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Organic geochemistry of sediments and gases in the borehole Umiivik-1, Svartenhuk Halvø, West Greenland

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Contents

Introduction

Although several types of crude oil have been found in seeps and slim-hole cores in recent years in West Greenland (Bojesen-Koefoed *et al.*, 1997a; Christiansen, 1993, Christiansen *et al.*, 1994a,b, 1995, 1996a,b,c, 1997) there is only limited knowledge on the actual source rocks. The detailed organic geochemistry, especially the distribution of biomarkers in the oils, provides some information on the type of organic material, the depositional environment and the thermal history of the source rocks. So far only limited data on thickness, areal distribution, generative potential and age of the source rocks exist ; in other words it is very difficult to use quantitative generation models in the present stage of exploration.

The exploration models that were developed and promoted in the early 1990's for both on- and offshore exploration in West Greenland are therefore rather conceptional as regards the source rock question. Main emphasis has been put on a mid-Cretaceous marine source rock (Cenomanian–Turonian) that was first suggested by Chalmers *et al.* (1993) on basis of World-wide analogies but later strongly supported by direct data from Ellesmere Island in Arctic Canada (Núñez-Betelu, 1993, 1994; Bojesen-Koefoed *et al.*, 1997b). Furthermore, there is very strong evidence of a latest Cretaceous - Paleocene deltaic source rock based on a very distinct biomarker composition of the "Marraat-type" oil (Christiansen *et al.*, 1994b,c, 1996a,b,c).

Based on discussions with the oil companies that have been or are considering exploration possibilities in West Greenland, the source rock question seems to be one of the main risk factors, if not the most critical factor. It is therefore generally accepted that the level of exploration interest in West Greenland would benefit strongly by actually demonstrating the existence of source rocks and by quantifying their generation potential. Based on this need funding of various projects including source rock studies was provided by the Danish Ministry of Energy and the Greenland Home Rule.

Background

The marine Cretaceous mudstones outcropping in the Svartenhuk Halvø area are the oldest known fully marine deposits from West Greenland (Fig. 1). Recently, these mudstones have been studied during field work by the Geological Survey of Greenland (GGU) in 1991 and 1992, a programme which also included 5 shallow boreholes to depths between 66 and 86 m (Christiansen, 1993; Christiansen *et al.*, 1994c). Based on analytical work from these cores and samples from nearby outcrops, thermally immature mudstones of Coniacian to Early Santonian have been documented age (see Nøhr-Hansen, 1994, 1996), thereby giving some hope that immature or early mature sediments of Cenomanian–Turonian age could be reached by drilling to relatively shallow depths (some hundreds of metres) along the southern shoreline of Umiivik (Fig. 2).

As a consequence of this a seismic programme involving the acquisition of a single refraction and reflection line was carried out in the summer of 1994 in order to prepare later drilling (Christiansen *et al.*, 1995a). A proposal for a drilling programme on Svartenhuk Halvø was made early in 1995 and the necessary funding was provided from the Danish State and the Government of Greenland (Bate & Christiansen, 1996).

The Umiivik-1 borehole was drilled in the period from 21 August to 13 September 1995 and terminated at a planned depth of 1200 m (Table 1). The hole was drilled by grønArctic Energy Inc. of Calgary, Alberta, Canada as part of a turnkey contract with the Government of Greenland, Minerals Office and with the Geological Survey of Denmark and Greenland (GEUS) providing the geological services prior to, during and after drilling. Umiivik-1 was drilled after the completion of grønArctic's own 1995 exploration programme on Nuussuaq which included three slim-hole exploration wells to depths of 901 m, 707 m and 399 m (see Christiansen *et al.,* 1996a). The drilling services on both Nuussuaq and Svartenhuk Halvø were provided by PetroDrilling Ltd. of Halifax, Nova Scotia, Canada, using a modified Longyear wire-line mineral drilling rig.

The Umiivik-1 borehole was positioned on the 1994 seismic line in an area with possibilities for a maximum thickness of what was predicted as Cenomanian/Turonian–Santonian mudstones in a broad syncline (see Bate, 1996 for further details).

Technical details of Umiivik-1 are given in the well completion report by Bate (1996) including a preliminary geological log, description of penetrated lithologies, sample lists and information on hydrocarbon shows. Preliminary results and the geological background for the drilling programme has been summarised by Bate & Christiansen (1996). More detailed descriptions and interpretation of the sedimentary facies are given by Dam (1997). The stratigraphic ages of the uppermost 650 m of the core are reported as Late Turonian to Early Coniacian by Nøhr-Hansen (1997) based on palynological dating, whereas the deeper part is thermally altered to such a degree that dating is not possible.

Penetrated interval

A total of 1200 m of core (GGU 439301) was drilled in Umiivik-1 (close to 100% recovery) with a core diameter of 63.5 mm in the uppermost 148 m and 47.6 mm in the remaining part.

Almost the entire core consists of Upper Cretaceous marine mudstones and Paleocene dolerite intrusions (Fig. 3). The mudstones are dark grey with abundant silty interbeds. Only few sandstone intervals were found (Fig. 3). A total of nineteen dolerite intrusions with a cumulative thickness of 238.25 m were intersected throughout the well. Especially the thick intrusions from 548 m to 598 m, from 849 m to 890 m, and from 952 to 1027 m have severely altered the marine mudstones, and have thereby limited the possibilities for both detailed organic geochemical and palynological studies in the deeper part of the well.

Analytical methods and organic geochemical programme

At the well site 'representative' samples were taken out and canned at approximately 3 metre intervals (see Bate, 1996). All other cores were wrapped in aluminium foil and packed in core boxes in order to avoid (or at least reduce) contamination.

Some cans were air freighted or brought back as hand luggage to Copenhagen during the drilling operation to allow quick analysis. The first results were available already in September 1995. The next round of analyses was carried out on the remaining cans that arrived in Copenhagen early November 1995.

The main part of the sample material was prepared and analysed at the source rock laboratory at GEUS; details on some of the analytical methods are given by Bojesen-Koefoed (1989). The gas composition and preparation for gas isotope composition was carried out at GEUS whereas the gas isotope composition was measured at the University of Copenhagen.

The analytical programme included the following techniques:

1) LECO/Rock Eval pyrolysis (n= 98);
2) Total sulphur analysis (n= 98);
3) Vitrinite reflectance, R_o (n= 20);
4) Extraction in a Soxtech apparatus with subsequent deasphalting and column separation into saturated and aromatic hydrocarbons and NSO compounds (n= 9);
5) Analysis of saturated hydrocarbons by gas chromatography (GC) and gas chromatography/mass spectrometry (GC/MS) (n= 9);
6) Head space gas composition (n= 27), C isotopes of methane (n= 17), in some cases also of ethane (n= 8) and propane (n= 6).

Analytical results

Screening of sediments (LECO/Rval pyrolysis and vitrinite reflectance)

A large number of mudstones distributed throughout the core of Umiivik-1 were analysed by LECO/Rock Eval pyrolysis, for sulphur analysis, and for vitrinite reflectance. Data are given in Table 2 and shown graphically on the log in Fig. 4 and in the cross plots in Figs 5 to 7.

The content of total organic carbon (TOC) is moderate to high with most values between 2% and 6% (average 3.42% ± 1.23%) (Table 2). The highest TOC values are from the uppermost 390 m of the core (average 4.22% ± 1.13%), whereas the deeper and thermally postmature — part below 405 m shows significantly lower values (average 2.85% ± 0.97%) (Table 2, Fig. 4). This variation in TOC may, however, be primary and not only controlled by differences in maturity level.

There is a significant variation in thermal maturity between the upper part of the core (above 390 m), and the deeper part below 405 m with only a thin transition zone. In the upper part the Hydrogen Index (HI) varies from 63 to 136 (average 95 ± 25). These values suggest a poor to fair source rock potential for oil (Fig. 5). In the lower part of the core HI values are typically below 25, in many cases below 10, suggesting a very high thermal maturity where all potential hydrocarbons have been generated and thermally cracked to gas (Table 2).

Total sulphur values (TS) typically vary from ~0.5% to 3.5% with a few very low and very high values (Table 2). This range of values suggests a marine depositional environment for most of the sediments (Fig. 6).

In the uppermost part of the core T_{max} values range from 427°C to 441°C (average 434° C when a few anomalous values are omitted); scattering is high revealing only a slightly increasing trend from 0 to 390 m. These values suggest that the sediments are thermally immature or at a level corresponding to the early part of the oil window. This is supported by the vitrinite reflectance measurements that in this depth interval range from 0.55% to 0.63% (Table 2, Figs 4 and 7).

In the lower part of the core T_{max} values are very high, in most cases between 500°C and 560°C or even undefined. These very high values are supported by vitrinite reflectance values between 1.7% and 4.3% (Table 2, Figs 4 and 7). Slightly lower T_{max} values between 450°C and 500° C are observed in the transitional interval (390 to 405 m), at ~730 m, and at ~1185 m. The very high maturity values seen to be controlled by the position of the sills (Fig. 4).

Bulk composition, GC and GC/MS analysis of sediments

Due to the high thermal maturity below ~405 m depth only 9 mudstones from the upper part of the core were extracted and analysed by gas chromatography (GC) and gas chromatography/mass spectrometry (GC/MS).

Extraction data are given in Table 3 and shown in Fig. 8. With exception of the deepest sample, the extracts are relatively homogeneous with moderate extractabilities between 17 and 36 mg SOM/g TOC. All the samples have a high concentration of asphaltenes (20-59%) and the deasphaltened extracts are dominated by NSO compounds (53-91%). The ratio of saturated to aromatic hydrocarbons is usually close to 1. A bulk composition of this type is common for mudstones with a low thermal maturity and a high content of terrestrially derived organic matter.

All gas chromatograms of the saturated hydrocarbons are shown in Fig. 9 and the calculated ratios given in Table 4. The samples are all rather similar (with the exception of the deepest one), all suggesting a significant input of terrestrial organic matter and a relatively low thermal maturity. The terrestrial fingerprint is evident from the high Pr/Ph values between 4.5 and 6.2 and the distinct odd-even predominance (CPI between I.12 and 1.62; Phillippi ratios between 1.33 and 2.19). The two latter ratios show a clear decrease with increasing depth as would be expected with increasing thermal maturity.

The distribution of biomarkers in the saturated fraction has been studied by using m/z 217 (and 218) mass fragmentograms for the steranes and m/z 191 (and 177, 355) for the terpanes. Generally, the terpanes occur in much higher concentration than the steranes. Figure 10 shows the terpane and sterane distribution for all samples; some of the parameters providing information on thermal maturity and depositional environment are listed in Tables 5 and 6.

The terpanes are dominated by pentacyclic terpanes (hopanes, moretanes and a few other compounds), whereas tricyclic terpanes occur only in very low concentrations. The ratio of H29/H30 varies from 0.69 to 1.20; bisnorhopane occur in remarkably high concentration in some samples and the H28/H30 ratio varies from 0.03 to 0.76. The extended hopanes show rapidly decreasing contents with increasing carbon number. With the exception of the two shallowest samples both H31 and H32 seem to have reached equilibrium of isomerization with 22S/22S+22R values between 0.55 and 0.60. The concentration of moretanes is moderate to high, and the $\alpha\beta/\alpha\beta+\beta\alpha$ ratio is between 0.68 and 0.84. Ts occurs in very low concentration compared to Tm with the exception of the two deepest samples. The ratio of Tm/Tm+17β shows values from 0.81 to 1 with a clear depth gradient (Table 4, Fig. 11). Bisnorlupane has not been recorded whereas oleanane/lupane occur in very low concentrations in a few samples.

The steranes are dominated by C29 steranes, especially high values are noted below 200 m. The steranes have not reached equilibrium of isomerization and the 20S/20S+20R values range from 0.12 to 0.51 with a clear depth gradient (Table 4, Fig. 11).

Gas geochemistry

Gas escaping from the core was noted already during the drilling campaign from 238 m to TD (see Bate, 1996; Bate & Christiansen, 1996) (Fig. 3). In some intervals the gas escape was audible (gas bursting against the aluminium foil in which the cores were wrapped) and formed a white froth on the surface of the core upon removal from the core barrel. Indications of gas are particularly common in the mudstones in the deeper part of the hole whereas they have not been noted in the intrusions (see Fig. 3). This suggests a very limited migration route, and most of the gas is assumed to be present in the actual source rock that has generated the hydrocarbons, presumably due to heating from the many intrusions.

Head space analyses on cans containing the core samples show that considerable quantities of gas were released from some intervals (Table 7). In many samples hydrocarbon gases made up 10 to 50% of the total headspace gas. These values are remarkably high considering that the cans typically were sealed several minutes after the core barrel was emptied at the surface. This suggests high concentrations of gas under pressure in the shale. The highest recorded gas values are from the intervals 100-300 m and 1150-1200 m, but high values have been observed scattered throughout the core. The samples with high hydrocarbon gas concentrations represent a very broad range in thermal maturity with measured vitrinite reflectances of the shales from 0.55% to more than 4% (Table 7).

Methane is the most abundant hydrocarbon gas in most samples, the C1/C2+C3 ratio being 3 to 200 with a general decrease with depth (Table 7). Especially samples from deeper than 794 m are very wet (C1/C2+C3 < 10), and one interval from 1151 to 1182 m shows very high concentrations of wet gases (including both normal and iso butane and pentane).

The isotope composition of the gases varies considerably, especially for methane where $\delta 13C$ ranges from -11.9 to -51.2 ‰, however, the richest gases in the deeper part of the core are relatively constant in composition (-32 to -37 ‰). The variation for ethane (-19.9 to -27.9 ‰) and propane (-21.5 to -24.6 ‰) is much smaller (Table 7). These isotope values together with the often relatively high wetness are in accordance with a thermogenetic origin of the gases, with some of the samples having a composition typical of gas associated with oil (Fig. 12). However, most of the gases plot outside the fields of typical oil associated gas and coal gas in the classification scheme of Figure 12. Loss of lighter gas components by diffusion would produce a trend similar to that observed in Figures 12 and 13. Diffusion will lead to enrichment of the heavier gas components and to isotopic fractionation as lighter isotopes diffuse more easily than heavier ones. In case of diffusion, the largest isotopic fractionation is to be expected for methane which also what is observed. Thus, the trend in gas composition is most likely explained by diffusion, although variation in source rock maturity may account for some of the differences observed.

The chemical and isotopic composition of headspace gas in canned cuttings from reservoirs encountered during drilling are most often similar to those of the reservoir gas obtained from testing. Thus, headspace gas may be considered to be representative of the hydrocarbon gases initially present in the rocks. Assuming that the chemical and isotopic compositions of the gases shown in Table 7 are similar to those of the rocks at the particular depths, we can conclude that diffusion of gases took place prior to coring of the rock.

Discussion and conclusions

Although it was in some ways disappointing that the Umiivik-1 borehole did not penetrate the base of the Cretaceous marine mudstones and that the deeper part of core has a too high thermal maturity to carry out palynological dating and detailed organic geochemistry some important analytical data have been obtained, especially for the discussion of the local and regional variation in thermal maturity and the distribution and potential of possible source rocks.

Based on the knowledge from the Umiivik-1 borehole and the experience from the later years in West Greenland it also possible to give some recommendations for further work in the Svartenhuk Halvø area that may be of importance for offshore exploration in nearby basins, but maybe also for the onshore basin.

Thermal maturity of sediments in Umiivik-1

Although many of the recorded thermal maturity parameters from screening, GC and GC/MS data are partly controlled by the type of organic matter in the mudstones, there are some very clear maturity trends in the Umiivik-1 hole. The sediments in the upper 390 m are thermally immature, but close to the upper part of the 'oil window', whereas all sediments below 405 m are postmature with respect to oil generation.

The boundary zone between the two maturity regimes is narrow (~15 m) and shows a distinct gradient. Although this boundary may be a fault zone (see Bate & Christiansen, 1996), there is probably a nearby intrusion in the underlying succession or in the fault plane that has a strong effect on the thermal maturity.

Based on a large number of parameters, a distinct increase in maturity is observed in the upper 400 m of core (see Figs 4 and 11).

The postmature succession in the lower part of the core shows a much more irregular variation in thermal maturity (from 1.7% to more than 4% vitrinite reflectance); a variation that to some degree seems to be controlled by the position of major intrusions. Based on the observed gradients some of the intrusions must be rather irregular in shape, or dykes may be present close to the hole. It should be noted that the maturity near TD is relatively low compared to most of the postmature succession with Ro values below 2%. This may suggest that less mature sediments may occur at deeper levels with few or no intrusions, and that such sediments could have a maturity in the lower part of the "oil window" or in the condensate zone.

Regional variation in thermal maturity

A very interesting variation in thermal maturity is observed when data from the Umiivik-1 core are compared with data obtained from the five 1992 shallow cores drilled by GGU in the nearby area:

400708: ~13 km NNW of Umiivik-1, altitude: 125 m, depth: 79 m.
400709: ~16 km NNW of Umiivik-1, altitude: 50 m, depth: 86 m.

400710: ~4 km SE of Umiivik-1, altitude: 157 m, depth: 66 m.
400711: ~4 km SE of Umiivik-1, altitude: 95 m, depth: 55 m
400712: ~2 km W of Umiivik-1, altitude: 5 m, depth: 80 m.

Technical details, sedimentary logs, and some organic geochemical data (LECO/Rock-Eval, extraction, GC, light-gas) from these boreholes are given by Christiansen *et al.* (1994c) whereas the previously unreported maturity parameters from GC/MS analyses are listed in Table 8. Generally, all five holes represent slightly higher topographical and stratigraphical levels than Umiivik-1. $T_{max.}$ values are almost identical to Umiivik-1 (with the exception of 400708 which is lower), whereas the more sensitive GC and GC/MS maturity parameters generally show slightly lower values for four of the holes than for even the shallowest part of Umiivik-1, and significantly lower values for 400708. The implication of this is that the maturity variation along the southern coast of Umiivik and probably also farther north is fairly constant and controlled by altitude only, whereas the westernmost locality (400708, NW of Firefjeld) has a slightly lower maturity. This also suggests that the presence of sills and dykes only have a very localised effect on the nearby sediments and not on the overall gradient of this rather large area.

If the maturity variation on Svartenhuk Halvø is compared with data from outcrop samples and shallow cores from Nuussuaq and from the holes drilled by grønArctic in 1995 (see Christiansen *et al.* 1996c) it is clear that the thermal maturity of the sediments close to or immediately below sea level on Svartenhuk Halvø is much lower than on the north coast of Nuussuaq (~600 m altitude difference), and slightly higher than on the southwest coast of Nuussuaq (~150 m altitude difference). The direct conclusion of this is that the thickness of the Tertiary volcanic succession (and possibly overlying post-volcanic sediments?) on this part of Svartenhuk Halvø as well as the postvolcanic uplift was less than on northern Nuussuaq.

Source rocks for oil and gas

The mudstones analysed from the Umiivik-1 core are organic-rich like many of the other Upper Cretaceous – Paleocene marine mudstone successions known from onshore West Greenland. Like most other examples the Hydrogen Index values are relatively low; only few samples can be classified as good source rocks and most examples are classified as poor to fair source rocks. It is, however, obvious that the overall richness in organic material and the extensive distribution of several km thick organic-rich mudstones give some possibilities for sourcing of even large hydrocarbon accumulations.

The high concentration of gas in many of the samples confirms the hydrocarbon potential of the Upper Cretaceous marine mudstones. The remarkable wetness of the gas that has been demonstrated in several intervals in the deeper, now thermally postmature, part of the core may be explained by diffusion of gas in the rocks prior to coring. Although the effects of gas diffusion complicate the gas-to-source rock correlation, there can be little doubt that several intervals had a significant potential for generating liquid hydrocarbons prior to the thermal alteration by the intrusions. Especially the interval from 1152 to 1182 m could represent such a postmature source rock. Based on stratigraphic knowledge from the uppermost 650 m of the core and the thickness of the penetrated mudstones below, this interval could include upper Cenomanian or lower Turonian strata.

