GEUS
Report file no.
13955

GANW-1

Stratigraphy, sedimentology and geochemistry of cores and other samples from the GANW-1 well, Nuussuaq, West Greenland. Report prepared for grønArctic Energy Inc., Calgary, Alberta, Canada, February 1995

Christiansen, F.G., Dam, G., Larsen, L.M., Nøhr-Hansen, H., Pedersen, A.K., Boserup, J., Bojesen Koefoed, J., Laier, T. & Pulvertaft, T.C.R.

Copenhagen
24-03-1997

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/36

Stratigraphy, sedimentology and geochemistry Of cores and other samples from the GANW#1 well Nuussuaq West Greenland

Report prepared for grønArctic Energy inc., Calgary Alberta, Canada, February 1995

Flemming Getreuer Christiansen, Gregers Dam, Lotte M. Larsen, Henrik Nøhr-Hansen, Asger K. Pedersen, John Boserup, Jørgen Bojesen-Koefoed, Troels Laier And T. Christopher R. Pulvertaft

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/36

Stratigraphy, sedimentology and geochemistry Of cores and other samples from the GANW#1 well Nuussuaq West Greenland

Report prepared for grønArctic Energy inc., Calgary Alberta, Canada, February 1995

Flemming Getreuer Christiansen, Gregers Dam,
Lotte M. Larsen, Henrik Nøhr-Hansen,
Asger K. Pedersen, John Boserup,
Jørgen Bojesen-Koefoed, Troels Laier
And T. Christopher R. Pulvertaft

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/36

Stratigraphy, sedimentology and geochemistry of cores and other samples from the GANW#1 well, Nuussuaq, West Greenland

Report prepared for grønArctic energy inc., Calgary, Alberta, Canada, February 1995

This report was originally prepared as a confidential report for grønArctic energy inc. Released April 1997

Flemming Getreuer Christiansen, Gregers Dam,
Lotte M. Larsen, Henrik Nøhr-Hansen,
Asger K. Pedersen, John Boserup,
Jørgen Bojesen-Koefoed, Troels Laier
and T. Christopher R. Pulvertaft

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

GEUS

CONTENTS

INTRODUCTION

The GANW#1 well (grønArctic Nuussuaq West #1) was drilled in the period from September 11 to October 5, 1994 in the Marraat area on western Nuussuaq, onshore West Greenland (Fig. 1, Table 1). This slim core hole was operated by the newly established company grønArctic Energy Inc. of Regina, Saskatchewan under a prospecting licence granted by the Mineral Resources Administration for Greenland a few weeks earlier.

Table 1. Technical data from the GANW#1 well

Well name:	grønArctic Nuussuaq West #1 (GANW#1)
Operator:	grønArctic Energy Inc, Regina, Saskatchewan, Canada.
Drill contractor:	Petro Drilling Ltd., Halifax, Nova Scotia, Canada.
Locality:	Marraat, Nuussuaq, West Greenland.
Coordinates:	70°31′25″N, 54°13′01″W.
Elevation:	14.6 m a.s.l.
Well spud date:	September 11, 1994.
Rig release date:	October 5, 1994.
Rig type:	Diamond drill Longyear Fly-in 38.
Hole diameter:	60 mm (2 23/64 inch.) (BQ rod).
Core diameter:	36.5 mm (1 7/16 inch.).
Total depth:	2625 ft (800 m), ~100% core recovery.
Status:	Suspended, planned to be re-entered in 1995.
Formations drilled:	Lower Tertiary volcanics and sediments (Vaigat Formation).

The Geological Survey of Greenland (GGU) carried out inspection with John Boserup on site throughout the drilling period and Gregers Dam for a shorter period, with the principal aim of preparing a preliminary geological description and collecting of sample material such as cores of sediments and oil-impregnated basalts, and gas and formation fluids under pressure.

After completion of the drilling programme and further negotiation with grønArctic Energy Inc. GGU took over the core which is now stored in Copenhagen. As part of an agreement between the Mineral Resources Administration for Greenland and grønArctic Energy Inc., all data from the well are confidential until the end of 1996 and GGU is obliged to deliver a report to the operator including a geological log of the core and a preliminary

sedimentological and stratigraphic analysis, and a description of geochemical results from analyses of the sediments penetrated, oil impregnations, gas and formation fluids before February 1st, 1995.

The GANW#1 well was drilled approximately 900 m north-west of the Marraat-1 site where GGU drilled a 448 deep well in 1993. Data from GGU's well and from the surrounding area, which was studied during geological field work in the summers of 1992, 1993 and 1994, are very important for comparison with the geological and analytical data from the GANW#1 well. Therefore the present report should be read together with the following reports, papers and manuscripts:

- The Marraat-1 well completion report by Dam & Christiansen (1994).
- A report on organic geochemical data from the Marraat-1 well and surrounding outcrops by Christiansen *et al.* (1994a).
- Several short papers from GGU's Report of Activities which provide the historical background with general information on field work and drilling in 1992, 1993 and 1994 (Christiansen, 1993; Christiansen *et al.*, 1994b; Christiansen *et al.*, in press).
- A manuscript prepared for *Bull. Can. Petrol. Geol.* which gives all organic geochemical data from the Marraat oil based on surface samples collected during field work in 1992, 1993 and 1994 as well as the Marraat-1 well (Christiansen *et al.* ms).

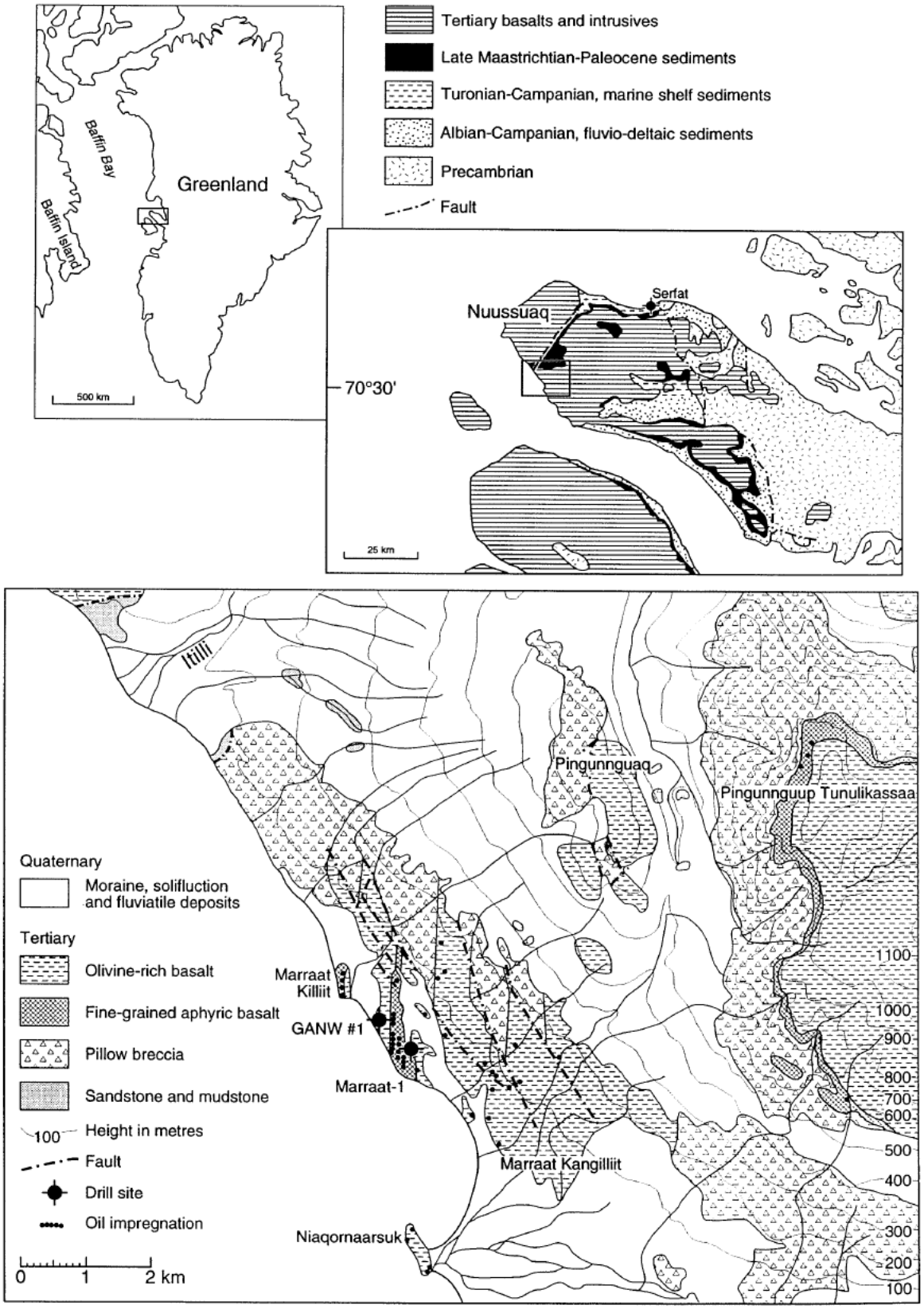

Fig. 1. Geological map of the Marraat are showing location of drill sites and oil-impregnation. Map based on Henderson (1975) and Christiansen *et al.* (ms).

VOLCANIC ROCKS

General

The dominant type of volcanic rock present in the well is *picrite*, an olivine-rich rock representing very primitive melt from the mantle. By crystal fractionation the picrite melt may lose olivine and develop successively into olivine-phyric and feldspar-phyric or aphyric basalt. Such rocks are only very sparsely represented in the well.

The volcanics are developed in three different facies.

1. The uppermost part of the well consists of *subaerial lava flows* often with reddish oxidised tops resulting from contact with air. The rocks are highly vesicular.
2. Below 65.5 m the volcanics are *hyaloclastite breccias*. These are clastic deposits produced when magma flows into water. The strong chilling effect of the water leads to quenching and disintegration into pillows with glass rinds and glass shards of all sizes. Hyaloclastite deposits may be produced by subaquatic eruptions or by subaerial lavas flowing into water. In contrast to lavas, hyaloclastites tend to build up thick deposits, and minimum water depths can be measured from the thickness of a single hyaloclastite unit.
3. Later intrusions such as *dykes* and *sills* can be recognised by their steep, chilled contacts and fine-grained massive interior. There are 7 or 8 intrusions in the well.

The volcanic rocks have been divided into consecutively numbered units representing either lava flows, hyaloclastite breccia units, or intrusions. The sedimentary horizons were also each allotted a number in the sequence.

Summary log

Unit 1, 2.25–6.71 m. Picrite, most probably a dyke. No upper contact.

Units 2–22, 6.71–65.48 m. A succession of *c.* 10 subaerial picrite lavas. 1 mm to 1 cm wide irregular cracks filled with fossiliferous limestone are seen down to 14.5 m (units 2–5). The limestone must have been deposited by infill of the cracks from the limestone layer on which the rig was situated.

Unit 18 is a picrite dyke.

Unit 22 at 60.80–65.48 m is a pillow lava transitional from subaerial to subaquatic facies.

Unit 23, 65.48–76.15 m is a picrite hyaloclastite breccia probably formed in the same eruptive event as unit 22. It rests on unit 24 which is a 30 cm thick deposit of reworked hyaloclastite sand. The water depth indicated by units 22+23 is *c.* 15 m.

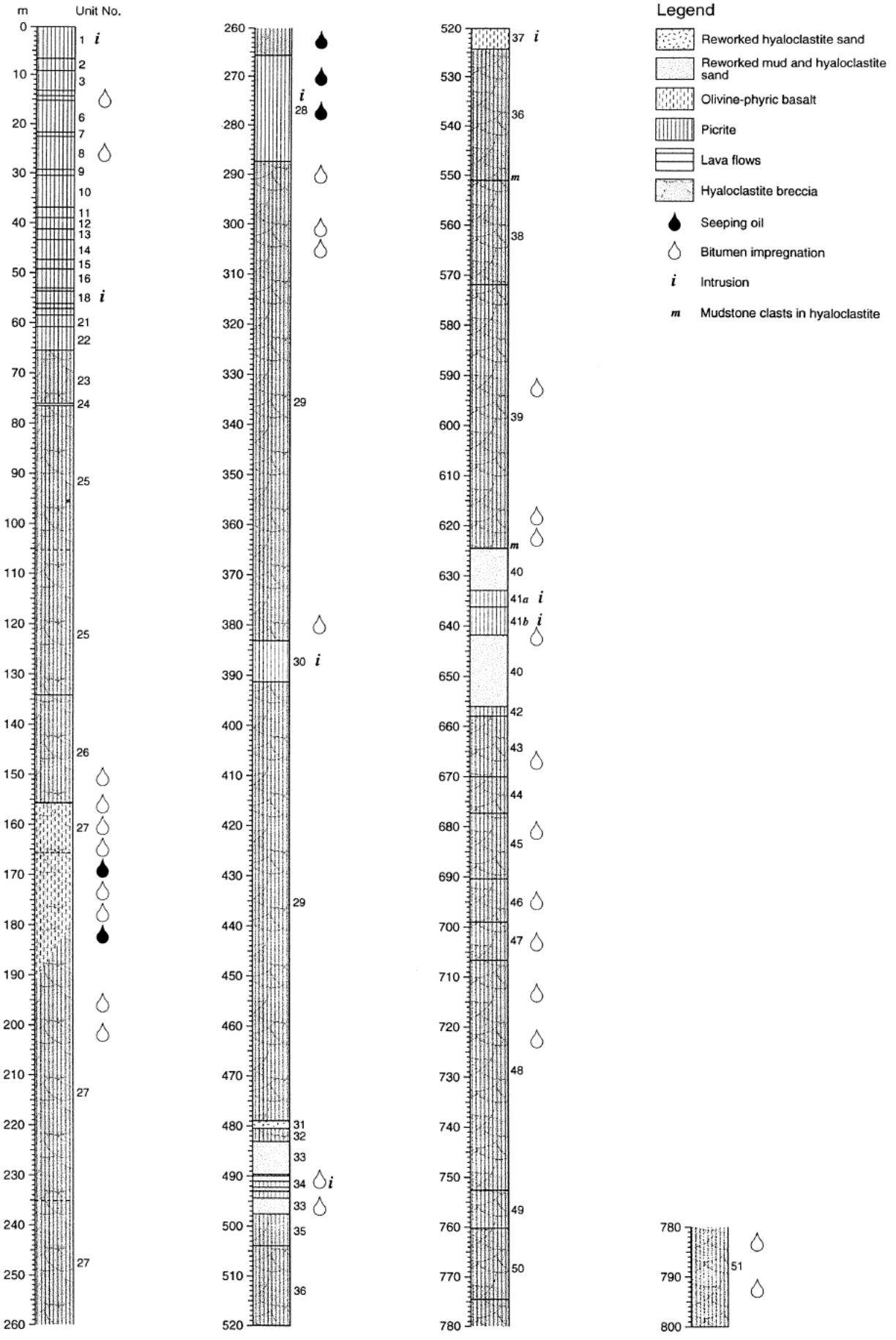

Fig. 2. Summary log of the GANW#1 well.

Units 25–26, 76.46–155.74 m. Two or perhaps three hyaloclastite picrite breccia units each 20–30 m thick. The content of pillows and pillow fragments is very variable; trains of pillow-rich rock occur intermittently. Each unit tends to show an overall fining upwards.

Unit 27, 155.74–265.75 m. A more than 100 m thick hyaloclastite breccia unit. In the upper part, 155.74 to *c.* 185 m, the rock is a fine-grained olivine-phyric basalt. At 180–190 m the rock type changes gradually into typical picrite; there is no boundary. The basaltic part is oil-impregnated (see later).

Unit 28, 265.75–287.40 m: Picrite intrusion, most probably a sill. This *c.* 21 m thick sill-like intrusion is correlated with a similar intrusion at 337–362 m in the Marraat-1 well. Oil impregnations (see later).

Unit 29, 287.40–478.86 m. Picrite hyaloclastite breccia. This nearly 200 m thick unit has no clear internal boundaries. It may be the same volcanic unit as unit 27 above the sill in which case the whole unit is *c.* 300 m thick, indicating a minimum water depth of this size. The rock is generally massive and monotonous, with fairly evenly distributed clasts; there are some parts with concentrations of larger clasts. At 371–376 m the rock is crushed and veined, the veins being filled with fibrous zeolites and a green, fibrous, asbestos-like mineral.

From *c.* 448 m there are traces of bedding in the hyaloclastite matrix. At 467.5 and 474 m there are two large (10–20 cm) clasts of highly vesicular, unchilled rock interpreted as lava fragments, showing that there was land in the neighbourhood. This thick unit rests on hyaloclastite sand (unit 31). There are no changes to the rock approaching the contact.

Unit 30 is a picrite dyke within unit 29. The thickness drilled is 8.2 m. Assuming an originally vertical dyke in a block tilted 20°, the dyke width is 2.8 m.

Unit 31, 478.86–480.52 m. Fine-grained hyaloclastite sand consisting of fresh glass shards in a carbonate matrix. No grain size variations; there is distinct reddening near the bottom of the layer, probably due to a clay component.

Unit 32, 480.52–483.10 m. Coarse hyaloclastite, picritic. There is bedding in the lowermost 60 cm, and clay content in the lowermost 20 cm. The hyaloclastite material is probably redeposited.

Unit 33–34, 483.10–497.50 m. Volcanogenic sediment (unit 33, total 11.6 m) and picrite intrusions (unit 34, total 2.8 m). The sediment is hyaloclastite sandstone and siltstone with distinct bedding inclined *c.* 20°. Grain size variable in layers which are unsorted or fining upwards. At 496.3 m: Fossil corals in a massive, unsorted hyaloclastite sand (see later).

Unit 34 consists of four small picrite intrusions, probably fingers from one and the same intrusion which has preferentially intruded into the incompetent, wet sediments of unit 33.

Unit 35, 497.50–503.90 m. Coarse picritic hyaloclastite breccia, very much crushed by drilling. The contact to unit 36 is marked by an abrupt change in grain size.

Unit 36, 503.90–551.00 m. The uppermost *c.* 0.25 m is a fine-grained hyaloclastite sand. This coarsens downwards through the uppermost metre into distinct picritic hyaloclastite. The rock is green from alteration into clay. From 505 m the rock is a coarse hyaloclastite breccia with intermittent zones of finer material showing bedding structures. From *c.* 530 m the matrix is agate-cemented, massive and hard, and the rock clasts including the olivine phenocrysts are very fresh. Between 543.3 and 551 m there is hyaloclastite sand with scattered mudstone clasts, and mudstone and siltstone clasts are very frequent in the lowest metre of the unit.

Unit 37 is a dyke of olivine-phyric basalt in unit 36. The thickness drilled is 4.3 m. Assuming an originally vertical dyke in a block tilted 20°, the dyke width is 1.5 m.

