Geologie en Mijnbouw 65: 57–74, 1986

Geology of the Tarfaya oil shale deposit, Morocco

Louis Leine
Kon. Shell Exploratie en Produktie Laboratorium, Volmerlaan 6, 2280 AB Rijswijk, The Netherlands

Received 9 December 1985; accepted in revised form 7 March 1986

Abstract

A description is given of the Tarfaya oil shale deposit which is located in the Moroccan Sahara along the Atlantic coast, at the latitude of the Canary Islands. The deposit consists of kerogenous chalks of Upper Cretaceous age, which are colloquially called 'oil shales' following general usage. The paper discusses the tectonic setting, stratigraphy and depositional environment of the kerogenous chalks and provides details on their petrography, chemical composition and mineralogy. Some mining criteria are also given such as oil yield, thickness and geological reserves of the oil shales, as well as characteristics of the overburden. Preliminary remarks are made regarding the hydrology of the mining area.

Introduction

In September 1981 Shell Prospecting B.V. and ONAREP (the Moroccan State Oil Company), entered into a joint venture agreement for the exploration, evaluation and – if economically feasible – the exploitation of the Tarfaya oil shale deposit. The joint venture holds a concession located along the Atlantic coast, east of Tarfaya, opposite the Canary Islands of Fuerteventura and Arrecife (Figs. 1 and 2). The concession area forms part of the Moroccan Sahara (province of Laayoune). BRPM (the Moroccan Mining Bureau) had carried out a reconnaissance of the oil shale deposit in 1975 by drilling 26 shallow boreholes in an area stretching from Tarfaya to some 110 km east. Using the results of this exploration, it was possible to outline broadly those areas containing shallow mineable reserves. Further exploration by ONAREP/Shell in 1982 concentrated on these areas. Operations consisted of detailed topographical mapping, drill-

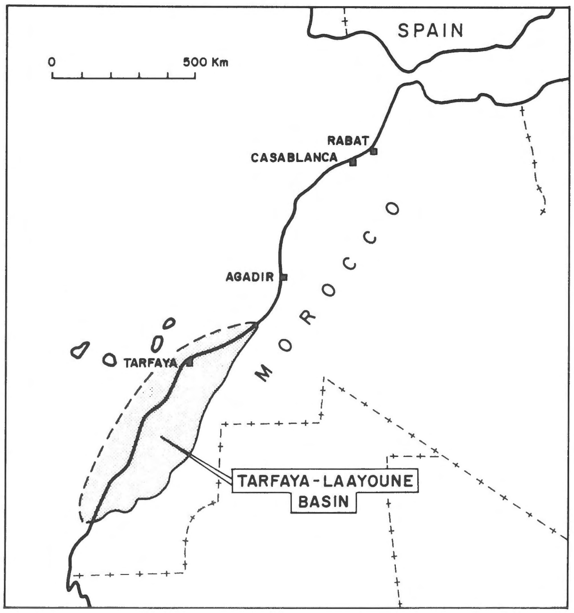


Fig. 1. Location map of the Tarfaya–Laayoune Basin.

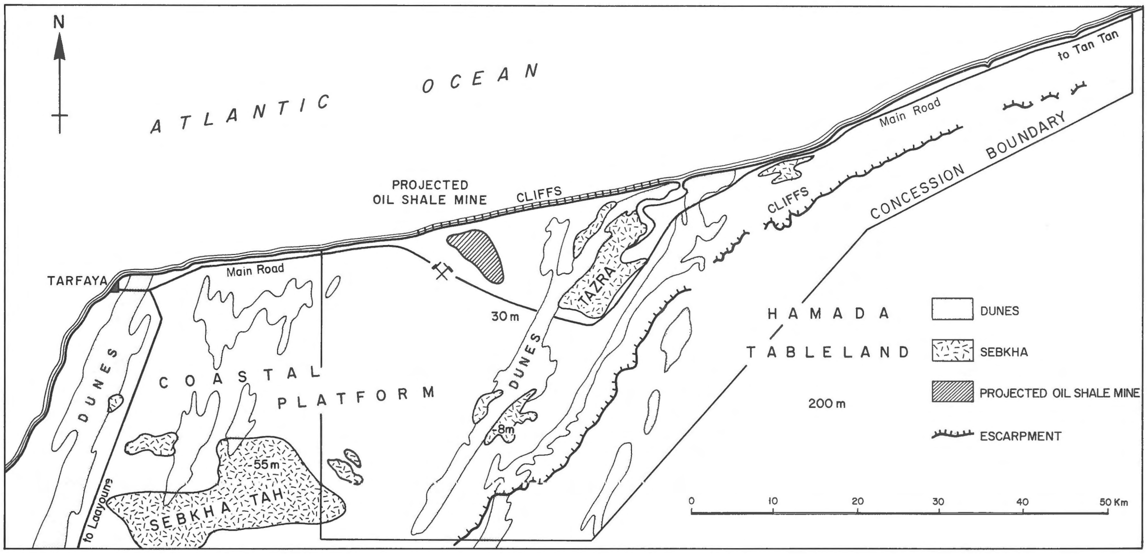


Fig. 2. Topography of the Tarfaya area.

ing of 55 shallow boreholes with a spacing of 2–3 km, petrophysical logging, digging of 5 prospect shafts for bulk sampling and analyses of some 3500 samples.

Geological setting

The oil shales were deposited in the Tarfaya-Laayoune Basin, extending onshore and offshore over an area of about 170.000 km^2 (Fig. 1). The basin has a Hercynian basement, composed of folded Precambrian and Palaeozoic crystalline rocks, that is unconformably overlain by a seaward thickening wedge of Mesozoic to Cenozoic sediments (Ranke et al. 1982; Wiedmann et al. 1982). More than 2000 m of Jurassic neritic carbonates were deposited in the Tarfaya area as evidenced by well Puerto Cansado-1 (Viotti 1966). Deltaic Wealden type sediments were deposited during the Early Cretaceous, followed by a transgressive Late Cretaceous sequence of carbonate shelf deposits (Choubert et al. 1966; Einsele & Wiedmann 1982). Part of the latter sequence is developed as kerogen-rich chalks, which are collognially called 'oil shales', following general usage.

During early Miocene times the Mesozoic strata were locally tilted and domed, and the anticline of Sebkha Tazra – situated in the concession area – was formed (Fig. 3). After formation of this anticline, erosion truncated the Upper Cretaceous; subsequently a relatively thin layer of Upper Tertiary/Quaternary – mainly belonging to the Moghrebian Formation – was deposited on the erosion surface (Choubert et al. 1966).

Tectonic deformation of the Upper Cretaceous is very gentle; the highest dip measured between boreholes is about one degree. Major faults have not been encountered in the area investigated in detail. Small faults with a vertical throw of 2 to 3 m might possibly occur, because they cannot be detected with a borehole spacing of 2 to 3 km. Vertical joints have been found in borehole cores and in outcrops of Upper Cretaceous strata along the coast.

Moghrebian Formation

The Moghrebian Formation is of Pliocene-Pleistocene age (Choubert et al. 1966). Its lower part consists of yellowish-brown sandy coquinoid limestones, deposited in a coastal marine to beach environment. These sandy limestones are often overlain by relatively soft dune sandstones, showing large-scale cross-bedding. The Moghrebian For-