None of the sediments analysed from the Umiivik-1 core show a direct geochemical correlation to the five distinct oil types that have been reported recently from the Disko-Nuussuaq area by Bojesen-Koefoed *et al.* (1997a) and Christiansen *et al.* (1997a,b). The Niaqornaarsuk, Marraat and Itilli oil types all show extensive evidence of angiosperm biomarkers, suggesting that the source rocks must be younger than the Umiivik-1 mudstones that only contain very low concentration of these distinct compounds. The Kuganguaq oil type is from a more terrestrial influenced source rock, whereas the Equalulik oil type is completely different and possibly of lacustrine origin.

However, the Umiivik-1 mudstones have some geochemical characteristics in common with the source rocks of the Kanguk Formation on Ellesmere Island, especially the remarkable high concentration of bisnorhopane (Bojesen-Koefoed *et al.* 1997b). The Kanguk Formation source rock was, however, deposited under more distal marine conditions and is slightly older (late Cenomanian to early Turonian) than the dated uppermost 650 m of the Umiivik-1 core.

It seems likely that the Coniacian–Santonian and possibly also older underlying mudstones have generated significant amounts of hydrocarbons in the large onshore areas covered by volcanic rocks on Svartenhuk Halvø, especially west and southwest of Umiivik. The present organic geochemical characterisation may serve as a good tool for future correlation studies if hydrocarbons are found at the surface in the coming years, or in possible new drilling.

Recommendations for future work on Svartenhuk Halvø

Svartenhuk Halvø is one of the least studied areas of the onshore Cretaceous–Tertiary in West Greenland, mainly due to the limited number and poor quality of outcrops that make detailed sedimentological studies and detailed sampling for biostratigraphy and organic geochemistry difficult but also due to its remoteness compared to Disko and Nuussuaq.

The results from Svartenhuk Halvø including the Umiivik-1 borehole, and the recent years' experience on Nuussuaq may, however, give some suggestions how the work can be continued in a successful way in order to get knowledge that will be relevant and encouraging for petroleum exploration in the future.

Based on the present organic geochemical result and the many other studies on material from Umiivik-1 it can be concluded that:

new deep drilling is risky and needs careful planning (and luck), it is not recommended for the time being;
"oil hunting" like on Nuussuaq could give some important break-throughs, especially along the coasts and in carefully selected structural zones;
further analytical work on existing material, especially a combination of hydrous pyrolysis, pyrolysis GC and microscope studies is likely to give important data on the generative potential of these possible source rocks that are thick and extensively distributed but with a low, but poorly quantified, potential;

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Figures

Tables

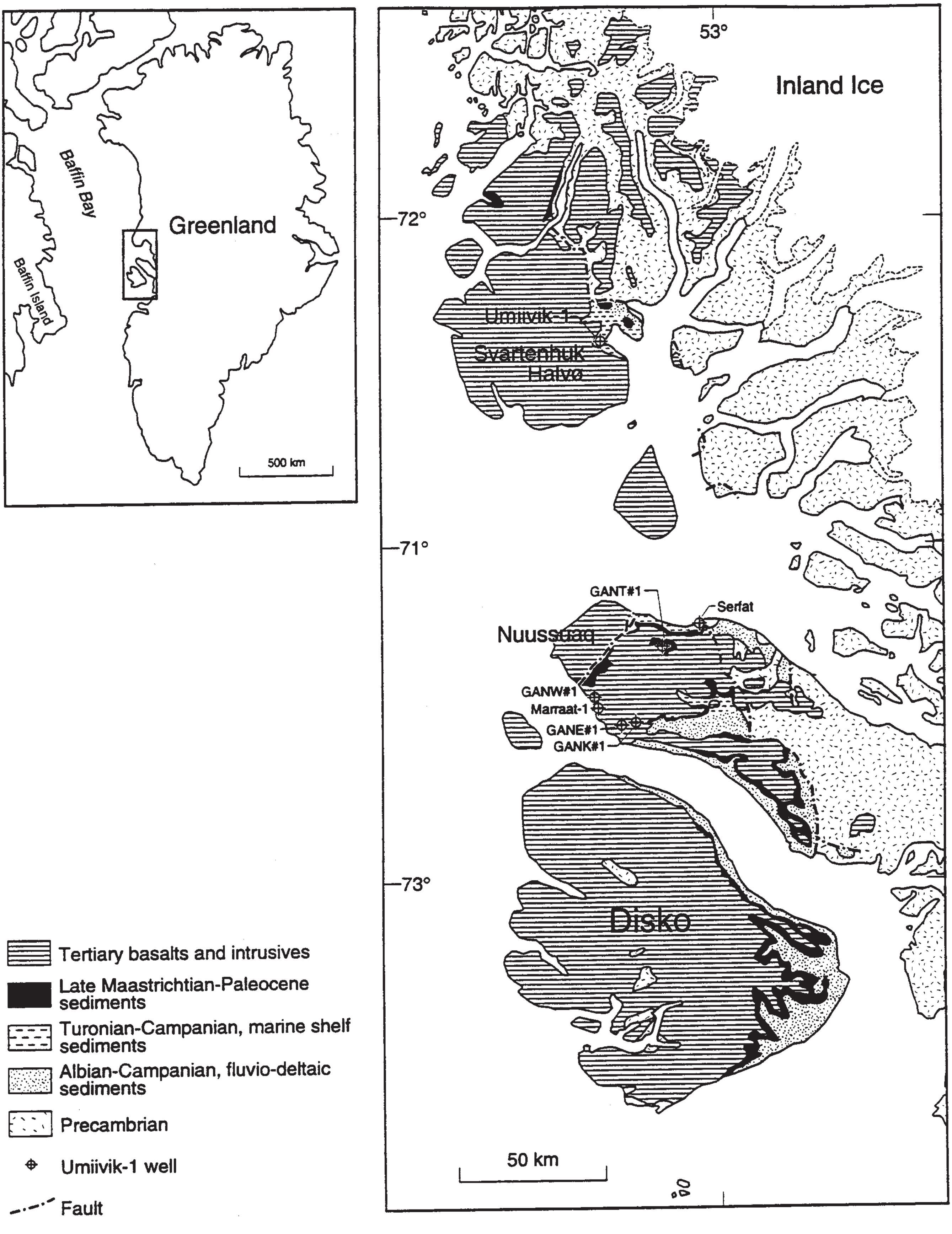

Baffin Bay
Baffin Island
Greenland
500 km
53°
Inland Ice
72°
Umiivik-1
Svartenhuk
Halvø
71°
GANT#1
Serfat
Nuussuaq
GANW#1
Marraat-1
GANE#1
GANK#1
73°
Disko
50 km
Tertiary basalts and intrusives
Late Maastrichtian-Paleocene sediments
Turonian-Campanian, marine shelf sediments
Albian-Campanian, fluvio-deltaic sediments
Precambrian
Umiivik-1 well
Fault

Fig. 1.

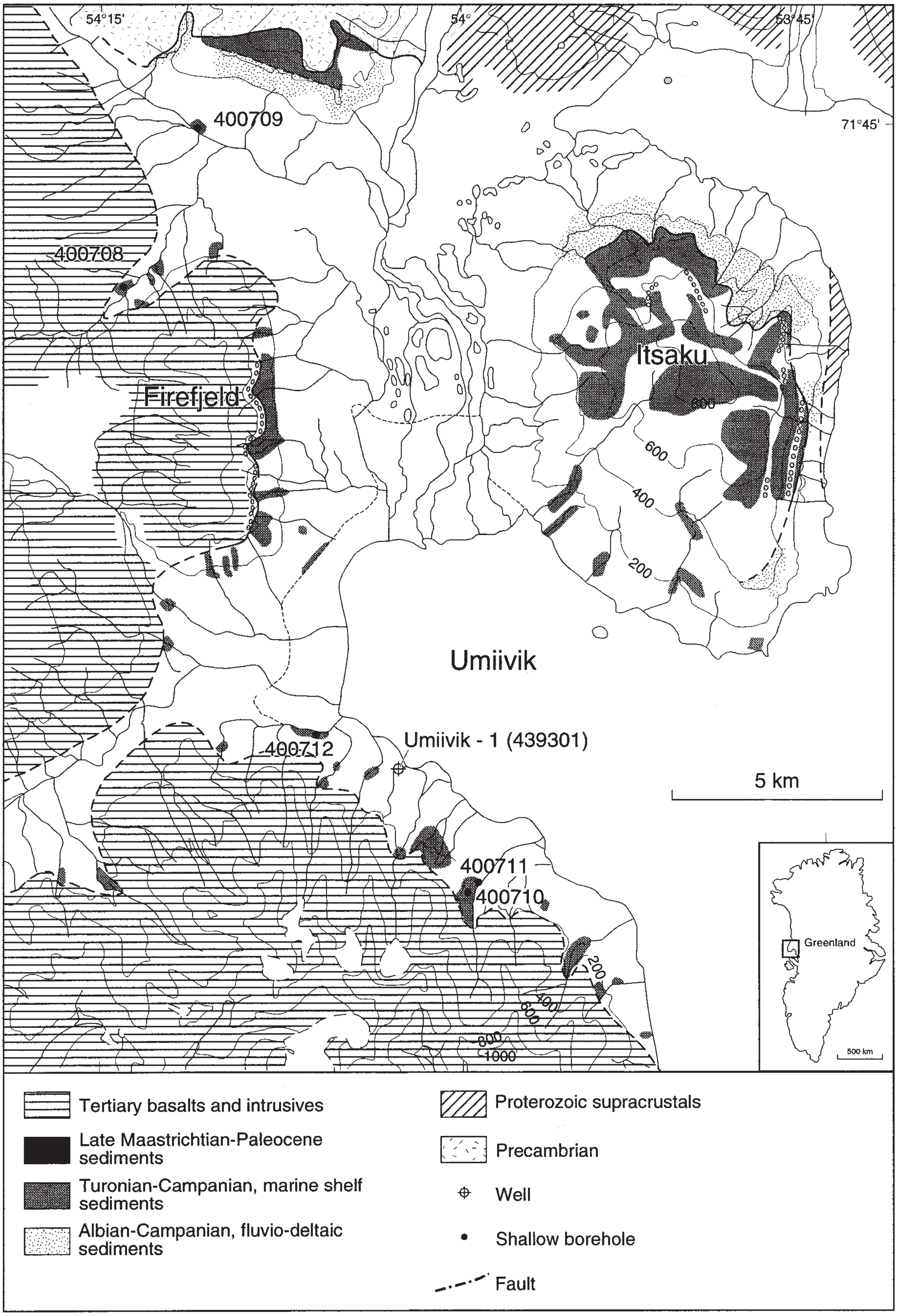
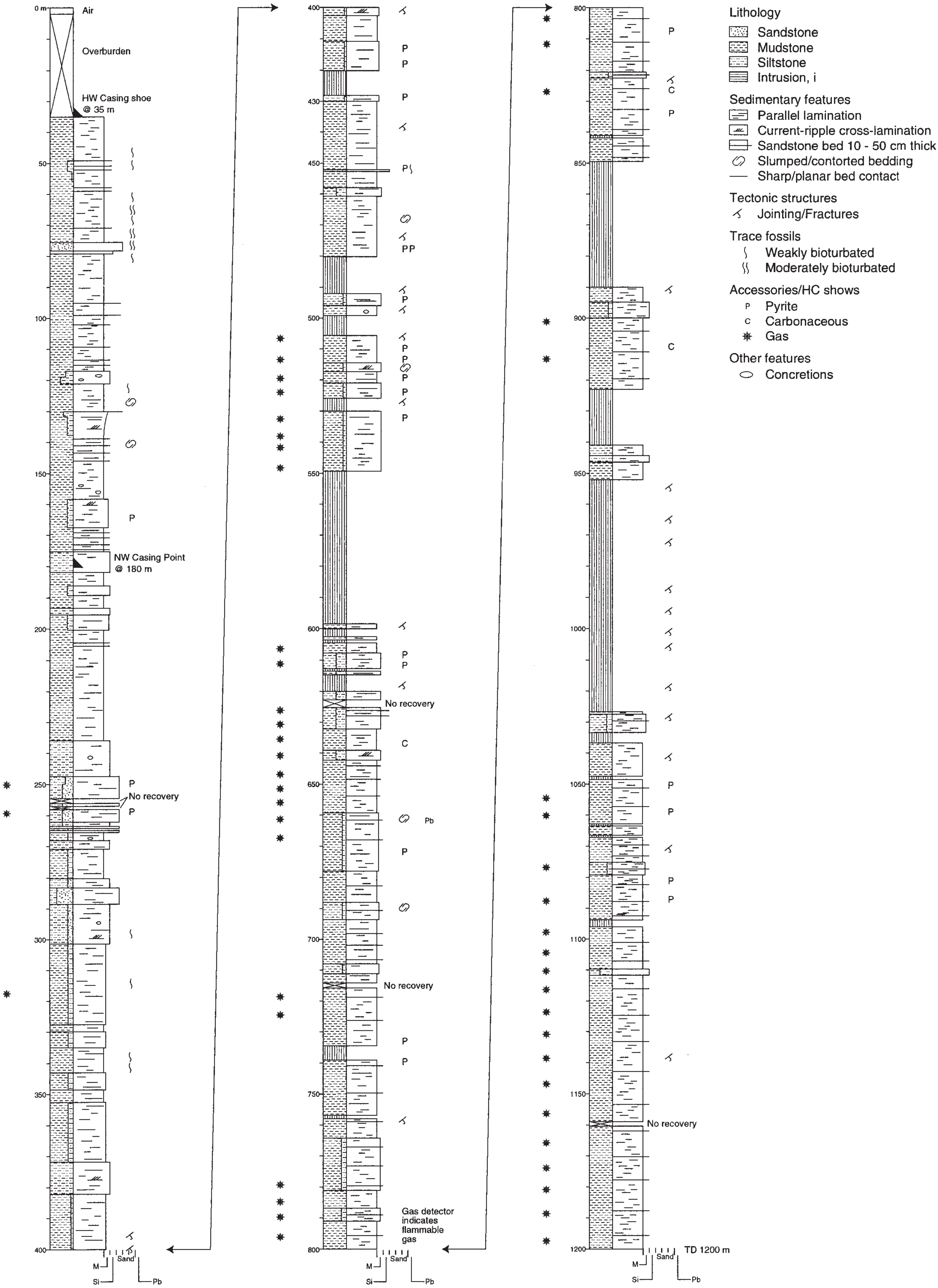

54°15'
54°
53°45'
71°45'
400709
400708
Firefjeld
Itsaku
600
600
400
200
Umiivik
400712
Umiivik - 1 (439301)
5 km
400711
400710
200
400
600
800
1000
Greenland
500 km
Tertiary basalts and intrusives
Late Maastrichtian-Paleocene sediments
Turonian-Campanian, marine shelf sediments
Albian-Campanian, fluvio-deltaic sediments
Proterozoic supracrustals
Precambrian
Well
Shallow borehole
Fault

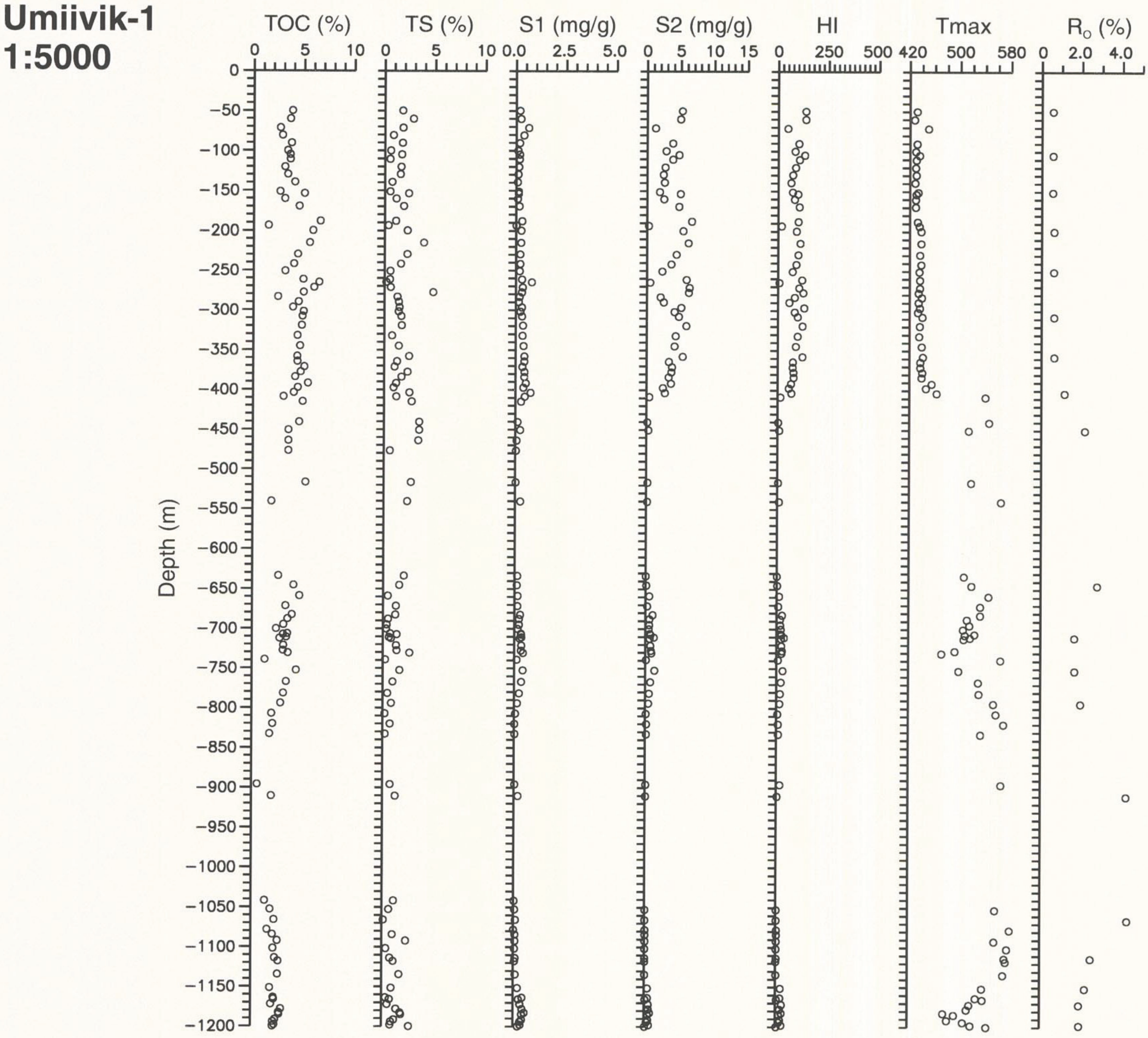
Fig. 2.

