unprocessed material could only be examined in reflected light, are listed in Table 2.

Where the amorphous exinite content is 60% or more of the total organic material, the shale or claystone is considered to be oil prone providing the TOC is sufficiently high (Dow and O'Connor, 1982). Palynological analyses confirm the presence of oil-prone kerogen in the P1-to-P interval and that the amorphous material, present in the pre-P1 sediments, was derived from degraded terrestrial material (Benson, 1988). The above results imply that both shale intervals, although presently in the dry gas phase, were potentially better quality source rocks.

Discussion

Shaly source rocks of Aptian-Barremian age (McMillan, 1988) are consistently developed across the structure although the lower interval appears to thin towards the south. The areal extent of the source rocks is in excess of 100 km², although in the Bredasdorp and Pletmos basins (South Africa) the same type of source

TABLE 2: Maceral Analyses

Depth (m)	% Inertinite	% Vitrinite	% Structured Exinite	% Amorphous Organic Material
3835	5	5	0	90
3871.5	10	10	0	80
3918	0	0	0	100
3946	0	0	0	100
4102	0	0	0	10
4141	5	5	5	85
4167	10	20	5	65

TABLE 3: Potential and location of source intervals

	Kudu 9A-2 (m)	Kudu 9A-3 (m)
Horizon P1-to-P oil prone	3830-3971	3846-3990
Horizon P2-to-P1 wet gas to oil prone	4102-4128	4097-4112
Horizon P2-to-P1 wet gas to oil prone	4140-4229	4128-4158
Horizon P2-to-P1 possibly wet gas prone	4294-4302	

rocks are persistent over tens of kilometres.

The original source quality and the quantity of hydrocarbons that can be generated can only be estimated by reference to examples from other basins. If the Kudu source rocks, which are of similar age and type to source rocks in the Bredasdorp basin, were originally oil prone, then the generating potential could have been equally high, i.e. 11 kg hydrocarbons/ton rock with up to half being oil (Davies, 1988).

The upper and lower limits of the source intervals are given in Table 3 together with the adjacent horizons and an indication of the probable original source potential.

The average of the chemical and optical palaeogeotemperature gradients is 3.8°C/100 m (extrapolated from the bottom of the oil window) and the depths to the various maturation stages derived from Dow and O'Connor (1982) are illustrated in Fig. 5. Both the chemical and optical data indicate that the top of the dry gas stage is several hundred metres shallower than expected and is reached at approximately 4000 m. This may represent an example of the thermal blanketing effect that a thick argillaceous interval can have on heat flow (Tissot and Welte, 1984): there are nearly 400 m of shales overlying horizon P1. The elevated maturation found below 4000 m, which may in fact commence a little shallower, is persistent with increasing depth and may represent the last vestige of an early period of very high heat flow.

The average of the present-day temperature gradients derived from static borehole temperatures (Soekor, 1989a,b), is 3.5°C/100 m. This is almost 10% lower than the average palaeotemperature gradient reported above and indicates that considerable local crustal(?) cooling has taken place since sedimentation commenced. The reduction in gradient in recent times may, in part, also reflect the removal of the thermal blanket effect due to microfracturing of the shale. The presence of quantities of free gas in the interval above 1400 m in Kudu 9A-2 is evidence of considerable vertical migration and could be related to late-stage migration through a microfractured shale. Although this gas is dry, the absence of higher homologues could be due to a natural chromatographic effect or to the action of bacteria on the ascending gas (cf. Whiticar *et al.*, 1985). Certainly, there is too little organic matter in the sediments to have generated methane by direct bacterial conversion (d. Hunt, 1979) and most of the gas was found in permeable sandy sediments.

