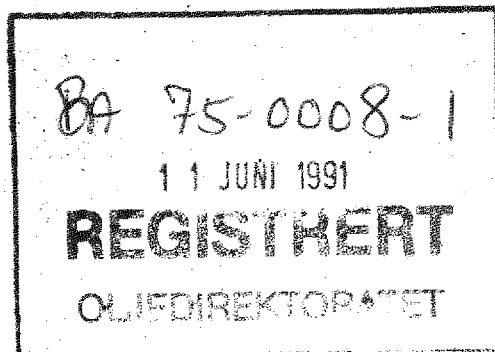


ROBERTSON RESEARCH INTERNATIONAL LIMITEDREPORT NO. 2940A STUDY OF THE MATURATION AND SOURCE ROCK POTENTIAL  
OF THE MOBIL NORWAY 33/12-4 WELL,  
NORWEGIAN NORTH SEA

by

B. S. COOPERC. DARLINGTONW. B. SIMPSONR. J. MORLEYJ. S. BUTTERWORTHProject No. RRI/756/IID/2107September, 1975Prepared for :Mobil Exploration Norway, Inc.,  
P. O. Box 510,  
Børehangeni,  
Stravanger,  
Norway.

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INTRODUCTION

A study of light hydrocarbon content, vitrinite reflectivity, spore colouration, maximum palaeotemperature and source rock potential has been carried out on samples from the section 5,480 to 9,500 feet of the Mobil Norway 33/12-4 Well.

Initially the organic richness of the samples was measured at intervals of fifty feet and, after reviewing these results and selecting samples by quality, source rock evaluation was carried out, usually at one hundred foot intervals.

Light hydrocarbon analysis, vitrinite reflectivity and spore colouration analysis have been carried out on selected samples throughout the well section and at intervals of up to two hundred and thirty feet. Maximum palaeotemperature analysis was carried out to coincide with the source rock sampling. Within the interval 8,090 to 8,600 feet many samples had been considerably contaminated by plastic, rubber and walnut shell additives and the samples were either poor or too small for geochemical analysis.

Apart from this interval, the samples, all obtained as wet ditch cuttings, were considered to be of fair to good quality for geochemical analysis after washing in cold water to remove drilling mud.

The age of the section ranges from Palaeocene to Upper Triassic.

## II

### RESULTS AND INTERPRETATION

#### A. MATURITY EVALUATION

Four methods have been used to give an integrated evaluation of the maturation state within this well. They are gaseous and gasoline hydrocarbon analysis, vitrinite reflectivity determination, spore colouration and maximum palaeotemperature analysis.

##### 1. Gaseous and Gasoline Hydrocarbon Analysis (Table 1 and Figures 1 & 2)

Hydrocarbons of the gaseous ( $C_1$  to  $C_4$ ) and gasoline range ( $C_5$  to  $C_7$ ) have been analysed to determine their quantities and relative proportions. Twenty-six samples have been analysed through the well section.

##### a) Gaseous Hydrocarbons

Only very small quantities of hydrocarbons in the range  $C_1$  to  $C_4$  (methane to n-butane) were found in the samples; in all samples less than 1 part per million was measured. It is probable that a loss of hydrocarbons has occurred, but it is believed that those remaining could still exhibit their original relative proportions and can be considered for the evaluation.

The results are presented in Table 1 and Figure 1. Over the interval 5,880 to 6,440 feet none of the gaseous hydrocarbons were recorded, while over the larger interval 5,480 to 7,340 feet only methane was recorded, in quantities not exceeding 26 ppb. From 7,440 feet the hydrocarbons from the  $C_2$  to  $C_4$  range were found, though with increasing depth down to 9,340 feet the total  $C_1$  to  $C_4$  gas content never exceeded 685 ppb. Within this interval from 7,760 to 8,540 feet only trace amounts of gases other than methane were noted from the samples. Apart from these samples the remainder of the interval showed methane ranging proportionally from 73% to 1% of the

total gas with the lowest proportions towards the base of the section. Two further samples from 7,540 and 9,340 feet showed only methane.

To conclude, in view of the rising total gas content and the decreasing proportion of methane, the section is thought to be transitionally mature at about 7,400 feet and mature from about 7,600 feet downwards.

#### b) Gasoline Hydrocarbons

Maturity is usually indicated when all the gasolines within the series C<sub>5</sub> to C<sub>7</sub> as listed in Table 1 are present in approximately equal proportions. Immature sediments often contain only a few of the components, making up a total gas content of generally less than 100 ppb.

From Figure 2 it can be seen that the total quantity of gasolines is low from 5,480 to 6,840 feet, not exceeding 394 ppb, while many of the component gasolines were not found. From 7,040 feet to 7,340 feet, the gasolines content increases from 710 ppb to 2,435 ppb and the number of component hydrocarbons increases. From 7,440 to 9,340 feet the relative proportions of the hydrocarbons is within the acceptable range for a mature sediment. Some of the component gasolines do appear to be absent through parts of this section, particularly 2-methyl hexane, 3-ethyl pentane and dimethyl pentane. This appears to be a particular feature and shows a similarity to the section 8,300 to 9,800 feet of the 33/9-3 well in that corresponding C<sub>5</sub> to C<sub>7</sub> hydrocarbons were absent in that well also.

In conclusion it is indicated by both these analyses that the section is immature to a depth of about 7,100 feet, transitionally mature from 7,100 to 7,600 feet and mature below 7,600 feet.

#### 2. Vitrinite Reflectivity (Tables 2 & 3 and Figure 3)

From Table 2 and Figure 2 it can be seen that the great range in vitrinite reflectivity values for each sample presents a complicated picture. Reworked material is common in all the samples analysed and

populations with reflectivities of around 0.76% and from 0.86% to 0.96% are particularly evident. Down the interval from 6,180 to around 8,800 feet, in the Tertiary-Cretaceous portion of the analysed section, a trend in vitrinite reflectivities is seen with values of 0.36% at the top and 0.52% at the base. This would indicate that the humic organic material becomes mature a little above the unconformity at which vitrinite reflectivity values of about 0.5% are reached. Below 8,900 feet the results are complicated by the large quantity of reworked material and low reflecting organic material. The latter material, with reflectivities of from 0.27% to around 0.49%, is thought to be composed of resins and spores which dominate the exinitic material below 8,900 feet. Reflectivity values of from 0.55% to 0.66% have been measured on vitrinite particles below 8,900 feet and are considered to be indigenous. From these results a distinct curve in the reflectivity gradient is interpreted, and indicates an increased rate of change of maturation with depth through the Jurassic and Triassic analysed sections of the well. From 8,900 feet depth, the section is considered quite mature for the sourcing of gaseous hydrocarbons from source rocks containing sufficient humic matter.

#### Examination in Ultraviolet light (Table 2)

On examination in ultraviolet light many samples showed variable fluorescence between one sample and another, spores being common in almost every sample analysed. These spores fluoresced yellow and orange in most samples, though yellow fluorescence seemed dominant above 8,000 feet. Spores and resins found below 8,900 feet fluoresced brown and seem indicative of a more increased state of maturity beneath the Cretaceous/Jurassic unconformity than above it. Only low to moderate contents of exinite were observed in most samples, though high contents of exinite were observed in samples from 7,290, 7,590, 7,690 and 9,140 feet.

### 3. Spore Colouration Analysis (Table 3 and Figure 4)

One effect of the maturation of sporopollenin is the increase in the visible colour pigmentation of sporopollenin from pale yellow through orange and brown to black. A ten point scale of colour indices has been used in this study which has spanned the section from 5,480 to 9,400 feet.

With increasing depth from 5,480 feet, spore colour indices show an almost uniform increase from about 4.5 to 6.5 at the base of the analysed section. There appears to be no fluctuation between the spore colours on either side of the Cretaceous/Jurassic unconformity. These results indicate that oil-prone types of organic matter will be mature below about 6,500 feet where spore colour indices of 5 are attained.

### 4. Maximum Palaeotemperature Analysis (Table 3 and Figure 5)

Results of the maximum palaeotemperature analysis show a large variation in palaeotemperatures, no particular trend being indicated with increasing depth. This is probably due to the large contributions of reworked kerogen in the total kerogen available in the analysis. A tentative palaeothermal gradient of low value has been interpreted, but is not considered to be an absolutely true plot of the palaeogeothermal gradient. The majority of the samples gave palaeotemperatures lying between 225°F and 265°F, and indicating that the section, at least below 7,000 feet, has reached the optimum temperature for the generation of medium and/or light oil.

### 5. Comparison of Maturation Indices (Table 3 and Figure 6)

From Figure 6 it can be seen that the plots of the vitrinite reflectivity, spore colouration and maximum palaeotemperature approach coincidence towards 10,500 feet. However, spore colouration analysis is in fairly good agreement with the proposed maximum palaeotemperature gradient through the analysed section. The maturity of humic, gas-prone material

is characterised by vitrinite reflectivity measurement and the maturation of oil-prone sapropelic material is characterised by the other two maturity indices. The reflectivity results alone seem to show the effects of the Cretaceous/Jurassic unconformity; it is suggested that the time interval represented by the unconformity was sufficient to affect the development of the vitrinite reflectivity, but the effect has been masked by a stronger heating event in more recent times shown by the more uniform maturation gradient exhibited by spore colours and the kerogen materials analysed for their maximum palaeotemperature. However, the vitrinite reflectivity data does suggest that gas-prone organic matter will be mature from about 8,600 feet.

Spore colouration, maximum palaeotemperature and gaseous and gasoline range hydrocarbons are in agreement that the section is immature for oil-prone types of material above 7,000 feet. The analysis of these light hydrocarbons has indicated a probable zone of transitional maturity to 7,600 feet from which depth the section becomes mature for oil to be sourced by appropriately kerogen rich sediments.

B. SOURCE ROCK EVALUATION (Table 4 and Figures 7, 8 and 9)

On the basis of organic carbon content, the section as a whole has been divided into four particular intervals for source rock evaluation.

a) Interval 5,480 to 6,950 feet (Samples 1 to 30)

This interval is represented by light olive-grey and light grey shales of Tertiary age. The organic carbon content of these shales is below average and ranges from 0.31% to 0.49%. The extractability of the organic matter in solvents ranges from 2.0% to 8.9%, except for samples 20, 22 and 26 from which higher extractabilities of 15.3% to 21.0% were recorded. Hydrocarbon contents are generally very low throughout the interval, the majority of samples having hydrocarbon abundances of less than 50 ppm. Sample 20, 6,440-50 feet, alone gave an average hydrocarbon content with



170 ppm hydrocarbons.

Due to the low proportion of hydrocarbons in the extracts of these samples, gas is the most likely hydrocarbon product. However, as the organic carbon contents are low, (less than 1.5%), these samples indicate that the sediments are insufficiently rich to source hydrocarbons.

b) Interval 6,990 to 8,600 feet (Samples 31 to 62)

At the top of this interval organic carbon contents rise sharply across the Tertiary-Upper Cretaceous boundary, contents increasing from 0.60% at 6,990-7,000 feet to 1.15% at 7,240-50 feet. Below this latter depth organic carbon contents are fairly uniform down to 8,550 feet, ranging from 0.77% to 1.70%, good average contents. An above average carbon content of 2.70% was recorded from sample 38, 7,340-50 feet.

Within the portion 7,840 to 8,600 feet of this interval, most of the samples contained contaminants and as a result only small quantities of material were isolated for analysis. Furthermore, very large extracts were recorded on some samples probably arising from residual particles of rubber and plastic which could not be separated physically. Uncontaminated samples gave extractabilities of 3.8% to 6.7% in the small interval 7,040 to 7,650 feet. A high value of 45.0% was recorded for sample 46, 7,760-70 feet, though in view of the very large organic extract of 5,130 ppm, contamination cannot be ruled out. The only reliable result from within the badly contaminated interval was an extractability of 9.2% from sample 61, 8,540-50 feet.

Over the small interval 7,040 to 7,770 feet, hydrocarbon contents are generally below average (less than 100 ppm), though average contents were recorded for sample 38, (7,340-50 feet) with 150 ppm hydrocarbons, and sample 46, (7,760-7,770 feet) with 240 ppm, though this latter sample could be contaminated. From 7,840 to 8,500 feet samples gave hydrocarbon contents ranging from 100 ppm to 570 ppm, average to above average contents,

but possibly affected to some extent by contamination. A result of a 240 ppm hydrocarbon in sample 61, 8,540-50 feet, is considered reliable and indicates a good average hydrocarbon abundance.

On considering likely hydrocarbon products from this interval, at least down to 7,770 feet, gas-prone types of organic matter seem dominant. Samples 38 to 40, 7,340 to 7,450 feet are sufficiently rich to source gas, but do not appear to be at an optimum state of maturation for the generation of this product. The samples analysed between 7,890 and 8,300 feet have provided insufficient results for their hydrocarbon product and richness to be reliably predicted, though if the hydrocarbon contents are representative of the in situ organic material then they indicate a tendency for oil rather than gas-dominant products. Indeed, the richness of samples 49, 50 and 51, and 55 and 56 would indicate fair to good potential oil sources. Sample 61, 8,540-50 feet, from which good results were obtained, indicates sediments with a fair potential for sourcing oil.

c) Interval 8,640 to 9,050 feet (Samples 63 to 70)

Within this interval dark grey shales of Lower Cretaceous and Jurassic age were encountered. Organic carbon contents increase sharply, the eight samples having generally above average contents which range from 1.94% to 3.28%. An individual, hand-picked dark grey shale from 8,790-8,800 feet, (sample 66), gave an organic carbon content of 7.4%.

The extractability of these samples is rather variable; values of from 1.9% to 23.0% being obtained. Hydrocarbon abundances are also erratic with a low 45 ppm content in sample 64 and above average contents of 350 ppm in sample 67, and 410 ppm in the composited samples 68 and 69. A very high value of 3,270 ppm hydrocarbons was measured on sample 70, 9,040-50 feet.

On considering likely hydrocarbon products and the richness of these

mature source beds, the following points are noted: a) samples 64, (8,690-8,700 feet), 66, (8,790-8,800 feet) and 67, (8,840-50 feet), indicate sediments with sufficient organic richness, and probable vertical extent, to provide good sources of gas, possibly with a little associated oil; b) the composite sample 68-69, (8,940-9,000 feet) is indicative of source rocks with a fair potential for sourcing gas and associated oil; c) sample 70, (9,040-50 feet), in view of its high hydrocarbon content, indicates a source rock with a very good potential for oil, although the very high proportion of hydrocarbons in the extract does not rule out staining by non-indigenous hydrocarbons.

d) Interval 9,090 to 9,500 feet (Samples 71 to 79)

The shales, mudstones and sands encountered in this interval characterise the boundary of the Lower Jurassic and the Triassic. Organic carbon contents are highly variable, ranging from 0.21% to 1.80% in these samples. The extractability of the samples varies from 7.0% to 14.7%, while the hydrocarbon contents are low and not exceeding 105 ppm in any of the samples fully analysed.