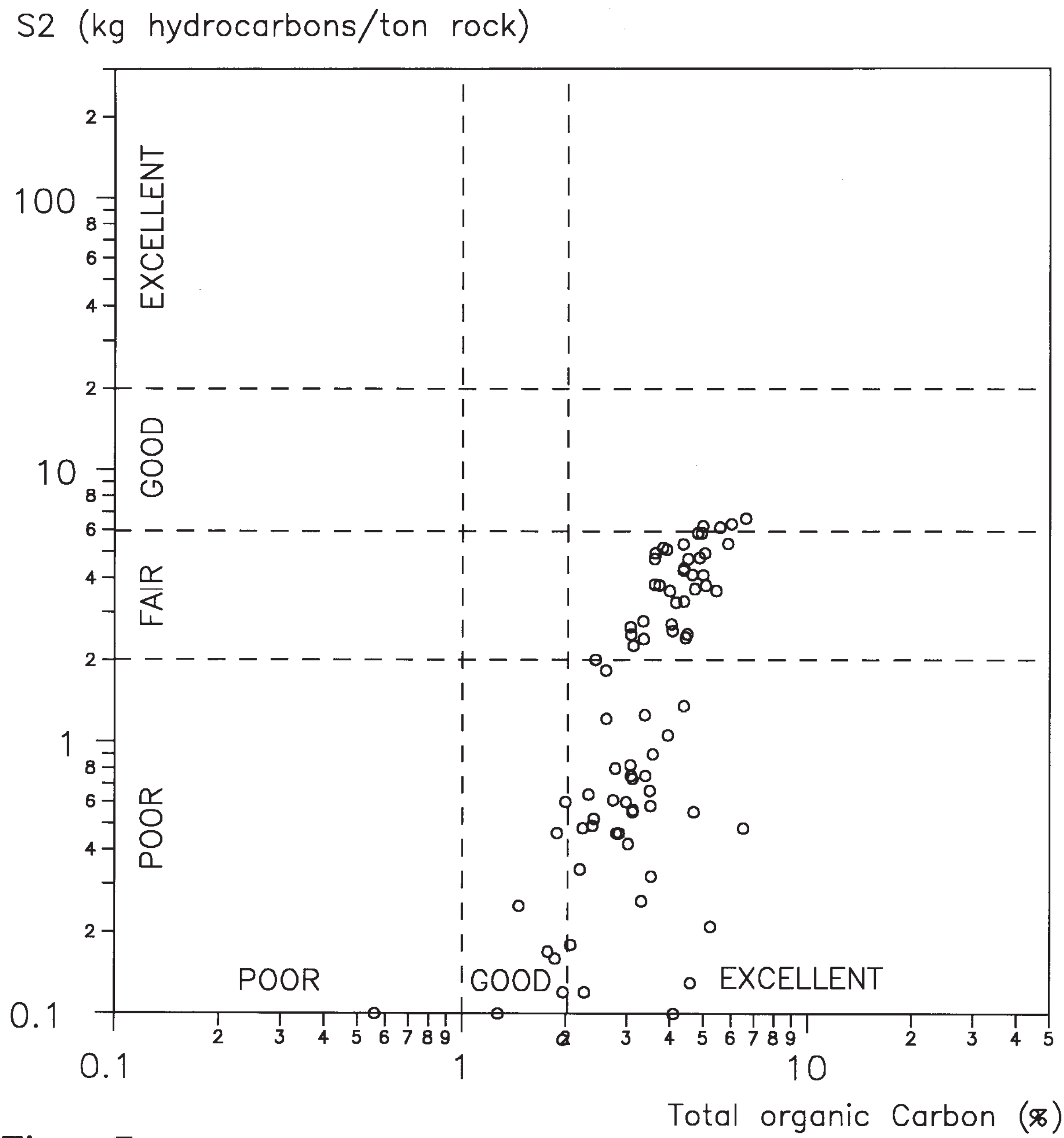


Air
Overburden
HW Casing shoe @ 35 m
NW Casing Point @ 180 m
No recovery
Gas detector indicates flammable gas
TD 1200 m
M
Si
Sand
Pb
Lithology
Sandstone
Mudstone
Siltstone
Intrusion, i
Sedimentary features
Parallel lamination
Current-ripple cross-lamination
Sandstone bed 10 - 50 cm thick
Slumped/contorted bedding
Sharp/planar bed contact
Tectonic structures
Jointing/Fractures
Trace fossils
Weakly bioturbated
Moderately bioturbated
Accessories/HC shows
Pyrite
Carbonaceous
Gas
Other features
Concretions

Fig. 3

Fig. 4





S2 (kg hydrocarbons/ton rock)
EXCELLENT
GOOD
FAIR
POOR
100
10
1
0.1
POOR
GOOD
EXCELLENT
0.1
1
10
Total organic Carbon (%)

Fig. 5

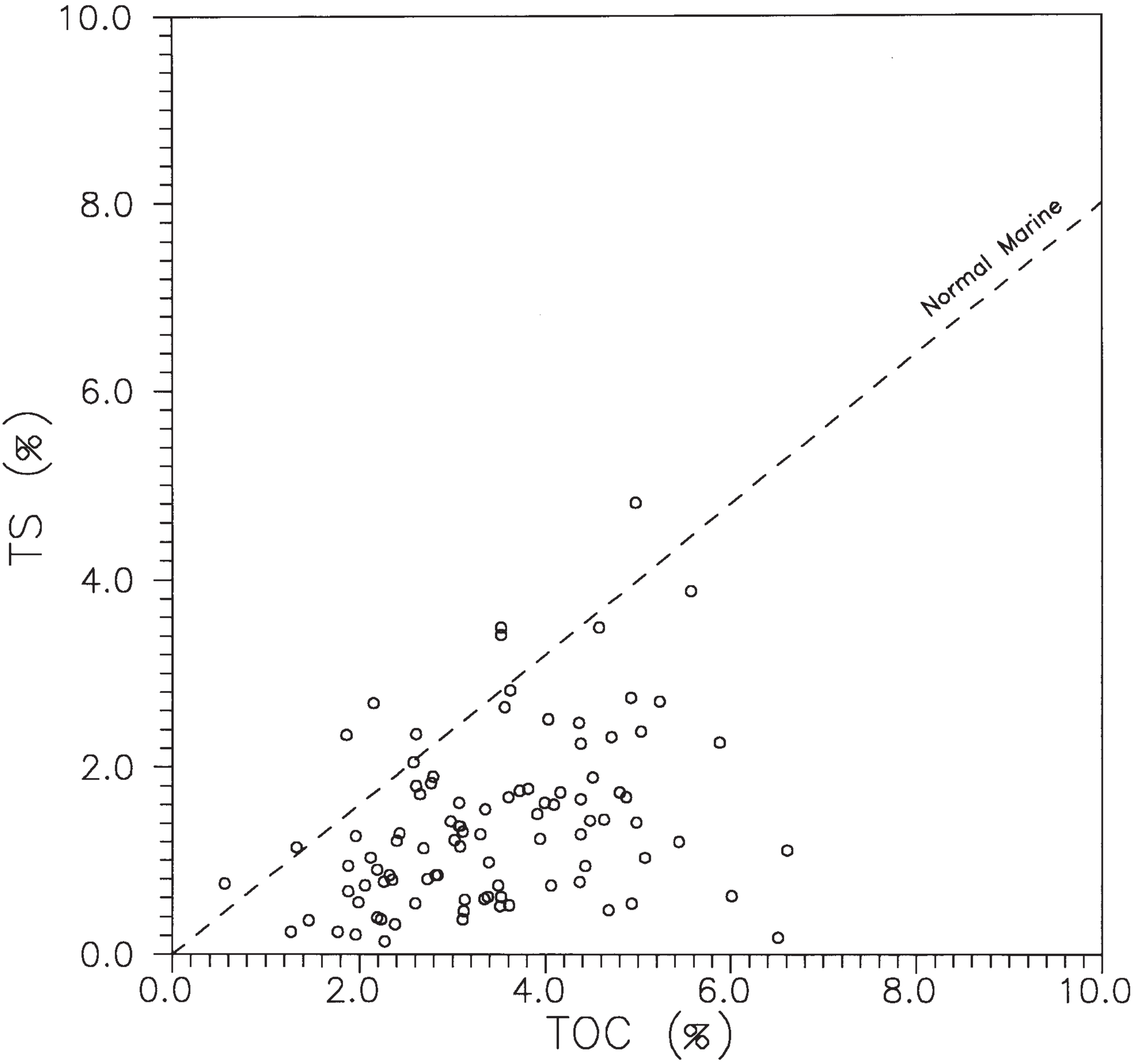
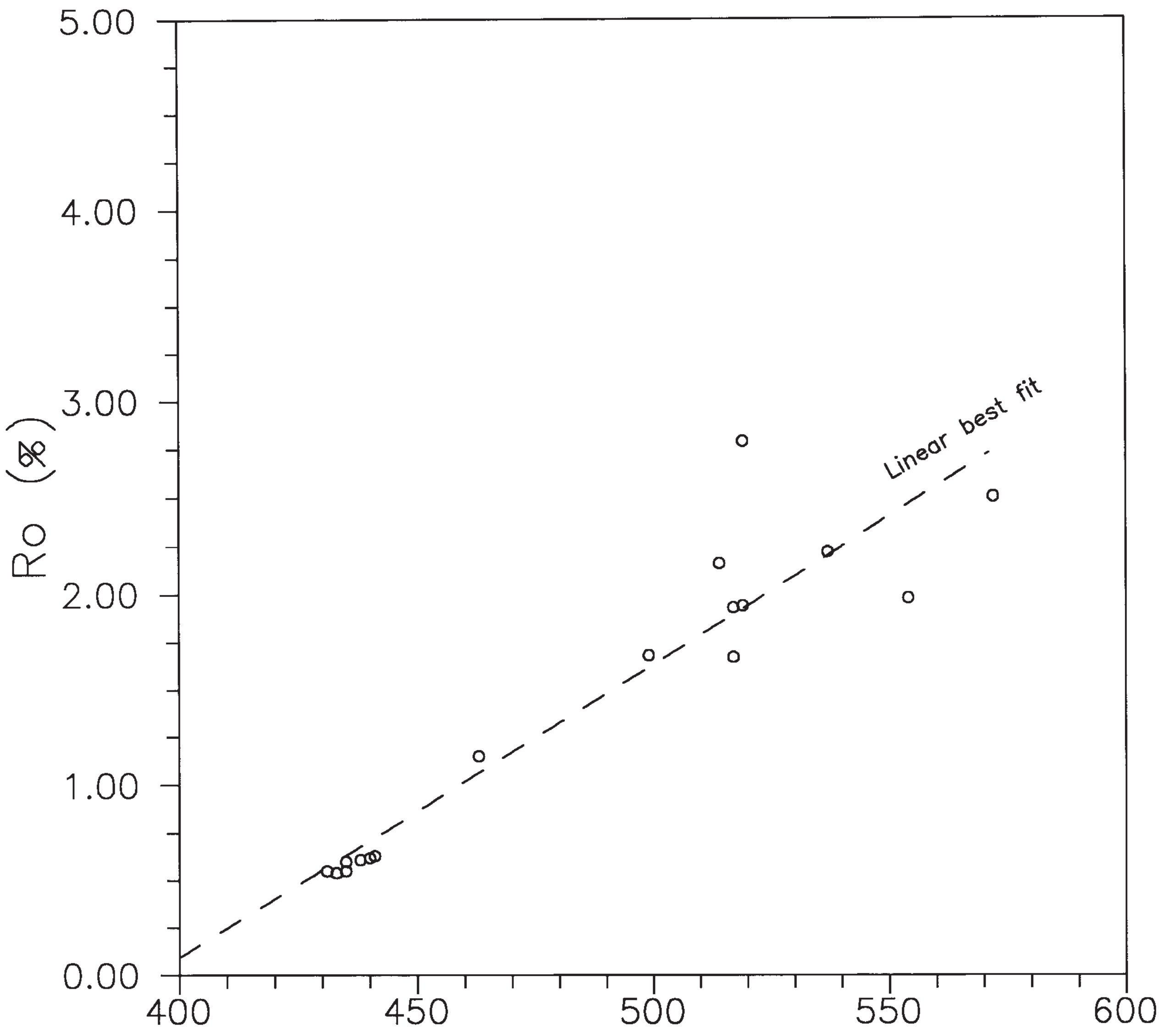


Fig. 6



5.00
4.00
3.00
2.00
1.00
0.00
Ro (%)
400
450
500
550
600
Tmax
Linear best fit

Fig. 7

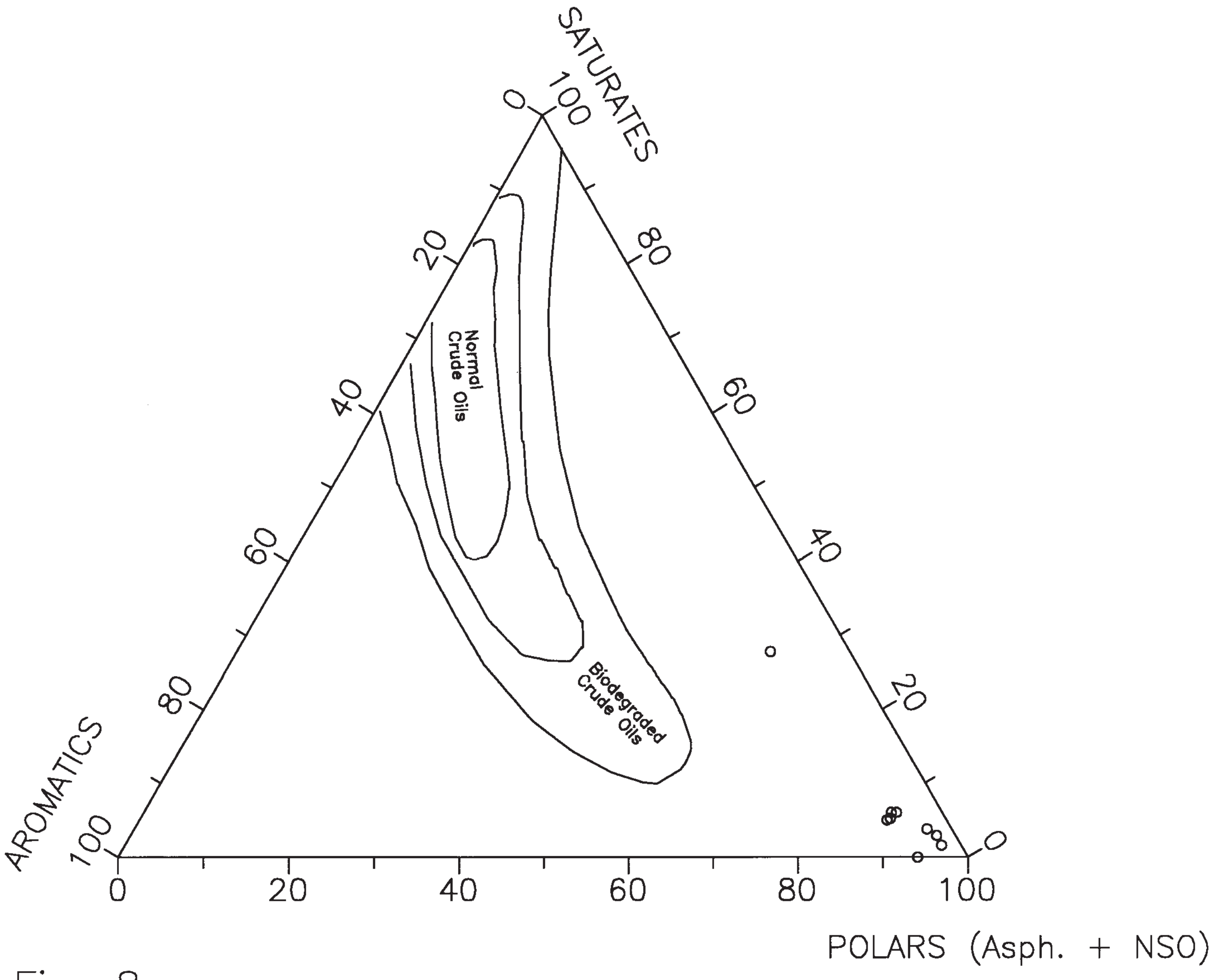

SATURATES
AROMATICS
POLARS (Asph. + NSO)
Normal Crude Oils
Biodegraded Crude Oils
0
20
40
60
80
100

Fig. 8

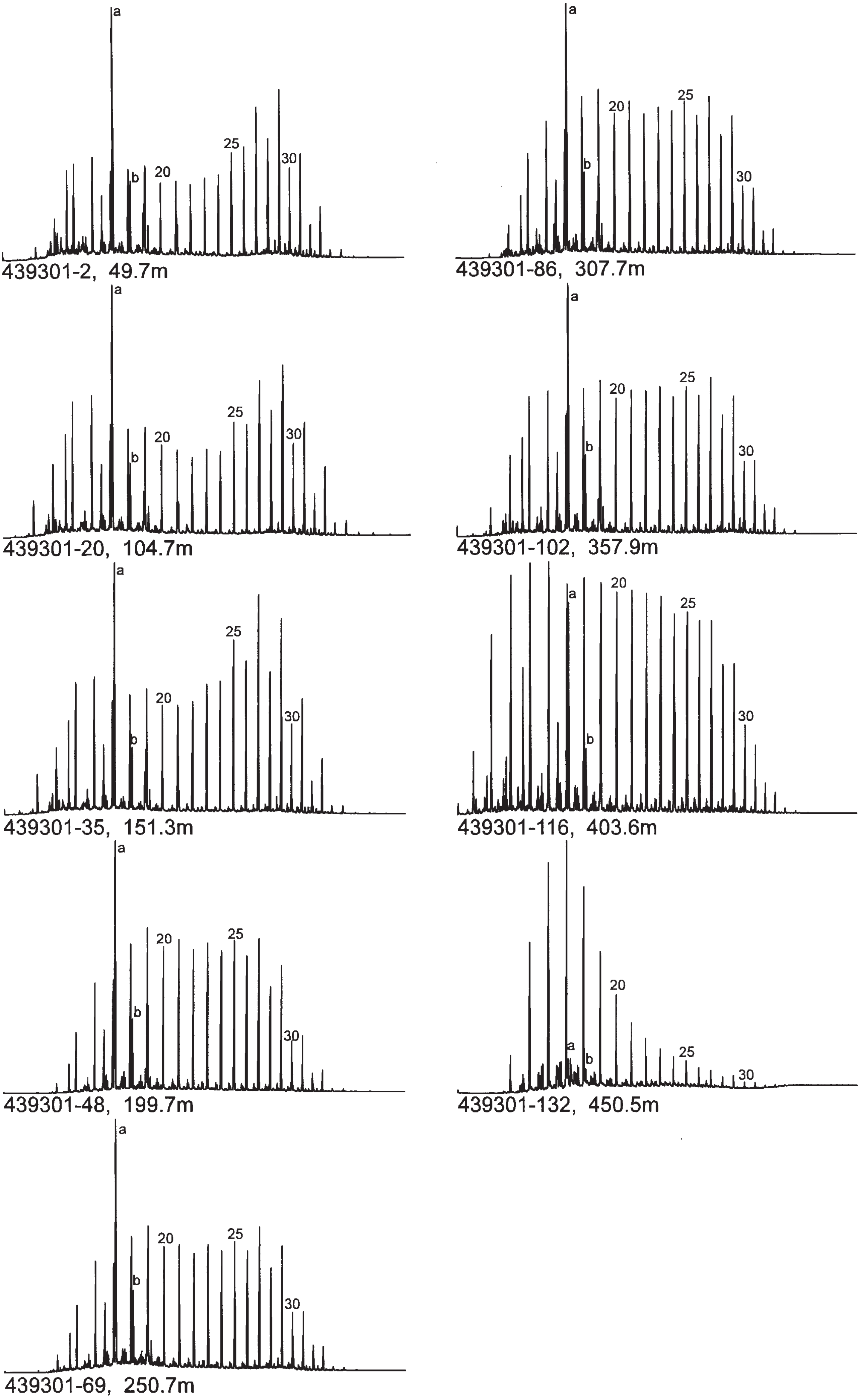
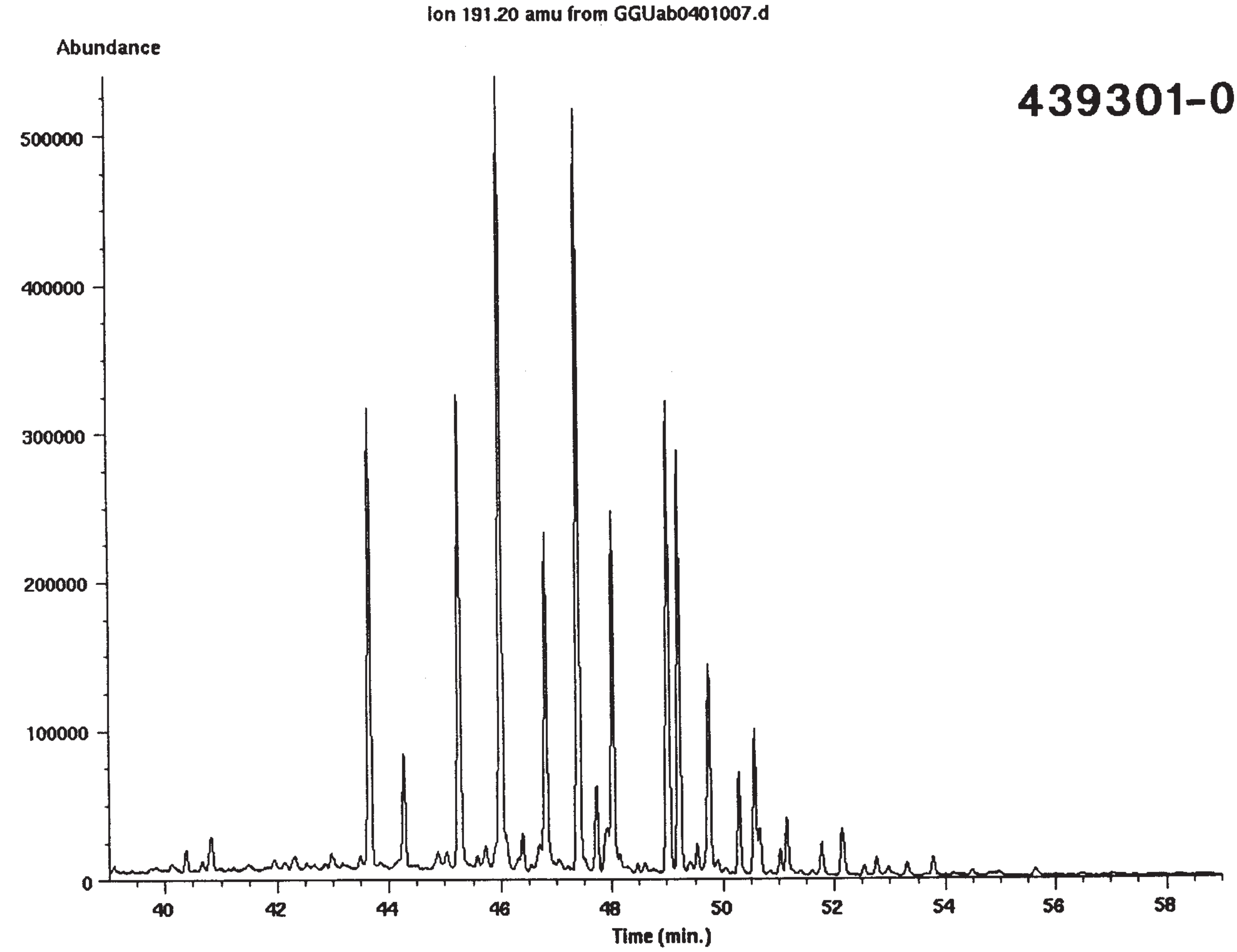

a
b
20
25
30
439301-2, 49.7m
439301-20, 104.7m
439301-35, 151.3m
439301-48, 199.7m
439301-69, 250.7m
439301-86, 307.7m
439301-102, 357.9m
439301-116, 403.6m
439301-132, 450.5m