Table 2. Correlation between the Marraat-1 and the GANW-1 drill cores

	Marraat-1	GANW-1
Limestone horizon	208-209 m	0 m
Picrite lavas	Units 71-78 209-235 m 8 lavas thickness 26 m	Units 2-21 7-61 m 19 lavas thickness 54 m
Pillow lava, picrite	Unit 79 upper part 235-237 m thickness 2 m	Unit 22 61-65 m thickness 5 m
Hyaloclastite breccia, picrite	Unit 79 237-307 m thickness 30 m	Unit 23 65-76 m thickness 11 m
Hyaloclastite sand	Unit 80 upper 307 m thickness 0.2 m	Unit 24 76-77 m thickness 0.3 m
Hyaloclastite breccia with frequent lava fragments; picrite	Unit 80 307-325 m thickness 18 m	Unit 25 77-134 m thickness 57 m
Hyaloclastite breccia, picrite	-	Unit 26 134-156 m thickness 22 m
Hyaloclastite breccia, olivine-phyric basalt to olivine-poor picrite	Units 81 and 83 325-448 m thickness > 98 m	Unit 27 upper part 156 - *c.* 190 m thickness 34 m
Picrite sill intrusion into unit 81-83 in Marraat-1 and into unit 29 in GANW-1	Unit 82 337-362 m thickness 25 m	Unit 28 266-287 m thickness 21 m
Hyaloclastite breccias (picrite) Two sediment horizons Dyke and sill intrusions	Not drilled	Unit 27 (most) – 51 Below *c.* 190 m thickness 609 m

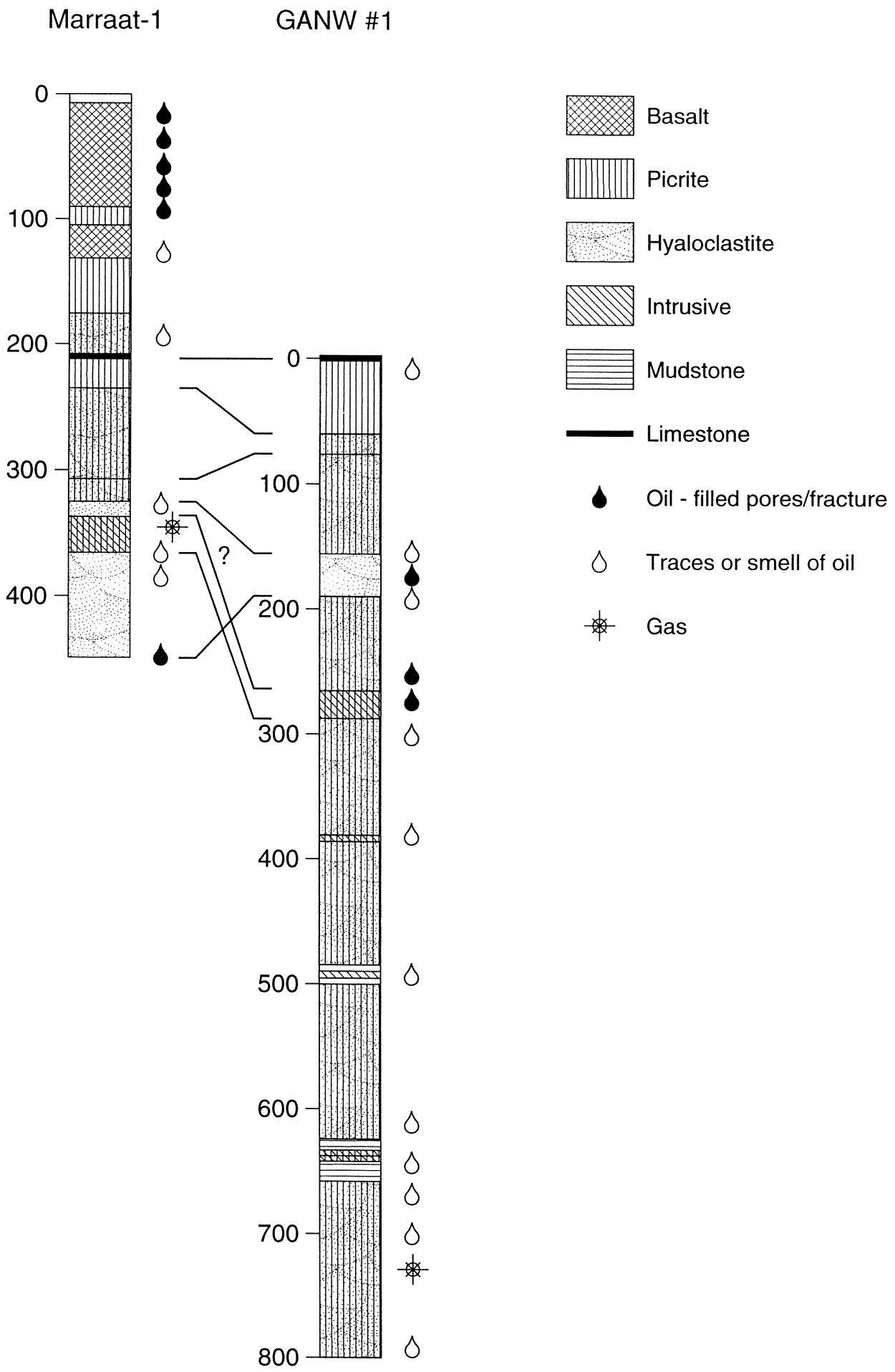

Fig. 3. Correlation between the Marraat-1 and GANW#1 wells.

Unit 38, 551.00–571.90 m. Clast-rich coarse hyaloclastite breccia. The lowermost part looks more like a pillow lava. The rock is picritic.

Unit 39, 571.90–624.54 m. A *c.* 52 m thick picritic hyaloclastite breccia unit. The uppermost 7 m are fine-clastic, coarsening downwards. The clast size in the whole unit is fairly small, rarely more than 5 cm. The rock is massive, with little veining. On approaching the bottom, the rock becomes clast-poor, and from *c.* 3 m above the bottom scattered clasts of mudstone are seen. *c.* 60 cm above the bottom intense veining starts; below *c.* 20 cm from the bottom there is strong carbonatisation, and the contact with the underlying sediment is a *c.* 5 cm thick carbonate vein. The sediment at the contact is tectonised and veined.

The contact between hyaloclastite breccia and sediment below is clearly tectonic. However, the fault does not have to be large; the hyaloclastite unit is evidently close to its original bottom, but it is not known how much sediment is missing.

Units 40–41, 624.64–656.00 m. Sediments (unit 40, total 22.4 m) and picrite intrusions (unit 41, total 9.0 m). The sediments are mudstones, siltstones and sandstones including arkosic sandstones, and coarse deposits with much hyaloclastite material including pillow fragments which are very strongly carbonatised. All material seems to be reworked.

Unit 41a is a steep picrite intrusion (dyke) that has hornfelsed the mudstones at the upper contact. Unit 41b is a picritic rock set through with vein systems and crush zones and with intermittent narrow zones of hyaloclastite. It is interpreted as an intrusion pillowed by contact with the wet sediments, but this is not sure. It is much more carbonatised than unit 41a and may be considerably older than this.

Unit 42, 656.00–657.85 m. Coarse hyaloclastite with mudstone clasts and mudstone matrix in the upper 20 cm. Strong carbonatisation. The rock is probably redeposited.

Units 43–47, 657.85–706.56 m. Five picrite hyaloclastite breccia units each 7–12 m thick. Each unit has a fine-grained upper part with more or less pronounced bedding, grading down into a central and lower part with larger clasts. The boundaries between units are not very sharp; sometimes there are thin stringers of mudstone. Especially unit 46 is oil-impregnated (see later).

Unit 48, 706.56–752.65 m. A 46 m thick picrite hyaloclastite unit. It is rather coarse with up to 30 cm pillows irregularly distributed; there are some finer intervals. At 739–752.6 m the rock looks more like a pillow lava with close-lying pillows up to 50 cm in size. There are scattered fragments of strongly vesicular, unchilled lava.

Unit 49, 752.65–760.20 m. Like units 43–47.

Units 50–51, 760.20–799.15 m. Two picrite hyaloclastite units 14 and 25 m thick. Both are relatively fine-grained and contain several large clasts of unchilled vesicular lava.

Unit 51 is coarse-grained in the lowermost 10 m and contains a 0.5 m large, partly vesicular lava pillow apparently *in situ*. The well bottoms in an at least 30 cm large picrite pillow.

Interpretation: the geological environment

The major part of the GANW#1 drill core is in submarine facies (from 65 m to the bottom at 798 m, i.e. 733 m). Although basin depths as large as this have been recorded from the south coast of Nuussuaq (Pedersen *et al.*, 1993), it is not possible to conclude that the basin at Marraat Killiit was so deep. There are some 18 separate hyaloclastite breccia units and two

sediment horizons which may indicate pauses in the volcanic activity, and movements may have occurred in the basin during the deposition of the succession. The largest minimum basin depth indicated is 284 m (taking units 27 and 29 as one depositional unit and correcting for an inclination of 20° of the succession).

The volcanic rocks in GANW#1 include the oldest known volcanics in West Greenland. Similarly old hyaloclastite breccias may crop out on the surface between the GANW#1 site and the Itilli fault, but these cannot be placed unequivocally in the succession. Local subaquatic eruption sites are known from the surface exposures.

The total hyaloclastite breccia succession in GANW#1 is among the thickest known in West Greenland. Sediment horizons as thick as 10–20 m very rarely occur intercalated among the hyaloclastites in other places. The sediments in GANW#1 have a high proportion of volcanogenic material which is considered to have been redeposited as debris flows (see next section). The drill site is situated close to or perhaps on the tectonically induced Itilli escarpment separating the shallow shelf areas on Nuussuaq from the deeper marine basin in the north-west (Dam & Sønderholm, 1994). The closest similarity to the succession in the GANW#1 drill core is probably shown by the thick hyaloclastite deposits in the western part of the Tunorsuaq valley in north-western Nuussuaq.

The following geological environment is envisaged:

Mounds of hyaloclastite breccia were built up from local submarine eruption sites. The eruptions produced thick lensoid deposits; large lateral variations such as seen in the correlation between the Marraat-1 and GANW#1 drill cores, which were drilled at sites only about 900 m apart, are a natural consequence of this (Fig. 1). Water-saturated material from the upper parts of these deposits would readily have been eroded and redeposited. At two times, mud and sand deposits lying higher up, above the Itilli escarpment, were redeposited as debris flows on the hyaloclastites. Some of the volcanics erupted through mudstones, and clasts of these may be found near the bottom of the eruptive units. Lava clasts are found in several hyaloclastite breccia units, indicating either that the volcanic piles built up above sea level or that the eruptions were at least partly subaerial. The lowest hyaloclastite breccia units (48–51, total 92 m) have a significantly higher frequency of lava clasts than overlying units (except for unit 25). This suggests lower sea level and/or closer proximity of emerged land during the formation of the oldest part of the succession.

After deposition of more than 700 m of hyaloclastite breccias the basin was filled up and the volcanism became subaerial. After deposition of some 60 m of lavas (27 m in the Marraat-1 well) there was a pause in volcanism and the lavas were weathered. The area then subsided and was again transgressed by the sea. A shallow-marine limestone horizon consisting of shell and coral fragments was deposited on the surface of the volcanics and seeped into cracks in

the underlying lavas. When volcanism resumed, the basin was again filled up with hyaloclastite breccias.

It is likely that in the Early Paleocene the Marraat Killiit area was situated in a marine basin with large submarine relief, close to the Itilli escarpment. Just how deep the basin was in this area is not known. Since the thickness of hyaloclastite breccia is dependent on the depth of the basin into which the lavas flowed, it is not possible to estimate the total thickness of the hyaloclastites in this area and hence the thickness of undrilled hyaloclastite succession at the GANW#1 well site is not known either.

Veins and traces of bitumen and oil

Summary of observations

15.1 m: Carbonate vein with possible bitumen.

24–26 m: Carbonate veins with bitumen in the core.

26–134 m: Very few veins.

From 134 m: Some veins with green saponite ± carbonate.

149–150 m (unit 26): 3 mm to 1 cm veins of saponite + carbonate, with stringers of dark bitumen along the vein sides.

155–188 m: Several up to 3 mm wide veins of brownish carbonate with bitumen. Between 157 and 158 m also scattered specks of bitumen within the hyaloclastite material. At 167 m oil seeping out on the core surface. At 181.5 m a 2 cm thick vein with 0.5 cm carbonate along the margins, quartz in the centre, and bitumen between the two minerals. At 183 m oil seeps in points on the core surface.

The bitumen-veined zone at 155–188 m is lithologically controlled. The rock is olivine-phyric basalt in contrast to the surrounding picrites.

From 188 m: Scattered white carbonate veins without any bitumen.

195 m: Some brownish carbonate veins with bitumen.

202 m: A 2 cm wide brownish carbonate vein with patches of bitumen.

From 202 m: Scattered white carbonate veins without any bitumen.

247–260 m: Several thick white carbonate ± quartz veins without any bitumen.

261 m: A 4 mm thick brownish carbonate vein with oil seeping out on the core surface.

270–279 m: At several levels white carbonate veins without bitumen, cut by later brownish carbonate veins with bitumen. Oil seeps out on the core surface at 271 m and 277 m.

289 m: 2 cm wide carbonate vein with yellowish margins and white centre. Traces of bitumen in margin.

290–292 m: Thin yellowish veinlets with traces of bitumen.

292–301 m: No veins.

301–305 m: Yellowish carbonate veins with bitumen. At 305 m strong bitumen impregnation and smell of oil.

305–371 m: Almost no veins.

371–376 m: Zone strongly disturbed by drilling. Veins and open vugs with white fibrous zeolite and an asbestos-like green silicate mineral. No bitumen. The rock is sheared.

376–381 m: No veins.

381–383 m: Clear honey-brown carbonate with bitumen. The carbonate fills irregular up to 1 cm large interstices in the hyaloclastite matrix. At 382 m the brown carbonate is cut by a 1 mm thin green silicate vein. Some shearing in the rock. Immediately below this level there is a dyke intrusion.

383–396 m: Dyke (to 391 m) and hyaloclastite with several veins of white zeolite, green silicates and calcite.

396–448 m: Very few veins. No bitumen.

448–450 m: 10 cm wide vein with white fibrous zeolite, euhedral calcite embedded in zeolite, and quartz mostly along the margins. No bitumen.

450–491 m: Very few veins.

491–499 m: Scattered carbonate + quartz veins. At 492 m brown staining and ?bitumen. At 496.5 m a fossil coral filled with brownish carbonate stained by bitumen.

449–560 m: Very few veins.

560–568 m: Some 1–3 cm wide veins with carbonate, saponite and quartz. No bitumen.

568–616 m: Very few veins. At 592 m a 2–3 mm vein of brownish carbonate with bitumen is cut by a white carbonate vein.

616–617 m: Veins and vein systems up to 3 cm wide with slightly brownish carbonate, ?bitumen, and a white fibrous silicate mineral.

624–625 m: Brownish carbonate vein with bitumen? A white carbonate vein cuts the brown one.

637–642 m: Thick white veins; much disturbance by drilling. At 642 m a brownish carbonate vein, probably with bitumen.

642–656 m: Sediment with no veins and no traces of bitumen.

656–680 m: No veins. At 667 m interstices in the hyaloclastite matrix are filled with a green silicate mineral and late brownish carbonate, probably with bitumen.

680 m: A 1 cm thick white vein with carbonate along the margins. Euhedral carbonate crystals overgrown by euhedral quartz project into the open centre. Along the outer margin of the vein the carbonate is stained brownish – ?bitumen.

682 m: Irregular veins with coarse carbonate with traces of early bitumen staining.

683–693 m: No veins.

693–696 m: "Primary" fractures in large picrite pillows contain large clear honey-brown carbonate crystals. Bitumen is released when the carbonate is dissolved in acid.

702 m: 2 mm wide veins with margins of brownish carbonate with bitumen, and centres of white carbonate.

709 m: 1 cm vein with saponite + carbonate; no bitumen.

712 m: 2–3 mm wide brownish carbonate vein with bitumen.

723 m: 2 cm wide vein system with saponite + carbonate; no bitumen.

724–753 m: No veins.

753–756 m: Several up to 3 cm thick, very steep to vertical saponite veins. No bitumen.

756–770 m: No veins.

770–780 m: Several up to 3 cm thick steep veins with saponite + carbonate ± quartz. At 780 m a 7 mm wide vein has carbonate and later quartz growing in euhedral crystals into the open centre of the vein. No bitumen.

782 m: 2 mm carbonate vein with slight bitumen staining.

792–793 m: 1–2 mm wide steep vein with brownish carbonate. Visible bitumen specks in both vein and neighbouring vesicles in the rock.

Conclusions

1. Bitumen is found at intervals throughout the entire GANW#1 drill core.

2. The bitumen is associated with carbonate in veins.

3. In most cases bitumen is found as discrete specks, mostly interstitially between the carbonate crystals. In a few cases (381–383 m and 693–696 m) the bitumen is finely dispersed within the carbonate crystals.

4. In the upper part of the core (0–*c.* 300 m) the bitumen-stained carbonate veins are later than carbonate veins without bitumen. In the lower part of the core (380–800 m) most of the bitumen-stained carbonate veins are earlier than carbonate veins without bitumen.

5. Carbonate veins without bitumen occur throughout the core.

6. Bitumen-impregnated carbonate veins are preferentially associated with dyke and sill intrusions and with a non-picritic (basaltic) hyaloclastite horizon at 155–188 m, probably because of the way these rocks fracture. Picrite lavas and hyaloclastites are not very good as bitumen retainers; this is also seen in the Marraat–1 well. None the less, there is fairly widespread bitumen veining in the lowest 200 m of picritic hyaloclastite breccias in the GANW#1 core.

FACIES DESCRIPTION OF THE SEDIMENTS

Sediments have been recognised at three intervals in the GANW#1 well: an upper unit from 483 to 497.5 m, a middle unit from 543.3 to 551 m, and a lower unit from 624.5 to 657.85 m (Fig. 2). The middle unit consists of only a single bed which consists of redeposited hyaloclastitic sandstone with scattered mudstone clasts less than 2 cm across; this unit is not discussed further in this report. The upper and lower sedimentary units are characterised by very different lithofacies, and are therefore described separately.

