

REPORT

SHALLOW DRILLING AND HEAT FLOW MEASUREMENT AT SITE 7317/02-U-01 (D85-V) ON THE STAPPEN HIGH IN THE BARENTS SEA



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REPORT

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SHALLOW DRILLING AND HEAT FLOW MEASUREMENT
AT SITE 7317/02-U-01 (D85-V) ON THE STAPPEN
HIGH IN THE BARENTS SEA

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SUMMARY:

In 1985 IKU carried out shallow drilling and heat flow measurement at site 7317/02-U-01 (D85-V) on the Stappen High to the southwest of Bjørnøya. The work was part of the project "Shallow seismic, shallow drilling and heat flow - Barents Sea 1985".

Recently, additional organic geochemical analyses, revised biostratigraphical dating and revised core description have been carried out.

KEY WORDS:	
Barents Sea	Tertiary
Stappen High	Heat flow
Bjørnøya West	

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1. INTRODUCTION

This report gives the result of the drilling and heat flow measurements at site 7317/02-U-01 (D85-V) in 1985 (Figure 1.1). The site was located on the western margin of the Stappen High in the Barents Sea. The data presented here comprise what was reported in the reports following the 1985 project in addition to new organic geochemical analyses and revised biostratigraphical dating of the Tertiary section of the core.

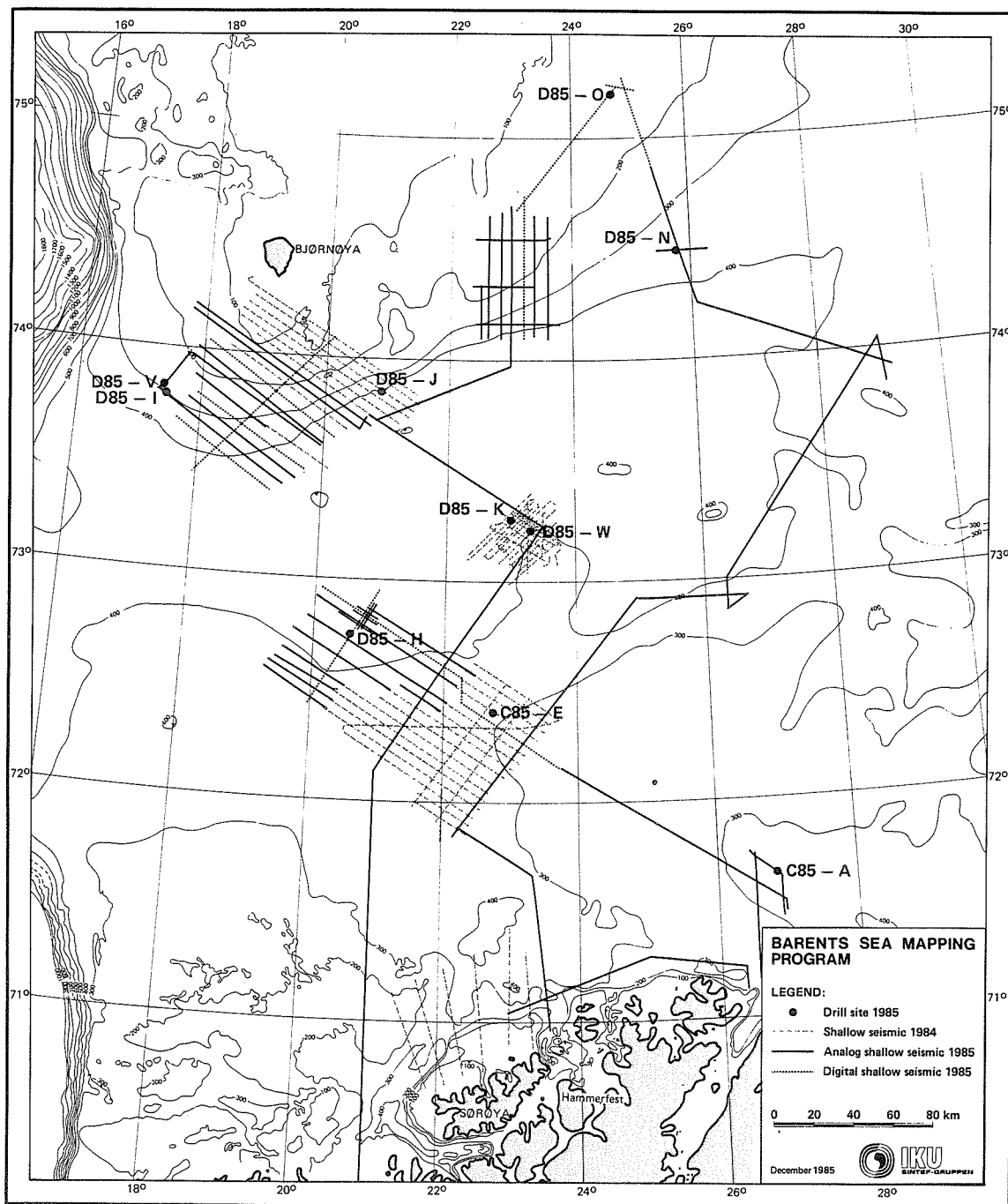


Figure 1.1 General map of the survey area showing shallow seismic 1984 and 1985 and shallow drilling sites 1985.

The work was part of the project "Shallow seismic, shallow drilling and heat flow - Barents Sea 1985", and the Norwegian drill ship M/S "Bucentaur" was used for the field work. Site 7317/02-U-01 was a combined location where heat flow was measured in the Quaternary overburden before about 10 m of the bedrock section was cored. The so-called Christensen coring device was applied for the bedrock coring. The relatively short bedrock core obtained is explained by this method being a slower coring method than the piggyback method more frequently applied today by IKU.

Because of some computer problems with the dynamic positioning system a first attempt of drilling at site 7317/02-U-02 (D85-I) was aborted only 5 m below seabed and the vessel was moved to site 7317/02-U-01 (D85-V) where a successful operation was completed.

2. SUMMARY

The operation at site 7317/02-U-01 (D85-V) was a combination of heat flow measurement and bedrock coring. The site was located on the western part of the Stappen High at 73°49'10.9"N, 17°22'04.5"E. Water depth was 295 m. The Quaternary overburden is about 45 m thick and consists of glacial deposits, probably mainly till. Below about 27.5 m the till is massive and very sandy. However, all the samples are rich in clay (30-50%) and probably have a permeability comparable to that of a claystone. The sediments are stiff and overconsolidated, but the consolidation becomes lower towards the base - possibly suggesting communication of fluid overpressure from the underlying bedrock. Finite ages of the sediments are not obtained, but they are probably late Pleistocene.

About 10 m of bedrock was cored between 46.40 m and 56.82 m below seabed.

The core consists of alternating layers and laminae of clayey siltstone and storm influenced deposits of matrix rich bioturbated sandstone.

The siltstone layers increase in thickness toward the top of the core while the thickness of the sandstone layers slightly decrease. The sediments were deposited in a marine environment and show an overall transgressive trend.

The common and well preserved dinoflagellate cysts offer good indications for an Early to early Middle Eocene age, of the cored bedrock unit.

Organic geochemical analysis revealed the presence of significant amounts of extractable organic matter associated with hydrocarbon gas in sediments of Quaternary age. The Quaternary and Tertiary strata samples contain quantities of thermally immature bitumen, especially the former. The bitumen shows evidence of a common source, although there is no suitable candidate for this source within the cored succession. The similarity in the bitumen composition suggests that some sort of redistribution mechanism has operated within the core, possibly redistributing the bitumen from a conduit horizon which coincides with the Quaternary/Tertiary unconformity. The immaturity of the bitumen argues against a large migration distance, and therefore provides some justification for postulating the presence of a nearby organic rich horizon of Tertiary age.

3. SEISMIC INTERPRETATION

Core 7317/02-U-01 (D85-V) was drilled in an area with locally thick overburden (Figure 3.1). The location is in an area with little seismic control, which made the age estimate very uncertain. However, the locations can be tied to the line IKU-172230A-89, from the drilling project in Bjørnøya West 1989, with only small projections (300 m to the west of sp 330 and 600 m to the east of sp 25 for the 7317/02-U-01 and -02 locations, respectively (Figure 3.2)).

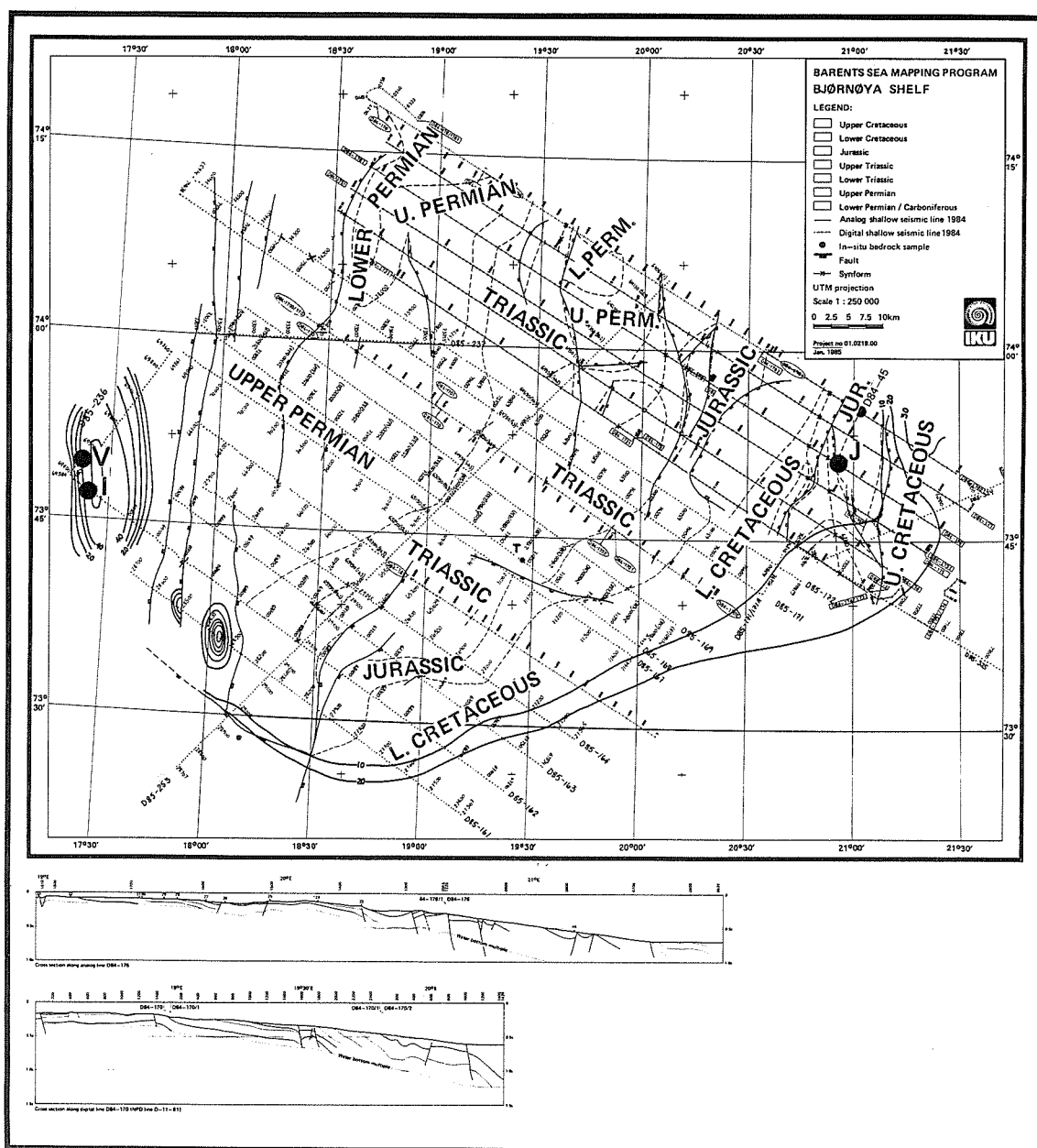


Figure 3.1 Preliminary geological map of the Stappen High showing location of sites 7317/02-U-01 (D85-V) and 7317/02-U-02 (D85-I) and isopachs of Quaternary overburden in metres.

A tie further to the west along line BV11, however difficult, indicates that the cored interval is located within the reflective sequence below the assumed "Mid Oligocene unconformity" and thus comparable to core 7316/06-U-02. The seismic line D85-162 where site D85-I was originally planned (Figure 3.3), shows a marked erosional surface which is not seen at site 7317/02-U-01 on line D85-236 (Figure 3.4). As there is a gap between the two lines, it was a question whether there is a fault between them or the sequences in the upper part of the sections are the same. In both cases, the sample taken at location -01 is younger than the planned sample at -02. Line IKU-172230A-89 confirms this. The difference can be interpreted to be approximately 250 msec. The angle between the two analog lines may also explain the apparent difference in erosion (one being a dip line, the other a strike line).

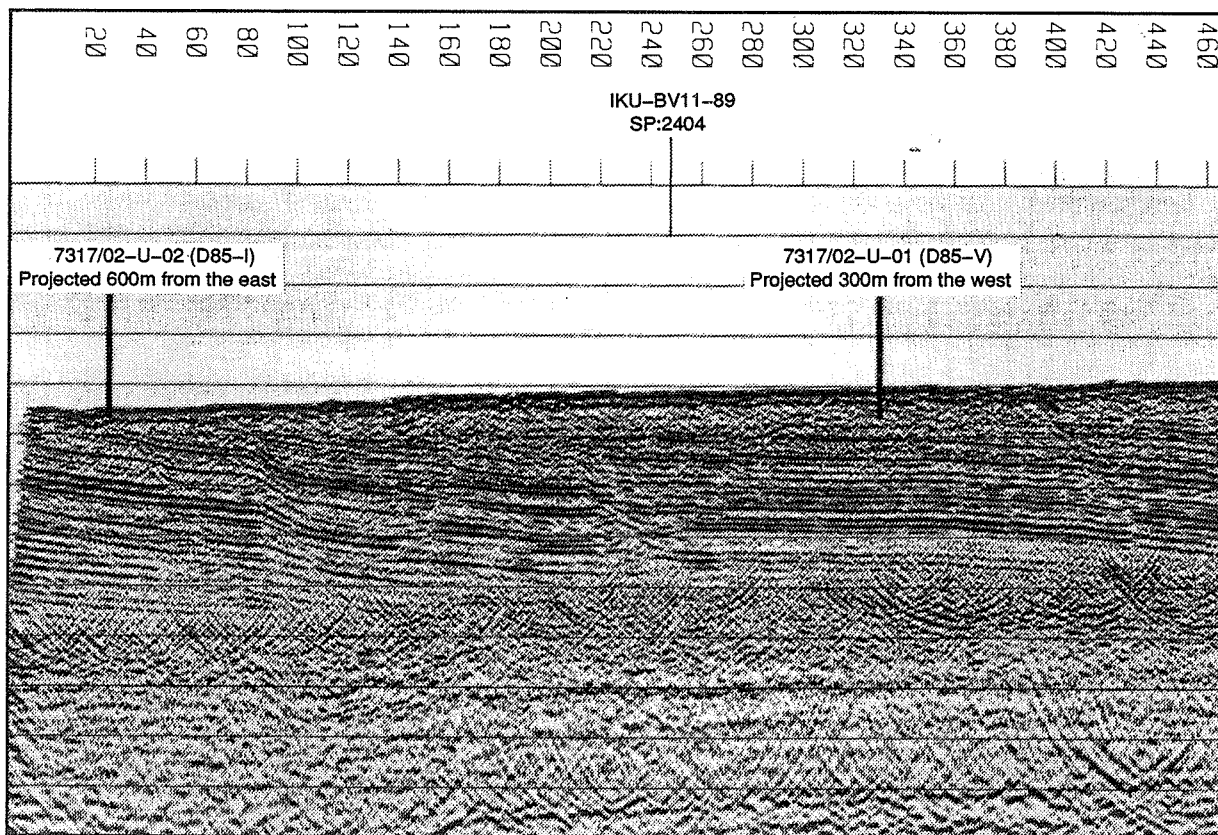


Figure 3.2 Digital seismic line IKU-172230A-89, with the two 1985 drilling sites projected onto.

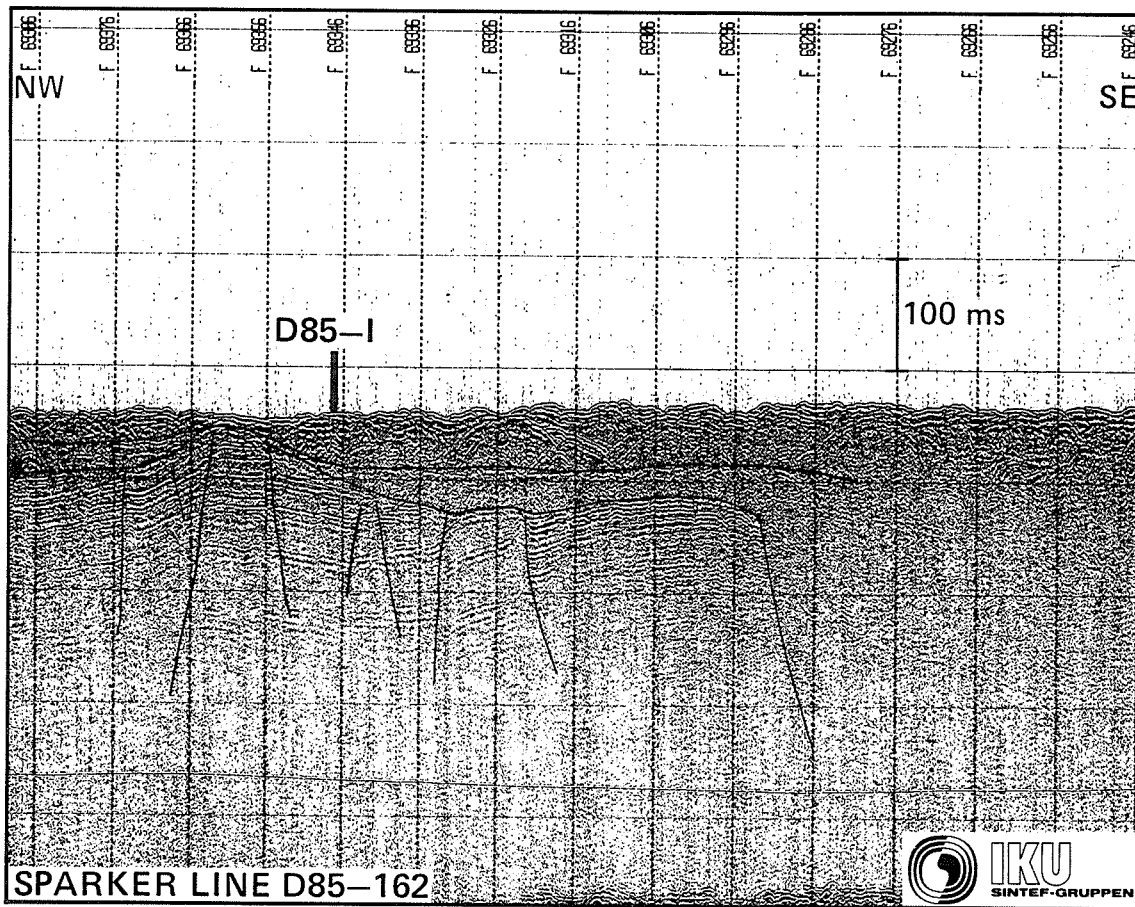


Figure 3.3 Shallow seismic (sparker) section at the abandoned site 7317/02-U-02 (D85-I).

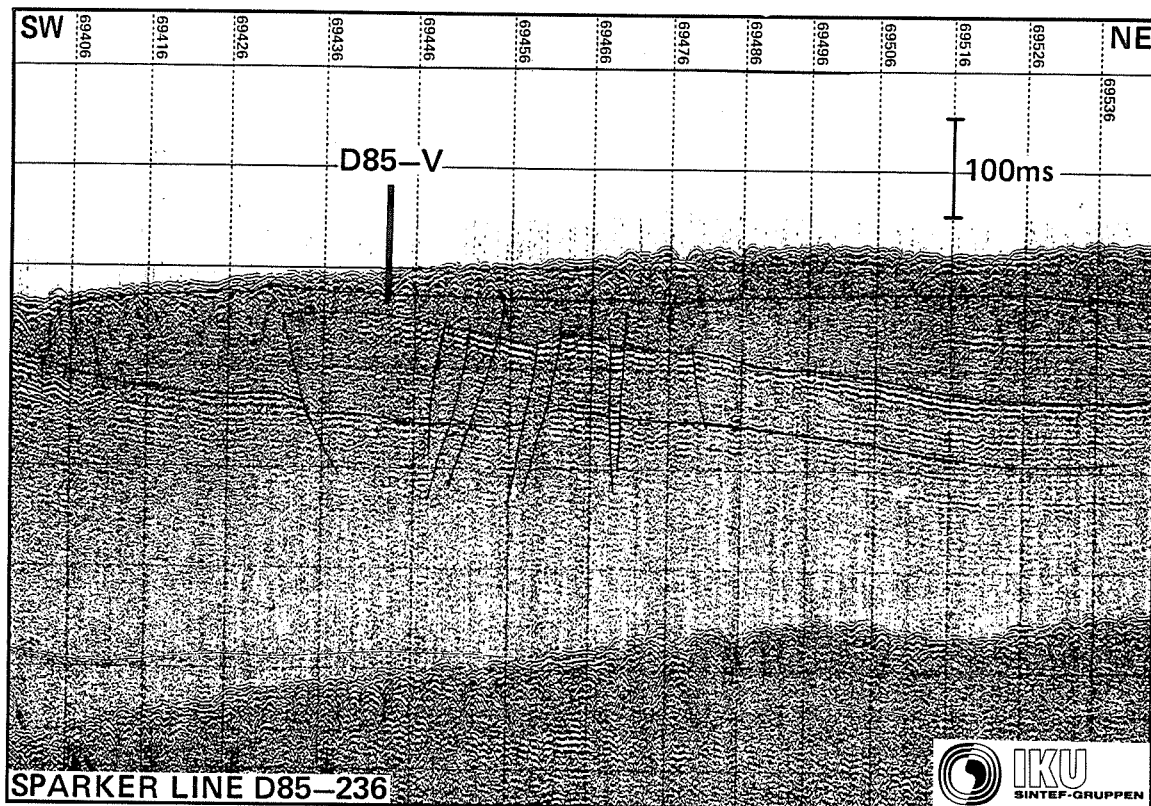


Figure 3.4 Shallow seismic (sparker) section at site 7317/02-U-01 (D85-V).

4. SEDIMENTOLOGY

4.1 Quaternary sediments

Quaternary samples were collected at six levels below seabed (approximately 14.5, 20.0, 25.0, 29.0, 40.0 and 44.5 m). Pre-Quaternary rocks were cored at 46.4 - 56.82 m below seabed. The sample at 44.61 - 44.40 m, does however penetrate fine sand sharply overlain by a muddy diamict at 44.5 m. The sand was disturbed, but partly consisted of well preserved, bioturbated silty sand clearly belonging to local bedrock. Hence, there is a one metre thick zone of disturbed/ tectonized sedimentary rocks at the base of the Quaternary sediments.

Above this, two lithozones can be distinguished within the Quaternary glaciogenic sediments. The lower lithozone, below about 27.5 m consists of homogeneous and rather massive olive grey very sandy (31-36%), silty (34-37%) clay (about 30%) with scattered fine gravel fragments. The samples in the upper lithozone above 27.5 m, are less sandy (49% clay, 39% silt and 11 - 12% sand) than the lower and are very dark grey in colour. Deformation/shearing is evident. Traces of banding/bedding found at about 15 m may suggest initial sedimentary stratification. Both lithozones are overconsolidated and have been overrun by grounded ice either compacting the sediments or eroding a previous sediment load. The permeability of these sediments is very low - comparable to a claystone/ siltstone.

The lower lithozone is considered most likely to be a till. Both lithozones contain, however, foraminifera diagnostic for a glaciomarine environment (reworked?) (Hald et al. in prep.), and the possible remnants of stratification found within the upper zone may suggest that it partly has a glaciomarine origin, only slightly deformed by an overriding ice-sheet. A conclusive age for the sediments cannot be given for any of the lithozones at present because of uncertain amino acid and ^{14}C results (Hald et al. in prep), but a Late Pleistocene age seems likely. A new attempt to date the sediments is currently being undertaken.

The oedometer data as well as index properties suggest that the consolidation level decreases slightly towards the base of the Quaternary sediments (Figure 4.1). The upper three oedometer tests yielded a preconsolidation (p_c') value comparable to a previous sediment cover of about 80 - 110 m above the present seabed, while the test at 40 m suggests

a preconsolidation level of 500 kN/m², which corresponds to a sediment cover of 50 m - only 10 metres more than the present. The lowest oedometer sample was considered disturbed (Table 7.4), but the trend is supported by the index parameters plotted in Figure 4.1, and a zone of lower compaction is considered evident.

We suggest that this may indicate a fluid overpressure in the lower part of the Quaternary sediments communicated from the underlying bedrock.

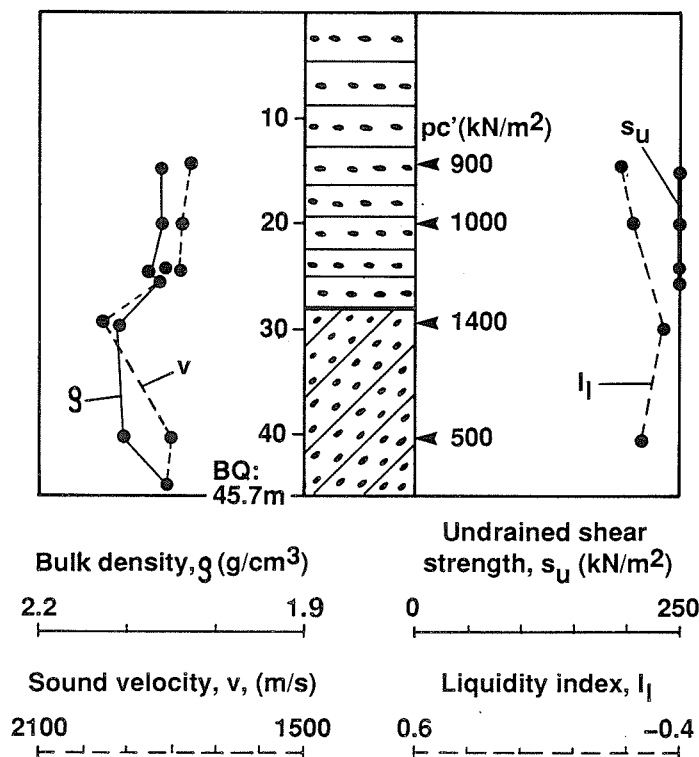


Figure 4.1 Undrained shear strength, index parameters and effective preconsolidation values (p_c'), for site 7317/02-U-01 plotted. A lithozone boundary is indicated at 27.5 m. The geotechnical parameter Liquidity index is defined as the $I_p = (w - w_p)/(w_l - w_p)$, where w is natural water content, w_p is plastic limit and w_l is liquid limit (water contents in percentage of dry sediment). Hence, I_p gives an indication of relative consolidation.

4.2 Bedrock core description

Core 7317/02-U-01 (D85-V) penetrates 10.42 m of poorly consolidated, very fine-grained sandstone and clayey siltstone between 46.40 m and 56.82 m below the sea floor (Figure 4.2). Sandstone is the predominant lithology, but laminae and layers of clayey siltstone/claystone occur throughout the core (see core photos in Appendix 2).

The different layers show quite different patterns of deformation due to coring. The siltstone and claystone layers and laminae have been dragged downward by the core barrel and cover the core as an up to 1 cm thick layer. The sand layers are thus cut and occur as "lenses" with concave bases and convex tops. The drilling has also in many cases disturbed the sedimentary structures and introduced artificial "structures" in the core.

From 56.82 m to 50.69 m thin layers of very fine-grained sandstone, 2-10 cm thick, separated by laminae of parallel laminated clayey siltstone are common. The boundaries between the layers are sharp, but fining upward laminae can be observed within some of the sand layers. Common primary structures within the sand are parallel lamination and ripples. These structures are, however, in most cases poorly preserved due to bioturbation and possibly disturbances due to water escape. The sand layers are generally thinner towards the top of this interval, while the finer grained layers increase slightly in thickness, from a few millimetres in the lower part of the core to a few centimetres in the upper metre.