A burial history diagram (Fig. 5) constructed for Kudu 9A-2 using time-temperature integrated generation windows from Cornelius (1975 - derived from the average palaeotemperature gradient) indicates that the source rocks were buried through the main oil generation window during the Campanian-to-Miocene. However, palaeontological data (McMillan, 1988) show that only the earliest Maastrichtian sediments are present while in other West Coast wells the Maastrichtian sequence is less complete. The seismic records also show evidence of at least 200 m of erosion at the top of the K 1-to-L sequence, although this is partly masked by the updip convergence of reflectors in the interval. If the rate of sedimentation prevailing in the earliest Maastrichtian continued until the late Maastrichtian (i.e., an extra 3 Ma), a further 400 m of sediments would have been deposited. The subsequent erosion of these sediments during the Tertiary uplift (as shown in Fig. 5) would have significantly altered the timing of the oil expulsion and reservoiring.

The limits of the main oil expulsion window in Fig. 5 have been calculated from a marine source rock of the same age and depositional environment and with similar organic material in the Bredasdorp basin (Davies, 1988). The intersections of the source rocks with these limits show that each of the source intervals passed through the oil expulsion window in short time intervals of 8 Ma each during the late Campanian to early Palaeocene, i.e. within a time period of 15 Ma. Any oil trapped in reservoirs in the vicinity would have been affected by the Tertiary structural movements partly due to movement of the reservoir spill-point in response to the changing attitude of the strata and partly because widespread faulting could have formed migration conduits through the overlying shales, thereby allowing the oil to escape. Oil may therefore have been rapidly expelled in quantity until about 60 Ma ago, after which gas expulsion would have predominated. Any oil unable to migrate far from the source would have been destroyed during the intervening period by increasing maturity associated with progressive burial.

It is unusual to find no evidence of trapped oil in the tight sands above the upper source interval from which expulsion is presumed to have occurred. Even the sands, which are reportedly argillaceous according to well-site lithological descriptions, contain none of the expected bituminous residues. Daily reports dealing with core 1 of Kudu 9A-1 noted the presence of "black shiny patches probably due to hydrocarbons", suggesting that at least some oil expulsion occurred. However, bitumen extract gas chromatography and optical analysis of this material show that it is exudatinitic derived from woody material.

It is possible that the absence of thick porous sands immediately above the upper source interval delayed migration of some oil until the sequence was buried deeper than the preservation limit for oil, in which case the oil would be cracked *in situ* to wet gas. However,