Fig. 9

439301-02



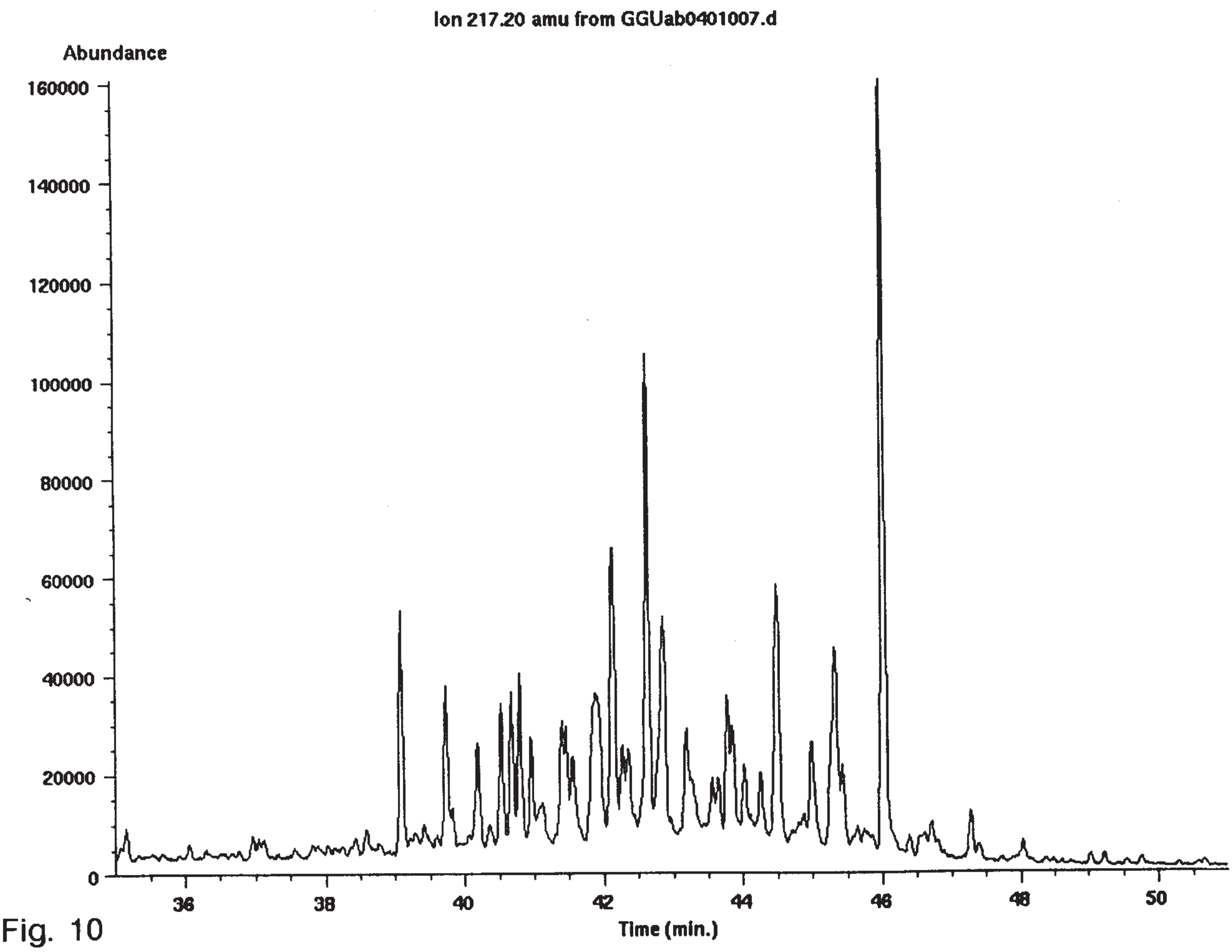
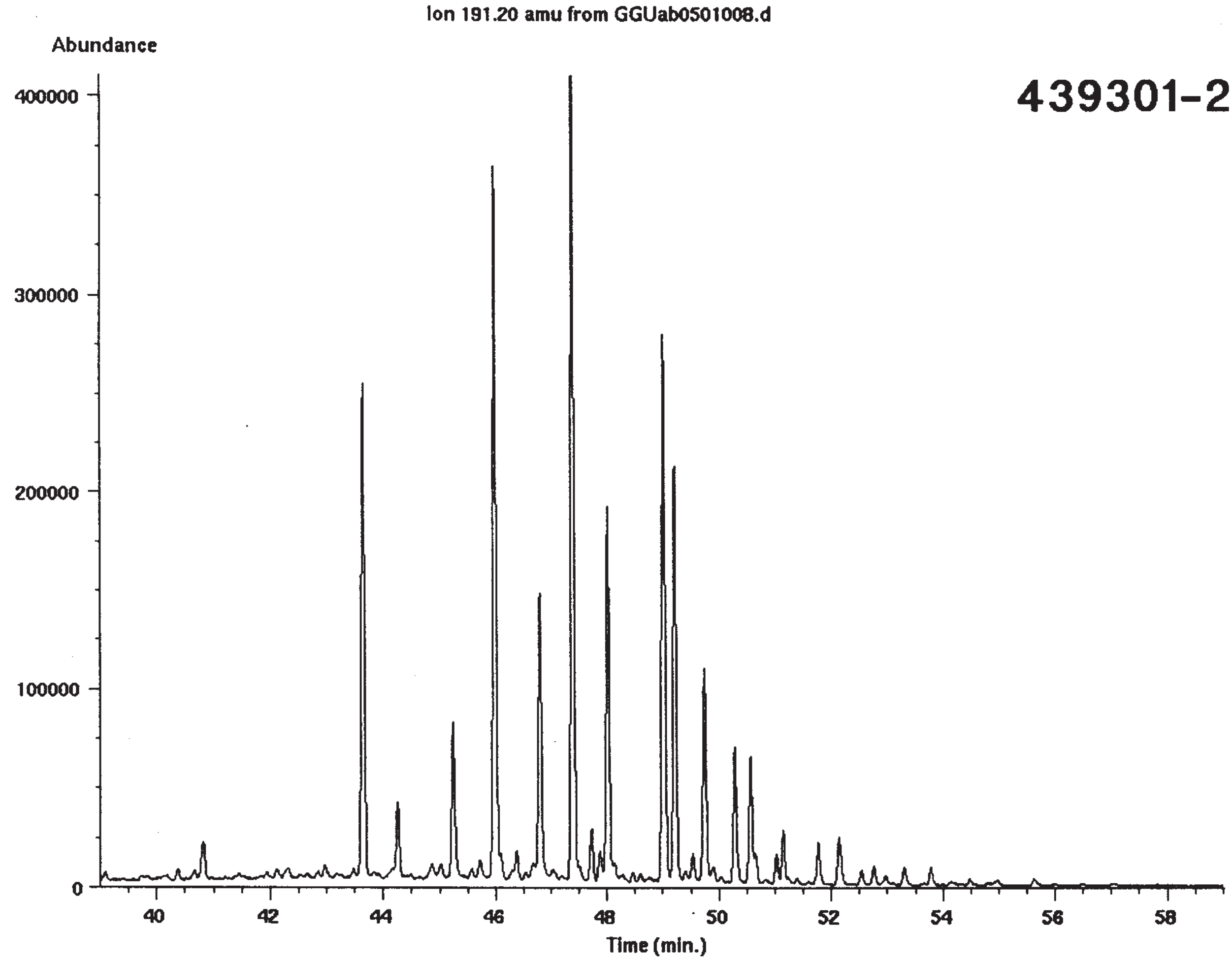


Fig. 10



439301-20

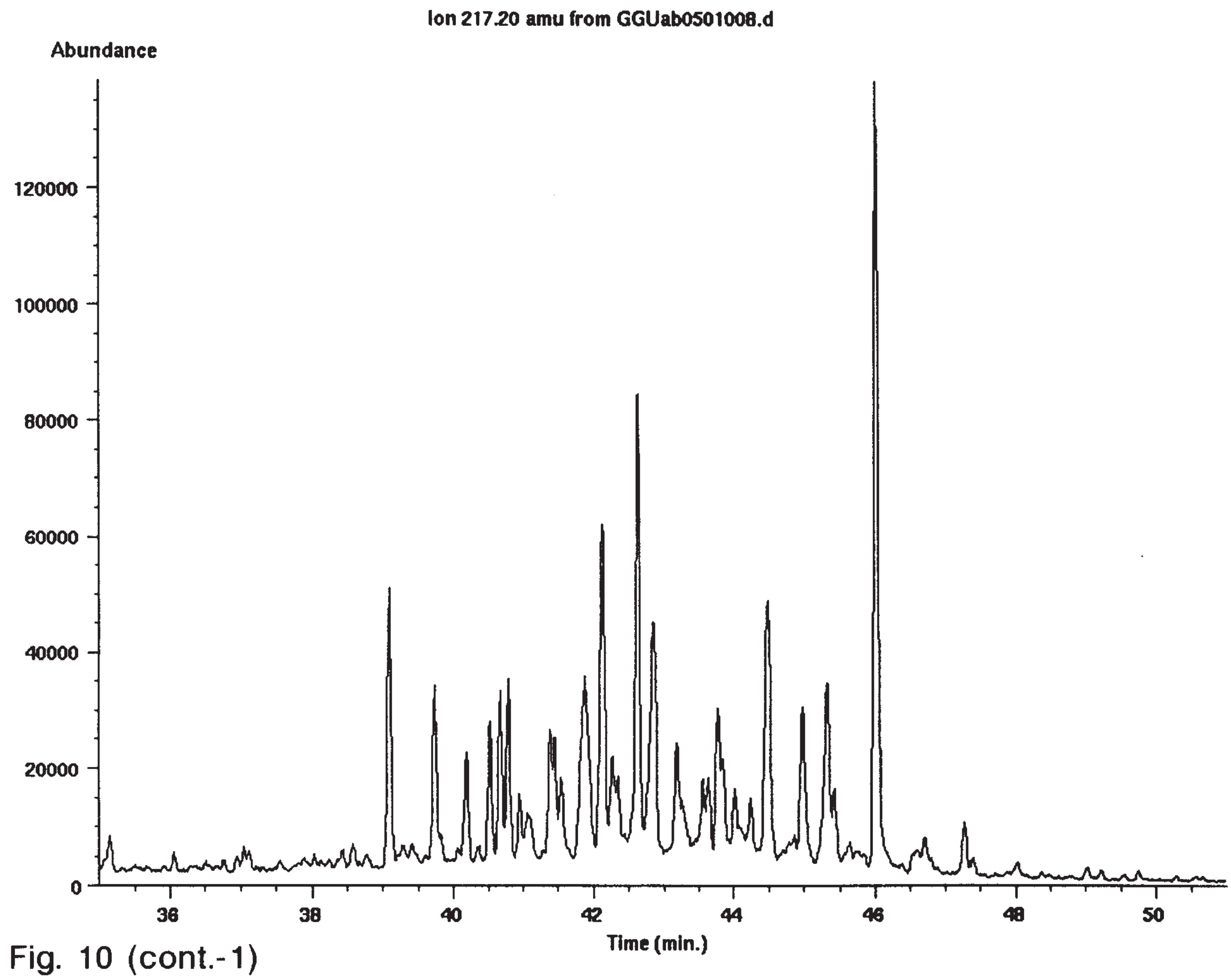
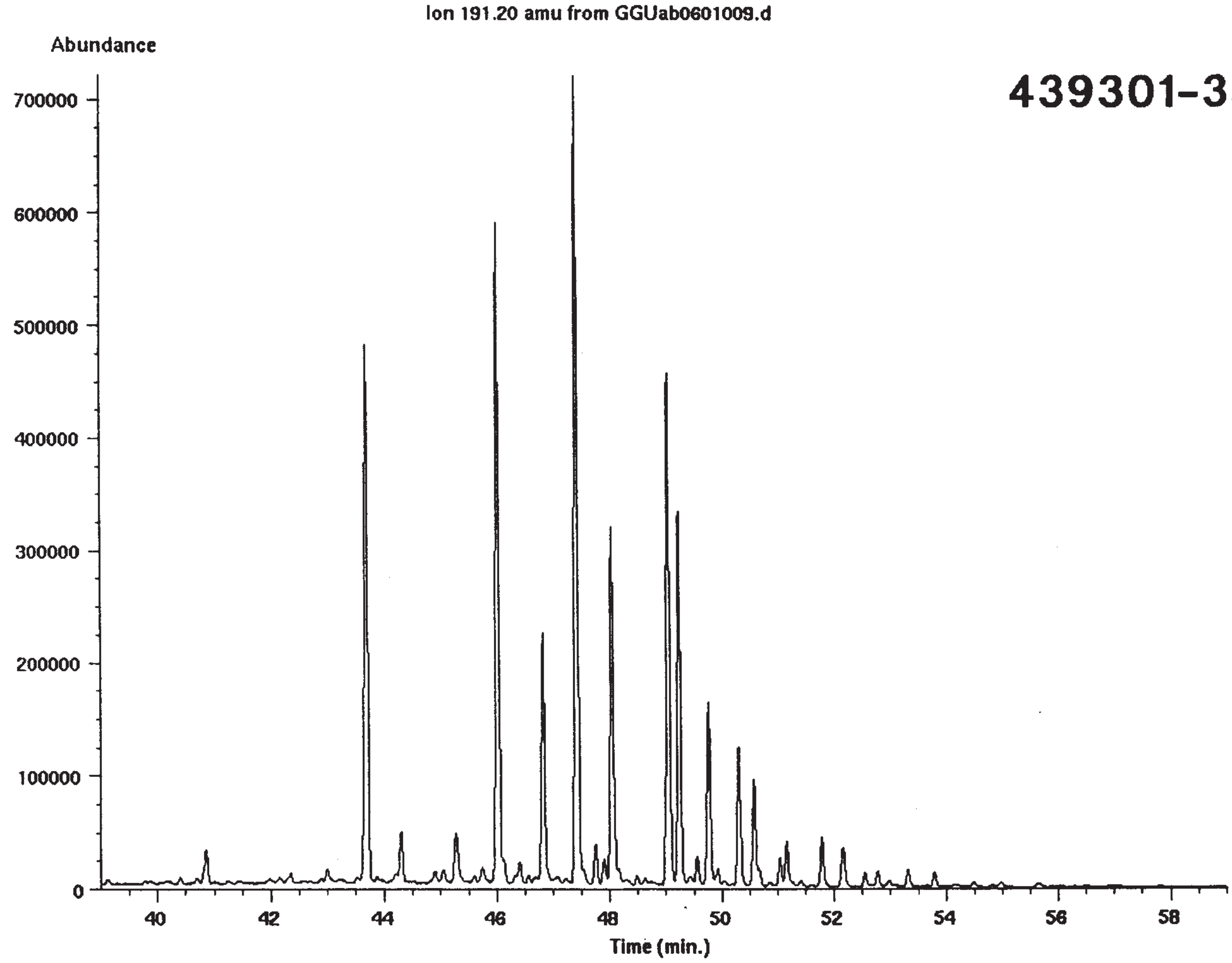


Fig. 10 (cont.-1)