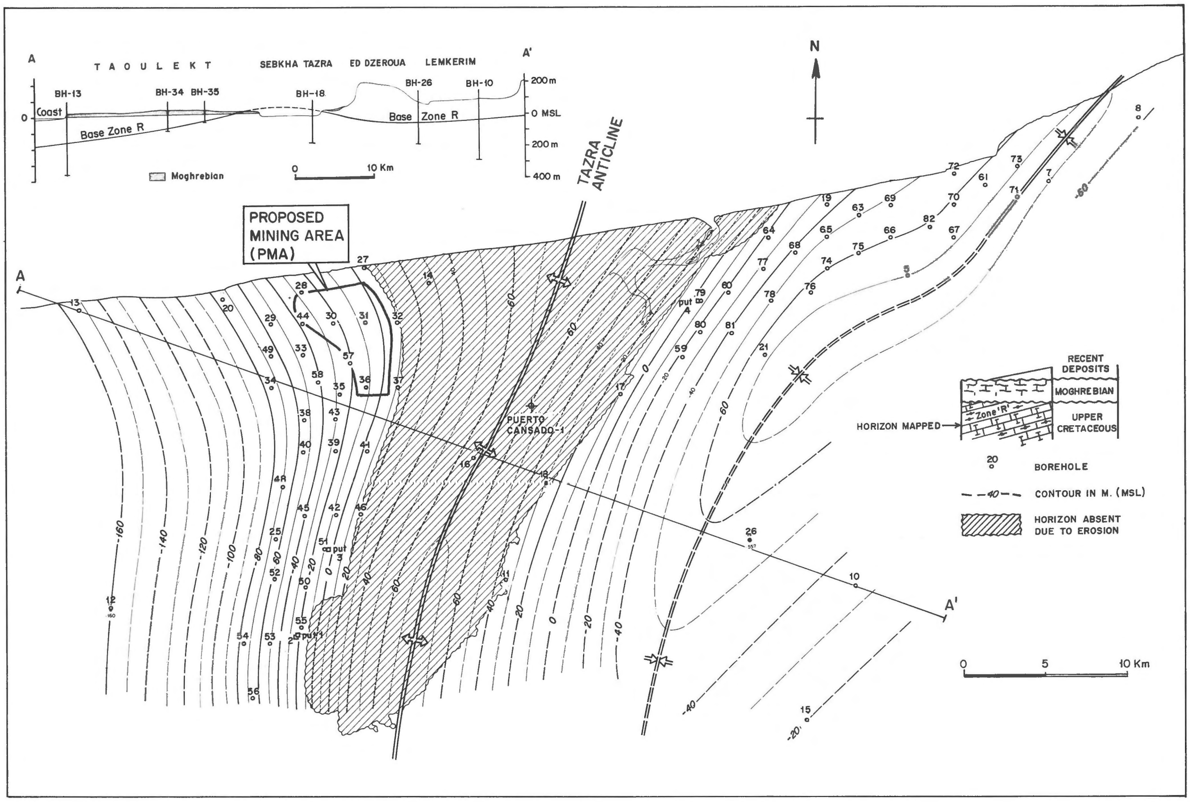


Fig. 3. Structural map of the Tarfaya area.

mation sometimes begins with a basal conglomerate overlying unconformably the Upper Cretaceous. Leaching of shell fragments has made the sandy limestones vuggy. Porosities were measured in a few core plugs and vary between 30 and 40 per cent. At the surface, the Moghrebian is mostly dense and hard due to deposition of secondary calcite in the pores (caliche formation).

The Pre-Moghrebian unconformity represents a Pliocene abrasion platform on which the sea transgressed southwards by cutting back a coastal cliff. The present escarpment – separating the coastal platform from the Hamada tableland – represents the ancient sea cliff (Fig. 2). It is the most inland shoreline and marks the limit of the Moghrebian deposition. The unconformity dips very gently N to NNW (fig. 4). In detail the unconformity plane shows undulations, which are exposed in the coastal cliffs.

Cretaceous stratigraphy

Information on the stratigraphy and lithology of the Cretaceous in the Tarfaya area is compiled in Table 1 (after Choubert et al. 1966; Viotti 1966 and own work). Deposition of oil shales/source rocks took place during Cenomanian, to Early Santonian, that is during a time span of some 11 million years. After a hiatus ranging from Upper Santonian to Lower Campanian, the sea transgressed in Upper Campanian times and source rock deposition resumed. The resulting source rock sequence in the Tarfaya area measures some 700–800 m, an exceptional thickness. The sequence consists of dark grey laminated kerogenous chalks, alternating with non-laminated lighter coloured limestones containing a lower kerogen content (Fig. 13). The latter are sometimes developed as nodular limestones. Intercalated in the sequence are concretions and lenses of chert and siliceous limestone.

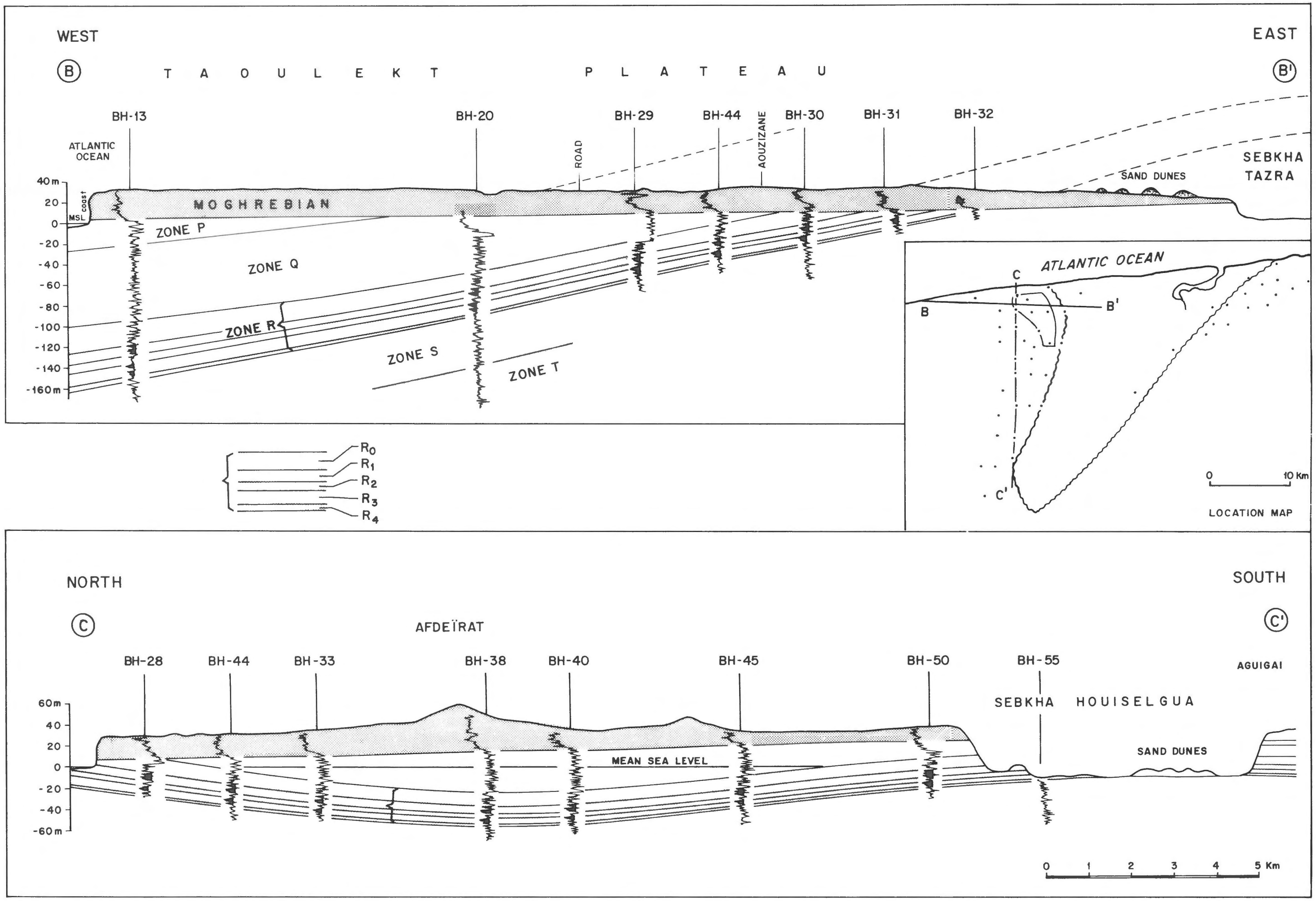


Fig. 4. Sections through the west flank of the Tazra anticline.

Table 1. Lithology and stratigraphy of Cretaceous-Tertiary in the Tarfaya area.

Age	Thickness (m)	Documentation	Lithology
Plio-Pleistocene (Moghrebian)	0–45	Outcrops and shallow BH	Sandstones Sandy coquinoid limestones
*			
Late Campanian	~40		OIL SHALE SEQUENCE Chalks with varying kerogen contents.
*			
Early Santonian Coniacian Turonian Cenomanian	~700	Outcrops and shallow BH	Intercalations of chert and siliceous limestones. Towards the top more silt-clay intervals
Early Cenomanian-Albian	310	Puerto Cansado-1	Clays, marls and fine grained sandstones
*			
Early Cretaceous	1345	Puerto Cansado-1	Red and green sandstones Congl. sandstones Intercalations of siltstones/claystones. Coal fragments

* Hiatus

These siliceous layers are usually very thin, i.e. less than 10 cm thick. Also marls and clays occur occasionally as intercalations. In many outcrops the kerogenous rocks have lost their original dark grey colour and weather white. The kerogenous chalks contain locally white phosphate nodules measuring up to 3 cm across.