Gaseous products are most likely from this interval, though only sample 78, (9,440-50 feet), marking the occurrence of coal, has sufficient organic richness to provide a gas source.

### III

#### CONCLUSIONS

As a result of the maturation study and source rock evaluation of the Mobil 33/12-4 Well, the following conclusions have been reached:

i) The interval 5,480 to 6,950 feet is immature and contains sediments with only low contents of organic carbon and hydrocarbons. For these reasons the interval appears devoid of any prospective source rocks.

ii) Oil-prone types of organic material reach maturity within the interval 6,990 to 8,600 feet. Considerable contamination of the samples has occurred in the lower portion of the interval and the true potential of the source rocks cannot be recognised, though some potential for oil-like products seems to exist. The upper portion of the section seems dominated by gas-prone organic material and some gas may have been generated.

(iii) The interval 8,640 to 9,050 feet appears to be mature for oil-prone and gas-prone types of organic material. Organic carbon contents are generally high and between 8,690 and 9,000 feet the sediments are prospective for gas with some associated oil. A sample from 9,040-50 feet has shown a very high content of hydrocarbons, but it is uncertain whether they are indigenous.

iv) The interval 9,090 to 9,500 feet is generally mature, but appears to contain little hydrocarbon source material apart from traces of coal which may source some gas.

TABLE 1

## GASEOUS AND GASOLINE RANGE HYDROCARBONS

CLIENT MOBIL

WELL 33/12-4

LOCATION NORTH SEA

GAS (C<sub>1</sub> - C<sub>4</sub>)

SAMPLE NO.	1		5		9		13	
	5480		5690		5880		6080	
DEPTH FEET	P. P. B.	%C <sub>1</sub> -C <sub>4</sub>	P. P. B.	%C <sub>1</sub> -C <sub>4</sub>	P. P. B.	%C <sub>1</sub> -C <sub>4</sub>	P. P. B.	%C <sub>1</sub> -C <sub>4</sub>
C <sub>1</sub>	13	100	8	100	*	*	*	*
C <sub>2</sub>	*	*	*	*	*	*	*	*
C <sub>3</sub>	*	*	*	*	*	*	*	*
iC <sub>4</sub>	*	*	*	*	*	*	*	*
nC <sub>4</sub>	*	*	*	*	*	*	*	*
TOTAL	13	100	8	100	*	*	*	*

GASOLINE RANGE (C<sub>5</sub> - C<sub>7</sub>)

SAMPLE NO.	1		5		9		13	
	5480		5690		5880		6080	
DEPTH FEET	P. P. B.	%C <sub>5</sub> -C <sub>7</sub>	P. P. B.	%C <sub>5</sub> -C <sub>7</sub>	P. P. B.	%C <sub>5</sub> -C <sub>7</sub>	P. P. B.	%C <sub>5</sub> -C <sub>7</sub>
ISO-PENTANE	3	4	5	6	tr	*	3	3
N-PENTANE	*	*	20	23	20	15	15	12
CYCLOPENTANE	*	*	*	*	45	33	50	39
2-ME. PENTANE	*	*	3	3	tr	*	tr	*
3-ME. PENTANE	*	*	3	3	tr	*	tr	*
N-HEXANE	85	96	35	40	50	37	45	35
ME. CYCLOPENTANE	*	*	7	8	4	3	8	6
CYCLOHEXANE	*	*	*	*	*	*	*	*
2-ME. HEXANE	*	*	*	*	*	*	*	*
3-ME. HEXANE	*	*	*	*	tr	*	*	*
3-ETHYLPENTANE	*	*	*	*	*	*	*	*
N-HEPTANE	*	*	15	17	tr	*	*	*
BENZENE	*	*	*	*	1	1	tr	*
DIME. PENTANE	*	*	*	*	*	*	*	*
ME. CYCLOHEXANE	*	*	*	*	15	11	8	6
TOTAL	88	100	88	(100)	135	(100)	129	(100)

TABLE 1 (Cont'd)

## GASEOUS AND GASOLINE RANGE HYDROCARBONS

CLIENT MOBIL

WELL 33/12-4

LOCATION NORTH SEA

GAS (C<sub>1</sub>-C<sub>4</sub>)

SAMPLE NO.	16		20		24		28	
	6220		6440		6640		6840	
DEPTH FEET	P.P.B.	%C <sub>1</sub> -C <sub>4</sub>	P.P.B.	%C <sub>1</sub> -C <sub>4</sub>	P.P.B.	%C <sub>1</sub> -C <sub>4</sub>	P.P.B.	%C <sub>1</sub> -C <sub>4</sub>
C <sub>1</sub>	*	*	*	*	37	100	19	100
C <sub>2</sub>	*	*	*	*	tr	*	*	*
C <sub>3</sub>	*	*	*	*	*	*	tr	*
iC <sub>4</sub>	*	*	*	*	*	*	*	*
nC <sub>4</sub>	*	*	*	*	*	*	*	*
TOTAL	*	*	*	*	37	100	19	100

GASOLINE RANGE (C<sub>5</sub>-C<sub>7</sub>)

SAMPLE NO.	16		20		24		28	
	6220		6440		6640		6840	
DEPTH FEET	P.P.B.	%C <sub>5</sub> -C <sub>7</sub>	P.P.B.	%C <sub>5</sub> -C <sub>7</sub>	P.P.B.	%C <sub>5</sub> -C <sub>7</sub>	P.P.B.	%C <sub>5</sub> -C <sub>7</sub>
ISO-PENTANE	20	5	3	2	tr	*	15	6
N-PENTANE	30	8	25	14	15	21	25	10
CYCLOPENTANE	tr	*	tr	*	*	*	tr	*
2-ME. PENTANE	25	6	8	6	*	*	15	6
3-ME. PENTANE	9	2	3	2	6	8	4	2
N-HEXANE	190	48	110	59	50	71	125	52
ME. CYCLOPENTANE	40	10	8	6	*	*	15	6
CYCLOHEXANE	tr	*	*	*	*	*	*	*
2-ME. HEXANE	*	*	*	*	*	*	*	*
3-ME. HEXANE	tr	*	*	*	*	*	*	*
3-ETHYLPENTANE	*	*	*	*	*	*	*	*
N-HEPTANE	10	3	5	3	*	*	10	4
BENZENE	15	4	8	6	*	*	9	4
DIME. PENTANE	*	*	*	*	*	*	*	*
ME. CYCLOHEXANE	55	14	15	8	*	*	20	8
TOTAL	394	(100)	185	(100)	71	(100)	238	(100)

TABLE 1 (Cont'd)

## GASEOUS AND GASOLINE RANGE HYDROCARBONS

CLIENT MOBIL

WELL 33/12-4

LOCATION NORTH SEA

GAS (C<sub>1</sub> - C<sub>4</sub>)

SAMPLE NO.	32		36		38		40	
	7040		7240		7340		7440	
DEPTH FEET	P. P. B.	%C <sub>1</sub> -C <sub>4</sub>	P. P. B.	%C <sub>1</sub> -C <sub>4</sub>	P. P. B.	%C <sub>1</sub> -C <sub>4</sub>	P. P. B.	%C <sub>1</sub> -C <sub>4</sub>
C <sub>1</sub>	16	100	26	100	*	*	35	73
C <sub>2</sub>	*	*	*	*	*	*	3	6
C <sub>3</sub>	*	*	*	*	*	*	*	*
iC <sub>4</sub>	*	*	*	*	*	*	4	9
nC <sub>4</sub>	*	*	*	*	*	*	6	12
TOTAL	16	100	26	100	*	*	48	100

GASOLINE RANGE (C<sub>5</sub> - C<sub>7</sub>)

SAMPLE NO.	32		36		38		40	
	7040		7240		7340		7440	
DEPTH FEET	P. P. B.	%C <sub>5</sub> -C <sub>7</sub>	P. P. B.	%C <sub>5</sub> -C <sub>7</sub>	P. P. B.	%C <sub>5</sub> -C <sub>7</sub>	P. P. B.	%C <sub>5</sub> -C <sub>7</sub>
ISO-PENTANE	50	7	85	13	85	3	135	10
N-PENTANE	135	19	140	20	145	6	235	17
CYCLOPENTANE	75	11	45	7	50	2	9	1
2-ME. PENTANE	40	6	65	10	55	2	205	15
3-ME. PENTANE	10	1	35	5	30	1	100	7
N-HEXANE	145	20	105	15	375	15	240	17
ME. CYCLOPENTANE	15	2	35	5	285	12	40	3
CYCLOHEXANE	5	1	*	*	430	18	35	3
2-ME. HEXANE	10	1	tr	*	*	*	50	4
3-ME. HEXANE	5	1	tr	*	80	3	75	5
3-ETHYLPENTANE	*	*	tr	*	tr	*	25	2
N-HEPTANE	150	21	55	8	215	9	115	8
BENZENE	15	2	10	1	235	10	25	2
DIME. PENTANE	*	*	*	*	tr	*	*	*
ME. CYCLOHEXANE	55	8	105	15	450	18	85	6
TOTAL	710	(100)	680	(100)	2435	(100)	1374	(100)

TABLE 1 (Cont'd)

## GASEOUS AND GASOLINE RANGE HYDROCARBONS

CLIENT MOBIL

WELL 33/12-4

LOCATION NORTH SEA

GAS (C<sub>1</sub> - C<sub>4</sub>)

SAMPLE NO.	42		44		46		51	
	7540		7640		7760		7990	
DEPTH FEET	P. P. B.	%C <sub>1</sub> - C <sub>4</sub>	P. P. B.	%C <sub>1</sub> - C <sub>4</sub>	P. P. B.	%C <sub>1</sub> - C <sub>4</sub>	P. P. B.	%C <sub>1</sub> - C <sub>4</sub>
C <sub>1</sub>	39	100	27	28	108	100	37	100
C <sub>2</sub>	*	*	tr	*	tr	*	*	*
C <sub>3</sub>	*	*	*	*	*	*	*	*
iC <sub>4</sub>	*	*	5	5	*	*	*	*
nC <sub>4</sub>	*	*	65	67	*	*	*	*
TOTAL	39	100	97	100	108	100	37	100

GASOLINE RANGE (C<sub>5</sub> - C<sub>7</sub>)

SAMPLE NO.	42		44		46		51	
	7540		7640		7760		7990	
DEPTH FEET	P. P. B.	%C <sub>5</sub> - C <sub>7</sub>	P. P. B.	%C <sub>5</sub> - C <sub>7</sub>	P. P. B.	%C <sub>5</sub> - C <sub>7</sub>	P. P. B.	%C <sub>5</sub> - C <sub>7</sub>
ISO-PENTANE	45	7	84	14	tr	*	195	5
N-PENTANE	85	13	134	21	10	4	275	7
CYCLOPENTANE	*	*	tr	*	*	*	15	< 1
2-ME. PENTANE	65	10	65	10	10	4	280	7
3-ME. PENTANE	35	5	33	5	10	4	150	4
N-HEXANE	135	20	106	17	55	23	520	14
ME. CYCLOPENTANE	25	4	37	6	tr	*	180	5
CYCLOHEXANE	30	5	35	6	15	6	35	1
2-ME. HEXANE	tr	*	tr	*	15	6	160	4
3-ME. HEXANE	50	8	26	4	30	13	210	5
3-ETHYLPENTANE	*	*	tr	*	*	*	310	8
N-HEPTANE	85	13	36	6	*	*	770	20
BENZENE	35	5	tr	*	15	6	tr	*
DIME. PENTANE	*	*	tr	*	*	*	tr	*
ME. CYCLOHEXANE	75	11	67	11	80	33	715	19
TOTAL	665	(100)	623	(100)	240	(100)	3815	(100)



TABLE 1 (Cont'd)

## GASEOUS AND GASOLINE RANGE HYDROCARBONS

CLIENT MOBIL

WELL 33/12-4

LOCATION NORTH SEA

GAS (C<sub>1</sub> - C<sub>4</sub>)

SAMPLE NO.	58		61		63		65	
DEPTH FEET	8390		8540		8640		8740	
	P. P. B.	%C <sub>1</sub> - C <sub>4</sub>	P. P. B.	%C <sub>1</sub> - C <sub>4</sub>	P. P. B.	%C <sub>1</sub> - C <sub>4</sub>	P. P. B.	%C <sub>1</sub> - C <sub>4</sub>
C <sub>1</sub>	33	100	10	100	25	100	14	11
C <sub>2</sub>	*	*	*	*	*	*	*	*
C <sub>3</sub>	*	*	*	*	*	*	11	9
iC <sub>4</sub>	*	*	*	*	*	*	13	10
nC <sub>4</sub>	*	*	tr	*	*	*	88	70
TOTAL	33	100	10	100	25	100	126	100

GASOLINE RANGE (C<sub>5</sub> - C<sub>7</sub>)

SAMPLE NO.	58		61		63		65	
DEPTH FEET	8390		8540		8640		8740	
	P. P. B.	%C <sub>5</sub> - C <sub>7</sub>	P. P. B.	%C <sub>5</sub> - C <sub>7</sub>	P. P. B.	%C <sub>5</sub> - C <sub>7</sub>	P. P. B.	%C <sub>5</sub> - C <sub>7</sub>
ISO-PENTANE	15	4	45	10	40	10	255	21
N-PENTANE	33	8	125	28	70	17	280	23
CYCLOPENTANE	6	1	9	2	tr	*	45	4
2-ME. PENTANE	27	6	25	6	35	9	110	9
3-ME. PENTANE	11	3	9	2	20	5	45	4
N-HEXANE	63	15	110	25	70	17	110	9
ME. CYCLOPENTANE	16	4	20	5	35	9	140	11
CYCLOHEXANE	14	3	15	3	35	9	110	9
2-ME. HEXANE	17	4	tr	*	tr	*	tr	*
3-ME. HEXANE	20	5	15	3	15	4	25	2
3-ETHYLPENTANE	tr	*	tr	*	tr	*	tr	*
N-HEPTANE	86	20	45	10	25	6	60	5
BENZENE	59	14	30	7	8	2	40	3
DIME. PENTANE	*	*	*	*	*	*	*	*
ME. CYCLOHEXANE	67	16	35	8	55	14	tr	*
TOTAL	424	100	442	100	408	100	1220	100

TABLE 1 (Cont'd)

## GASEOUS AND GASOLINE RANGE HYDROCARBONS

CLIENT MOBIL

WELL 33/12-4

LOCATION NORTH SEA

GAS (C<sub>1</sub> - C<sub>4</sub>)