439301-35



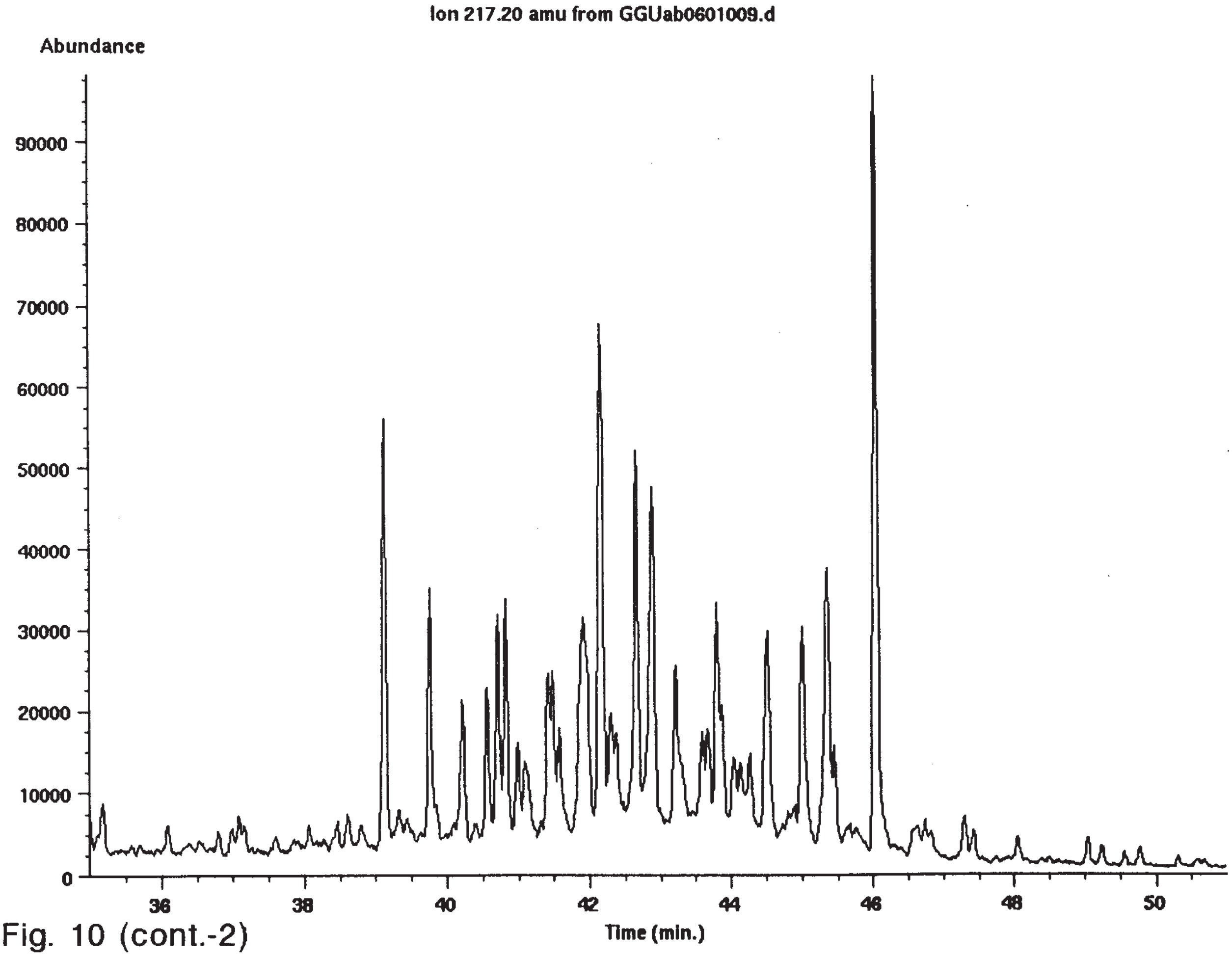
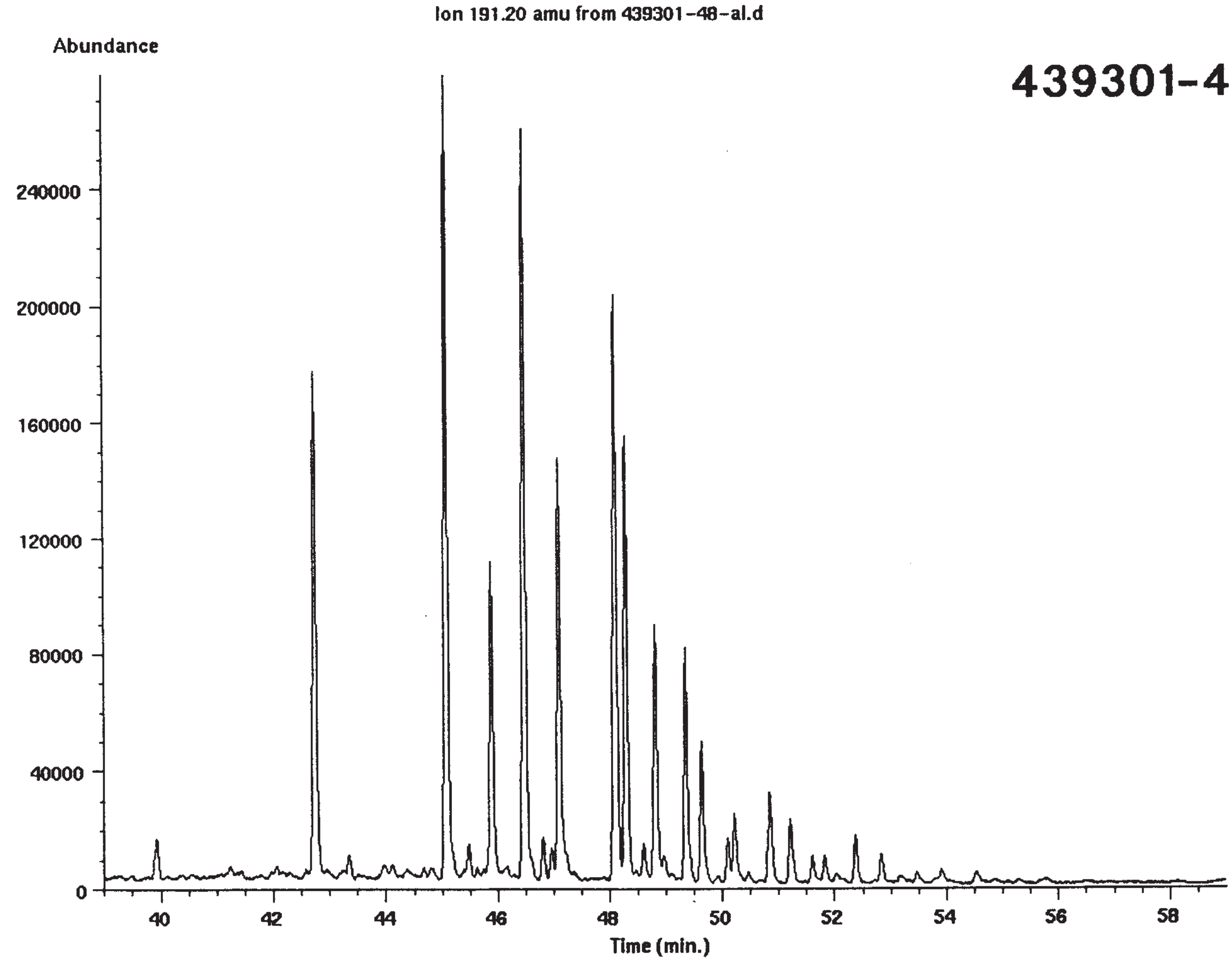


Fig. 10 (cont.-2)

439301-48



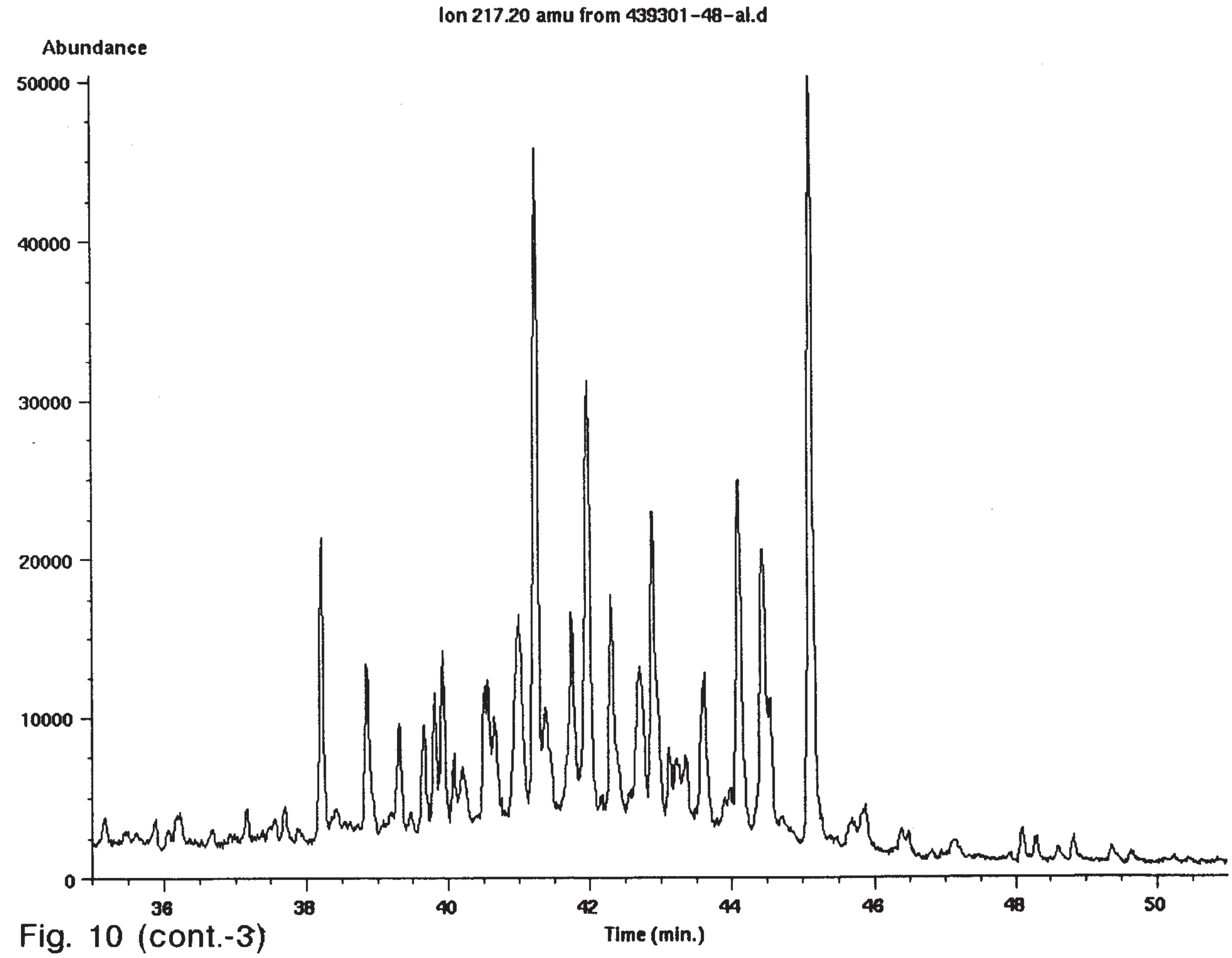
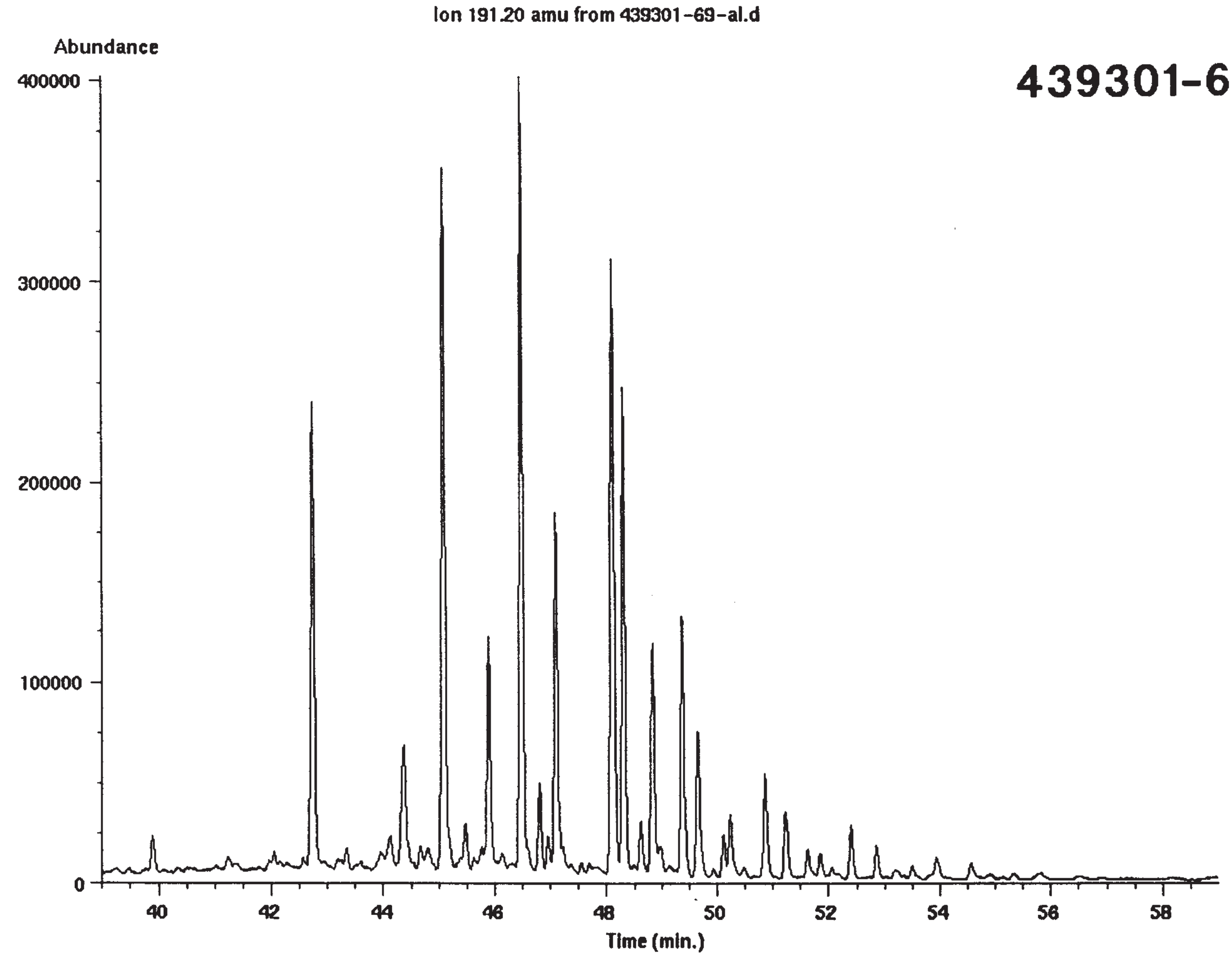


Fig. 10 (cont.-3)

439301-69



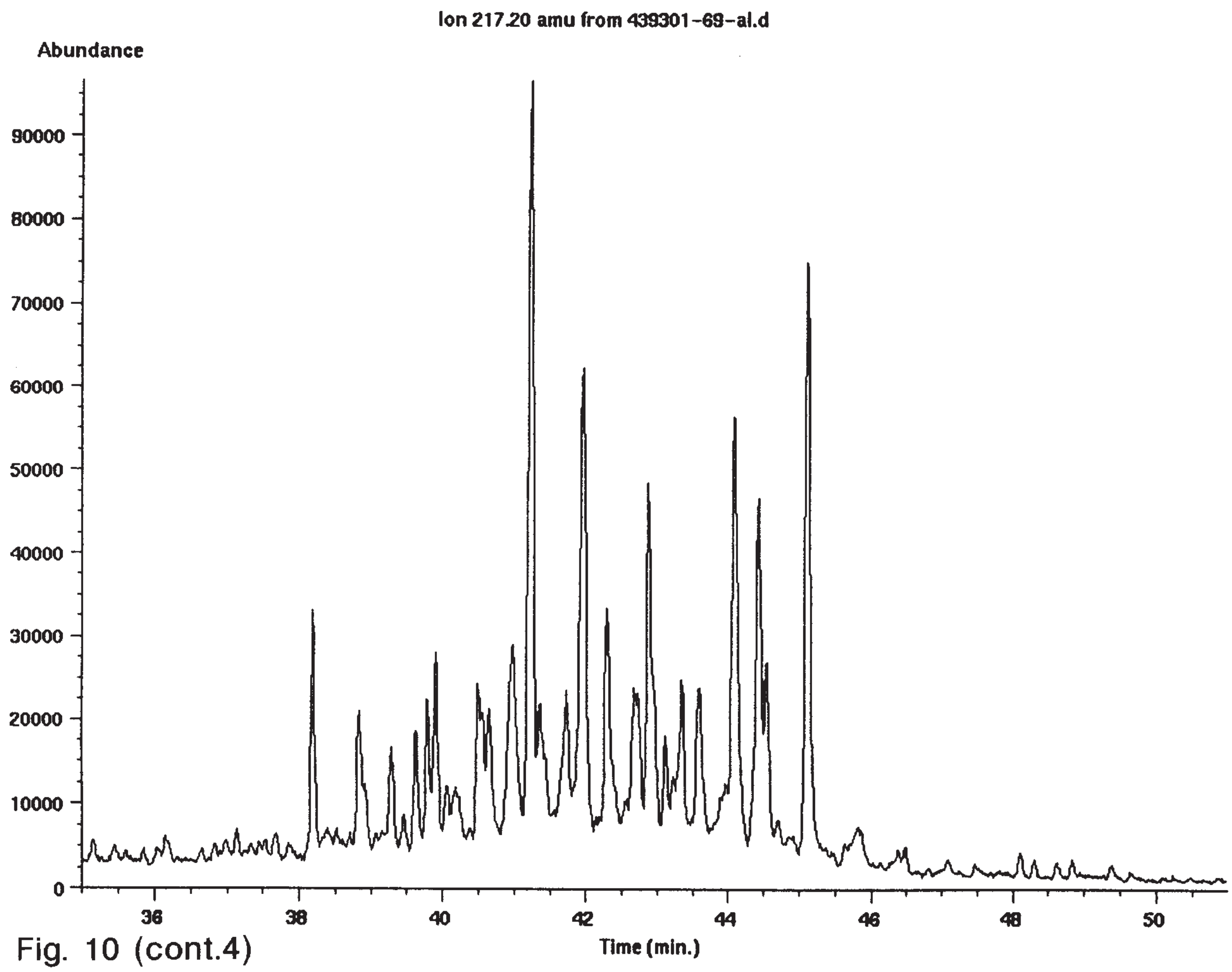
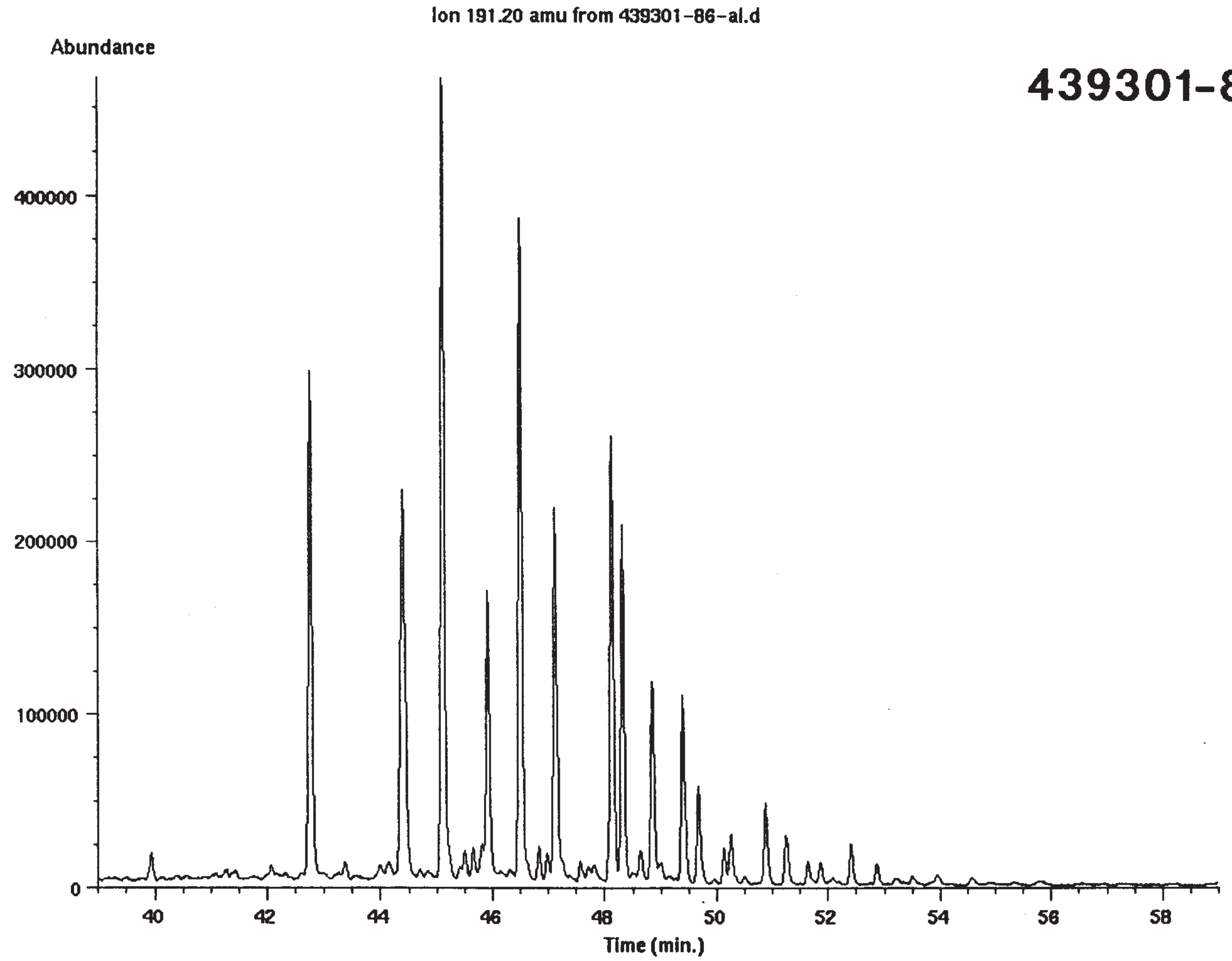