Figure 5 shows a composite log over an interval of some 680 m, representing the major part of the oil shale sequence. The average oil yield over the total interval is 29 l/t and the average organic carbon content 4.3%. The richest oil shales were deposited in Late Cenomanian and Early Turonian. Log correlation of the oil shale sequence was found to be excellent and hence a subdivision of the most important part of the sequence was established with the help of petrophysical logs (Fig. 6). Zones P and T are distinguished, which have a higher gamma ray reading than Zones Q, R and S. Likewise Zone R ('Zone Riche') is distinguished on the density logs as a zone with lower densities and hence higher oil yields than Zones Q and S. Zone R has been further subdivided using the density logs into subzones R_0, R_1, R_2, R_3 and R_4, of which subzones R_3

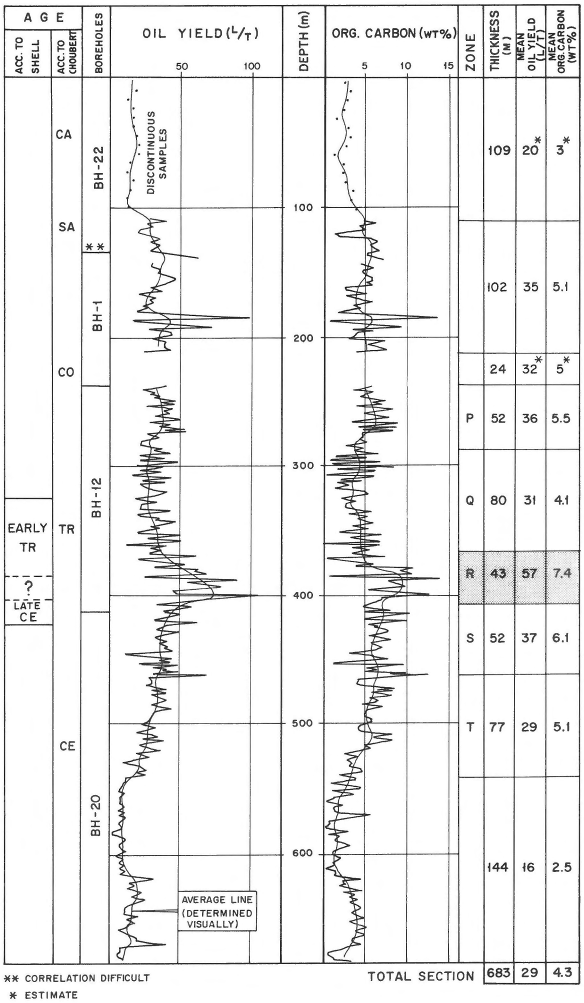


Fig. 5. Composite log showing oil yield and organic carbon content in the Upper Cretaceous, Tarfaya area.

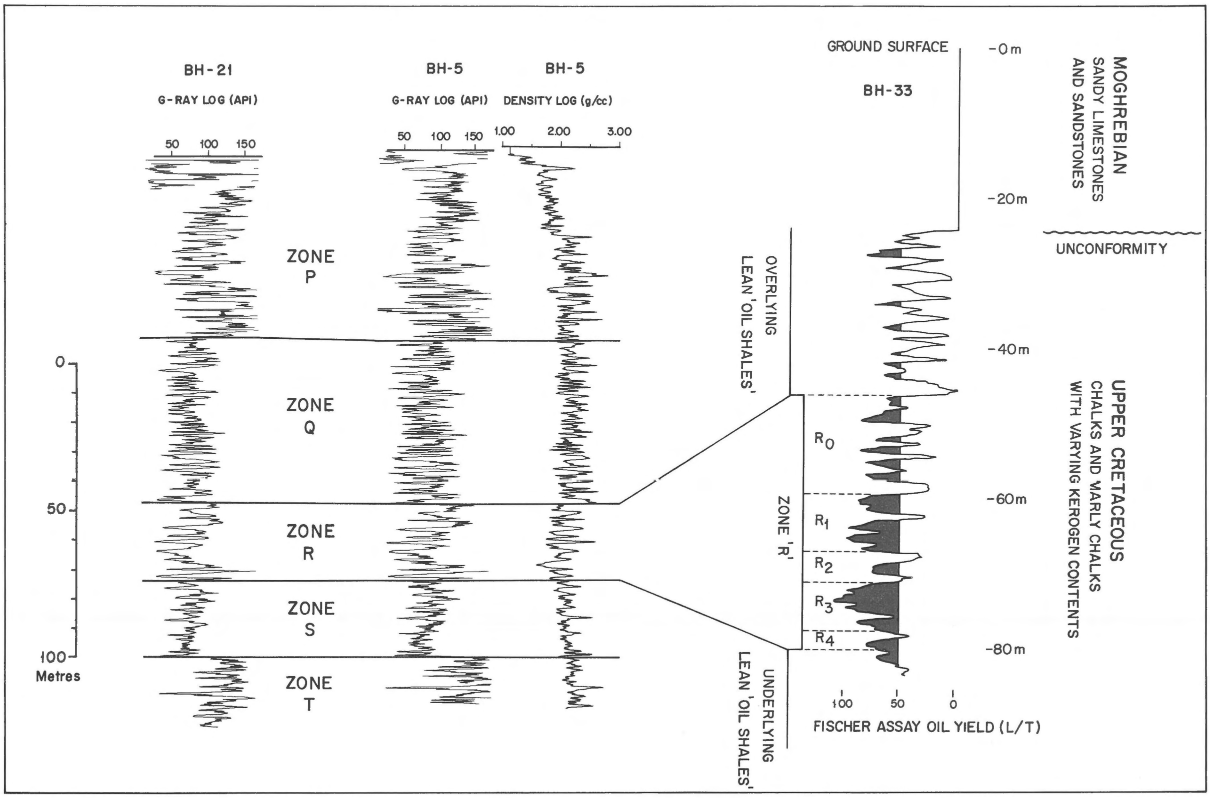


Fig. 6. Lithostratigraphic subdivision of the Upper Cretaceous oil shale sequence.

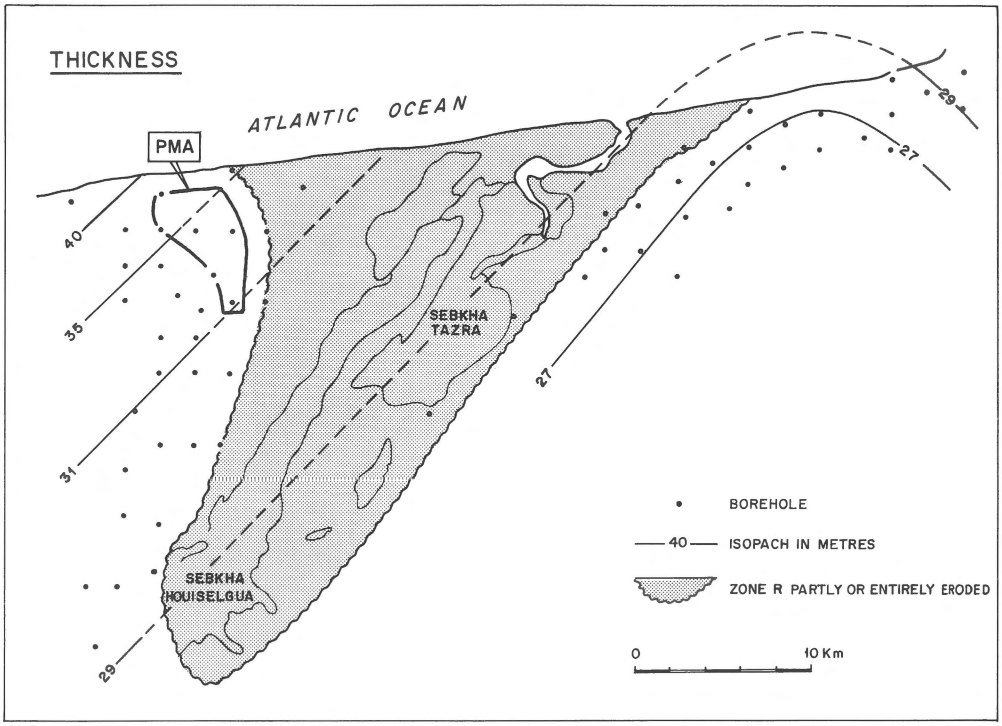
and R_1 have the highest oil yields (Fig. 6). The richest oil shale layer – the 'Niveau Riche' – with an oil yield of up to 110 l/t and a thickness of 1–2 m forms part of subzone R_3. The subdivision of Zone R was established in order to consider three different mining cases, viz.:

Case 1: Zone R ($R_0 + R_1 + R_2 + R_3 + R_4$)
Case 2: Subzones $R_1 + R_2 + R_3$
Case 3: Subzones $R_1 + R_3$

Case 1 has the greatest thickness but the lowest mean oil yield, whereas
Case 3 has the smallest thickness but the highest mean oil yield.