SAMPLE NO.	66		68		70		72	
DEPTH FEET	8790		8940		9040		9140	
	P.P.B.	%C <sub>1</sub> -C <sub>4</sub>	P.P.B.	%C <sub>1</sub> -C <sub>4</sub>	P.P.B.	%C <sub>1</sub> -C <sub>4</sub>	P.P.B.	%C <sub>1</sub> -C <sub>4</sub>
C <sub>1</sub>	7	1	6	13	16	9	10	38
C <sub>2</sub>	tr	*	*	*	*	*	*	*
C <sub>3</sub>	139	20	tr	*	19	11	tr	*
iC <sub>4</sub>	79	12	tr	*	15	8	tr	*
nC <sub>4</sub>	460	68	39	87	130	72	16	62
TOTAL	685	100	45	100	180	100	26	100

GASOLINE RANGE (C<sub>5</sub> - C<sub>7</sub>)

SAMPLE NO.	66		68		70		72	
DEPTH FEET	8790		8940		9040		9140	
	P.P.B.	%C <sub>5</sub> -C <sub>7</sub>	P.P.B.	%C <sub>5</sub> -C <sub>7</sub>	P.P.B.	%C <sub>5</sub> -C <sub>7</sub>	P.P.B.	%C <sub>5</sub> -C <sub>7</sub>
ISO-PENTANE	35	10	90	12	203	10	80	12
N-PENTANE	45	13	130	18	315	15	120	18
CYCLOPENTANE	10	3	15	2	43	2	15	2
2-ME. PENTANE	20	6	55	8	135	6	45	7
3-ME. PENTANE	10	3	30	4	80	4	25	4
N-HEXANE	30	9	95	13	212	10	85	13
ME. CYCLOPENTANE	35	10	75	10	186	9	65	10
CYCLOHEXANE	35	10	75	10	183	9	65	10
2-ME. HEXANE	*	*	tr	*	57	3	tr	*
3-ME. HEXANE	15	4	20	3	83	4	15	2
3-ETHYLPENTANE	tr	*	*	*	79	4	*	*
N-HEPTANE	35	10	30	4	167	8	25	4
BENZENE	10	3	15	2	67	3	18	3
DIME. PENTANE	*	*	*	*	*	*	tr	*
ME. CYCLOHEXANE	75	21	100	13	295	14	90	14
TOTAL	355	100	730	100	2105	100	648	100

TABLE 1 (Cont'd)

## GASEOUS AND GASOLINE RANGE HYDROCARBONS

CLIENT MOBIL

WELL 33/12-4

LOCATION NORTH SEA

GAS (C<sub>1</sub> - C<sub>4</sub>)

SAMPLE NO.	74		76					
	9240		9340					
DEPTH FEET	P. P. B.	%C <sub>1</sub> -C <sub>4</sub>	P. P. B.	%C <sub>1</sub> -C <sub>4</sub>	P. P. M.	%C <sub>1</sub> -C <sub>4</sub>	P. P. M.	%C <sub>1</sub> -C <sub>4</sub>
C <sub>1</sub>	150	63	14	100				
C <sub>2</sub>	tr	*	*	*				
C <sub>3</sub>	30	12	*	*				
iC <sub>4</sub>	5	2	*	*				
nC <sub>4</sub>	54	23	*	*				
TOTAL	239	100	14	100				

GASOLINE RANGE (C<sub>5</sub> - C<sub>7</sub>)

SAMPLE NO.	74		76					
	9240		9340					
DEPTH FEET	P. P. B.	%C <sub>5</sub> -C <sub>7</sub>	P. P. B.	%C <sub>5</sub> -C <sub>7</sub>	P. P. B.	%C <sub>5</sub> -C <sub>7</sub>	P. P. B.	%C <sub>5</sub> -C <sub>7</sub>
ISO-PENTANE	225	25	37	9				
N-PENTANE	275	31	53	13				
CYCLOPENTANE	35	4	8	2				
2-ME. PENTANE	tr	*	27	7				
3-ME. PENTANE	85	10	19	5				
N-HEXANE	45	5	59	15				
ME. CYCLOPENTANE	55	6	35	9				
CYCLOHEXANE	*	*	32	8				
2-ME. HEXANE	85	10	17	4				
3-ME. HEXANE	*	*	8	2				
3-ETHYLPENTANE	*	*	4	1				
N-HEPTANE	tr	*	25	6				
BENZENE	*	*	16	4				
DIME. PENTANE	tr	*	*	*				
ME. CYCLOHEXANE	80	9	59	15				
TOTAL	885	100	399	100				

TABLE 2.

VITRINITE REFLECTIVITY AND FLUORESCENCE DATA

<u>DEPTH IN FEET</u>	<u>AVERAGE REFLECTIVITIES AND RANGES IN PERCENT</u>	<u>ORGANIC CONTENT</u>	<u>FLUORESCENCE, COLOURS OF SPORES AND RESINS ETC.</u>
6,080	0.28 - 1.19	-	-
6,180	0.36 - 0.87	-	-
6,280	0.36 - 0.87	-	-
7,290	0.40 - 0.88	moderate to high	orange
7,390	0.44; 0.68; 1.01	moderate	orange
7,490	0.35; 0.76; 0.98	low to moderate	yellow and orange
7,590	0.45; 0.64; 0.91	high	yellow and orange
7,690	0.56; 0.82; 1.08	moderate to high	orange
7,790	0.45; 0.56; 1.04	moderate	yellow and orange
7,990	0.45; 0.57 - 1.20	low	yellow and orange
8,390	0.43; 0.65 - 1.52	low	yellow and orange
8,540	0.58; 0.75 - 1.46	low	yellow and orange
8,640	0.77	low	none
8,690	0.65	low	none
8,790	0.29; 0.52; 0.79	low	brown resins
8,840	0.31; 0.52; 1.01	moderate	brown resins
8,940	0.36; 0.49; 0.91	moderate	brown resins
9,040	0.27; 0.49; 0.68 - 0.90	moderate	brown spores
9,090	0.33; 0.55; 0.86	moderate	brown spores
9,140	0.45; 0.60; 0.88	moderate to high	brown spores
9,190	0.49; 0.66; 0.88	low	brown spores
9,240	0.37; 0.54; 0.66; 0.72-1.44	moderate	none
9,290	0.52; 0.76; 0.96	moderate	none
9,340	0.37; 0.49; 0.91; 1.5	low	none
9,390	0.45; 0.79; 0.96 - 1.6	moderate	yellow spores

TABLE 3

## MATURATION EVALUATION DATA

COMPANY: MOBIL NORWAY

WELL: 33/12-4

LOCATION: NORTH SEA

SAMPLE DEPTH ( FEET ) OR NOTATION	SAMPLE TYPE	GENERALISED LITHOLOGY	MAXIMUM PALAEOTEMP- ERATURE °F	VITRINITE REFLECTIVITY %	SPORE COLOURATION (1-10)	LIGHT HYDROCARBONS
1. 5480- 500	Ctgs	Lt ol-gy sl calc sh+50% lt brn-gy sl calc sh	-	-	4.5	Immature
2. 5540- 60	"	Ditto+60% ditto+ mnr wht sltst	< 274	-	-	-
3. 5580- 600	"	Ditto+50% ditto+ mnr wht. sltst	-	-	5	-
4. 5640- 60	"	Ditto+20% ditto+ mnr ditto	< 281	-	-	-
5. 5690- 700	"	Ditto+30% ol-gy sl calc mdst	-	-	5	Immature
6. 5740- 50	"	Ditto+30% ol-gy sl calc mdst	243	-	-	-
7. 5750- 800	"	Ditto+60% ditto+ 10% slt	-	-	4.5	-
8. 5850- 60	"	Ditto+mnr ditto	245	-	-	-
9. 5880- 900	"	Ditto	-	-	5.5	Immature
10. 5920- 40	"	Ditto	245	-	-	-
11. 5980- 6000	"	Ditto	-	-	5	-
12. 6020- 40	"	Ditto	250	-	-	-
13. 6080- 100	"	Ditto	-	0.28	5	Immature
14. 6120- 40	"	Ditto+40% lt gn- gy sh	264	-	-	-
15. 6180- 200	"	Ditto	-	0.36	5	-
16. 6220- 40	"	Ditto	253	-	-	Immature
17. 6280- 300	"	Ditto+mnr lt brn- gy sh	-	0.36	5	-
18. 6340- 50	"	Ditto+40% lt gn- gy sh	253	-	-	-
19. 6390- 400	"	Lt gn-gy sh+mnr lt brn-gy sh	-	-	5	-
20. 6440- 50	"	Lt ol-gy calc sh	246	-	-	Immature

TABLE 3 (Cont'd)

## MATURATION EVALUATION DATA

COMPANY: MOBIL NORWAY

WELL: 33/12-4

LOCATION: NORTH SEA

SAMPLE DEPTH ( FEET ) OR NOTATION	SAMPLE TYPE	GENERALISED LITHOLOGY	MAXIMUM PALAEOTEMP- ERATURE °F	VITRINITE REFLECTIVITY %	SPORE COLOURATION (1-10)	LIGHT HYDROCARBONS
21.6490- 500	Ctgs	Lt ol-gy calc sh +mnr lt brn-gy sh	-	-	5	-
22.6520- 40	"	Ditto	223	-	-	-
23.6580- 600	"	Ditto +(mnr chk?)	-	-	5	-
24.6640- 60	"	Lt gy calc sh	240	-	-	Immature
25.6690- 700	"	Ditto	-	-	4.5	-
26.6740- 50	"	Lt gy calc sh+10% snd	238	-	-	-
27.6790- 800	"	Ditto+15% lt brn- gy sh	-	-	5	-
28.6840- 50	"	Ditto+15% ditto	223	-	-	Immature
29.6890- 900	"	Ditto+10% ditto	-	-	5	-
30.6940- 50	"	Ditto	243	-	-	-
31.6990- 7000	"	Ditto	-	-	5	-
32.7040- 50	"	Ditto	248	-	-	Immature
33. 7090- 100	"	Ditto+mica	-	-	5-5.5	-
34. 7140- 50	"	Medium lt gy sh+ mica+walnut shell	-	-	-	-
35. 7190- 200	"	Ditto+ditto	218	-	5	-
36. 7240- 50	"	Med gy sl calc sh	-	-	-	Transitional
37. 7290- 300	"	Med lt gy sl calc sh	210	0.40	5.5-6	-
38. 7340- 50	"	Med lt gy sh+ walnut shell	<264	-	-	Transitional
39. 7390- 400	"	Ditto	-	0.44	5-5.5	-
40. 7440- 50	"	Ditto+walnut shell	221	-	-	Transitional
41. 7490- 500	"	Ditto	-	0.35	5-5.5	-

TABLE 3 (Cont'd)

## MATURATION EVALUATION DATA

COMPANY: MOBIL NORWAY

WELL: 33/12-4

LOCATION: NORTH SEA

SAMPLE DEPTH ( FEET ) OR NOTATION	SAMPLE TYPE	GENERALISED LITHOLOGY	MAXIMUM PALAEOTEMP- ERATURE °F	VITRINITE REFLECTIVITY %	SPORE COLOURATION (1-10)	LIGHT HYDROCARBONS
42. 7540- 50	Ctgs	Med lt gy sh+ walnut shell	221	-	-	Transitional
43. 7590- 600	"	Ditto	-	0.45	5-5.5	-
44. 7640- 50	"	Ditto	227	-	-	Mature
45. 7690- 700	"	Ditto	-	0.56	5.5-6	-
46. 7760- 70	"	Ditto	231	-	-	Mature
47. 7790- 800	"	Ditto	-	0.45	5.5-6	-
48. 7840- 50	"	Med gy sh	239	-	-	-
49. 7890- 900	"	Ditto	228	-	-	-
50. 7940- 50	"	Ditto	-	-	-	-
51. 7990- 8000	"	Ditto/sl slt	266	0.45	6	Mature
52. 8040- 50	"	Ditto	-	-	-	-
53. 8090- 100	"	Ditto+mica	-	-	-	-
54. 8190- 200	"	Ditto walnut shell	-	-	-	-
55. 8240- 50	"	Med gy/dk gy sh	<274	-	-	-
56. 8290- 300	"	Insufficient	-	-	-	-
57. 8340- 50	"	Med gy sh	-	-	-	-
58. 8390- 400	"	Ditto	-	0.43	6	Mature
59. 8440- 50	"	Insufficient	-	-	-	-
60. 8490- 500	"	Gy sh small	-	-	-	-
61. 8540- 50	"	Med gy sl calc sh	290	0.58	6	Mature
62. 8590- 600	"	Cement	-	-	-	-

TABLE 3 (Cont'd)

## MATURATION EVALUATION DATA

COMPANY: MOBIL NORWAY

WELL: 33/12-4

LOCATION: NORTH SEA

SAMPLE DEPTH ( FEET ) OR NOTATION	SAMPLE TYPE	GENERALISED LITHOLOGY	MAXIMUM PALAEOTEMP- -ERATURE °F	VITRINITE REFLECTIVITY %	SPORE COLOURATION (1-10)	LIGHT HYDROCARBONS
63. 8640- 50	Ctgs	Med dk gy sl calc sh	-	0.77	5.5-6	Mature
64. 8690- 700	"	Ditto+30% wht lstn+30% red calc mdst	< 255	0.65	6	-
65. 8740- 50	"	Ditto+50% red/brn calc mdst	-	-	6	Mature
66. 8790- 800	"	Med gy sh+30% dk gy sh	258	0.52	5.5-6	Mature
67. 8840- 50	"	Med dk gy sh	258	0.52	-	-
68. 8940- 50	"	Ditto	-	0.49	-	Mature
69. 8990- 9000	"	Ditto	-	-	-	-
70. 9040- 50	"	Ditto	222	0.49	-	Mature
71. 9090- 100	"	Med gy sh+30% yell/brn mdst	-	0.55	-	-
72. 9140- 50	"	Ditto+10% brn mdst	261	0.60	-	Mature
73. 9190- 200	"	Ditto+30% ditto+ 10% wht calc sst	-	0.66	5.5-6	-
74. 9240- 50	"	Ditto+80% yell/ brn calc clyst	-	0.66	6	Mature
75. 9290- 300	"	Ditto+60% yell/ brn/pp sl calc mdst	248	0.52	6.5	-
76. 9340- 50	"	Mtl pp/yell sl calc mdst	-	0.49-0.91	6.5	Mature
77. 9390- 400	"	Ditto+20% caved sh	242	0.45-0.79	6.5	-
78. 9440- 50	"	Red brn slty mdst+20% lt gy sh +tr coal	-	-	-	-
79. 9490- 500	"	Ditto+15% ditto	238	-	-	-