At 50.69 m a 14 cm thick intraformational conglomerate occurs. It consists of rounded and angular clasts of claystone and laminated siltstone in a sandy matrix.

The interval from 50.55 m and to the top of the core consists of sediments similar to those described in the lower interval, i.e. sand with thin laminae and layers of clayey siltstone in the lower part gradually changing to thicker and coarser grained sandy siltstone layers in the upper part of the core. There is also a thin layer of intraformational conglomerate at 48.40 m. The sandstone layers are generally very fine-grained with a high content of matrix, occasionally showing fining upward parallel lamination and ripples.

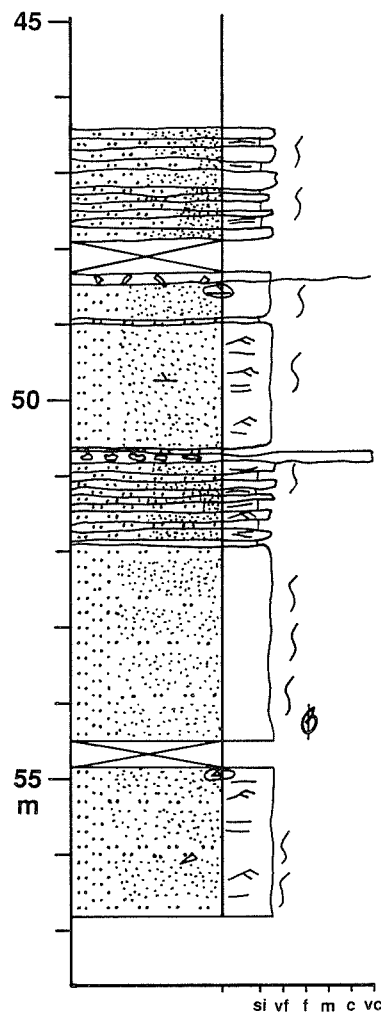


Figure 4.2 Lithological column of core 7317/02-U-01 (D85-V).

Bioturbation is common over the entire interval.

The cored sediment was deposited in a marine environment as shown by the presence of marine fossils. Further, the fossils are indicative of an open marine environment.

The lithology, mainly clayey and silty sediments with sharp boundaries and occasionally fining upward within each layer indicate sedimentation from suspension, the sandstone layers and the conglomerates probably being storm influenced. The increased thickness of the siltstone layers toward the top of the core may reflect an overall transgressive trend.

4.3 X-ray diffraction analysis

The XRD-analyses of samples from core 7317/02-U-01 show very little mineralogical variation (Table 4.1). The major crystalline phases are quartz, albite, potassium feldspar and clay minerals, while carbonate minerals are minor. The plagioclase-alkalifeldspar ratio is about 1 in all samples except the uppermost one at 46.60 m, where the albite content is considerably higher than the alkalifeldspar content. This may be a diagenetic effect.

Table 4.1 Mineralogical composition (wt%) of core 7317/02-U-01 (D85-V).

Depth (m)	Qtz	K-fsp	Plag	Musc Ill	Mix	Chl	Kaol	Smec	Cal	Dol	Kut	Sid	Pyr	Ap	Amph	Gyp
46.60	54.0	5.0	12.0	7.0	5.3	3.1	6.4	3.1	-	0.3	2.2	0.3	1.7	-	-	-
47.60	59.0	4.0	5.4	6.7	8.5	2.7	0.9	8.5	-	0.4	1.3	-	1.8	-	-	0.9
48.60	58.0	9.4	13.0	2.5	7.5	4.1	2.5	0.6	0.3	0.6	1.3	-	0.6	-	-	-
49.60	56.0	7.3	12.0	5.5	5.5	2.0	6.0	1.8	-	1.3	1.0	-	1.5	-	-	-
50.60	54.0	7.5	10.0	6.5	9.0	1.8	9.3	-	-	-	1.1	-	0.7	-	-	-
51.60	49.0	10.0	8.3	10.0	5.9	5.9	2.8	-	0.6	0.6	0.9	0.3	3.1	-	1.5	1.9
52.60	55.0	5.5	9.1	10.0	9.1	3.1	3.3	1.0	-	0.7	1.7	1.7	0.5	1.0	-	0.7
53.60	55.0	11.0	11.0	5.3	4.3	7.3	-	0.8	-	0.3	1.8	0.3	2.8	-	-	-
54.10	45.0	11.0	11.0	9.0	9.5	2.3	8.7	0.3	-	0.8	0.8	0.3	2.3	-	-	-
55.10	56.0	7.4	12.0	7.7	6.5	3.8	3.2	-	-	2.4	1.2	0.3	0.3	-	-	-
56.10	55.0	9.2	8.3	6.4	3.5	4.3	4.7	2.1	-	1.7	1.2	-	1.4	-	-	1.9

4.4 Petrophysics

Natural γ -radiation

Potassium and total radiogenic activity show moderate variations in this core while U and Th are nearly constant (Figure 4.3).

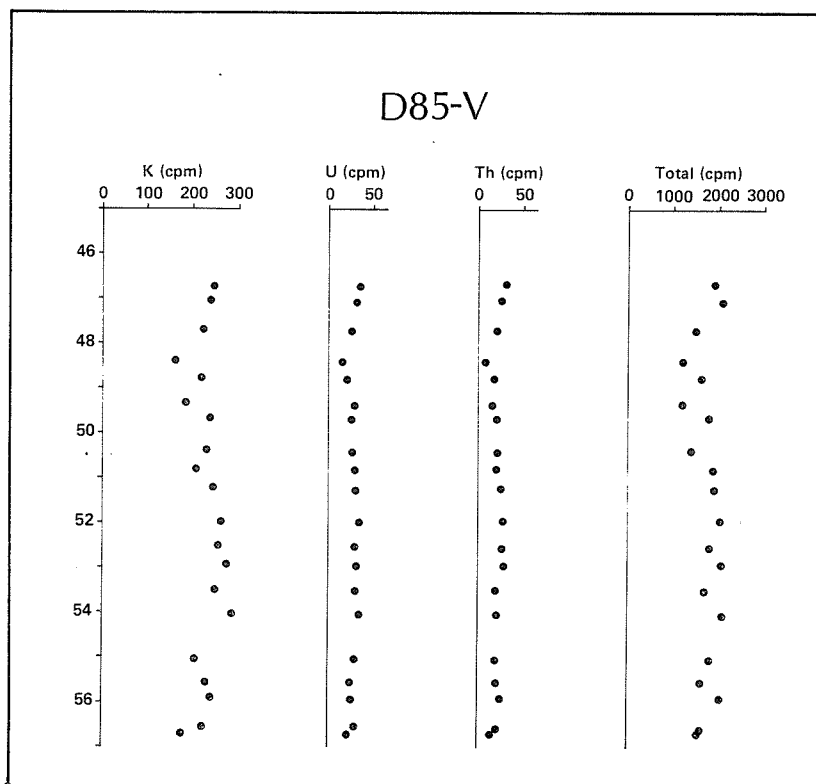


Figure 4.3 Natural γ -radiation of core 7317/02-U-01 (D85-V). Units are in counts per minute (cpm).

Sound velocity

The measured sound velocity is 1700 - 1800 m/s in this core. This may be too low due to possible disruption of structures and textures of the rock during the drilling operation.

Porosity and permeability

Porosity and permeability were not measured in this core. Both are probably very low due to the high clay and silt content.

5. BIOSTRATIGRAPHY

Core 7317/02-U-01 contains common and well preserved dinoflagellate cysts, but only very sparse microfossil assemblages have been recovered. In the previous Shallow Drilling Barents Sea 1985 report (21.3405.00/01/85) (Fjerdingsstad et al. 1985) the core was dated as Eocene. Based on the recent evidences obtained from the Shallow Drilling Bjørnøya West 1989 (Bugge et al. 1990), a recent re-examination of the palynomorph assemblages offered a more precise age-determination of the cored unit. Based on the evidences discussed below, the core is inferred to be of Early to early Middle Eocene age.

Comparable to what was found in the 1989 Shallow Drilling coreholes, reworked Cretaceous (?Aptian - Cenomanian) dinoflagellates are present through core 7317/02-U-01.

The lowermost examined sample at 56.60 m yielded, among others the dinoflagellates *Cordosphaeridium cantharellum*, *Areosphaeridium dictyoplokus* and *Selenopemhix nephroides*. In the Eocene Series of southern England the earliest appearance of *C. cantharellum* and *S. nephroides* is known to occur in the Middle Eocene (i.e. beds correlative with the NP 16 Zone), while *A. dictyoplokus* has its earliest occurrence within the upper Lower Eocene (i.e. beds correlative with the NP Zone 13) (Bujak et al. 1980).

In a recent study of the Eocene to Pliocene palynology of the ODP Leg 104 on the Vøring Plateau, Manum et al. (1989) found that *Areosphaeridium dictyoplokus* has its earliest occurrence at the base of the *Adnatosphaeridium vittatum* Zone which they inferred to be of Middle Eocene age. However, the chronostratigraphic position of the *A. vittatum* Zone was disputed by Goll (1989), who suggested that the zone may also include upper Lower Eocene sediments. On the Vøring Plateau *Cordosphaeridium cantharellum* has its earliest occurrence within the lower part of the overlying *Deflandrea* sp. B Zone of Manum et al. (1989) of Middle Eocene age.

The dinoflagellate assemblage in core 7317/02-U-01 appears comparable to those found in core 7316/06-U-02 from the IKU 1989 Shallow Drilling (Bugge et al. 1990). The key species *Cordosphaeridium cantharellum*, *Areosphaeridium dictyoplokus* and *Selenopemhix nephroides* also appear from the base of core 7316/06-U-02.

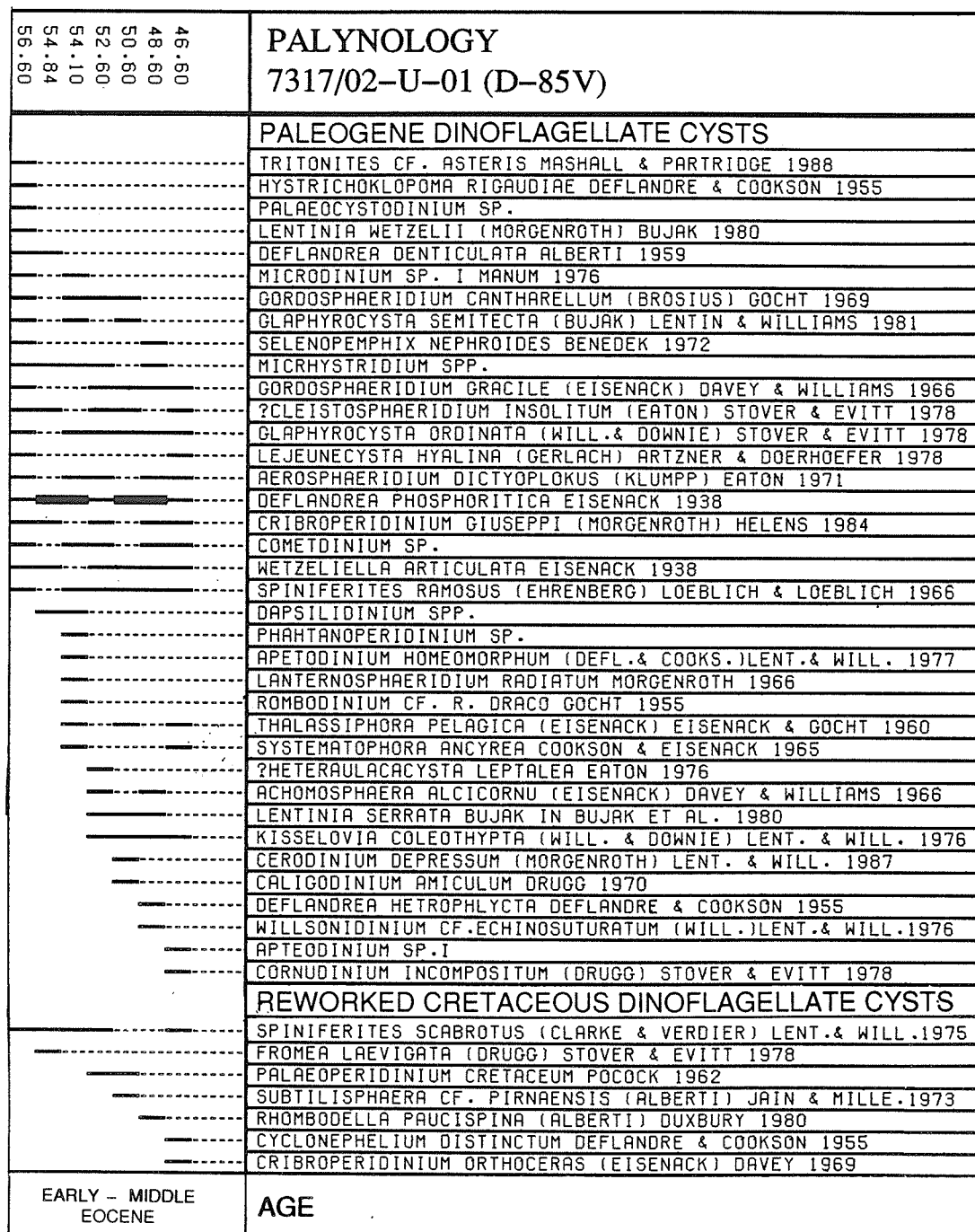


Figure 5.1 Distribution chart of dinoflagellates in core 7317/02-U-01, sorted according to earliest occurrence.

Comparable to what observed in 7317/02-U-01 *Deflandrea phosphoritica* is the most prominent species at several levels in core 7316/06-U-02. *Areosphaeridium dictyoplokus* and *Cribroperidinium giuseppi*, which range through both cores, suggest that both 7317/02-U-01 and 7316/06-U-02 are not younger than Late Eocene. In core 7316/06-U-02 the regular occurrence of *Apectodinium homeomorphum* was listed as an evidence for an age not younger than Middle Eocene. In core

7317/02-U-01 this species was found in a single sample from the middle part. Recent studies in the Haltenbanken area and calibrations with the microfossil biostratigraphic events in the Bjørnøya West area, suggest that *A. homeomorphum* does not range above the early Middle Eocene (i.e. 46 Ma) in these northern waters (although it is known to range into NP 17 Zone correlative beds in southern England).

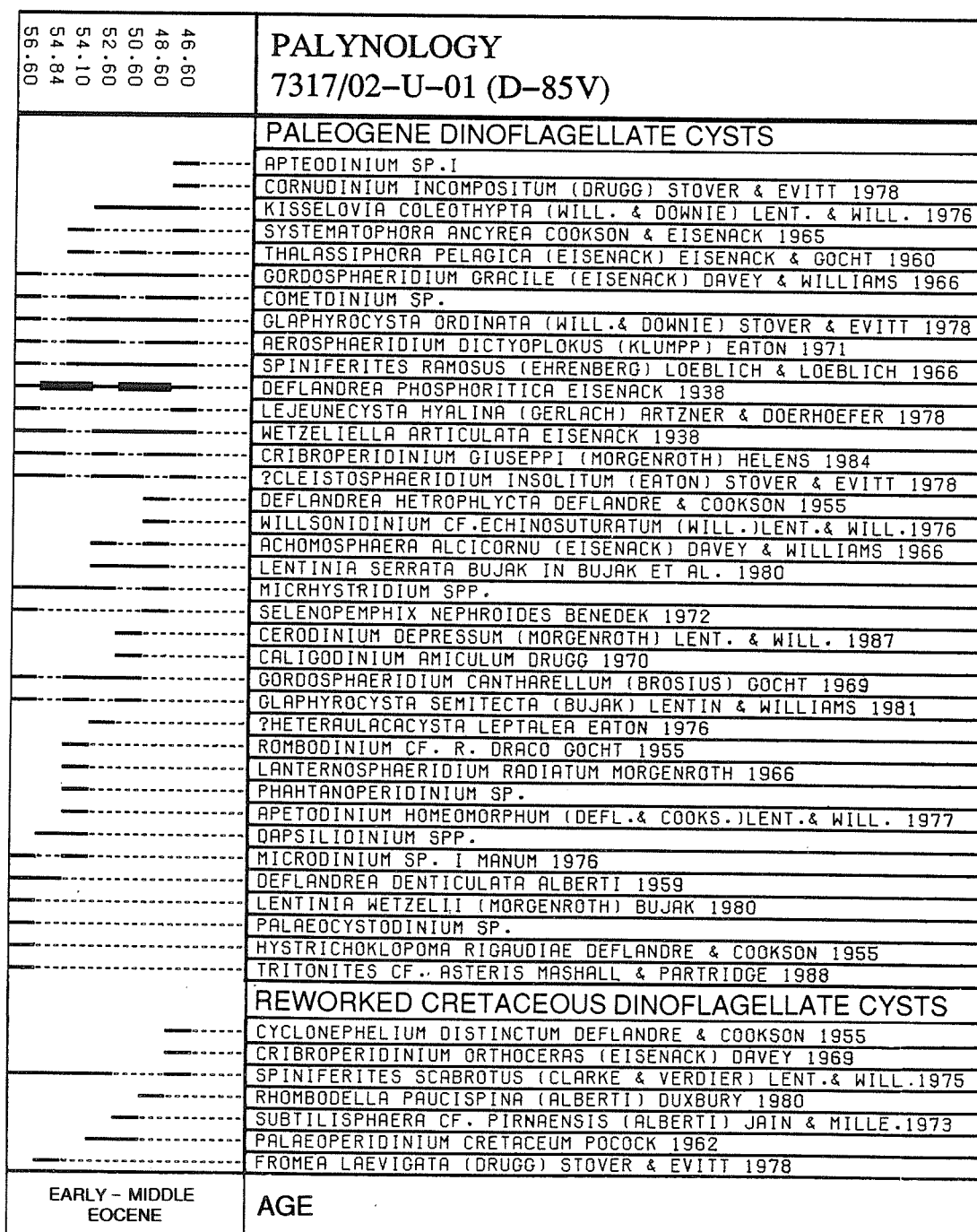


Figure 5.2 Distribution chart of dinoflagellate cysts in core 7317/02-U-01, sorted according to latest occurrence.

Corrudinium incompositum which is found in the uppermost sample from 7317/02-U-01 (46.60 m), has its earliest appearance within the *Adnatosphaeridium vittatum* Zone on the Vøring Plateau (Manum et al. 1989). This species was, however, found in the Lower Eocene deposits in core 7316/06-U-02 and also extends down into the Lower Eocene in the Haltenbanken area. As previously mentioned the *A. vittatum* Zone of Manum et al. (1989) may also include upper Lower Eocene sediments.

In contrast to core 7317/02-U-01 the more fine-grained clastic sediments in core 7316/06-U-02 yielded fairly common foraminifera, together with some ostracods and siliceous microfossils. The microfaunas offer a definitive indication of an Early Eocene age for the lower part of core 7316/06-U-02 and early Middle Eocene age for the upper part (Bugge et al. 1990). Although, this has not been confirmed by microfaunal evidences, the close affinities of the dinoflagellate assemblages of core 7317/02-U-01 and 7316/06-U-02 suggest that these are contemporaneous. This observation and the biostratigraphic signals listed above, are strong indications for a Late Eocene to Early Middle Eocene age (i.e. 46 - 58 Ma) for the cored unit at location 7317/02-U-01.

6. ORGANIC GEOCHEMISTRY

6.1 Introduction

During the 1985 study of the material from core 7317/02-U-01, the bedrock was found to contain only very low amounts of organic matter (<0.4%). However, significant concentrations of hydrocarbon gas were observed in two canned Quaternary samples at 14.64 m and 20.20 m. The gas in the lower of these samples was found to contain significant amounts of C_{2+} compounds (Table 6.1), suggesting a catagenic origin for this gas. This possibility was further supported by a $\delta^{13}C_{CH_4}$ ratio of -45.4 o/oo and an iC_4/nC_4 ratio of 0.26 (Table 6.1).

The aim of the current project is to further investigate the occurrence of free hydrocarbons in the succession penetrated by core 7317/02-U-01. Of particular interest is the possibility that liquid bitumen may be associated with the Quaternary gas shows.

The analytical program used for this study lays emphasis on the investigation and description of any extractable organic matter which may be present in the core. The analyses include liquid chromatography, gas chromatography of the saturate fraction and combined gas chromatography-mass spectrometry (GC-MS) of the same fraction. The procedures followed are more fully described in Appendix 1.

6.2 Analytical results

Selection of samples

Samples were picked on the basis of TOC and gas data from the 1985 shallow drilling report.

The specific samples with high gas contents in the Quaternary sequence consisted of loose sand and were therefore considered unsuitable for further analysis. The closest suitable samples at 24.60 m and 25.49 m were selected for extraction. One sample (29.64 m) close to the upper intra-Quaternary boundary at 27.5 m and one sample from 44.40 m situated closer to the boundary between the overburden and bedrock were also selected for analysis. From the Tertiary sequence three additional samples were selected for analysis. One of the samples was taken at the top of the bedrock, at

46.91 m to study phenomena at the boundary while two other samples were selected to provide data on the two main lithologies in the bedrock, i.e. sandstone and claystone. The samples at 29.64 m and 46.91 m were selected in order to better define possible bitumen variations associated with the intra-Quaternary and Quaternary-Tertiary boundaries, respectively.

TOC

The samples are lean to fair in total organic carbon content (TOC), i.e. 0.3 to 1.2 wt% TOC (Table 6.2). The highest TOC values were found in the Quaternary samples which have an average value of 0.88 wt% TOC. The samples from the bedrock have a lower average TOC content of 0.33 wt% TOC.

Extraction

Although very small amounts of rock were available for extraction with resultingly low extraction yields in the range of 4-11 mg, enough material was available to proceed with the analyses. The low extraction yields (mg EOM) may result in some of the reported fraction weights in the extraction table (Table 6.3) being slightly erroneous.

The lowermost Quaternary sample at 44.40 m gave the highest yield of extractable organic matter (EOM) of ca. 1200 ppm, of which nearly 30% represented hydrocarbon compounds. The concentration of total EOM decreases slightly upwards in the Quaternary succession through 1000 ppm at 29.64 m to ca. 1100 ppm close to the intra-Quaternary boundary at ca. 27.5 m. Above this boundary, there is a marked decrease in EOM concentration to ca. 700 ppm. The asphaltene content of the Quaternary extracts decreases from 500 ppm at 44.40 m to between 329 ppm and 365 ppm in the upper three samples. In contrast, the hydrocarbon concentration decreases from 351 ppm at 44.40 m to 104 ppm at 29.64 m, followed by an increase to between 212 ppm and 258 ppm in the two samples above the intra-Quaternary boundary.

A much sharper decrease in the concentration of EOM, hydrocarbons and asphaltenes was observed between the lowermost Quaternary sample and the Tertiary bedrock samples. The concentration of EOM in the Tertiary samples was ca. 20-25% of that observed in the sample at 44.40 m. The sample from 46.91 m at the Quaternary/Tertiary boundary contained 200 ppm EOM, which is the lowest yield in the entire succession. The evolution of extraction yields is clearly visible in the EOM components versus depth plot in Figure 6.1.

Gas Chromatography of the Saturated Hydrocarbon Fraction

Gas chromatograms of the saturate fraction from the seven samples are shown in Figure 6.2. The n-alkane envelope in the Quaternary samples shows a decrease in the prominence of the lower molecular weight hydrocarbons with decreasing depth, while the distribution of higher molecular compounds remains largely constant, the upper three samples being relatively similar in appearance. The odd over even predominance appears to be less pronounced in the samples at 44.40 m and 46.91 m than in the other three samples, and is reflected in low CPI values of 1.8 and 1.1 respectively (Table 6.3).

Pristane/ nC_{17} and Phytane/ nC_{18} ratios are both fairly constant in the four Quaternary samples, with values of ca. 1.7 and 0.9, respectively.

The saturated hydrocarbon gas chromatograms of the two lower Tertiary samples were distinguished by very prominent n-alkane peaks in the range nC_{14} to nC_{17} . In contrast, the saturated hydrocarbon gas chromatogram of the uppermost Tertiary sample shows an n-alkane distribution dominated by higher molecular weight compound peaks with a CPI value approaching equality. The very narrow range of lower molecular weight compounds in the two lowermost samples is rather unusual, and is often associated with contamination by refined hydrocarbon products. The sample from the Quaternary/Tertiary boundary has a very low concentration of saturates, but shows a regular n-alkane distribution with distribution maximum at $n-C_{27}$. The pristane/ nC_{17} values are much lower for the Tertiary samples than for the Quaternary samples but they may be based on contaminants for the two lowermost samples and are thus of little value.

It is possible that the original n-alkane distribution in the lower two Tertiary samples was similar to that of the uppermost Tertiary sample, but has been overprinted by a contaminant. The source of such a contaminant is uncertain.

Gas Chromatography - Mass Spectrometry (Saturate Fraction)

Three samples were selected at 24.60 m, 29.64 m and 44.40 m for biomarker analysis of the bitumen in the Quaternary succession (Figure 6.3). Two samples were also selected from 46.91 m and 56.10 m in the Tertiary succession. All five samples have rather immature terpane distributions with

prominent $\beta\beta$ -hopane peaks. These peaks are most prominently developed in the Tertiary samples, and are least well developed in the sample at 44.40 m. The Quaternary samples are distinguished from the Tertiary samples by the significant concentration of peak (Z) attributed to bisnorhopane. The relatively immature appearance of the m/z 191 mass fragmentograms is contradicted by the occurrence of relatively prominent peaks representing C_{23} - C_{26} tricyclic terpanes. Increased prominence of these compounds is usually attributed to either microbial input, maturation and/or migration.

In contrast to the rather immature appearance of the m/z 191 mass fragmentograms, the m/z 217 mass fragmentograms show a slightly more mature distribution of compounds with relatively prominent diasterane peaks. The sterane composition of the Quaternary samples is rather similar, and is distinguished from the Tertiary samples by the relatively greater prominence of peaks attributed to the $\alpha\alpha\alpha R$ steranes. The proportion of the C_{27} to C_{29} $\alpha\alpha\alpha R$ steranes is similar in all five samples, with the C_{29} $\alpha\alpha\alpha R$ sterane being the more prominent.

The distribution of sterane and terpene compounds in general suggests a low, pre-oil window maturity for the extracts, while the similarities in composition suggest a common source for all five extracts. The increased prominence of diasteranes in the lowermost Tertiary sample may reflect the contamination postulated from the gas chromatography data, but the diasteranes are even more dominant in the sample from the boundary, 46.91 m.

6.3 Discussion of organic geochemical results

The occurrence of significant concentrations of EOM in the Quaternary succession penetrated by core 7317/02-U-01 is consistent with a catagenic origin for the gas in the sample at 20.20 m. Excluding the possibility of contamination in the two Tertiary samples at 50.10 m and 56.10 m, the pristane/phytane and biomarker data suggest a common immature source for the bitumen in all five samples.

There is no obvious source for the EOM within the cored succession, although the relatively high TOC contents in the Quaternary interval may reflect included Mesozoic rock fragments in the clays. The Tertiary claystone horizon sampled at 56.10 m obviously has no hydrocarbon generation potential itself. This leaves only the fact that the EOM must have been introduced into the cored succession by one mechanism or another.

The low maturity level of the extracts is a strong argument against significant migration of the EOM, although the similarity in EOM composition in the drilled interval can only be explained by some sort of EOM redistribution mechanism.

The most obvious possibility is basically a migration mechanism, wherein the EOM was emplaced by migration. The increased concentration towards the Quaternary/Tertiary boundary may suggest that this unconformity surface may provide a migration pathway. Unconformity surfaces are often associated with relatively coarse sand or gravel layers, although in core 7317/02-U-01, such a layer is currently not proven. The Quaternary/Tertiary boundary in this core is apparently rather difficult to distinguish, although it is rather sandy. The distribution of EOM would therefore require seepage of hydrocarbons from a nearby subcropping organic-rich shale horizon, presumably of Tertiary age since the nearest subcropping Mesozoic rocks are relatively distant. The seeped hydrocarbons would then move along the unconformity surface for a short distance, while also seeping vertically. In the shallower samples, some modification of the EOM due to either biodegradation, water-washing or loss of lower molecular weight compounds might be expected.

