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GCB/97/83

JULY 1983

GEOCHEMISTRY BRANCH

THE SOURCE POTENTIAL OF THE WELL 2/1-5; CENTRAL NORTH SEA, NORWAY.

by

M.P. Dee and P.C. Mason

Work by:

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Approved by:

S.W. Richardson

Memorandum

To Dr A.M. Spencer, BP Petroleum Development, Norway

From S.W. Richardson, Geochemistry Branch, Sunbury

Our ref GCB/97/83

Date 28th July 1983

Your ref

Subject THE SOURCE POTENTIAL OF THE WELL 2/1-5: CENTRAL NORTH SEA, NORWAY

The attached report shows moderate to good remaining potential through much of the Upper Jurassic mudstone sequence (Figure B), despite the fact that these rocks are well into the oil-generation window. The correlation with gamma activity (Figure C) may help you to interpret source richness where you do not have such detailed pyrolysis cover.

S.W. RICHARDSON
EXTENSION 2881

Attachment

MEMORANDUM

TO	Dr. M.J. Gibbons Geochemistry Branch, Sunbury	DATE	6.4.83
FROM	A.M. Spencer, Stavanger	YOUR REF.	
SUBJECT	GEOCHEMICAL STUDIES - WELL 2/1-5	OUR REF.	AMS/lu/66511

As we discussed during your recent visit (your memo of 25 March), the 550 m thick Jurassic mudstone sequence (3880 - c. 4430 m) we have encountered in this well gives us, for the first time in Norway, the opportunity to try to get knowledge of the detailed stratigraphical distribution of source richness in, particularly, the U. Jurassic. We have taken 60 + SWC in this interval. I attach a xerox copy of a GSR form (1201) to allow the study to be initiated.

In case you need them, I shall also send to you all of the canned wet geochem samples from the well. (Note that we do NOT wish you to undertake a standard well geochemistry study: studies on previous wells give sufficient standard information). When it is slabbed, we shall also send to you samples from our mudstone core (3934-3951 m), which you can also use.

Please note, also, that the biostratigraphic analysis of this mudstone interval is very important to us. Biostrat studies of the cuttings encountered major problems due to caving of material. The biostratigraphers must, therefore be provided with part of each SWC. Also, we shall send a few of the sandstone SWC to Sedimentary Petrology Branch.

Yours sincerely,
for BP PETROLEUM DEVELOPMENT LTD., NORWAY U/A

A.M. Spencer

A.M. Spencer
Chief Geologist

cc. B.G. Williams
V. Wiik
Dr. G.A. Booth, Stratigraphy Branch, Sunbury

DATA BANK SUMMARY SHEET

Coordinates of area and/or wells described.

56° 47' 54" N
03° 12' 21" E

Country/Area:

NORWEGIAN SECTOR NORTH SEA

Basin(s):

F010 CENTRAL GRABEN

Stratigraphic range covered:

LOWER CRETACEOUS TO JURASSIC

Report does/~~does not~~ contain significant well data.

Keywords:

SIDEWALL CORES
PYROLYSIS
SOLUBLE EXTRACTS
GC - MS.

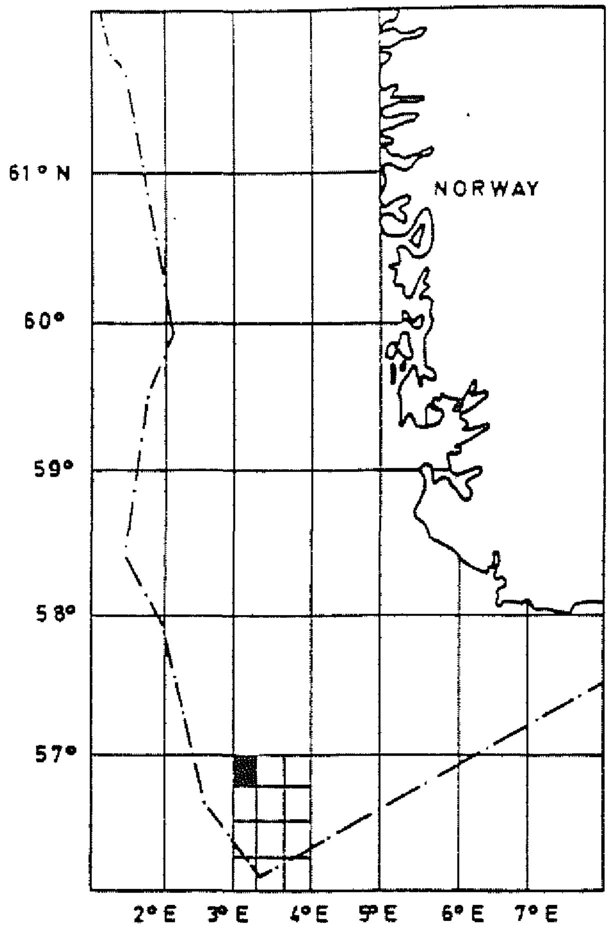
CONTENTS

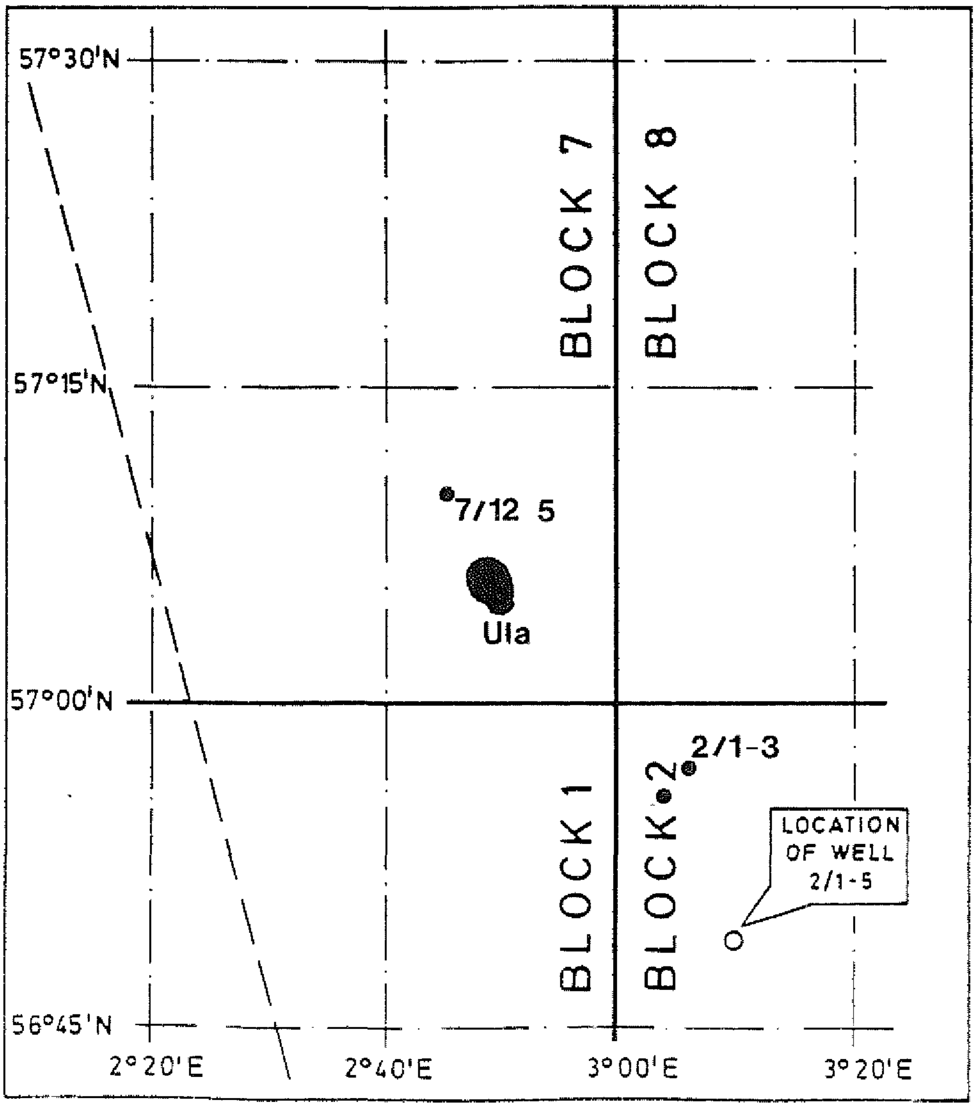
1. INTRODUCTION

The well 2/1-5 is sited on the edge of the Central Graben within the Norwegian sector of the North Sea. It lies south east of BP's Ula field and is on the southern flank of the same salt-induced structure as the 2/1-3 discovery.

The well penetrates 550m of Jurassic mudstones enabling the detailed stratigraphic distribution of source potential to be investigated. Consequently fifty mudstone and two limestone sidewall cores from the Jurassic interval were examined.

LOCATION MAP WELL 2/1-5





(fig A)

2. RESULTS AND DISCUSSION

2.1 Maturity

Although a maturity study was not requested, limited data are available from a number of sources:-

a) The extraction of two samples from 4100 and 4173m provides some maturity data. The n-alkane distributions (figs 7 and 8) show these sediments to be mature, with CPI values of 1.07 and 1.08 respectively. Poor resolution of their GC-MS fragmentograms prevents an accurate maturity estimate being made. However the molecular parameters show the samples to be mature.

b) The product indices (P1/P1+P2) of all the samples screened by pyrolysis are greater than 10% indicating a mature, currently generating source interval.

c) Thermal Volatilate (P1) chromatograms show a mature oil-like distribution confirming this as an 'active' source rock.

d) Vitrinite reflectance data from two adjacent wells , 2/1-2 (2) and 2/1-3 (3), suggest that Late Jurassic sediments between 3800m and 4000m are marginally to early mature (4). In 2/1-5, where the majority of samples lie below 4km, mature sediments can be expected.