TABLE 4

## SOURCE ROCK EVALUATION DATA

COMPANY: MOBIL NORWAY

WELL: 33/12-4

LOCATION: NORTH SEA

SAMPLE DEPTH (FEET) OR NOTATION	SAMPLE TYPE	ANALYSED LITHOLOGY	ORGANIC CARBON % OF ROCK	TOTAL EXTRACT P.P.M.	EXTRACT % OF ORGANIC CARBON	HYDRO- CARBONS P.P.M. OF ROCK	HYDRO- CARBONS % OF EXTRACT	TOTAL ALKANES % HYDRO- CARBONS
1. 5480- 500	Ctgs	Lt ol-gy sl calc sh+ 50% lt brn-gy sl calc sh	0.37	-	-	-	-	-
2. 5540- 60	"	Ditto+60% ditto+mnr wht sltst	0.42	210	5.0	80	36	81
3. 5580- 600	"	Ditto+50% ditto+mnr wht sltst	0.31	-	-	-	-	-
4. 5640- 60	"	Ditto+20% ditto+mnr ditto	0.45	200	4.4	20	11	100
5. 5690- 700	"	Ditto+30% ol-gy sl calc mdst	0.38	-	-	-	-	-
6. 5740- 50	"	Ditto+30% ol-gy sl calc mdst	0.35	180	5.1	20	*	*
7. 5790- 800	"	Ditto+60% ditto+10% slt	0.39	-	-	-	-	-
8. 5850- 60	"	Ditto+mnr ditto	0.40	230	5.8	20	8	82
9. 5880- 900	"	Ditto	0.32	-	-	-	-	-
10. 5920- 40	"	Ditto	0.34	180	5.3	25	14	86
11. 5980- 6000	"	Ditto	0.36	-	-	-	-	-
12. 6020- 40	"	Ditto	0.38	230	6.0	40	18	88
13. 6080- 100	"	Ditto	0.33	-	-	-	-	-
14. 6120- 40	"	Ditto+40% lt gn-gy sh	0.34	230	6.8	25	12	100
15. 6180- 200	"	Ditto	0.40	-	-	-	-	-
16. 6220- 40	"	Ditto	0.42	210	5.0	20	9	78
17. 6280- 300	"	Ditto+mnr lt brn gy sh	0.40	-	-	-	-	-
18. 6340- 50	"	Ditto+40% lt gn-gy sh	0.44	390	8.9	45	12	85
19. 6390- 400	"	Lt gn-gy sh+mnr lt brn-gy sh	0.42	-	-	-	-	-
20. 6440- 50	"	Lt ol-gy calc sh	0.46	860	18.7	170	20	72

TABLE 4 (Cont'd)

## SOURCE ROCK EVALUATION DATA

COMPANY: MOBIL NORWAY

WELL: 33/12-4

LOCATION: NORTH SEA

SAMPLE DEPTH (FEET) OR NOTATION	SAMPLE TYPE	ANALYSED LITHOLOGY	ORGANIC CARBON % OF ROCK	TOTAL EXTRACT P.P.M.	EXTRACT % OF ORGANIC CARBON	HYDRO- CARBONS P.P.M. OF ROCK	HYDRO- CARBONS % OF EXTRACT	TOTAL ALKANES % HYDRO- CARBONS
21.6490- 500	Ctgs	Lt ol-gy calc sh+mnr lt brn-gy sh	0.37	-	-	-	-	-
22.6520- 40	"	Ditto	0.40	840	21.0	110	12	91
23.6580- 600	"	Ditto+(mnr chk?)	0.42	-	-	-	-	-
24.6640- 60	"	Lt gy calc sh	0.41	80	2.0	20	*	*
25.6690- 700	"	Ditto	0.45	-	-	-	-	-
26.6740- 50	"	Lt gy calc sh+10% fn snd	0.49	750	15.3	75	10	88
27.6790- 800	"	Ditto+15% lt brn-gy sh	0.43	-	-	-	-	-
28.6840- 50	"	Ditto+15% ditto	0.41	270	6.6	20	7	100
29.6890- 900	"	Ditto+10% ditto	0.44	-	-	-	-	-
30.6940- 50	"	Ditto	0.43	260	6.0	45	17	100
31.6990- 7000	"	Ditto	0.60	-	-	-	-	-
32.7040- 50	"	Ditto	0.77	370	4.8	25	7	100
33.7090- 100	"	Ditto+mica	1.07	-	-	-	-	-
34.7140- 50	"	Medium lt gy sh+mica + walnut shell	0.60	-	-	-	-	-
35.7190- 200	"	Ditto+ditto	0.93	480	5.2	50	11	100
36.7240- 50	"	Med gy sl calc sh	1.15	-	-	-	-	-
37.7290- 300	"	Med lt gy sl calc sh	1.44	550	3.8	30	6	100
38.7340- 50	"	Med lt gy sh+walnut shell	2.70	1290	4.8	150	12	92
39.7390- 400	"	Ditto	1.64	-	-	-	-	-
40.7440- 50	"	Ditto+walnut shell	1.65	1100	6.7	100	9	95
41.7490- 500	"	Ditto	1.47	-	-	-	-	-

TABLE 4 (Cont'd)

## SOURCE ROCK EVALUATION DATA

COMPANY: MOBIL NORWAY

WELL: 33/12-4

LOCATION: NORTH SEA

SAMPLE DEPTH ( FEET ) OR NOTATION	SAMPLE TYPE	ANALYSED LITHOLOGY	ORGANIC CARBON % OF ROCK	TOTAL EXTRACT PPM.	EXTRACT % OF ORGANIC CARBON	HYDRO- CARBONS P.P.M. OF ROCK	HYDRO- CARBONS % OF EXTRACT	TOTAL ALKANES % HYDRO- CARBONS
42. 7540- 50	Ctgs	Med lt gy sh+walnut shell	1.23	690	5.6	75	11	100
43. 7590- 600	"	Ditto	1.42	-	-	-	-	-
44. 7640- 50	"	Ditto	1.37	650	4.7	75	12	100
45. 7690- 700	"	Ditto	0.91	-	-	-	-	-
46. 7760- 70	"	Ditto	1.14	5130	45.0	240	5	100
47. 7790- 800	"	Ditto	0.81	-	-	-	-	-
48. 7840- 50	"	Med gy sh	1.14	*	*	100	*	>80
49. 7890- 900	"	Ditto	1.32	*	*	420	*	>80
50. 7940- 50	"	Ditto	0.80	-	-	-	-	-
51. 7990- 8000	"	Ditto	0.74) )	*	*	) 200	*	>80
52. 8040- 50	"	Ditto	1.20)	*	*	)	*	
53. 8090- 100	"	Ditto+mica	1.10	-	-	-	-	-
54. 8190- 200	"	Ditto walnut shell	1.19	-	-	-	-	-
55. 8240- 50	"	Med gy/dk gy sh	1.00	*	*	) 570	*	) >80
56. 8290- 300	"	Ditto	1.70	*	*	)	*	)
57. 8340- 50	"	Med gy sh	1.20	-	-	-	-	-
58. 8390- 400	"	Ditto	1.20	-	-	-	-	-
59. 8440- 50	"	Ditto	1.55	-	-	-	-	-
60. 8490- 500	"	Gy sh small	1.69	-	-	-	-	-
61. 8540- 50	"	Med gy sl calc sh	0.77	710	9.2	240	33	90

TABLE 4 (Cont'd)

## SOURCE ROCK EVALUATION DATA

COMPANY: MOBIL NORWAY

WELL: 33/12-4

LOCATION: NORTH SEA

SAMPLE DEPTH (FEET) OR NOTATION	SAMPLE TYPE	ANALYSED LITHOLOGY	ORGANIC CARBON % OF ROCK	TOTAL EXTRACT PPM.	EXTRACT % OF ORGANIC CARBON	HYDRO- CARBONS P.P.M. OF ROCK	HYDRO- CARBONS % OF EXTRACT	TOTAL ALKANES % HYDRO- CARBONS
62. 8590- 600	Ctgs	Cement	-	-	-	-	-	-
63. 8640- 50	"	Med dk gy sh calc sh	2.61	-	-	-	-	-
64. 8690- 700	"	Ditto+30% wht lstn+ 30% red calc mdst	3.08	600	1.9	45	8	100
65. 8740- 50	"	Ditto+50% red/brn calc mdst	2.48	-	-	-	-	-
66. 8790- 800	"	Med gy sh+30% dk gy sh	2.68	2560	9.6	250	10	81
67. 8840- 50	"	Med dk gy sh	1.94	4460	23.0	350	8	87
68. 8940- 50	"	Ditto	3.28)	1880	15.9	410	22	78
69. 8990- 9000	"	Ditto	2.24)					
70. 9040- 50	"	Ditto	3.06	3910	12.8	3270	84	40
71. 9090- 100	"	Med gy sh+30% yell/ brn mdst	0.69	480	7.0	105	22	87
72. 9140- 50	"	Ditto+10% brn mdst	1.44	1960	13.6	70	4	80
73. 9190- 200	"	Ditto+30% ditto+10% wht calc sst	1.23	-	-	-	-	-
74. 9240- 50	"	Ditto+80% yell/brn calc clyst	0.21	-	-	-	-	-
75. 9290- 300	"	Ditto+60% yell/brn/pp sl calc mdst	0.62	900	14.5	20	2	100
76. 9340- 50	"	Mt1 pp/yell sl calc mdst	0.18	-	-	-	-	-
77. 9390- 400	"	Ditto+20% caved sh	0.57	810	14.7	30	4	68
78. 9440- 50	"	Red brn slty mdst+20% lt gy sh+tr coal	1.80	-	-	-	-	-
79. 9490- 500	"	Ditto+15% ditto	0.80	620	7.8	70	11	56
ORGANIC CARBON DETERMINATION								
66. 8790- 800	Ctgs	Dk gy sh	7.4					