The main flaw in this explanation is the relatively low maturity of the EOM, which would generally be taken to preclude migration. In such a case, some sort of transport mechanism would be required, possibly associated with general subsurface fluid movement.

The overall similarity of the EOM in the seven samples would tend to rule out an origin from older (e.g. Mesozoic) rock chips enclosed in the Quaternary clay or mud-clasts in the sandstone. If such a situation were the case, then a greater degree of heterogeneity would be expected. In addition, the Quaternary clays themselves are too thermally immature to allow themselves to be considered as a source of the bitumens. To investigate this further, it is suggested that rock chips are picked out from the Quaternary sediment samples and analysed separately.

6.4 Conclusion of organic geochemistry

The Quaternary and Tertiary strata samples from core 7317/02-U-01 contain quantities of thermally immature bitumen, especially the former. The bitu-

men shows evidence of a common source, although there is no suitable candidate for this source within the cored succession. The similarity in the bitumen composition suggests that some sort of redistribution mechanism has operated within the core, possibly redistributing the bitumen from a conduit horizon which coincides with the Quaternary/Tertiary unconformity. The immaturity of the bitumen argues against a large migration distance, and therefore provides some justification for postulating the presence of a nearby organic-rich horizon of Tertiary age.

TABLES AND FIGURES

ORGANIC GEOCHEMISTRY

Table 6.1 Interstitial gas data from 7317/02-U-01 well. Gas yield (μl gas per kg dry sediment) and gas composition (%).

SITE	D85-V	D85-V
DEPTH(M)	14.64	20.20
GRIDNR	0014-64	0020-00

COMPOUND		
Methane	45.01	5540.19
Ethane	1.85	1504.54
Propane	4.32	3766.09
i-Butane	0.00	469.33
Butane	0.00	1737.50
? RI= 417	0.00	0.00
i-Pentane	0.00	236.23
n-Pentane	0.00	164.90
CyC5	0.00	30.50
2,3dMeC4	0.00	4.76
2MeC5	0.00	43.04
3MeC5	0.00	20.56
n-Hexane	0.00	27.62
MeCyC5	0.00	69.98
? RI= 638	0.85	0.00
Benzen	0.00	12.82
CyC6	0.00	10.66
2MeC6	0.00	3.84
2,3dMeC5	0.00	4.42
3MeC6	0.00	7.20
1c,3dMeCyC5	0.00	13.31
1t,3dMeCyC5	0.00	11.58
i-Octane	0.00	18.11
n-Heptane	0.00	11.48
MeCyC6	0.00	25.99
2,4dMeC6	0.00	2.98
? RI= 743	0.00	3.22
1,2,4tMeC5	0.00	0.00
1,2,3 "	0.00	3.51
Toluene	0.00	8.79
4MeC7	0.00	2.02
1,4dMeCyC6	0.00	2.69
? RI= 842	0.00	5.43
? RI= 843	0.00	0.00
SUM	52.00	13763.30

SITE	D85-V	D85-V
DEPTH(M)	14.64	20.20
GRIDNR	0014-64	0020-00

COMPOUND		
Methane	86.50	40.27
Ethane	3.56	10.94
Propane	8.30	27.37
i-Butane	0.00	3.41
Butane	0.00	12.63
? RI= 417	0.00	0.00
i-Pentane	0.00	1.72
n-Pentane	0.00	1.20
CyC5	0.00	0.22
2,3dMeC4	0.00	0.03
2MeC5	0.00	0.31
3MeC5	0.00	0.15
n-Hexane	0.00	0.20
MeCyC5	0.00	0.51
? RI= 638	1.64	0.00
Benzen	0.00	0.09
CyC6	0.00	0.08
2MeC6	0.00	0.03
2,3dMeC5	0.00	0.03
3MeC6	0.00	0.05
1c,3dMeCyC5	0.00	0.10
1t,3dMeCyC5	0.00	0.08
i-Octane	0.00	0.13
n-Heptane	0.00	0.08
MeCyC6	0.00	0.19
2,4dMeC6	0.00	0.02
? RI= 743	0.00	0.02
1,2,4tMeC5	0.00	0.00
1,2,3 "	0.00	0.03
Toluene	0.00	0.06
4MeC7	0.00	0.01
1,4dMeCyC6	0.00	0.02
Values used for normalisation:		
MUL/KG	52.00	13757.90

$\delta^{13}\text{C}$ isotope value for methane from the sample at 20.20 m in core 7317/02-U-01 -45.4 o/oo

Table 6.1 cont.

Adsorbed gas data from 7317/02-U-01 (D85-V) well. Gas yield (µl gas per kg dry sediment).

SITE	D85-V	D85-V	D85-V	SITE	D85-V	D85-V	D85-V
DEPTH (m)	0.30	14.64	20.20	DEPTH (m)	0.30	14.64	20.20
GRIDNR	0000-00	0014-64	0020-00	GRIDNR	0000-00	0014-64	0020-00
-----				-----			
COMPOUND				COMPOUND			
Methane	913.74	168.89	148.72	Benzen	11.01	0.79	9.38
Ethene	0.00	1.09	0.69	3,3dMeC5	0.00	0.00	0.00
Ethane	61.71	12.47	17.97	CyC6	0.86	0.19	1.76
Propene	0.00	0.29	0.18	2MeC6	0.42	0.00	0.28
Propane	21.86	5.65	81.94	2,3dMeC5	0.00	0.00	0.36
? RI= 333	3.29	6.20	7.59	1,1dMeCyC5	0.00	0.00	0.00
i-Butane	6.65	1.89	21.78	3MeC6	0.59	0.00	0.56
Butene	0.00	0.00	0.13	1c,3dMeCyC5	0.00	0.00	1.56
Butane	5.61	1.60	85.01	1t,3dMeCyC5	0.00	0.00	1.53
neoC5	0.00	0.00	0.00	i-Octane	0.00	0.00	2.17
? RI= 424	0.00	0.00	0.00	? RI= 694	0.91	0.00	0.18
? RI= 426	0.00	0.00	0.26	n-Heptane	0.48	0.00	0.85
? RI= 431	4.03	1.86	1.78	MeCyC6	2.62	0.37	4.14
i-Pentane	4.86	1.28	17.75	? RI= 737	0.00	0.00	0.60
? RI= 475	0.00	0.00	0.25	1,2,4tMeC5	0.00	0.00	0.25
? RI= 490	0.47	0.00	0.00	? RI= 752	0.00	0.00	0.38
? RI= 493	0.00	0.00	0.00	2,3,4tMeC5	0.00	0.00	0.00
n-Pentane	2.26	0.44	13.22	Toluene	5.78	0.53	8.85
? RI= 508	0.67	0.20	0.18	1,1,2tMeC7	0.00	0.00	0.00
DCM	1.41	0.23	0.77	? RI= 765	0.00	0.00	0.00
neoC6	0.00	0.00	0.00	4MeC7	0.00	0.00	0.12
? RI= 538	1.15	0.00	0.70	3,4dMeC7	0.00	0.00	0.00
CyC5	0.00	0.13	4.19	? RI= 773	0.00	0.00	0.00
2,3dMeC4	0.48	0.14	0.64	2,2,5tMeC7	0.00	0.00	0.00
2MeC5	1.67	0.23	3.61	1,4dMeCyC6	0.00	0.00	0.34
3MeC5	0.92	0.19	1.98	? RI= 783	0.00	0.00	0.00
n-Hexane	1.05	0.00	2.68	1,1dMeCyC6	0.00	0.00	0.00
MeCyC5	1.03	0.45	9.31	? RI= 795	0.00	0.00	0.00
2,4dMeC5	0.00	0.00	0.00	? RI= 798	0.00	0.00	0.00
2,2,3tMeC4	0.00	0.00	0.00	n-Octane	0.00	0.00	0.28
? RI= 638	0.00	0.00	0.00				
? RI= 639	4.33	1.19	1.61				

Table 6.1 cont.

Adsorbed gas data from 7317/02-U-01 well (D85-V).
Gas composition (%).

SITE	D85-V	D85-V	D85-V	SITE	D85-V	D85-V	D85-V
DEPTH (m)	0.30	14.64	20.20	DEPTH (m)	0.30	14.64	20.20
GRIDNR	0000-00	0014-64	0020-00	GRIDNR	0000-00	0014-64	0020-00
-----				-----			
COMPOUND				COMPOUND			
Methane	87.08	85.38	33.42	1c,3dMeCyC5	0.00	0.00	0.35
Ethene	0.00	0.55	0.15	1t,3dMeCyC5	0.00	0.00	0.34
Ethane	5.88	6.31	4.04	i-Octane	0.00	0.00	0.49
Propene	0.00	0.05	0.04	? RI= 694	0.09	0.00	0.04
Propane	2.08	2.86	18.41	n-Heptane	0.05	0.00	0.19
i-Butane	0.63	0.95	4.89	MeCyC6	0.25	0.19	0.93
Butene	0.00	0.00	0.03	? RI= 737	0.00	0.00	0.13
Butane	0.53	0.81	19.10	1,2,4tMeC5	0.00	0.00	0.06
neoC5	0.00	0.00	0.00	? RI= 752	0.00	0.00	0.09
? RI= 424	0.00	0.00	0.00	2,3,4tMeC5	0.00	0.00	0.00
? RI= 426	-1.00	-1.00	-1.00	Toluene	0.55	0.27	1.99
? RI= 431	-1.00	-1.00	-1.00	1,1,2tMeC7	0.00	0.00	0.00
i-Pentane	0.46	0.65	3.99	? RI= 765	0.00	0.00	0.00
? RI= 490	0.04	0.00	0.00	4MeC7	0.00	0.00	0.03
? RI= 493	0.00	0.00	0.00	3,4dMeC7	0.00	0.00	0.00
n-Pentane	0.22	0.22	2.97	? RI= 773	0.00	0.00	0.00
neoC6	0.00	0.00	0.00	2,2,5tMeC7	0.00	0.00	0.00
CyC5	0.00	0.07	0.94	1,4dMeCyC6	0.00	0.00	0.08
2,3dMeC4	0.05	0.07	0.14	? RI= 783	0.00	0.00	0.00
2MeC5	0.16	0.12	0.81	1,1dMeCyC6	0.00	0.00	0.00
3MeC5	0.09	0.10	0.45	? RI= 795	0.00	0.00	0.00
n-Hexane	0.10	0.00	0.60	? RI= 798	0.00	0.00	0.00
MeCyC5	0.10	0.23	2.09	n-Octane	0.00	0.00	0.06
2,4dMeC5	0.00	0.00	0.00				
2,2,3tMeC4	0.00	0.00	0.00	Values used for normalisation:			
? RI= 638	0.00	0.00	0.00				
? RI= 639	0.41	0.60	0.36	MUL/KG	1049.30	197.80	445.00
Benzen	1.05	0.40	2.11				
3,3dMeC5	0.00	0.00	0.00				
CyC6	0.08	0.10	0.39				
2MeC6	0.04	0.00	0.06				
2,3dMeC5	0.00	0.00	0.08				
1,1dMeCyC5	0.00	0.00	0.00				
3MeC6	0.06	0.00	0.13				

Table 6.2 Data from carbon and/or sulphur analysis.

Location : 7317/02-U-01
 Date : 90.05.03

IKUNO	FRAC NAME	DEPTH (m)	SAMPLE TYPE	TOC (%)	Total Carbon (%)	Total Sulphur (%)	Carbonate CaCO ₃ (%)
C2450	BULK	14.64	OTHER	0.61	-1	-1	-1
C2451	BULK	20.00	OTHER	0.32	-1	-1	-1
C3369	BULK	24.60	OUTCR	1.24	-1	-1	-1
C3369	ESED	24.60	OUTCR	1.21	-1	-1	-1
C3370	BULK	24.75	OUTCR	1.27	-1	-1	-1
C3371	BULK	25.49	OUTCR	1.24	-1	-1	-1
C3371	ESED	25.49	OUTCR	1.23	-1	-1	-1
G1126	BULK	29.64	OUTCR	0.68	-1	-1	-1
G1126	ESED	29.64	OUTCR	0.63	-1	-1	-1
C3372	BULK	44.40	OUTCR	0.92	-1	-1	-1
C3372	BULK	44.40	OUTCR	0.80	-1	-1	-1
C3372	ESED	44.40	OUTCR	0.77	-1	-1	-1
C3373	BULK	44.56	OUTCR	0.46	-1	-1	-1
G1127	BULK	46.91	OUTCR	0.34	-1	-1	-1
G1127	ESED	46.91	OUTCR	0.37	-1	-1	-1
C2878	BULK	49.10	CORE	0.18	-1	-1	-1
C2879	BULK	50.10	CORE	0.31	-1	-1	-1
C2879	ESED	50.10	CORE	0.31	-1	-1	-1
C2880	BULK	53.10	CORE	0.33	-1	-1	-1
C2881	BULK	55.10	CORE	0.33	-1	-1	-1
C2882	BULK	56.10	CORE	0.32	-1	-1	-1
C2882	BULK	56.10	CORE	0.43	-1	-1	-1
C2882	ESED	56.10	CORE	0.40	-1	-1	-1

Carbonate content computed from difference TC-TOC,
 assuming that all carbonate is CaCO₃.

-1 - No data available.

Table 6.3 Weight of chromatographic fractions.

Location : 7317/02-U-01
Date : 90.05.07

IKUNO	FRAC NAME	DEPTH (m)	SAMPLE TYPE	ROCK EXTR. (g)	EOM (mg)	ASPH (mg)	SAT HC (mg)	ARO HC (mg)	POLAR COMP. (mg)	HC (mg)	NONHC* (mg)	TOC (%)
C3369	ESED	24.60	OUTCR	14.0	10.0	4.6	2.4	1.2	3.9	3.6	6.4	1.21
C3371	ESED	25.49	OUTCR	8.5	6.5	3.1	0.8	1.0	2.9	1.8	4.7	1.23
G1126	ESED	29.64	OUTCR	10.4	11.4	3.6	0.5	0.6	3.3	1.1	10.3	0.63
C3372	ESED	44.40	OUTCR	7.2	9.1	3.6	0.8	1.7	2.4	2.5	6.6	0.77
G1127	ESED	46.91	OUTCR	32.0	6.0	1.7	0.2	0.7	2.2	0.9	5.1	0.37
C2879	ESED	50.10	CORE	13.5	4.2	2.2	1.1	1.0	2.3	2.1	2.1	0.31
C2882	ESED	56.10	CORE	28.1	8.0	2.3	1.2	1.2	3.7	2.4	5.6	0.40

Concentration of EOM and chromatographic fractions.

Location : 7317/02-U-01
Date : 90.05.07

(Weight ppm of rock)

IKUNO	FRAC NAME	DEPTH (m)	SAMPLE TYPE	EOM	ASPH	SAT HC	ARO HC	POLAR COMP.	HC	NONHC*
C3369	ESED	24.60	OUTCR	714	329	172	86	275	258	456
C3371	ESED	25.49	OUTCR	765	365	99	113	340	212	553
G1126	ESED	29.64	OUTCR	1092	345	46	58	312	104	988
C3372	ESED	44.40	OUTCR	1264	500	117	234	334	351	913
G1127	ESED	46.91	OUTCR	188	53	8	23	68	31	157
C2879	ESED	50.10	CORE	311	163	80	71	169	151	160
C2882	ESED	56.10	COR	285	82	43	43	133	86	199

Table 6.3 cont. Concentration of EOM and chromatographic fractions.

Location : 7317/02-U-01
Date : 90.05.07

(mg/g toc)

IKUNO	FRAC NAME	DEPTH (m)	SAMPLE TYPE	EOM	ASPH	SAT HC	ARO HC	POLAR COMP.	HC	NONHC*
C3369	ESED	24.60	OUTCR	59.0	27.2	14.2	7.1	22.7	21.3	37.7
C3371	ESED	25.49	OUTCR	62.2	29.7	8.1	9.2	27.6	17.3	44.9
G1126	ESED	29.64	OUTCR	173.3	54.7	7.3	9.2	49.5	16.5	156.8
C3372	ESED	44.40	OUTCR	164.1	64.9	15.2	30.4	43.4	45.6	118.5
G1127	ESED	46.91	OUTCR	50.7	14.7	2.0	6.1	18.3	8.1	40.6
C2879	ESED	50.10	CORE	100.4	52.6	25.9	23.0	54.6	48.9	51.5
C2882	ESED	56.10	CORE	71.2	20.5	10.7	10.7	33.2	21.4	49.8

Composition of EOM and chromatographic fractions.

Location : 7317/02-U-01
Date : 90.05.07

IKUNO	FRAC NAME	DEPTH (m)	SAMPLE TYPE	ASPH EOM (%)	SAT EOM (%)	ARO EOM (%)	HC EOM (%)	POLAR EOM (%)	SAT ARO x 100
C3369	ESED	24.60	OUTCR	46.0	24.1	12.0	36.1	38.5	200.0
C3371	ESED	25.49	OUTCR	47.7	13.0	14.8	27.8	44.4	87.5
G1126	ESED	29.64	OUTCR	31.6	4.2	5.3	9.5	28.5	80.0
C3372	ESED	44.40	OUTCR	39.6	9.3	18.5	27.8	26.5	50.0
G1127	ESED	46.91	OUTCR	28.3	4.0	12.0	16.0	36.1	33.3
C2879	ESED	50.10	CORE	52.4	25.8	22.9	48.7	54.4	112.5
C2882	ESED	56.10	CORE	28.8	15.1	15.1	30.2	46.7	100.0

NONHC* is determined as the difference between eom and hc. With the low fraction weights in this samples, the NONHC will be different to the sum of asph and polar comp.

Table 6.4 Ratios derived from gas chromatograms of saturated hydrocarbons.

Location : 7317/02-U-01

Date : 90.05.02

IKUNO	FRAC NAME	DEPTH	Pri	Pri	Phy	A	n-C17	n-C31	CPI 1	CPI 2
			$\frac{\text{Phy}}{\text{Phy}}$	$A = \frac{\text{Pri}}{\text{n-C17}}$	$B = \frac{\text{Phy}}{\text{n-C18}}$	$\frac{A}{B}$	$\frac{\text{n-C17}}{\text{n-C27}}$	$\frac{\text{n-C31}}{\text{n-C19}}$		
C3369		24.60	2.1	1.6	1.0	1.6	0.4	1.6	3.1	3.1
C3371		25.49	2.1	1.8	1.0	1.8	0.5	1.0	2.7	2.8
G1126		29.64	2.2	1.7	0.8	2.1	0.9	1.3	2.1	1.8
C3372		44.40	2.2	1.7	0.8	2.0	1.4	0.5	1.8	1.7
G1127		46.91	1.6	0.8	0.7	1.1	0.3	3.2	1.1	1.1
C2879		50.10	2.3	0.6	0.8	0.7	7.6	0.8	4.4	3.7
C2882		56.10	2.3	0.8	1.2	0.7	5.9	1.5	3.0	2.3

$$\text{CPI1} = \frac{1}{2} * \left(\frac{\text{C25} + \text{C27} + \text{C29} + \text{C31}}{\text{C24} + \text{C26} + \text{C28} + \text{C30}} + \frac{\text{C25} + \text{C27} + \text{C29} + \text{C31}}{\text{C26} + \text{C28} + \text{C30} + \text{C32}} \right)$$

$$\text{CPI2} = 2 * \text{C27} / (\text{C26} + \text{C28})$$

Ratios involving pristane and phytane are calculated from peak areas.
All other ratios are calculated from peak heights.

Table 6.5 Molecular ratios from sterane and terpane mass chromatograms.

IKUNO	Depth (m)	$\alpha\beta/\alpha\beta+\beta\alpha^1)$	%22S ²⁾	% $\beta\beta^3)$	%20S ⁴⁾
C3369	24.60	0.73	43.8	31.2	18.2
G1126	29.64	0.73	51.8	33.5	19.5
C3372	44.40	0.75	49.7	37.6	19.2
G1127	46.91	0.77	56.4	50.0	28.7
C2882	56.10	0.76	55.7	52.3	25.6

1) E/(E+F) in m/z 191.

2) % distribution between first and second eluting isomers of extended hopanes.

3) r+s/(q+t+r+s).

4) q/(q+t).

Table 6.6 Molecular ratios from terpane and sterane mass chromatograms.

IKUNO	Depth (m)	Q/E ¹⁾	T _m /T _s ²⁾	X/E ³⁾	Z/E ⁴⁾	a/a+j ⁵⁾
C3369	24.60	0.04	6.55	0.04	0.28	0.40
G1126	29.64	0.05	6.43	0.04	0.17	0.43
C3372	44.40	0.08	5.17	0.04	0.16	0.46
G1127	46.91	0.19	1.70	0.06	0.08	0.61
C2882	56.10	0.06	1.69	0.03	0.10	0.50

1) Relative abundance of tricyclic terpanes (Q/E in m/z 191).

2) B/A in m/z 191.

3) Relative abundance of unknown (X/E in m/z 191).

4) Relative abundance of bisnorhopane (Z/E in m/z 191).

5) Relative abundance of rearranged steranes (a/a+j in m/z 217).

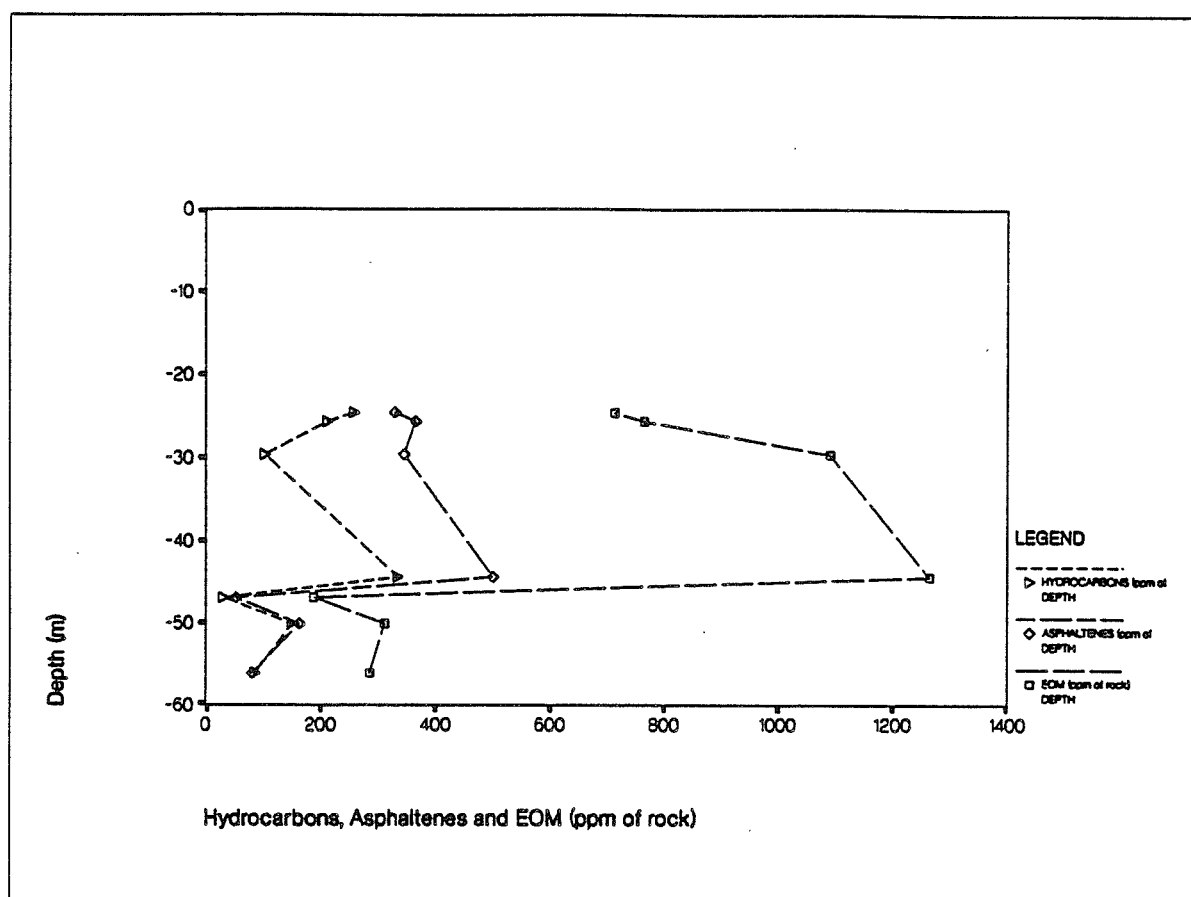


Figure 6.1 Variation in concentration of EOM components with depth. Well 7317/02-U-01.