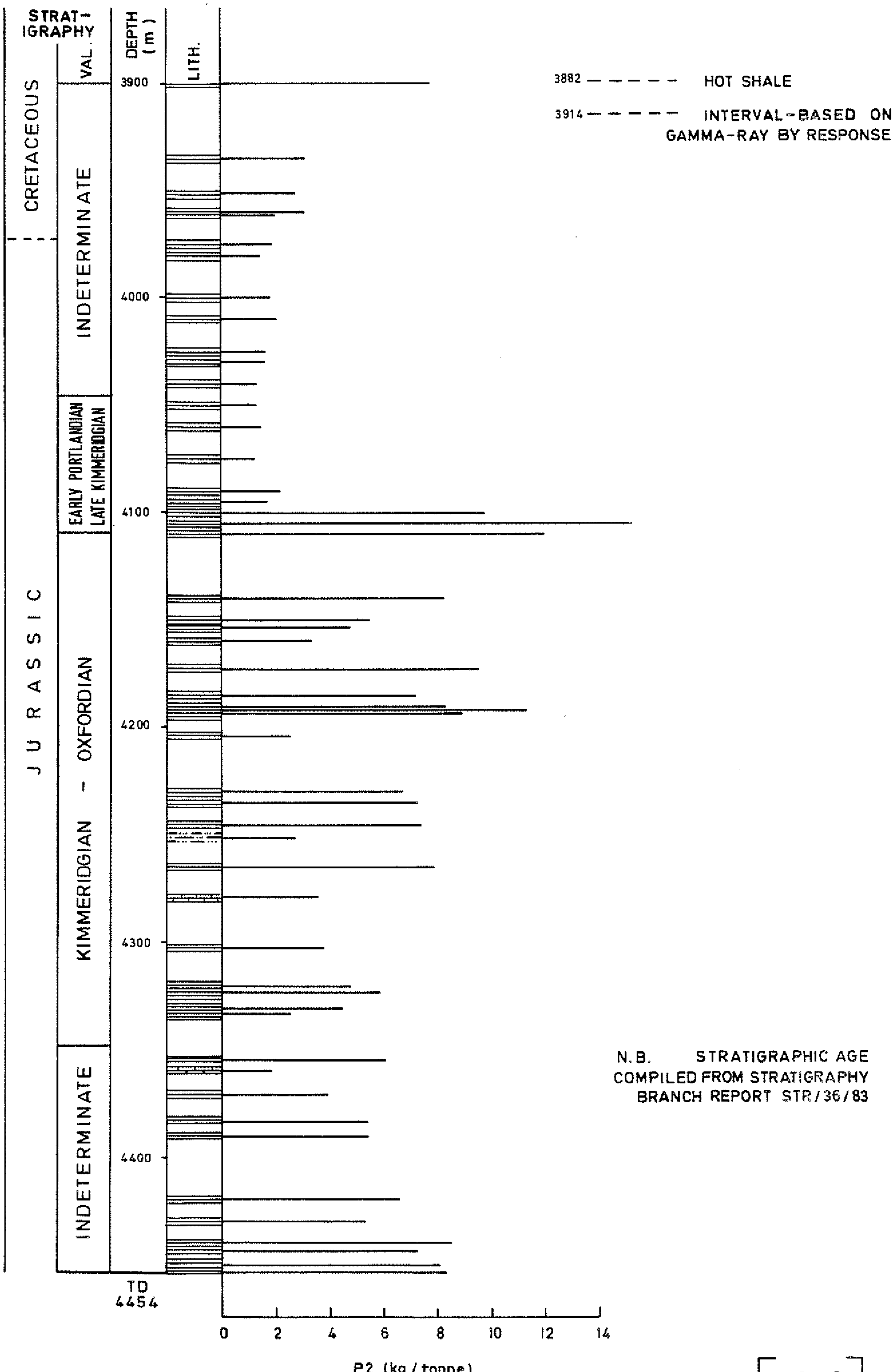
In summary, the available data suggest that the examined samples are from a mature generating source interval.

2.2 Stratigraphic Distribution of Source Potential

Pyrolysis screening of the samples indicates generally moderate to good source potential throughout the 550m mudstone sequence. Figure B illustrates the stratigraphic distribution of this potential; with the dating provided by Stratigraphy Branch (5) and the 'hot-shale' unit (3882-3914m) identified by gamma-ray log response (6). Only one sample (3900m) falls within the hot-shale unit and shows good oil prone potential (P2 yield = 7.7 Kg/t and GOGI = 0.28).

The interval between 3935m (Indeterminate Jurassic/Cretaceous) and 4095m (Early Portlandian - Late Kimmeridgian) has only poor to moderate source potential (P2 = 1.3 - 3.2 Kg/t). Pyrolysis-gc analysis of the sample from 3960m (P2 = 3.1 Kg/t) gives a GOGI of 0.42, indicating a gas and oil prone potential. This drop in oil source potential concurs with the passing of the hot-shale unit.

STRATIGRAPHIC DISTRIBUTION OF SOURCE POTENTIAL WELL 2/1-5 NORWAY



N.B. STRATIGRAPHIC AGE COMPILED FROM STRATIGRAPHY BRANCH REPORT STR/36/83

FIG. B

However, between 4095m and 4100m (Early Portlandian - Late Kimmeridgian) the source potential shows a marked increase, from P2 = 1.8 kg/t to P2 = 9.8 kg/t. A band of generally good source potential (P2 >5 kg/t) continues down through the Kimmeridgian - Oxfordian (4109 - 4358m) and Interdeterminate sequences to TD at 4454m. Within this, zones of more moderate potential (1.5<P2<5kg/t) are identified, particularly between 4250m (Kimmeridgian - Oxfordian) and 4371m (Indeterminate).

The gamma-ray log reflects these generally higher pyrolysis yields by showing a marked sustained increase in response coinciding with the top of the interval of enriched source potential. Many of the lower yields recorded between 4100m and TD can be identified as troughs on the log. Figure C illustrates a relationship between the log response and pyrolysis yield. A reading of 70 API units for these mudstones appears to mark the boundary of good source potential. The scatter in points, especially at higher values, may be function of Kerogen type and the rate of its breakdown in a mature generating sequence.

Work by Stratigraphy Branch at BP Sunbury (5) has identified the top of the hot shale "palynofacies type" as coinciding with the top of the gamma-ray log "hot-shale unit" (3882-3914m). But unlike the log response, which decreases between 3914 and 4100m, the hot shale palynofacies is present throughout the interval of lower log response and pyrolysis yields. This lack of response/potential may possibly be explained by the dilution of organic matter due to increased sedimentation rates. The base of this characteristic palynofacies is not seen above 4150m, below which depth palynomorphs are absent and palynological organic residues are severely degraded and blackened.

Pyrolysis-gc analyses of selected samples indicate gas and oil prone potential. However, with levels of maturity approaching OGM, ca 50% of the original source potential could have been liberated, mainly as liquid hydrocarbons. Consequently the original oil proneness of the sediments would have been greater than that currently recorded.

GAMMA-RAY LOG RESPONSE (API UNITS) VS P2 PYROLYSIS YIELD (KG/T)