Depositional environment of oil shales

Examples of 'Cretaceous anoxic events' (cf. Arthur & Schlanger 1979; Jenkyns 1980) have been described from various parts of the world and the Tarfaya oil shale deposit is one of them. Some authors (e.g. Einsele & Wiedmann 1982) have suggested that upwelling conditions occurred in the Tarfaya area in order to explain the richness of organic matter in the sediments and the anoxic bottom conditions. Others favour the idea of density stratification and stagnation due to more saline bottom waters. Thierstein & Berger (1978) envisage these saline waters to be derived from the South Atlantic, which was an isolated evaporitic basin in Mid Cretaceous time. Busson (1984) thinks that the saline bottom waters might be the result of the Late Cretaceous transgression over the Northwest African continent upon which pre-existing Cenomanian gypsum and salt deposits were present. Intervals of laminated kerogen-rich chalks alternate with layers of light coloured kerogen-poor limestones pointing to an alternation of periods characterised by an anoxic and a more oxygenated



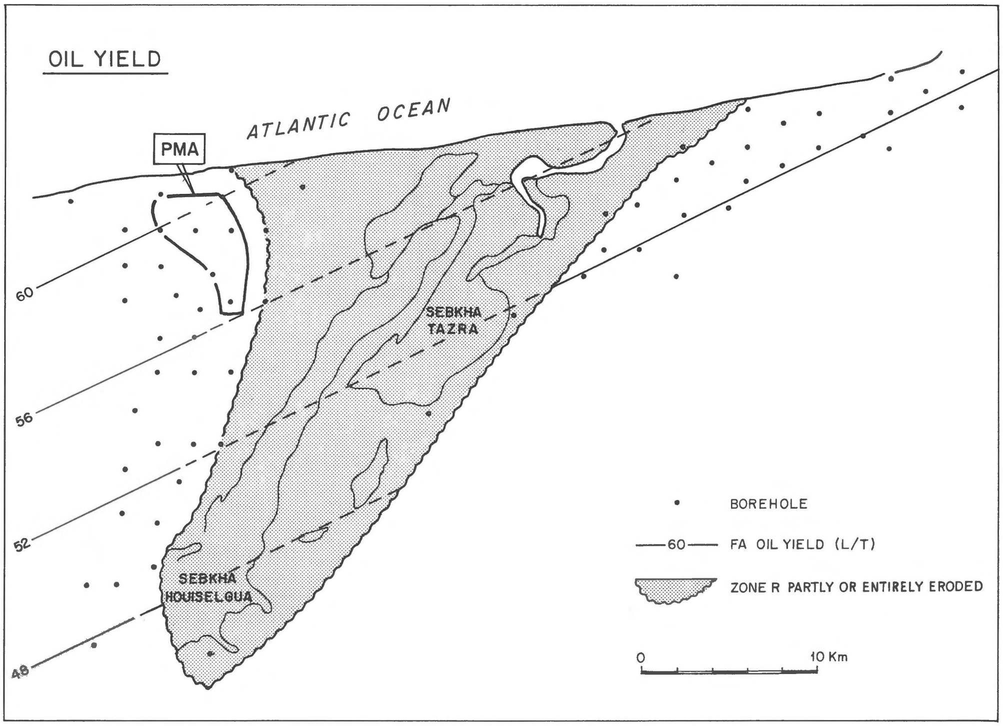


Fig. 7. Thickness and oil yield map of zone R.

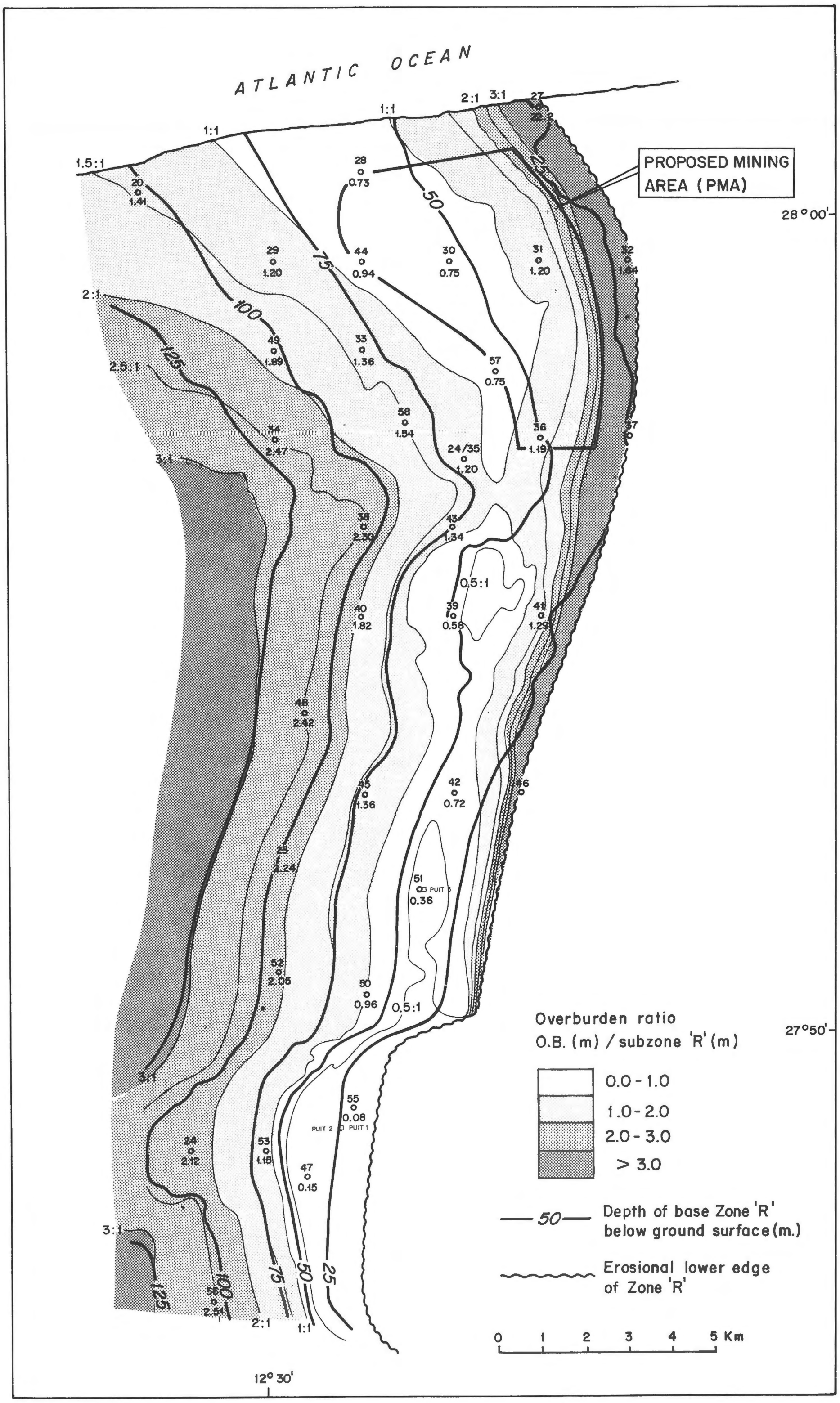


Fig. 8. Overburden ratios for zone R in the west flank area.

sea-bottom. The richest oil shales were deposited during the time of maximum marine transgression (Late Cenomanian and Turonian).

Thickness of Zone R

Part of the Upper Cretaceous section is eroded in the core of the Tazra anticline. As a result of this, Zone R is partly or entirely absent in the area indicated on Figure 7. The full development of Zone R prior to erosion shows a relatively simple picture. Its thickness increases generally in a NW direction, the exception being in the eastern part of the east flank where the thickness increases towards the NE. The greatest thickness in the Tazra anticline has been encountered in the northern part of the west flank close to the coast: 42 m in BH 20. Zone R is also thickly developed further westwards, where a borehole encountered a thickness of some 55 m directly south of Tarfaya. In the areas where Zone R is truncated by the pre-Moghrebian unconformity, its thickness rapidly decreases to zero over a distance of 3 to 9 km (Fig. 4).

Overburden

The overburden of Zone R is composed of lean oil shales, the Moghrebian Formation and Recent deposits (mainly sand dunes). Fortunately the overburden in nearly the entire west flank is devoid of any major sand dunes. In Sebkha Houiselgua, the Moghrebian Formation has been eroded and Zone R is exposed (Fig. 4). In cross-section the part of the overburden composed of lean oil shales has the shape of a wedge, confined between the sub-horizontal pre-Moghrebian unconformity and the dipping top of Zone R.

Figure 8 shows the overburden ratios, that is overburden thickness divided by oil shale thickness, for Zone R in the west flank area. A north-south trending zone of lowest overburden ratios is centred on the erosional upper edge of Zone R. At this edge the thickness of the overlying lean oil shales is zero, whereas Zone R still has its full thickness. West of the edge the overburden thickness increases, whereas east of the edge the thickness of Zone R decreases due to its erosion. Figure 8 shows that there are large areas on the west flank, where the overburden ratios are less than 1.0. The overburden ratios for Zone R in the east flank area show a similar picture as on the west flank. Again a zone of low overburden ratios follows the erosional upper edge of Zone R. The overburden ratio maps highlight areas of relatively low mining costs.