Upper sedimentary unit: 483–497.5 m

Thinly interbedded sandstone and mudstone

This interval consists entirely of heterolithic deposits composed of graded laminae and thin beds of fine- to coarse-grained sandstone overlain by dark parallel-laminated mudstone (Fig. 4). The sandstones are from 1 mm to 90 cm in thickness, usually have sharp, locally scoured bases, and consist of volcanic material. They show normal grading, and are usually structureless. A few scattered volcanic clasts occur in the heterolithic deposits. The sandstone laminae usually show pinch-and-swell structure. One bed shows scattered fragments of scleractinian corals belonging to the species *Dendrophyllia candelabrum*. At 496.28 m a nearly intact branched colony occurs and 17 cm above there are two branches that are possibly connected. The coral fragments do not show any signs of tearing due to transportation (S. Floris, pers. comm. 1995). Some of the branches are hollow and have not been filled with mud. One of the branch fragments is tinted brownish due to bitumen impregnation. The deposits are carbonatised throughout.

The thinly interbedded sandstones and mudstones are interpreted as deposits of traction and fall-out processes associated with various stages of sedimentation from waning turbidity currents. They correspond to Facies D of Mutti & Ricci Lucchi (1978) and Mutti (1992). No evidence of wave- and storm-action has been recognised, suggesting that deposition took place

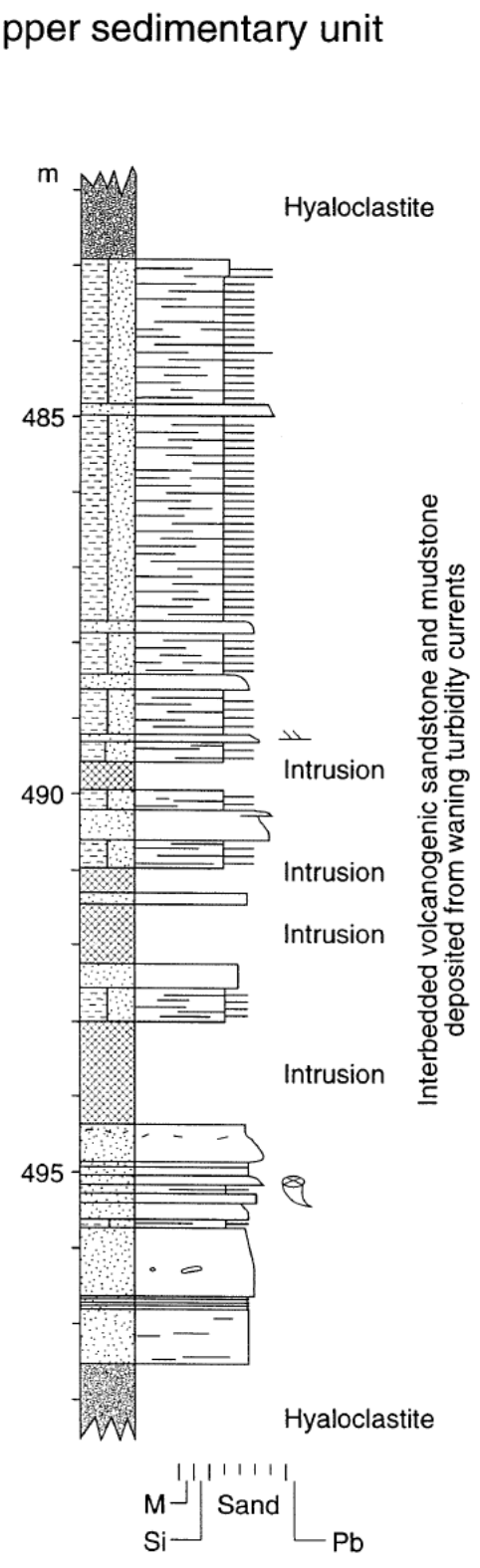

Fig. 4. Detailed log of the upper sedimentary unit in the GANW#1 well.

below storm-wave base. The coral *Dendrophyllia candelabrum* is well known from the Lower Danian of Nuussuaq (Floris, 1972). This coral was azooxanthellate (not light-dependent) and its presence suggests water depths ranging from 50 to 300 m (Floris, 1972; Bernecker & Weidlich, 1990) and that there was a fairly shallow shelf or platform close to the Marraat area at the time of deposition. The lack of mudstone in some of the corals suggests that they were transported either while still alive or shortly after their death (S. Floris, pers. comm. 1995).

Lower sedimentary unit: 624.5–657.85 m

This interval can be divided into three interbedded facies: chaotic beds, sandstones and conglomerates (Fig. 5).

Chaotic beds

The chaotic beds consist of dark grey contorted mudstone showing a very poor lamination, structureless mudstone with evenly scattered volcanic fragments and mudstone intraclasts grading upward into conglomeratic beds, and mudstones with thin irregular sand stringers.

The chaotic beds are up to 7 m thick and are bounded by sandstones and conglomerates. The volcanic clasts consist of pebble- and cobble-sized carbonatised pillow and hyaloclastitic fragments. The chaotic beds are characterised by lack of any visible basal scours.

The chaotic beds were deposited by down-slope displacement of semi-consolidated sediments and volcanic eruption products. The lack of basal scours and the presence of volcanic fragments floating in a muddy matrix indicate erosion of older up-slope volcanic eruption products and suggest deposition from cohesive debris flows (cf. Lowe, 1979; Mutti, 1992). The carbonatisation of the volcanic fragments suggests a marine depositional environment.

Sandstones and conglomerates

The conglomerates are composed of volcanic eruption products with few scattered mudstone intraclasts. They are clast-rich to clast-poor cobble and pebble conglomerates with a matrix consisting of a mixture of mud and hyaloclastic glass. The clasts are mainly composed of angular pillow fragments. Classifying the conglomerates on the presence or absence of grading allows subdivision into ungraded, normally graded and inversely graded. No stratification has been observed, but the core is, however, probably too slim to allow recognition of any stratification. It is therefore meaningless to go into a detailed discussion of transport mechanisms and depositional processes. The presence of floating pillow

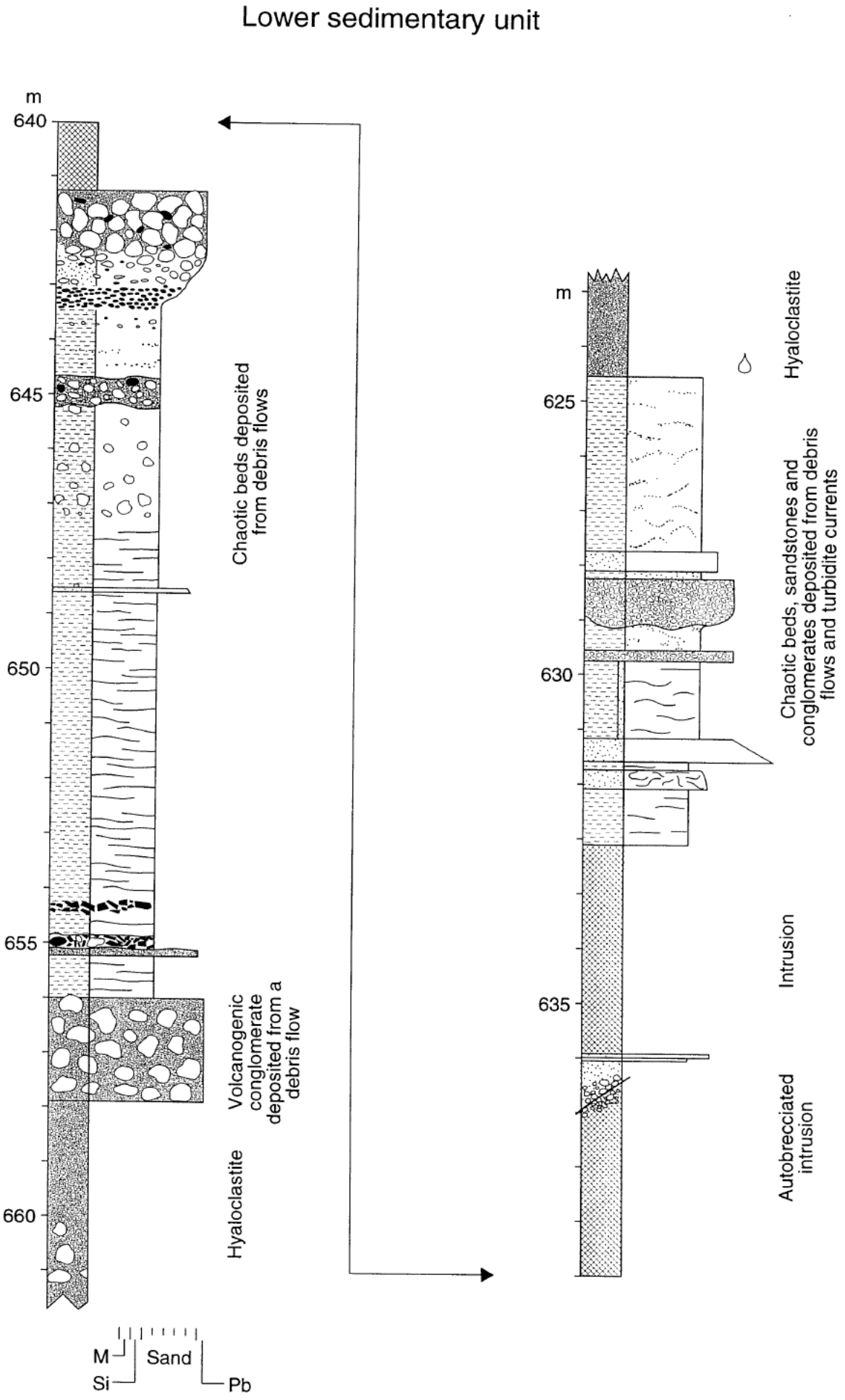

Fig. 5. Detailed log of the lower sedimentary unit in the GANW#1 well.

fragments within a glassy and muddy matrix, suggests, however, that the conglomerates were most likely deposited from debris flows.

The sandstones are very similar to the clast-poor conglomerates and just lack the pillow fragments as clasts. They are medium- to coarse-grained; stratification has not been recognised. Two of the beds show a slight fining-upward tendency, suggesting that they were deposited from coarse-grained high-density turbidity currents. One bed (628 m) consists of quartzitic sandstone.

The close association with hyaloclastites suggests that the debris flows most likely were triggered by small earthquakes in connection with volcanic eruptions. Initiation of debris flows demands a surface slope of at least 1° (Nardin *et al.*, 1979). Both the glassy matrix and the pillow fragments are carbonatised, suggesting a marine depositional environment. No evidence of wave- and storm-action has been recognised, suggesting that deposition took place below storm-wave base.

PALYNOSTRATIGRAPHY OF THE SEDIMENTS

A preliminary palynological examination has been carried out using four samples from the lower sedimentary unit (624.5–657.85 m; the same samples were analysed by GC and GC/MS, see later). The organic material is dominated by irregular charcoal particles (95 %), whereas dinoflagellate cysts (marine indicators) and spores and pollen (terrestrial indicators) constitute less than 5 % of the organic material. The references to species are not listed in the reference list, but may be found in Lentin & Williams (1993).

One sample (GGU 380101-17) yielded a thermally affected, but moderately diverse (8 species) dinoflagellate cyst flora. Eighty specimens were recorded from the sample.

The presence of the stratigraphically important species *Isabelidinium*? *viborgense* Heilmann-Clausen, 1985, *Palaeocystodinium bulliforme* Ioannides 1986, *Palaeoperidinium pyrophorum* (Ehrenberg, 1838), Sarjeant, 1967b; emend. Gocht & Netzel, 1976, *Hystrichosphaeridium proprium proprium* Marheineche, 1992 and *Cerodinium striatum* (Drugg, 1967) Lentin & Williams, 1987, indicate a Paleocene age for the sample.

Isabelidinium? *viborgense* has a very narrow stratigraphic occurrence in the earliest Late Paleocene in the North Sea area where, according to Heilmann-Clausen (1985) and Powell (1992), it has been recorded only from the earliest Thanetian (NP 5 Biozone). The three species *P. bulliforme*, *P. pyrophorum* and *C. striatum* all have a last occurrence in the middle Thanetian (NP 7) in the North Sea area (Heilmann-Clausen, 1985; Powell, 1992).

Isabelidinium? *viborgense* has previously been reported from the Kangilia section on the north coast of Nuussuaq by Hansen (1980) as *Albertia dilwynense* (now *Senegalinium*?

dilwynense (Cookson & Eisenack, 1965c) Stover & Evitt, 1978). Hansen (1980) recorded the species from an interval between 715 m a.s.l. (330 m above the major submarine channel of Early Maastrichtian age (Nøhr-Hansen, 1994)) and the top of the Kangilia Formation at 880 m a.s.l. just below the Paleocene volcanic breccia. Hansen (1980) dated the interval as NP 4 to NP 5–6, which approximately correlates with the record of the species from the North Sea area but disagrees with Jürgensen & Mikkelsen's (1974) record of nannoplankton characteristic of NP 3 in samples situated just below the volcanic breccia on the north coast of Nuussuaq. Piasecki *et al.* (1992) recorded *I.? viborgense* from intravolcanic clastic sediments from south-west Nuussuaq and suggested a correlation to nannoplankton zone NP 5 for these sediments.

The conclusion from the discussion above is that the species *I.? viborgense* may have an earlier stratigraphic first occurrence (NP 3, middle Danian, middle Early Paleocene) and maybe a longer stratigraphic range (NP 3–5) in West Greenland than recorded from the North Sea area (NP 5) — that is if one accepts the nannoplankton dating by Jürgensen & Mikkelsen (1974). On the other hand if the nannoplankton dating is ignored, the conclusion based on comparison with the known range of *I.? viborgense* from the North Sea is that the upper part of the Kangilia Formation at Kangilia on the north coast of Nuussuaq (Hansen, 1980), part of the intra-volcanic clastic sediment from south-west Nuussuaq (Piasecki et al., *1992)*, and the lower sedimentary unit from GANW#1 at Marraat are all of NP 5 age (early Thanetian/early Late Paleocene).

SAMPLES

Most of the analysed samples were collected during the drilling activities and transported back to Copenhagen as hand luggage or as air freight. Additional material for analysis was taken from the complete core that was shipped back to Copenhagen, where it arrived in early December 1994.

Core pieces of sedimentary or volcanic rocks were either wrapped in aluminium foil or sealed in small brown 200 ml glass bottles in order to avoid contamination. Water samples were collected in 500 l Duran glass bottles, gas samples in a steel cylinder or by syringes and injected to 'venoject' glass collecting tubes.

In addition to these geological samples a number of potential contaminants were also collected, e.g. fuel, rod grease, ball bearing grease, crayons used for marking of cores and various muds. Organic geochemical analysis of these materials has been and is still being carried out for comparison with not only the GANW#1 core material but also with other cores drilled by Falconbridge Ltd. with the same rig earlier during the summer of 1994. There seem to be serious problems with contamination, and cores pieces with a low extractability of

organic material often show signs of refined oil products which seem to have originated from a typical marine oil. However, samples with a reasonably high extractability, such as the analysed sediments, do not show any evidence of this contamination, probably due to dilution.

ANALYTICAL METHODS

The sample material was analysed at the Geological Survey of Denmark, the methods including the following:

1) Leco/RockEval pyrolysis (n = 34).
2) Vitrinite reflectance (n = 4).
3) Extraction in a Soxtech apparatus with subsequent deasphalting and column separation into saturated and aromatic hydrocarbons and NSO compounds (n = 5).
4) Analysis of saturated hydrocarbons by gas chromatography (GC) and gas chromatography/mass spectrometry (GC/MS) (n = 5).
5) Head space gas composition (n = 8), C and H isotopes of methane, ethane and propane (n = 1).
6) Water geochemistry, measurement of pH, alkalinity, major anions and cations (n = 6).

Details on some of the analytical methods are given by Bojesen-Koefoed (1989) and Christiansen *et al.* (1989).

RESULTS OF ORGANIC GEOCHEMISTRY

LECO/Rock Eval pyrolysis and vitrinite reflectance

Of the total of 34 samples analysed by LECO/Rock Eval pyrolysis, six are from the upper sedimentary unit (483–497.5 m) and the remaining 28 are from the lower sedimentary unit (624.5–657.85 m). Data are given in Table 3 and shown graphically on the log in Fig. 6. Here it is clearly demonstrated that there is a considerable variation in thermal maturity within the lower sedimentary unit, whereas the few analysed samples from the upper unit have a low content of TOC (Total Organic Carbon) and poorly defined thermal maturity parameters.

The T_{max} values, which generally are excellent thermal maturity indicators, show a distinct variation. Most T_{max} values are between 437° and 444°C which corresponds to the upper part of the oil window. A number of samples show much higher values, or do not define values,

which indicates a strong thermal alteration caused by the sill/dyke in the interval from 633 to 636 m. Slightly increased T_{max} values between 446° and 456°C are noted at some metres distance from the sill/dyke (Fig. 6). The thickness of this thermal aureole is greater than expected for a sill with a thickness of only 3 m. However, the orientation and true dimension of the intrusion is not known.

The general background in thermal maturity is further supported by the four recorded vitrinite reflectance values which are in the range 0.6-0.8% with a distinct gradient approaching the sill. It is interesting to note that the thermal maturity does not seem to increase towards the overlying hyaloclastite suggesting that volcanic material had cooled before settling in its final position of rest on the sea floor.

Generally the content of total organic carbon (TOC) in the upper sedimentary unit is very low, with values between 0.1 and 0.6%. With the exception of one sample, the lower sedimentary unit shows higher values between 2 and 3 %. The Hydrogen Index (HI) is lower than 100 in all the samples, typically between 70 and 90. HI values are lower in the mature to postmature sediments closest to the sill (Fig. 6). The maximum value of only 100 suggests that an oil source rock is not present and that there is only a minor potential for gas.

Extraction, bulk composition

Oil-impregnated basalts

So far only one sample of oil-impregnated basalt (a partly mineral-filled fracture zone in a hyaloclastite) has been extracted (Table 4). Additional analyses are under completion. The sample in question is from a depth of 301.7 m, and especially the interval below contains a number of oil-filled fractures.

The extract is comparable to other Marraat oils with a rather low content of asphaltenes and a dominance of saturated over aromatic hydrocarbons (Table 4).

Sediments

The extracts of the four mudstones are relatively homogeneous with moderate to high extractabilities between 24 and 53 mg SOM/g TOC (Table 4). All the samples have a high concentration of asphaltenes and the deasphaltened extracts are dominated by NSO compounds (Table 4). Saturated and aromatic hydrocarbons occur in almost equal amounts. Such a bulk composition is common in mudstones with a low thermal maturity and a high content of terrestrially derived organic matter. With increasing thermal maturation the concentration of hydrocarbons, especially saturated hydrocarbons, will increase.