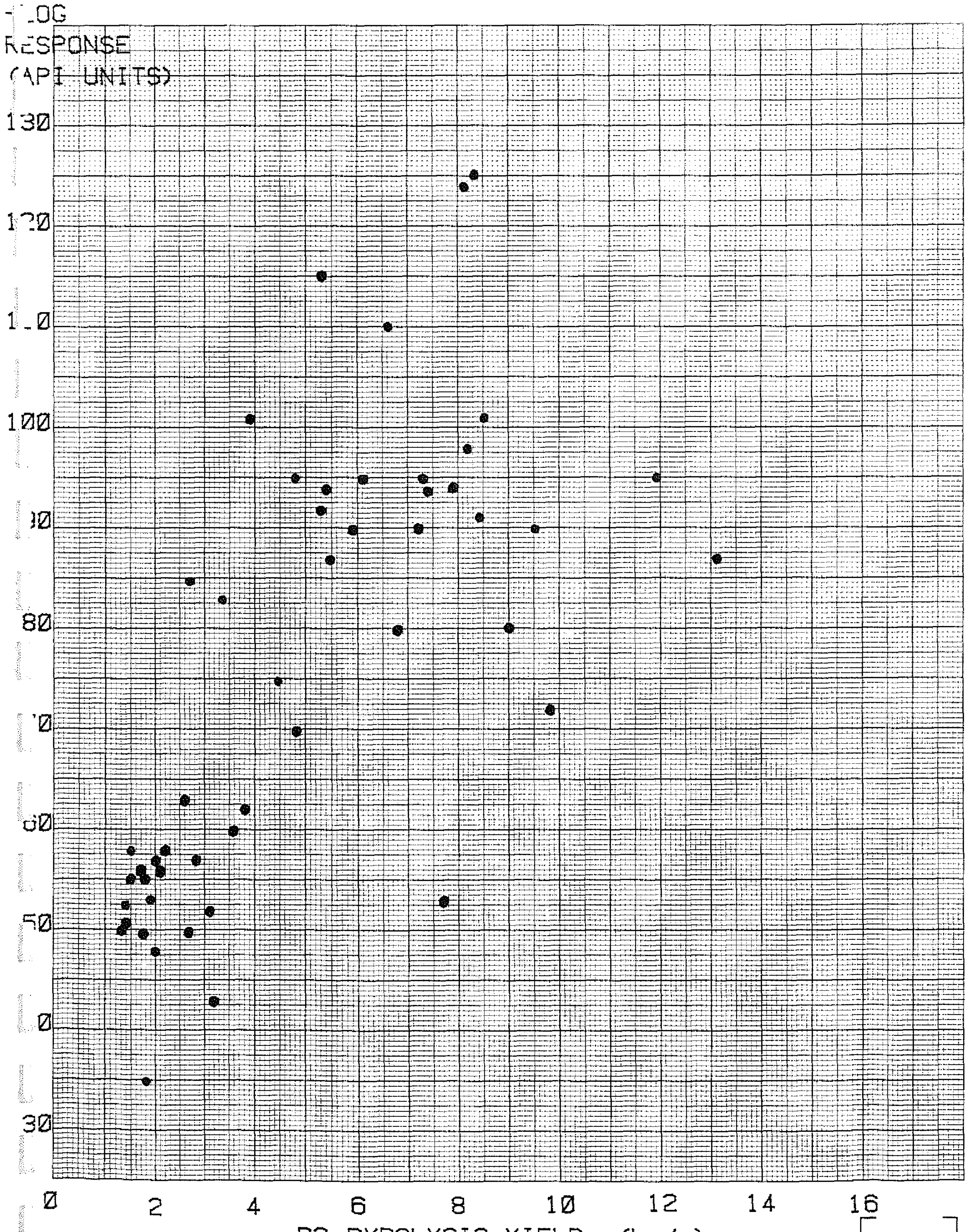


fig C

BP. 14. (JAN. 62)

3. CONCLUSIONS

1) Limited maturity data suggest that the examined samples are from a mature, generating, source interval.

2) The Late Jurassic/Early Cretaceous "hot-shale" unit (3882-3914m) has good oil and gas source potential.

3) The underlying zone of Indeterminate and Early Portlandian to Late Kimmeridgian age (3915-4095m) shows predominantly moderate source potential. This is reflected in a low gamma-ray log response.

4) Between 4100m and TD at 4454m the sediments of Kimmeridgian, Oxfordian (and possibly older) age show an increase in source potential, that is reflected in high gamma-ray log response.

5) Pyrolysis-gc shows this good source potential to be gas and oil prone. However at levels of maturity approaching OGM, up to 50% of the original source potential may have been generated as liquid hydrocarbons. Consequently the original potentials were probably better and more oil prone than those recorded in this report.

4. REFERENCES

1.	Spencer, A.M.	1983	Memorandum to Dr. M.J. Gibbons, dated 6/4/83.
2.	Geochem Laboratories (UK) Ltd	1978	Geochemical Evaluation of the BP - NOCS 2/1-2 well, Norwegian North Sea.
3.	IKU	1980	Source Rock analyses of well 2/1-3.
4.	Cooper, M.J. Dungworth, G. Richardson, S.W. Taylor, S.	1982	A Geochemical evaluation of the Norwegian Offshore Continental Shelf between 56° and 59° North. GCB/07/82
5.	Lowe, S.P.	1983	The Biostratigraphy of the well 2/1-5, Norwegian North Sea STR/36/83.
6.	Schlumberger	1983	Gamma-ray log for the BP et al well 2/1-5, Norway.

TABLE 1

ROCK-EVAL AND PYROLYSIS DATA

WELL: 2/1-5
LOCATION: OFFSHORE NORWAY

Interval	DEPTH (m)	P1 KG/TONNE	P2 KG/TONNE	GOGI	TOC (%wt)	HYDROGEN INDEX
INDETERMINATE	3900	2.2	7.7	.28		
INDETERMINATE	3935	.9	3.2			
INDETERMINATE	3952	.8	2.8			
INDETERMINATE	3960	1.6	3.1	.42		
INDETERMINATE	3961	.7	2			
INDETERMINATE	3975	.8	2			
INDETERMINATE	3980	.4	1.5			
INDETERMINATE	4000	.4	1.9			
INDETERMINATE	4010	.5	2.1			
INDETERMINATE	4025	.8	1.7			
INDETERMINATE	4030	.5	1.7			
INDETERMINATE	4040	.3	1.4			
EARLY PORTLANDIAN TO LATE KIMMERIDGIAN	4050	.5	1.4			
EARLY PORTLANDIAN TO LATE KIMMERIDGIAN	4060	.5	1.5			
EARLY PORTLANDIAN TO LATE KIMMERIDGIAN	4075	.4	1.3			
EARLY PORTLANDIAN TO LATE KIMMERIDGIAN	4090	.5	2.2			
EARLY PORTLANDIAN TO LATE KIMMERIDGIAN	4095	.7	1.8			
EARLY PORTLANDIAN TO LATE KIMMERIDGIAN	4100	2.4	9.8			
EARLY PORTLANDIAN TO LATE KIMMERIDGIAN	4105	2.2	13.1			
KIMMERIDGIAN TO OXFORDIAN	4110	2.6	11.9	.37		
KIMMERIDGIAN TO OXFORDIAN	4140	2	8.2	.38		
KIMMERIDGIAN TO OXFORDIAN	4150	1.6	5.5	.39		
KIMMERIDGIAN TO OXFORDIAN	4153.5	1.5	4.8			
KIMMERIDGIAN TO OXFORDIAN	4160	1.3	3.4			
KIMMERIDGIAN TO OXFORDIAN	4173	2.2	9.5	.31		
KIMMERIDGIAN TO OXFORDIAN	4185	2.1	7.2			
KIMMERIDGIAN TO OXFORDIAN	4191	2.3	8.4			
KIMMERIDGIAN TO OXFORDIAN	4192	2.3	9			
KIMMERIDGIAN TO OXFORDIAN	4193	2.3	9			
KIMMERIDGIAN TO OXFORDIAN	4207	1.1	2.6			
KIMMERIDGIAN TO OXFORDIAN	4230	1.8	6.8	.43		
KIMMERIDGIAN TO OXFORDIAN	4235	1.9	7.3			
KIMMERIDGIAN TO OXFORDIAN	4245	1.8	7.4	.43		
KIMMERIDGIAN TO OXFORDIAN	4252	.5	2.7			
KIMMERIDGIAN TO OXFORDIAN	4264.9	1.9	7.9	.5		
KIMMERIDGIAN TO OXFORDIAN	4279	1	3.6			
KIMMERIDGIAN TO OXFORDIAN	4303	1.5	3.8			
KIMMERIDGIAN TO OXFORDIAN	4320	1.8	4.8			
KIMMERIDGIAN TO OXFORDIAN	4323	1.6	5.9	.38		
KIMMERIDGIAN TO OXFORDIAN	4330.9	2	4.5			
KIMMERIDGIAN TO OXFORDIAN	4333	1.3	2.6			
INDETERMINATE	4355	2	6.1	.42		
INDETERMINATE	4360	.6	1.8			
INDETERMINATE	4371	1.6	3.9			
INDETERMINATE	4384	2	5.3	.49		
INDETERMINATE	4390	2.1	5.4			
INDETERMINATE	4420	2.3	6.6	.56		
INDETERMINATE	4430	2.2	5.3			

TABLE 1 CONT.

ROCK-EVAL AND PYROLYSIS DATA

WELL: 2/1-5
LOCATION: OFFSHORE NORWAY

	DEPTH (m)	P1 KG/TONNE	P2 KG/TONNE	GOGI	TOC (%wt)	HYDROGEN INDEX
INDETERMINATE	4440	2.5	8.5	.51		
	4444	2.2	7.3			
	4450	1.8	8.1	.47		
	4454 TD	2.4	8.3			

NOTE:- GOGI VALUE IS A NUMERICAL REPRESENTATION OF THE SOURCE POTENTIAL OF A SAMPLE AT ITS PRESENT MATURITY. INTERPRETATION WITHOUT REFERENCE TO PYROLYSATE DISTRIBUTION & MATURITY MAY BE MISLEADING !

TABLE 2

SEDIMENTS SOLUBLE EXTRACT DATA

WELL: 2/1-5
LOCATION: OFFSHORE NORWAY

DEPTH (m)	TOC %wt	TSE/TOC o/oo	SAC/TOC o/oo	CPI	ASPHALTENES %wt
4100	n.d.	n.d.	n.d.	1.07	.4
4173	n.d.	n.d.	n.d.	1.08	.4