Oil yields

Routine analyses of core samples comprised modified Fischer assays (FA), organic carbon and mineral carbon content, as well as organic carbon content of the FA residues. Figure 9 shows how these analyses are related to the mineral and elemental composition of an oil shale (dry basis). From this figure it can be seen that the % wt kerogen can be calculated from the % wt FA residue and the % wt

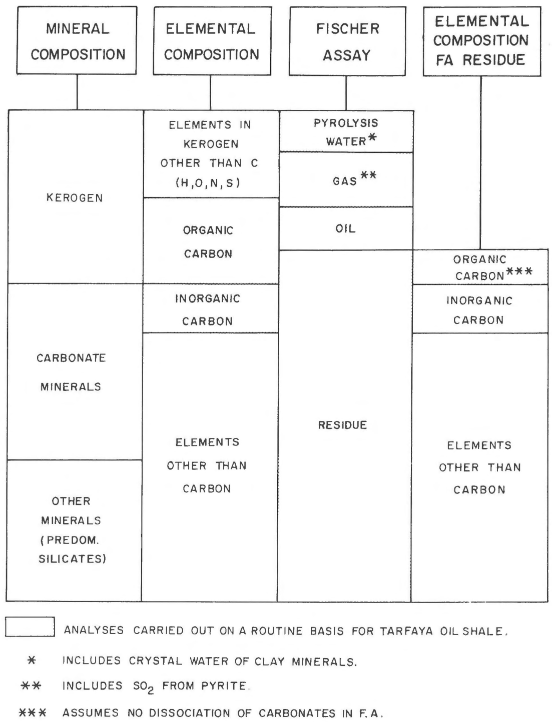


Fig. 9. Schematic comparison of results of various oil shale analyses (dry basis).

organic carbon in the FA residue by using the following formula:

$$\text{Kerogen} = 100 - \text{FA residue} + \left(\text{Org. C residue} \times \frac{\text{FA residue}}{100}\right)$$

The kerogen contents thus calculated are based on measurements which are independent from measurements of oil yield and organic carbon content of the oil shale. These three variables have a strong and positive correlation as shown by Figure 10.

The FA oil yields also show a strong inverse relationhips with the density logs, as indicated in Figure 11. The density logs of all the boreholes show a marked regularity of the oil shale sequence over the entire deposit with a perfect correlation between boreholes. Therefore the oil yields must also show a regular distribution. Figure 7 shows that there is an increase in oil yield from SE to NW for boreholes that penetrated the full thickness of Zone R. Not shown in this figure are irregularities in average oil yield of Zone R due to erratic measurement errors, which have been removed statistically.

There is a rather strong relationship between the oil yield and the thickness of Zone R (Fig. 7). Both increase from SE to NW and therefore the shale of the northern part of the west flank is most attractive economically. Moreover, overburden ratios found in this part of the deposit are not unduly high (Fig. 8). The oil yield distribution for areas of the west flank where Zone R is complete, as well as for areas where it is partly eroded, is shown in Figure 12. The oil yields in the latter areas are generally higher than in areas where Zone R is complete. This is because erosion has removed (part of) subzone R_0, which has a relatively low oil yield, thereby increasing the quality of the remainder of Zone R. It is only towards the erosional lower edge of Zone R – where the remainder is composed of the relatively low yielding R_4 – that the quality decreases again.

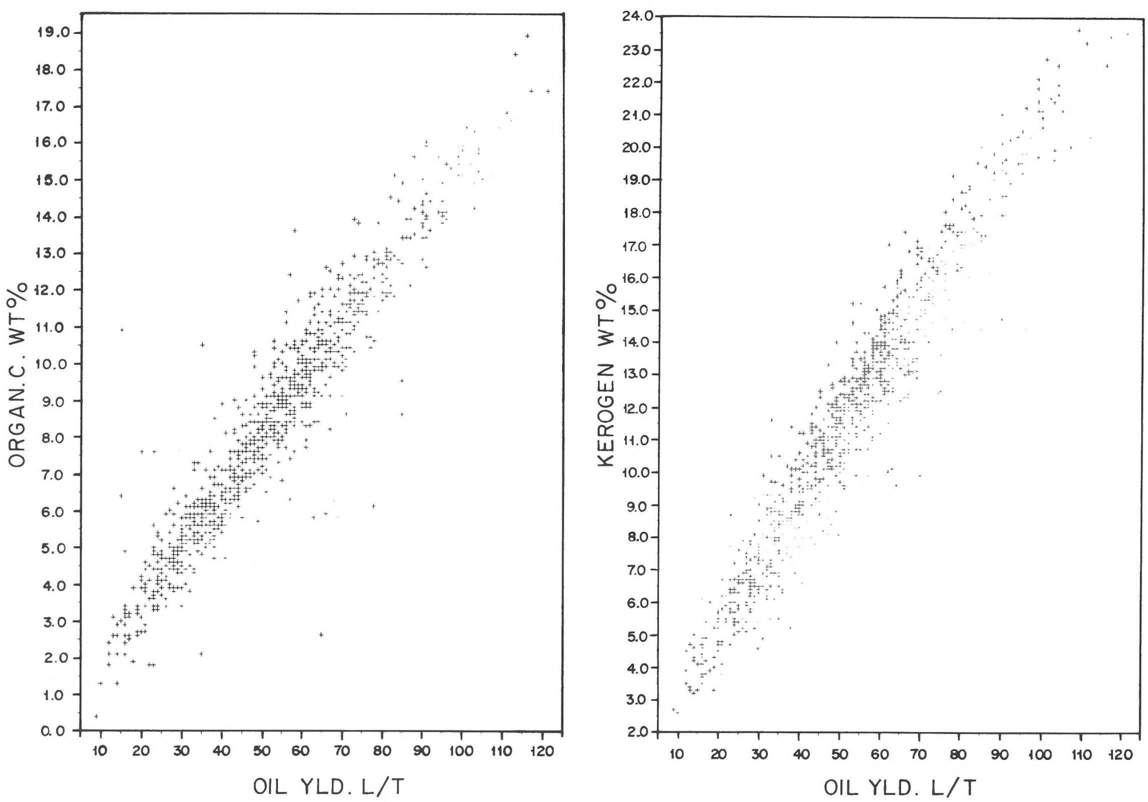


Fig. 10. Cross-plot of FA oil yield versus organic carbon content (left) and kerogen content (right) for zone R (n = 1000).

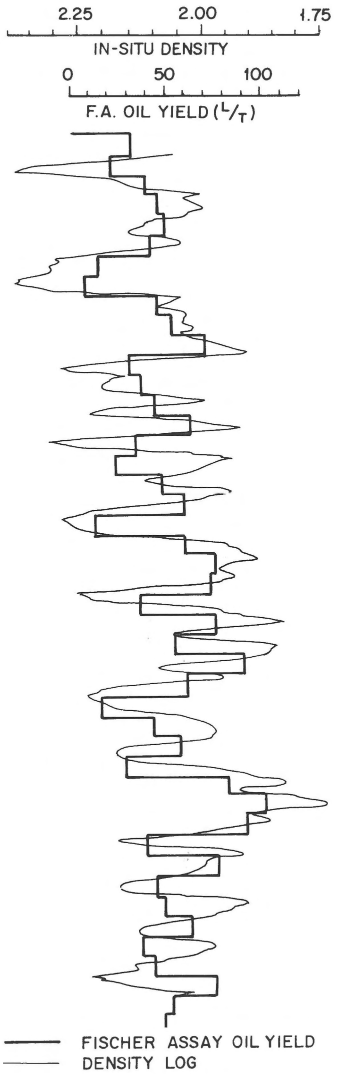


Fig. 11. Relation between density log and FA oil yield for BH 35.

Table 2 shows that oil yields can be improved by selective mining techniques of the better quality subzones of R at the expense of increased stripping ratios and a poorer resource utilisation in terms of total recoverable oil.

Table 2. Oil yield and thickness of Zone R and its subzones in the northern part of the west flank (area with partly eroded oil shales excluded).