Table 3. LECO/Rock Eval pyrolysis and vitrinite reflectance data

GGU No.	Depth (m)	TOC (%)	S1	S2	HI	T_{max} (°C)	R_o (%)	n
380101-59	484.7	0.21	0.01	0.03	15			
380101-60	486.9	0.09	0.01	0.00				
380101-55	487.6	0.57	0.05	0.13	23	445		
380101-56	488.3	0.54	0.05	0.13	24	446		
380101-57	491.3	0.14	0.03	0.00				
380101-58	492.6	0.52	0.08	0.02	4			
380101-30	624.8	2.41	0.23	2.14	89	437		
380101-31	627.2	2.99	0.30	2.87	96	440		
380101-15	628.0	2.92	0.29	2.82	96	437	0.62±0.26	(79)
380101-32	630.0	2.08	0.15	1.32	64	443		
380101-33	630.9	2.07	0.14	0.96	46	443		
380101-34	631.0	2.66	0.22	1.72	65	449		
380101-35	631.7	2.26	0.24	0.69	31	455		
380101-36	632.4	2.03	0.22	0.46	23	530		
380101-37	632.8	2.15	0.17	0.25	12	527		
380101-38	636.3	0.65	0.14	0.16	25			
380101-39	644.4	3.22	0.47	1.34	42	456		
380101-40	645.7	2.03	0.22	1.06	52	449		
380101-41	646.8	2.15	0.18	1.26	59	448		
380101-42	647.3	2.25	0.19	1.32	59	446		
380101-17	647.5	3.17	0.30	2.41	76	444	0.83±0.06	(57)
380101-43	648.0	2.89	0.23	1.63	56	444		
380101-18	648.8	3.14	0.39	3.17	100	442	0.74±0.07	(69)
380101-44	649.4	3.06	0.29	2.30	75	442		
380101-45	650.0	2.72	0.25	1.77	65	444		
380101-19	650.3	2.48	0.26	1.75	70	441	0.73±0.08	(79)
380101-46	650.7	2.32	0.16	1.33	57	442		
380101-47	651.8	2.76	0.30	1.94	70	444		
380101-48	651.9	2.78	0.25	1.99	72	444		
380101-49	652.6	2.92	0.30	2.22	76	442		
380101-50	653.1	2.68	0.28	1.93	72	442		
380101-51	654.0	3.04	0.28	2.61	86	443		
380101-52	654.8	2.97	0.27	2.52	85	440		
380101-53	655.7	2.43	0.16	1.58	65	442		
380101-54	656.2	2.19	0.15	1.35	62	442		

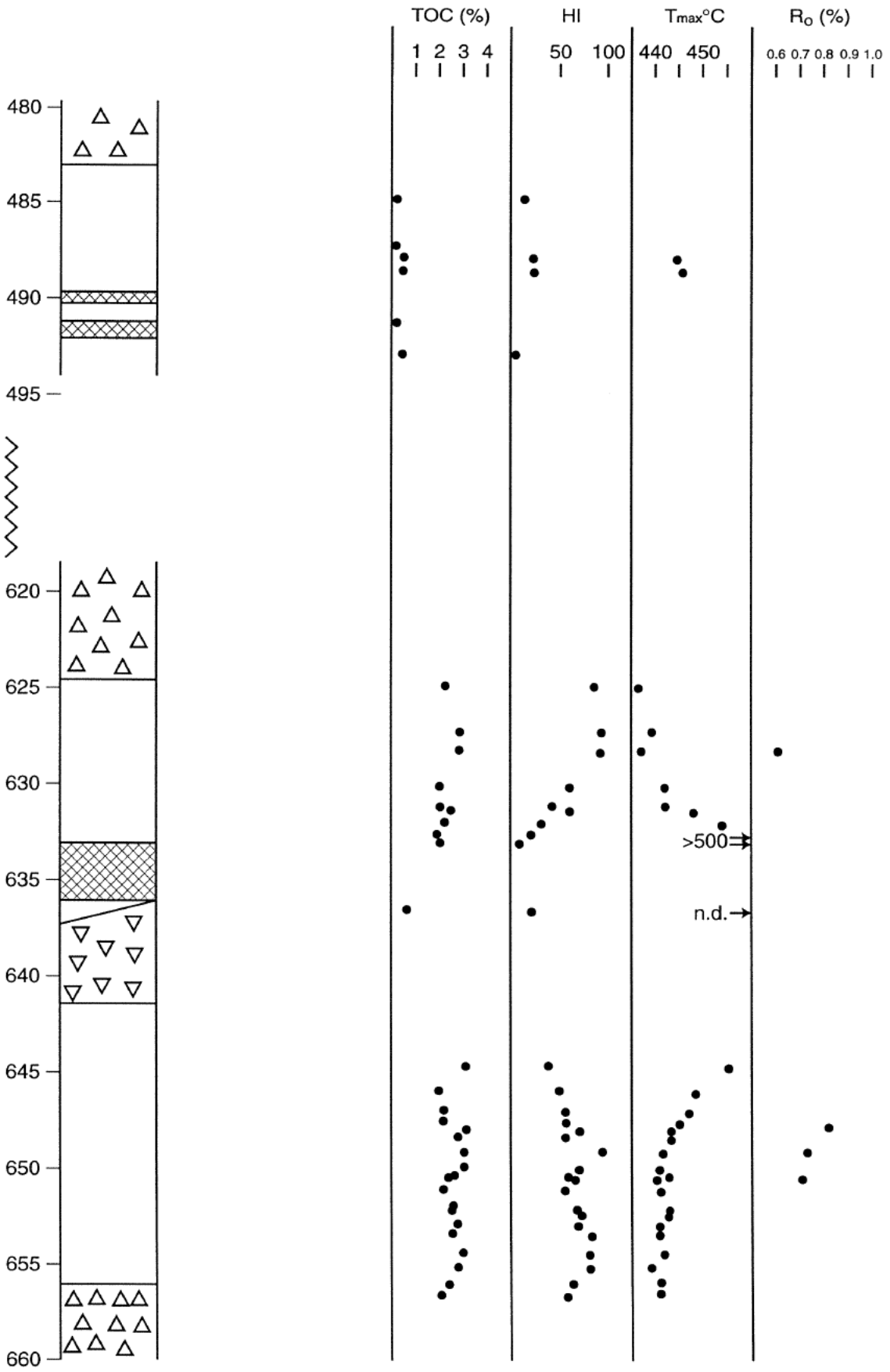

Fig. 6. Simplified log of the upper and lower sedimentary units with analytical screening data (TOC, HI, T_{max}, R_o).

Gas Chromatography (GC) and Gas Chromatography/Mass Spectrometry (GC/MS) of saturated hydrocarbons

Oil-impregnated basalts

The gas chromatogram of the saturated hydrocarbons from the oil-filled fracture in the basalt is shown in Fig. 7a and the calculated ratios are given in Table 5. This sample is very similar in composition to other oils from the Marraat area (see Christiansen *et al.*, 1994a, ms) and is characterised by a high Pr/Ph ratio, a high waxiness and a moderate odd-even predominance. The degree of degradation is low with the exception of some light-end evaporation (*n*-alkanes shorter than 16).

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) for the terpanes. Fig. 8a shows the terpane and sterane distributions; some of the parameters providing information on thermal maturity and depositional environment are listed in Table 6 and 7.

The biomarker distribution is this sample is very similar to all other analysed oils from the Marraat area (Christiansen *et al.*, 1994a, ms). The biomarkers distribution is very distinct, especially due to the high concentration of bisnorlupane and oleanane. Furthermore a number of biomarkers suggest a relatively low thermal maturity (upper part of 'oil window') and that the source is a typical deltaic mudstone of latest Cretaceous or Early Tertiary age (see details in Christiansen *et al.*, 1994a, ms).

Sediments

The gas chromatograms of the saturated hydrocarbons from the four analysed mudstone samples are shown in Fig. 7b–e and the calculated ratios given in Table 5. The samples are rather similar, all suggesting a significant input of terrestrial organic matter and a relatively low thermal maturity. The maturity-dependent parameters such as Pr/*n* C17, CPI, Philippi values and waxiness follow the same pattern as indicated by T_{max} values and vitrinite reflectance, with 380101-15 being the most immature sample. The terrestrial fingerprint is especially evident from the high Pr/Ph values between 6 and 7 and the distinct odd-even predominance (Fig. 7b–e, Table 5). It is remarkable that one of the biomarkers, bisnorlupane, occurs in such high concentrations that it is observed in the gas chromatograms.

The distribution of biomarkers in the saturated fractions has been studied by using m/z 217 (and 218) mass fragmentograms for the steranes and m/z 191 (and 177) for the terpanes. Generally the terpanes occur in much higher concentrations than the steranes. Fig. 8b–e show

Table 4. Extraction data

GGU No.	Depth (m)	Extract[1]	Asph (%)	Sat (%)	Aro (%)	NSO (%)	Sat/Aro
380101-05	301.7	n.a.	6.5	64.1	8.8	27.2	7.3
380101-15	628.0	53	52.6	18.6	20.6	60.8	0.9
380101-17	647.5	24	46.3	17.2	17.2	65.5	1.0
380101-18	648.8	27	42.2	12.9	19.4	67.7	0.7
380101-19	650.3	26	57.5	10.0	12.5	77.5	0.8

1: (mg SOM/g TOC)
n.a.: not available

Table 5. Gas chromatography data

GGU No.	Depth	Pr/Ph	Pr/*n*C17	Pr/*n*C18	Iso/*n*C	CPI	Philippi	Waxiness
380101-05	301.7	4.20	0.69	0.13	0.19	1.19	1.44	0.66
380101-15	628.0	6.54	5.95	0.99	1.79	1.56	2.07	2.16
380101-17	647.5	6.17	2.72	0.45	0.85	1.37	1.87	0.50
380101-18	648.8	6.46	3.40	0.56	1.04	1.44	1.97	0.67
380101-19	650.3	6.87	3.27	0.48	0.94	1.33	1.76	0.49

Table 6. GC/MS data on thermal maturity

GGU No.	Depth (m)	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
380101-05	301.7	0.15	0.95	0.59	0.60	0.86	0.44	0.40
380101-15	628.6	0.01	0.94	0.59	0.61	0.64	n.a.	n.a.
380101-17	647.5	0.01	0.97	0.59	0.62	0.62	(0.51)	(0.38)
380101-18	648.8	0.01	0.96	0.61	0.62	0.64	(0.51)	(0.41)
380101-19	650.3	0.01	0.95	0.60	0.59	0.62	(0.52)	(0.46)

n.a.: not available

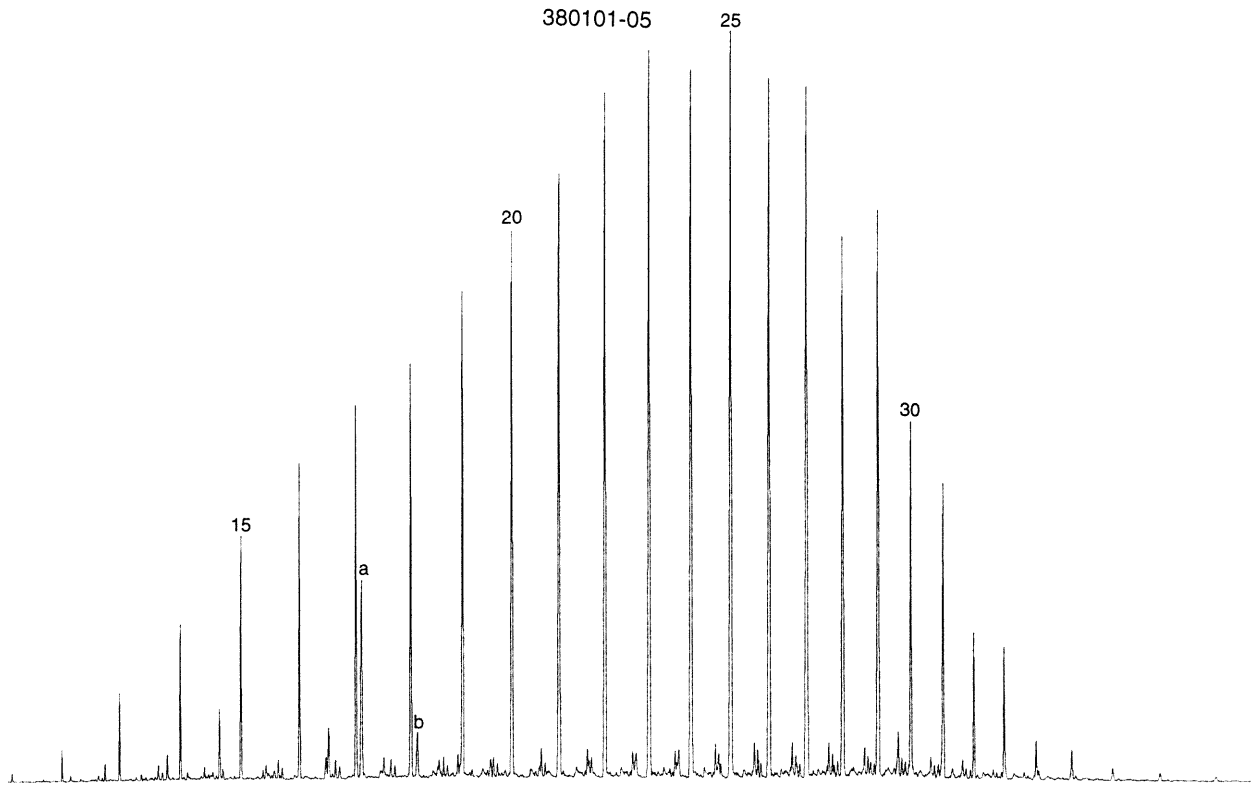

Fig. 7a. Gas chromatogram of saturated hydrocarbons.
a: pristane, b: phytane, the numbers are *n*-alkane carbons numbers.

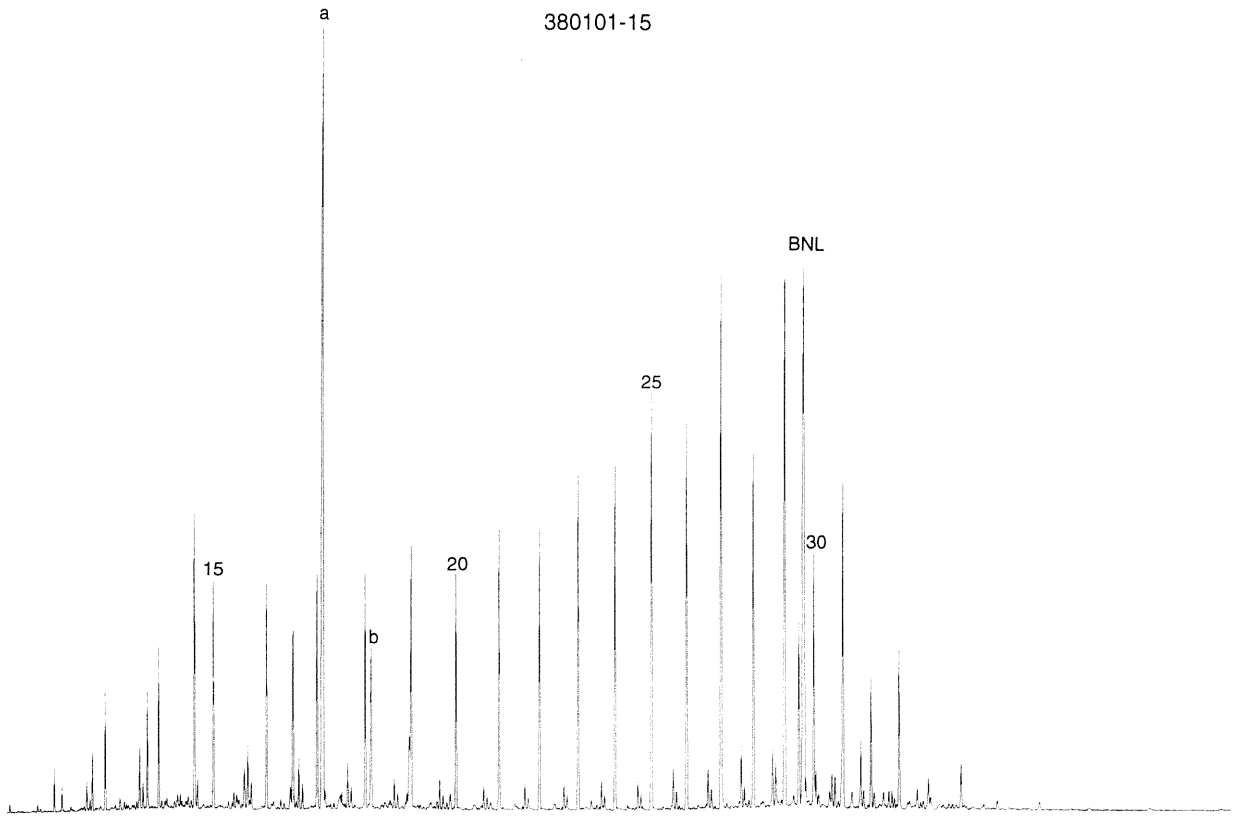

Fig. 7b. Gas chromatogram of saturated hydrocarbons.
a: pristane, b: phytane, the numbers are *n*-alkane carbons numbers.

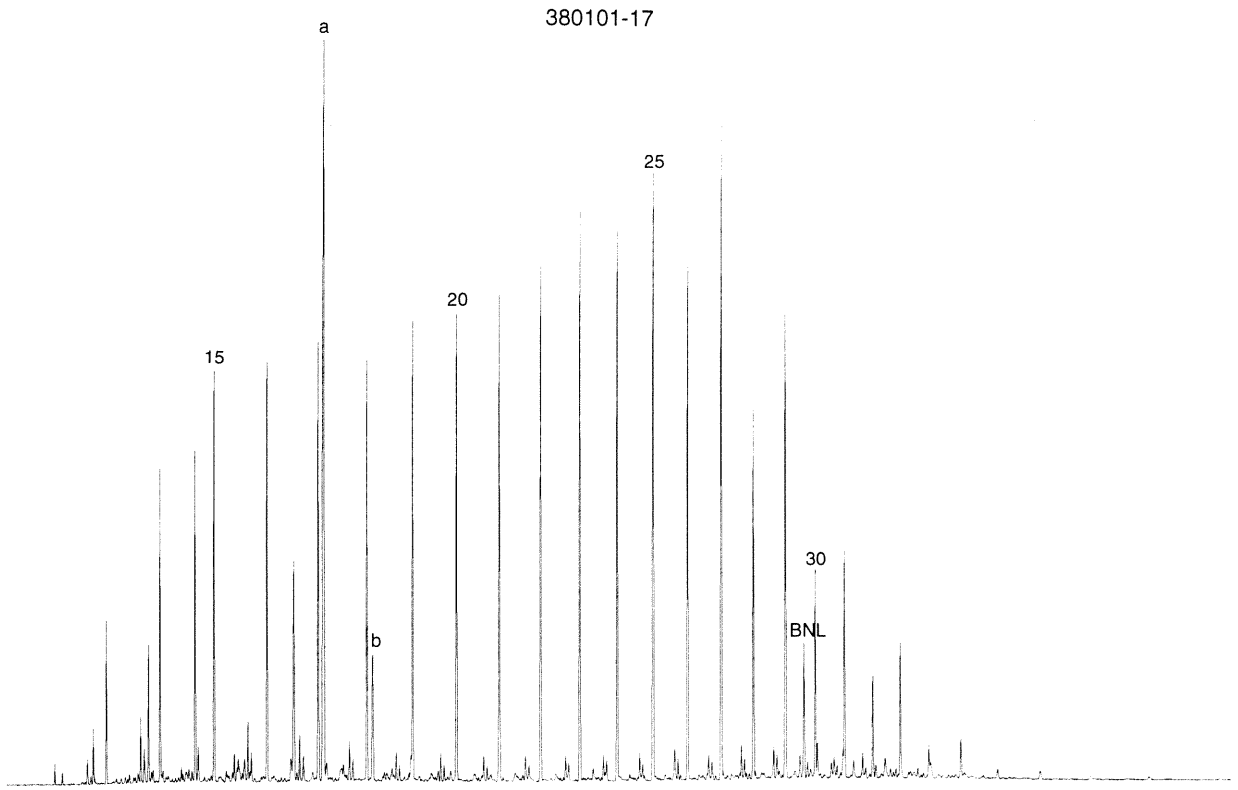

Fig. 7c. Gas chromatogram of saturated hydrocarbons.
a: pristane, b: phytane, the numbers are *n*-alkane carbons numbers.