TABLE 3

SEDIMENTS SOLUBLE EXTRACT DATA

WELL: 2/1-5
LOCATION: OFFSHORE NORWAY

DEPTH(m)	%SAC	%TSE	PRIST/PHYT	PRIST/C-17	PHYT/C-18
4100	73.7	.751	1.35	.46	.43
4173	65.4	.686	1.64	.78	.59

Table 4

Lithology Description

SWC No	Depth	Description
2	4454	Mudstone, dk grey/brown, carbonaceous
3	4450	Mudstone, dk grey/brown, carbonaceous
4	4444	Mudstone, dk grey/brown, carbonaceous
5	4440	Mudstone, dk grey/brown, carbonaceous
6	4430	Mudstone, dk grey, very carbonaceous
7	4420	Mudstone, dk grey, very carbonaceous
10	4390	Mudstone, dk grey/brown, very carbonaceous
11	4384	Mudstone, dk grey/brown, very carbonaceous
12	4371	Mudstone, dk grey to black
13	4360	Limestone, med to dk grey, hard
14	4355	Mudstone, dark brown, carbonaceous, calcareous
15	4333	Mudstone, dark brown, carbonaceous, calcareous
17	4330.9	Mudstone, dk brown to black
19	4323	Mudstone, dk brown to black
20	4320	Mudstone, a/a, calcareous
21	4303	Mudstone, a/a, very carbonaceous
23	4301.5	Sandstone, off white, QTZ, med sort, well cemented, calc.
24	4301	Sandstone, brown, QTZ, poorly cemented
26	4279	Limestone, dark brown, very carbonaceous
30	4267.5	Sandstone, brown/white, QTZ, friable, Tr. of Glauconite
32	4258	Sandstone, brown, QTZ, firm to hard, fine, well cem. calc.
46	4207	Mudstone, dark grey, firm, blocky, very calcareous, carbonceou
49	4198	Sandstone, dark brown-oil stained, QTZ, fine
50	4197	Sandstone, a/a, mod. vis por. non calcareous
51	4196	Sandstone, dark brown-oil stained, QTZ fine
54	4193	Mudstone, dark grey, carbonaceous, very calcareous
55	4192	Mudstone, dark brown, layers of $CaCO_3$
56	4191	Mudstone, dark brown to black, calcareous, carbonaceous
58	4185	Mudstone, dark grey to brown to black, calcareous, carbonaceou
59	4173	Mudstone, black, calcareous, very carbonaceous
61	4160	Mudstone, dark grey, slightly calcareous, carbonaceous
63	4153.5	Mudstone, dark grey, fissile
64	4150	Mudstone, dark brown, very calcareous, very carbonaceous
65	4140	Mudstone, dark grey, soft
72	4274	Sandstone, off white to brown, soft, fine to medium
73	4264-9	Mudstone, dark grey to black
74	4258	Sandstone, brown, QTZ, friable, fine, well cemented, calcareou
77	4254	Sandstone, brown, QTZ, friable, fine, med, sorting
79	4252	Siltstone, dark red/brown, argillaceous, calcareous
81	4245	Mudstone, dark grey to black, very carbonaceous
82	4235	Mudstone, a/a, non-calcareous
83	4230	Mudstone, a/a
89	4196	Sandstone, dk brown-oil stained, fine QTZ
90	4195	Sandstone a/a friable, good visible porosity, Tr. Glaucouite
92	4110	Mudstone, dk grey to black calcareous, carbonaceous
93	4105	Mudstone, a/a
94	4100	Mudstone, black, calcareous, carbonaceous
96	4090	Mudstone, dk grey, soft, silty, calcareous, carbonaceous
100	4095	Mudstone, dk grey, very calcareous.
102	4075	Mudstone, grey, firm to hard, calcareous

Table 4

Lithology Description Cont.

SWC No	Depth	Description
103	4060	Mudstone, dk grey, subfis, silty, calcareous, carbonaceous
104	4050	Mudstone, grey, soft to firm, very calc.
105	4040	Mudstone, grey, soft to firm, very calcareous
106	4030	Mudstone, a/a
107	4025	Mudstone, a/a
108	4010	Mudstone, a/a
109	4000	Mudstone, a/a
110	3980	Mudstone, grey, soft to firm, very calcareous
111	3975	Mudstone, dk grey, soft to firm, calcareous
112	3961	Mudstone, a/a
113	3960	Mudstone, a/a
114	3952	Mudstone, dk grey, firm, subfis, very calcareous
115	3935	Mudstone, dk grey, soft, calcareous
116	3900	Mudstone, dk grey brown, firm, calcareous, carbonaceous

Table 5

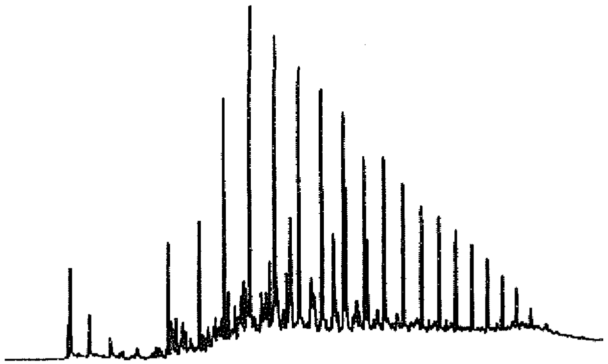
Biostratigraphical Summary (5)

	(All depths in metres BRT)	
Quaternary		
Recent to Pleistocene	180 - 464	
Tertiary	492 - 3240	
Late Pliocene	492 - 680	
Early Pliocene	730 - 910	
Late Miocene	930 - 1780	
Middle to Early Miocene	1790 - 2080	
Late Oligocene	2100 - 2280	
Early Oligocene to Late Eocene	2330 - 2660	
Early Eocene	2680 - 2950	
Paleocene	2960 - 3240	
Cretaceous	3250 - 3875	
Maastrichtian	3250 - 3500	
Early Maastrichtian to Late Campanian	3520 - 3660	
Late Campanian	3670 - 3700	
Santonian to Turonian	3750	
Cenomanian	3770	
Albian	3780	
Early Aptian to Hauterivian	3800 - 3830	
Valanginian	3839 - 3875	
		3882m - top of "hot-shale palynofacies"
Indeterminate	3900 - 4046	From 3900m - 4454m Geochemical Source Potential Analyses.
Jurassic	4046 - 4348	
Early Portlandian to Late Kimmeridgian	4046 - 4109	
Kimmeridgian to Oxfordian	4110 - 4348	
Indeterminate	4358 - 4454 (TD)	

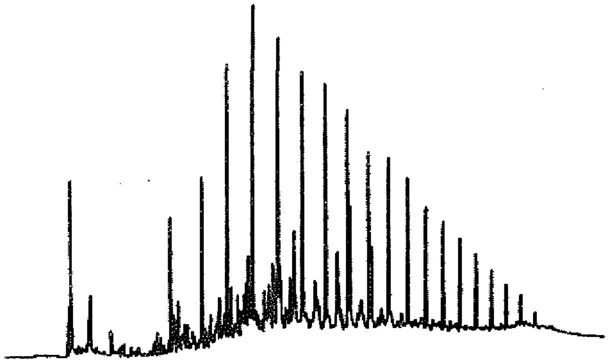
Table 6

GC - MS Molecular Parameters

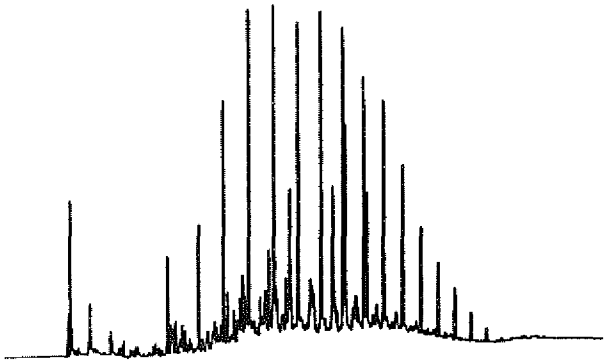
Parameter \ Sample	4100m	4173m
H1	0.56	0.53
H2	0.56	0.53
H3	0.84	0.86
H6	0.85	0.87
S1	0.40	0.46
S2	0.82	0.79
S3	32:30:38	39:26:35



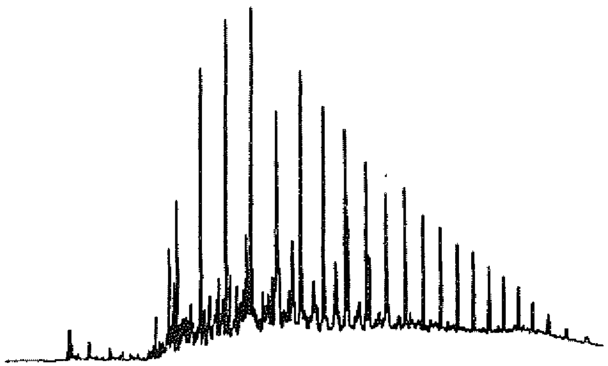
SAMPLE: 2/1-5 3800m



SAMPLE: 2/1-5 4140m



SAMPLE: 2/1-5 3980m

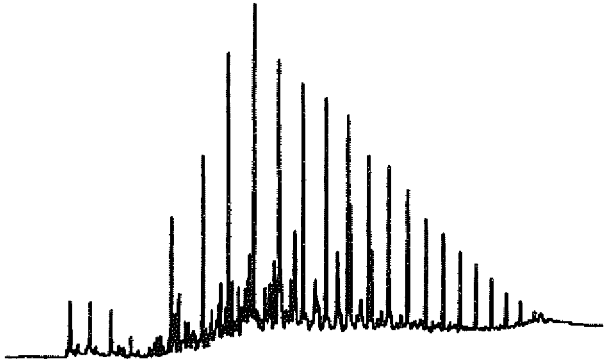


SAMPLE: 2/1-5 4110m

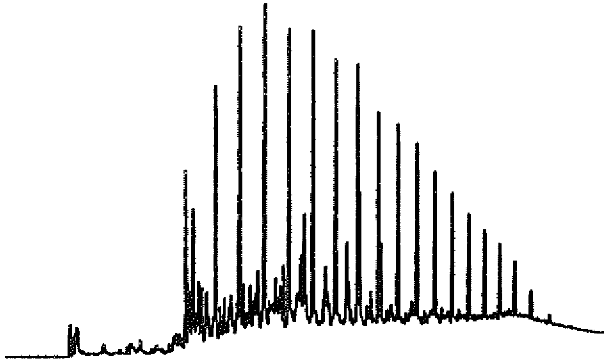
GEOCHEMISTRY BRANCH, BP SUNBURY

THERMAL VOLATILATES (P1)

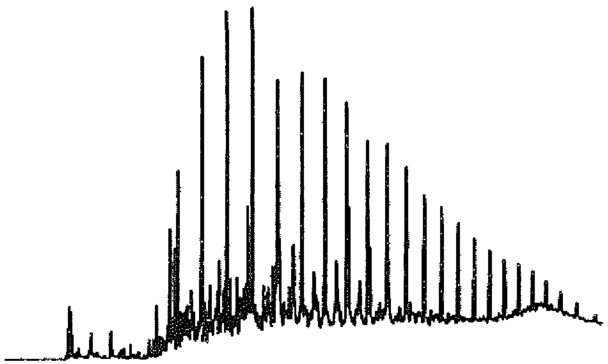
[fig.1]