	Average oil yield (1/t)	Thickness (m)
Zone R	57–62	33–42
Subzone R_{1+2+3}	66–72	17–23
Subzone R_{1+3}	74–82	13–17

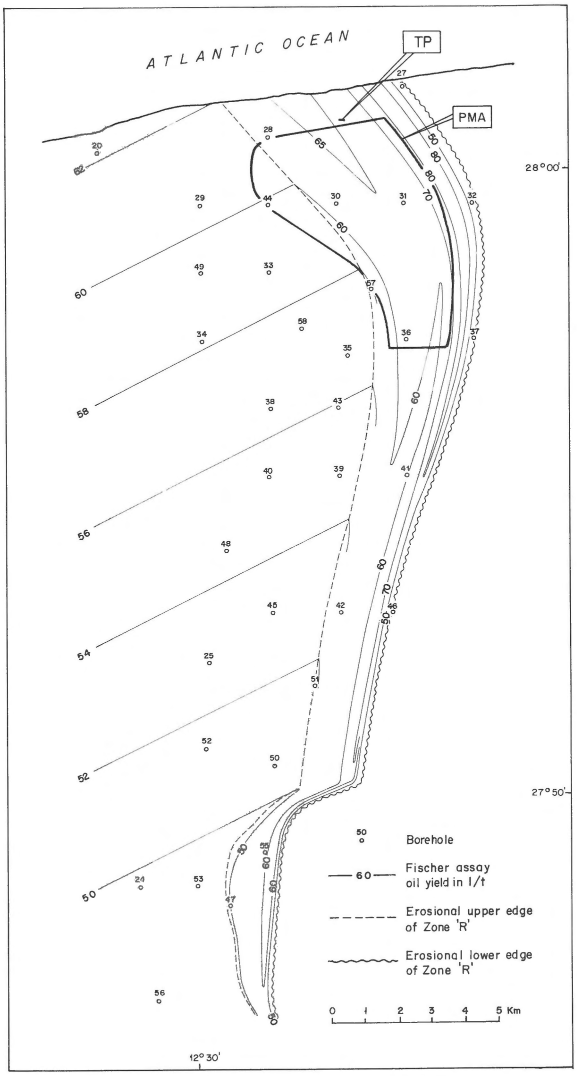


Fig. 12. Oil yield of zone R in the west flank area.

Geological reserves

Reserves have been calculated for those areas where the base of Zone R is shallower than 125 m below the surface.

Table 3 shows that the total volume of oil which is contained in Zone R is some 5 billion barrels. For every 100 m increase in the cut-off depth, these reserves of Zone R increase by approximately 5 billion barrels. Thus, total reserves down to a depth of 225 m will be in the order of 10 billion barrels. The west flank is more attractive than the east flank, because the reserves are larger, the mean

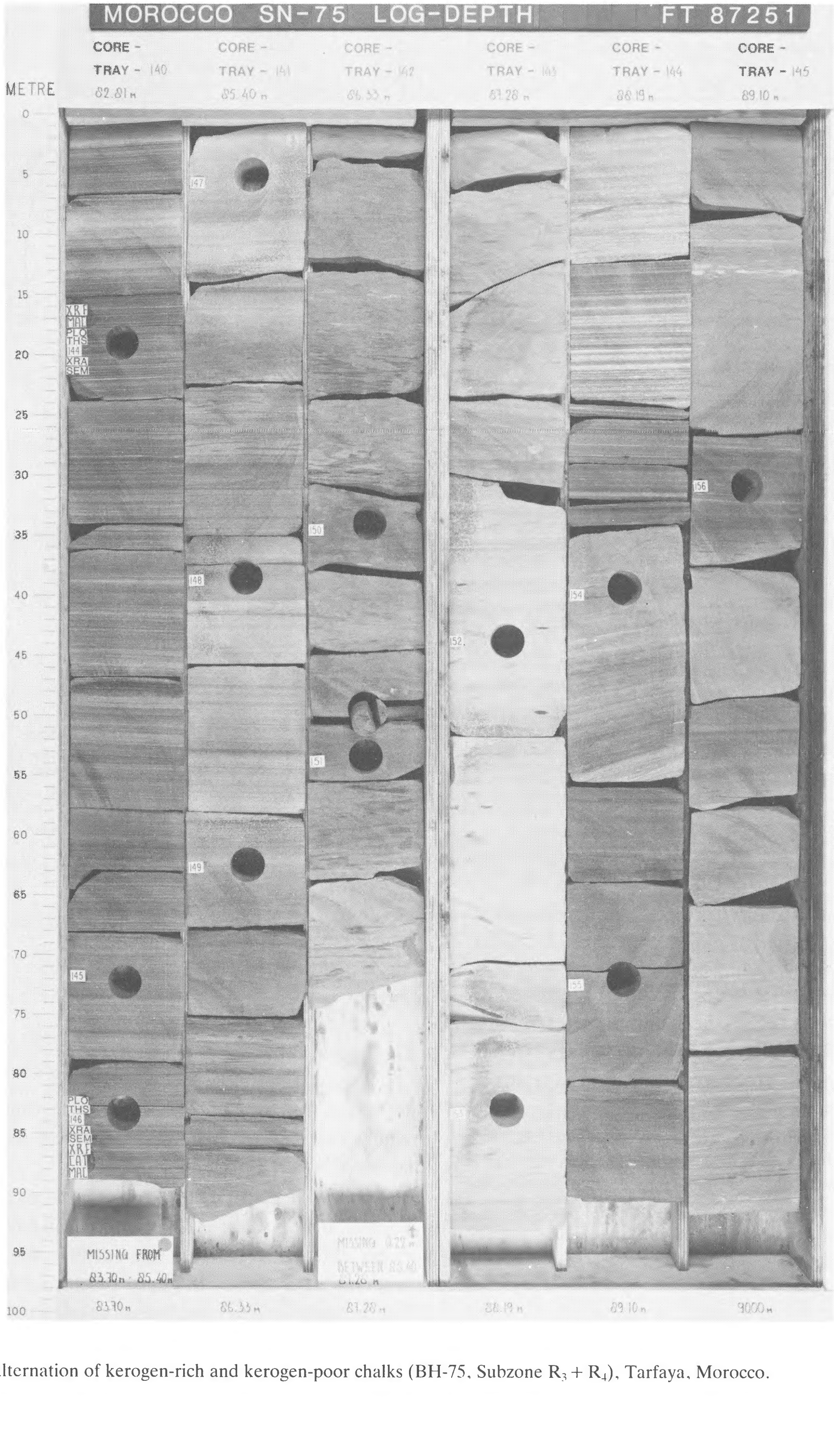


Fig. 13. Alternation of kerogen-rich and kerogen-poor chalks (BH-75, Subzone $R_3 + R_4$), Tarfaya, Morocco.

Table 3. Reserves of Zone R (area with partly eroded oil shales included).

	West flank	East flank	Total
Area (km^2)	206	140	346
Mean thickness oil shale (m)	28	25	27
Mean overburden ratio (m^3/m^3)	1.58	1.75	1.64
Mean oil yield (1/t)	56	53	55
Tonnes of oil shale (10^{6}t)	8900	5500	14400
Oil reserves (10^6 bbls)	3200	1800	5000

grade of the shales is better, and the oil shale thickness and overburden ratio is more favourable.

Petrographic description

Figure 13 shows that the oil shale sequence is composed of an alternation of dark (kerogen-rich) layers and light-coloured (kerogen-poor) layers, which vary in thickness from 5 to 250 cm. The light layers are sometimes developed as limestone nodules. The kerogen-rich layers often show macroscopically a fine lamination of alternating darker and lighter laminae. Up to about 20 laminae were counted per 1 cm interval. Some of the lighter laminae are almost entirely composed of foraminifera (Fig. 14). Internally the laminae show a micro-flaser structure, as revealed by microscopic investigation (Fig. 15) (see also Einsele & Wiedmann 1982). These structures are formed by an alignment of flattened pellets and wavy kerogen flakes parallel to the stratification. In the light-coloured layers the micro-flaser structure is either weakly developed or absent.

Microscopic investigations – using magnifications of 30–250 × – show that the oil shales are composed of four main components:
- carbonate faecal pellets;
- tests of foraminifera;
- kerogen;
- matrix, mainly composed of carbonate.

These components can be better distinguished in the kerogen-rich layers than in the kerogen-poor layers, because the carbonate components of the latter merge into each other as a result of recrystallisation. The following components can occasionally be seen in thin section (see also Einsele & Wiedmann 1982):
- calcispheres;
- shell fragments of lamellibranchs, sometimes concentrated in thin layers;
- fish remains;
- sparry carbonate cement, particularly present in kerogen-poor layers;
- quartz and pyrite.

The samples have also been investigated by scan-

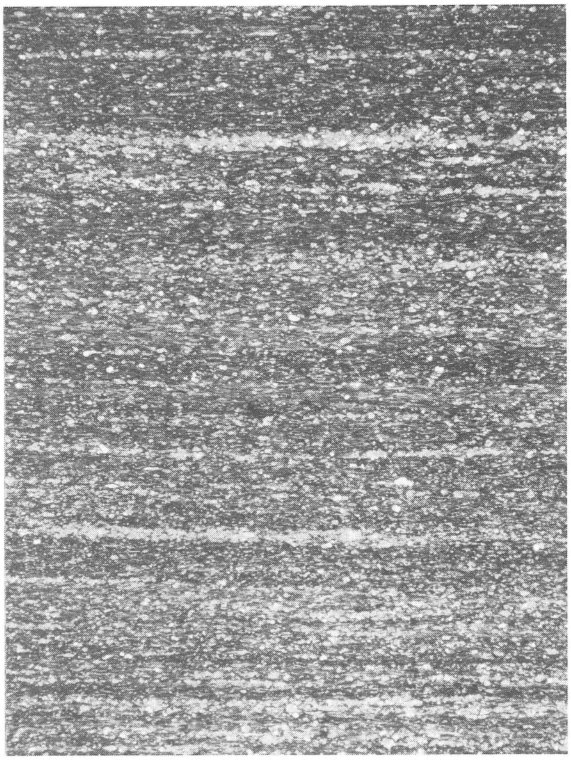


Fig. 14. Thin section of a kerogen-rich chalk from the 'Niveau Riche' of Subzone R_3, showing thin laminae of foraminiferal packstones (white), as well as laminae with different kerogen contents. Thickness of the laminae varies from about 0.2 to 1.5 mm. ∅ = 43.4% Grain density = 2.17 – Magnification 7×, BH75 Depth 83.64 m.