FIGURE 1

GASEOUS (C<sub>1</sub> - C<sub>4</sub>) HYDROCARBONS

COMPANY : MOBIL NORWAY

WELL : 33/12-4

LOCATION : NORTH SEA

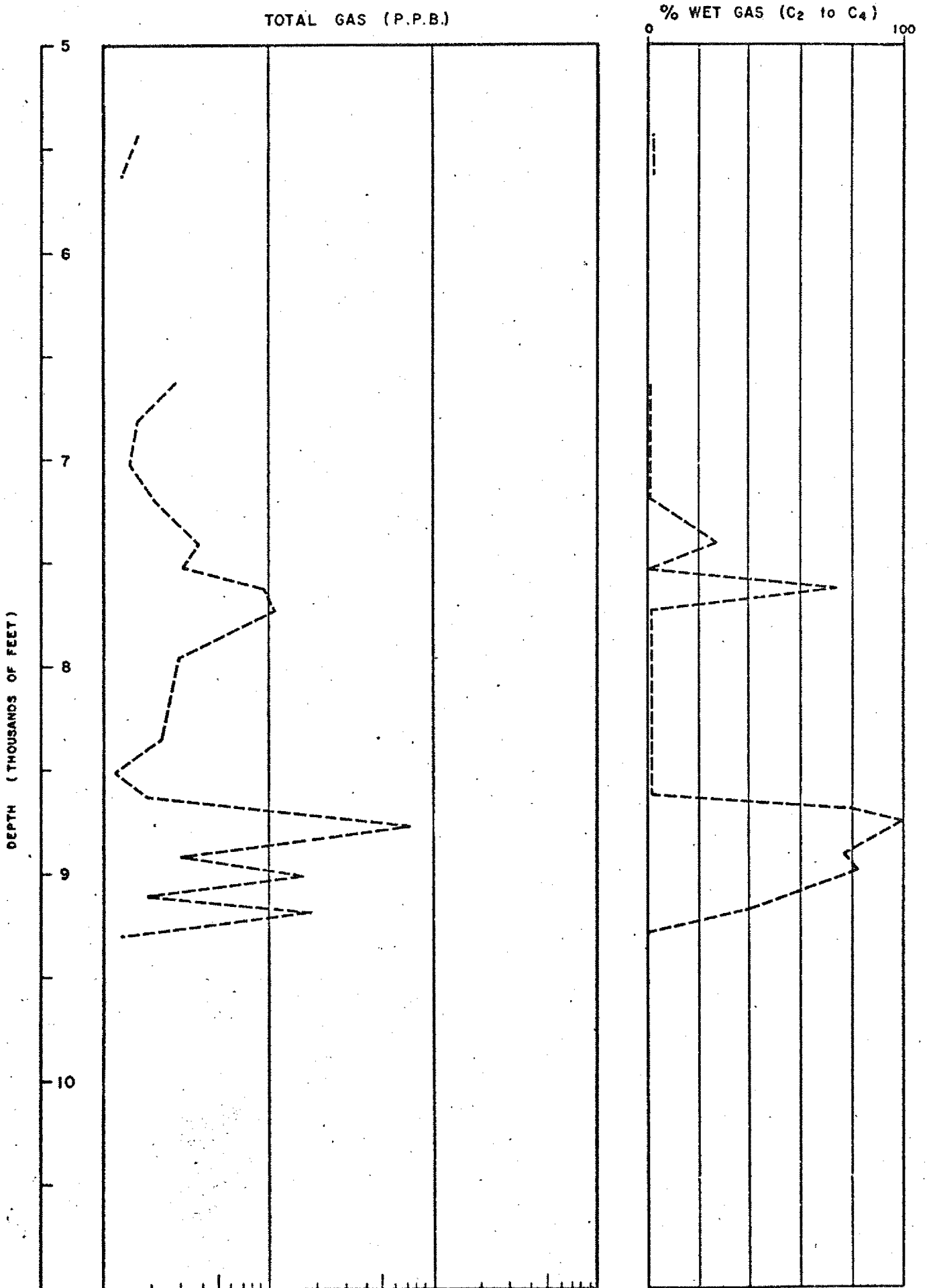


FIGURE 2

GASOLINE RANGE (C<sub>5</sub>-C<sub>7</sub>) HYDROCARBONS

COMPANY : MOBIL NORWAY

WELL : 33/12-4

LOCATION : NORTH SEA

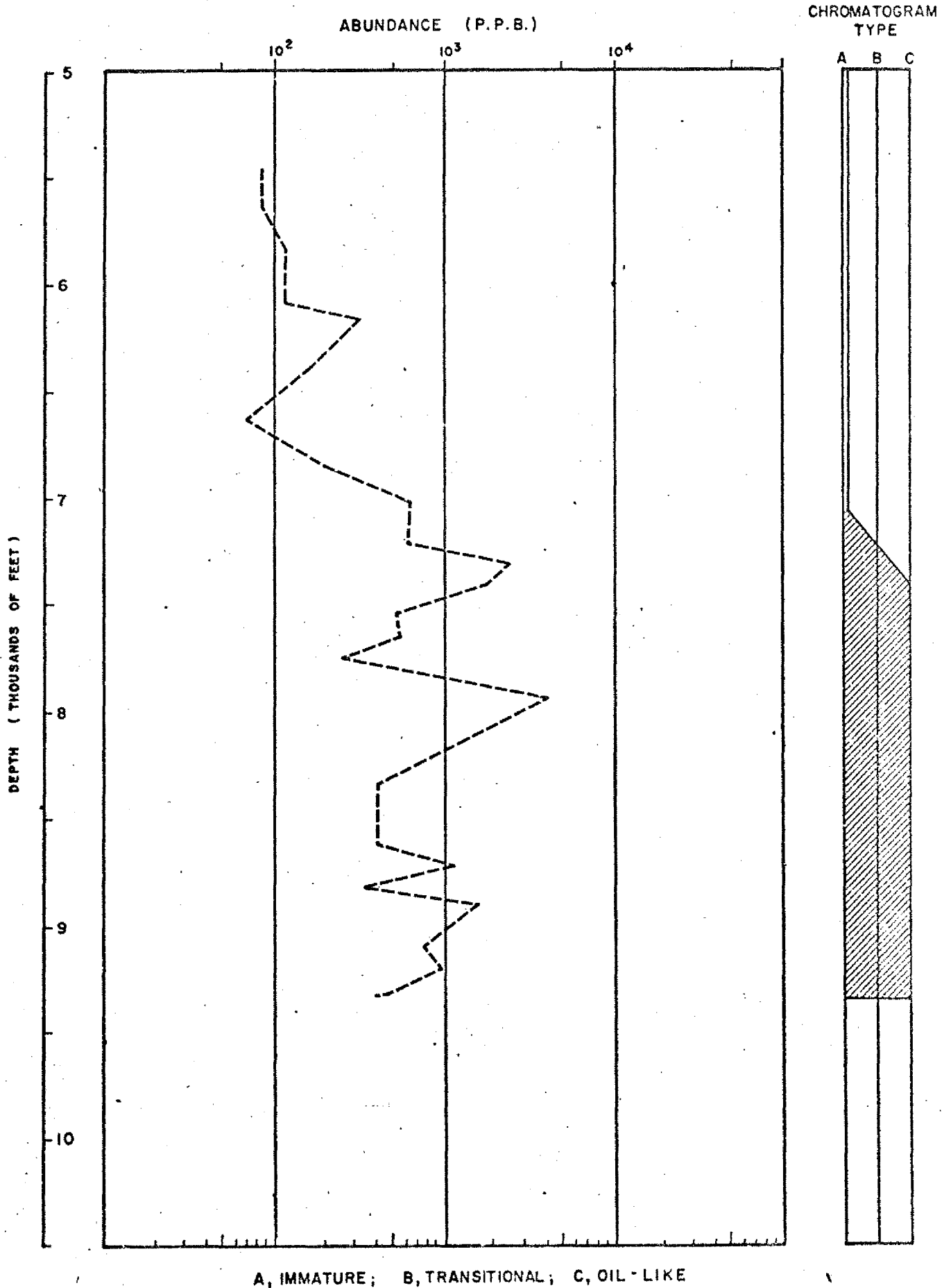


FIGURE 3  
VITRINITE REFLECTANCE AGAINST DEPTH

COMPANY : MOBIL NORWAY

WELL : 33/12-4

LOCATION : NORTH SEA

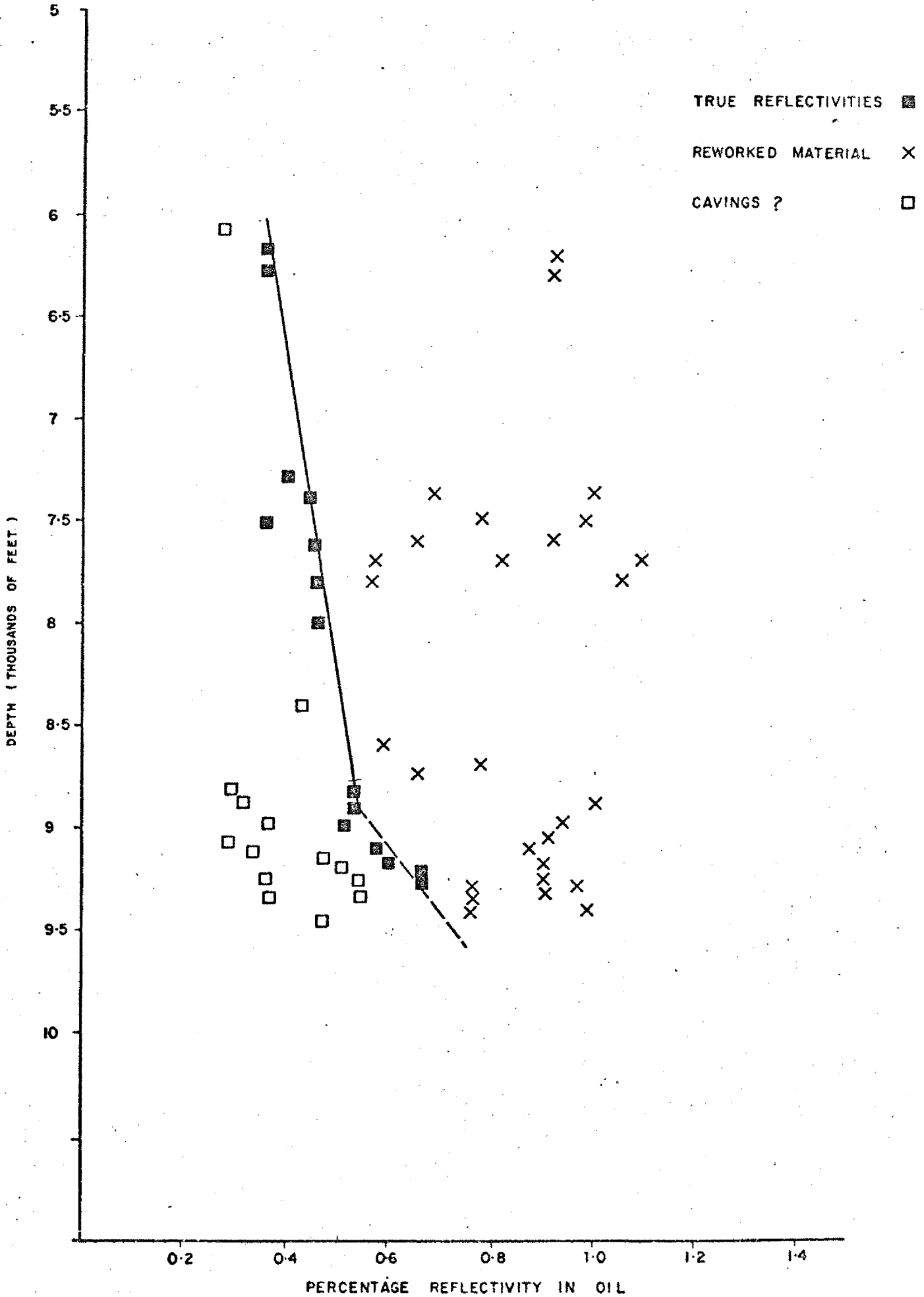


FIGURE 4  
SPORE COLOURATION INDICES AGAINST DEPTH

COMPANY : MOBIL NORWAY

WELL : 33/12-4

LOCATION : NORTH SEA

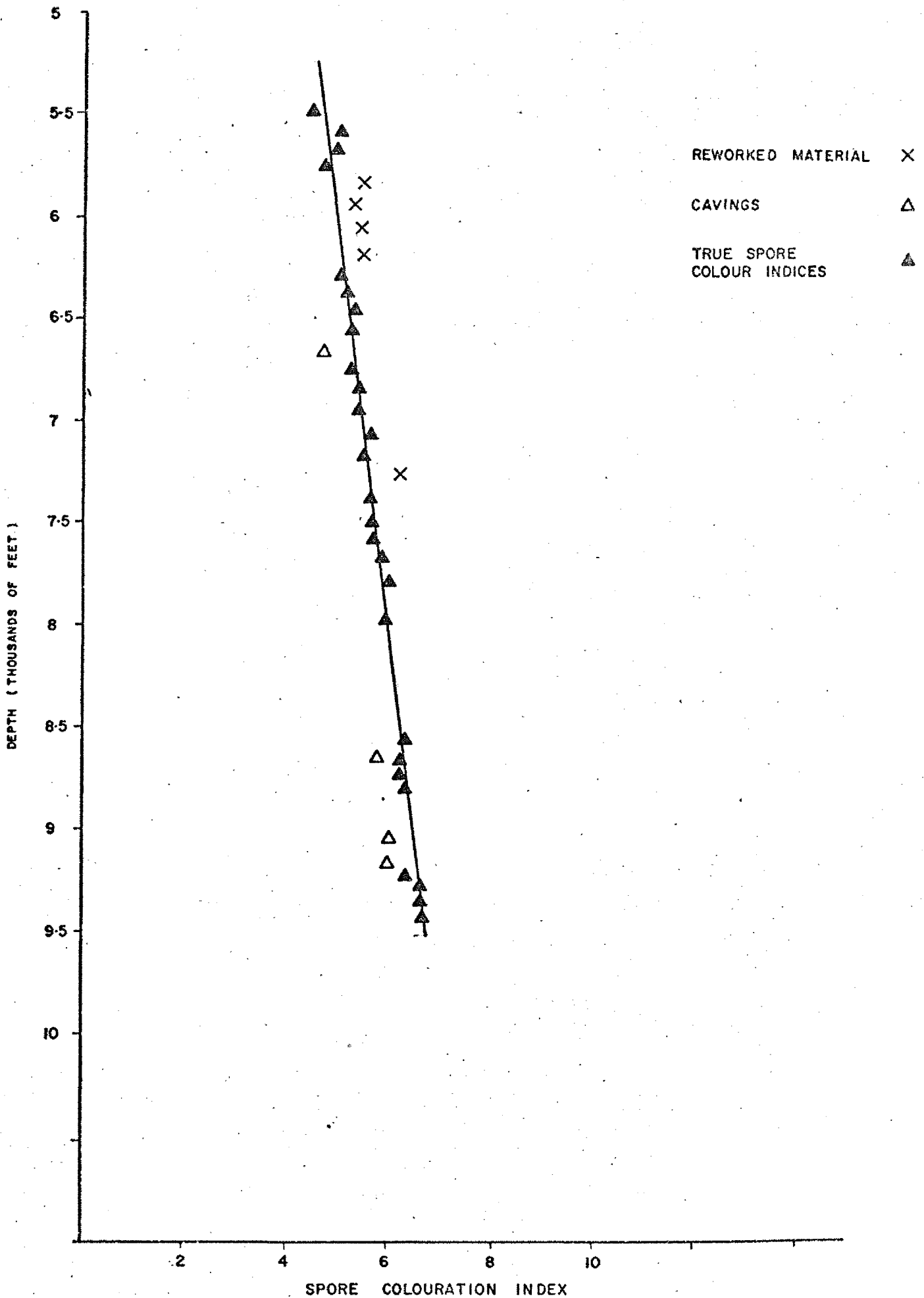




FIGURE 5

MAXIMUM PALAEOTEMPERATURE AGAINST DEPTH

COMPANY : MOBIL NORWAY

WELL : 33 / 12 - 4

LOCATION : NORTH SEA

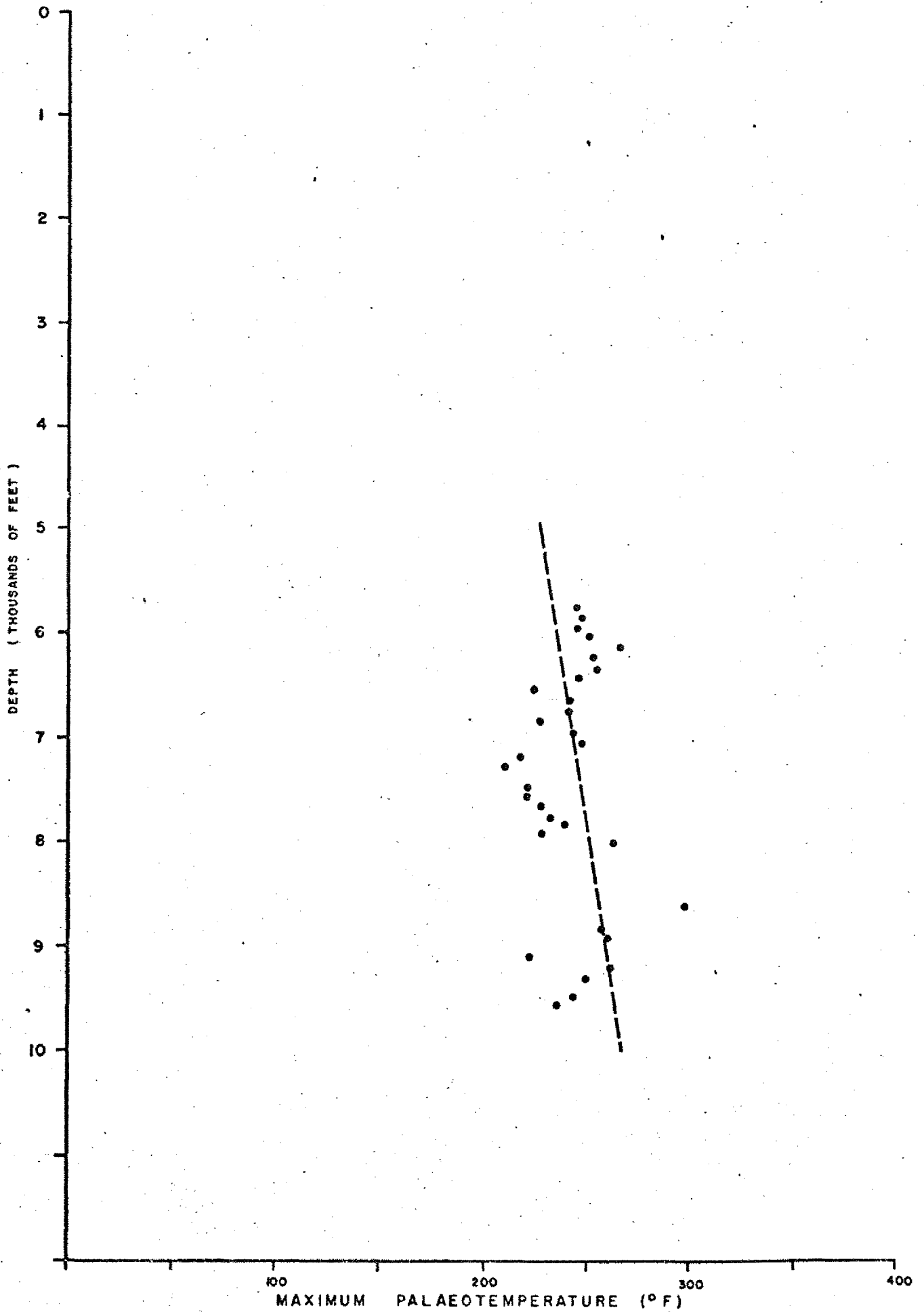


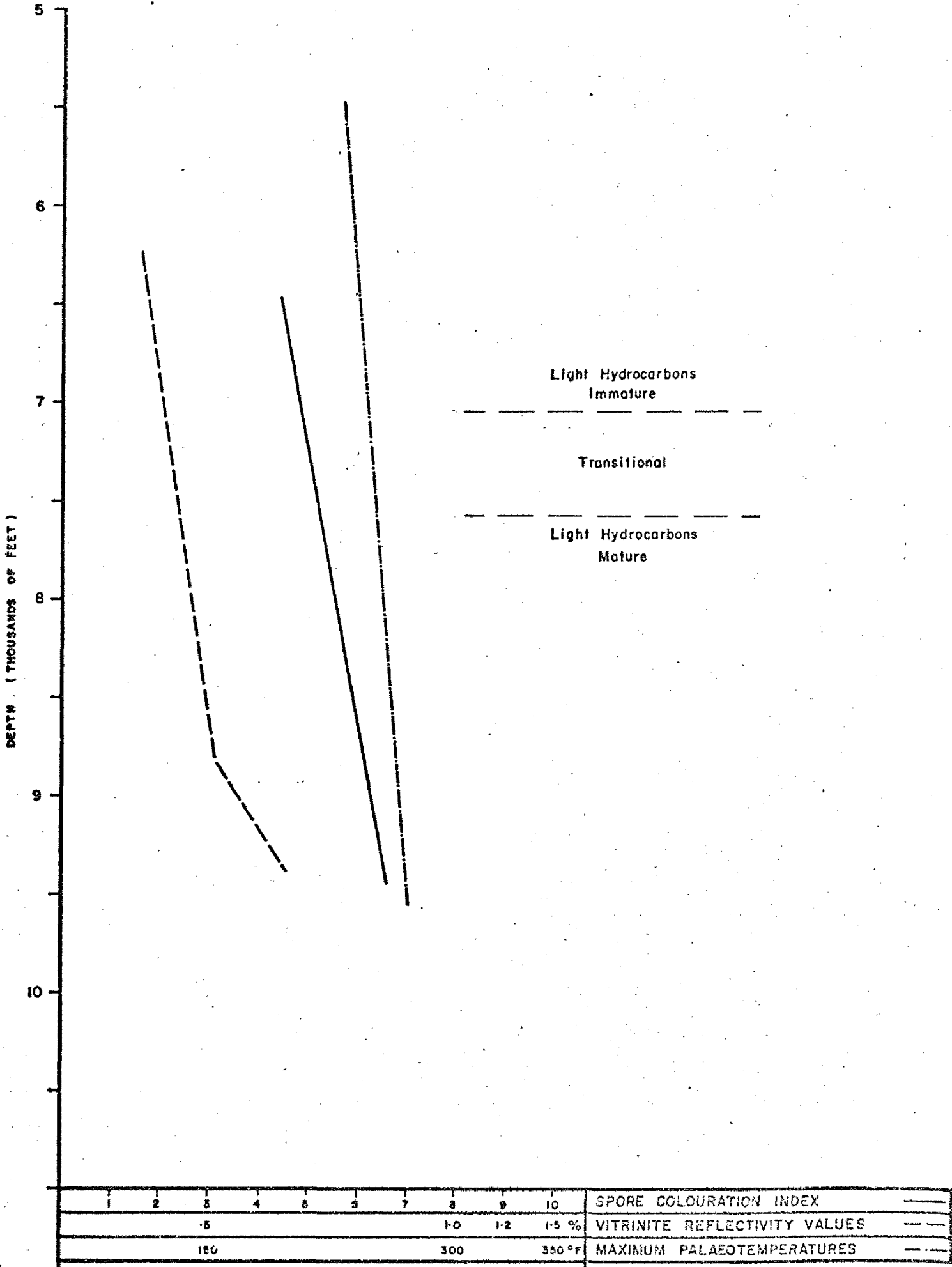
FIGURE 6

MATURATION INDICES AGAINST DEPTH

COMPANY: MOBIL NORWAY

WELL: 33/12-4

LOCATION: NORTH SEA



1	2	3	4	5	6	7	8	9	10	SPORE COLOURATION INDEX	---
		0.5				1.0	1.2	1.5	%	VITRINITE REFLECTIVITY VALUES	---
		150				300		350	°F	MAXIMUM PALAEOTEMPERATURES	---

FIGURE 7  
 TYPE OF HYDROCARBON PRODUCT FROM SOURCE ROCKS  
 COMPANY : MOBIL NORWAY  
 WELL : 33/12-4  
 LOCATION : NORTH SEA