Fig. 10 (cont.4)

439301-86



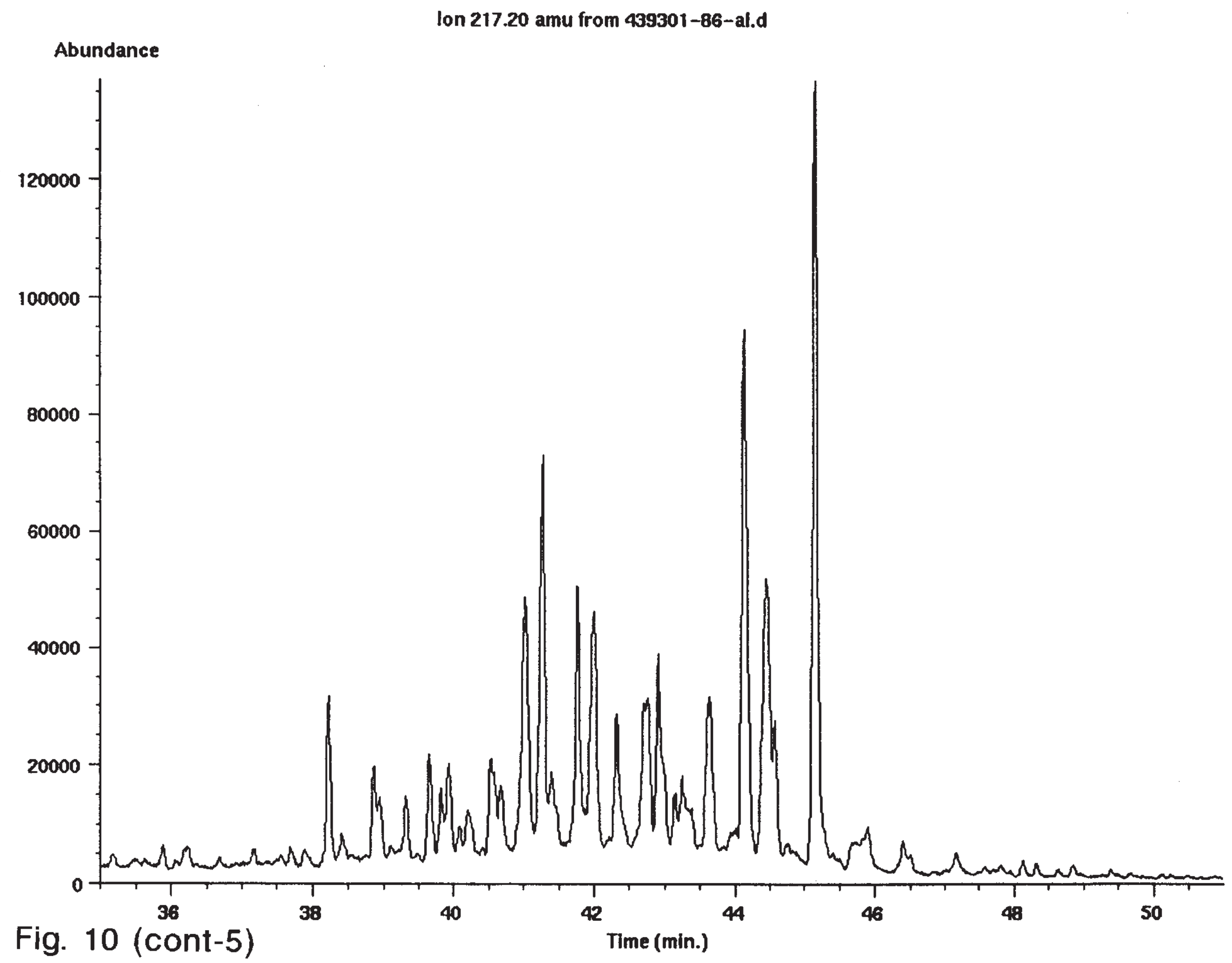
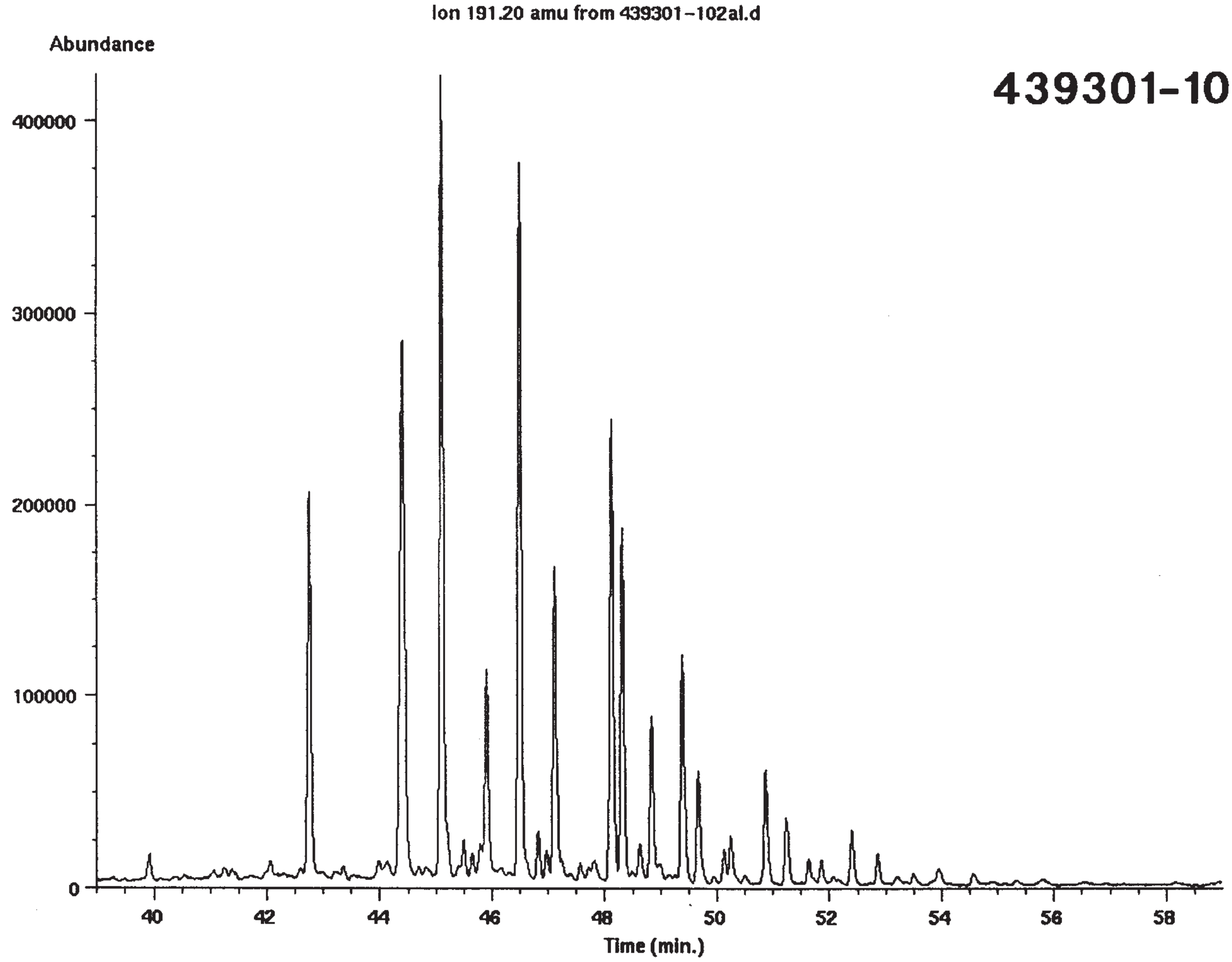


Fig. 10 (cont-5)

439301-102



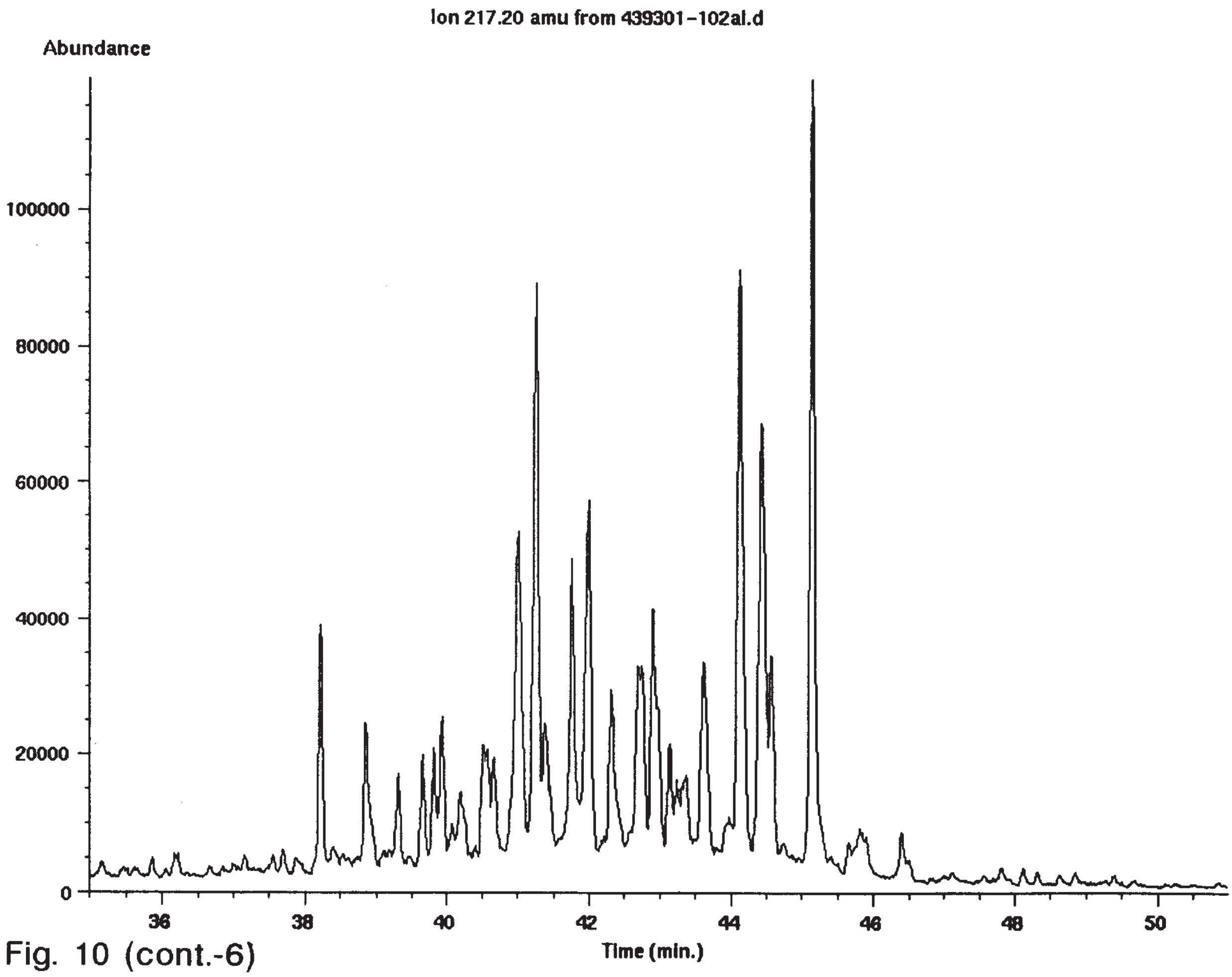
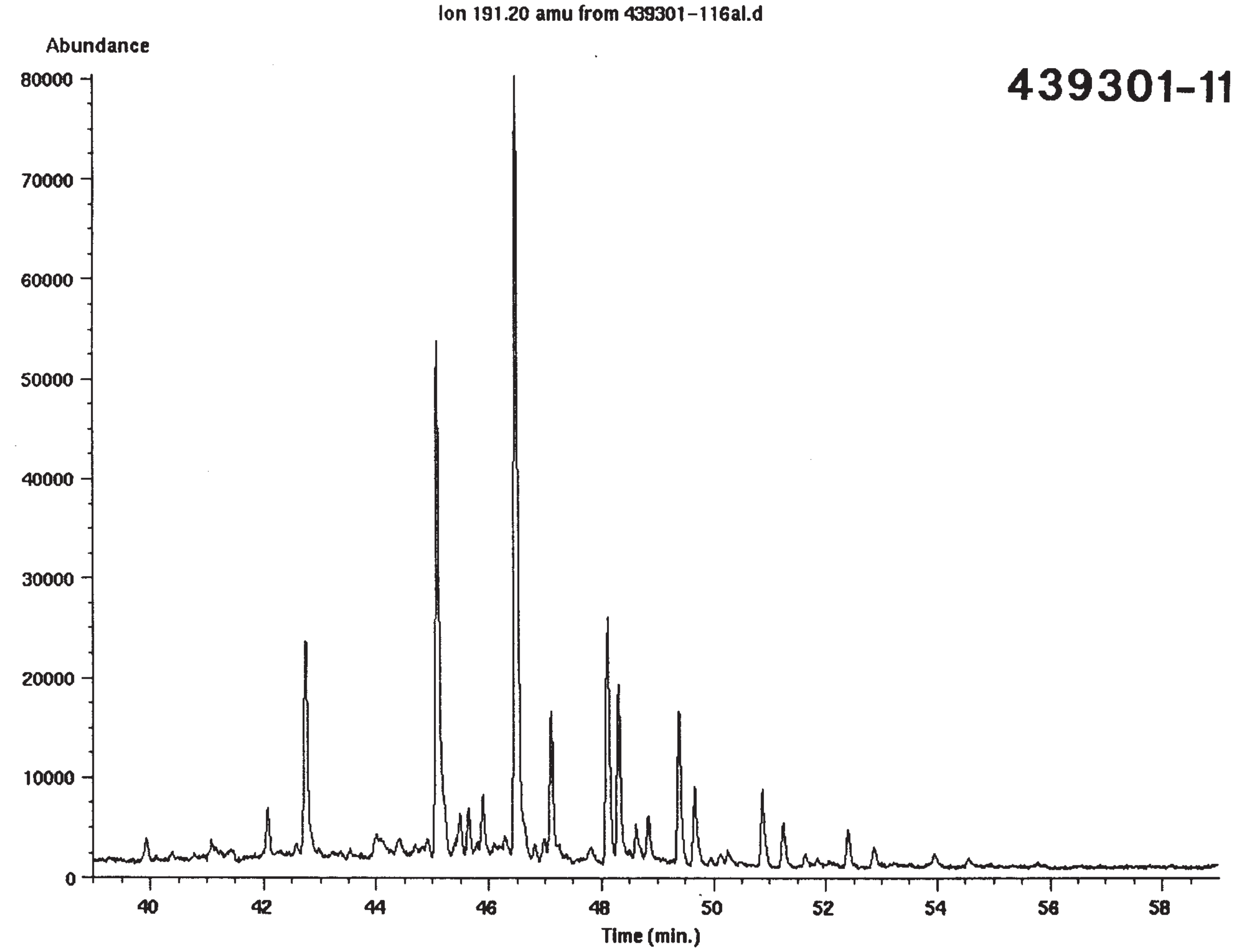


Fig. 10 (cont.-6)

439301-116



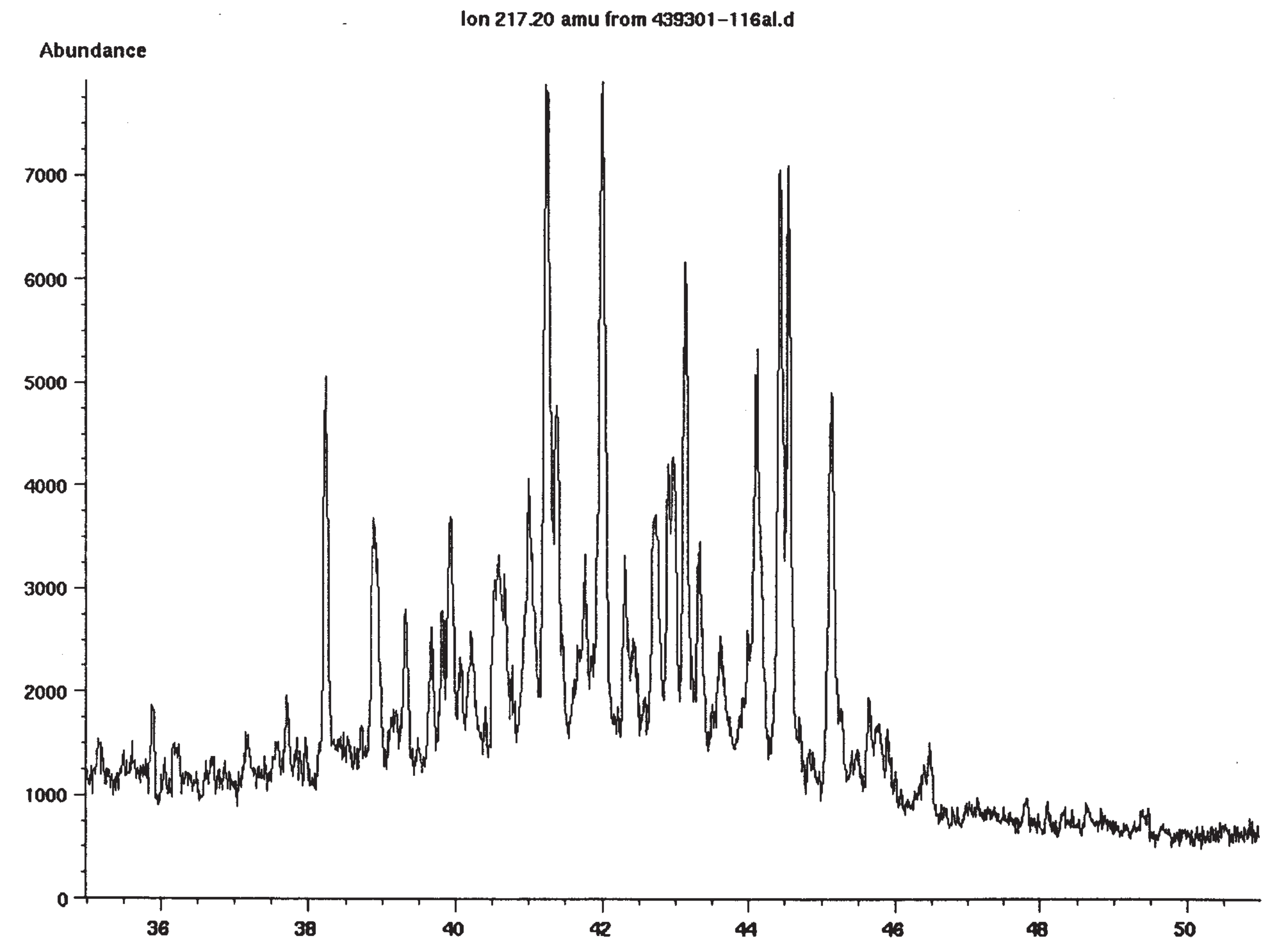
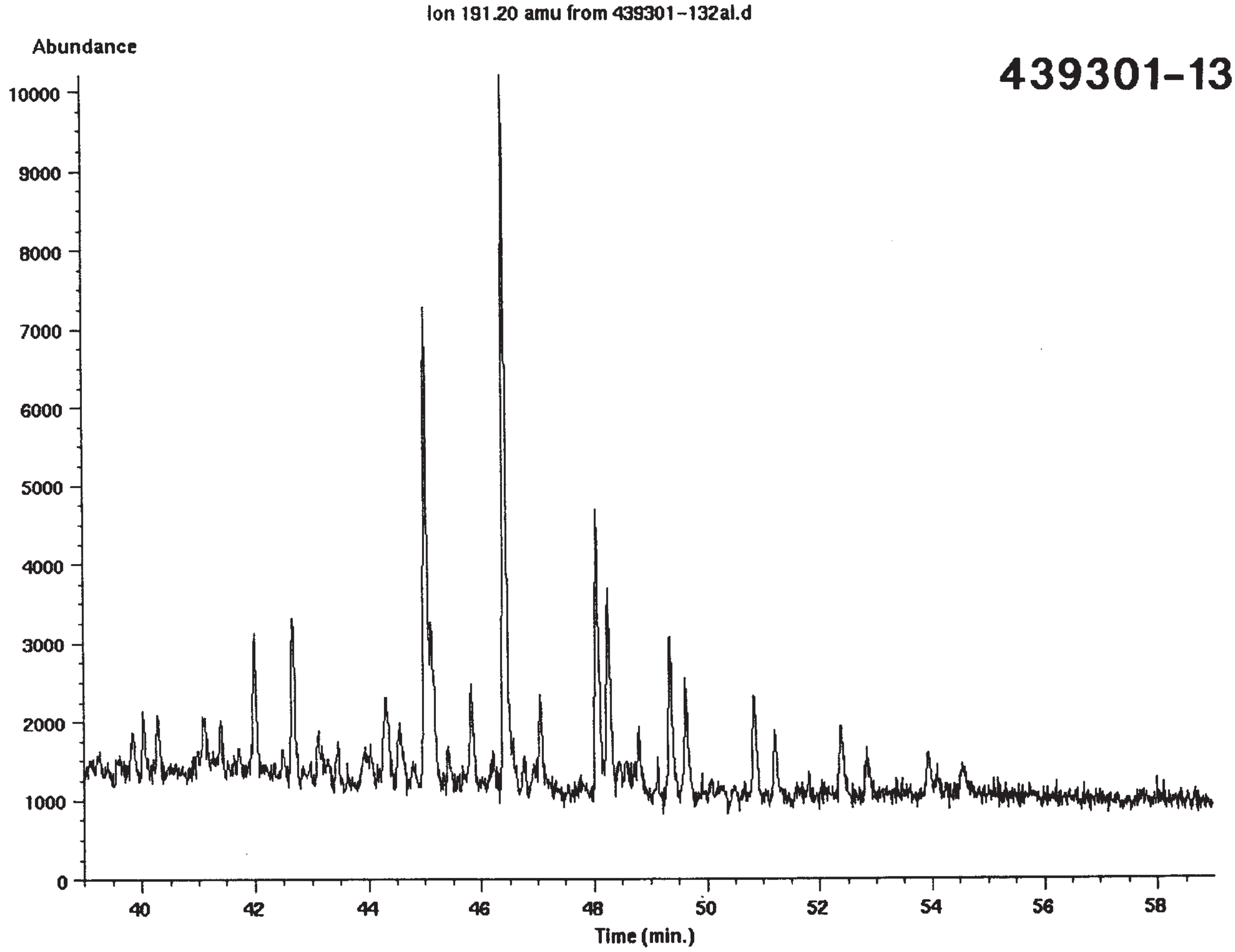