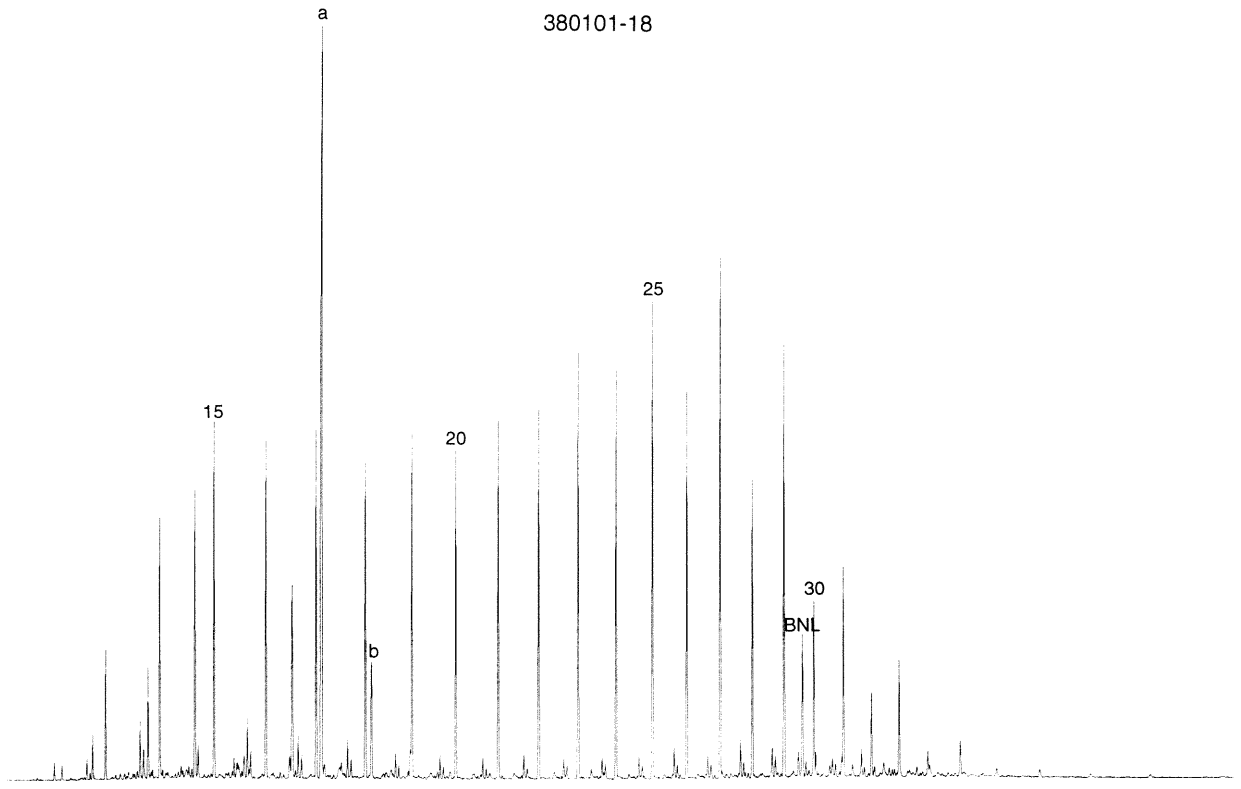

Fig. 7d. Gas chromatogram of saturated hydrocarbons.
a: pristane, b: phytane, the numbers are *n*-alkane carbons numbers.

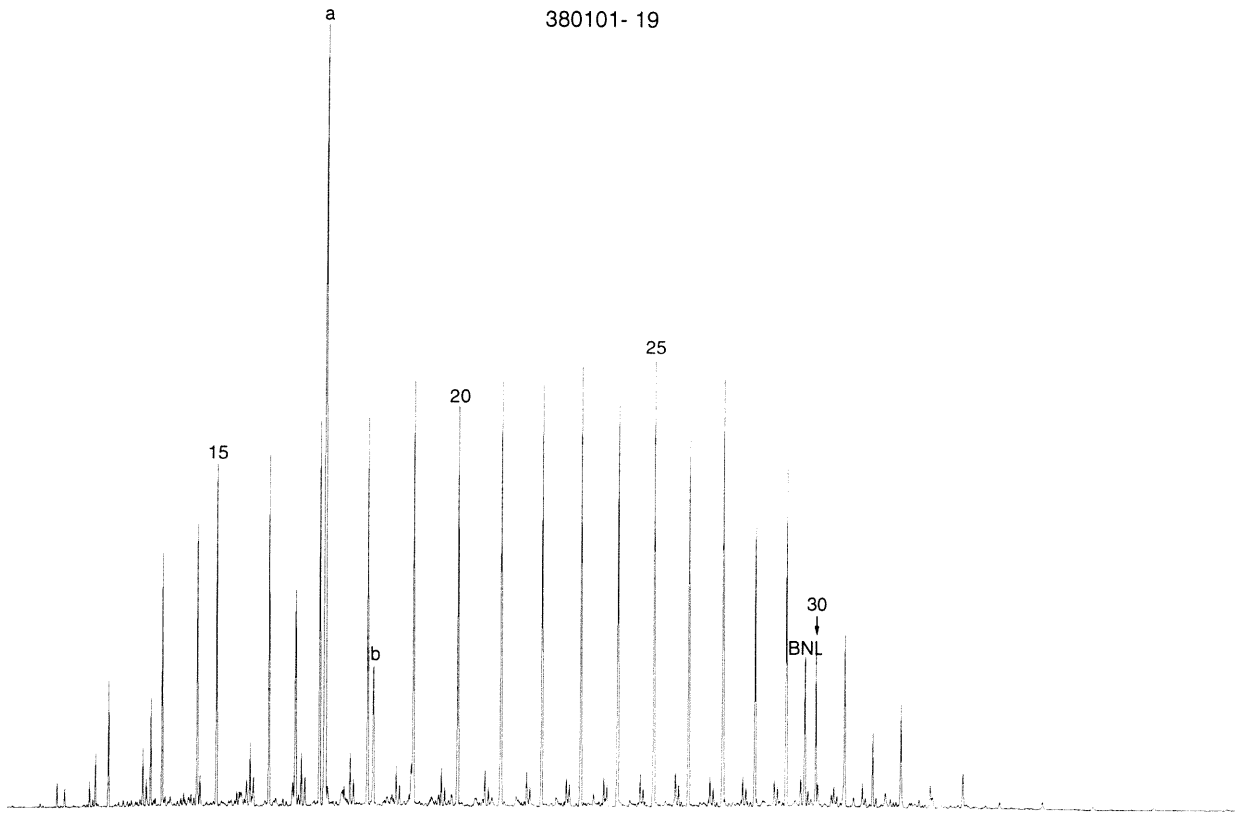

Fig. 7e. Gas chromatogram of saturated hydrocarbons.
a: pristane, b: phytane, the numbers are *n*-alkane carbons numbers.

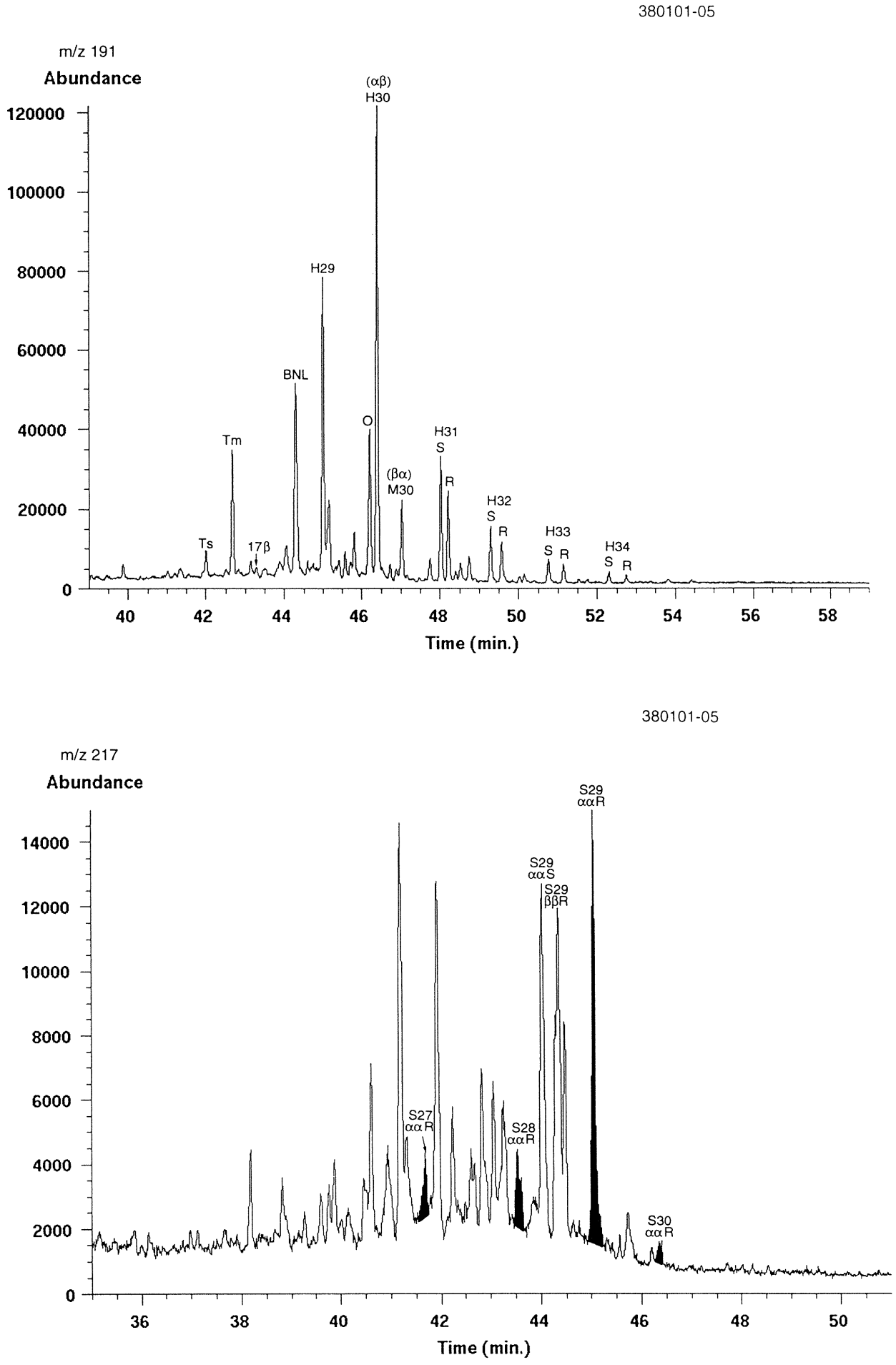

Fig. 8a. Mass chromatograms of terpanes (m/z 191) and steranes (m/z 217).
The Compound assignment is explained in Table 10.

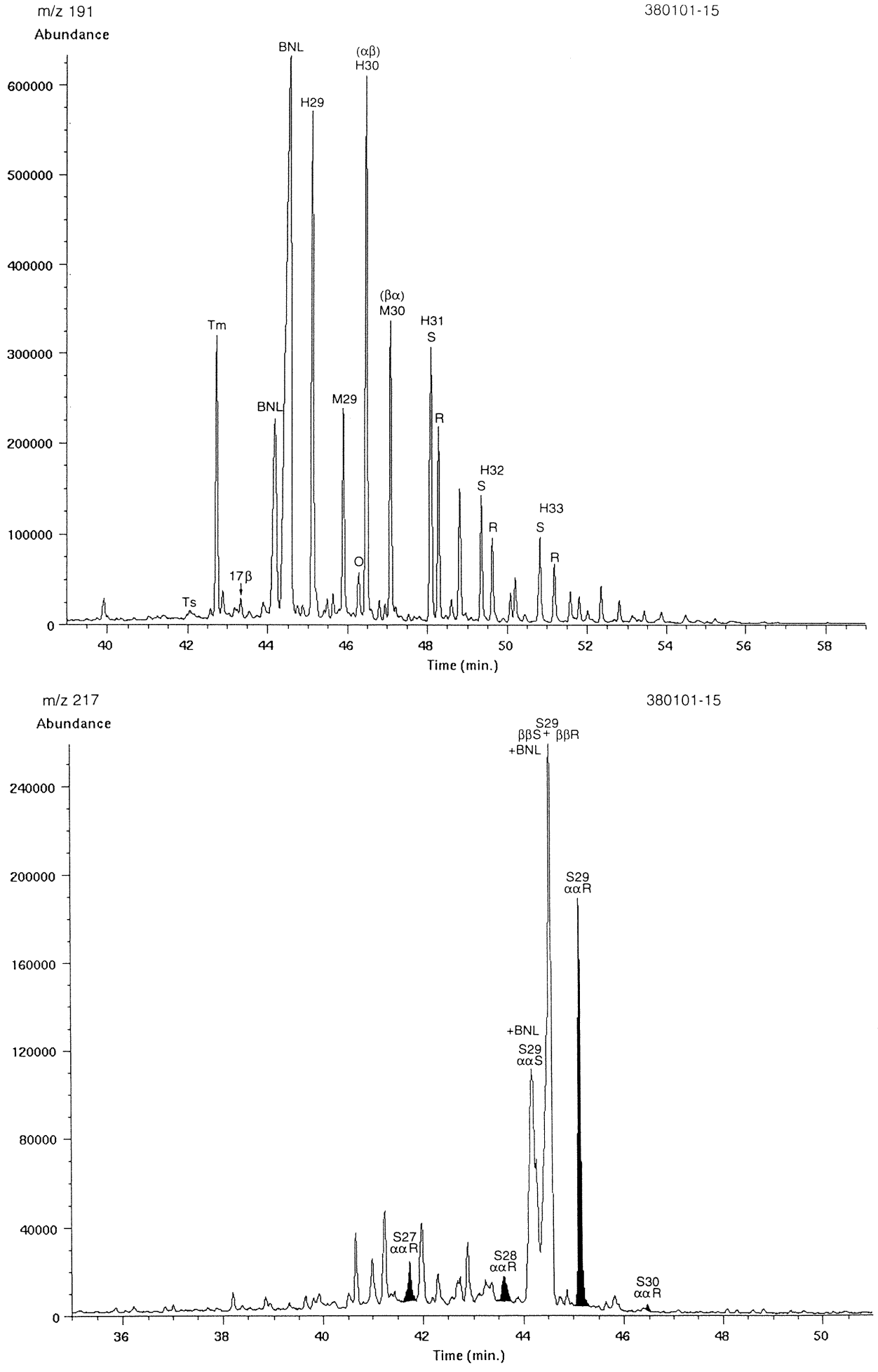

Fig. 8b. Mass chromatograms of terpanes (m/z 191) and steranes (m/z 217).
The Compound assignment is explained in Table 10.

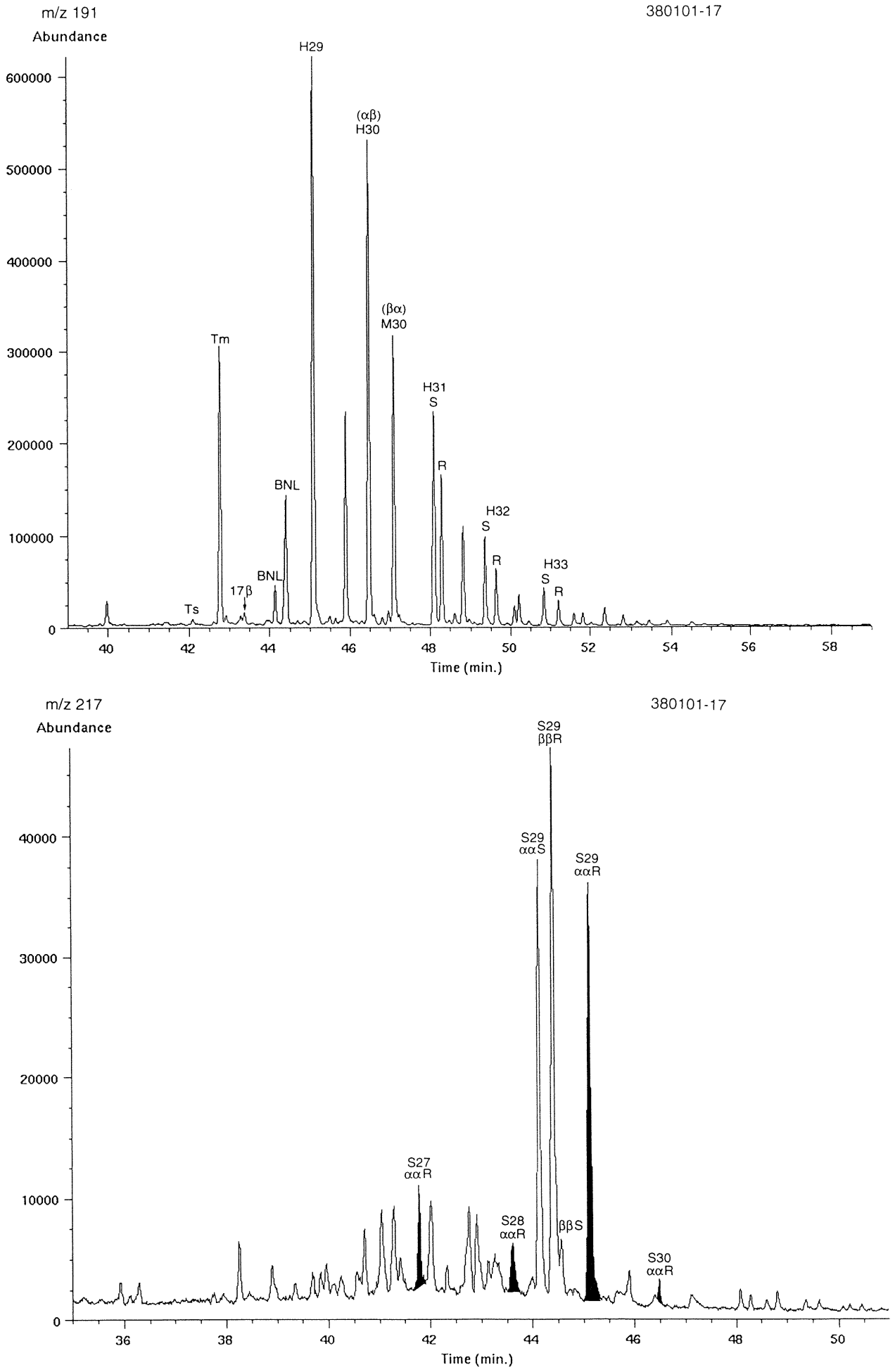

Fig. 8c. Mass chromatograms of terpanes (m/z 191) and steranes (m/z 217).
The Compound assignment is explained in Table 10.