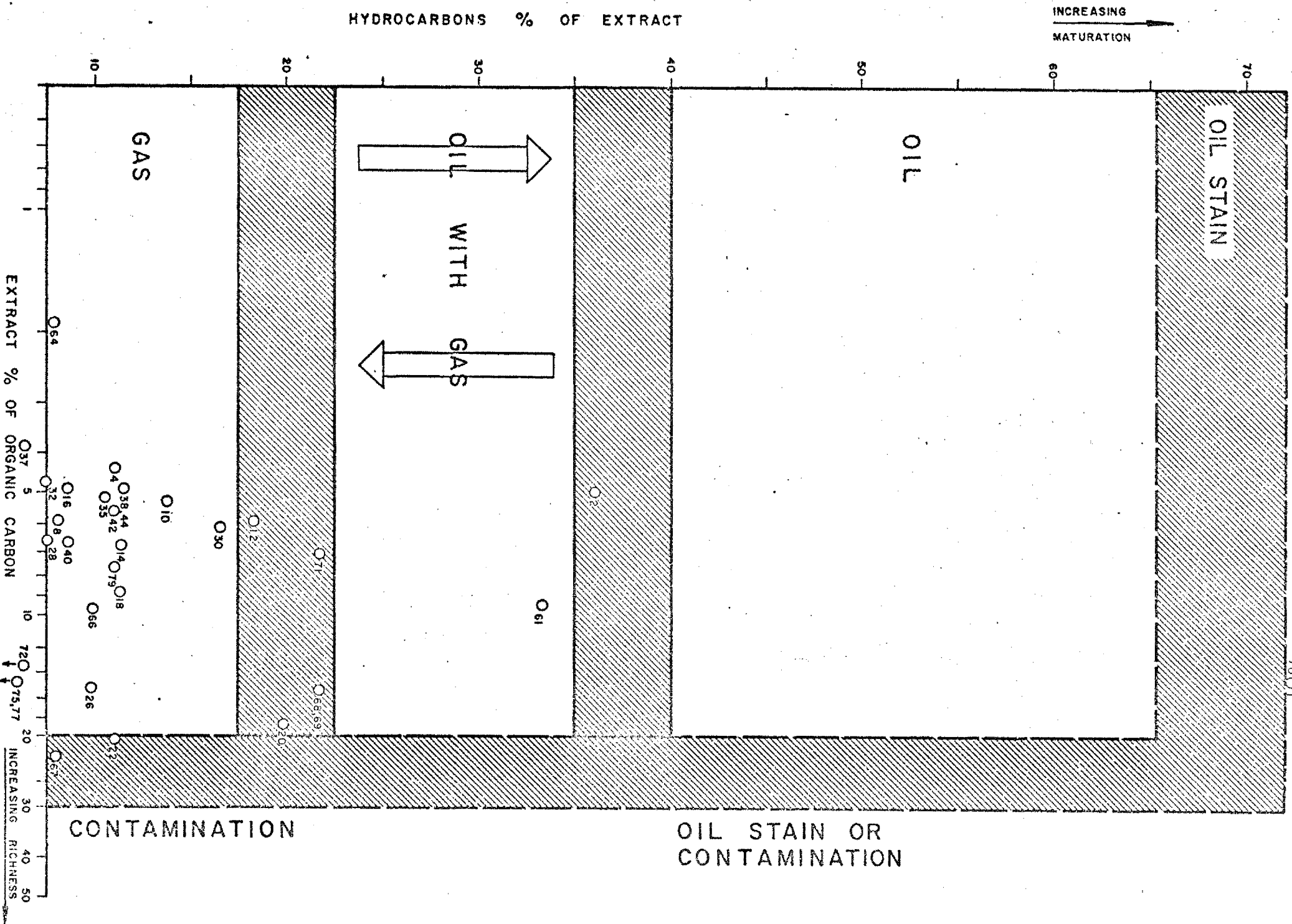


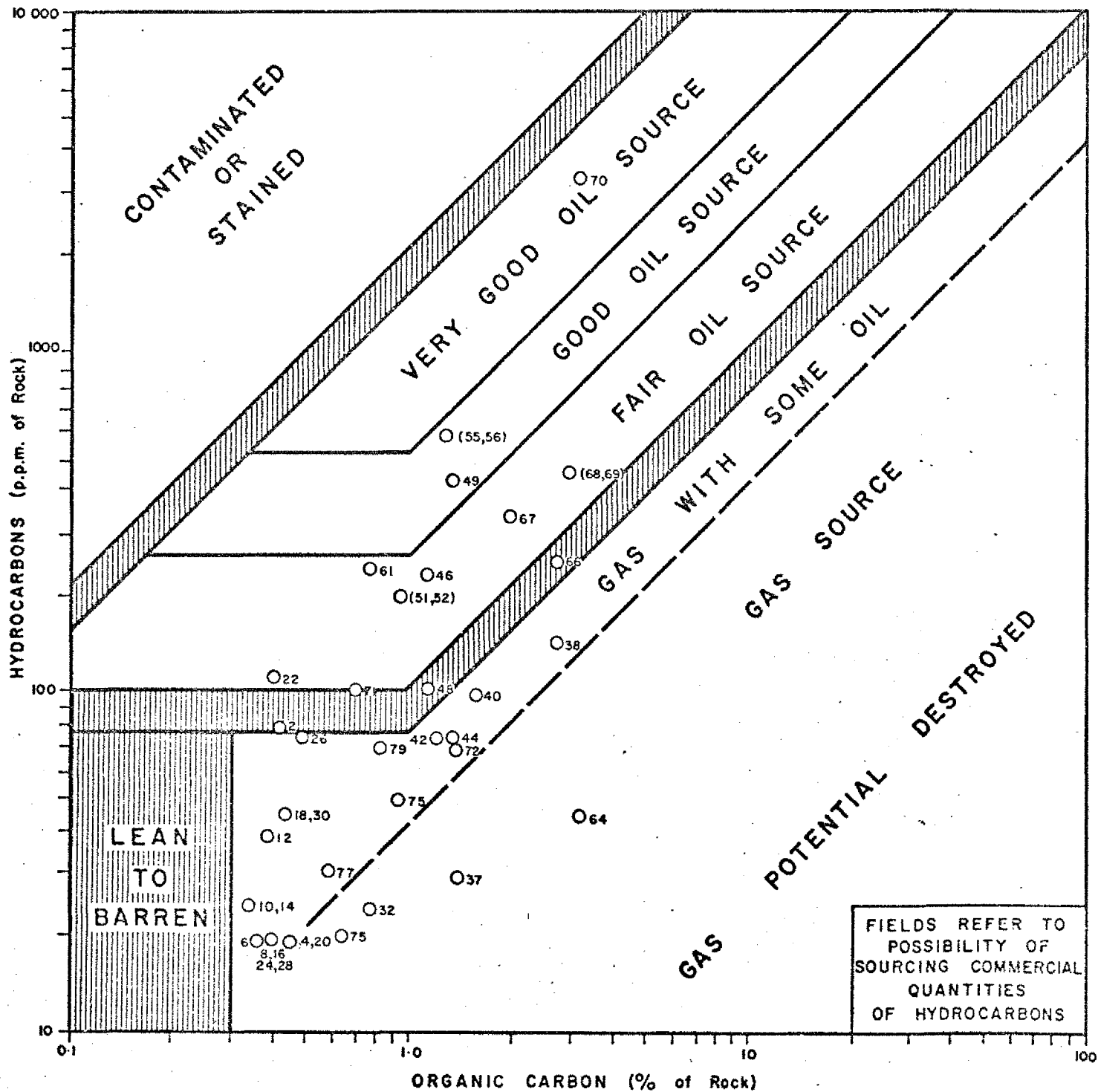
FIGURE 8

MATURE SOURCE ROCK RICHNESS

COMPANY : MOBIL NORWAY

WELL : 33/12-4

LOCATION : NORTH SEA



# WELL SUMMARY CHART

33/12-4

LOCATION : NORTH SEA

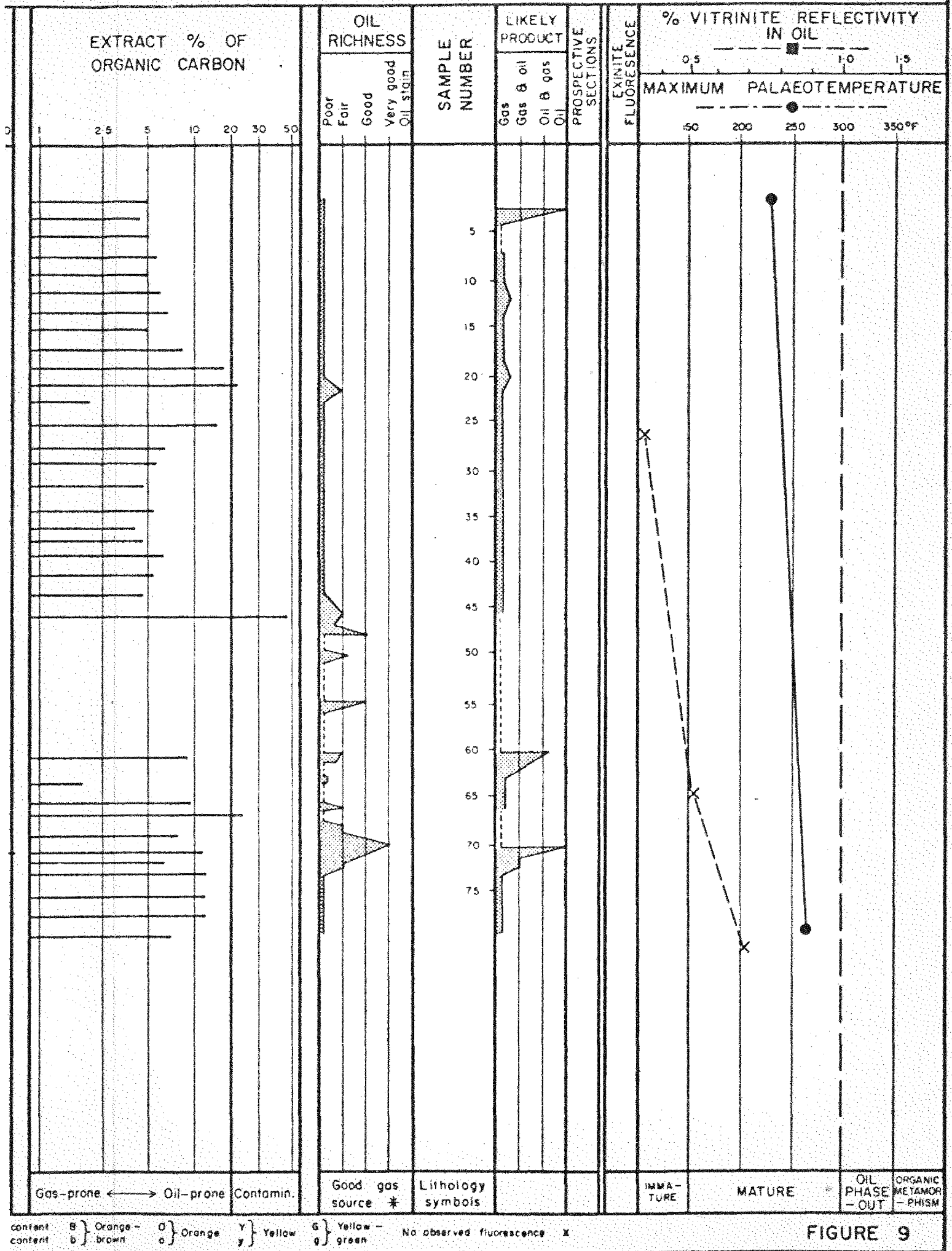


FIGURE 9

## APPENDIX II

### DESCRIPTION OF ANALYTICAL AND INTERPRETATIVE TECHNIQUES

#### SOURCE ROCK POTENTIAL ANALYSIS

##### 1. Definition of Problem

###### a. Type of Hydrocarbon

Compared with their ancient counterparts, recent sediments have low hydrocarbon contents and many of the hydrocarbons which are present not only in ancient sediments, but also in crude oils, are absent. This is particularly true of the hydrocarbons with between two and fourteen carbon atoms in the molecule (Sokolov, 1959; Dunton and Hunt, 1962; Kvenvolden, 1962) which constitute about 50% of most crudes. Clearly, recent sediments cannot yield compounds which they do not contain and therefore cannot source oil (Erdman, 1961). The Russians report accumulations of biologically-generated dry gas at relatively shallow depths (age uncertain) but these occurrences are anomalous and non-predictable. With the possible exception of methane, recent sediments do not possess a present source potential for hydrocarbons.