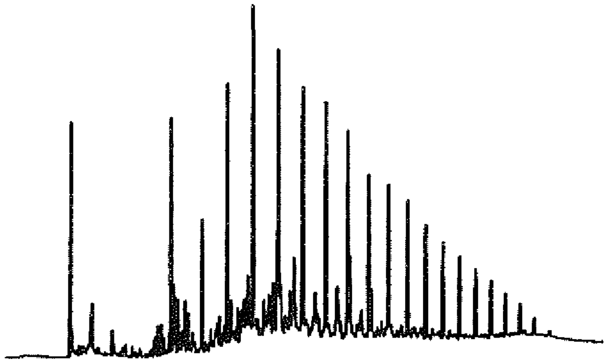
SAMPLE: 2/1-5 4150m



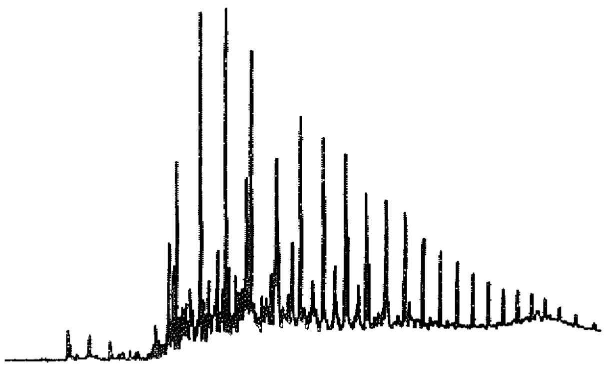
SAMPLE: 2/1-5 4200m



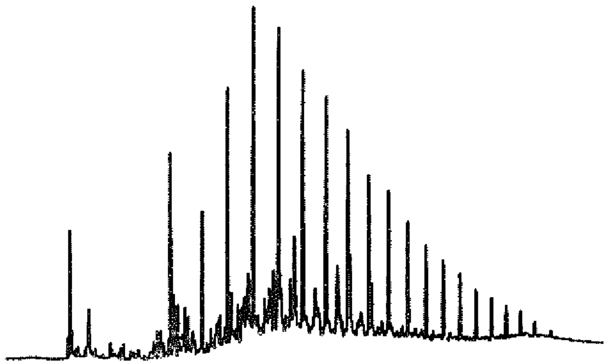
SAMPLE: 2/1-5 4179m



SAMPLE: 2/1-5 4245m



SAMPLE: 2/1-5 4192m

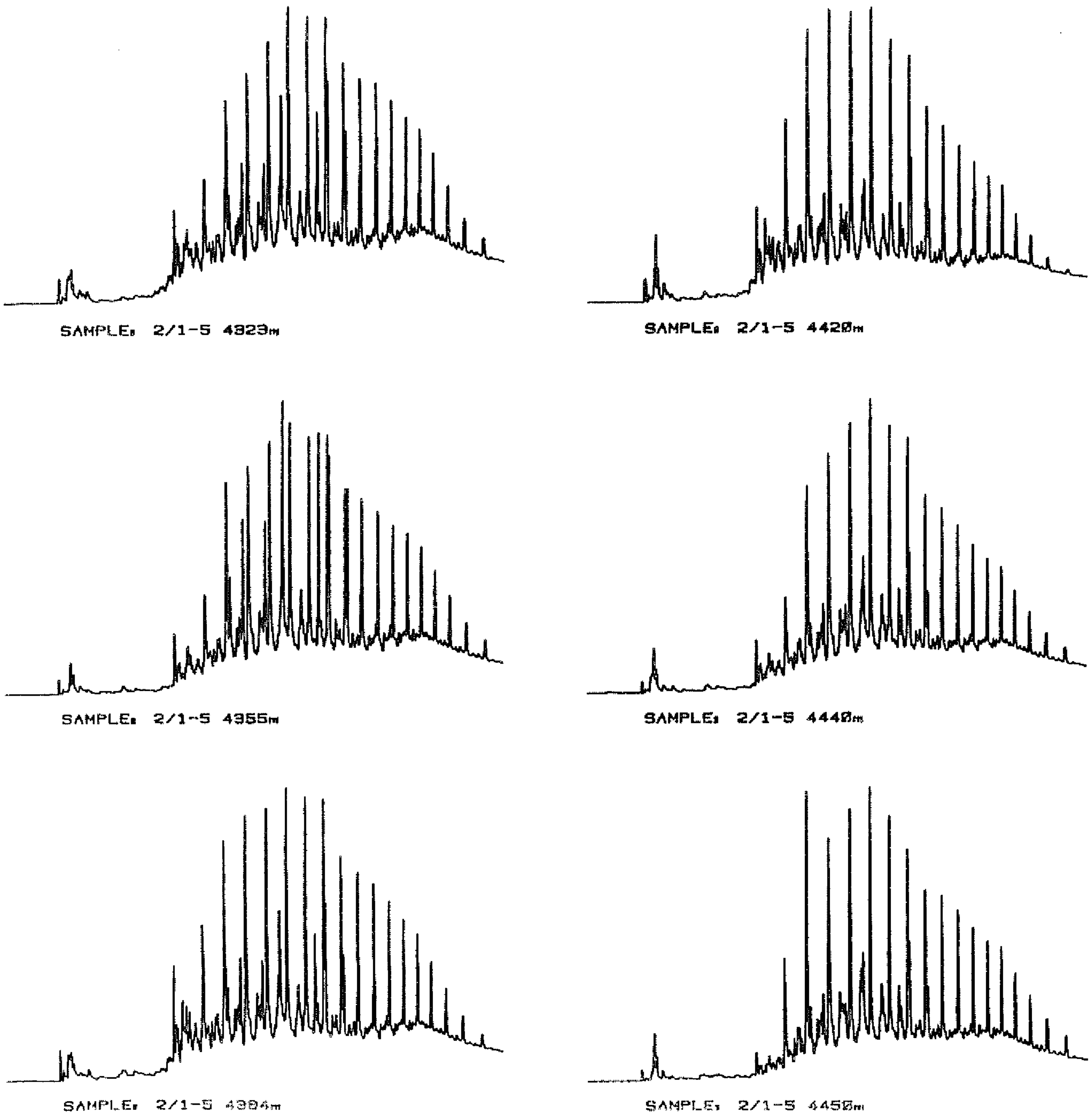


SAMPLE: 2/1-5 4204.9m

GEOCHEMISTRY BRANCH, BP SUNBURY

THERMAL VOLATILATES (P1)

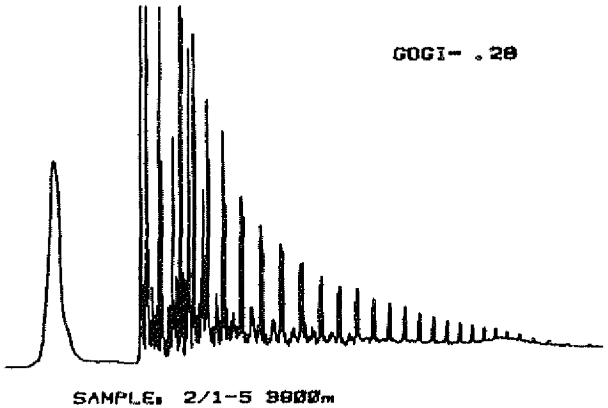
[fig.2]

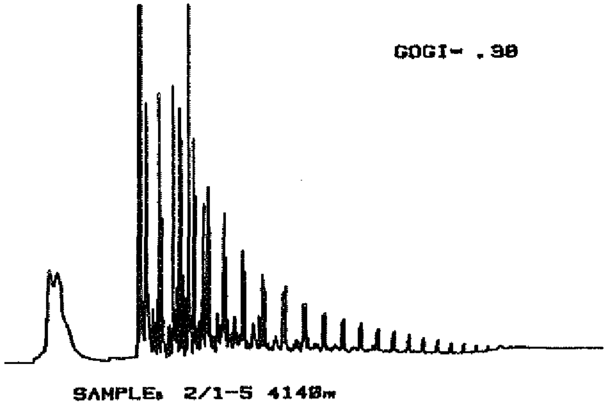


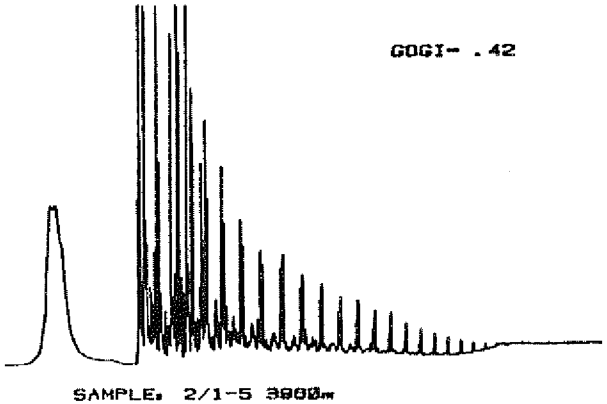
GEOCHEMISTRY BRANCH, BP SUNBURY

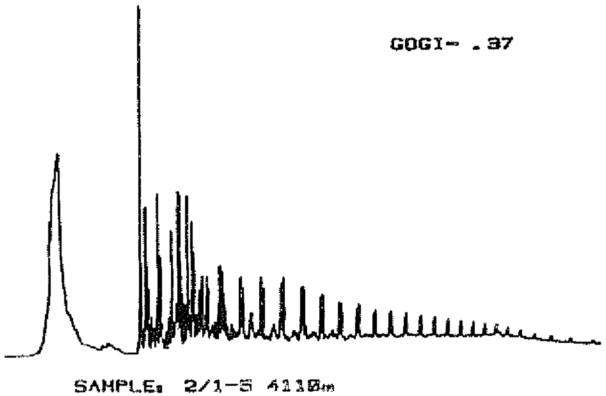
THERMAL VOLATILATES (P1)