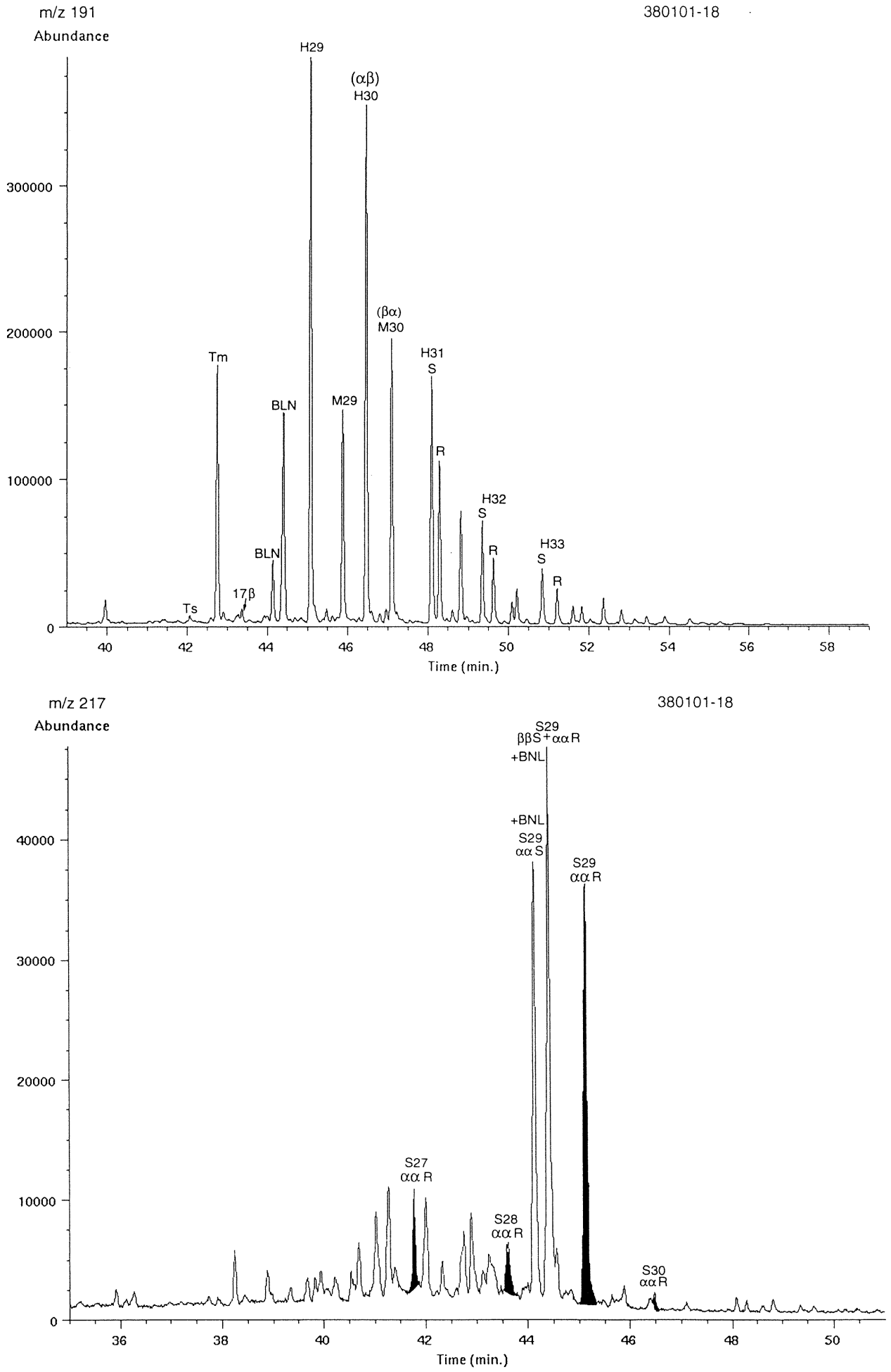

Fig. 8d. Mass chromatograms of terpanes (m/z 191) and steranes (m/z 217).
The Compound assignment is explained in Table 10.

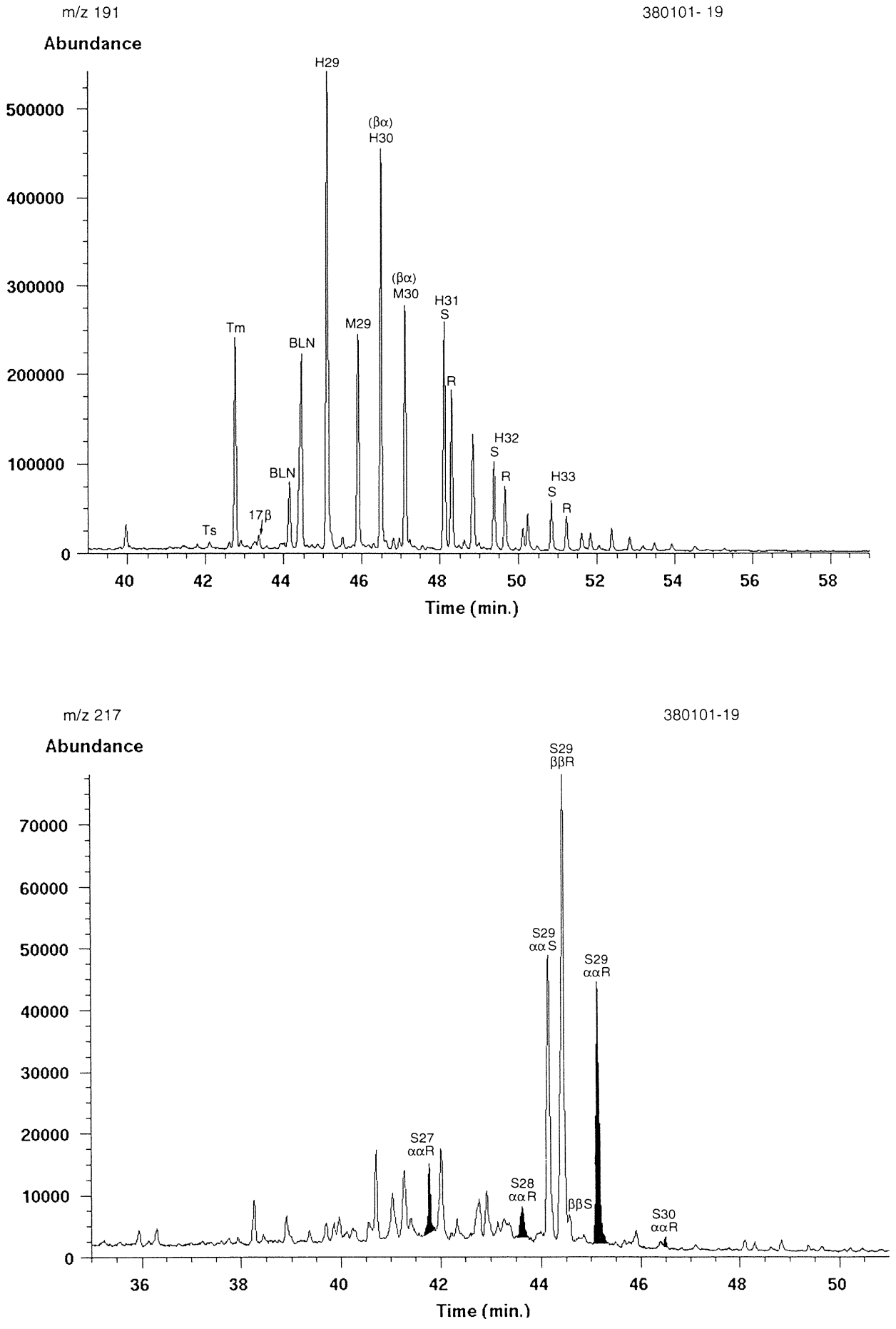

Fig. 8e. Mass chromatograms of terpanes (m/z 191) and steranes (m/z 217).
The Compound assignment is explained in Table 10.

the terpane and sterane distributions; some of the parameters providing information on thermal maturity and depositional environment are listed in Tables 6 and 7.

The terpanes are dominated by pentacyclics (hopanes, moretanes and a few other compounds), whereas the tricyclic triterpanes only occur in very low concentrations. H29 and H30 occur in almost equal amounts whereas the extended hopanes show rapidly decreasing contents with increasing carbon number. Both the H31 and H32 have reached equilibrium of isomerisation with 22S/22S+22R values close to 0.6 (Table 6). Ts occurs in very low concentration compared to Tm. The concentration of moretanes is relatively high with ratios of $\alpha\ \beta\ /\beta\ \alpha+\alpha\ \beta$ between 0.62 and 0.64. The most distinct biomarker is bisnorlupane which occurs in very high concentrations, especially in the most immature sample 380101-15. Two isomers, probably 17α(H)-23,28 bisnorlupane and 17β(H)-23,28 bisnorlupane (Rullkötter *et al.*, 1982), are present. The high concentration of bisnorlupane causes some problems since this compound is also noted in the 217 mass fragmentogram where it coelutes with the $\alpha\ \alpha$ S C29 steranes. Therefore the ubiquitously applied sterane isomerisation maturity indicator cannot be calculated. The steranes are completely dominated by C29 steranes, however, C30 steranes are present in minor amounts (Table 7).

Depositional environment of mudstones, geochemical evidence

The previous studies of the Marraat oil have provided some clear geochemical fingerprints of the source rock and its depositional environment (Christiansen *et al.*, 1994a, ms). The analysed sediments in the present study do share some organic geochemical characteristics with the Marraat oil but it is quite obvious that they *not* the source for the oil.

The mudstones penetrated clearly were deposited in a marine environment as indicated by the sedimentology and the presence of marine dinoflagelates and corals. A number of biomarkers and especially the presence of C30 steranes also suggest a marine influence; however, most parameters indicate a strong input of terrestrially derived organic matter. In general most parameters suggest that the mudstones are even more dominated by terrestrial material than the source rock for the Marraat oil.

The two biomarkers oleanane and bisnorlupane are important for correlation but their environmental significance as more or less marine versus terrestrial is not fully understood. Oleanane is only present in minor amounts whereas the rare biomarker bisnorlupane is present in the sediments in even higher concentrations than in the Marraat oil.

Based on the available material it seems most likely the source rock for the Marraat oil was deposited under more marine conditions than the mudstones in the GANW#1 well core, indicating that if they have the same age, the source rock for the Marraat oil is most likely to be found farther to the south-west, west or north-west.

Thermal maturity

The analysed oil impregnation and the analysed sediments provide some very important data on the thermal maturity of the subsurface in the Marraat area.

The analysed oil impregnation from ~302 m is within the same maturity range as all other analysed oil samples from the Marraat area. All these samples, whether they came from deeper than 400 m below sea level in the Marraat-1 well or higher than 1000 m above sea level ~8 km northeast of the drill site, suggest that the source rock for the oil is (or was) in the upper (shallower) part of the oil window.

The sediments penetrated between 624.55 m and 657.85 m depth in the GANW#1 well show some variation in maturity. However, this variation is clearly related to thermal alteration from the sill/dyke which occurs between 633 and 636 m. The background maturity suggests a situation before or close to onset of oil generation (T_{max} ~437°C, R_o ~0.6%). Compared in detail, a number of biomarker maturity indicators suggest that these mudstones have a *lower* thermal maturity than the source rock which generated the Marraat oil (note the higher CPI and Philippi ratios, higher Pr/*n*C17, the higher content of bisnorlupane and with two isomers present, the very low concentration of Ts and the higher concentrations of moretanes in the sediment extracts compared to the oil). Some parameters do not show any difference (e.g. hopane isomerisation and relative amount of 17β(H) trisnorhopane), whereas the sterane parameters are difficult to interpret due to coelution with bisnorlupane.

Based on the present data it can be concluded that there is a good chance that the sediments underlying the base of the volcanics are in the early or middle part of the oil window. Neither source rock 'overcooking' nor oil reservoir cracking are likely to have taken place in a zone at least one kilometre thick below present TD of the GANW#1 well.

GAS GEOCHEMISTRY

Gas under pressure was recorded at several levels in the Marraat-1 and the GANW#1 wells. Furthermore, evidence of gas seepage has been noted during field work in 1991–94 on Disko, Nuussuaq and Svartenhuk Halvø, and gas was also discovered by Falconbridge Ltd. in 1994 during drilling in a mineral exploration programme on the north coast of Nuussuaq.

One of the major problems in the interpretation of data from these various sources of gas is the sampling technique. Natural gas easily becomes mixed with atmospheric air, and chromatographic separation (relative loss of methane) and fractionation of gases (loss of light isotopes) have been documented for some of the gas containers (unpublished DGU and GGU studies in progress).

The analysed gas from the Marraat-1 hole was mainly taken from bottles of formation fluids, whereas most of the other gases seeping to the surface in pingos (from the Aaffarsuaq valley on Nuussuaq and the Kuganguaq valley on Disko) or lakes (Gassøen, ~6km NE of Marraat) were collected in cans with a high risk of contamination or degradation. Some of the parameters from these samples have, however, been included in Fig. 9 but the analytical data are not listed here.

One sample from the GANW#1 well (GGU No. 380105) from a depth of 721 m, was properly sampled from the well head in a steel cylinder and a full suite of analyses has been carried out on this (Fig. 8, Table 8). The analytical data show some contamination with atmospheric air (~16%). It has been possible to measure the head space composition of a normal series of organic gases up to iso and normal butane; furthermore the carbon isotopic compositions of methane, ethane and propane have been analysed (Table 8).

The gas has a moderate wetness and a hydrogen and carbon isotope composition of methane that clearly suggest a thermogenic origin (Figs 9 and 10). Applying the empirical relations between methane, ethane and propane isotope composition given by either Faber (1987) and Jenden & Kaplan (1989), the gas seems to have an origin from a source rock with a low thermal maturity and a dominance of type III kerogen (Figs 11 and 12).

Such a low maturity for the gas is comparable with the low maturity of the Marraat oil (see discussion above and details in Christiansen *et al.,* 1994a, ms). This suggests that the oil and gas may be closely associated, although the values based on methane suggest that this oil-associated gas may be mixed with minor amounts of biogenic gas.

Table 7. GC/MS data on depositional environment

GGU No.	Depth (m)	BNL*/H30	H29/H30	O/H30	(%ααR) S27	(%ααR) S28	(%ααR) S29	(ααR) S27/S29	(ααR) S30/SUM
380101-05	301.7	0.39	0.63	0.63	11	13	76	0.15	0.04
380101-15	628.6	1.40	0.93	0.08	9	5	86	0.10	0.01
380101-17	647.5	0.33	1.19	0.00	18	9	73	0.24	0.04
380101-18	648.8	0.53	1.11	0.00	18	9	73	0.25	0.03
380101-19	650.3	0.65	1.19	0.00	20	7	77	0.27	0.02

* both isomers

Table 8. Gas composition. Heads space analysis (%) and stable isotope composition

GGU No.	Depth (m)	O_2	N_2	CO_2	CH_4	C_2H_6	C_3H_8	iC_4H_{10}	nC_4H_{10}
380105	721	2.87	13.91	0.03	83.22	0.61	0.13	0.015	0.010

GGU No.	Depth (m)	δ^2H CH_4	$\delta^{13}C$ CH_4	$\delta^{13}C$ C_2H_6	$\delta^{13}C$ C_3H_8
380105	721	-199	-43.3	-28.1	-27.1

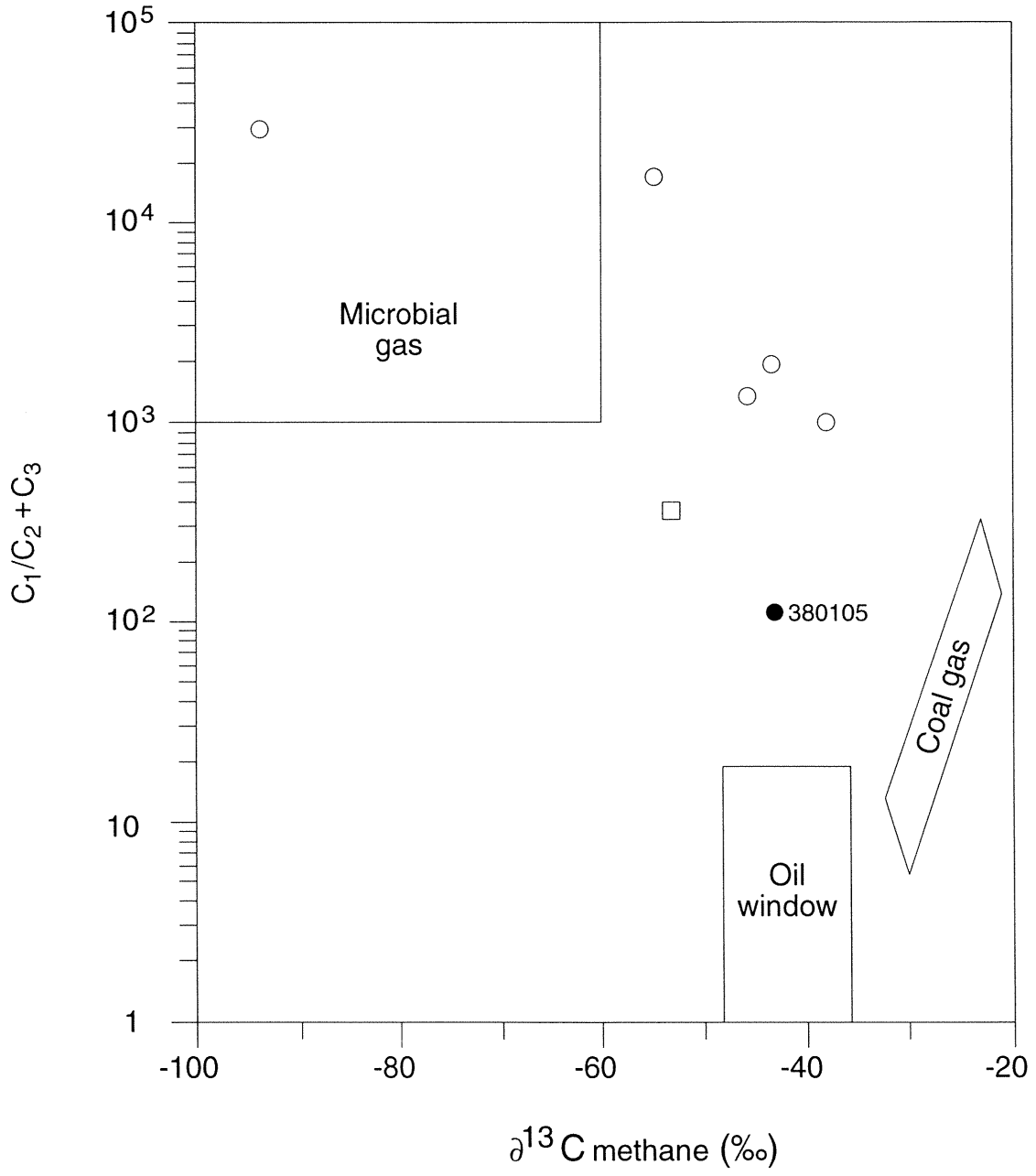

Fig. 9. C1/C2+C3 (= 'wetness') versus C-isotope composition of methane. The compositional fields are modified from Schoell (1984). Filled circle: GANW#1, Filled squares: Marraat-1, Open circles: Various pingos.