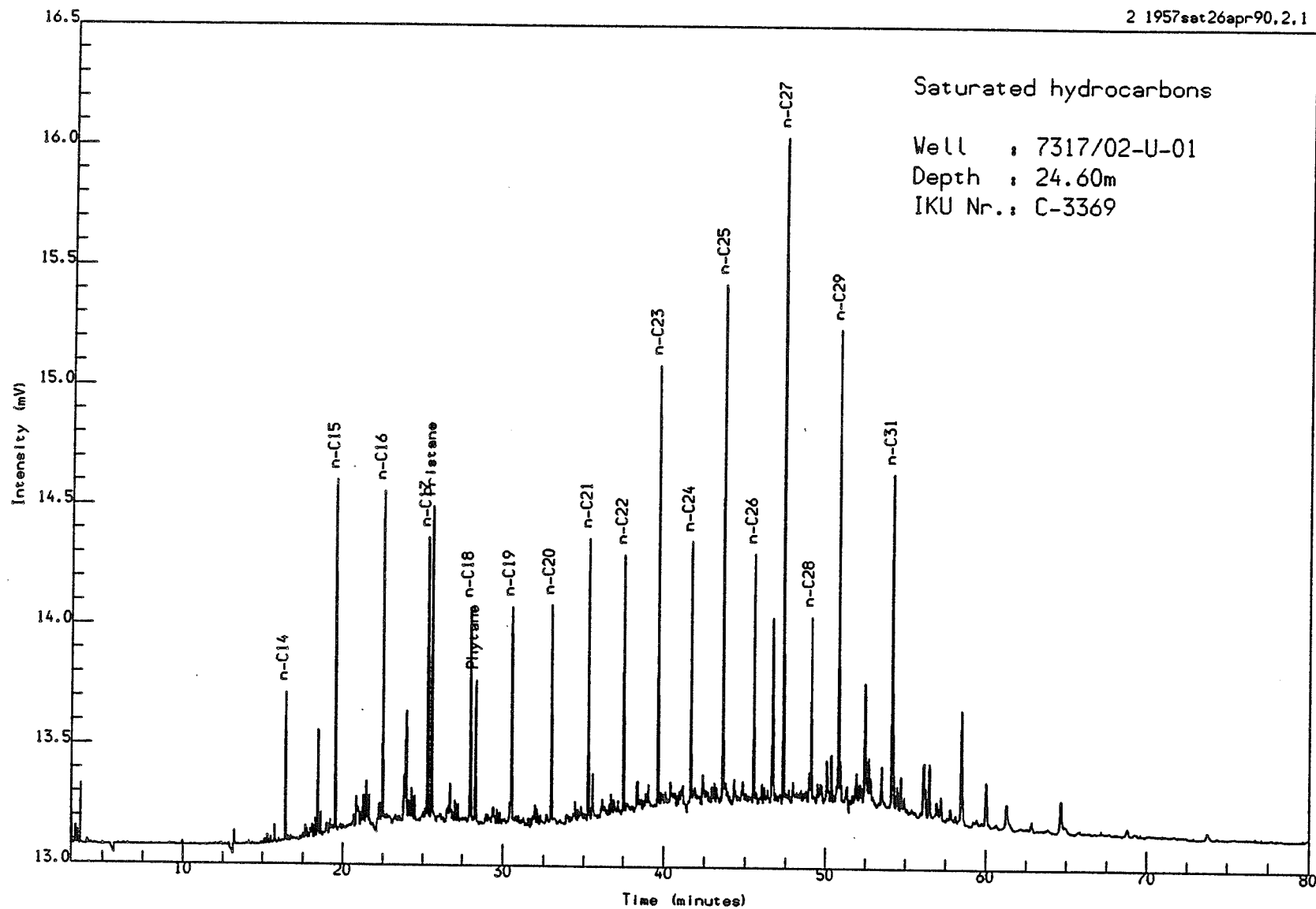


Figure 6.2 Gas chromatograms of saturate fraction

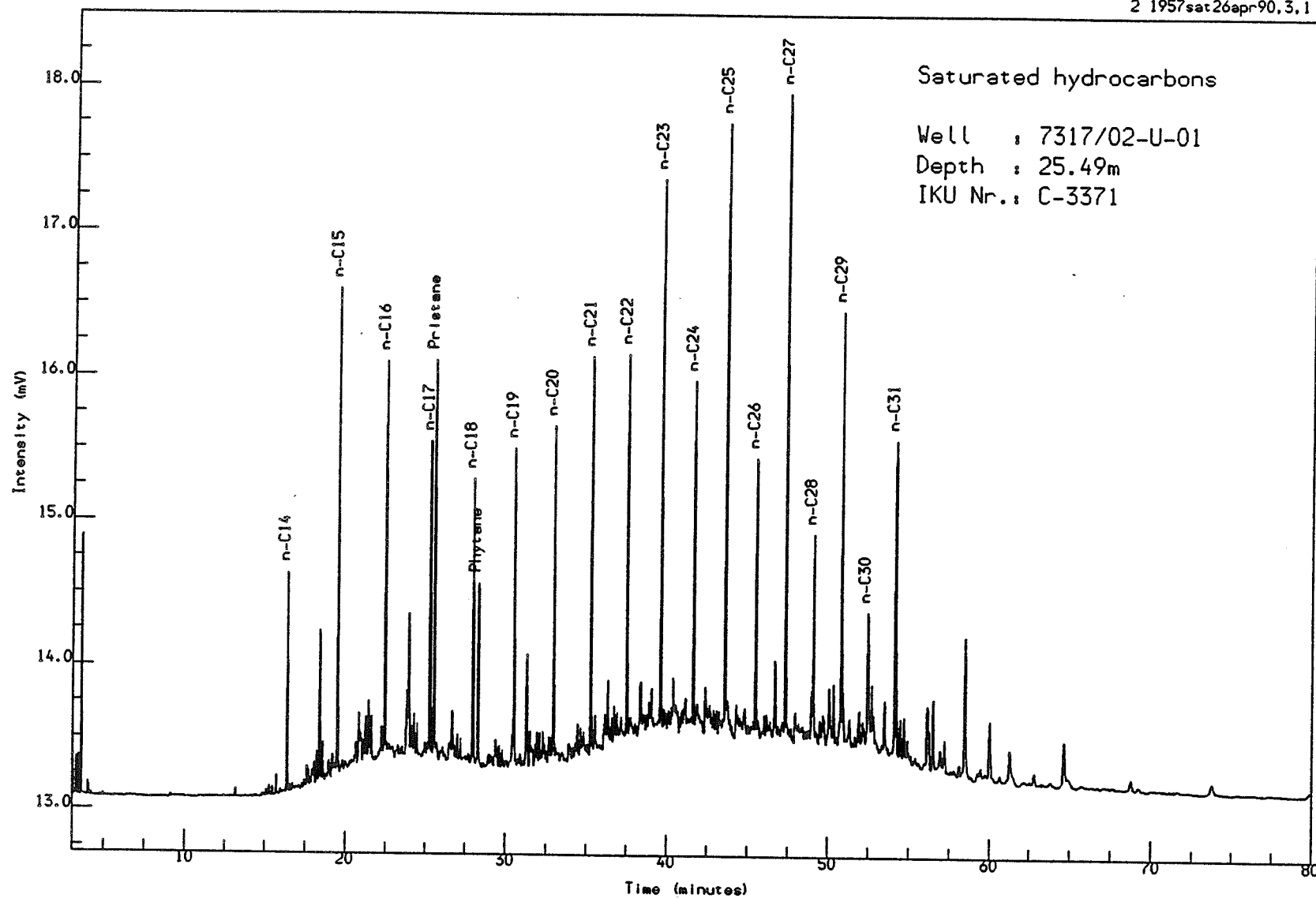


Figure 6.2 cont. Gas chromatograms of saturate fraction

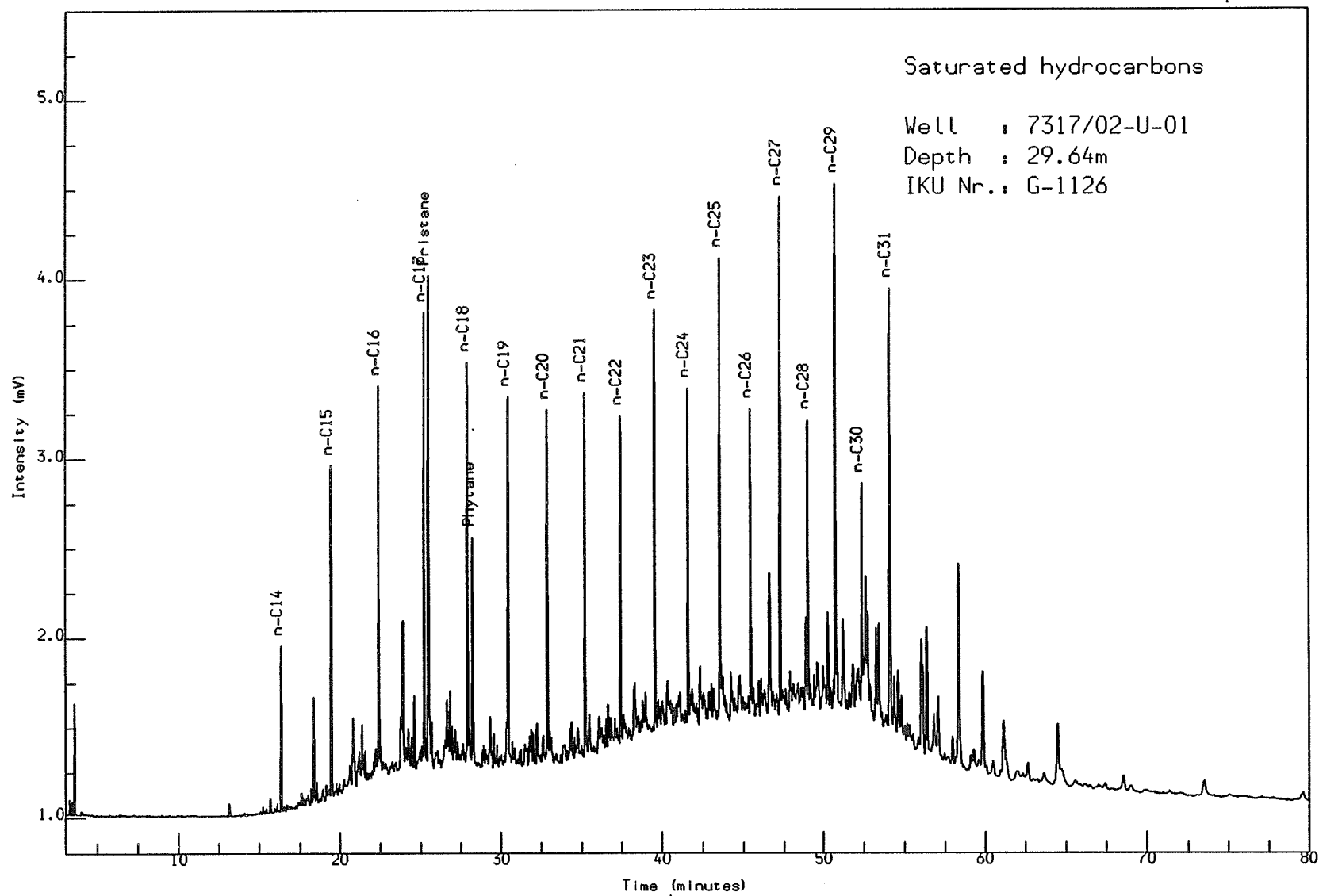


Figure 6.2 con. Gas chromatograms of saturate fraction

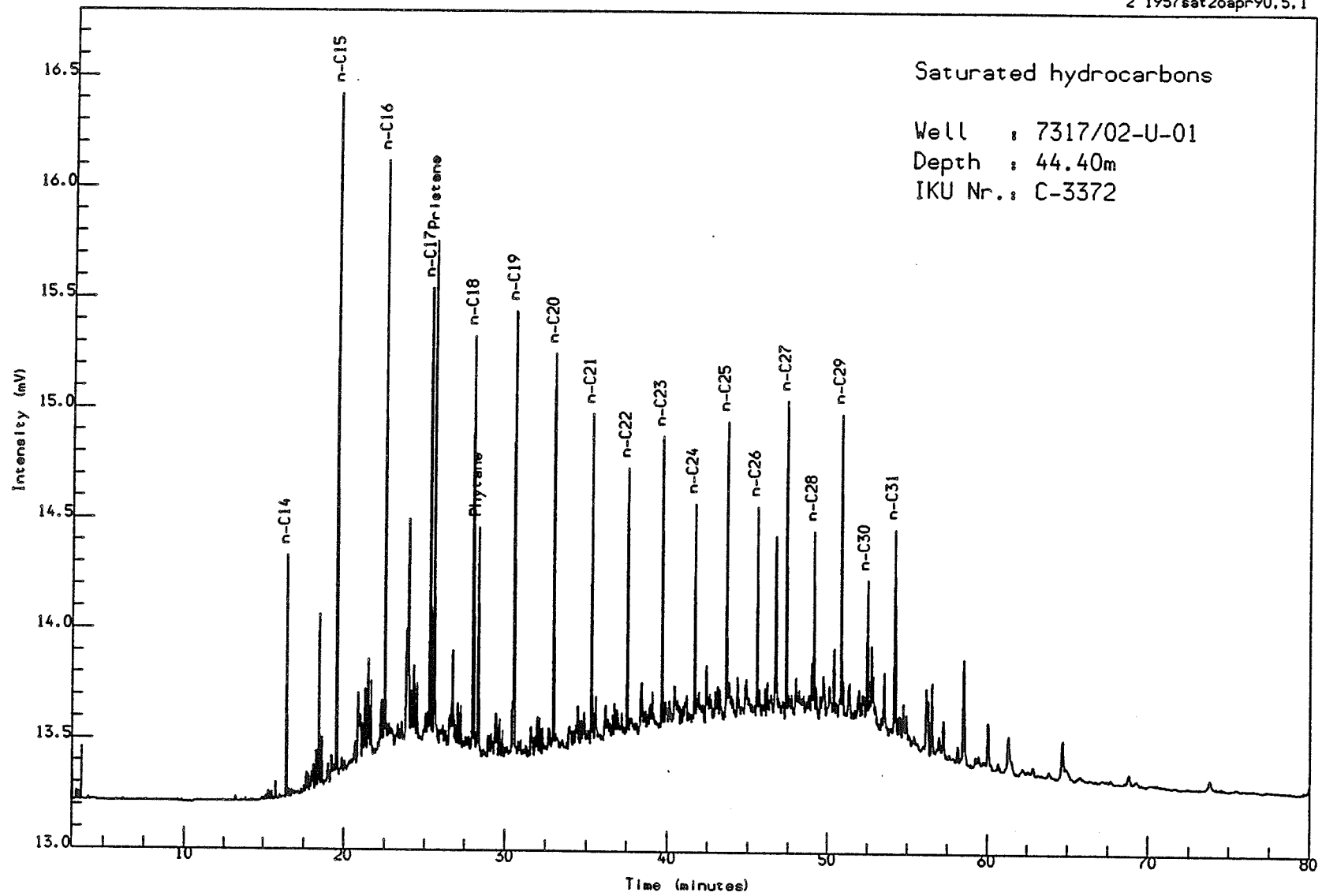


Figure 6.2 cont. Gas chromatograms of saturate fraction

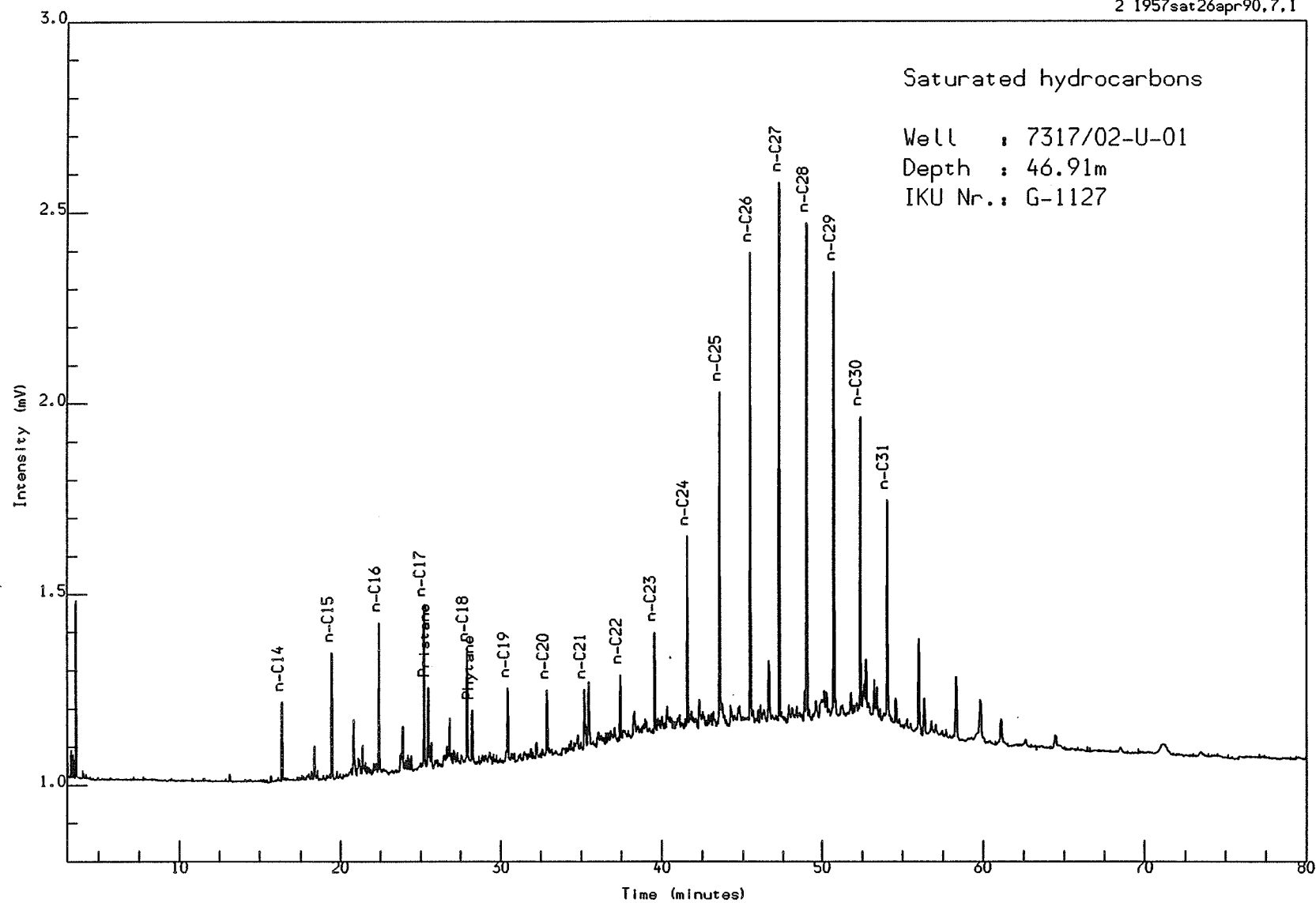


Figure 6.2 con. Gas chromatograms of saturate fraction

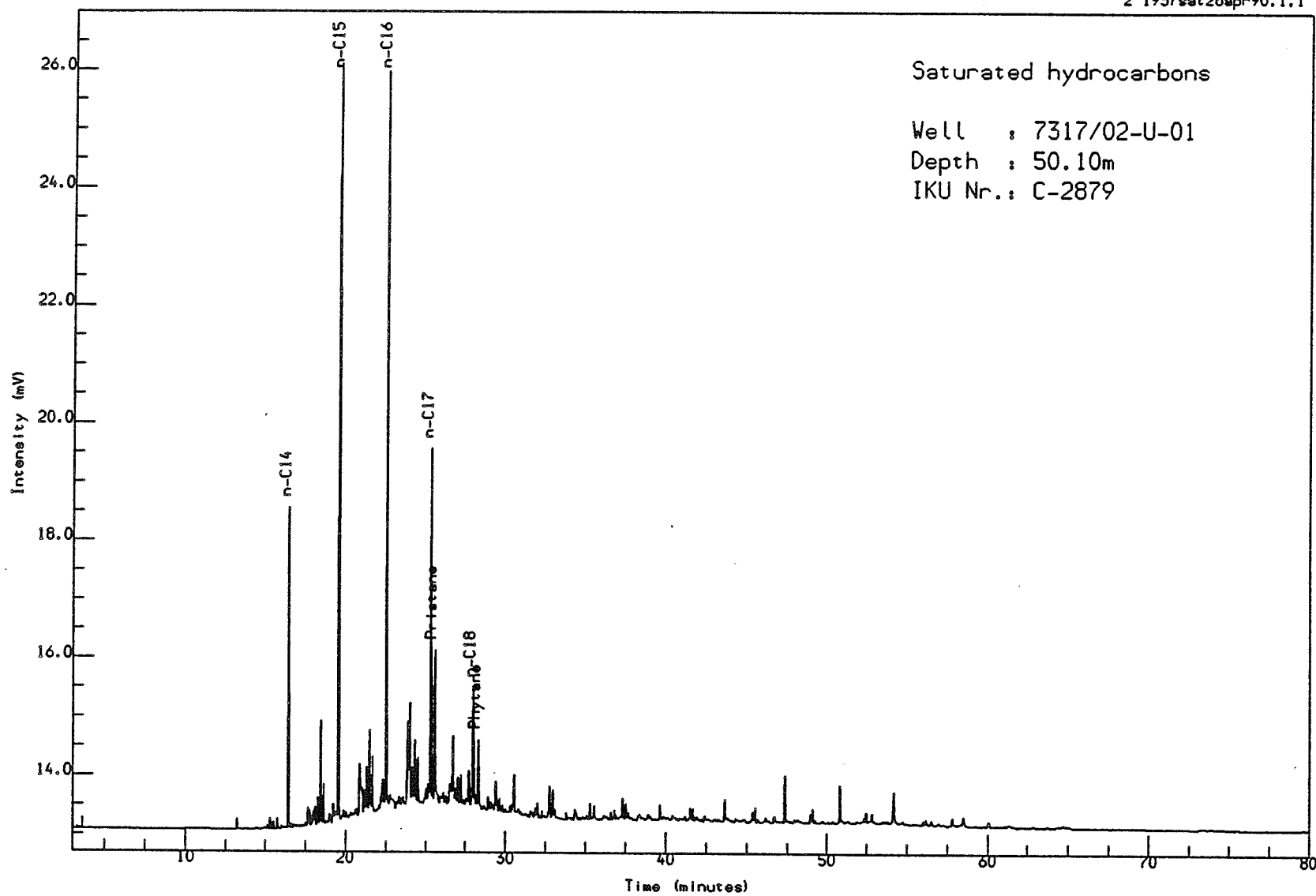


Figure 6.2 cont. Gas chromatograms of saturate fraction

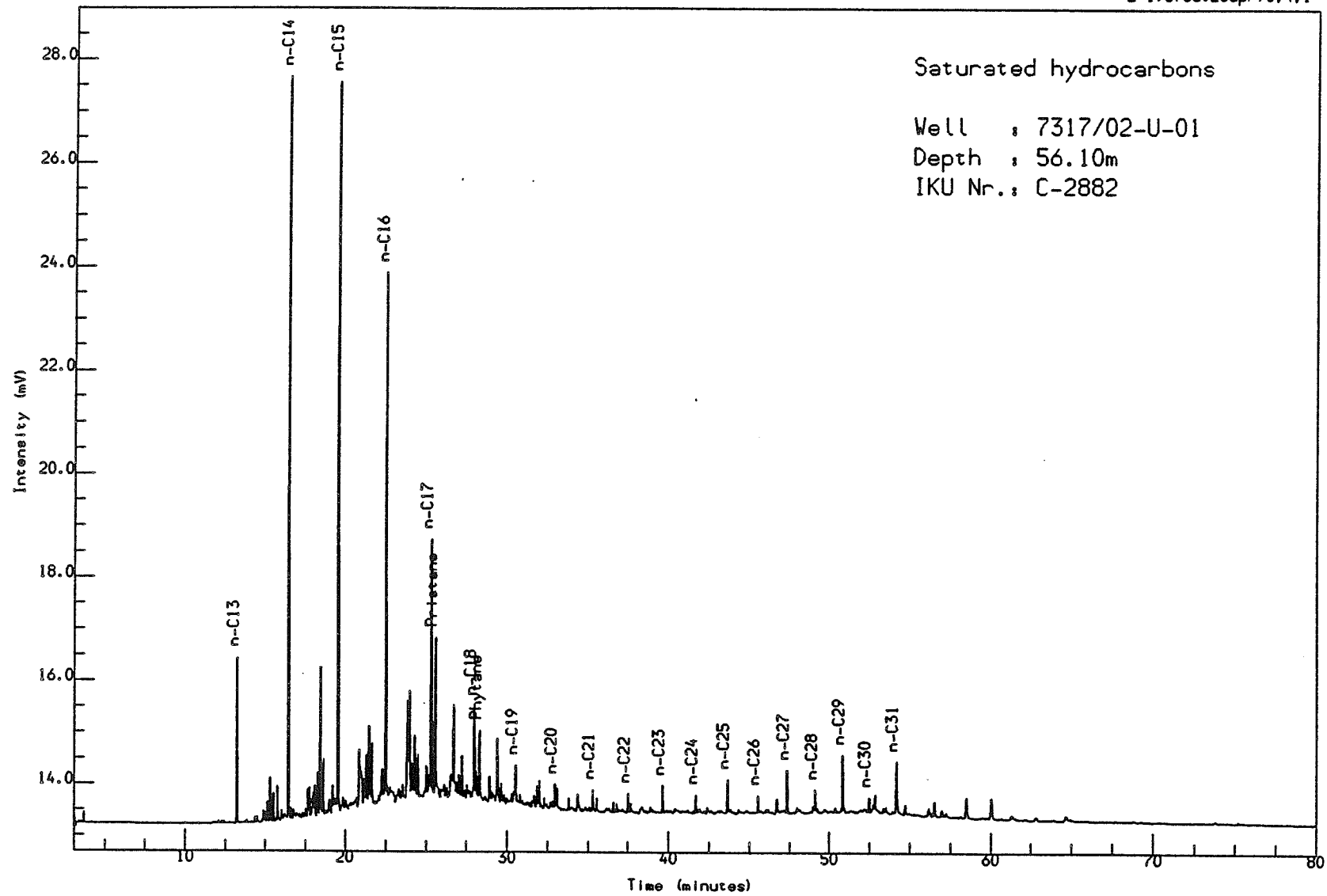


Figure 6.2 cont. Gas chromatograms of saturate fraction

*Figure 6.3 Mass fragmentograms of m/z 191 (terpanes)
and m/z 217, 218 (steranes).*

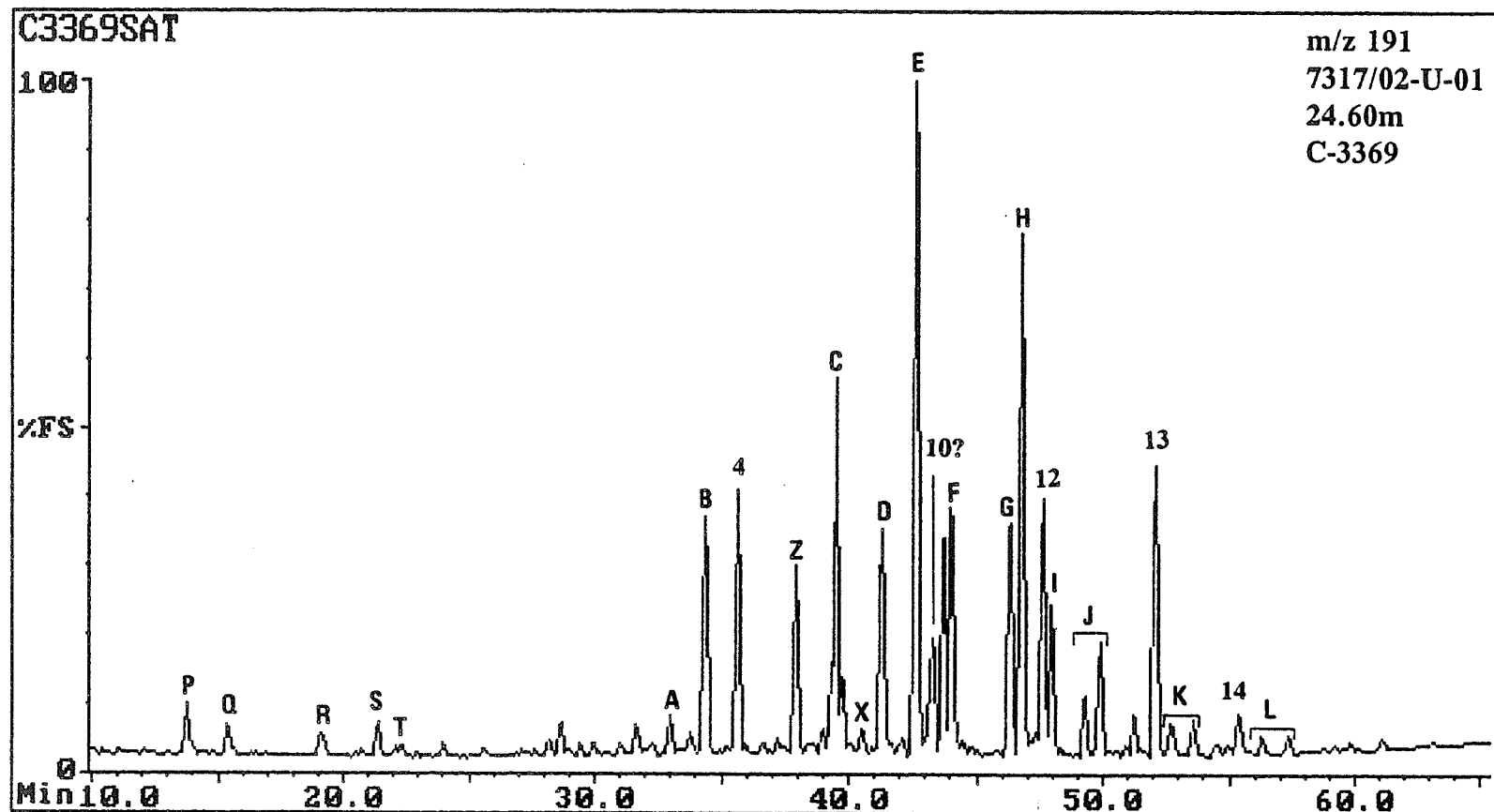
Key for m/z 191 (terpanes):

Peak code	Identification	C-atoms : double bonds
P	C ₂₃ tricyclic terpane	(C _{23:0})
Q	C ₂₄ tricyclic terpane	(C _{24:0})
R	C ₂₅ tricyclic terpane (17R,17S)	(C _{25:0})
S	C ₂₄ tetracyclic terpane	(C _{24:0})
T	C ₂₆ tricyclic terpane (17R,17S)	(C _{26:0})
A	18 α (H)-trishomohopane, Ts (?)	(C _{27:0})
B	17 α (H)-trishomohopane, Tm	(C _{27:0})
4	17 β (H)-trishomohopane	(C _{27:0})
Z	28,30-Bishomohopane	(C _{28:0})
C	17 α (H), 21 β (H)-norhopane	(C _{29:0})
5	nor-hop- $\Delta^{13(18)}$ -ene	(C _{29:1})
X	Unknown terpane	(C _{30:0})
D	17 β (H),21 α (H)-norhopane (= normoretane)	(C _{29:0})
E	17 α (H),21 β (H)-hopane	(C _{30:0})
10	17 β (H),21 β (H)-norhopane	(C _{29:0})
F	17 β (H),21 α (H)-hopane (= moretane)	(C _{30:0})
G	17 α (H),21 β (H)-homohopane (22S)	(C _{31:0})
H	17 α (H),21 β (H)-homohopane (22R)	(C _{31:0})
12	17 β (H),21 β (H)-hopane	(C _{30:0})
I	17 β (H),21 α (H)-homohopane (= homomoretane)	(C _{31:0})
J	17 α (H),21 β (H)-bishomohopane (22S,22R)	(C _{32:0})
13	17 β (H),21 β (H)-homohopane	(C _{31:0})
K	17 α (H),21 β (H)-trishomohopane (22S,22R)	(C _{33:0})
14	17 β (H),21 β (H)-bishomohopane	(C _{32:0})
L	17 α (H),21 β (H)-tetrakishomohopane (22S,22R)	(C _{34:0})
M	17 α (H),21 β (H)-pentakishomohopane (22S,22R)	(C _{35:0})