Fig. 10 (cont.-7)

439301-132



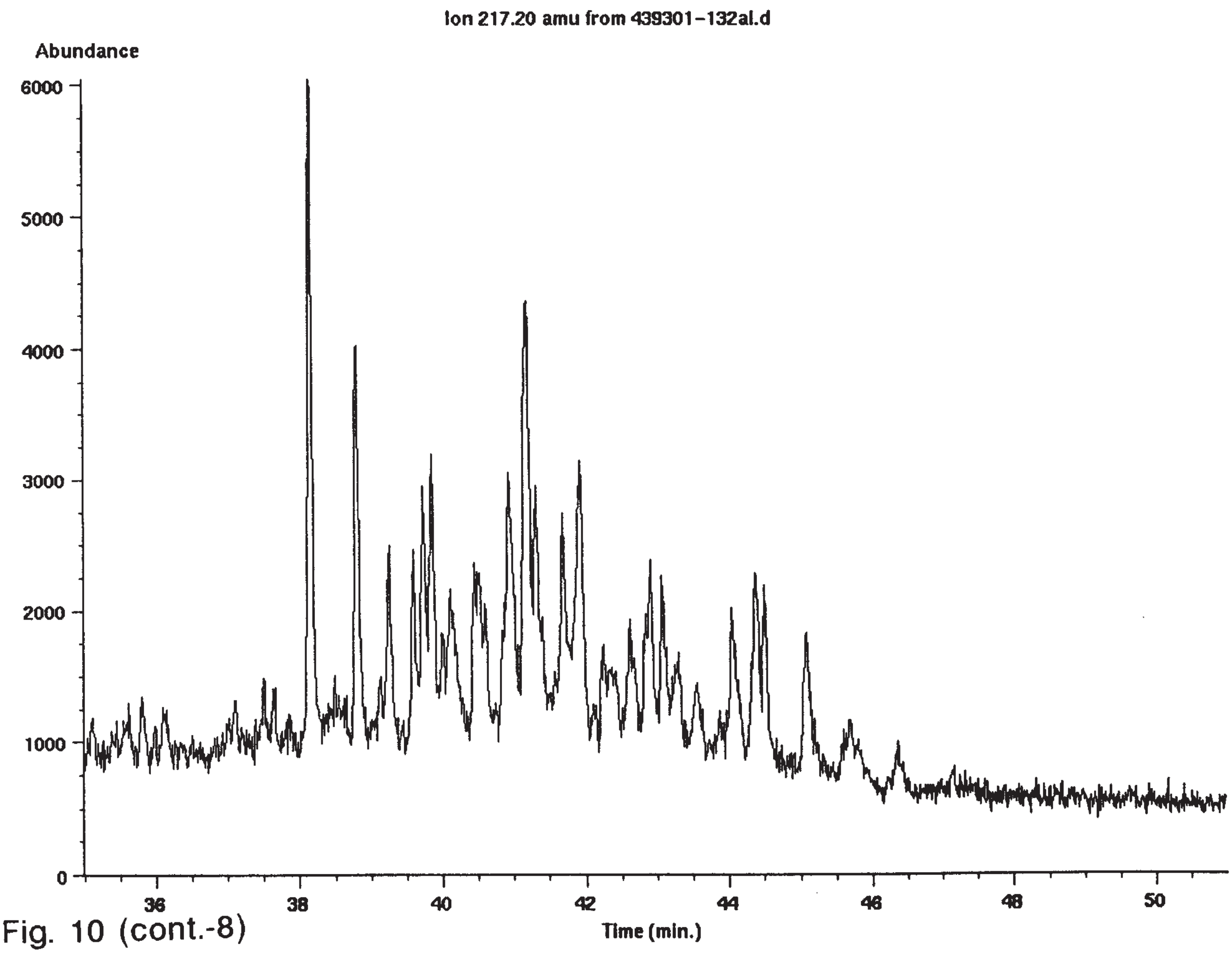
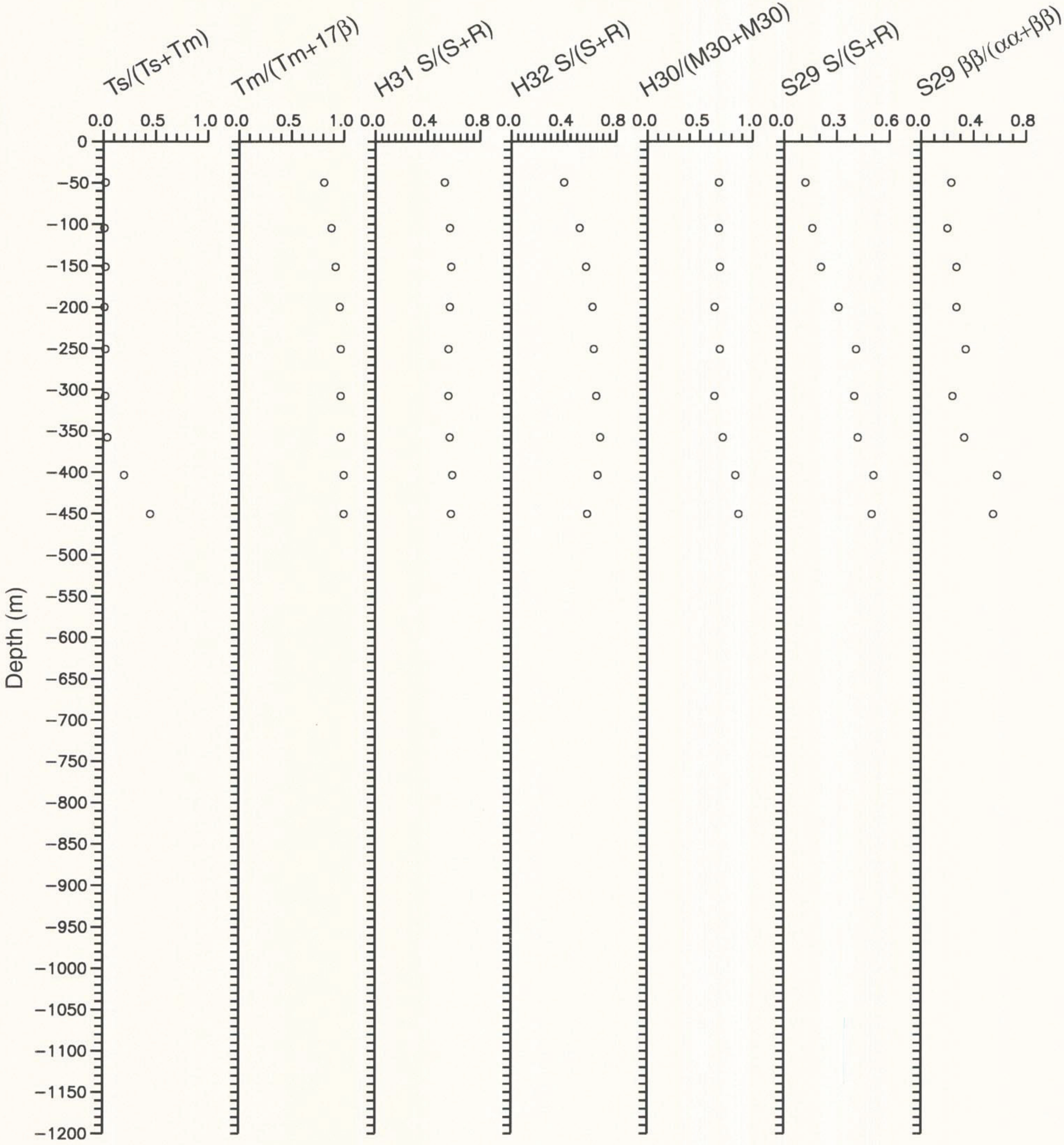
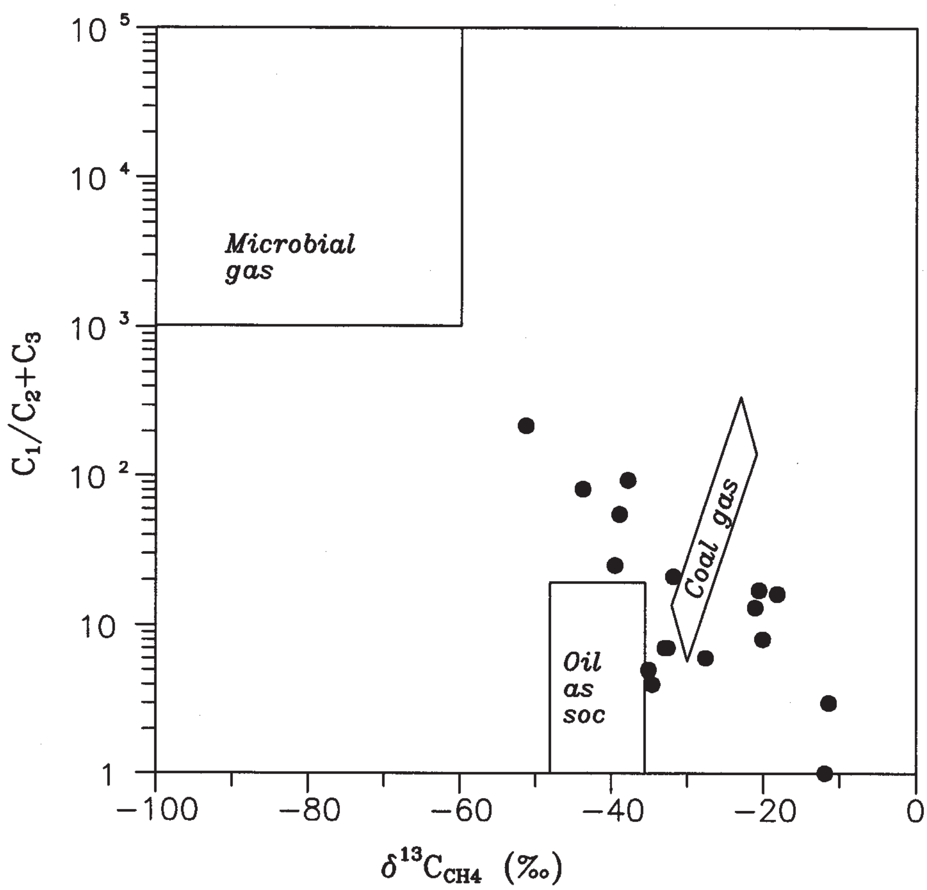


Fig. 10 (cont.-8)

Fig. 11

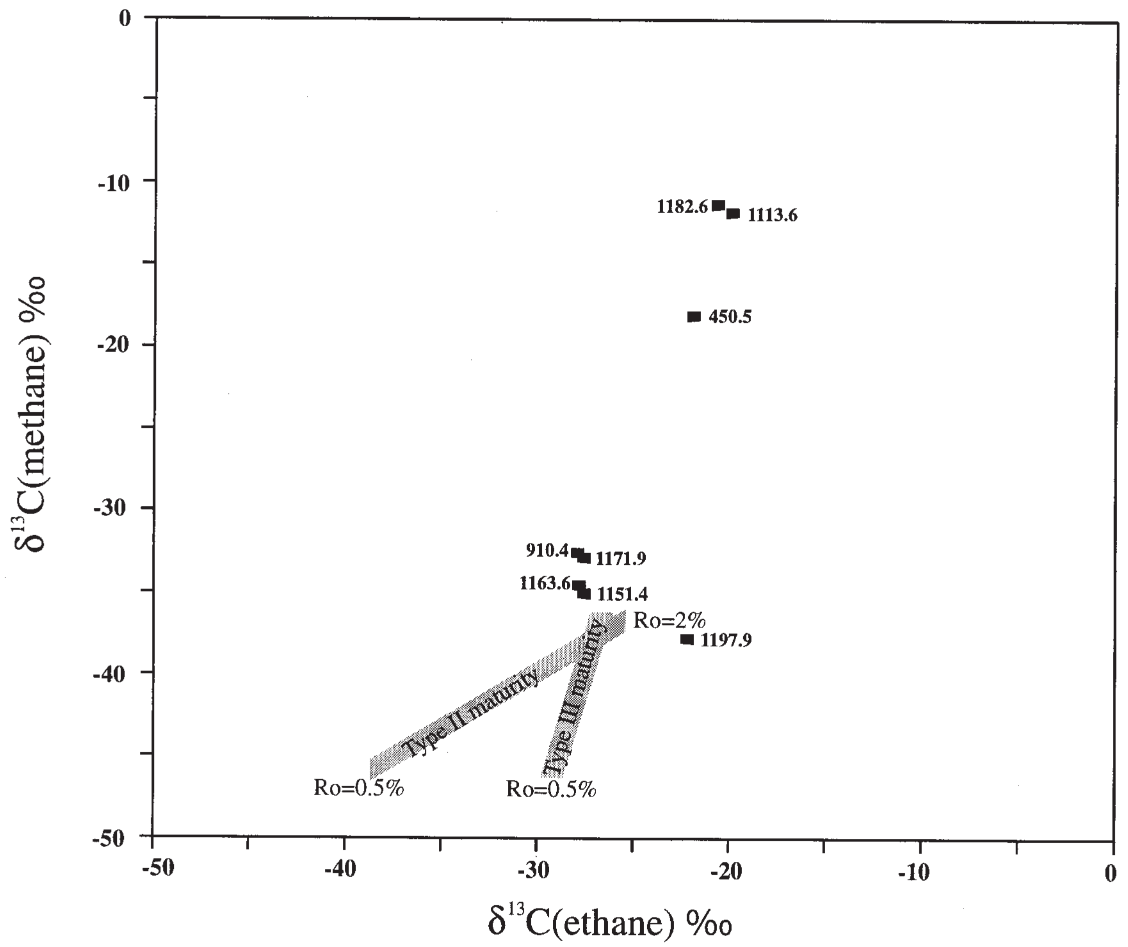
Umiivik-1
1:5000





10^5
10^4
10^3
10^2
10
1
C_1/C_2+C_3
Microbial gas
Coal gas
Oil as soc
−100
−80
−60
−40
−20
0
$\delta^{13}C_{CH4}$ (‰)

Fig. 12



0
-10
-20
-30
-40
-50
-50
-40
-30
-20
-10
0
δ13C(methane) ‰
δ13C(ethane) ‰
1182.6
1113.6
450.5
910.4
1171.9
1163.6
1151.4
Ro=2%
1197.9
Type II maturity
Type III maturity
Ro=0.5%
Ro=0.5%

Fig. 13a

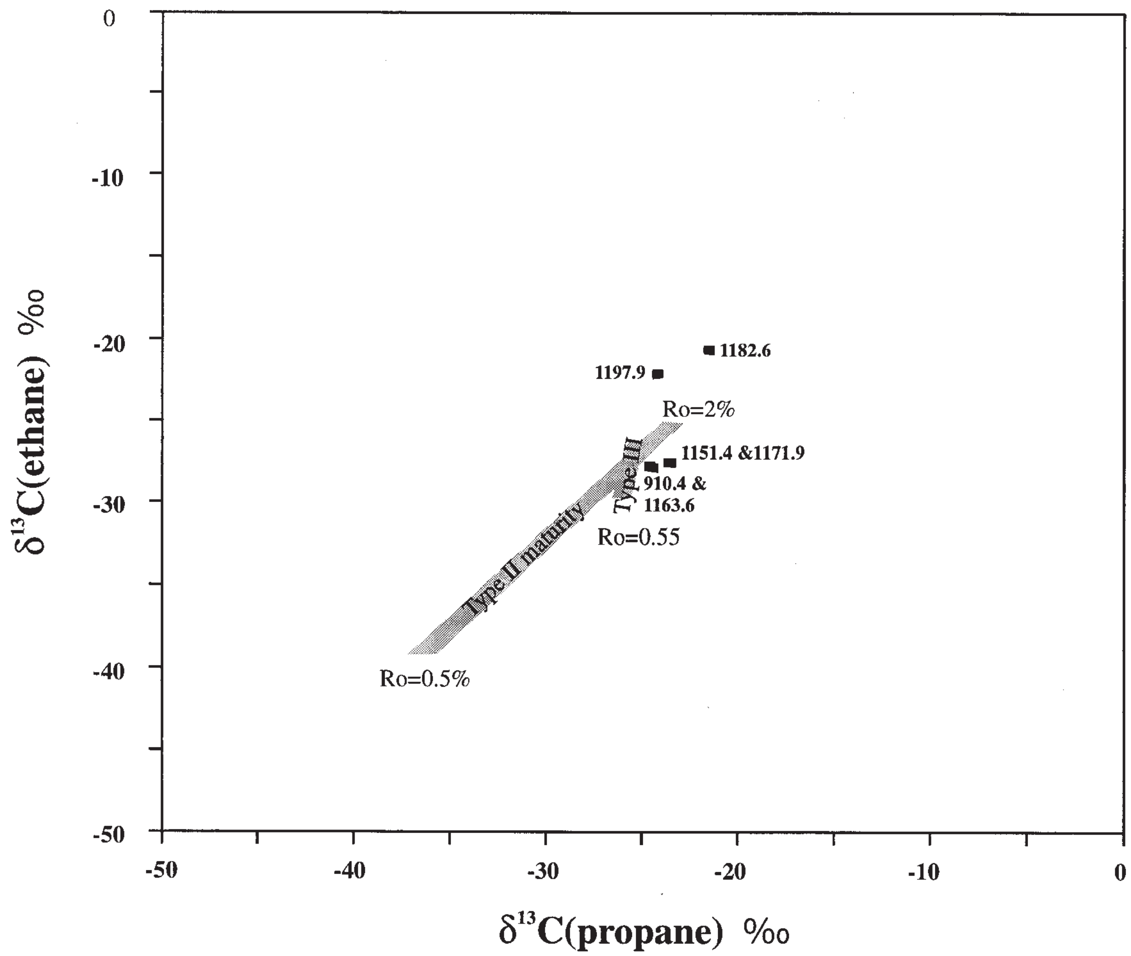

0
-10
-20
-30
-40
-50
-50
-40
-30
-20
-10
0
δ13C(ethane) ‰
δ13C(propane) ‰
1182.6
1197.9
Ro=2%
1151.4 &1171.9
910.4 &
1163.6
Type III
Type II maturity
Ro=0.55
Ro=0.5%