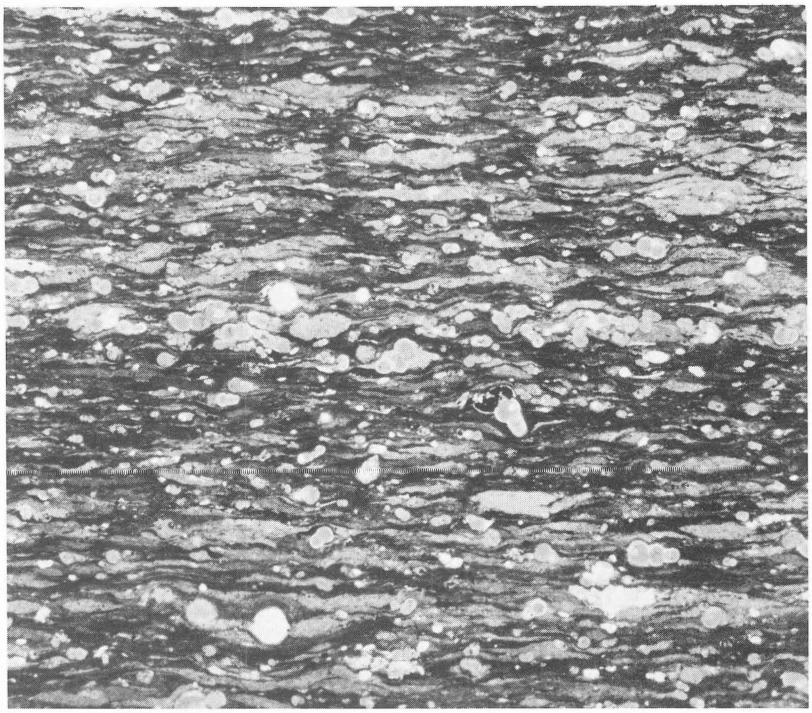


Fig. 15. Photograph of a kerogen-rich lamina showing a wavy lenticular structure, composed of dark brown kerogen, lenses of flattened faecal pellets and foraminifera. Most of the chambers of the latter are still open (gray), but some are filled with calcite (white) or pyrite (black, in centre of photograph) – Magnification 50×, same sample as Plate 2.

ning electron microscopy using magnifications of 3000–10000×. This shows that the faecal pellets and a major part of the matrix are composed of coccoliths. The matrix is further composed of micrite (i.e. clay-sized carbonate grains). Thus, the Tarfaya oil shales are basically chalks with varying kerogen contents.

The faecal pellets have probably been produced by marine copepods, feeding on phytoplankton (a.o. coccolithophorids). The pellets in the kerogen-rich layers are more flattened than in the kerogen-poor layers. This might be explained by early lithification, which appears to be more pronounced in the kerogen-poor layers, with as a consequence less compaction.

Tests of planktonic foraminifera constitute generally 5–20% of the rocks. Most of them are Hedbergella and Heterohelix. In the kerogen-rich intervals, the majority of the test-chambers are totally open, whereas in the kerogen-poor intervals they are mostly filled with sparry calcite or are completely recrystallised. Apparently, the abundance of kerogen in the kerogen-rich layers has hampered precipitation and recrystallisation of carbonate.

Porosity and moisture

Figure 16 shows that the porosity decreases with decreasing kerogen content from 40% to 20%. The lower porosity of the kerogen-poor chalks is due to filling of the chambers of the foraminifera with calcite, as well as precipitation and recrystallisation of calcite within the faecal pellets and matrix. As expected for chalks, the permeabilities are very low, viz. 0.14–0.65 mD.

Practically all the fresh, unweathered oil shales are situated below the water table and their pores are found completely filled with water. Hence the rock intervals with higher kerogen contents have higher moisture and, of course, higher oil yields.

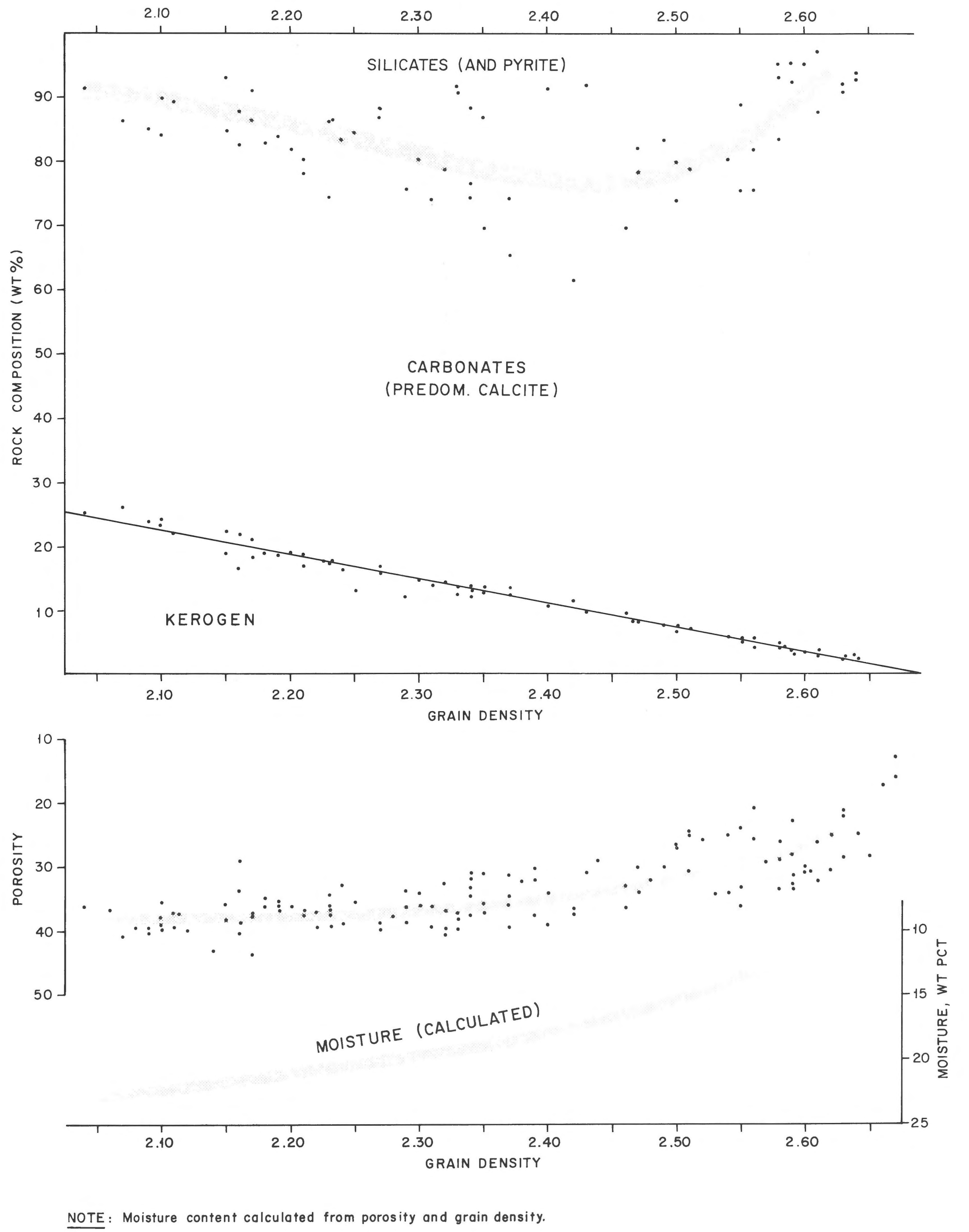


Fig. 16. Relation between rock composition (dry basis), grain density and porosity of Zone R.

The average water content of Zone R is about 20% wt, whereas the overlying lean oil shales of Zone Q have an average moisture of some 12% wt.

Characterisation of kerogen

Microscopic investigation of oil shale samples shows that the maceral composition of the kerogen is very uniform. The main variation observed between the samples is in the quantity of organic matter, whereas the type of organic matter remains constant. The main maceral is organic matter, which is probably of algal origin but partly to entirely transformed by bacteria into a structureless mass (SOM). Accessory macerals in the oil shales all belong to the liptinite group: liptodetrinite, alginite and rare to few sporinite. Acritarchs (algal cysts) have also been found.