UG LAB-BASE
Sample:22.1957.00

The TRIO-1 GC-MS Data System

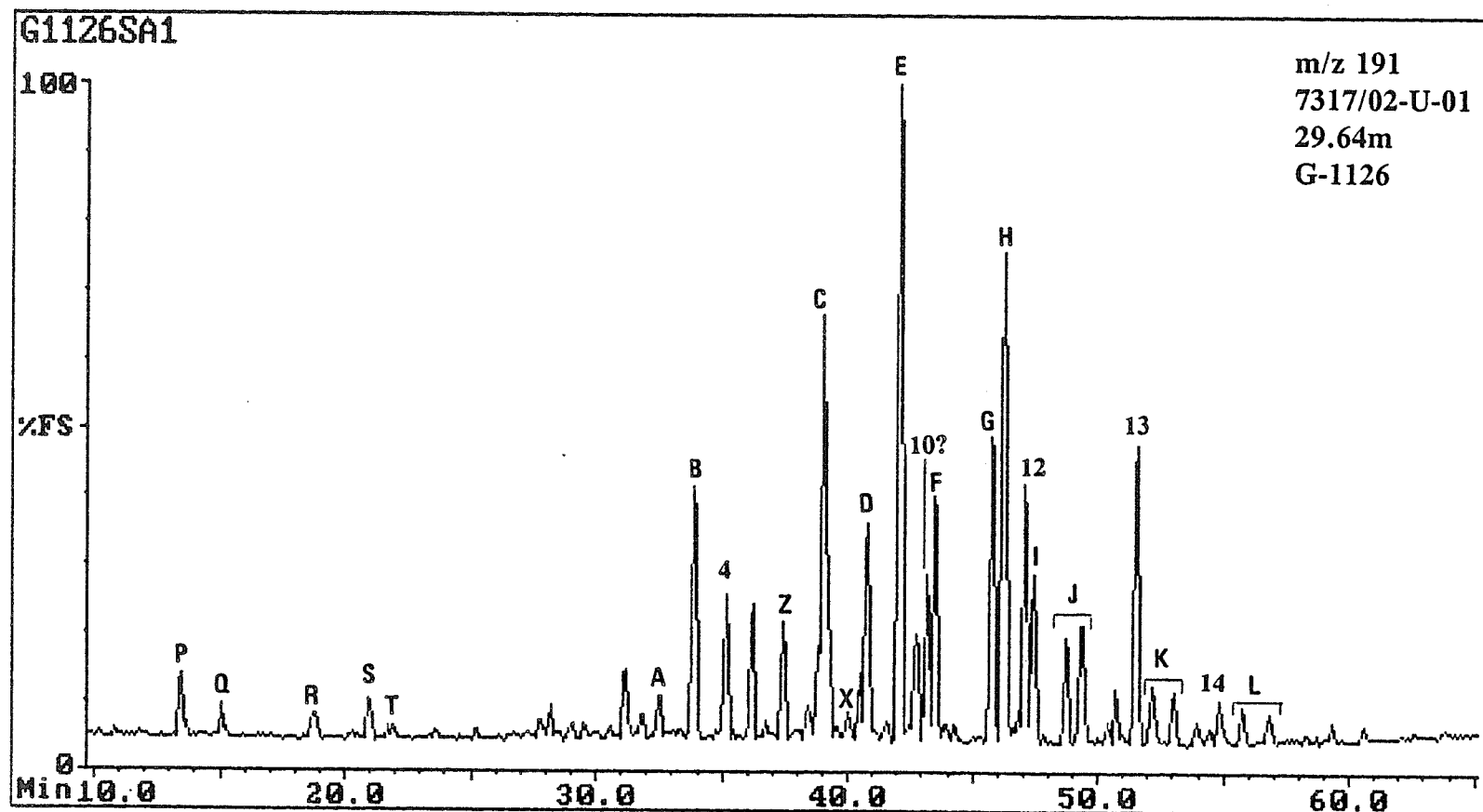
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UG LAB-BASE
Sample:22.1957.00

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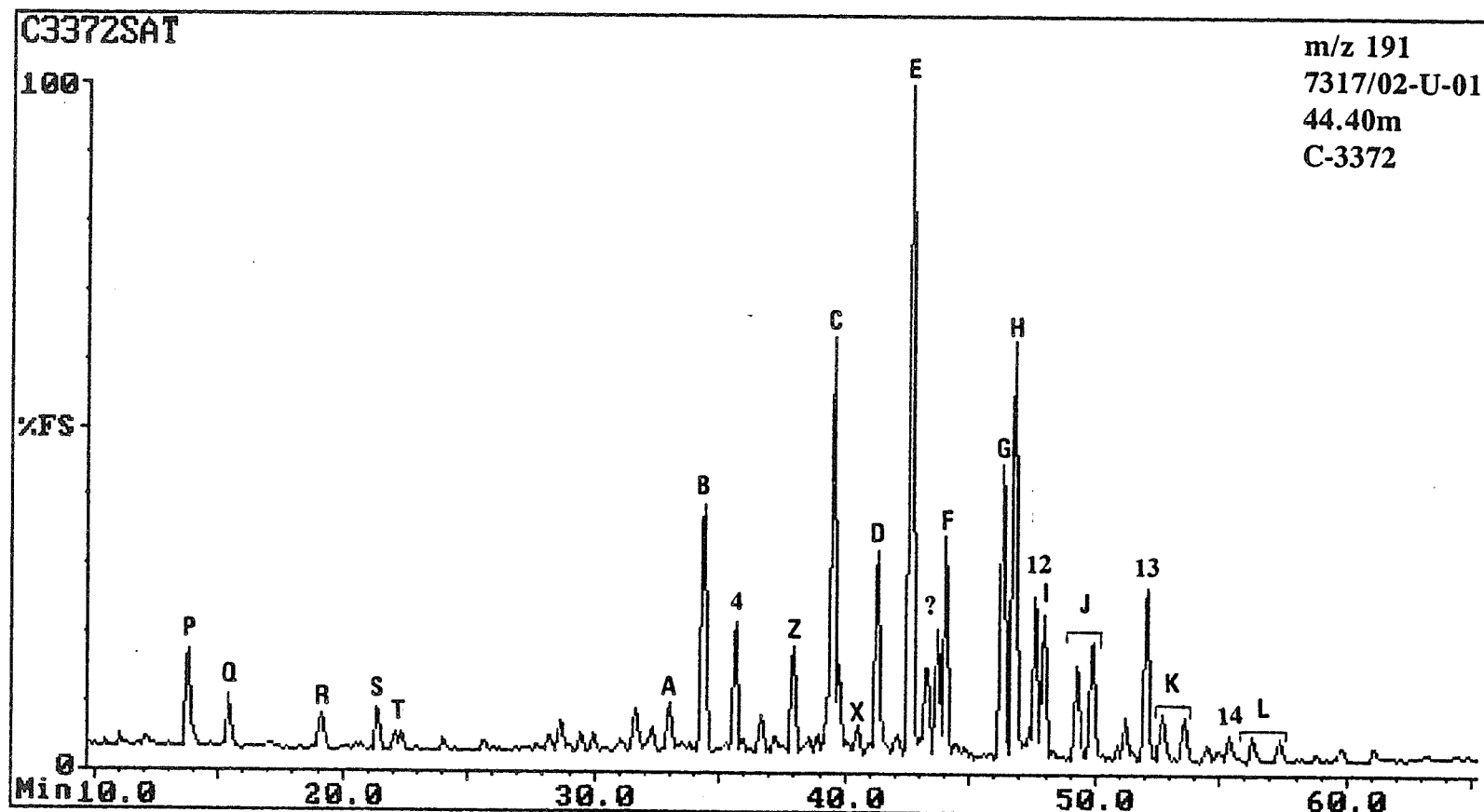
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UG LAB-BASE
Sample:22.1957.00

The TRI0-1 GC-MS Data System

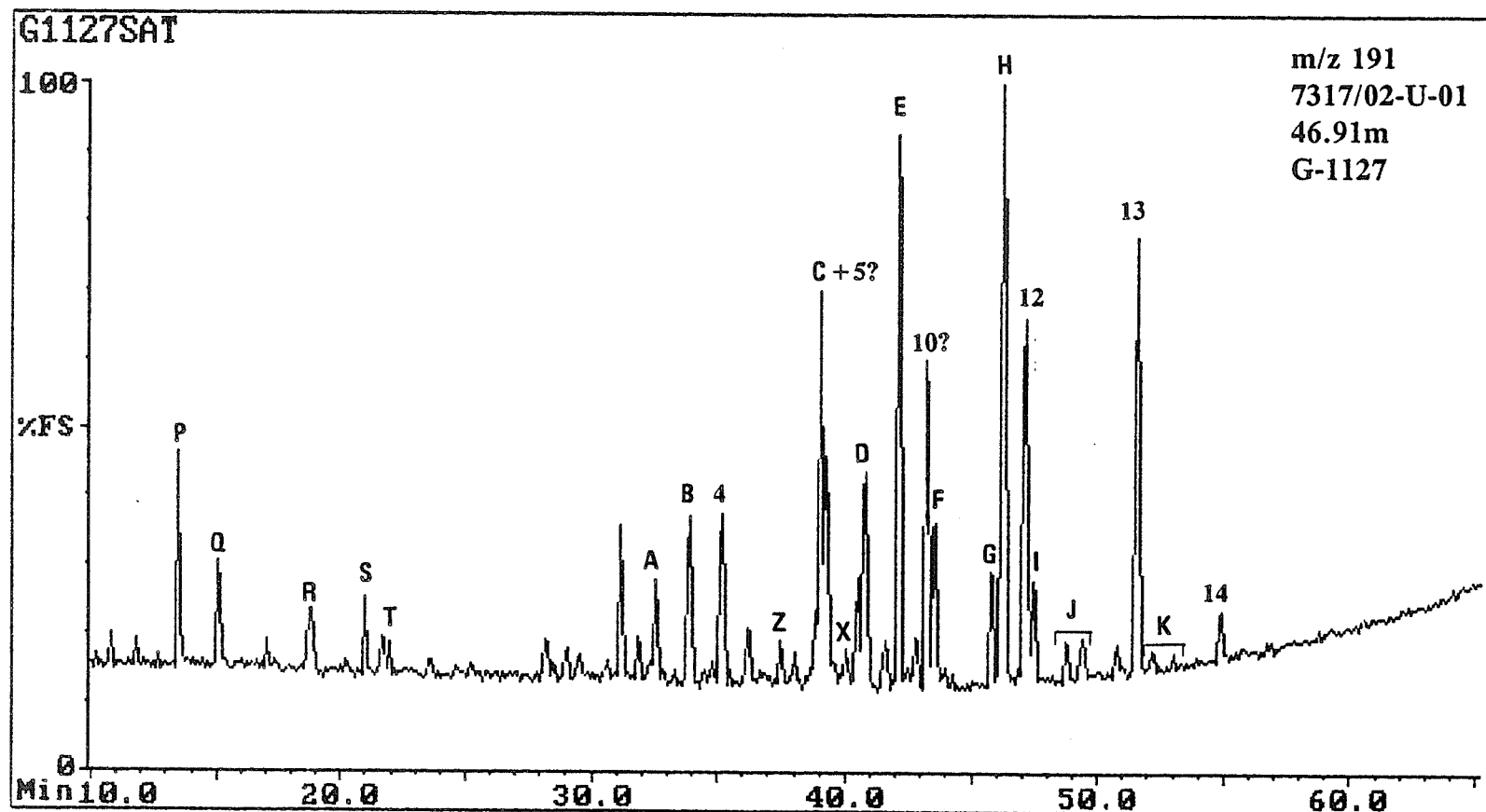
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Sample:22.1957.00

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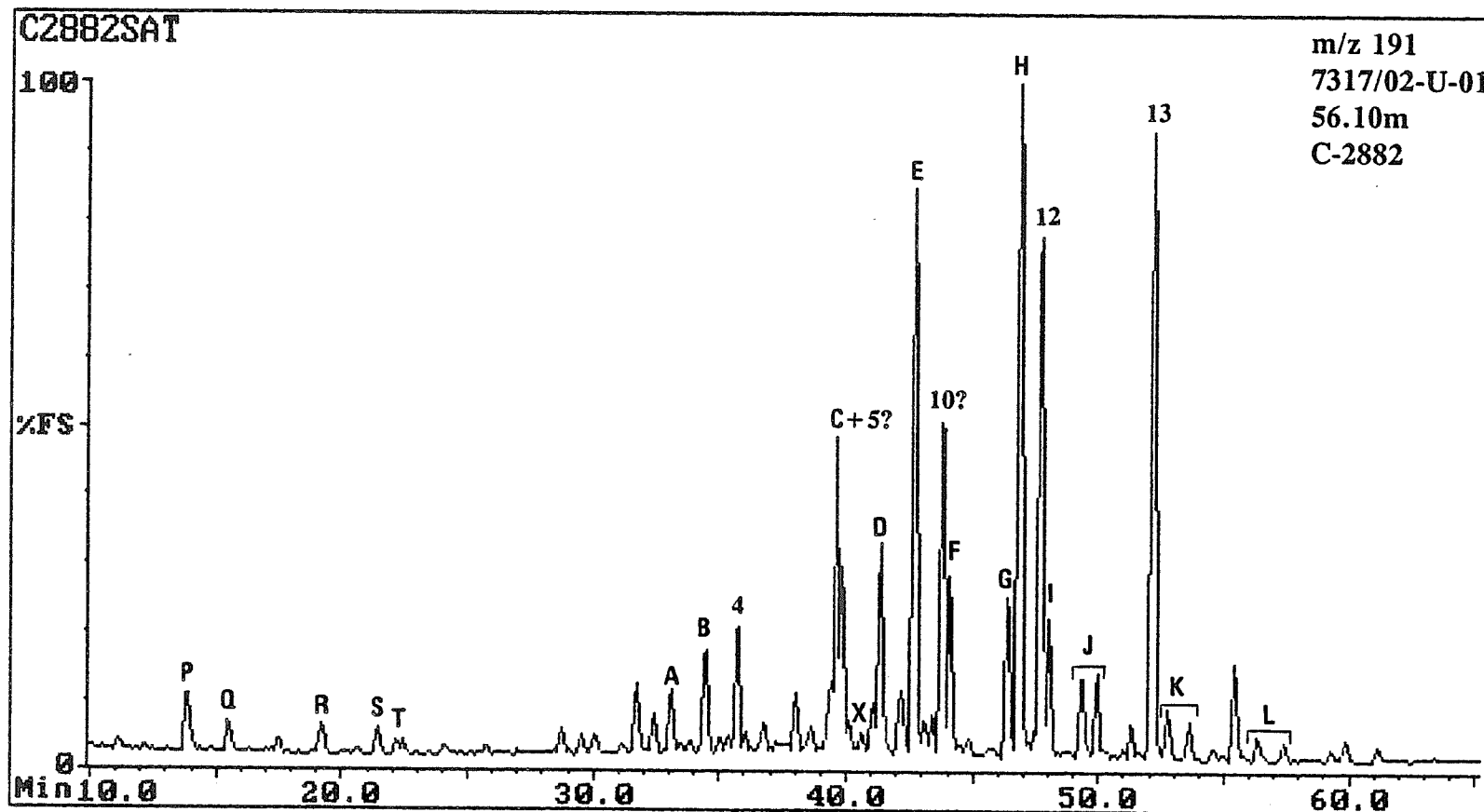
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UG LAB-BASE
Sample:22.1957.00

The TRIO-1 GC-MS Data System

Instrument:EI 4121



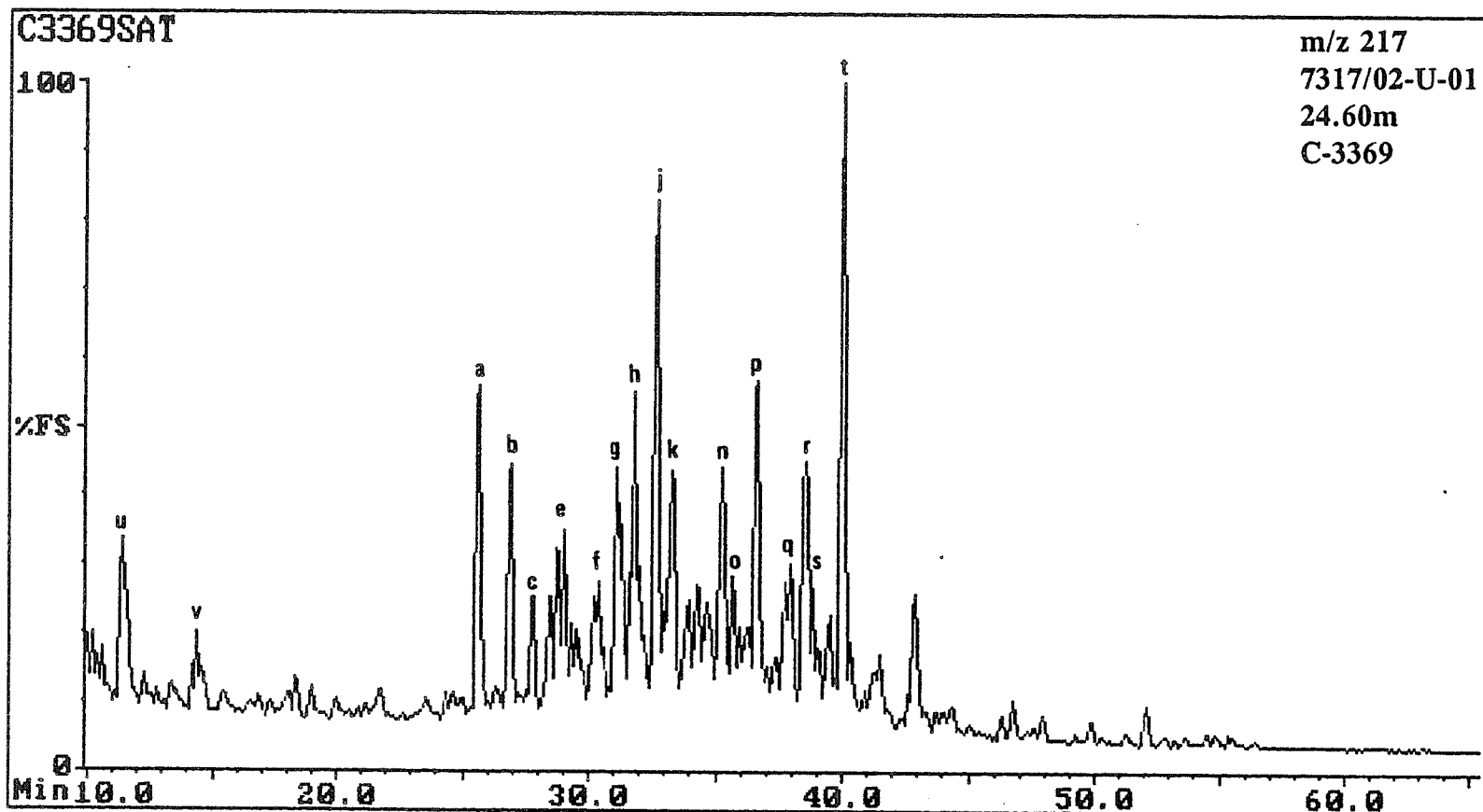
Key for m/z 217 and 218 (steranes):

Peak code	Identification	Formula
u	5 α (H)-sterane	C ₂₁ H ₃₆
v	5 α (H)-sterane	C ₂₂ H ₃₈
a	13 β (H),17 α (H)-diasterane (20S)	C ₂₇ H ₄₈
b	13 β (H),17 α (H)-diasterane (20R)	C ₂₇ H ₄₈
c	13 α (H),17 β (H)-diasterane (20S)	C ₂₇ H ₄₈
d	13 α (H),17 β (H)-diasterane (20R)	C ₂₇ H ₄₈
e	13 β (H),17 α (H)-diasterane (20S)	C ₂₈ H ₅₀
f	13 β (H),17 α (H)-diasterane (20R)	C ₂₈ H ₅₀
g	13 α (H),17 β (H)-diasterane (20S)	C ₂₈ H ₅₀
	+ 14 α (H),17 α (H)-sterane (20S)	C ₂₇ H ₄₈
h	13 β (H),17 α (H)-diasterane (20S)	C ₂₉ H ₅₂
	+ 14 β (H),17 β (H)-sterane (20R)	C ₂₇ H ₄₈
i	14 β (H),17 β (H)-sterane (20S)	C ₂₇ H ₄₈
	+ 13 α (H),17 β (H)-diasterane (20R)	C ₂₈ H ₅₀
j	14 α (H),17 α (H)-sterane (20R)	C ₂₇ H ₄₈
k	13 β (H),17 α (H)-diasterane (20R)	C ₂₉ H ₅₂
l	13 α (H),17 β (H)-diasterane (20S)	C ₂₉ H ₅₂
m	14 α (H),17 α (H)-sterane (20S)	C ₂₈ H ₅₀
n	13 α (H),17 β (H)-diasterane (20R)	C ₂₉ H ₅₂
	+ 14 β (H),17 β (H)-sterane (20R)	C ₂₈ H ₅₀
o	14 β (H),17 β (H)-sterane (20S)	C ₂₈ H ₅₀
p	14 α (H),17 α (H)-sterane (20R)	C ₂₈ H ₅₀
q	14 α (H),17 α (H)-sterane (20S)	C ₂₉ H ₅₂
r	14 β (H),17 β (H)-sterane (20R)	C ₂₉ H ₅₂
	+ unknown sterane	
s	14 β (H),17 β (H)-sterane (20S)	C ₂₉ H ₅₂
t	14 α (H),17 α (H)-sterane (20R)	C ₂₉ H ₅₂