With increasing burial, it is observed that not only are the missing hydrocarbons formed, but the total hydrocarbon abundance increases (Philippi, 1965). This process is called maturation. The hydrocarbons are generated either from kerogen (insoluble organic matter) via non-hydrocarbon intermediaries (Tissot et al., 1971) or directly from the non-hydrocarbons which were originally present. In both cases, the non-hydrocarbons are the common denominator and hence source rock evaluation must consider the total soluble extract, which is the sum of the non-hydrocarbons (future potential) and the hydrocarbons (present potential). Catalytic cracking is probably

APPENDIX I

ABBREVIATIONS USED IN ANALYTICAL DATA SHEETS

-	-	Sample not analysed			
*	-	No results obtained			
C.M.T.	-	Cement	L.C.M.	-	Lost circulation material
Cht	-	Chert	Qtz	-	Quartz
Snd	-	Sand	Sst	-	Sandstone
Slt	-	Silt	Sltst	-	Siltstone
Cgl	-	Conglomerate	Mdst	-	Mudstone
Clyst	-	Claystone	Cly	-	Clay
Sh	-	Shale	Dol	-	Dolomite
Lstn	-	Limestone	Chk	-	Chalk
Lig	-	Lignite	Musc	-	Muscovite
Sndy	-	Sandy	Silty	-	Silty
Shly	-	Shaly	Arg	-	Argillaceous
Aren	-	Arenaceous	Carb	-	Carbonaceous
Calc	-	Calcareous	Mic	-	Micaceous
Ool	-	Oolitic	Sil	-	Siliceous
Fer	-	Ferruginous	Lam	-	Laminae/laminated
Frag	-	Fragments	Pp	-	Purple
Brn	-	Brown	Yel	-	Yellow
Gy	-	Grey	Gn	-	Green
Ol	-	Olive	Blk	-	Black
Wht	-	White	Bl	-	Blue
Mtl	-	Mottled	Vgt	-	Variegated
Sft	-	Soft	Hd	-	Hard
Tr	-	Trace	Occ	-	Occasional
Sl	-	Slightly	V	-	Very
Lt	-	Light	Dk	-	Dark
Med	-	Medium	Crs	-	Coarse
Mnr	-	Minor (< 10%)	Pyr	-	Pyrite/pyritic
Gy-gn	-	Greyish green	Gn-gy	-	Greenish grey
Gn/gy	-	Green and/to grey			

significant in hydrocarbon generation, particularly in explaining differences between argillaceous and calcareous rocks, but the preference for normal hydrocarbons rather than their branched isomers shows that thermal cracking is dominant in maturation.

Hence, in response to the greater temperatures generated by increasing depths of burial, a negligible source potential is gradually replaced by a realisable potential for hydrocarbons. The first maturation reactions to occur are those which have low activation energies, such as the thermal generation of dry gas (methane). Light liquid hydrocarbons are still absent at this level of maturation which is termed IMMATURE. Immature rocks cannot source oil and only limited amounts of dry gas should be anticipated.

At higher temperatures, light liquid hydrocarbons are formed by the thermal cracking of larger molecules (Rogers and Koons, 1971; Bailey et al., 1973a; Durand and Espitalie, 1972). The sediments are now MATURE. The initial hydrocarbon liquids which are available for migration away from mature source rocks are heavy condensates (Savvina and Velikhovskii, 1968) and young oils with gravities of approximately 20°API (Rogers, Bailey et al., 1972). Tars result from the alteration of pre-existing crude oils and are not a primary product (Bailey et al., 1973b). As thermal maturation proceeds, more and more of the lighter hydrocarbons are cracked off the heavier compounds and the source rocks yield lighter crudes which ultimately, are replaced by light condensates. Hydrocarbon liquids can only be yielded by mature source rocks and the most prolific generation probably occurs in the centre of the maturation range between approximately 175°F and 275°F (Kartsev et al., 1971; Kontorovich, 1968; Radchenko, 1968; etc.). Although gas may also be found in rocks other than those which are mature, it is within the mature and more advanced stages that the most



copious production occurs (Modelevskiy et al., 1972). Some sediments are gas-prone at levels of thermal alteration equivalent to the mature stage (Staplin, 1969; see below).

At advanced levels of thermal alteration ORGANIC METAMORPHISM destroys not only the ability of source rocks to yield liquid hydrocarbons but also any liquids which had previously accumulated in reservoirs. Only dry gas, which may contain significant amounts of  $H_2S$  and  $CO_2$  can now be generated. With progressive metamorphism, the kerogen becomes increasingly rich in carbon and a poorer gas source until eventually it is converted into graphite and loses all potential even for dry gas. The mature level is replaced by the organic metamorphic state at a temperature approximately  $150^{\circ}F$  lower than that necessary for greenschist metamorphism (Evans and Staplin, 1971) and hence thousands of feet above the first conventional metamorphism readily visible in hand specimen.

By definition, kerogen is that fraction of the total organic matter (commonly over 90%) which is insoluble in organic solvents. It consists of the organic matter which was sedimented and survived diagenesis, modified by the products of bacterial metabolism. Kerogen varies in character as a function of the proximity of the basin of deposition to sources of land plant and algal (freshwater or marine) debris. Although source rocks are laid down sub-aqueously rather than subaerially, their organic matter may originate either within the water body or from land (Rodionova and Maximov, 1970). This in turn affects the type of hydrocarbons which the sediment will yield : woody organic matter tends to be gas-prone regardless of its level of maturation (Staplin, Bailey et al., 1973); epicuticular plant waxes are a rich source of paraffinic-base crudes (Hedberg, 1968; Biederman, 1969; Reed, 1969), and the associated plant material is a more prolific

source of gas than algal debris, which is primarily a rich source of more normal crudes.

b. Source Richness

Good source rocks must contain abundant hydrocarbons which are able to migrate into the reservoir. Migration is most efficient when the source and reservoir facies are interfingered. Thick shale intervals are less suitable.

Petroleum geochemistry is concerned with the source richness aspect. Lean rocks are unable to yield commercial amounts of hydrocarbons to the reservoir. As major hydrocarbon accumulations are the exception rather than the rule it is likely that the most favourable sources are of above average richness (i.e. shales with more than 1.14% organic carbon and 96 ppm heavy hydrocarbons (Gehman, 1962)), and this is borne out by experience. Although carbonates and particularly argillaceous carbonates, can source oil, the best sources are generally shales and siltstones. Sandstones are seldom significant as their organic matter content is not only low but has been oxidised during deposition, thus largely destroying its hydrocarbon potential. The lagoonal sands described by Palacas et al. (1972) are exceptional in the quality of their organic matter but are still lean.

As the soluble fraction of organic matter (soluble extract or bitumen) is generally less than 10% of the total and of this less than one half is hydrocarbons, sediments with less than approximately 0.3% organic carbon can be ignored. The best sources have more than approximately 2% organic carbon but excessively rich rocks such as oil shales and cannel coals may not realise their anticipated potential for oil (humic coals may be prolific gas sources). This is because migration of the liquid hydrocarbons may be prevented by their adsorption upon the abundant organic matter (Erdman, 1961; Philippi,

1965). As a result, a rock with 100 ppm heavy hydrocarbons (i.e. average shale) may have some source potential for oil if it contains 0.8% organic carbon but not at 8% organic carbon when the hydrocarbon to organic carbon ratio is an order of magnitude lower.

The higher the hydrocarbon to organic carbon ratio, the better the source (Erdman, 1961; Philippi, 1965). Immature rocks may be potentially rich sources but at their present level of maturation have low hydrocarbon to organic carbon ratios. This problem of evaluating future source potential is overcome by considering the ratio of soluble extract to organic carbon.

Source richness is also a function of kerogen type. Algal debris is commonly richer than land plant debris but nevertheless the latter is a perfectly valid exploration objective.

c. Conclusions

Source rock evaluation must include consideration of both the richness of the source and the type of hydrocarbon it will yield in its present maturation state. This necessitates analytical data on the total soluble extract, the proportion of hydrocarbons within it, and the organic carbon content.

2. Analytical Techniques

The analytical laboratory of Robertson Research International Limited is supervised by a qualified chemist. High standards are maintained and blanks are run routinely. Prior to submission for analysis, the samples are washed free from drilling mud and hand picked to remove obvious cavings and particulate contamination reflecting the drilling techniques employed (lost circulation material, paint etc.). Samples are crushed to minus 60 mesh and split into two, one portion being used for organic carbon determination and the other for extraction.

Carbonate material is removed from the first split by acid attack and the organic carbon content then measured with a Leco carbon analyser in which the amount of CO<sub>2</sub> generated by heating is calibrated by the change in thermal conductivity.

The other sample portion is Soxhlet extracted for 12 hours with 2:1 benzene-methanol to give the total soluble extract (saturates, aromatics and resins plus asphaltenes). The extract is then redissolved in n-pentane and saturates and aromatics separated and measured by high pressure liquid chromatography using a carbon specific FID detector for quantification. This technique is more rapid than conventional liquid chromatography and can handle smaller samples.

### 3. Presentation and Interpretation of Data

The geochemical interpretation includes graphical presentations to highlight the exploration significance of the data.

Three diagrams are involved in the evaluation of source rock potential. The first of these ("Type of Hydrocarbon Product from Source Rocks") deals with the type of hydrocarbon (gas, oil) which the samples can yield at the present time. The two axes are the proportion of hydrocarbons in the total soluble extract and the proportion of the total organic carbon which the soluble extract constitutes - i.e. it is a plot of maturation state (incorporating the influence of different types of organic matter) against richness. Samples which are heavily oil-stained, or contaminated with other non-indigenous hydrocarbons (e.g. pipe dope etc.) can be recognised and the remainder qualified in terms of the type of hydrocarbon for which they have present potential. This decision is a function of the proportion of hydrocarbons in the total extract; with increasing maturation, the proportion of hydrocarbons increases (Tissot et al., 1971, etc.) indicating the onset and continued enhancement of oil source potential. Naturally there are "grey"

areas between fields; within the central field, oil potential increases at the expense of gas in an upwards direction. The ratio of saturated (paraffins) to aromatic hydrocarbons is also considered but does not appear in the diagram. If a sample has some oil potential, its richness can be evaluated with the next diagram.

The source richness of samples which are sufficiently mature to yield oil can be determined directly from a plot of hydrocarbon abundance against organic carbon content ("Mature Source Rock Richness"). An estimate can also be made of the potential richness of immature samples (i.e. richness if the sample were mature in a down-dip position). The plot is divided into fields which are labelled to facilitate an evaluation of the relative amounts of liquid hydrocarbons which can be anticipated from a particular sediment. Samples with less than 0.3% organic carbon and 100 ppm hydrocarbons are considered to be too lean to constitute an effective source. Oil potential is divided from gas-with-minor-oil potential by the 100 ppm hydrocarbon line up to an organic carbon content of 1% using the reasoning that an effective oil source must be richer than the average shale (96 ppm hydrocarbons, 1.14% organic carbon; Gehman, 1962). In more organically-rich sediments, natural chromatography may prevent the release of liquid hydrocarbons into the reservoir and hence the extension of the boundary follows a hydrocarbon to organic carbon ratio value of 0.01. The oil field is divided into fair (commercial oil in non-frontier areas), good (major oil, commercial in all areas) corresponding closely with Philippi's (1965) definition of a source rock, and very good (highly desirable) source rocks. If the hydrocarbon to organic carbon ratio is above 0.2, the sample is oil-stained or otherwise contaminated with non-indigenous hydrocarbons. Naturally, lesser contamination may be present in samples which apparently possess oil source potential. The recognition of such effects requires an experience factor. Samples which fall into the gas-with-oil or gas field

may contain significant quantities of heavy hydrocarbons but cannot source significant oil due to natural chromatography or the inadequate generation of the lighter liquid hydrocarbons necessary for migration. The potential of mature (oil-prone) samples equivalent to the immature (gas-prone) samples which were analysed can be estimated by assuming that ultimately, approximately 50% of the total extract will be converted into hydrocarbons.

The final diagram ("Source Rock Summary Chart") integrates the lithology of the samples as analysed, with certain analytical results (organic carbon content and hydrocarbon abundance with appropriate cut-offs, and EPOC, extract percent of organic carbon, which is the percentage of the organic carbon soluble in organic solvents), and the interpretations derived above (richness and product type). Maximum palaeotemperature measurements are included for ease of reference and comparison. The data are plotted against depth and the good source intervals can be recognised at a glance. EPOC is a measure of the potential source quality of immature samples, and the required additional burial to achieve maturity can be estimated from the temperatures necessary for maturity and the palaeogeothermal gradient. Using the same reasoning, the depth to organic metamorphism (and hence dry gas potential) can be estimated. If a section is gas-prone the maximum palaeotemperature can indicate why : immaturity, metamorphism, or organic matter unfavourable for oil generation.

Following the discovery of liquid hydrocarbons, it is important for future play evaluations to recognise those intervals which have demonstrated their oil potential.