120 samples of Tarfaya oils shales have been analysed by Pyrolysis Flame Ionisation Detection, which is comparable to the Rock Eval method. For all samples $S_1 = 0$, indicating that there are no free hydrocarbons in the oil shales. The average hydrogen index is 700 mg HC/g org. C and the average Tmax is 450° C. Therefore the kerogen is of type II, which is in agreement with the microscopical observations (SOM).

The maximum depth of burial of Zone R has probably never been more than 500–600 m and hence the kerogen of the Tarfaya deposit may be expected to be immature. Further evidence for this assumption is found in the presence of chlorophyllinite in the oil shales. This is a red fluorescent maceral derived from the chlorophyll of plants (presumably algae in the case of the Tarfaya shales). This maceral has only been found in low rank coal deposits (Tertiary brown coals) and in the immature oil shales of the Nördlinger Ries (Germany) (pers. comm. Dr C.C.M. Gutjahr). Apparently, chlorophyllinite cannot sustain a higher maturity.

Another argument for the immature nature of the Tarfaya oil shale is that exposure of the kerogen to ultraviolet light increases its fluorescence. This light is able to alter the kerogen photochemically, which points to its unstable immature nature (Teichmüller & Ottenjann 1977).

Chemical and mineralogical composition

The oil shales (chalks) are mainly composed of calcite, kerogen and quartz and further contain small amounts of clay minerals (illite, montmorillonite and kaolinite), pyrite, feldspar, dolomite and apatite. Table 4 shows that the main elements determined in the oil shales are Ca, C, Si, A1, Fe, Mg, S and H. The difference between the sum of these elements and 100% should be mainly assigned to oxygen and possibly further to potassium and sodium. The concentrations of U ($<$ 100 ppm), V ($<$ 1000 ppm) and Ni ($<$ 250 ppm) are too low for commercial production. Einsele & Wiedmann (1982) give the following mean values for other trace elements in the Tarfaya oil shales (calculated for dry sediment, free of carbonate): Zn (400 ppm), Cr (120 ppm), Cu (20–30 ppm), Pb (20–30 ppm) and Mo (5–70 ppm). This shows that these heavy metals also occur in concentrations too low to be used as by-products.

Hydrology

The hydraulic properties of the Moghrebian Formation and the Late Cretaceous chalks are important factors in consideration of surface mining of the Tarfaya deposit. El Hebil & Meilhac (1977) report that both formations have similar hydraulic properties, that is overall permeabilities ranging from 10^{-6} to 10^{-4} m/s (i.e. 100–10000 mD). Cores of the Moghrebian Formation show indeed that the rocks can be highly porous and permeable, but the permeability measured on core plugs of the kerogenous chalks is very low (less than 1 mD). The reason for the difference between core plug permeability and the overall permeability might be due to fracturing of the oil shale formation.

In areas where the Moghrebian is present and the pre-Moghrebian unconformity is above sea level, the water table is usually found close to this unconformity. In areas where the Moghrebian is absent, the water table seems to follow the contact between weathered and fresh oil shales. In sebkhas the water table is often found close to the sebkha floor.

Table 4. Elemental composition in % wt for dry samples of dark kerogen-rich layers (10 samples) and light-coloured kerogen-poor layers (7 samples).

	Kerogen-rich layers		Kerogen-poor layers	
	Variation	Average	Average	Variation
Ca	22.7–27.3	24.7	31.4	30.8–34.2
Mg	0.08–0.40	0.18	0.31	0.06–0.54
Al	0.43–1.64	0.86	0.41	0.51–0.92
Si	2.2–7.2	4.4	2.3	1.1–4.2
Fe	0.29–0.86	0.54	0.19	0.08–0.31
Ni	0.010–0.023	0.015	0.002	0.0015–0.004
S	2.5–4.3	3.0	0.4	0.2–0.7
P	0.047–0.100	0.084	0.023	0.017–0.034
Cl	0.023–0.28	0.093	0.066	0.017–0.16
C	18.8–29.1	23.2	12.6	11.9–13.9
H	1.67–2.63	1.99	0.34	0.16–0.45

For all samples: U < 0.010; V < 0.1; As < 0.005; Cd < 0.005; Sb < 0.025; Hg < 0.015; Se < 0.005;

Analyses of ground water samples show that they have similar relative proportions of the various ions as sea-water, but the concentrations are extremely variable. In other words, most of the water samples are either diluted or concentrated sea-water. Concentration can be explained by evaporation, but dilution implies one or more sources of fresh water, either rain or subsurface water with a relatively low salinity (possibly artesian water).

The average yearly precipitation in the Tarfaya area is 41 mm. El Hebil & Meilhac (1977) estimate that about 8% of this rain water – 3300 m^3/year/km^2 –would feed the unconfined Moghrebian-Cretaceous common aquifer. The fact that the chemical composition of the ground water is related to that of sea-water might imply that inflow of sea-water into the formation has taken place either recently or in the past (Moghrebian transgression). The deeper benches of future surface mines will be below sea level and hence the possibility exists that sea-water will flow along fissures into the mine. Recently a trial pit was excavated between boreholes 27 and 28 at a distance of 1 km from the coast (TP in Fig. 12). No major inflow of water into the pit was observed below sea level.

Summing-up

The Tarfaya oil shale deposit is favourably situated close to the Atlantic coast at shallow depth and contains large reserves of moderate grade oil shales, which are ideally suited to open-pit mining. The northern part of the west flank of the Tazra anticline appears to be the most attractive area for exploitation. Overburden ratios here are relatively low and the oil shales slightly thicker and of better average oil yield than elsewhere. Shale oil reserves in this area are more than sufficient for a 50 000 bbl/day project operating over 30 years. Drawbacks of the Tarfaya oil shales from the oil recovery view point are high moisture contents (average 20% wt) and high carbonate contents (average 70% wt, dry basis). On the positive side, these shales, being kerogenous chalks, are relatively friable and require low amounts of energy for crushing and grinding. A further advantage is the certainty of an unlimited water supply – in the form of sea-water – which is required for cooling in the process plant and for slurrying of processed shale.

Acknowledgement

I am indebted to Mr. A.A. Bal for his help with the construction of some of the figures and for the stimulating discussions on the subject, and to Shell Internationale Petroleum Maatschappij BV, The Hague for permission to publish this paper. I like to thank Dr Nejmy El Mokhtar of ONAREP for his co-operation during the field operations.

References

Arthur, M.A. & Schlanger, S.O. 1979 Cretaceous 'Oceanic Anoxic Events' as causal factors in development of reef-reservoired giant oil fields – AAPG Bulletin, 63 (6): 870–885

Busson, G. 1984 Relations entre la sédimentation du Crétacé moyen et supérieur de la plate-forme du nord-ouest africain et les dépôts contemporains de l'Atlantique centre et nord – Eclogae geol. Helv., 77 (2): 221–235

Choubert, G., Faure Muret, A & Hottinger, L. 1966 Aperçu géologique du bassin côtier de Tarfaya – Notes Mém. Serv. Géol. Maroc, 175 (1): 9–219

Einsele, G. & Wiedmann, J., 1982 Turonian black shales in the Moroccan coastal basins: First upwelling in the Atlantic Ocean? In: U. von Rad et al. (ed.), Geology of the northwest African continental margin – Springer Verlag: 396–414

El Hebil, A. & Meilhac, A. 1977 Ressources en eau du Maroc – Domaine atlasique et sud-atlasique – Province de Tarfaya au sud de l'Oued Dra – Notes Mém. Serv. Géol. Maroc, 231: 335–351

Jenkyns, H.C. 1980 Cretaceous anoxic events: from continents to oceans – J. Geol. Soc. London, 137: 171–188

Ranke, U., Von Rad, U. & Wissmann, G. 1982 Stratigraphy, facies and tectonic development of the on- and offshore Aaiun-Tarfaya basin – A review. In: U. von Rad et al. (ed.), Geology of the northwest African continental margin – Springer Verlag: 86–105

Teichmüller, M. & Ottenjann, K. 1977 Liptinite und lipoide Stoffe in einem Erdölmuttergestein – Erdöl U. Kohle, 30: 387–398

Thierstein, H.R. & Berger, W.H. 1978 Injection events in ocean history – Nature: 276, 461–465

Viotti, C. 1966 Résultats stratigraphiques du sondage Puerto Cansado-1 du Bassin côtier de Tarfaya – Notes Mém. Serv. Géol. Maroc, 175 (1): 225–249

Wiedmann, J., Butt, A. & Einsele, G. 1982 Cretaceous stratigraphy, environment and subsidence history at the Moroccan continental margin. In: U. von Rad et al. (ed.), Geology of the northwest African continental margin – Springer Verlag: 366–395