UG LAB-BASE
Sample:22.1957.00

The TRIO-1 GC-MS Data System

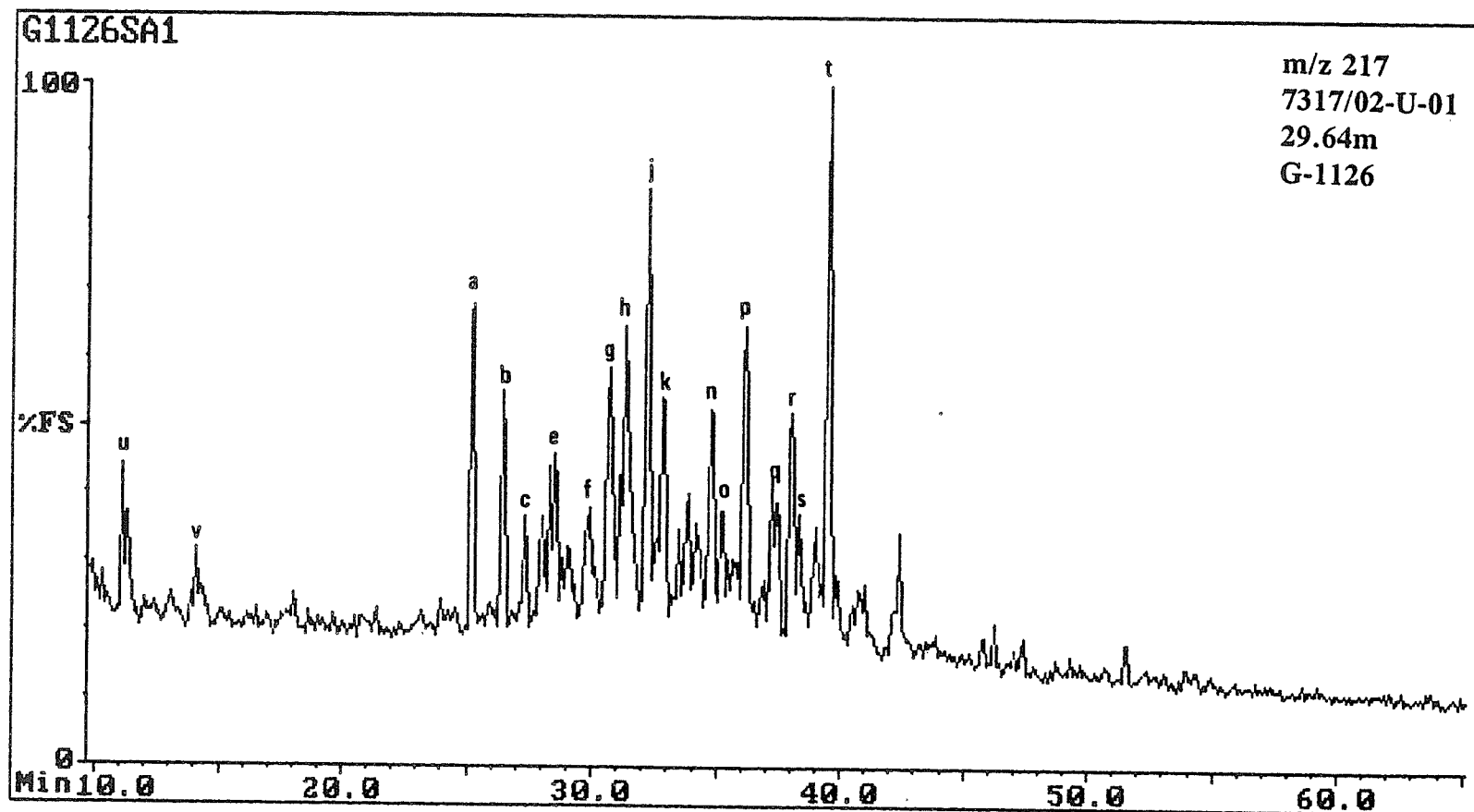
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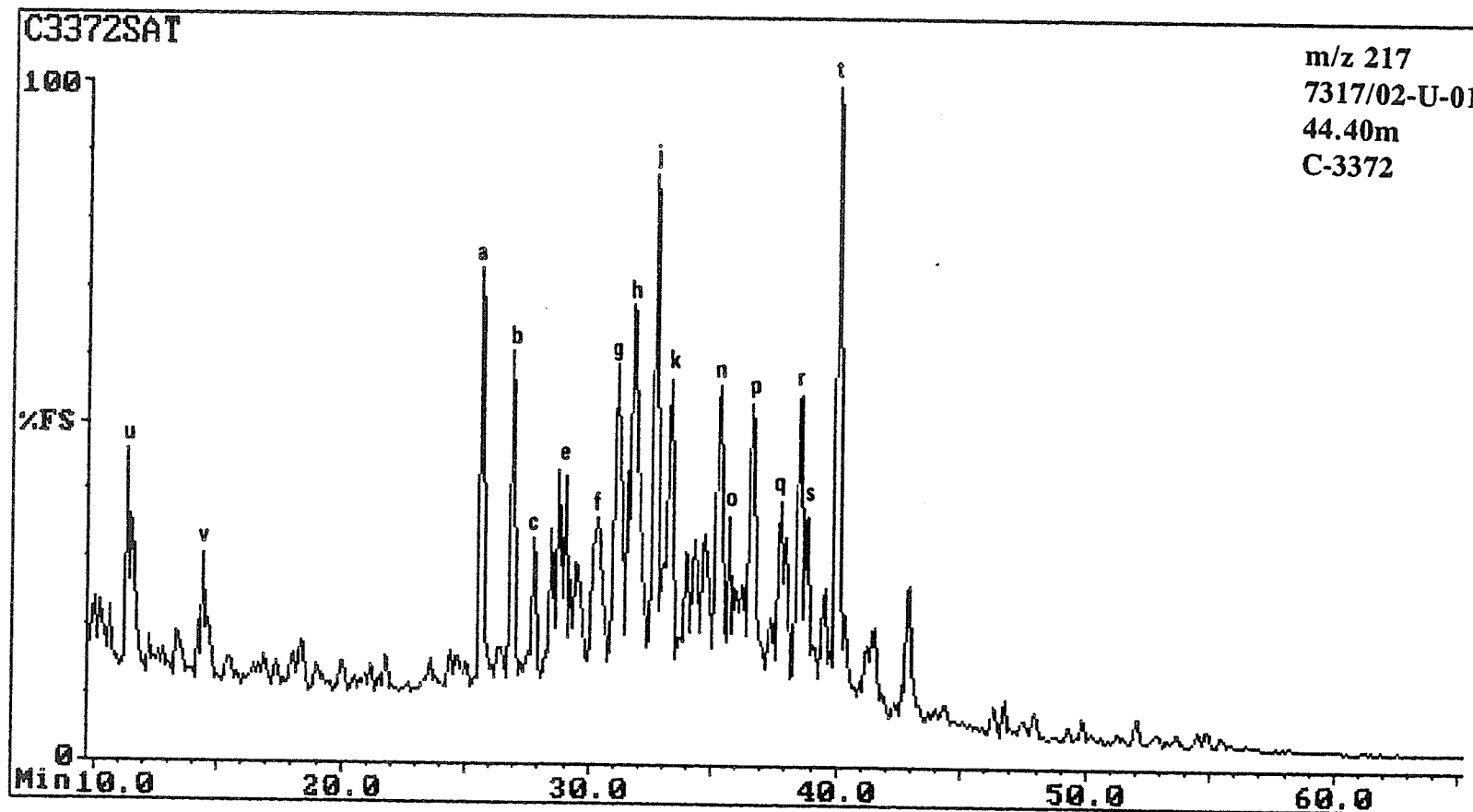
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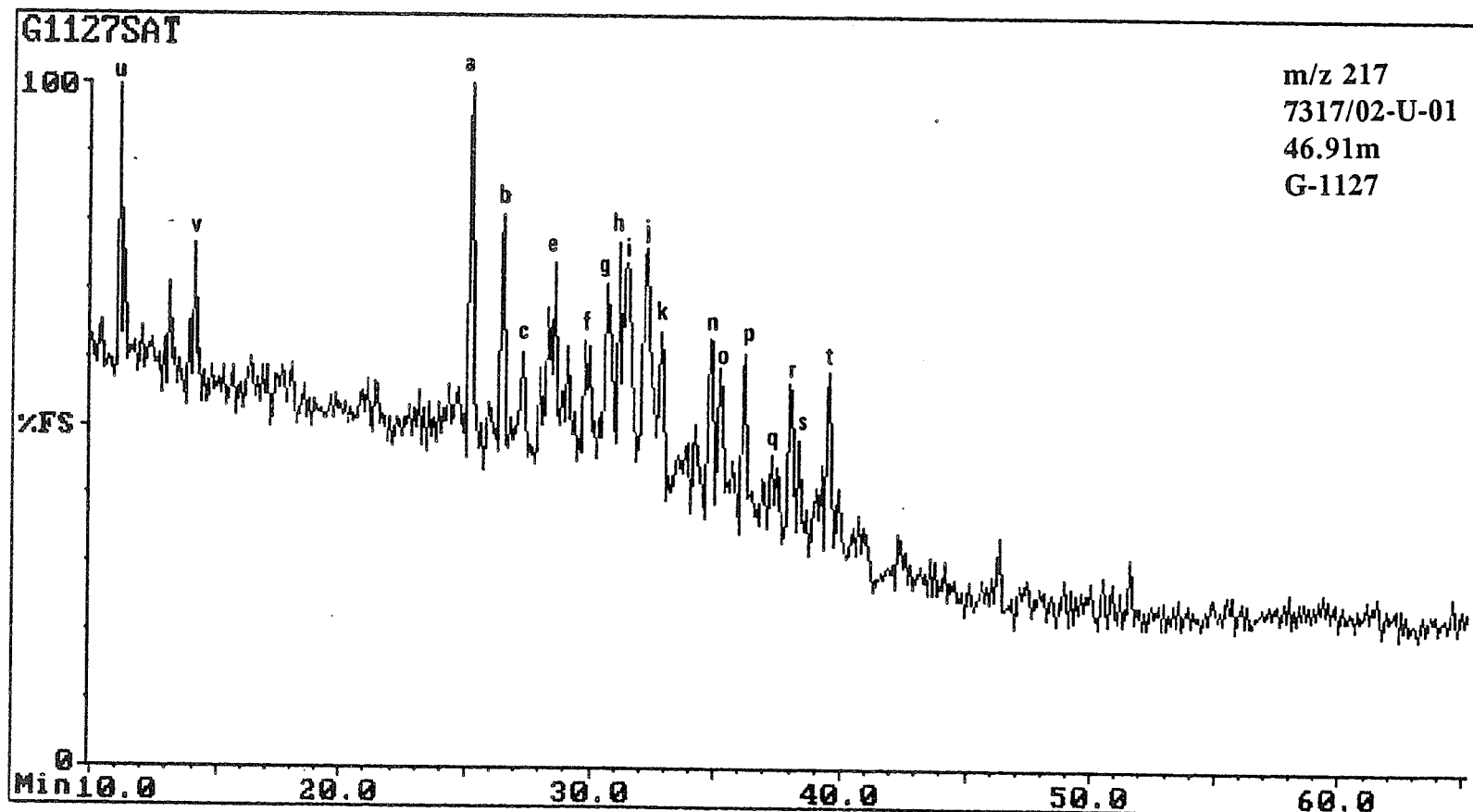
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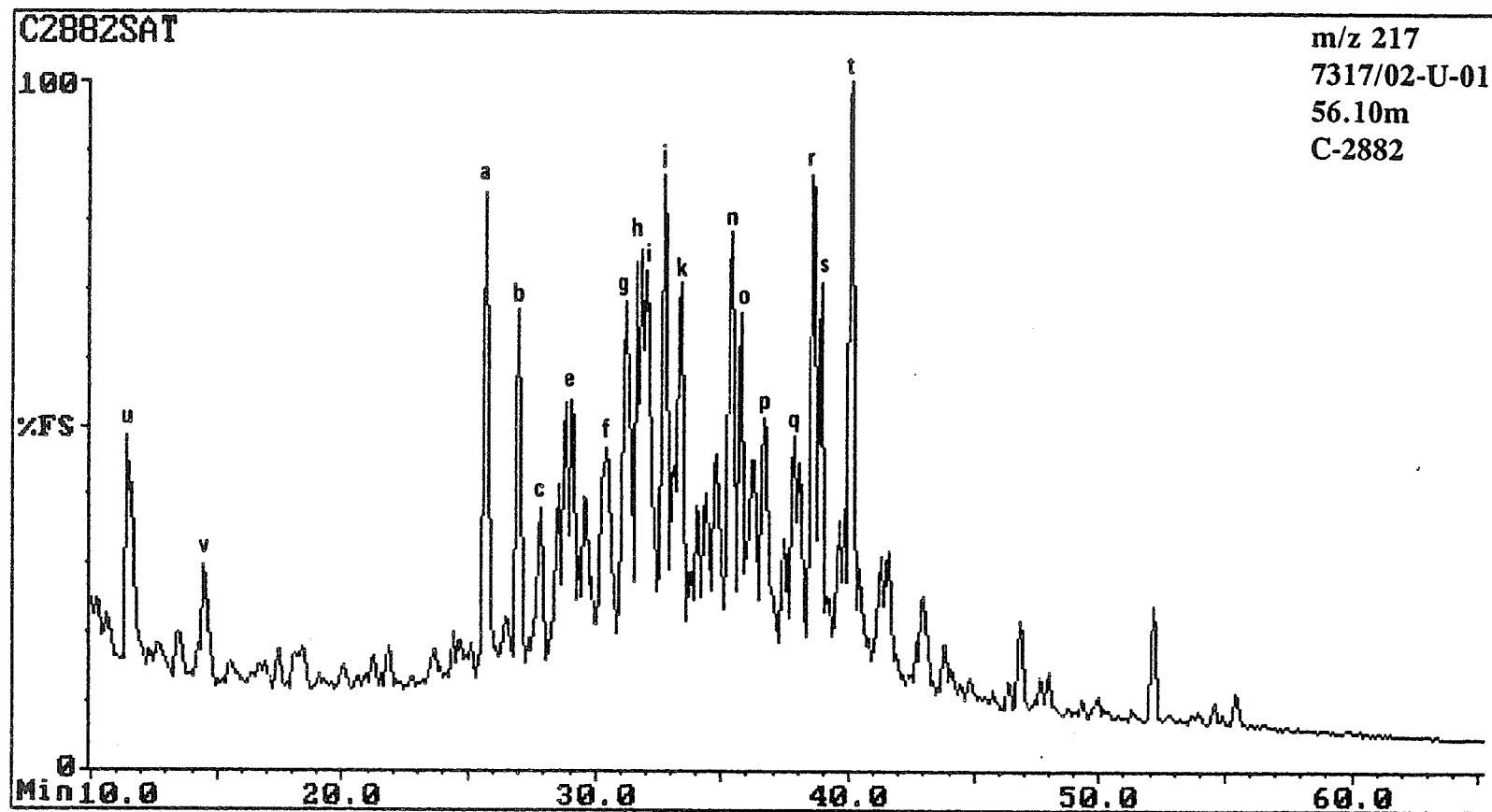
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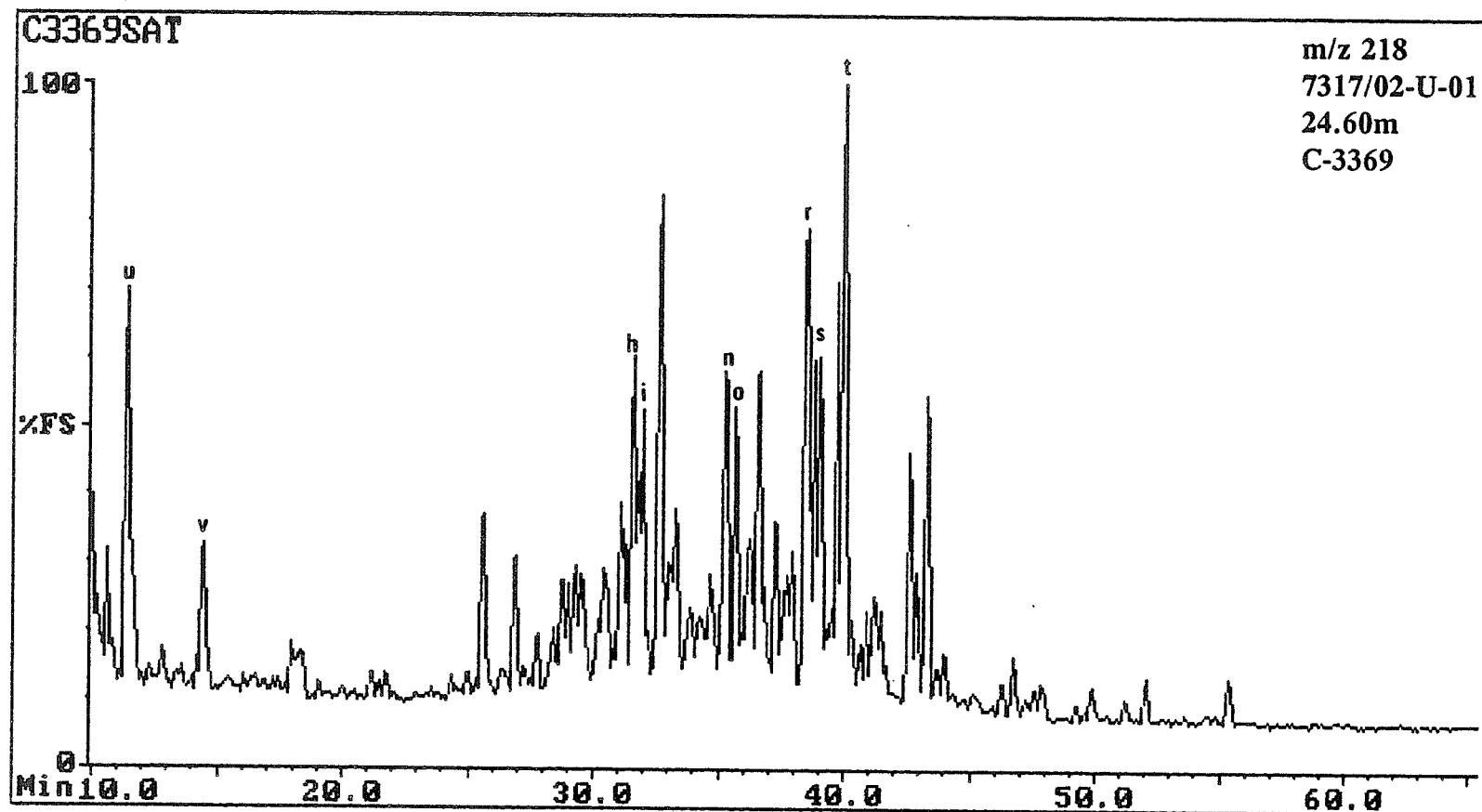
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UG LAB-BASE
Sample: 22.1957.00

The TRI0-1 GC-MS Data System

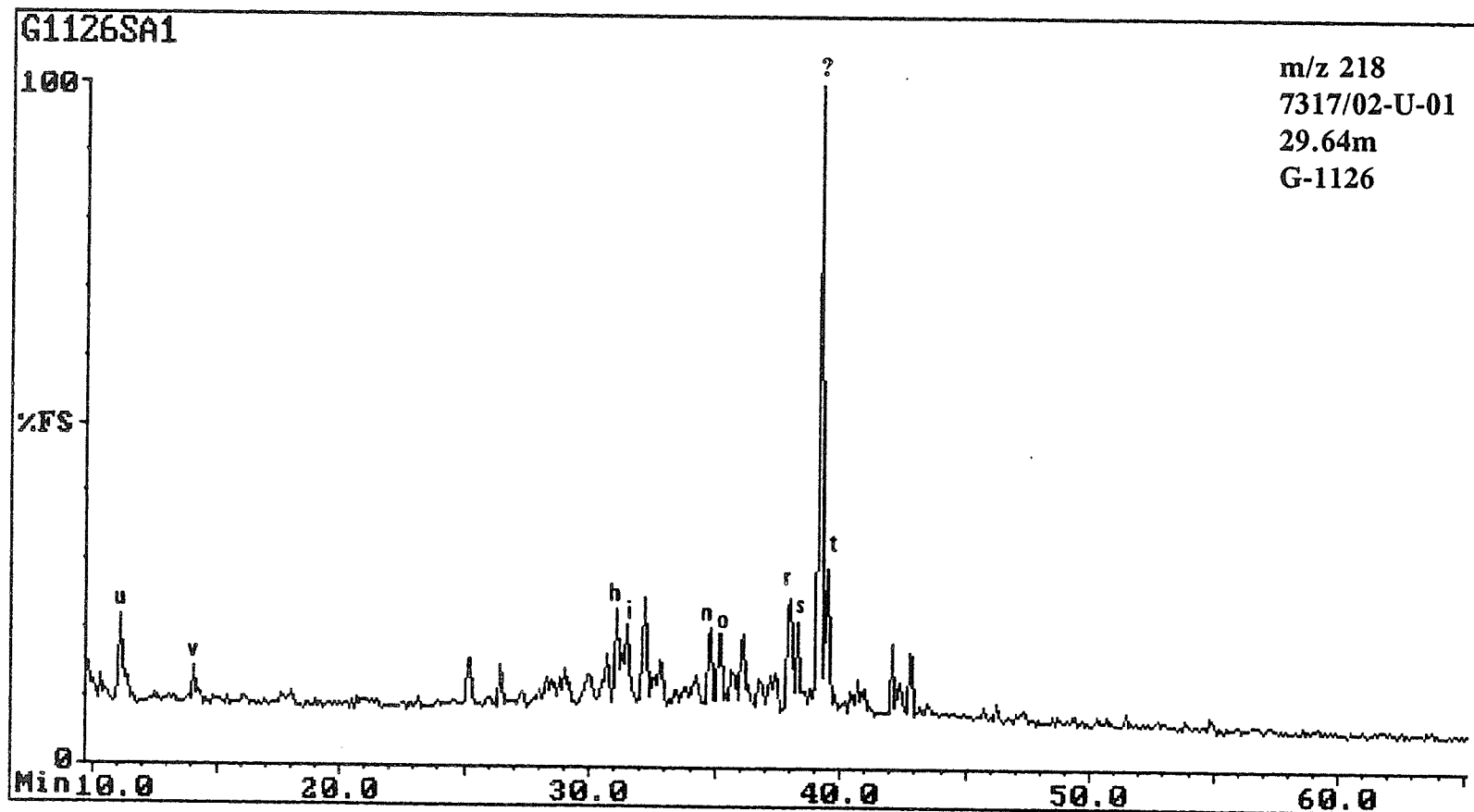
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UG LAB-BASE
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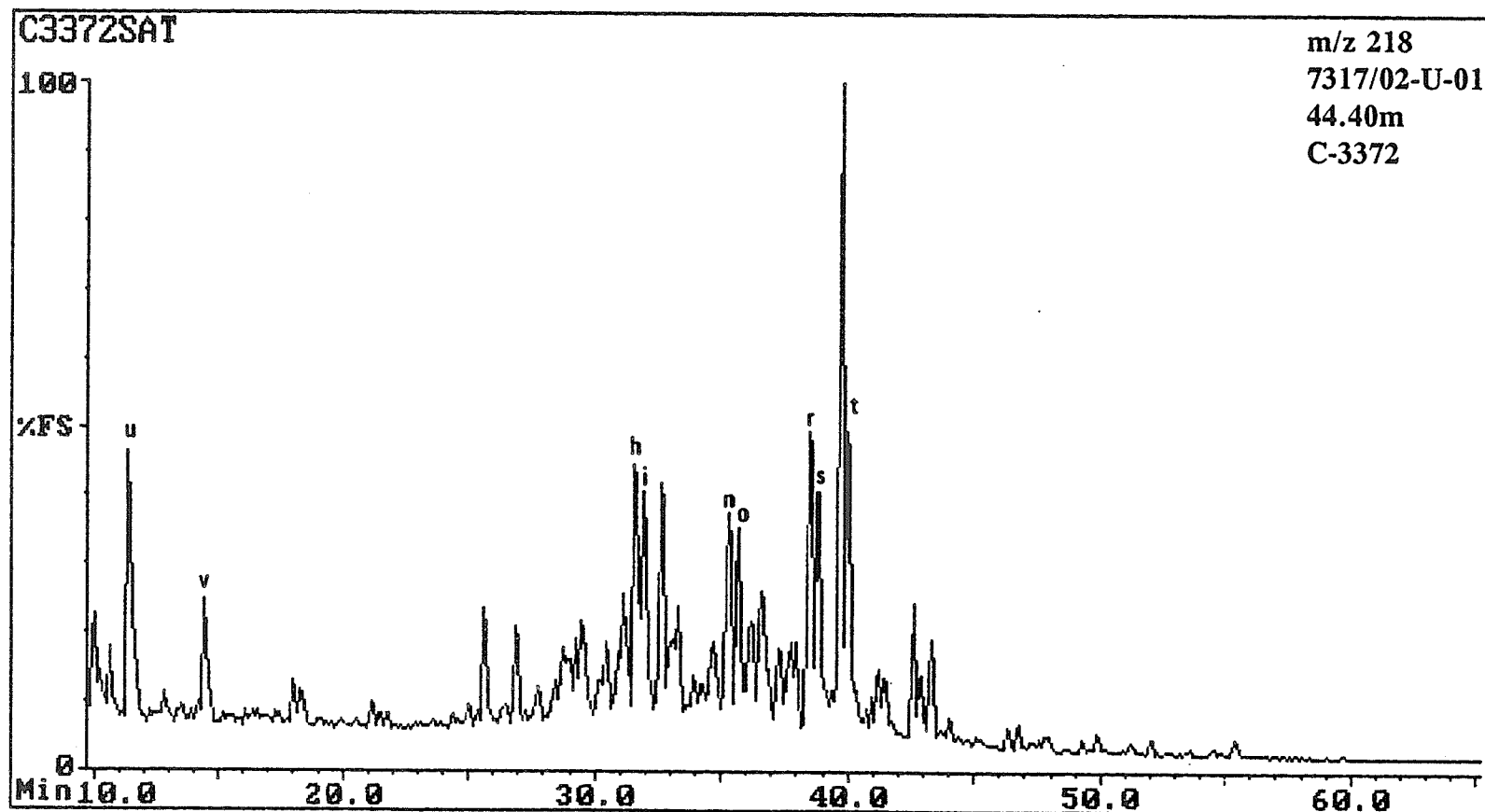
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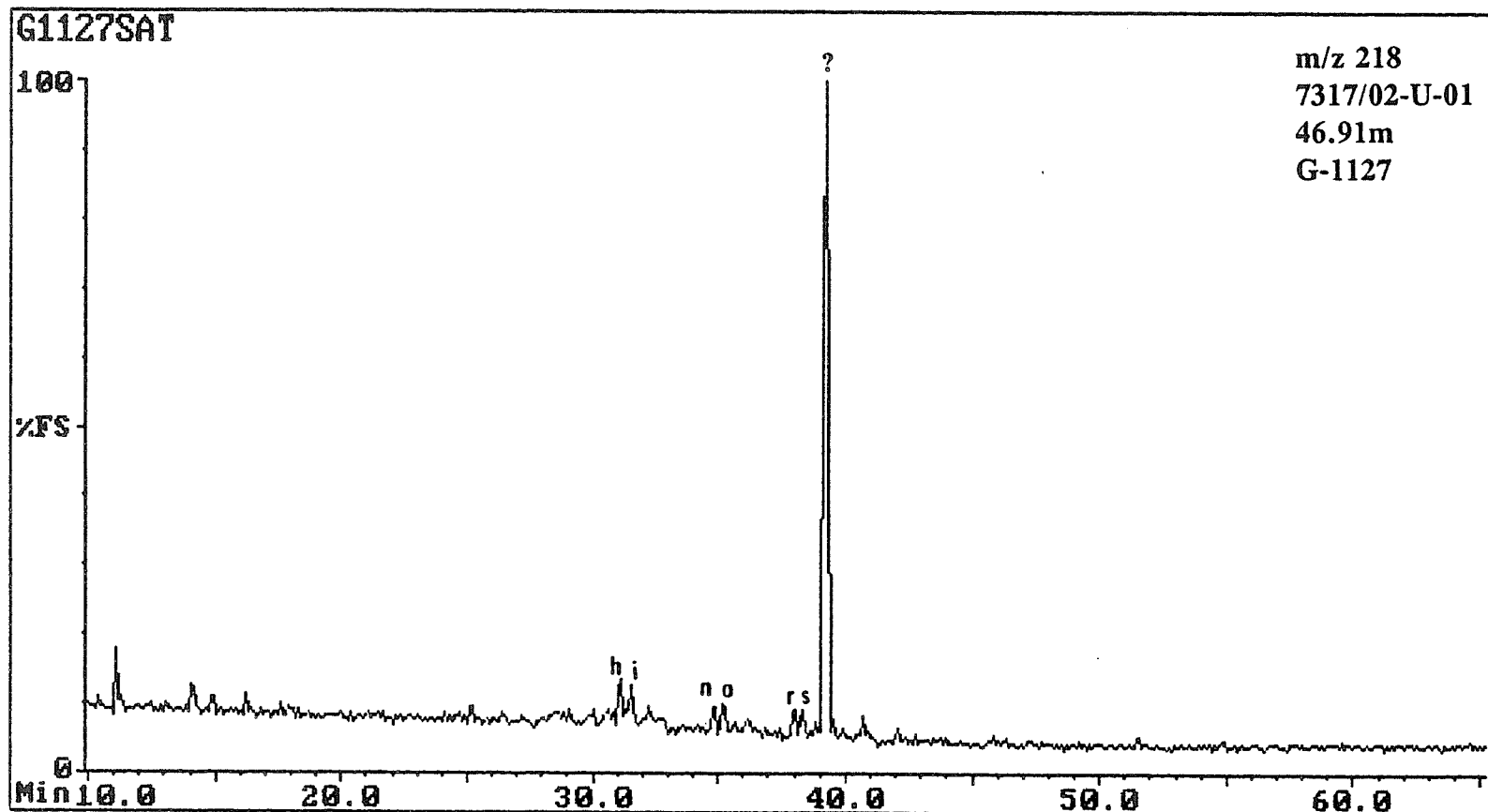
Instrument:EI 4121



UG LAB-BASE
Sample:22.1957.00

The TRIO-1 GC-MS Data System

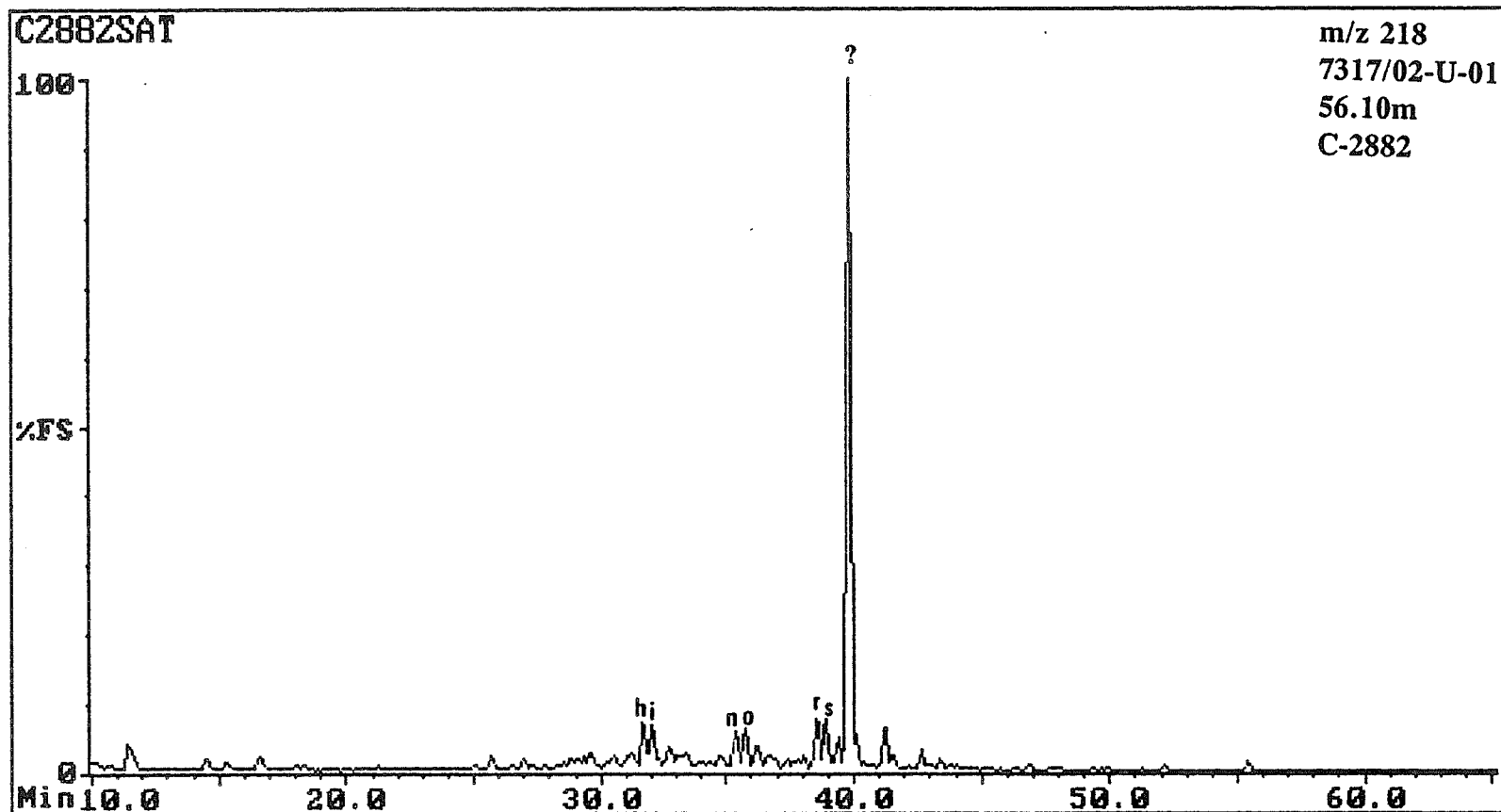
Instrument:EI 4121



VG LAB-BASE
Sample:22.1957.00

The TRI0-1 GC-MS Data System

Instrument:EI 4121



7. HEAT FLOW MEASUREMENTS

7.1 Summary

The heat flow data has been obtained by measuring temperature and thermal conductivity mainly in Quaternary sediments down to about 46 m below seabed. Downhole temperature measurements were performed by use of a high precision temperature probe developed by Fugro/Omegalink. The probe was mounted on a penetrometer device inside the API 5" drill string and pushed into undisturbed Quaternary sediments.