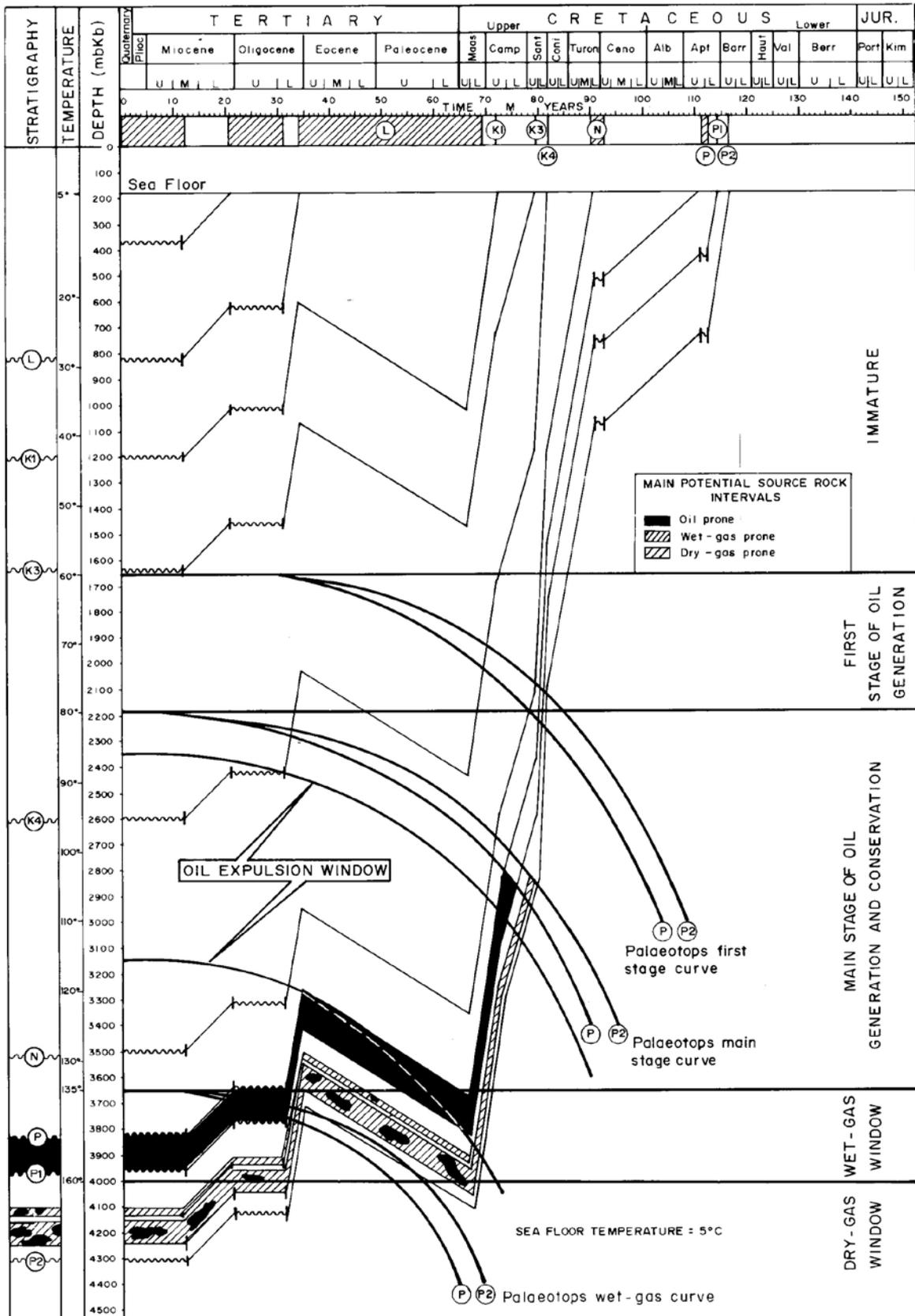


Fig. 5: Burial history diagram for Kudu 9A-2 based on a palaeogeothermal gradient of 3.8°C to 3650 m. See text for discussion.

two thin sands immediately below this source could have been potential reservoirs for oil. The absence of bitumen traces further suggests that either oil was not trapped or, if it had been, that it had all escaped from the trap and migrated updip.

The lower source interval contains abundant amorphous organic material which usually indicates significant oil potential, whereas the chemical analyses suggest a lower original potential. The apparent contradiction is resolved if it is assumed that some amorphous material had low hydrogen contents (Thompson and Dembicki, 1986) or was derived from degraded terrestrial material (Powell *et al.*, 1982). The sands above and below this interval are tight (according to the composite log) and oil expulsion may therefore have been retarded. The possible source interval intersected by core 1 in Kudu 9A-2 may have had oil potential although, similarly, the expelled quantities would have been limited by the absence of adjacent migration conduits.

Conclusion

Based on the data presented, there is a probability that oil has been expelled from the upper, and possibly even the lower, source interval. Updip migration may have occurred but was possibly limited by the lack of thick, continuous migration conduits. Secondary migration may also have occurred following Tertiary movements and oil may be found further updip above a depth of 3500 m (the oil preservation limit).

Prospects of finding wet gas with condensate in quantity are promising. The generation of wet gas probably reached a peak during the last 10 Ma and this gas, together with any gas generated from thermally cracked oil, could well be retained in reservoirs shallower than 4000 m.

The quantities of relatively dry gas that have been generated in the near vicinity of the well site must be very large, whether from cracked oil or primary generation from type II and III organic matter. Only a portion of this was found at the well site and the temperatures are clearly not high enough to have affected the stability of the methane (Tissot and Welte, 1978). There must, therefore, have been large-scale updip or vertical migration of dry to wet gas and this could form the basis for future exploration. If organic quality and quantity extend downdip, then targets containing gas could, with suitable migration routes and sealing sediments, be found further offshore.

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