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## APPENDIX II

### MAXIMUM PALAEOTEMPERATURE ANALYSIS

#### 1. Definition of Problem

Recent sediments not only have a lower total abundance of hydrocarbons than more ancient sedimentary rocks, but those hydrocarbons with between two and fourteen carbon atoms in the molecule which are present in ancient sediments and which constitute up to fifty percent of a typical crude oil, are largely absent (Sokolov, 1957; Dunton and Hunt, 1962; Kvenvolden, 1962). Hence such rocks are unable to source oil (Erdman, 1961) but may have a limited potential for dry gas. Russian authors have reported accumulations of biologically-generated (biogenic) gas from young sediments but such instances are anomalous, non-predictable and cannot form the basis of an exploration play. With burial, hydrocarbon abundance increases (Philippi, 1965; Tissot et al., 1971) and more significantly, the previously absent lighter liquid hydrocarbons appear (Rogers and Koons, 1972; Durand and Espitalie, 1973; Bailey et al., 1973). This process is called maturation. Although catalytic cracking is undoubtedly significant, particularly in explaining differences between argillaceous and calcareous source rocks, the preference displayed for straight-chain compounds rather than their branched isomers indicates that maturation is dominated by the thermal cracking of pre-existing large molecules. In other words, it is temperature dependent.

As the formation temperatures due to burial increase, but prior to the appearance of all the  $C_2$  to  $C_{14}$  hydrocarbons, the rocks develop some, but still limited, potential for dry gas. At this level of maturation they are still described as "IMMATURE".

When a complete spectrum of hydrocarbons has been generated, the sediments possess the ability to source liquid hydrocarbons and are termed

"MATURE". The initial products are heavy condensates (Savvina and Velikhovskii, 1968), and young oils (not tars) with gravities of around 20° API (Rogers, Bailey et al., 1972). As the maturation process proceeds, lighter oils are generated until eventually the heavier molecules are largely broken down and a potential for light condensate results. Naturally, the oil-condensate boundary is transitional. Liquid hydrocarbons can only be sourced by mature sediments. The most prolific gas sources correspond either to the mature or more advanced levels of thermal alteration (Modelevsky et al., 1972). With further thermal alteration only the lightest hydrocarbon, methane, is left and the source rocks only have a potential for dry gas. This is termed the level of "ORGANIC METAMORPHISM" and again, is transitional to the mature stage. Particularly in carbonates, the gas may be sour (Kozlov, 1950). Organic metamorphism occurs at temperatures approximately 150° F lower than those corresponding to the onset of the greenschist facies of conventional metamorphism (Evans and Staplin, 1971). The organic matter in "sediments" which have suffered greenschist facies metamorphism is converted to graphite and does not retain any potential for hydrocarbons.

Gas may be sourced without oil but oil is always accompanied by gas and hence the term "oil potential" is purely relative. Some sediments which should be sufficiently mature to source oil are in fact gas-prone due to the character of the kerogen which they contain (Staplin, 1969; Staplin, Bailey et al., 1973). Woody kerogen tends to yield dominantly gas whilst non-woody land plant material and algal debris are both oil-prone if mature, although the former yields more associated gas and requires a somewhat higher temperature to become mature (Nalivkin et al., 1967; Kontorovich, 1968). The influence of organic matter type is evaluated by integrating maximum palaeo-temperature with source rock potential analysis unless a palynological examination is requested.

The length of time over which a sediment is exposed to a given temperature is also important as time and temperature are to some degree exchangeable and a reaction will proceed more nearly to completion if a longer time is allowed (Lopatin, 1971; Welte, 1972). The effect of time can be gauged from the fact that a Cretaceous sediment becomes mature at a temperature approximately  $10^{\circ}\text{F}$  lower than that necessary for a comparable Miocene rock.

Although the effects of kerogen type and time must be recognised, temperature dominates the maturation process. Approximate values can be applied to the various levels of maturation discussed above :

$150^{\circ}\text{F}$  for the immature gas to mature transition (Correia, 1969; Kartsev et al., 1971; Louis and Tissot, 1967; Kontorovich, 1968),  $300^{\circ}\text{F}$  for the oil to light condensate transition (Momper, 1972) and  $350^{\circ}\text{F}$  for the condensate to metamorphosed dry gas transition (Evans and Staplin, 1971; Momper, 1972). If the temperature to which a rock has been exposed can be measured, the sediment can be fitted into the correct slot (immature, mature, metamorphosed) and predictions can be made concerning neighbouring sections with different burial histories.

## 2. Analytical Techniques

Samples are washed and hand-picked to remove both contamination introduced during drilling and caved material, before being described and then submitted for analysis. The inorganic material is qualitatively removed by digesting the samples with acid and the kerogen concentrate is washed with an organic solvent to remove non-indigenous hydrocarbons.

During thermal cracking, free radicals (with unpaired electrons) are generated (Duchesne et al., 1961; Retcofsky et al., 1968; Marchand et al., 1969). Those which are associated with aromatic ring structures are protected from further reaction and provide a record of the thermal history

of the kerogen. Hence, the higher the maximum temperatures to which the sample is exposed, the greater the number of unpaired electrons per unit of kerogen. These unpaired electrons are studied with an electron spin resonance spectrometer which measures the absorption, by kerogen placed in a varying magnetic field, of a fixed microwave frequency. Three parameters are obtained:

- a.  $N_g$  - the number of unpaired electrons per gramme of organic carbon;
- b.  $g$  - the spectroscopic splitting factor;
- c.  $W$  - the width of the resonance signal in gauss.

Several hundred samples which, from geological and palaeontological reasoning, are believed to be at their maximum depth of burial at this time, have been selected as standards. Their formation temperatures are known from reliable formation and drillstem tests and from E-log measurements. The three ESR parameters discussed above have been calibrated against these formation temperatures and hence the maximum palaeotemperatures of unknown samples can be established. The practical application of ESR techniques has been discussed by Pusey (1973).

Internal standards are run constantly and reproducibility is excellent ( $\pm 15^\circ\text{F}$ ).

### 3. Presentation and Interpretation of Data

The maximum palaeotemperature values are presented in tabular form and are illustrated graphically in two diagrams to facilitate their direct correlation with other geological data.

The first diagram is a plot of maximum palaeotemperature values against present-day depth of burial. A regression line is fitted to the data points and its correlation coefficient calculated (the data may indicate several legs rather than a single regression line). Its slope gives the

palaeothermal gradient and the temperature at which it intercepts the surface is also quoted. Surface intercepts significantly higher than the temperatures prevailing in the basin of deposition, and jumps within the subsurface data points, both indicate the removal of section by erosion. Igneous activity may be recognised by distortion of the data.

The relevance of maximum palaeotemperature measurements to petroleum geochemistry is illustrated by the second diagram ("Source Rock Product as a Function of Thermal Alteration") which is a plot of temperature against the age of the rock (in millions of years). Uphole samples are plotted towards the top of the diagram and those which have experienced higher temperatures occur lower down.

The diagram is divided into three major fields all of which are transitional one to the other, but within each of which there is a most likely product :

1. The immature field has a potential only for dry gas and not for oil or other liquid hydrocarbons. Indeed, except at higher temperatures, it generally has a poor potential even for gas.
2. The mature field is the only one from which liquid hydrocarbons can be sourced. At the low temperature end it is prone to yield heavy condensates and young oils with gravities around 20°API. With higher temperatures, lighter oils are sourced until eventually, the oil field phases into the light condensate field within which the probability of oil diminishes progressively and that of gas increases. Oil potential is probably maximal between 175°F and 275°F. Oil generation is always accompanied by gas.
3. The field of organic metamorphism has a potential only for dry gas - sometimes with significant non-hydrocarbon contents. In carbonates the gas may be sour. At more advanced levels of metamorphism the

kerogen becomes increasingly carbon-rich and possesses a lower potential which is effectively destroyed prior to the onset of greenschist metamorphism.

Oil may be accumulated in an immature section if the reservoir is in communication with mature source rocks downdip. In contrast, organic metamorphism destroys not only the oil potential of source rocks but also any liquid hydrocarbons which had accumulated in reservoirs and hence metamorphosed sections are always dry gas objectives.

In addition to evaluating the present maturation state of a section, maximum palaeotemperature measurements can also be used predictively. For example, if a well only penetrated immature strata, the palaeothermal gradient can be projected (assuming constancy) downwards to estimate the depths at which the temperatures necessary for the onset of maturation and also organic metamorphism are achieved, thus defining the "oil envelope". Such predictions can also be extrapolated to include potential plays in nearby areas with similar depositional histories to provide pre-drill information.

It should be noted that interpretations discussed above may not apply to over-pressured sections due to the restraints imposed upon migration in such intervals.

A simplified composite of these two diagrams is included in the Source Rock Summary Chart to facilitate the integration of the total data pertaining to source rock evaluation.

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## VITRINITE REFLECTIVITY ANALYSIS

### 1. Definition of Problem

Recent and very immature sediments can yield biologically-generated dry gas (which is only trapped under unusual conditions such as gas hydrate formation) but cannot source either oil or condensate. In response to the higher temperatures resulting from increased depths of burial, immature rocks become mature and then, at even higher temperatures, organically metamorphosed. This is discussed in greater detail in the 'Source Rock Potential' section. As immature sediments generally have little economic significance, whereas only mature sediments can yield oil, and metamorphosed sediments have a potential only for dry gas (often in major amounts), it is important to recognise the maturation state of the source rocks in the section.

This can be achieved by measuring the reflectivity (i.e. the proportion of the light from the light source which is reflected by the polished surface) of vitrinite macerals within the total kerogen. As the level of maturation increases, so too do the vitrinite reflectivity values, which can therefore be used to estimate the maturation state of the kerogen.

### 2. Analytical Techniques

The rock cuttings are mounted in a one-inch block of clear plastic resin and then ground and polished using successively finer grades of alumina until a good surface is achieved.

Reflectivity determinations are carried out on a Leitz M.P.V. micro-photometer using optical glasses as standards. The field of measurement is adjusted to the size of the particle but is generally in the order of 2-3 microns. All measurements are made at a wavelength of 546 nm in oil of R.I. 1.516.

Whenever possible, twenty vitrinite particles are measured in sediment samples and the results used to construct a histogram and to calculate the mean value of the sample.

Using the whole sediment sample rather than a kerogen concentrate has the following advantages :

- it is easier to distinguish vitrinite from the other kerogen macerals, the measurement of which would give incorrect results;
- reworked and caved material can be more easily recognised and avoided;
- the possibility of alteration (oxidation) of the vitrinite during concentration is eliminated;
- oxidation caused by the excessive heating inherent in incorrect sample drying techniques (e.g. infra-red lamps) at the wellsite can be recognised and avoided.

### 3. Presentation and Interpretation of Data

An advantage of this method is that individual macerals can be examined and only those which are truly representative (i.e. ignoring reworked, caved and artificially oxidised material) recorded. Reworked material is commonly present and is a serious disadvantage of all the methods which involve the examination and measurement of the gross kerogen rather than of its individual macerals, as maturation levels significantly too high may be indicated. If this is the case then, for example, an uninteresting immature interval may be interpreted to be a prospective mature horizon. The same would be true if an interpretation were based upon artificially oxidised material whereas the use of caved sediments would underestimate the true level of maturation.

The analytical data, a histogram of these reflectivity determinations and the mean values for each sample are presented. In some cases three mean values are quoted; one referring to those measurements which are considered to be representative of the indigenous, unoxidised vitrinite (underlined), one referring to measurements on caved material, and one referring to reworked material. In most cases only one or two values will be quoted depending on the depth in the section. In addition, the equivalent, dry-ash-free carbon content of an equivalent coal is supplied for comparison with the work of Teichmuller (1971). Two diagrams are involved in the interpretation of the results. The first is a plot of the change in vitrinite reflectance with depth in the well section. Reflectivity determinations based upon indigenous material are distinguished from those which are judged to be caved or reworked. A line is fitted to the selected data points. The second diagram is a plot of depth in the well section against the carbon content of an equivalent coal on the dry-ash-free basis. This diagram is included to give an indication of the 'rank' gradient down the hole.

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## LIGHT HYDROCARBON ANALYSIS

### 1. Definition of Problem

Recent and immature sediments either do not contain the light hydrocarbons with between two and fourteen carbon atoms or contain only a few of the isomers which are present in mature sediments and crude oils. Yet these hydrocarbons which are absent or largely absent from immature sediments commonly constitute up to 50% of a crude oil and are totally dominant in condensates. Furthermore, in oil and condensates the relative proportions of the individual hydrocarbons are totally different from those in recent sediments. Clearly, immature sediments cannot yield something which they do not contain and hence cannot source oil and condensate to associated reservoirs.

Mature sediments however, resemble crudes in that all of the light hydrocarbons are present and hence, by virtue of this, are able to source liquid hydrocarbons. This is the most definitive method of determining whether or not a source rock has a potential for oil. The richness of the rock and hence the amount of oil it can yield is reflected in the abundance of the light hydrocarbons, although the heavy hydrocarbons are a better measure of richness.

The changes in the total  $C_2-C_{14}$  fraction can conveniently be traced by observing the  $C_2$  to  $C_7$  hydrocarbons.

This reasoning is developed more fully in the section dealing with the Source Rock Potential Analysis.

## 2. Analytical Techniques

The C<sub>1</sub> through C<sub>4</sub> hydrocarbons which are gaseous at room temperature, are released by blending the washed sample to a fine powder in a modified coffee grinder. The abundance and composition of the freed gases are measured gas chromatographically. This analysis provides a quantitative measure of the sample as received, but unless the samples are canned most of these gases are lost before the samples are received at the laboratory.

A semi-quantitative measure of the C<sub>5</sub> through C<sub>7</sub> hydrocarbons can be provided on samples which have not dried out and for this analysis, canning is not necessary. These hydrocarbons are released from the washed sample by heating and, as before, measured gas chromatographically.

## 3. Presentation and Interpretation of the Data

The C<sub>1</sub>-C<sub>4</sub> and C<sub>5</sub>-C<sub>7</sub> data are tabulated as p.p.m. or p.p.b. of the rock and each compound is expressed as a percentage of the total C<sub>1</sub>-C<sub>4</sub> or C<sub>5</sub>-C<sub>7</sub> hydrocarbons.

Two diagrams are involved in the interpretation. That for the C<sub>1</sub>-C<sub>4</sub> gaseous hydrocarbons illustrates the change in abundance and composition (% C<sub>1</sub> and % C<sub>2</sub>-C<sub>4</sub>) with increasing depth. The second diagram involves the C<sub>5</sub>-C<sub>7</sub> gasoline range hydrocarbons and is a plot of the abundance of the total C<sub>5-7</sub> hydrocarbons and of the chromatogram type against depth in the well. The chromatograms are described as types A, B, or C. Type A is immature and such source rocks do not have a potential for liquid hydrocarbons. Type B is transitional between types A and C and indicates that maturation has started to generate the lighter hydrocarbons. Type C chromatograms are typical of mature source rocks which have a potential for liquid hydrocarbons or of sediments which have been affected by migrated hydrocarbons. These gasoline range data give a very definitive evaluation of the potential of the section (oil or gas) and of its richness.