At levels corresponding to each temperature measurement, Quaternary sediment samples were collected and subjected to thermal conductivity measurement by use of a needle probe. Based on this information mean heat flow values have been calculated.

In addition to these measurements a 3 m long spear with thermistors mounted in fixed positions was used in order to obtain temperatures close to the seabed. However, this data was not used to calculate heat flow.

Both the needle probes and the thermistors as well as the respective amplifiers have been subjected to thorough pre- and post-calibration. Final system resolution and accuracy for the temperature measurements are estimated to be within 0.008°C and 0.02°C, respectively.

The thermal conductivity was measured in the laboratory on board, and it is concluded that neither the temperature nor the pressure change itself influenced significantly. A secondary but significant effect of pressure release has occurred because some samples were found to contain gas dissolved in the pore water. This resulted in gas voids being formed in the laboratory, which influenced the thermal conductivity measurements. The necessary correction for this is found to be an increase in the average measured thermal conductivity of 4%.

Representative samples have been subjected to measurement of both vertical and horizontal thermal conductivity and these values were found to differ in average by 13% for all the 1985 samples investigated. As the on board measurements were carried out slightly obliquely to the horizontal direction, we suggest a reduction of 10% in these values for the calculation of vertical heat flow.

Correction of the measured temperatures and temperature gradients due to transient effect from late Quaternary climatic changes have been quantified for two alternative glacial history models. This effect is found to be different for the different sites. Maximum effect is found to occur on site C85-A closer to the mainland. From the results of the different topics studied we have arrived at the following suggested final heat flow value (Table 7.1).

Table 7.1 Field results and final heat flow values at site 7317/02-U-01.

Site	Field results		Suggested adjusted results	
	(HFU)	(mW/m ²)	(HFU)	(mW/m ²)
7317/02-U-01	1.62	76.8	1.61	67.4

The results are adjusted for anisotropy of thermal conductivity, gas voids in some cores and late Quaternary climatic effects.

Table 7.2 Final measured gradient. R-SQUARE is the standard coefficient of determination for regression (least square fit for all temperature-depth points). Values near 1.0 indicate good fit; values near zero indicate poor fit. N = number of temperature-depth points.

SITE	GEOGRAPHICAL COORDINATES	WATER DEPTH (m)	QUATERNARY THICKNESS (m)	GRAD (mdegC/m)	N	R-SQUARE
7317/02-U-01	73°49'10.924" 17°22'04.526"	295.5	45.69	36.8	5	0.9953

7.2 Thermal conductivity

Summary

The need for correction of the measured thermal conductivity values due to differences in temperature and pressure from in situ to laboratory conditions has also been investigated. The temperature is found to be insignificant because of the low water content of the samples.

It has been found that due to the pressure release from in situ to laboratory conditions, gas dissolved in the pore water was released and formed gas voids. These gas voids have resulted in reduced thermal conductivity being measured in the laboratory. The necessary average correction expressed as a correction factor to the measured values was 1.04.

Differences in vertical and horizontal thermal conductivity have also been investigated (Table 7.7) and the mean factor of anisotropy in thermal conductivity of all 1985 samples is calculated to 1.11. As the on board measurements mainly are believed to represent the horizontal thermal conductivity, we suggest that these values are reduced by 10%.

Analyses of physical properties

Several physical properties are analysed on selected Quaternary samples. A purpose of these analyses is to enable correlations of these properties with thermal conductivity. In the literature such correlations are given both on a theoretical basis (conductivity of multi compound media) as well as on an empirical basis (a.o. Bullard & Day 1961, Lachenbruch & Marshall 1966, Johansen 1975, Matsuda & von Herzen 1985). Thus, such correlations of the Barents Sea data both provide quality control and increase the confidence of the final thermal conductivity values.

Results from these analyses are given in Tables 7.3 - 7.6.

Table 7.3 summarizes the following parameters:

- thermal conductivity, K , ($\text{mcal } ^\circ\text{C}^{-1} \text{ cm}^{-1} \text{ s}^{-1}$)
- water content, w , (% of dry weight)
- bulk density, γ , (kN/m^3)

- undrained shear strength, S_u , (kN/m^2)
- sound velocity, V_s , (m/s)

Table 7.3 Results from laboratory analyses of the Quaternary core material.

SAMPLE ANALYSIS SHALLOW DRILLING BARENTS SEA 1985									
SITE	DEPTH (m)	T.CON. mcg/ °Ccms	WATER %	DENS. kN/m^3	SH.STR. kN/m^2	GR.SIZE	VELOC. m/s	OEDOM.	TRIAx
D85-V	0.03	3.49							
	0.03	3.62							
	0.14	4.21							
	0.24	4.73							
	0.27	4.19							
	0.42	5.20							
	14.67	4.07	23.2	20.5		x			
	14.77	3.83						x	x
	14.82		22.3	20.6	>250.0	x	1720		
	20.06		21.2	20.6	>250.0		1810	x	x
	20.10	4.32							
	20.20	4.28	20.3	20.8					
	24.48	3.94							
	24.58	4.03							
	24.61		20.6	20.7	>250.0	x	1715		
	24.75		19.4	20.8	>250.0	x	1800		
	24.84	3.44							
	24.97	3.89							
	25.12	3.74			>250.0				
	25.34	3.67							
	25.46	4.32							
	25.49		21.1	20.6	>250.0	x	1790		
	29.63	4.59	15.7	21.1			1950	x	x
	29.76	5.09	16.2	21.7					
	29.79					x			
	39.95		16.4	21.4				x	x
	40.06		18.2	21.0		x	1780		
	40.12	4.53							
	40.19	4.41							
	44.40		20.6	20.5		x	1810		
	44.50	4.62							
	44.56		19.1	19.6		x			
	44.59	4.88							
	45.82	4.91							
	45.94	4.50							
	45.97		18.0	19.5		x	970		
	54.84		28.0	19.0		x	1680		

Advanced soil mechanical property testing (triaxial and oedometer testing) is carried out at SINTEF's Division of Geotechnical Engineering (Senneset 1986) and the results from these tests are summarized in Table 7.4. The following abbreviations are used.

- W - water content (% water of dry weight)
- W_L - liquid limit (% water of dry weight)
- W_P - plasticity limit (% water of dry weight)
- a - Coulombian attraction (kN/m^2)
- c_v - coefficient of consolidation (m^2/yr)
- m - deformation modulus number
- S_u - undrained shear strength (kN/m^2)
- $\tan\phi$ - tangent of angle of failure
- ϵ_f - deformation at failure
- p_o' - effective overburden pressure (kN/m^2)
- p_c' - effective preconsolidation pressure (kN/m^2)

Table 7.4 Results from soil mechanical testing of Quaternary core material.

Boring No.	Sample depth m	W %	Index properties				Overburden pressure $\sim p_o'$ kN/m ²	Oedometer tests			Triaxial tests			Remarks
			w_L %	w_p %	Unit weight kN/m ³	S_u kN/m ²		p_c' kN/m ²	Modulus number m	Coeff. of consolid. c_v m ² /gr.	Attraction a kN/m ²	tan ϕ	Def. at failure ϵ_f %	
D 85-V	14.64-14.78	23.2	50.5	27.3	20.5	135	154	900	7	0.5	20	0.51	8	Partly disturbed
	20.06-20.21	20.3	50.4	25.8	20.8	175	213	1000	12.5	0.9	50	0.45	5	Good
	29.63-29.77	16.2	43.1	22.7	21.7	(480)	341	1400	13	-	20	0.73	4	Good
	39.92-40.06	16.4	40.7	21.2	21.4	340	447	500	27.5	1.0	50	0.52	6	Disturbed

Table 7.5 Total organic carbon (TOC) and total carbon (TC) in per cent of sediment.

DEPTH (M)	TOC%	TC%
24.60	1.24	1.58
24.75	1.27	1.76
25.49	1.24	1.62
44.40	0.92	1.17
44.56	0.46	0.67

Table 7.6 Semiquantitative mineral composition interpreted from X-ray diffractograms, bulk samples (wt% minerals).

Sample depth (m)	29.63	40.12	24.97	25.46	44.59	24.84	14.77
Quartz	45	19	30	28	57	29	18
Alk. fld.	6	2	5	4	5	3	3
Plagioclase	10	5	19	18	8	15	12
Musc. Ill. 10Å	17	25	13	15	14	16	24
Mix. clay 10-14 Å	7	24	4	11	6	7	7
Chlorite	3	7	9	5	8	7	26
Smectite	-	9	1	-	-	1	-
Kaolinite	11	6	14	17	2	18	8
Calcite	-	-	-	-	-	-	-
Dolomite	-	-	1	1	-	-	-
Siderite	-	tr	2	-	-	2	-
Pyrite	1	1	2	1	tr	2	2

Alk.fld. = Alkalifeldspar

Musc./ill = Muscovite/Illite (mainly illite in these samples).

Dolomite and siderite are questionable, the reflections interfere with mica and feldspars.

Table 7.6.b *Semiquantitative mineral composition interpreted from X-ray diffractograms, fractioned samples (wt % minerals).*

Depth: 24.60					Depth: 24.75	
Fraction	< 4 um (52.5%)	4-63 um (32.9%)	>63 um (14.6%)	bulk	Fraction	< 4 um
Mineral					Mineral	
Quartz	3.6	3.4	55.3	11.1	Quartz	3.6
K-feldspar	1.5	1.0	7.9	2.3	K-feldspar	0.6
Plagioklase	3.8	3.4	22.4	6.4	Plagioklase	2.4
Mica	25.1	29.2	2.6	23.2	Mica	23.1
Chlorite	34.4	40.4		31.9	Chlorite	39.2
Kaolinite	-	-	7.9	tr	Kaolinite	-
Smectite	14.9	2.0	-	8.5	Smectite	15.9
Mixed 10-14 Å	15.7	20.3	-	14.9	Mixed 10-14 Å	15.0
Calcite	-	-	-	-	Calcite	-
Dolomite	-	-	-	-	Dolomite	-
Siderite	-	-	-	-	Siderite	-
Pyrite	0.5	-	3.9	0.8	Pyrite	-
Amphibole	0.4	-	-	tr	Amphibole	0.2

Depth: 25.49		Depth: 44.40 m	
Fraction	< 4 um	Fraction	< 4 um
Mineral		Mineral	
Quartz	3.7	Quartz	2.6
K-feldspar	0.6	K-feldspar	1.1
Plagioklase	2.2	Plagioklase	2.7
Mica	30.3	Mica	37.3
Chlorite	35.8	Chlorite	32.7
Kaolinite	-	Kaolinite	1.4
Smectite	11.6	Smectite	19.7
Mixed 10-14 Å	15.7	Mixed 10-14 Å	1.9
Calcite	-	Calcite	0.1
Dolomite	-	Dolomite	-
Siderite	-	Siderite	-
Pyrite	0.1	Pyrite	0.5
Amphibole	-	Amphibole	-

Comparative measurements of thermal conductivity

A selection of Quaternary samples have been subjected to thermal conductivity measurements at two independent laboratories, the Chalmers Technical University in Gothenburg, Sweden, and the Geophysical Laboratory at the University of Aarhus, Denmark (Table 7.7).

All the measurements are performed by use of a standard needle probe with the following specifications:

Chalmers:

probe length 40.0 mm
probe diameter 0.9 mm

University of Aarhus:

probe length 50 mm and 80 mm
probe diameter 1.5 mm

All conductivity values are given in $\text{mcal } ^\circ\text{C}^{-1} \text{ cm}^{-1} \text{ s}^{-1}$ ($=0.4186 \text{ W/mk}$).

The results from Chalmers Technical University give slightly lower values than the analysis at the University of Aarhus. It is suggested that these values may be slightly too low due to undersaturation of the samples (Wilén pers. commun. 1986).

The following abbreviations are used:

University of Aarhus:

K^1_h - horizontal thermal conductivity

K^1_v - vertical thermal conductivity

$A = \frac{K^1_n}{K^1_v}$ - coefficient of anisotropy

Chalmers Technical University:

K^2 - thermal conductivity

Table 7.7 Comparison of different thermal conductivity measurements on Quaternary samples.

Site	Depth(m)	Geophysical Laboratory, University of Aarhus			Department of geology Chalmers Technical University	
		K_h^1 (mcal °C ⁻¹ cm ⁻¹ s ⁻¹)	K_v^1 (mcal °C ⁻¹ cm ⁻¹ s ⁻¹)	$A = \frac{K_h^1}{K_v^1}$	K^2 (mcal °C ⁻¹ cm ⁻¹ s ⁻¹)	
085-V	19.97-20.05	3.76	3.77	0.99	3.4	
	24.45-24.52	3.49				
	24.74-25.00	3.65	3.05	1.21	2.8	
	25.26-25.45	3.75				
	29.40-29.60	4.79	4.56	1.05	4.8	
	40.12-40.25	4.16				

Anisotropy of thermal conductivity

Numerous papers and reports describe anisotropy in the thermal conductivity of sedimentary rocks. The possible presence of this effect in Quaternary sediments has, however, generally been neglected (N. Balling pers. commun. 1986).

At the University of Aarhus a number of the tested samples have been measured with respect to thermal conductivity both in the horizontal and the vertical direction. Though the statistical base is somewhat scarce the results clearly indicate that anisotropy in thermal conductivity is present in the stiff, consolidated Quaternary samples from the Barents Sea. This anisotropy, A , defined as horizontal-, divided by vertical thermal conductivity is presented in Table 7.7.

All the thermal conductivity values reported from the on board measurements are measured by the needle probe method by either pushing the needle axially into the core samples or with an angle that may deviate in the order of 50-60° from the axis of the cores. All the cores are obtained with a vertical axis. As the needle probe measures thermal conductivity perpendicular to the needle axis, it can be seen from a simple geometrical sketch that the results from the on board measurements are dominated by the horizontal thermal conductivity component.

Our conclusion is therefore that the thermal conductivity measurements as they are given in Table 7.3 may be approximately 10% higher than the vertical thermal conductivity of the tested samples, and we suggest that for calculation of vertical heat flow one should correct the measured values by a factor of 0.91 (0.91=1/1.1).

7.3 Correction for perturbations in measured temperatures due to the late Quaternary history

Summary

Possible perturbations in the measured data due to topographic relief and the glacial history are investigated.

The effects from topographic relief and lateral variations in Quaternary sediment thickness close to the heat flow sites are found to be negligible.

Based on published information and data gathered within the Barents Sea Mapping Program we have deduced two alternative glacial history models causing minimum and maximum transient effects on the measured temperatures. These models are used as input to computer calculations of maximum and minimum perturbations.

The maximum and minimum transient effects on the measured gradients are summarized in Table 7.10.

This effect varies from site to site. Maximum effect is found to occur at site C85-A where the disturbance on the present day gradient is between

$$-3.6 \cdot 10^{-3} \text{ } ^\circ\text{C/m} \text{ and } -6.2 \cdot 10^{-3} \text{ } ^\circ\text{C/m}$$

depending on the temperature history models. The lowest effect is found at site D85-0 where the maximum glaciation effect implies a disturbance of

$$-1.1 \cdot 10^{-3} \text{ } ^\circ\text{C/m}.$$

Objective and limitations

Supracrustal geological processes and climatic changes will cause variations in the boundary conditions for heat flow through the earth's crust.

The transient effect on the present vertical heat flow from previous climatic changes will vary with depth as a function of the time span since

the events occurred and of the actual temperature amplitudes involved.

Therefore, in order to be able to compare the heat flow data collected in the present project (15-70 m below the seabed) with similar data from exploration wells (1000-4500 m below the seabed) it is necessary to apply a correction model which implies none or negligible corrections at an average well depth of 2000-3000 m.

Werner (1985) relates a time span of 200 000 years to a depth range of 10 km. Nielsen & Balling (1985) showed an example where the effects from a temperature change of 10°C 10 000 years ago are totally damped at 2000 m. With the temperature amplitudes and the combinations of different temperature events through time that are used in our models, the deduced corrections to be applied at 2000-3000 m can be neglected.

Conclusively, the shallow heat flow data (15-70 m) should be comparable to exploration well data if they are corrected for late Quaternary climatic changes according to the models below.

In our study we have chosen a time span of 245 000 years for the climatic correction models. This span is chosen because 245 000 y. BP is regarded as the best estimate of the onset of the warm Holsteinian interglacial before the Saalian glacial period (N. Balling, pers. commun. 1986).

The effect from erosion and deposition within the same time span as for the climatic history should also be considered in order to have a more complete reduction of shallow data for comparison with well data. However, such events are less established than the temperature history at our sites. Furthermore, as several episodes of erosion and deposition may have occurred, the summarised effect of these processes may largely be cancelled. The effect from the topographic relief and lateral variations in Quaternary sediment thickness is found to be negligible for all the heat flow sites. Thus, only corrections for climatic variations are included in the present study.

Status of knowledge about the glacial history of the area

Introduction

This Chapter provides a rather extensive discussion of the status regarding knowledge about the glacial history of the Barents Sea. Based on this discussion we have suggested two alternative temperature history models from the area implying a maximum (model I) and a minimum (model II) effect on heat flow measured in shallow boreholes.

The Quaternary is characterised by large changes in climate with glaciations and interglaciations.

Investigations in the north Atlantic (Shackleton et al. 1982) indicate that extensive ice sheets existed in the northern hemisphere about 2.4 mill y BP. From then on there have been alterations between glacial and interglacial periods. The exact time for the first glaciation may, however, be disputed.

Published knowledge

The knowledge of how the last ice age (the Weichselian) developed and receded in the Barents Sea is scarce compared with the western and southern part of the European ice sheet. This relation is even more pronounced going back in time to the last interglacial (the Eemian) and the preceding glacial (the Saalian) and interglacial (the Holsteinian).

For the present purpose the need for a detailed glacial history decreases with increasing age, and we have done the following simplifications:

For the interstadials Holsteinian and Eemian we have assumed that the climate was as today (Holsteinian in Europe was actually slightly cooler and Eemian slightly warmer). The duration of Eemian is in this context fixed between 115 000-130 000 B.P. (Sejrup in press) and we assume that the Holsteinian interglacial terminated around 185 000 BP (Denton & Hughes 1983).

The second last glacial period in our model, the Saalian had a more extensive ice cover than the Weichselian (Nilsson 1983) and there are no stratigraphical work done in Scandinavia which are of any help in reconstructing the conditions in the Barents Sea. We have therefore assumed

that the Barents Sea was covered by an ice sheet in large parts of this period. As a crude simplification we have not taken into account any interstadials in this period.

Our tentative relation between period nomenclature and age for the present purpose can thus be summarized as follows:

Weichselian ice age	10 000 - 115 000 BP
Eemian interglacial	115 000 - 130 000 BP
Saalian ice age	130 000 - 185 000 BP
Holsteinian interglacial	185 000 - 245 000 BP

Complicating factors for the glacial history of the area may be:

- The ice cover on Svalbard and adjacent areas was possibly not in phase with the southern and western margin of the European ice sheet. (Boulton 1979; Boulton et al. 1982; Landvik pers. commun. 1986).
- The ice sheet in the Barents Sea will be depending on ice feeding from as much as three possible different glacier domes. (Denton & Hughes 1981): A) the ice sheet draining northwards through Finnmark (sev. authors). B) Southerly drainage from a postulated ice dome east of Svalbard (Salvigsen 1981, Salvigsen & Nydal 1981, Häggbom 1982, Boulton et al. 1982, Elverhøi & Solheim 1983, Solheim & Kristoffersen 1984). C) Feeding from a postulated culmination to the east (the Kara ice dome) (Schytt et al. 1968; Grosswald 1980; Denton & Hughes 1981).

The present published knowledge of the glacial history of the Barents Sea, which is based mainly on recent marine geological data and shore line investigations from the Svalbard archipelago, can briefly be summarised as done by Vorren & Kristoffersen (1986):

1. Grounded glaciers reached the shelf edge in front of Bjørnøyrenna at least four times during the late Cenozoic (Solheim & Kristoffersen 1984).
2. The northern Barents Sea was covered by an ice sheet in Late

Weichselian (Salvigsen 1981; Salvigsen & Nydal 1981).

3. Spitsbergenbanken was covered by an ice sheet, possibly as late as the Late Weichselian (Elverhøi & Solheim 1983; Solheim & Kristoffersen 1984).

Vorren & Kristoffersen (1986) describes undated ridges in the southwestern Barents Sea which they argue to represent the maximum of a Weichselian ice sheet.

In other words there does not exist an unambiguous model of glaciation for the last 200 000 years BP in the study area. To bypass this problem we are largely bound to use models of glaciations from other places. This is generally the same approach as presented by Sættem et al. (1985). However, in the present work we pay more specific attention to results from Svalbard and the Norwegian mainland.

Western Norway. In this area there are many papers summing up the Weichselian stratigraphy (a.o. Mangerud 1981; Andersen et al. 1981). For the coastal areas Sejrup (in press) has summarised and correlated the existing works. His juxtaposition is the northernmost well-funded model of Weichselian stratigraphy and we use this model as a support in the Barents Sea. His model consists of four interstadials and five stadials in the timespan between Eem and Allerød. He regards this as a minimum number of interstadials.

The duration of the interstadials are in principle uncertain and in our models we use Sejrup's inferred time estimate of the different events (Figures 7.2 and 7.3).

Troms. In the coastal area the ice sheet has transgressed sorted sediments dated to 27 000 BP (Andreassen et al. 1984). Vorren et al. (1983) have shown that the ice sheet occupied the outer part of the continental shelf after about 36 000 BP, and Rokoengen et al. (1979) indicated that the ice sheet may have reached the shelf edge as late as about 13 300 BP.

Finnmark. In the southwestern part of Finnmarksvidda several ice free periods are recognised, but none of them are dated (Olsen & Hamborg 1983, 1984).

Svalbard. The investigations by Salvigsen (1981) and Salvigsen & Nydal (1981) show that Svalbard was completely covered by an ice-sheet at least once, probably in Early Weichselian. The Late Weichselian glaciation was limited and local in the western part, while the eastern part of the archipelago was covered by an ice sheet.

In the scope of this presentation Boulton et al. 1982 are largely in agreement with Salvigsen & Nydal (1981). Boulton et al. (1982) is modified and presented in Figures 7.2 and 7.3.

Barents Sea. Solheim & Kristoffersen (1984) regard the pre-Late Weichselian glacial chronology as completely open due to lack of stratigraphical tie points. However, presenting arguments for a maximum age of a few hundred thousand years for a moraine ridge complex in the western part of Bjørnøyarennna, they suggest that the last ice sheet that extended westwards into the deeper parts of Bjørnøyarennna was of Saalian or Early Weichselian age.

This is in agreement with Salvigsen & Nydal (1981) and Landvik (pers. commun.) who find that the most extensive ice cover on Svalbard occurred in early Weichselian, while Troitsky et al. (1979) and Miller (1982) suggest a Saalian age. For the Late Weichselian Elverhøi & Solheim (1983) find it most probable that the ice sheet was limited to the bank areas (present water depth 300-400 m) and thus forming a calving bay in Bjørnøyarennna. Still they are open for the possibility that also a Late Weichselian ice sheet extended westwards to form parts of the ridge complex in the western part of Bjørnøyarennna.

Sparker data collected within the IKU Barents Sea Mapping Program shows evidences of a wedge shaped (in NW-SE cross section) deposit north of Nordkapp. The northwestern limitation of this deposit subparallels the present 300 m water depth contour on the map in Figure 7.1 and could tentatively be correlated with Elverhøi & Solheim's (1983) ice margin at 300-400 m water depth on the northern flank of Bjørnøyarennna, thus supporting the Bjørnøyarennna calving bay theory.

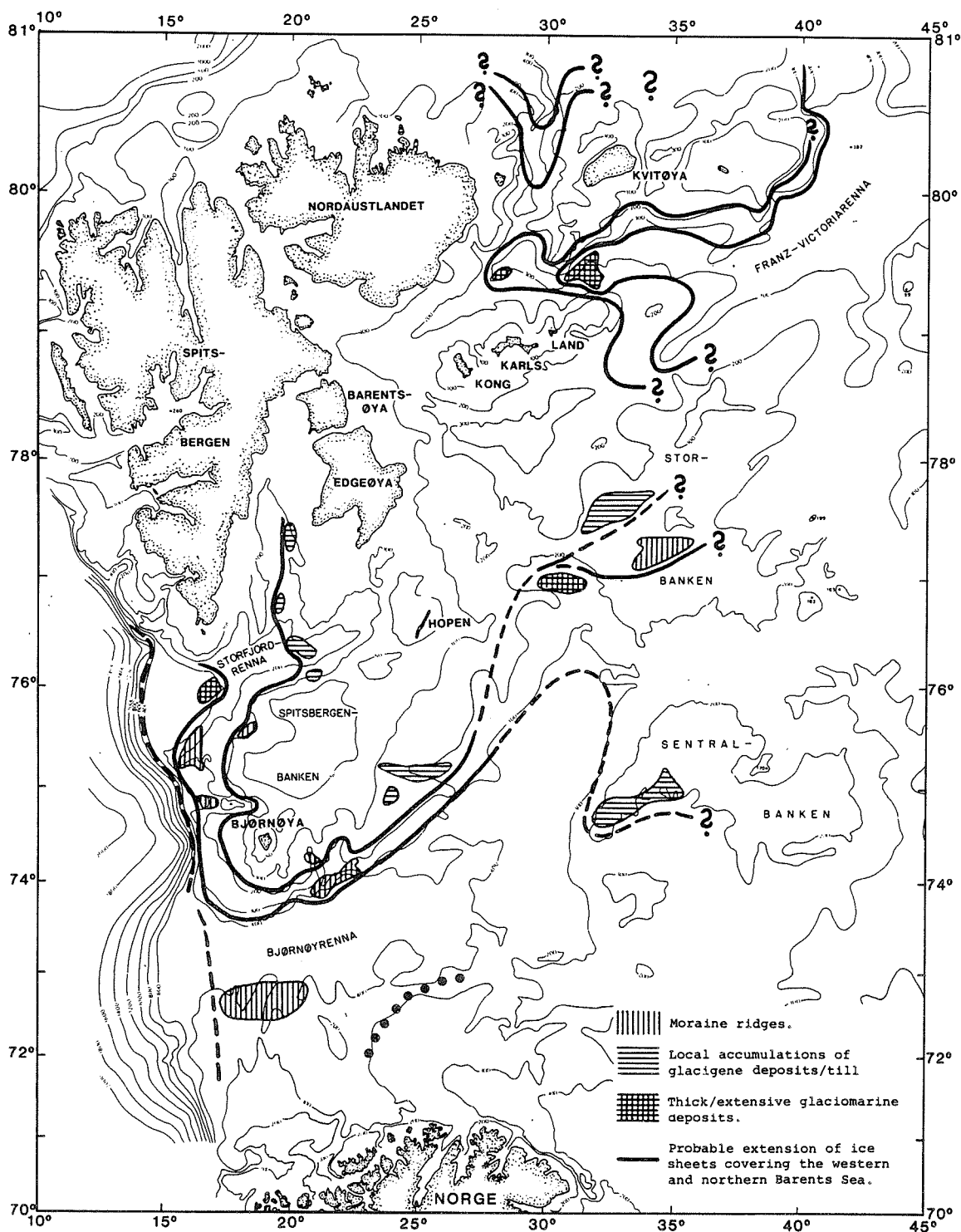


Figure 7.1 Bathymetric map showing features related to former ice margins in the Barents Sea. Modified after Elverhøi and Solheim (1983). The heavy, dotted line shows the approximate western termination of a wedge shaped sediment thickening interpreted from IKU sparker data. Open circles indicate a tentative ice sheet margin related to this feature.