[fig.3]





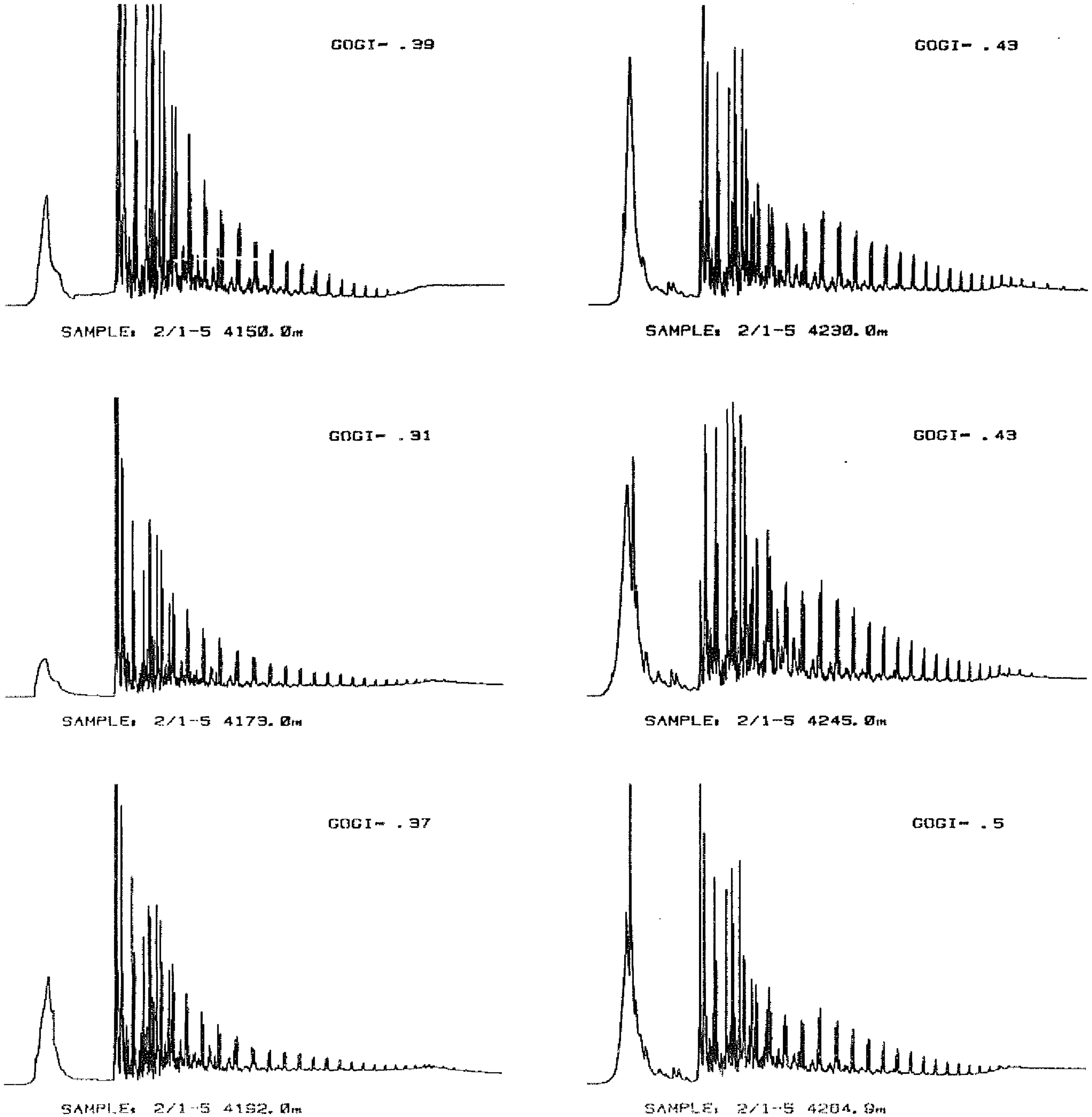




GEOCHEMISTRY BRANCH, BP SUNBURY

KEROGEN PYROLYSATES (P2)

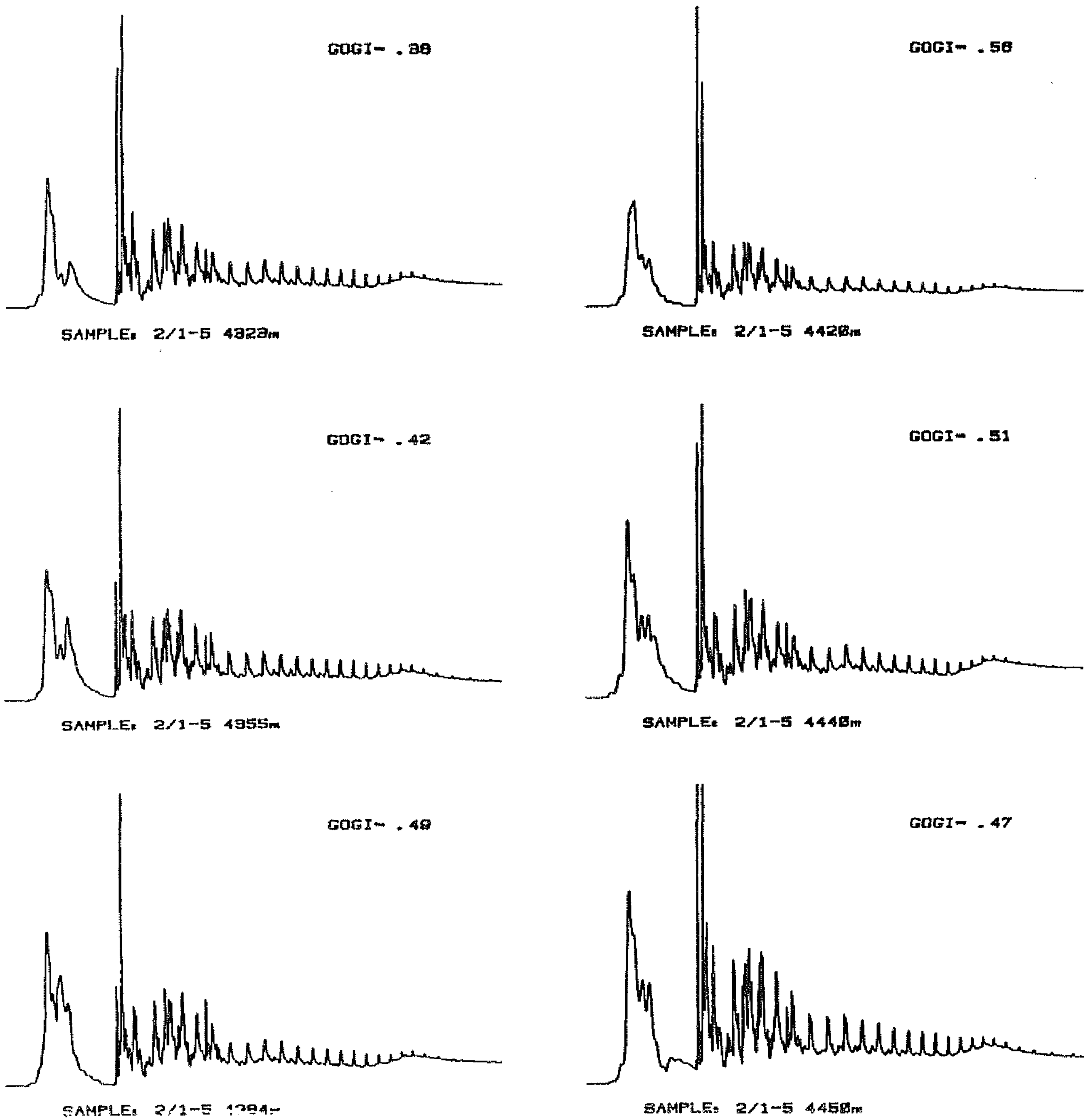
[fig.4]



GEOCHEMISTRY BRANCH, BP SUNBURY

KEROGEN PYROLYSATES (P2)