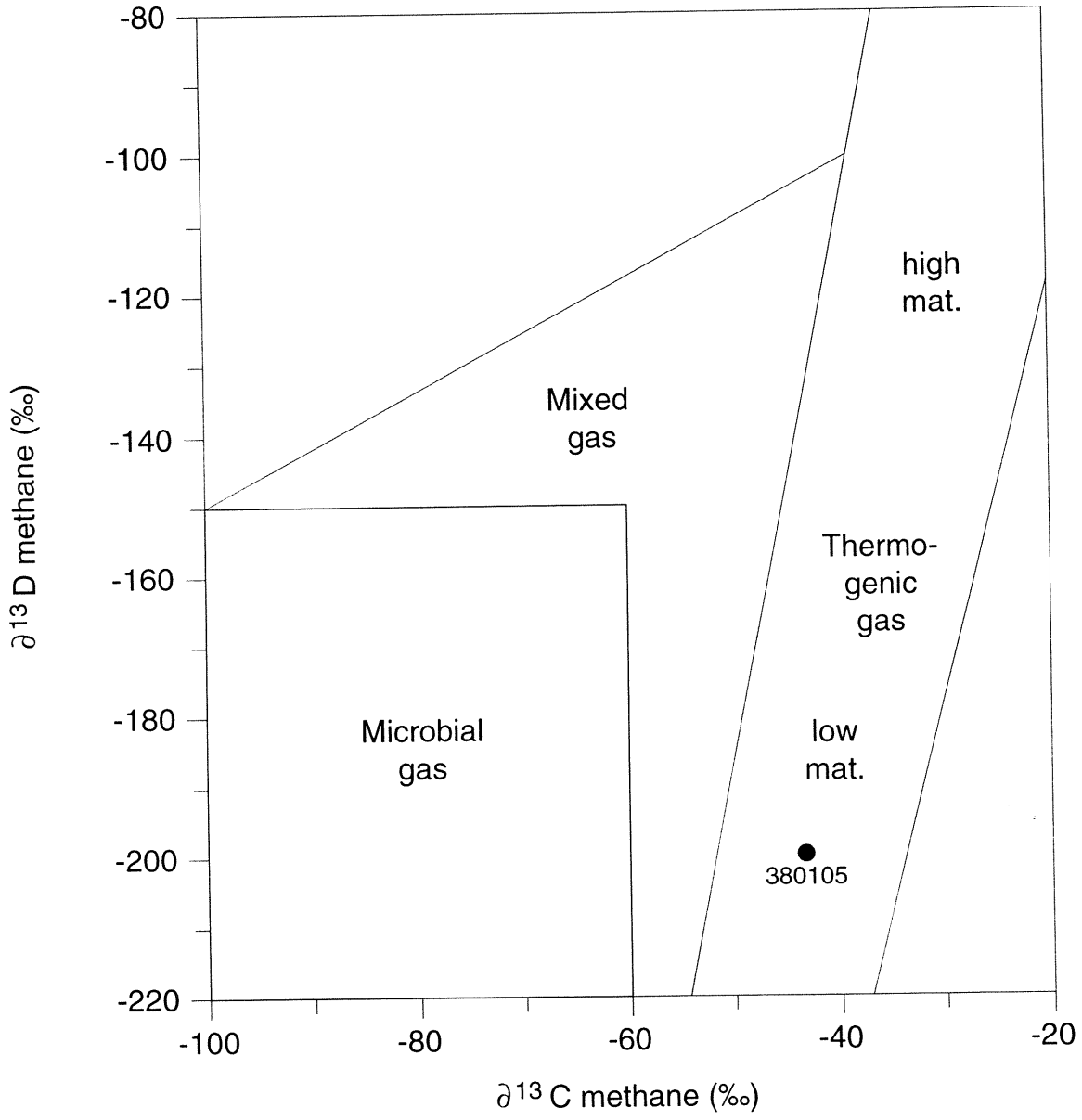

Fig. 10. C-isotope versus H-isotope composition of methane. The compositional fields are modified from Jenden & Kaplan (1989).

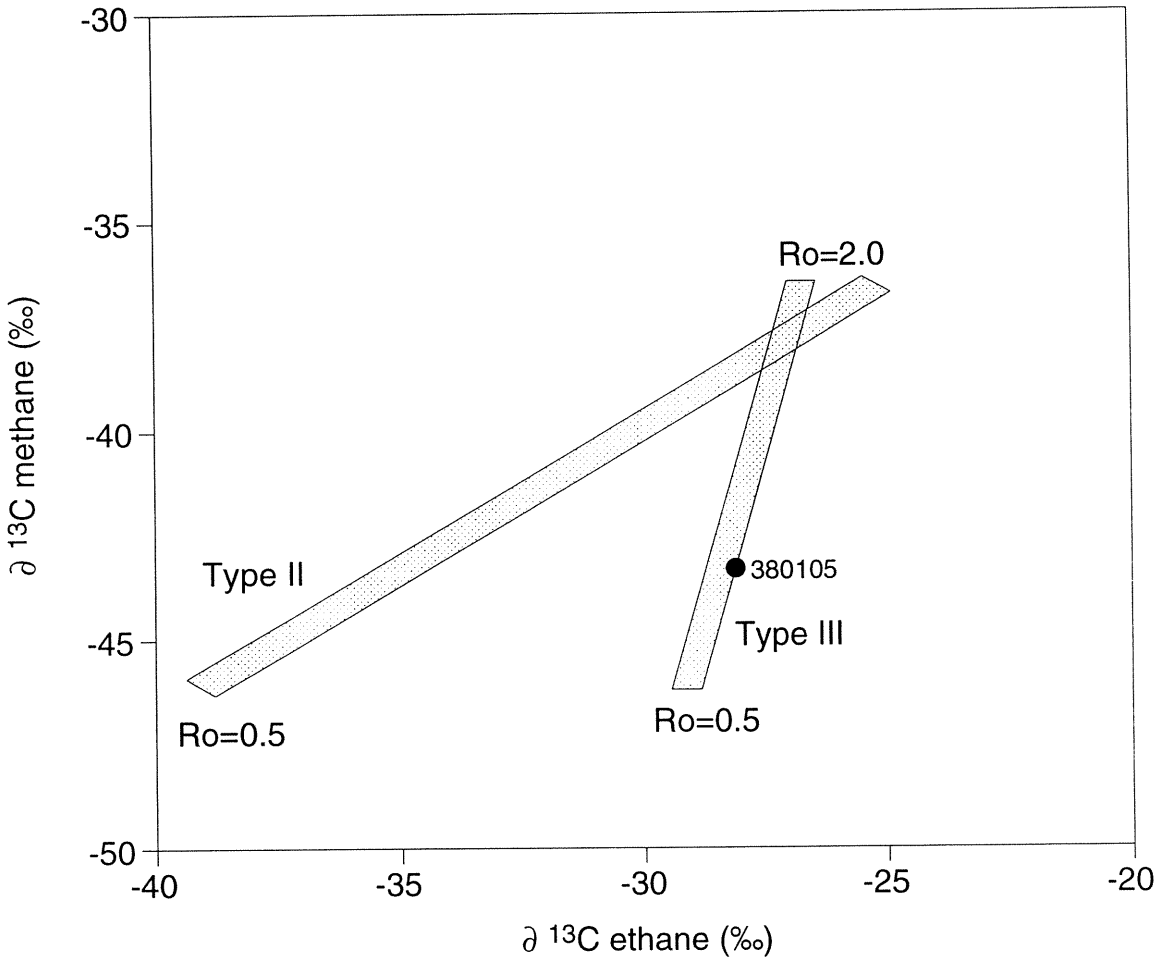

Fig. 11. C-isotope composition of methane versus ethane. Maturity lines are calculated from Faber (1987) for Type II kerogen and from Jenden & Kaplan (1989) for Type III kerogen.

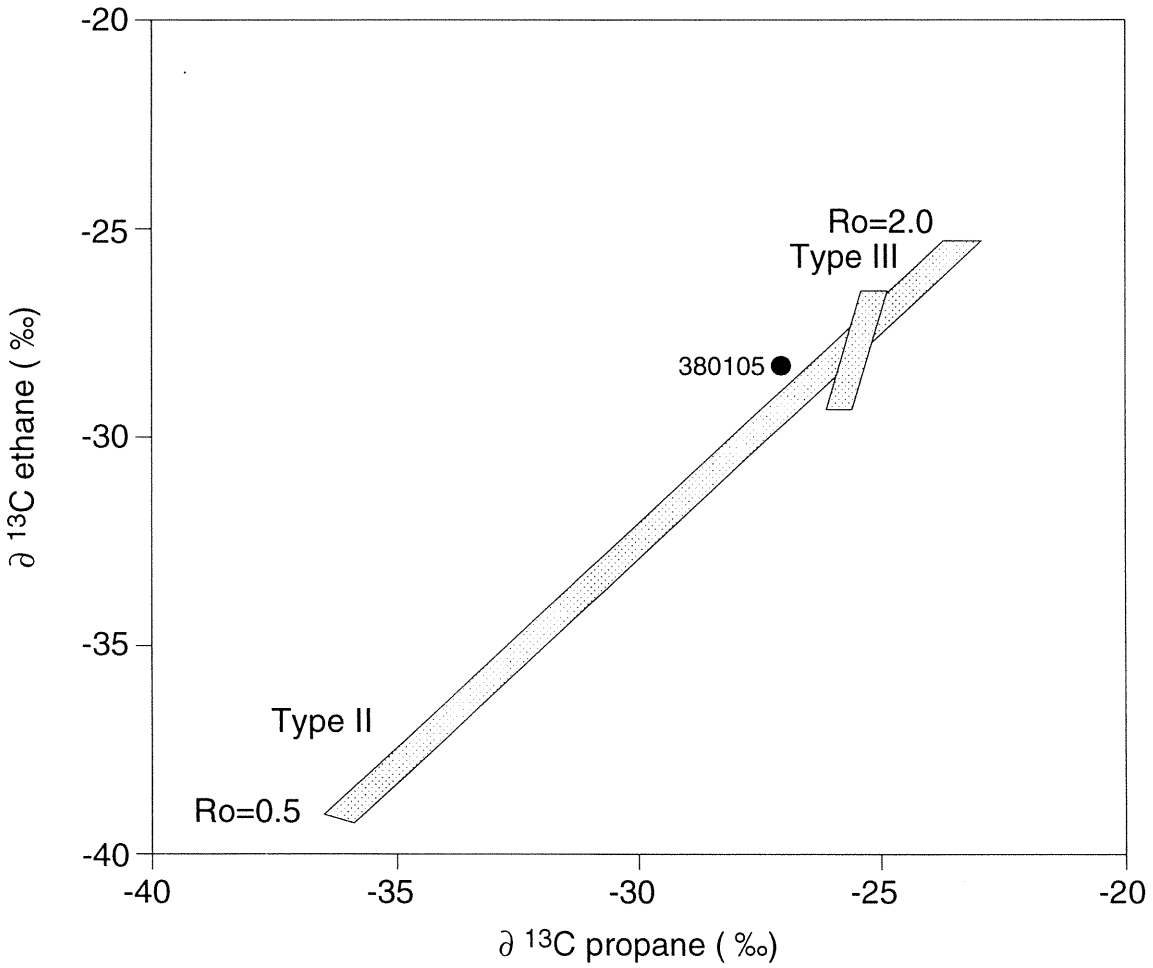

Fig. 12. C-isotope composition of ethane versus propane. Maturity lines are calculated from Faber (1987) for Type II kerogen and from Jenden & Kaplan (1989) for Type III kerogen.

WATER CHEMISTRY

Water under pressure was recorded both in the Marraat-1 and the GANW#1 wells. The waters were sampled at the surface (from the flare line); in the Marraat-1 hole the actual formation waters were also sampled from several metre-thick intervals using 40 cm long packers and a Montejus pump (see details in Dam & Christiansen, 1994). Furthermore, waters under pressure have been collected from two pingos (in the Aaffarsuaq valley on Nuussuaq and in the Kuganguaq valley on Disko) and from the shallow holes drilled by GGU on Svartenhuk Halvø in 1992. In order to interpret the analytical results several samples of sea water and river water that was used as drilling fluid were also analysed. All available analytical data are given in Table 9; some of the most distinctive parameters are plotted in Figs 13 and 14.

Unfortunately, there is no detailed record of the drilling fluid used, whether this was fresh water or sea water, or of the amount of salt and mud added with drilling depth. Therefore some of the waters that reappear at the surface are likely to be a mixture of fresh water, sea water, added salt and mud, and presumably formation water.

Two levels in the GANW#1 well had water under pressure, the first encountered was at the base of the casing at ~199 m (sample 380109), the other was associated with gas at ~721 m (sample 380122 shortly after the 'kick' and sample 380123 collected about 20 minutes later). Sample 380109 is very close to sea water in composition although there is a significant increase in Ca to Mg (both relative and in absolute values) (Table 9, Figs 13 and 14). Samples 380122 and 380123 are rather different with a salinity of ~27% and ~49% of sea water respectively. The cation ratios suggest that these waters are not a simple mixture of fresh water and sea water; again a relative increase in Ca to Mg is noted.

Highly saline brines like those in the Marraat-1 well have not been recorded from samples from the GANW#1 well, although the existence of such formation fluids may be proved after proper pumping. Most of the formation fluids from the Marraat-1 well have a higher salinity than sea water and a very high Ca to Mg ratio suggesting a deep basin brine origin. The significant variation in geochemistry from level to level in the Marraat-1 hole still needs explanation.

None of the pingos or shallow drill holes show evidence of highly saline waters; however, the waters collected have a higher salinity than in any river waters (Table 9, Fig. 14). It should be noted that the waters from the pingo in Aaffarsuaq showed a rather consistent composition through time, even over a year (1991–1992).

Table 9. Water Chemistry

GGU No.	Depth (m)	Date	pH	Alk	Cl	SO_4	Na	K	Ca	Mg	Cl/SO_4	Na/K	Ca/Mg
					mg / l								
GANW#1 drilling fluids													
380109*	~199	13/9/94	8.37	0.77	18680	2100	8706	406	654	977	8.90	21.4	0.67
380117	~368	21/9/94	12.06	14.21	2920	0	1473	49	260	0.09		30.1	2889
380122*	~721	02/10/94	7.69	2.95	4830	906	2152	102	136	317	5.33	21.1	0.42
380123*	~721	02/10/94	7.77	1.43	9040	1295	3401	99	1359	346	6.98	34.4	3.93
Marraat-1 formation fluids													
408010	~41 (1)	29/10/93	7.71	0.82	28600	1446	8820	171	7100	760	19.78	51.6	9.34
408011	~41 (2)	29/10/93	7.42	0.92	29200	1484	9650	188	6740	790	19.68	51.3	8.53
408012	~41 (3)	29/10/93	7.69	1.05	30300	1624	11400	224	5950	870	18.66	50.9	6.84
408020	~82 (1)	29/10/93	7.56	0.54	28700	1238	7540	115	8520	610	23.18	65.6	13.97
408021	~82 (2)	29/10/93	7.41	0.58	29600	1252	8180	126	8560	630	23.64	64.9	13.59
408022	~83 (3)	29/10/93	7.64	0.65	29500	1254	8100	126	8520	630	23.52	64.2	13.52
408034*	~346	19/08/93	7.24	0.42	26400	1558	6760	166	8060	630	16.94	40.7	12.79
408035*	~346	19/08/93	7.15	0.43	26500	1276	6780	167	8160	630	20.77	40.6	12.95
Pingo, Aaffarssuaq, Nuussuaq													
358472*	–	17/08/91	8.78	46.6	256	200	1135	9.48	3.68	86	1.28	119.7	0.04
400843*	–	14/07/92	8.97	42.6	248	178	1110	9.74	1.68	68.5	1.39	114.0	0.02
400844*	–	14/07/92	8.97	29.7	53.1	177	750	6.72	2.46	54.5	0.30	111.6	0.05
400894*	–	14/08/92	8.78	44.8	258	180	1140	9.28	2.63	76.5	1.43	122.8	0.03
Pingo, Kuganguaq, Disko													
409129*	–	06/08/93	7.20	0.32	4.64	78.4	41.4	0.25	2.06	0.21	0.06	165.6	9.81
Svartenhuk Halvø, GGU drillhole 400708													
402618*	–	10/08/92	9.02	5.70	39.9	8.37	173.2	1.07	2.14	1.34	4.77	161.9	1.59
Svartenhuk Halvø, GGU drillhole 400709													
402642*	–	12/08/92	8.77	6.63	287	16.3	322	1.69	3.88	1.66	17.6	190.5	2.33
River Water, Svartenhuk Halvø													
402619	–	10/08/92	7.80	0.82	0.69	1.87	4.71	0.14	10.2	3.06	0.37	33.6	3.33
River Water, near GANW#1													
380133	–	02/10/94	8.20	3.20	13	11	20.7	0.29	32.4	17.5	1.18	71.4	1.85
Sea Water, Vaigat (near Marraat-1)													
408036	–	29/10/93	7.94	2.10	19500	2340	10150	402	430	1230	8.33	25.2	0.36
Sea Water, Vaigat (near GANW#1)													
380132	–	02/10/94	7.94	2.20	18930	2033	8797	403	412	1217	9.31	21.8	0.34