Construction of glaciation models

As can be seen from the previous discussion the geological data makes several models of glaciation possible.

In this work we are interested in the "coldest" and "warmest" probable temperature history.

We have therefore reconstructed what we regard as the probable maximum and minimum glacial influence in the area. These reconstructions are respectively combined with ice thicknesses which give the "warmest" and "coldest" condition at the base of the glacier.

These models are based on the following strong simplifications for the positions of the ice margin:

- 1) The ice-sheet was non existent or had retreated to the mainland.
- 2) The ice-margin was situated at 300-400 m present water depth forming a calving bay in Bjørnøyareenna.
- 3) The ice-sheet was calving at the continental margin.

I Maximum glaciation

Glaciers extending to the shelf edge occurred during Saale and Early Weichselian. In addition there were two periods when ice sheets grounded on the shallow banks in the Middle and Late Weichselian.

II Minimum glaciation

Saalian glaciation with an ice-sheet extending to the shelf edge. Early, Middle and Late Weichselian ice sheets grounded on the shallow banks and did not extend to the shelf edge.

Temperatures underneath the Barents Sea ice sheets

There are several opinions with regard to gradients and thicknesses of a Barents Sea ice sheet. In large there are two main temperature conditions to be considered, namely frozen (T_c) and wet-based (T_m) glaciers (cold and temperate glaciers).

For wet based glaciers there are grossly two main alternative approaches

when calculating surface profiles of an ice sheet: A low profile ice sheet is a consequence of the model by Boulton & Jones (1979) which assumes that 90% of the movement of a glacier is due to deformation in the underlying sediments. The profile of an ice sheet will thus mainly depend on the shear strength of the underlying confined mixture of water and sediments.

The other model for temperate glaciers is based on internal flow of the ice (Paterson 1981) and ice sheet profiles given by Hughes (1981, Figure 5.8). The same profiles are used in the reconstruction by Hughes et al. (1981) of a Late Weichselian ice sheet in the northern hemisphere.

Our model II, representing a "warm" ice, is based on a low profile, wet-based ice sheet. We have assumed a shear strength of 20kPa (0.2 bar) in the sediments just underneath the ice sheet (Boulton & Jones 1979, Figure 5).

In cold based ice sheets the deformation in the sole of the glacier is supposed to decrease strongly. Most of the movement will take part within the ice body. This is expected to give steeper gradients of the ice sheet surface and a greater maximum ice sheet thickness. According to the reconstruction of the maximum Late Weichselian ice sheet by Hughes et al. (1981), the temperature below the maximum Barents Sea glacier would be below the pressure melting point, T_m , for all our heat flow sites except from C85-A and C85-E. Though Orheim (pers. commun. 1985) tends to assume that most of the large Barents Sea ice sheet (sheets) had temperatures equal to T_m .

In our model I, for a "cold" ice we have chosen the steepest probable ice profile by Hughes (1981, 1 in Figure 5.8). We have furthermore chosen $T_c = T_m$ as an average temperature condition for the lifetime of a cold based ice sheet.

In a closed system underneath an ice sheet the pressure melting point temperature, T_m , will follow the phase equilibrium function for ice and fresh water. As a function of pressure this equilibrium temperature decreases with about $7 \cdot 10^{-3}$ K/atm or approximately 0.7 K/1000 m ice thickness (Sugden & John 1976).

From our alternative assumptions about ice margin positions and ice sheet profiles we have arrived at alternative ice sheet thicknesses for each heat flow site. The corresponding temperatures are presented in Tables 7.8 and 7.9.

Table 7.8 *Temperature ($T_c = T_m$), underneath an ice sheet assuming the "cold" glaciation model (Model I).*
 1) *The ice sheet terminates at the continental margin.*
 2) *The ice sheet is restricted to the shallow banks.*

Site	Average temperature under a cold based ice. Model I (°C)	
	1) (°C)	2) (°C)
D85-V	-0.9	-0.8

Table 7.9 *Pressure melting point temperature, T_m , underneath an ice sheet assuming the warm glaciation model (Model II).*
 1) *The ice-sheet terminates at the continental edge.*
 2) *The ice-sheet is restricted to the shallow banks.*

Site	Pressure melting point temperature. Model II.	
	1) (°C)	2) (°C)
D85-V	-0.5	-0.8

Sea water temperatures

For a simplified temperature model it may be assumed that the annual mean sea bottom temperature was as today during the whole Holocene period and in all periods between the glaciations. This temperature has been obtained by extrapolation of temperature gradients from the boreholes. The effect of variations in thermal conductivity with depth is accounted for.

The shelf area in front of a marine ice sheet will normally have abundant icebergs or be covered by an ice sheet or drifting ice. Under such conditions it can be assumed that the sea water even down to 400 m depth was between the freezing point for sea water (about -2.1°C) and the freezing point for fresh water (about 0°C). The actual temperature would

vary with the salinity of the water and with depth.

Hald (pers. commun. 1985) tends to believe that most likely the sea water temperatures for a setting as described above would be between 0°C and -1°C. The exceptions would be if salt brines were developed as a result of increased salinity due to freezing of ice in the upper part of the water column - a process that could result in temperatures near -2.1°C close to the sea bed.

A temperature of -0.5°C may probably be chosen as an average value under such conditions, and if this approximation also is valid for site D85-0 it implies that the sea water temperature at this site has been roughly the same since the deglaciation as it is today.

Temperature history models

Based on the above discussions we have arrived at two temperature history models which we believe give realistic boundaries for maximum (Model I) and minimum (Model II) perturbation on heat flow data measured in the upper 10-100 m below the sea bed (Figures 7.2 and 7.3).

Y. BP.	SITE		References:
	WESTERN NORWAY Sejrup (in press)	SVALBARD Boulton 1982	
0			
10 000			1.75
13 000			
18 000			
20 000		?	-0.8
25 000		?	
30 000			1.75
34 000		?	-0.8
40 000			
50 000			1.75
60 000		?	
70 000		?	-0.8
75 000			
80 000			
90 000			-0.9
100 000			
110 000			
120 000			1.75
130 000			
140 000			
150 000			
160 000	?	?	-0.9
170 000			
180 000			
190 000			
200 000			1.75
240 000			

 Not glaciated.
 The site is covered by an ice sheet.
 Arctic sea water conditions. Tentative

bsmp90/report/AH1/81/mas 31-MAY-90

**MINIMUM GLACIATION MODEL
EXTENSIVELY WET BASED ICE SHEET**

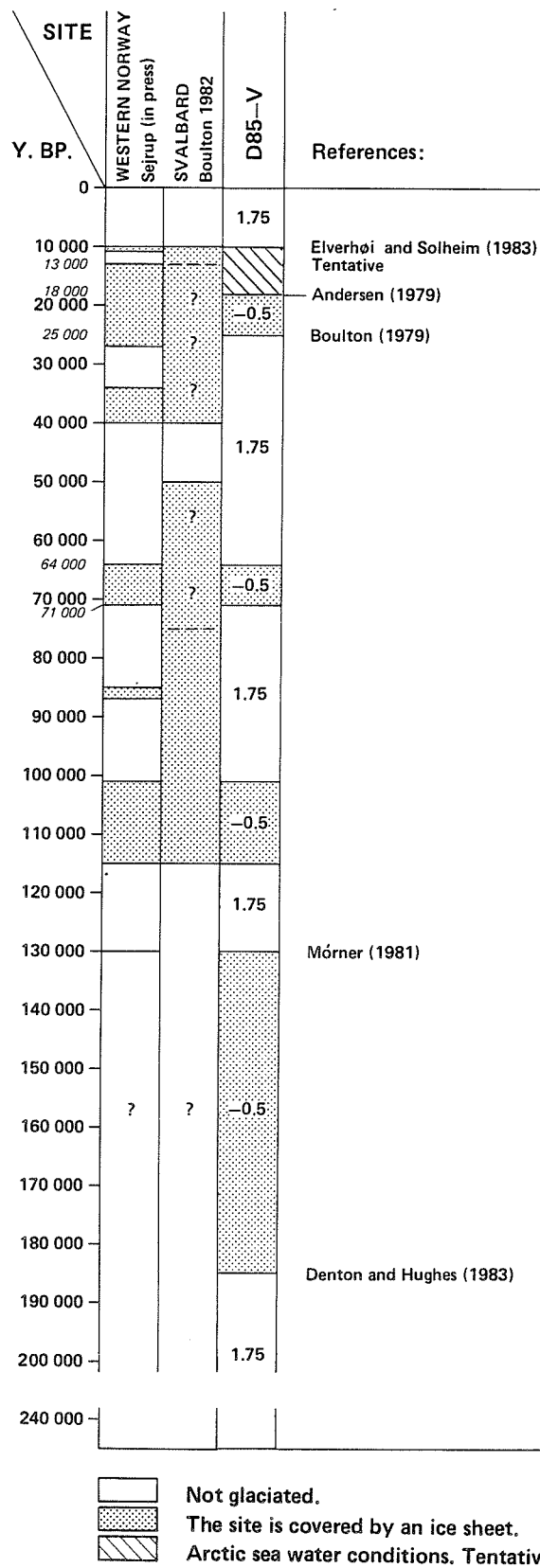


Figure 7.3 Temperature history model II. Extensive wet based ice sheets combined with minimum glaciation models.

Calculation of climatic perturbations

Method and assumptions

The calculation of the theoretical transient effect upon the measured temperatures is calculated at the Geophysical Laboratory, Department of Geology, at the University of Aarhus in Denmark. This work follows a scheme earlier published by this institution (Balling et al. 1981) and the mathematical part will not be further discussed here.

A stepped temperature versus time-function is applied. Input to this function is taken from the temperature history in Figures 7.2 and 7.3.

The present day surface temperature is chosen as reference level. This temperature is deduced from an extrapolation of the depth/temperature profile obtained in the boreholes, taking into account the vertical variations in thermal conductivity.

The calculations are based on a theoretical half space with a constant thermal diffusivity. The thermal diffusivity is proportional to the thermal conductivity and inversely proportional to the specific heat per volume. For the Barents Sea samples, the average value for thermal diffusivity will be about $0.4 \times 10^{-6} \text{ m}^2\text{s}^{-1}$ to $0.6 \times 10^{-6} \text{ m}^2\text{s}^{-1}$. Calculations are done using both these alternatives.

Table 7.10 summarizes the calculated disturbances of the temperature gradients. To arrive at maximum and minimum correction alternatives, temperature history model I is combined by a thermal diffusivity of $0.4 \times 10^{-6} \text{ m}^2\text{s}^{-1}$, whereas temperature history model II is combined with a thermal diffusivity of $0.6 \times 10^{-6} \text{ m}^2\text{s}^{-1}$. This table thus provides extreme boundaries for the details presented in Table 7.11.

Table 7.10 Maximum and minimum disturbance of temperature gradients based on temperature history models I and II.

Site	Depth (m)	Temperature gradient disturbance ($^{\circ}\text{Cm}^{-1}$)	
		Temperature history model I. Thermal diffusivity $0.4 \times 10^{-6} \text{ m}^2\text{s}^{-1}$ ($10^{-3} \text{ }^{\circ}\text{C m}^{-1}$)	Temperature history model II. Thermal diffusivity $0.6 \times 10^{-6} \text{ m}^2\text{s}^{-1}$ ($10^{-3} \text{ }^{\circ}\text{C m}^{-1}$)
D85-V	"	-3.2	-1.9

Table 7.11 Calculated correction of measured temperatures and temperature gradients for site D85-I and site D85-V. Assumed thermal diffusivity of underground: $0.6 \times 10^{-6} \text{ m}^2/\text{s}$.

Depth below sea bed (m)	Temperature history model I		Temperature history model II	
	Temperature disturbance (°C)	Gradient disturbance (°C/m)	Temperature disturbance (°C)	Gradient disturbance (°C/m)
0.0	0.000	-.0026	0.000	-.0016
5.0	-.013	-.0026	-.008	-.0016
10.0	-.026	-.0026	-.016	-.0016
15.0	-.039	-.0026	-.024	-.0016
20.0	-.052	-.0026	-.032	-.0016
25.0	-.066	-.0026	-.040	-.0016
30.0	-.079	-.0026	-.048	-.0016
35.0	-.092	-.0026	-.056	-.0016
40.0	-.105	-.0026	-.064	-.0016
45.0	-.118	-.0026	-.072	-.0016
50.0	-.131	-.0026	-.080	-.0016
55.0	-.144	-.0026	-.088	-.0016
60.0	-.157	-.0026	-.096	-.0016
65.0	-.170	-.0026	-.104	-.0016
70.0	-.183	-.0026	-.112	-.0016
75.0	-.196	-.0026	-.120	-.0016
80.0	-.209	-.0026	-.128	-.0016
85.0	-.222	-.0026	-.136	-.0016
90.0	-.235	-.0026	-.144	-.0016
95.0	-.248	-.0026	-.152	-.0016
100.0	-.261	-.0026	-.160	-.0016

B: Thermal diffusivity of the underground: $0.4 \times 10^{-6} \text{ m}^2/\text{s}$.

Depth below sea bed (m)	Temperature history model I		Temperature history model II	
	Temperature disturbance (°C)	Gradient disturbance (°C/m)	Temperature disturbance (°C)	Gradient disturbance (°C/m)
0.0	0.000	-.0032	0.000	-.0020
5.0	-.016	-.0032	-.010	-.0020
10.0	-.032	-.0032	-.020	-.0020
15.0	-.048	-.0032	-.030	-.0020
20.0	-.064	-.0032	-.039	-.0020
25.0	-.080	-.0032	-.049	-.0020
30.0	-.096	-.0032	-.059	-.0020
35.0	-.112	-.0032	-.069	-.0020
40.0	-.128	-.0032	-.079	-.0020
45.0	-.144	-.0032	-.089	-.0020
50.0	-.160	-.0032	-.098	-.0020
55.0	-.176	-.0032	-.108	-.0020
60.0	-.192	-.0032	-.118	-.0020
65.0	-.208	-.0032	-.128	-.0020
70.0	-.224	-.0032	-.137	-.0019
75.0	-.240	-.0032	-.147	-.0019
80.0	-.256	-.0032	-.157	-.0019
85.0	-.272	-.0032	-.166	-.0019
90.0	-.288	-.0032	-.176	-.0019
95.0	-.303	-.0032	-.186	-.0019
100.0	-.319	-.0032	-.195	-.0019

Topographic effects

Topographic corrections to the thermal gradient is necessary in areas with marked local variations in surface altitude. This is necessary when the surface towards which the heat flows (representing a boundary condition) is at different levels and has different temperatures in short enough distances away from the site to affect the downward temperature increase (i.e. the topography causes the heat flow to deviate from the vertical).

The topographic effect on temperature gradients can be estimated by an equation derived by Jaeger (1965) (in Kappelmayer & Haenel 1974):

$$G = G_u - \frac{x \cdot \Delta T_o}{T_i (x^2 + z^2)}$$

where

- G is the apparent gradient influenced by topography
- G_u is corrected thermal gradient in the underground
- x is the distance away from the site to a change in annual surface temperature ΔT_o .
- z is the depth below the surface of the site.

On land the use of this equation is relatively simple as the mean annual temperature for a given region generally can be expressed as a linear function of altitude. In the sea water masses, however there may exist different sheets of water with different temperatures. Mean annual temperature difference within a given water depth range at a specific geographical position is therefore influenced by 1) the depth to the boundary between different water masses, and 2) the mean annual temperatures within the actual water masses.

In our case we have considered the topographic relief on all our sites (as revealed by our shallow seismic data), and for the "worst case" quantified what magnitude of T° that is necessary to make the topographic effect significant.

A similar discussion can be carried out to show that effects from actual lateral variations in Quaternary thickness can be neglected.

The topographic effect from relict plough marks from drifting icebergs (Lien 1983) is also found negligible. For this case the topographic conditions may be less favourable. To, however, is quite insignificant, and this will imply a negligible correction.

7.4 Shallow probe data

Introduction

During the 1985 IKU shallow drilling and heat flow cruise a gravity spear with fixed thermistors was used to measure temperature to a maximum depth of approximately 3 m below the sea floor. Corresponding thermal conductivity values were obtained by use of the needle probe method on sediment samples collected by a gravity corer (Sættem et al. 1985).

The aim of these shallow probe data was to evaluate the potential for measuring heat flow by use of a relatively simple device lowered to the sea floor.

An evaluation of the results from these measurements is carried out by Omegalink International Ltd. (Zielinski 1986b).

Methods

The shallow probe data were investigated with a two-fold purpose:

- 1) To evaluate the feasibility and limitations of using the shallow probe equipment to measure heat flow
- 2) To (if possible) calculate heat flow from shallow probe data

Zielinski & Bruchhausen (1983) describes a method for calculating a steady state temperature gradient from measurements in the upper few metres of the underground. This method relies on input about mean annual surface temperature T_s , annual temperature amplitude, A , and the time t_0 when $T = T_s$.

For the Barents Sea data A and t_0 are unknown. T_s can be established with high accuracy from extrapolation from the borehole temperature data, taking into account the variation in thermal conductivity with depth.

Zielinski et al. (1986b) have proposed a method whereby values for A and t_0 are obtained as best fit values based on an algorithm similar to those described by Zielinski & Bruchhausen (1983), with the following known input parameters.

- the steady state gradient
- temperatures at approximately 1, 2 and 3 metres
- mean annual surface temperature

Results

An attempt has been made to extrapolate the calculated values for A and t_0 to the sites where only shallow probe data exists and at these sites calculate the steady state thermal gradient by following the scheme of Zielinski & Bruchhausen (1983).

The conclusion is that this is not possible with only three temperature depth points from the upper 3 m below the sea bed.

However, further investigation and sensitivity tests of the method have given rather optimistic results regarding the use of a longer (up to 10 m) shallow probe device with several thermistors to measure heat flow. Our conclusion can be summarized as follows:

1. Temperature/depth data from shallow drilling boreholes (10-50 m) can be used to calibrate measurements from the upper 10 m below the sea bed (which are influenced from the seasonal temperature variations).
2. The results from this calibration can be extrapolated to a certain distance from the shallow drilling site. When doing this proper consideration of oceanographic conditions will be required.
3. The resolution of a heat flow value resulting from 8 temperature/depth points between 0 m and 10 m below the sea bed with a resolution of 0.001°C of each temperature measurement, may be better than 20% of the actual steady state heat flow value.

Though the resolution of the data obtained by the method indicated above is lower than is the case in the state of the art measurements from shallow drillings, we feel that the method has a high potential which should be investigated further. This method may especially be useful in studies of fluid flow in the underground (a.o. Zielinski & Bruchhausen 1983; Zielinski et al. 1985).

For such studies high accuracy and resolution of the measured heat flow is not of the same importance as when the objective of the measurements is to extrapolate temperatures at depth. However, fluid flow studies would require collection of heat flow data with a spatial density far greater than what is realistic for the shallow drilling method (provided that sufficient density of shallow drilling data or actual annual temperature curves for the bottom water for calibration purposes exist) and this method would economically enable heat flow profiles to be gathered across structures like basin rims, major fault zones, traps etc.

7.5 Final heat flow values

Final measurement results (field results)

Table 7.12 summarizes the final field measured gradients and heat flow values. The values given are not corrected for any influence from in situ versus laboratory conditions, climatic corrections etc. and thus represent final field results.

Table 7.12 Final measured gradients and heat flow values (field results). R-SQUARE is the standard coefficient of determination for regression (least square fit for all temperature-depth points). Values near 1.0 indicate good fit; values near zero indicate poor fit. 1 HFU = 1 mcal cm²s⁻¹.

SITE	GRAD(mdegC/m)	N	R-SQUARE	Kav (mcal °C ⁻¹ cm ⁻¹ s ⁻¹)	MHF(HFU)
D85-V	36.8	5	0.9953	4.41	1.62

Correction of thermal conductivity values

Pressure release effects

The correction to apply for difference in temperature and pressure in laboratory versus in situ conditions have been found negligible.

From data about water content, bulk density and mineralogy it is found that the samples have expanded since they were retrieved from the borehole. This is probably due to dissolved gas in the pore water, being released and forming gas voids in atmospheric pressure. This is also supported by results from organic geochemical analyses (Fjerdingsstad et al. 1985). A further support to this theory is the large scatter in thermal conductivity versus depth.

The representative correction for the actual depth interval can be expressed as a correction factor " k_g " that can be applied directly to K_{av} in the Table 7.12 above.

" k_g " is defined as

$$k_g = \frac{\text{C-IN SITU}}{\text{C-MEAS}}$$

The resulting correction factor " k_g " found representative for the depth intervals corresponding to the temperature measurements is $k_g = 1.04$.

Thermal conductivity anisotropy

The thermal conductivity measurements carried out at the University of Aarhus give clear indications of an anisotropy in the thermal conductivity of the Quaternary samples from the Barents Sea.

The factor of anisotropy, A , is defined as:

$$A = \frac{k_h}{k_v}$$

A is calculated from 28 pairs of horizontal versus vertical thermal conductivity, and though the statistics is limited, the trend is clear and the following mean value can be calculated.

$$A_{\text{mean}} = 1.13$$

(Standard deviation 0.14)

K_{av} in Table 7.12 above is believed to be largely representative for the horizontal thermal conductivity and a reduction of K_{av} should be included in the vertical thermal conductivity. We therefore suggest a correction factor k_{av} of 0.91 to be applied ($0.91 = 1/1.1$).

Correction due to topographic effects and glacial history

Effects on measured temperature gradients from topographic relief on the sea floor are found to be negligible.

The variations in paleotemperatures due to the glacial history is evaluated for the last 245 000 years. This effect is found to vary depending upon glaciation models and site locations. Maximum and minimum effects are calculated based on two glaciation models. The result of this is summarized in Table 7.10, and in the Table 7.13 below this effect is expressed as a correction factor to the actual measured temperature gradient for each individual site.

Table 7.13 *Correction factors to apply on measured temperature gradients due to the maximum and minimum glaciation models.*

SITE	Correction factor	
	Model I	Model II
D85-V	1.09	1.05

Discussion

Table 7.14 summarizes the various correction factors that can be applied to the measured results.

We feel that the correction for anisotropy in the thermal conductivity is relatively clearly expressed in our data and therefore include this correction in our recommended adjusted heat flow values.

Table 7.14 Final heat flow values and possible corrections (expressed as correction factors).

SITE	Field results		Correction of thermal conductivity		Correction for glacial history	
	(HFU)	(mW/m ²)	k_g	$k_a = \frac{1}{A_{mean}}$	Model I	Model II
D85-V	1.62	76.8	1.04	0.91	1.09	1.05

Correction due to erroneous measurements due to gas expansion in the samples under laboratory conditions is documented with somewhat less certainty. An important input to these calculations is the solid density of the mineral fraction. This is estimated from the mineralogy and not measured. Still, we feel that the results from these calculations support earlier observations about gas content and large scatter in plots of thermal conductivity versus depth as all results point out that this effect may be present especially in the samples. We therefore suggest that also this effect is accounted for.

The correction for the effects from the glacial history can be done according to either of the two glaciation models presented in Section 7.3. These two models are believed to represent the maximum and minimum likely transient effect on the present shallow temperature gradients. From scientific evidences it is not possible to prefer one of the models. However, tentatively we would suggest to use Model II for this correction.

From the above discussion and Table 7.14, we may therefore summarize the field results and final adjusted results for the heat flow sites as

presented in Table 7.15.

Table 7.15 Field results and final heat flow values.
A: Field results.
B: Final results. (Adjusted for anisotropy, gas, climatic effects. See discussion in text.)

Site	A: Field results		B: Suggested final results	
	(HFU)	(mW/m ²)	(HFU)	(mW/m ²)
D85-V	1.62	76.8	1.61	67.4

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APPENDIX 1

ANALYTICAL METHODS

Total Organic Carbon

Bulk samples were crushed in a disk mill or mortar. Aliquots of the samples and also of extracted sediments were then weighed into Leco crucibles, then treated three times with hot 10% HCl in order to remove carbonate, and finally washed four times with distilled water in order to remove any traces of HCl. The crucibles were then placed on a hot plate (60°C) and dried for 24 hours. The total organic carbon (TOC) content of the dried samples was determined using a Leco CS 244 carbon/sulphur analyser.

The instrument was calibrated using a sediment standard with 2.72% carbon. Calibration and blank runs were carried out every 15th measurement.

Extractable Organic Matter

Powdered rock was extracted by Soxhlet apparatus for 18 hours. Boiling dichloromethane (DCM) containing 7%(v/v) methanol was used as solvent.

DCM of organic geochemical grade was used and blank analyses indicated that the occurrence of contaminating hydrocarbons was negligible. Activated copper fillings were used in order to remove any free sulfur from the samples.

After extraction, the solvent was evaporated using a Büchi Rotavapor and the amount of extracted organic matter (EOM) was determined.

Medium-pressure liquid chromatography (MPLC)

The extracts were diluted in DCM (1:3 mg/μl) and the asphaltenes were precipitated using excess n-pentane (40:1 pentane: (DCM+EOM)). The asphaltene fraction was weighed after drying at 50°C for 12 hours.

The remaining maltenes were separated into saturated, aromatic and non-hydrocarbon fractions using a MPLC system with n-hexane as eluant (Radke et al. 1980). The various fractions were concentrated using a Büchi Rotavapor. Then they were transferred to glass vials. The remaining solvent was removed and fraction weights determined.

Gas chromatographic analysis

The saturated fractions were diluted with n-hexane and analysed on an HP-5730A gas chromatograph equipped with a 15m DB-1 fused silica column (0.25mm i.d., 0.25µm film). Hydrogen was used as a carrier gas with a flow rate of about 1.5 ml/min. Injections were performed in split mode (split ratio 1:10). The temperature program used was 80°C (2min.) - 4°C/min. - 280°C.

All the data from the GC analyses were processed on a VG Multichrom lab-data system.

Gas chromatography - mass spectrometry (GC-MS)

GC-MS analyses were performed on a VG TRI0-1 quadrupole GC-MS-DS system. A HP-5890II GC was fitted with a fused silica DB-5 capillary column (30 m x 0.3mm i.d.). Helium (1.5 ml/min.) was used as a carrier gas and the injections were performed in split mode (1µl, split ratio 1:15). The GC oven was programmed from 180°C (1 min.) to 310°C at 1.7°C/min.

The saturated hydrocarbons were analysed in multiple ion mode (MID) at a scan cycle time of approximately 2 secs. The mass spectrometers operated at 70eV electron energy with an ion source temperature of 200°C. Data acquisition was performed using VG data systems .

Peaks were identified by comparison with elution patterns in certain mass-chromatograms. Peak ratios were calculated from peak heights in the appropriate mass chromatograms.

INTERPRETATION LEVELS

1. TOTAL ORGANIC CARBON (TOC)

TOC (wt%)	Richness of source rock

<0.5	Poor Source Rock
0.5-1	Fair Source Rock
1-2	Good Source Rock
>2	Rich Source Rock

2. EXTRACTABLE ORGANIC MATTER (OR SOLUBLE BITUMEN)

a) Data Supplied

Weight of extracted rock	(g)
EOM extractable organic matter	(mg, mg/g of rock, mg/g TOC)
Sat saturated hydrocarbons	(mg, mg/g of rock, mg/g TOC, wt% of EOM)
Aro aromatic hydrocarbons	(mg, mg/g of rock, mg/g TOC, wt% of EOM)
HC/EOM = (Sat+Aro)/EOM	(wt%)
Non-HC/EOM	(wt%)
HC/non-HC x 100	
Sat/Aro x 100	

b) Interpretation of source-rock richness based on hydrocarbon content.

Hydrocarbon content is dependent on maturity, total organic carbon content and kerogen type as well as being influenced by migrated hydrocarbons. The values should therefore be treated as a rough guide only.

Source rock richness	HC (ppm of rock)

Poor	<100
Fair	100-250
Good	250-500
Rich	>500

SHALLOW DRILLING AND HEAT FLOW MEASUREMENT AT SITE 7317/02-U-01 (D85-V) ON THE STAPEN HIGH IN THE BARENTS SEA



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