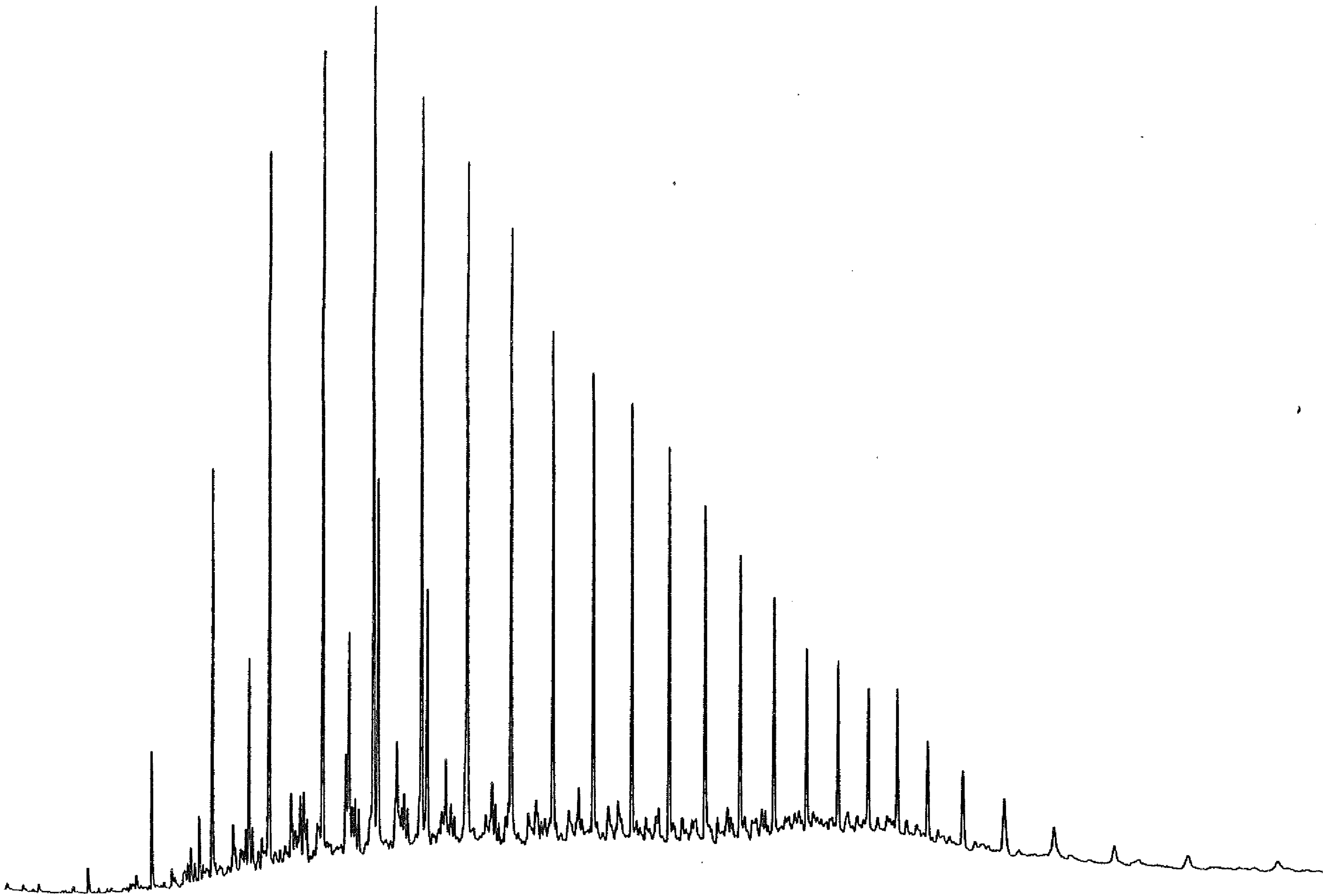
[Fig.5]



GEOCHEMISTRY BRANCH, BP SUNBURY

KEROGEN PYROLYSATES (P2)

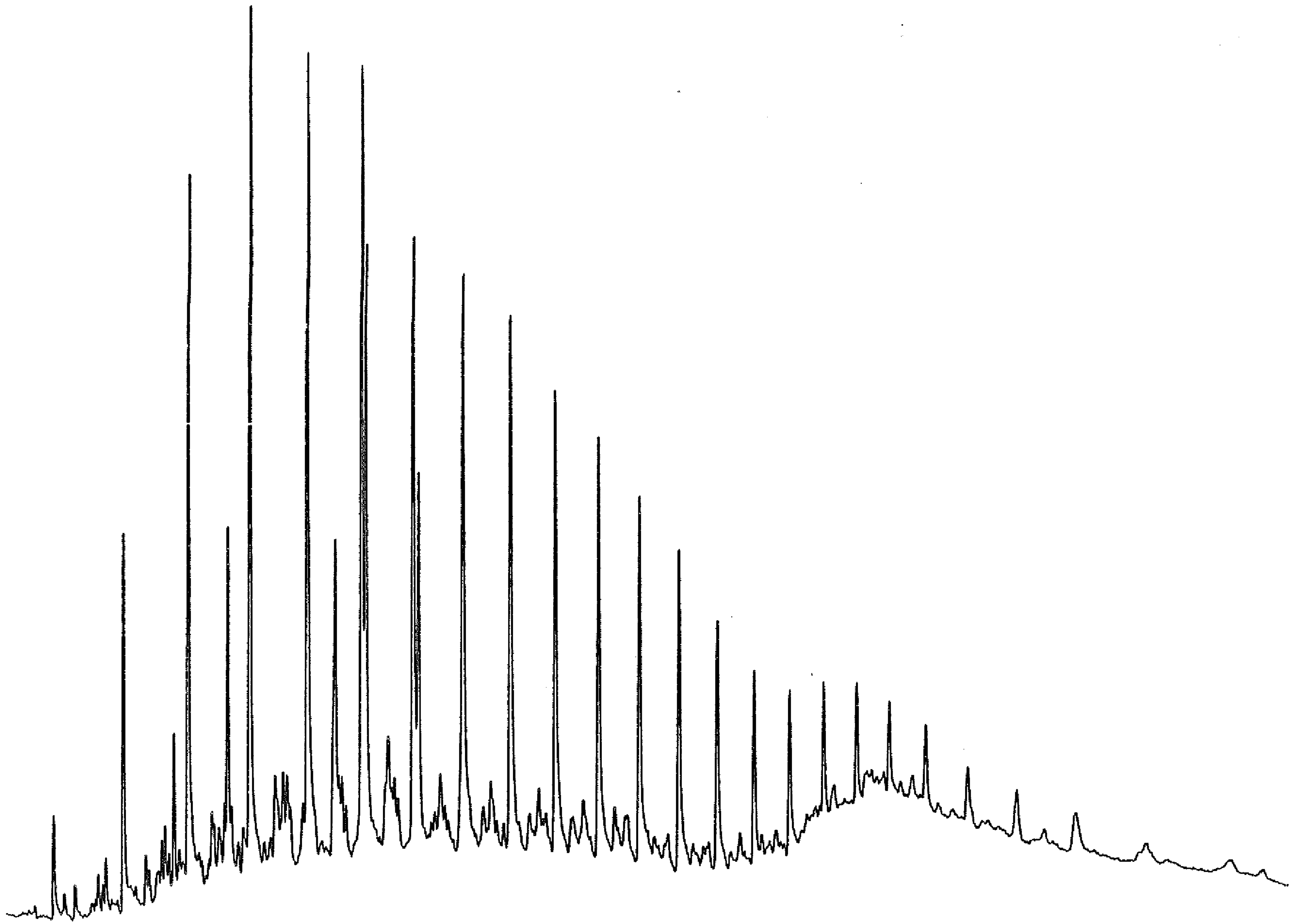
[fig.6]



SAMPLE: 2/1-5 4100 SATURATES FRACTION

[Fig. 7]

[fig.8]