* water under pressure
Depth is recorded in metres below drillsites

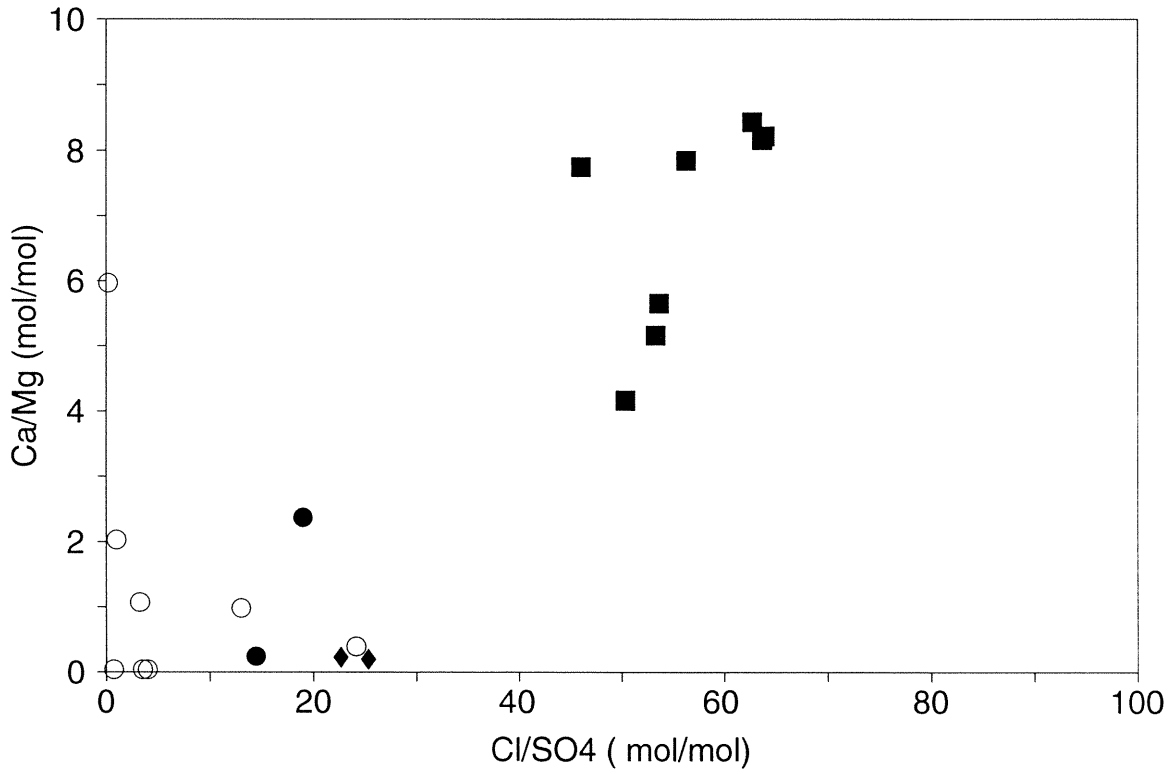

Fig. 13. Cl/SO_4 (mol/mol) versus Ca/Mg (mol/mol) for various formation and surface waters at Marraat and in the surrounding area. Filled circles: GANW#1, Filled squares: Marraat-1, Filled diamonds: Sea water, Open circles: Various pingos and surface waters.

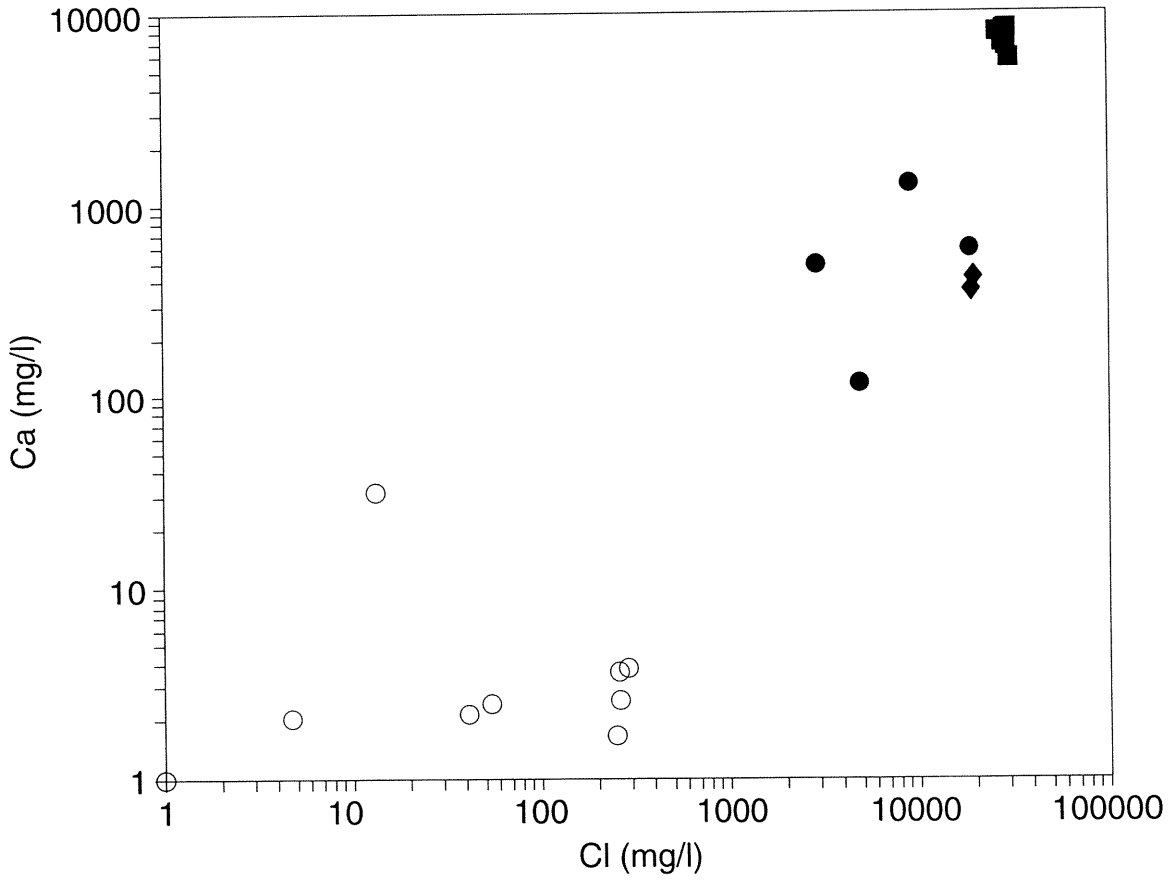

Fig. 14. Cl (mg/l) versus Ca (mg/l) for various formation and surface waters at Marraat and in the surrounding area. Signatures like Fig. 13.

CONCLUSIONS

Based on the analytical data presented in this report the following main conclusions can be drawn concerning the volcanic rocks and sediments penetrated, the oil impregnation, and the gas and water recovered from the GANW#1 well:

- The well penetrated a volcanic succession of 61 m of subaerial picrite lavas and *c.* 740 m of submarine picrite hyaloclastite (vertical, not stratigraphical, thicknesses). Several eruptive units can be discerned, and the eruption sites are inferred to be local. Because the well is situated in an area where there was considerable submarine relief, it is not possible to estimate the total thickness of hyaloclastites and hence the thickness of hyaloclastite yet to be drilled. There are 7 or 8 intrusions (dykes and sills) in the well.

- Three intervals with sediments were penetrated in the GANW#1 well. The sediments consist of interbedded mudstone, sandstone and conglomerate, and were deposited from turbidite and debris flows. The sandstones and conglomerates are composed of reworked hyaloclastic material, and were deposited in a marine environment below storm-wave base. The debris flows were most likely triggered by small earthquakes in connection with volcanic eruptions. In one bed fragments of a scleractinian coral (*Dendrophyllia candelabrum*) were encountered. This coral is typical of the Lower Danian of Nuussuaq. The dinoflagellate cysts from the lower sedimentary unit suggest an Early to earliest Late Paleocene age (NP 3–5) for these sediments.

- Carbonate veins with bitumen are found at intervals throughout the core. In the upper part of the core the bitumen-stained carbonate is later than carbonate without bitumen, while in the lower part it is mostly earlier. The bitumen-impregnated carbonate veins are preferentially associated with dyke and sill intrusions and a non-picritic hyaloclastite horizon, probably because of the way in which these rocks fracture.

- The oil that fills fractures in the volcanics is very similar to all other oil impregnations from the Marraat area and the Marraat-1 well. The source rock for this oil was deposited in an environment with much terrestrially derived organic matter but also with a marine influence. The source rock is probably a deltaic or prodeltaic mudstone of latest Cretaceous or Early Tertiary (Paleocene) age.

- The sediments do not contain potential source rocks for oil and only have a limited gas potential. The thermal maturity is low, corresponding to the upper part of the oil window. The maturity is lower than for the Marraat oil source rock. Neither source rock 'overcooking' nor oil reservoir cracking are likely to have taken place in a zone at least one kilometre thick below present TD of the GANW#1 well.

- The organic geochemistry of the sediments shows that the organic matter is dominated by terrestrially derived material. The geochemistry is in many ways similar to the Marraat oil but there are also many significant differences.

- If the source rock for the Marraat oil is of the same age as the penetrated sediments, this source rock is most likely to occur in a distal (more marine) position relative to the drill site, e.g. to the south-west, west or north-west.

- The gas geochemistry clearly suggests a thermogenic origin of the gas. The source rock has a relatively low thermal maturity (R_o ~0.7%) and is dominated by Type III kerogen. The gas is most likely associated in origin with the Marraat oil.

- The chemistry of the waters from the GANW#1 well does so far not prove the existence of any highly saline deep sedimentary brines.

Acknowledgements: Jette Halskov, Vibber Hermansen, Carsten Thuesen and Nina Turner helped with the technical preparation of the report.

References

Bernecker, M. & Weidlich, O. 1990: The Danian (Paleocene) coral limestone of Fakse, Denmark. *Facies* **22**, 103–138.

Bojesen-Koefoed, J. 1989: Organisk-geokemiske screeninganalyser, metoder og resultater. Analysemetoder ved DGU's source rock laboratorium. *Danmarks Geol. Unders. intern rapport* **5**, 39 pp.

Christiansen, F. G. 1993: Disko Bugt Project 1992, West Greenland. *Rapp. Grønlands geol. Unders.* **159**, 47–52.

Christiansen, F. G., Dam, G., McIntyre, D. J., Nøhr-Hansen, H., Pedersen, G. K. & Sønderholm, M. 1992: Renewed petroleum geological studies onshore West Greenland. *Rapp. Grønlands geol. Unders.* **155**, 31–35.

Christiansen, F. G., Bojesen-Koefoed, J. & Nytoft, H. P. 1994a: Organic geochemistry of oil-impregnated cores from the Marraat-1 well, Nuussuaq, West Greenland – comparison with surface samples. *Open File Ser. Grønlands geol. Unders.* **94/8**, 26 pp., 6 tables, 8 figures.

Christiansen, F. G., Dam, G. & Pedersen, A. K. 1994b: Discovery of live oil at Marraat, Nuussuaq: field work, drilling and logging. *Rapp. Grønlands geol. Unders.* **160**, 57–63.

Christiansen, F. G., Marcussen, C. & Chalmers, J. A. in press: Geophysical and geological activities in the Nuussuaq–Svartenhuk Halvø Area 1994 - promising results for an onshore exploration potential. *Rapp. Grønlands geol. Unders.*

Christiansen, F. G., Bojesen-Koefoed, J., Dam, G., Nytoft, H.-P., Larsen, L. M., Pedersen, A. K. & Pulvertaft, T. C. R. ms: The Marraat oil discovery on Nuussuaq, West Greenland: evidence for a latest Cretaceous–earliest Tertiary oil-prone source rock, offshore West Greenland, Labrador and in Melville Bay. Manuscript prepared for *Bull. Can. Petrol. Geol.*

Dam, G. & Christiansen, F. G. 1994: Well summary, Marraat-1, Nuussuaq, West Greenland. *Open File Ser. Grønlands geol. Unders.* **94/11**, 27 pp., 4 figures, 7 appendices.

Dam, G. & Sønderholm, M. 1994: Lowstand slope channels of the Itilli succession (Maastrichtian–Lower Paleocene), Nuussuaq, West Greenland. *Sediment. Geol.* **94**, 49–71.

Faber, E. 1987: Zur Isotopengeochemie gasförmiger Kohlenwasserstoffe. *Erdöl, Erdölgas & Kohle* **103**, 210–218.

Floris, S. 1972: Scleractinian corals from the Upper Cretaceous and Lower Tertiary of Nûgssuaq, West Greenland. *Bull. Grønlands geol. Unders.* **100**, 132 pp., 8 plates (also *Meddr Grønland*, **196, 1**).

Hansen, J. M. 1980: Stratigraphy and structure of the Paleocene in central West Greenland and Denmark. Unpubl. lic. scient. thesis, Geological Institute, Univ. Copenhagen, 156 pp.

Henderson, G. 1975: Stratigraphy and structure of the Tertiary volcanic rocks of the Marrait kitdlît area, Nûgssuaq. *Rapp. Grønlands geol. Unders.* **69**, 11–16.

Heilmann-Clausen, C. 1985: Dinoflagellate stratigraphy of the uppermost Danian to Ypresian in the Viborg 1 borehole, central Jylland, Denmark. *Geol. Surv. Denmark* A. **7**, 69 pp.

Jenden, P. D. & Kaplan, I. R. 1989: Origin of natural gas in Sacramento basin, California. *Bull. Amer. Ass. Petrol. Geol.* **73**, 431–453.

Jürgensen, T. & Mikkelsen, N. 1974: Coccoliths from volcanic sediments (Danian) in Nûgssuaq, West Greenland. *Bull. geol. Soc. Denmark.* **23**, 225–230.

Lentin, J. K. & Williams G. L. 1993: Fossil dinoflagellates: index to genera and species 1993 edition. *Am. Ass. strat. Palynol. Contr. Ser.* **28,** 856 pp.

Lowe, D.R. 1979: Sediment gravity flows: their classification and some problems of application to natural flows and deposits. *Soc. Econ. Paleontol. Mineral. Spec. Publ.* **27**, 75–82.

Mutti, E., & Ricci Lucchi, F. 1978: Turbidites of the northern Apennines: introduction to facies analysis. *International Geology Review* **20**, 125–166.

Mutti, E. 1992: Turbidite sandstones. Agip and Instituto di Geologia, University of Parma, 275 pp.

Nardin, T. R., Hein, F. J., Gorsline, D. S., & Edwards, B. D. 1979: A review of mass movement processes, sediment and acoustic characteristics, and contrasts in slope and base-of-slope systems versus canyon-fan-basin floor systems. *Soc. Econ. Paleontol. Mineral. Spec. Publ.* **27**, 61–73.

Nøhr-Hansen H. 1994: Dinoflagellate cyst biostratigraphy of the Upper Cretaceous black mudstones between Niaqornat and Ikorfat on the north coast of Nuussuaq, West Greenland. *Open File Ser. Grønlands geol. Unders.* **94/14**, 24 pp., 4 figures, 6 range charts, 8 plates.

Pedersen, A. K., Larsen, L. M. & Dueholm, K. S. 1993: Geological section along the south coast of Nuussuaq, central West Greenland. 1:20 000. *Grønlands geol. Under.*, coloured geological sheet.

Piasecki, S., Larsen, L. M., Pedersen, A. K. & Pedersen, G. K. 1992: Palynostratigraphy of the Lower Tertiary volcanics and marine clastic sediments in the southern part of West Greenland Basin: implications for the timing and duration of the volcanism. *Rapp. Grønlands geol. Unders.* **154**, 13–31.

Powell, A. J. 1992: Dinoflagellate cysts of the Tertiary System. *In* Powell, A. J. (ed.) *A stratigraphic Index of Dinoflagellate Cysts*, 155-252. British Micropal. Soc.

Rullkötter, J., Leythaeuser, D. & Wendisch, D. 1982: Novel 23, 28-bisnorlupanes in Tertiary sediments. Widespread occurrence of nuclear demethylated triperpanes. *Geochim. Cosmochim. Acta* **46**, 2501–2509.

Schoell, M. 1984: Stable isotopes in petroleum research. *In* Brooks, J. & Welte, D. (ed.) *Advances in Petroleum Geochemistry*, Vol. 1, 215-245, London: Academic Press.

F. G. C., G. D., L. M. L., H. N.-H., J. B. & T. C. R. P. Geological Survey of Greenland, Copenhagen.

A. K. P., Geological Museum, Øster Voldgade 5–7, 1350 Copenhagen K.

J. B.-K. & T. L., Geological Survey of Denmark, Thoravej 8, 2400 Copenhagen NV.

Table 10. Compound assignment of terpanes and steranes (Fig. 8, Tables 6 and 7)

Terpanes

Ts	C_{27}	18α(H)	trisnorneohopane		
Tm	C_{27}	17α(H)	trisnorneohopane		
17β	C_{27}	17β(H)	trisnorneohopane		
BSL	C_{28}	17α(H)	bisnorlupane		
H29	C_{29}	17β(H)	norhopane		
M29	C_{29}	17β(H)	21α(H)	normoretane	
0	C_{30}	18α(H)	oleanane		
αβ H30	C_{30}	17α(H),	21β(H)	hopane	
βα M30	C_{30}	17β(H),	21α(H)	moretane	
H31	C_{31}	17α(H),	21β(H)	homohopanes	(22S + 22R)
H32	C_{32}	17α(H),	21β(H)	bishomohopanes	(22S + 22R)
H33	C_{33}	17α(H),	21β(H)	trishomohopanes	(22S + 22R)

Steranes

S27 ααR	C_{27}	5α(H),	14α(H),	17α(H)	sterane	(20R)
S28 ααR	C_{28}	5α(H),	14α(H),	17α(H)	sterane	(20R)
S29 ααR	C_{29}	5α(H),	14α(H),	17α(H)	sterane	(20R)
S30 ααR	C_{30}	5α(H),	14α(H),	17α(H)	sterane	(20R)
S29 ααS	C_{29}	5α(H),	14α(H),	17α(H)	sterane	(20S)
S29 ββR	C_{29}	5α(H),	14β(H),	17β(H)	sterane	(20R)
S29 ββS	C_{29}	5α(H),	14β(H),	17β(H)	sterane	(20S)
S30 ααS	C_{30}	5α(H),	14α(H),	17α(H)	sterane	(20S)