Fig. 13b

Table 1. Pertinent well data for Umiivik-1

Well name:	Umiivik-1
Operator:	Goverment of Greenland, Minerals Office turnkey contract with grønArtic Energy Inc., Calgary, Canada
Drilling Contractor:	Petro Drilling Ltd., Halifax, Nova Scotia, Canada
Locality:	Svartenhuk Halvø, West Geenland
Co-ordinates:	71°36´42´´N. 54°02´31´´W
Elevation:	~5 m a. s. l.
Well spud date:	21 August 1995
Termination:	13 September 1995
Rig released:	15 September 1995
Total depth:	1200 m. ~ 100% recovery
Rig type:	Longyear fly-in 50 diamond core drill, adapted mining rig
Hole diameter:	0–148 m: 96.0 mm (NQ rods), 148–1200 m: 75.8 mm (NQ rods)
Core diameter:	0–148 m: 63.5 mm, 148–1200 m: 47.6 mm
Status:	Plugged and abandoned
Main target:	Stratigraphic well with the main aim to demonstrate a Cenomanian – Turonian marine source rock for oil
Formation drilled:	Upper Cretaceous marine mudstones (1200 m) with occasional Tertiary intrusions
Hydrocarbons:	Gas bleeding from core within mudstone sections

Table 2. Screening data, **Core 439301 (Umiivik-1)**

Depth	GEUS No	TOC(%)	TS(%)	S_1	S_2	HI	T_{max}(°C)	R_0(%)	n
49.7m	-2	3,81	1,77	0,18	5,18	136	431	0,55	78/92
60.1m	-5	3,62	2,82	0,23	4,94	136	427		
71.4m	-9	2,61	1,8	0,62	1,22	47*	449*		
80.6m	-12	2,82	0,84	0,38	0	0*	n.d*		
90.3m	-15	3,72	1,75	0,17	3,78	102	431		
99.8m	-19	3,34	0,59	0,09	2,79	83	429		
104.7m	-20	3,6	1,68	0,17	4,72	131	435	0,55	72/75
110.5m	-22	3,61	0,52	0,16	3,8	105	430		
120.3m	-25	3,07	1,62	0,13	2,65	86	429		
129.5m	-28	3,35	1,55	0,1	2,4	72	430		
139.3m	-31	4,06	0,73	0,07	2,57	63	428		
151.3m	-35	2,6	0,54	0,12	1,84	71	433	0,54	57/60
153.6m	-36	5,03	2,38	0,12	4,94	98	430		
160.2m	-38	3,08	1,15	0,08	2,49	81	429		
169.5m	-41	4,51	1,89	0,16	4,72	105	429		
187.9m	-46	6,61	1,11	0,3	6,63	100	432		
193.4m	-47	1,46	0,36	0,01	0,25	17	435		
199.7m	-48	5,88	2,26	0,26	5,36	91	438	0,61	48/60
214.8m	-52	5,57	3,88	0,25	6,14	110	438		
229.5m	-60	4,38	2,25	0,21	4,36	100	436		
241.7m	-64	3,99	1,62	0,21	3,6	90	438		
250.7m	-69	3,13	0,58	0,18	2,27	72	435	0,6	55/60
261.3m	-70	4,93	0,54	0,3	5,86	119	436		
264.8m	-72	6,51	0,18	0,79	0,48	7*	565*		
271.4m	-74	6,01	0,62	0,34	6,32	105	436		
277.6m	-76	4,97	4,81	0,3	6,21	125	434		
283.3m	-78	2,43	1,29	0,18	2,02	83	439		
289.7m	-80	4,48	1,43	0,14	2,5	56	434		
296.4m	-82	3,91	1,5	0,3	5,1	130	436		
301.7m	-84	4,98	1,41	0,22	4,11	83	433		
307.7m	-86	4,87	1,68	0,31	4,76	98	440	0,62	53/63
319.2m	-90	4,8	1,73	0,36	5,86	122	436		
331.9m	-94	4,37	0,77	0,34	4,28	98	435		
344.7m	-98	4,63	1,44	0,39	4,13	89	439		
357.9m	-102	4,36	2,47	0,43	5,34	122	441	0,63	53/63
364.3m	-104	4,38	1,28	0,43	3,3	75	437		
371.0m	-106	5,07	1,03	0,34	3,77	74	437		
377.4m	-108	4,71	2,32	0,44	3,66	78	440		
383.8m	-110	4,16	1,73	0,43	3,27	79	439		
391.6m	-112	5,44	1,2	0,51	3,61	66	455*		
397.2m	-114	4,43	0,94	0,39	2,43	55	446*		
403.6m	-116	4,03	2,51	0,75	2,72	68	463*	1,15	42/61
408.5m	-118	3,02	1,22	0,46	0,42	14*	540*		

n.d: not defined

* elevated value due to thermal effect of dykes and sills or occasionally hydrothermal solutions (omitted from calculations)

Continued at next page

Table 2. Screening data, **Core 439301 (Umiivik-1) continued**

Depth	GEUS No	TOC(%)	TS(%)	S_1	S_2	HI	T_{max}(°C)	R_0(%)	n
414.7m	-120	4,92	2,74	0,28	0	0*	n.d.*		
440.4m	-128	4,58	3,49	0,11	0,13	3*	546*		
450.5m	-132	3,52	3,49	0,24	0,32	9*	514*	2,16	101/101
463.9m	-136	3,52	3,41	0,07	0	0*	n.d.*		
476.7m	-140	3,52	0,61	0,04	0	0*	n.d.*		
516.3m	-152	5,23	2,7	0,03	0,21	4*	518*		
540.3m	-160	1,86	2,34	0,26	0,16	9*	565*		
633.5m	-188	2,58	2,05	0,13	0,01	0*	507*		
645.2m	-192	4,09	1,6	0,11	0,1	2*	519*	2,79	100/100
658.7m	-196	4,68	0,47	0,15	0,55	12*	546*		
671.5m	-200	3,3	1,28	0,14	0,26	8*	553*		
682.5m	-203	3,94	1,23	0,28	1,06	27*	533*		
687.7m	-204	3,51	0,51	0,22	0,58	17*	512*		
695.0m	-207	3,11	0,37	0,22	0,55	18*	516*		
700.1m	-208	2,38	0,32	0,16	0,49	21*	506*		
706.1m	-210	3,49	0,73	0,33	0,66	19*	524*		
707.2m	-217	3,08	1,37	0,34	0,75	24*	509*		
710.7m	-212	3,38	0,61	0,35	1,26	37*	517*	1,67	64/64
712.3m	-213	2,73	0,8	0,26	0,61	22*	507*		
721.1m	-215	3,11	1,31	0,35	0,73	24*			
727.5m	-217	3,07	1,37	0,33	0,82	27*	493*		
730.6m	-218	3,56	2,64	0,43	0,9	25*	472*		
739.0m	-221	1,27	0,24	0,12	0,1	8*	565*		
752.5m	-225	4,38	1,66	0,42	1,36	31*	499*	1,68	89/110
767.0m	-229	3,39	0,98	0,35	0,75	22*	530*		
781.4m	-233	3,12	0,46	0,24	0,56	18*	531*		
794.0m	-237	2,84	0,84	0,15	0,46	16*	554*	1,98	70/80
807.1m	-241	1,96	0,21	0,06	0,12	6*	558*		
819.9m	-245	2,06	0,73	0,02	0,18	9*	570*		
832.6m	-249	1,77	0,24	0,03	0,17	10*	534*		
895.8m	-269	0,56	0,75	0,04	0,1	18'	566*		
910.4m	-274	1,96	1,26	0,2	0,08	4*	n.d.*	4,24	100/100
1041.5m	-314	1,33	1,14	0,03	0	0*	n.d.*		
1052.5m	-318	1,88	0,67	0,06	0,04	2*	557*		
1065.6m	-322	2,27	0,14	0,1	0,04	2*	n.d.*	4,3	92/121
1078.1m	-326	1,58	20,09	0,01	0,07	4*	580*		
1084.2m	-328	2,12	1,03	0,08	0,08	4*	n.d.*		
1092.1m	-330	2,61	2,35	0,08	0,08	3*	556*		
1101.6m	-334	2,19	0,39	0,06	0,04	2*	576*		
1113.6m	-337	2,35	0,79	0,09	0,06	3*	572*	2,5	83/83
1117.7m	-338	2,69	1,13	0,06	0,04	1*	574*		
1134.4m	-342	2,65	1,71	0,1	0,06	2*	570*		
1151.4m	-346	1,88	0,94	0,21	0,46	24*	537*	2,22	72/85
1163.6m	-349	2,23	0,37	0,44	0,48	22*	527*		
1165.6m	-350	2,26	0,77	0,26	0,12	5*	538*		
1171.9m	-352	1,99	0,55	0,34	0,6	30*	517*	1,93	44/44
1177.9m	-354	2,98	1,42	0,44	0,6	20*	513*		
1182.6m	-355	2,77	1,83	0,55	0,8	29*	476*		
1184.7m	-356	2,79	1,9	0,42	0,46	16*	493*		
1191.4m	-358	2,4	1,21	0,42	0,52	21*	482*		
1194.0m	-359	2,19	0,9	0,34	0,34	16*	507*		
1197.9m	-360	2,32	0,84	0,35	0,64	28*	519*	1,94	55/55
1199.7m	-361	2,15	2,68	0,22	0,06	3*	544*		

Table 3. Extraction data, **Core 439301 (Umiivik-1)**

Depth	GEUS No	Extract[1]	Asph(%)	Sat(%)[2]	Aro(%)[2]	NSO(%)[2]	Sat/Aro
49.7m	-2	34[E]	46,3	9,3	13,1	77,6	0,71
104.7m	-20	29[E]	47,1	9,9	12,3	77,8	0,8
151.3m	-35	36[E]	52,4	12,6	12,6	74,7	1
199.7m	-48	17[E]	58,5	3,8	5,7	90,6	0,77
250.7m	-69	28[E]	59	7,1	5,4	87,5	1,31
307.7m	-86	19[E]	53,6	8,1	6,5	85,5	1,25
357.9m	-102	23[E]	47,8	11,5	10,3	78,2	1,12
403.6m	-116	31[E]	20,5	35	11,7	53,3	2,99
450.5m	-132	7[E]	12	0	6,7	93,3	0

1: (mg SOM/g TOC)

2: relative concentration of asphaltene-free extract

E: core crushed and extracted

Table 4. Gas chromatography data, **Core 439301 (Umiivik-1)**

Depth	GEUS No	Pr/Ph	Pr/*n* 17	Ph/*n* C18	Iso/*n* C	CPI	Philippi[2]
49.7m	-2	4,96	4,35	1,14	1,4	1,61	2,19
104.7m	-20	5,27	3,26	0,81	1,07	1,57	2,07
151.3m	-35	5,53	3,08	0,67	0,95	1,64	2,17
199.7m	-48	6,16	2,84	0,45	0,76	1,37	1,97
250.7m	-69	5,34	3,21	0,62	0,91	1,34	1,91
307.7m	-86	5,4	2,43	0,47	0,72	1,32	1,92
357.9m	-102	5,23	2,68	0,56	0,81	1,36	1,91
403.6m	-116	4,56	0,83	0,19	0,31	1,12	1,33
450.5m	-132	2,17	0,21	0,13	0,14	1,14	1,32

1: defined as 2x (C23+C25+C27+C29+C31) / C22 + 2x (C24+C26+C28+C30) + C32
2: defined as 2x C29 / (C28+C30)

Table 5. GC/MS data on thermal maturity, **Core 439301 (Umiivik-1)**

Depth	GEUS No	Ts/Ts +Tm	Tm/Tm +17β	H31 22S/22S +22R	H32 22S/22S +22R	H30 αβ/αβ +βα	S29 20S/20S +20R	S29 ββ/αα +ββ
49.7m	-2	0,02	0,81	0,53	0,4	0,68	0,12	0,23
104.7m	-20	0,01	0,88	0,57	0,52	0,68	0,16	0,2
151.3m	-35	0,02	0,92	0,58	0,57	0,69	0,21	0,27
199.7m	-48	0,01	0,96	0,57	0,62	0,64	0,31	0,27
250.7m	-69	0,02	0,97	0,56	0,63	0,69	0,41	0,34
307.7m	-86	0,02	0,97	0,56	0,65	0,64	0,4	0,24
357.9m	-102	0,04	0,97	0,57	0,68	0,72	0,42	0,33
403.6m	-116	0,2	1	0,59	0,66	0,84	0,51	0,58
450.5m	-132	0,45	1	0,58	0,58	0,87	0,5	0,55

Table 6. GC/MS data on depositional environment, **Core 439301 (Umiivik-1)**

Depth	GEUS No	BNL/H30	H28/H30	H29/H30	O/H30	S27[1]	S28[1]	S29[1]	S27/S29[2]
49.7m	-2	0	0,62	1,05	0	31	17	52	0,61
104.7m	-20	0	0,18	0,88	0	30	17	53	0,57
151.3m	-35	0	0,06	0,82	0	26	16	58	0,45
199.7m	-48	0	0,01	1,07	0	17	13	70	0,24
250.7m	-69	0	0,16	0,88	0	14	16	70	0,2
307.7m	-86	0	0,58	1,2	0,01	20	13	67	0,31
357.9m	-102	0	0,76	1,14	0	21	15	74	0,34
403.6m	-116	0	0,03	0,66	0,02	24	16	60	0,41
450.5m	-132	0	0,13	0,69	0	43	18	39	1,1

1: calculated as % of C_{27}, C_{28} and C_{29} for $\alpha\alpha$R isomers in m/z 217.

2: calculated as ratio of C_{27} to C_{29} of $\alpha\alpha$R isomers in m/z 217.

Table 7. Gas data, **Core 439301 (Umiivik-1)**

Depth	GEUS No	CH_4 ppm	C_2H_6 ppm	C_3H_8 ppm	iC_4H_{10} ppm	nC_4H_{10} ppm	iC_5H_{12} ppm	nC_5H_{12} ppm
49.7m	-2	182	13					
104.7m	-20	331000	728	797	223	151		
151.3m	-35	44900	2650	782	215	84	34,7	
199.7m	-48	201400	2020	464	tr	tr		
250.7m	-69	39480	1750	599	39,5	56,7		
307.7m	-86	148000	2017	660	tr	tr		
357.9m	-102	7800	176	65	tr	tr		
403.6m	-116	77500	2570	580	40	92		
450.5m	-132	68500	3700	500	78	82		
645.2m	-192	432	4190	2140	96,9	56,1	3,7	
682.5m	-203	189	703	286	23,1	24,8		
710.7m	-212	88	899	439	52,8	74,7	16,6	10,9
730.6m	-218	924	282	70	4,88	6,78	1,14	0,79
752.5m	-225	404200	17600	1940	155	175		
794.0m	-237	43920	6400	1280	167	124		
910.4m	-274	410960	51080	6540	590	293	29,6	
1065.6m	-322	49940	5540	925	100	100		
1084.2m	-328	1930	335	41	6,36	7,18	1,55	0,47
1113.6m	-337	2820	3040	617	61	39,7	4,43	1.20
1151.4m	-346	425000	77120	12930	2470	1490	658	184
1163.6m	-349	348000	79500	17460	4000	2160	872	219
1171.9m	-352	410000	46800	9340	2000	1400	622	200
1182.6m	-355	38960	9210	2910	690	570	250	92
1197.9m	-360	313000	2100	1270	270	258	95	41,5

Table 7. Gas data, **Core 439301 (Umiivik-1)** continued

Depth	GEUS No	wetness[1]	$\delta 13C_1$ o/oo	$\delta 13C_2$ o/oo	$\delta 13C_3$ o/oo	R_0
49.7m	-2					0,55
104.7m	-20	217	-51,2			0,55
151.3m	-35	13,1	-21,1			0,54
199.7m	-48	81,1	-43,7			0,61
250.7m	-69	16,8	-20,6			0,6
307.7m	-86	55,3	-38,9			0,62
357.9m	-102					0,63
403.6m	-116	24,6	-39,5			1,15
450.5m	-132	16,3	-18,2	-21,9		2,16
645.2m	-192					2,79
682.5m	-203					
710.7m	-212					1,67
730.6m	-218					
752.5m	-225	20,7	-31,8			1,68
794.0m	-237	5,7	-27,6			1,98
910.4m	-274	7,1	-32,6	-27,9	-24,4	4,24
1065.6m	-322	7,7	-20,1			4,3
1084.2m	-328					
1113.6m	-337		-11,9	-19,9		2,5
1151.4m	-346	4,7	-35,1	-27,6	-23,6	2,22
1163.6m	-349	3,6	-34,6	-27,8	-24,6	
1171.9m	-352	7,3	-32,9	-27,6	-23,5	1,93
1182.6m	-355	3,2	-11,4	-20,7	-21,5	
1197.9m	-360	92,8	-37,8	-22,2	-24,2	1,94

1: Calculated as $CH_4/C_2H_6 + C_3H_8$ (only for samples with CH_4> 10000 ppm)

Table 8. GC and GC/MS data on thermal maturity from GGU 1992 shallow core

Depth	GEUS No	Altitude	CPI	Philippi	Tm/Tm +17β	H31 22S/ 22S+22R	H32 22S/ 22S+22R	S29 20S/ 20S+20R
44.9m	400708-30	~80	?	?	0,54	0,23	0,22	0,1
71.5m	400708-31	~53	?	?	0,52	0,21	0,21	0,05
33.5m	400709-28	~17	1,59	2,19	0,7	0,42	0,37	0,2
72.0m	400709-29	~-22	1,33	1,85	0,79	0,46	0,37	0,1
22.7m	400710-18	~133	1,59	2,32	0,72	0,46	0,35	0,11
51.8m	400710-19	~75	1,52	2,01	0,76	0,51	0,4	0,11
14.7m	400711-15	~80	1,68	2,42	0,71	0,47	0,38	0,14
52.2m	400711-16	~43	1,7	2,31	0,78	0,51	0,42	0,12
25.2m	400712-19	~-20	1,35	1,9	0,83	0,53	0,44	0,12
30.2m	400712-20	~-29	1,48	2	0,82	0,52	0,44	0,15
	400712-18				0,78	0,48	0,32	0,11
80.0m	400712-10	~-75	1,53	2,2	0,91	0,57	0,51	0,23