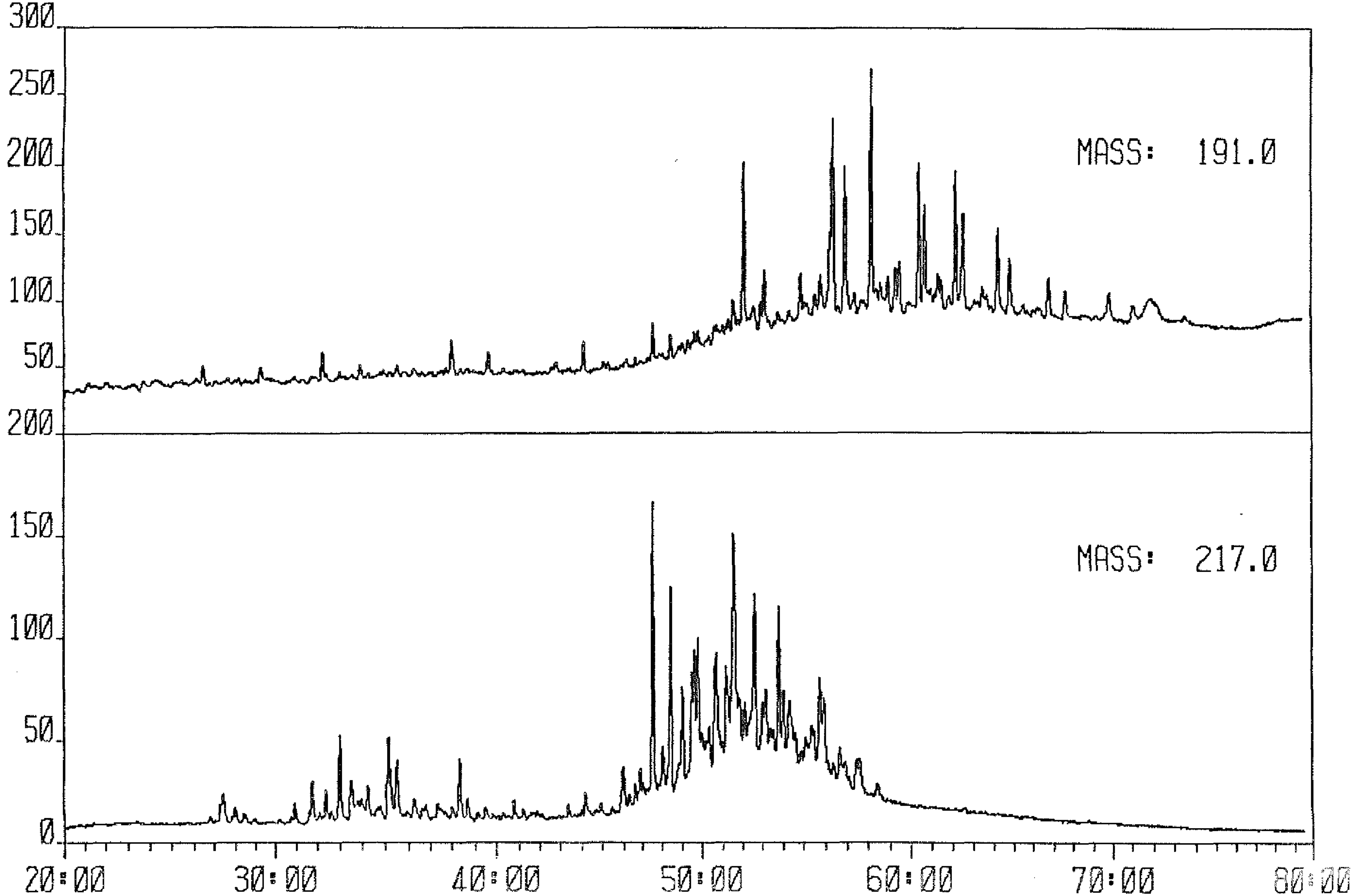


SAMPLE: 2/1-5 4173 SATURATES FRACTION

ANALYSIS NAME: DM00:[300,301]M935.MIS;1   V04.0   WINDOW: 1

TITLE: 4100M SED EXT EX 2/1-5

OPERATOR: C MAILE   DATE: 14-JUN-83 11:50:15

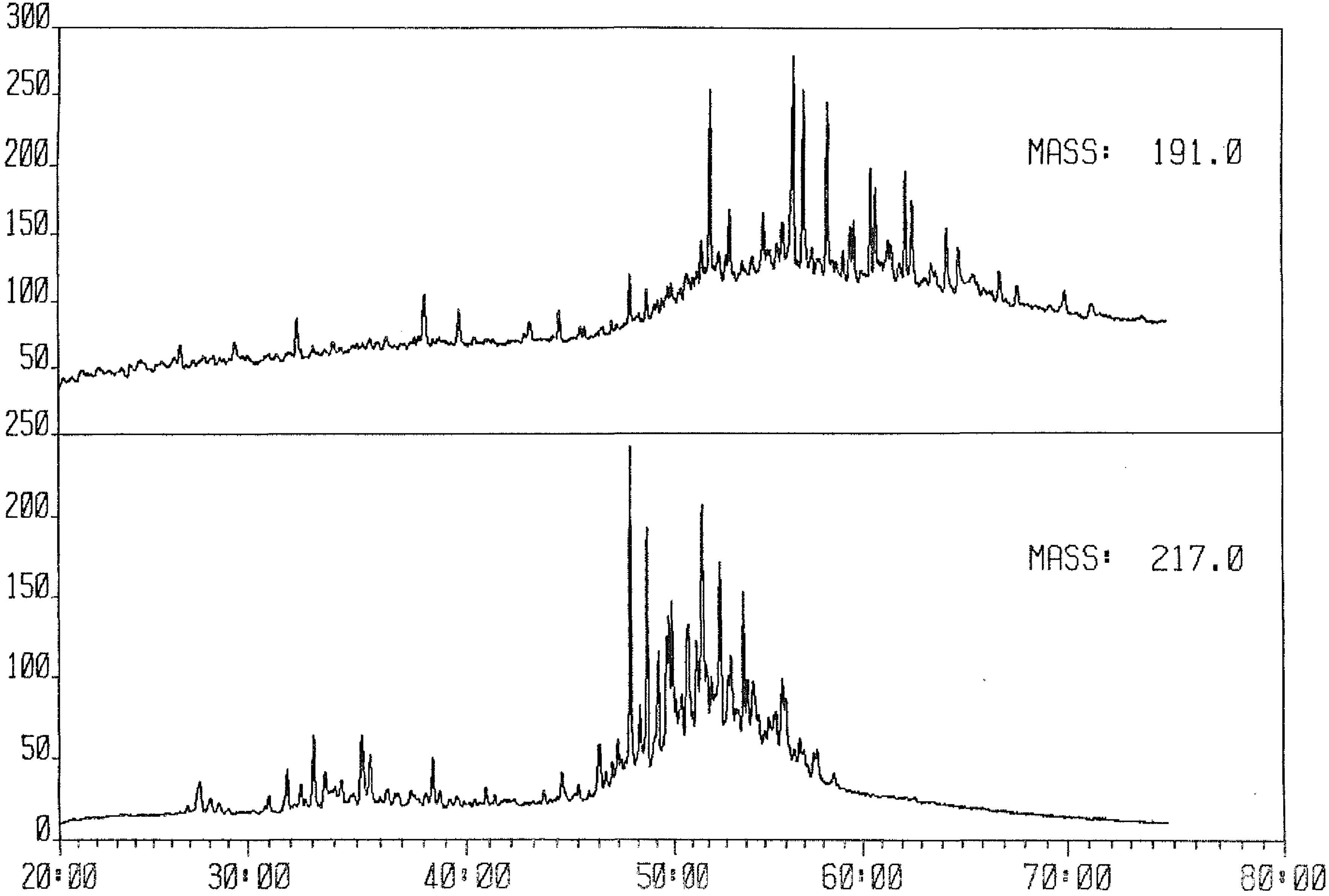


(fig 9)

ANALYSIS NAME: DM00:[300,301]M936.MIS;1 V04.0 WINDOW: 1

TITLE: 4173M SED EXT EX 2/1-5

OPERATOR: C MAILE DATE: 14-JUN-83 13:15:50



(fig 10)

Appendix 1.

Maturity data from adjacent wells
2/1-2 and 2/1-3.

TABLE A

VITRINITE REFLECTANCE DATA

WELL: NOCS 2/1-2
LOCATION: OFFSHORE NORWAY

DEPTH (m)	REFLECTANCE VALUES(%Ro)	COMMENTS
2248	.45(19)	GEOCHEM LABS
2250	.39(18)	
2350	.43(20)	
2352	.44(20)	
2450	.47(20)	
2600	.49(20)	
2700	.41(21)	
3270	.43(7)	
3313	.53(13)	

FIGURES IN PARENTHESES INDICATE NUMBER OF READINGS
SEE LIST OF ABBREVIATIONS OVERLEAF

TABLE B

VITRINITE REFLECTANCE DATA

WELL: NOCS 2/1-3
LOCATION: OFFSHORE NORWAY

DEPTH (m)	REFLECTANCE VALUES(%Ro)	COMMENTS
2250	.3(20)	IKU
2370	.41(22)	
2500	.36(20)	
2530	.41(21)	
2700	.41(22)	
2820	.43(20)	
2880	.38(21)	
2940	.34(22)	
3140	.52(7)	
3420	.41(20)	
3480	.44(21)	
3540	.44(12)	
3690	.3(21)	
3787	.35(8)	
3811	.58(14)	
3880	.68(20)	
3980	.9(13)	
4012	1.03(23)	

FIGURES IN PARENTHESES INDICATE NUMBER OF READINGS
SEE LIST OF ABBREVIATIONS OVERLEAF

Arkiveres ved rapport rec. 16.12.82. 725.3 2/1-4

DIAGENETIC HISTORY OF THE UPPER JURASSIC SANDSTONE 2/1-4, 2/1-3.

Comments to report by Mayall.

Non-ferroan calcite cement must be very early, as stated in the report, an interpretation which is later supported by isotope analyses indicating that the cement was precipitated by fresh water at low temperatures. The non-ferroan nature of the calcite suggests oxidizing porewater and the source may have been biogenic aragonite reprecipitated as calcite.

Kaolinite may have formed during leaching, associated with this period of fresh water flushing.

The timing of the formation of feldspar overgrowth is pulseling. Textural evidence of the relationship between the feldspar overgrowth and the carbonate cement may be, as the report suggests, that feldspar overgrowth predates the carbonate cement. Feldspar overgrowth must then have formed very early in marine porewater prior to fresh water flushing as the coast prograded.

I do not know of any example of feldspar overgrowth occurring in the short time (perhaps a few ten thousands of years between deposition and aragonite-calcite transformation).

The feldspar overgrowth has a brown colour and the report (p.10) suggests staining by hydrocarbon. The hydrocarbon staining is in the report interpreted to be present in microporosity formed by later leaching. An alternative interpretation of these observations is that feldspar overgrowth formed later than the calcite cement growing between the clastic feldspar grains and the calcite cement dissolving and replacing the latter.

Authigenic feldspar is not likely to precipitate normal meteoric water and may have formed during upwards migration of compactional with a higher ionic strength, possibly influenced by underlying evaporites. This process may have been accompanied by early migration of hydrocarbons from downfaulted shales and from brown oil-staining on the authigenic feldspar. The bitumen occurring in the micropores, i.e. between the minerals, may have been introduced at that time. Clastic feldspar and to a lesser extent the more stable overgrowth must then have been subjected to a second period of leaching, possibly associated with dissolution and reprecipitation of carbonate. It is difficult to know if this later leaching phase is associated with renewed meteoric water flushing or migration of CO_2 rich compactional water. Ferroan dolomite may also have formed during this phase.

Summary.

The interpretation of the diagenetic history outlined above can be summarized in the following phases:

1. Early marine diagenesis: a) phosphate cementation - marine porewater just below sediment water interphase.
2. Meteoric water flushing: cementation of non-ferroan calcite from biogene carbonate. Leaching of feldspar and precipitation of kaolinite in the uppermost meters of the sandstone. Precipitation of some quartz cements.
3. Migration of compactional porewater with higher ionic strength and hydrocarbons. Formation of authigenic feldspar, hydrocarbon (bitumen) staining.
4. Second leaching phase by meteoric water or CO_2 rich compactional water, possibly along faulting. Dissolution of clastic feldspar and to a lesser extent overgrowth.
5. Compaction and pressure solution - quartz overgrowth. Formation of stylolites.