THE HARLINGEN FIELD, THE ONLY GAS FIELD IN THE UPPER CRETACEOUS CHALK OF THE NETHERLANDS[1]

W. J. VAN DEN BOSCH[2]

ABSTRACT

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The Harlingen gas field, at the top of the Chalk, is situated in Petroland's Leeuwarden Concession in the province of Friesland, northern Netherlands. The structural closure developed partly during the Early Oligocene, after approximately 500 m of sediment had been deposited on top of the Chalk. Shortly hereafter, gas migrated into the structure. The presence of the gas strongly reduced the further loss of porosity and permeability by diagenesis, whereas the overpressuring reduced further compaction. A final deformation phase, probably at the end of the Early Miocene, slightly enhanced the curvature at the top Chalk and gently folded the then relatively porous gas cap, resulting in a folded gas-water contact. Unlike the situation in the Chalk fields in the Central North Sea, fracturing of the reservoir is very limited and has not resulted in increased effective permeability. This is probably due to the weak curvature of the structure. Notwithstanding the low average permeability (1-2 mD), a production rate of over 60 000 m³/day was maintained for a period of five months after stimulation, without any signs of pore collapse, common in many unfractured chalk reservoirs elsewhere. A field development plan is being considered.

INTRODUCTION

The Harlingen Field is a gas field in the uppermost part of the Late Cretaceous Chalk. It is situated in the western part of the province of Friesland (northern Netherlands) within the Leeuwarden Concession. This area was originally held by Petroland B.V. and partners as a drilling permit and forms part of the Leeuwarden Concession since February 17, 1969 (Fig. 1). Today, the Harlingen Field is the only gas accumulation in the Chalk of The Netherlands for which development is considered.

THE FIELD'S HISTORY

The discovery well, Harlingen-1, was drilled in 1964 on the southern tip of the field (Fig. 2). It also discovered a second gas field in the Lower Cretaceous Vlieland Formation (COT-
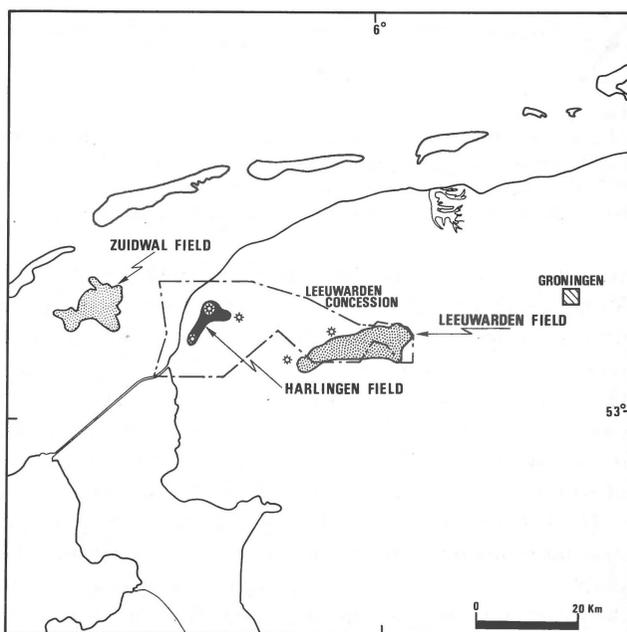

Fig. 1
Index map. The map shows the position of the Harlingen Field (black) and the location of Petroland's larger (dotted) and smaller (gas symbol) gas fields in the Lower Cretaceous.
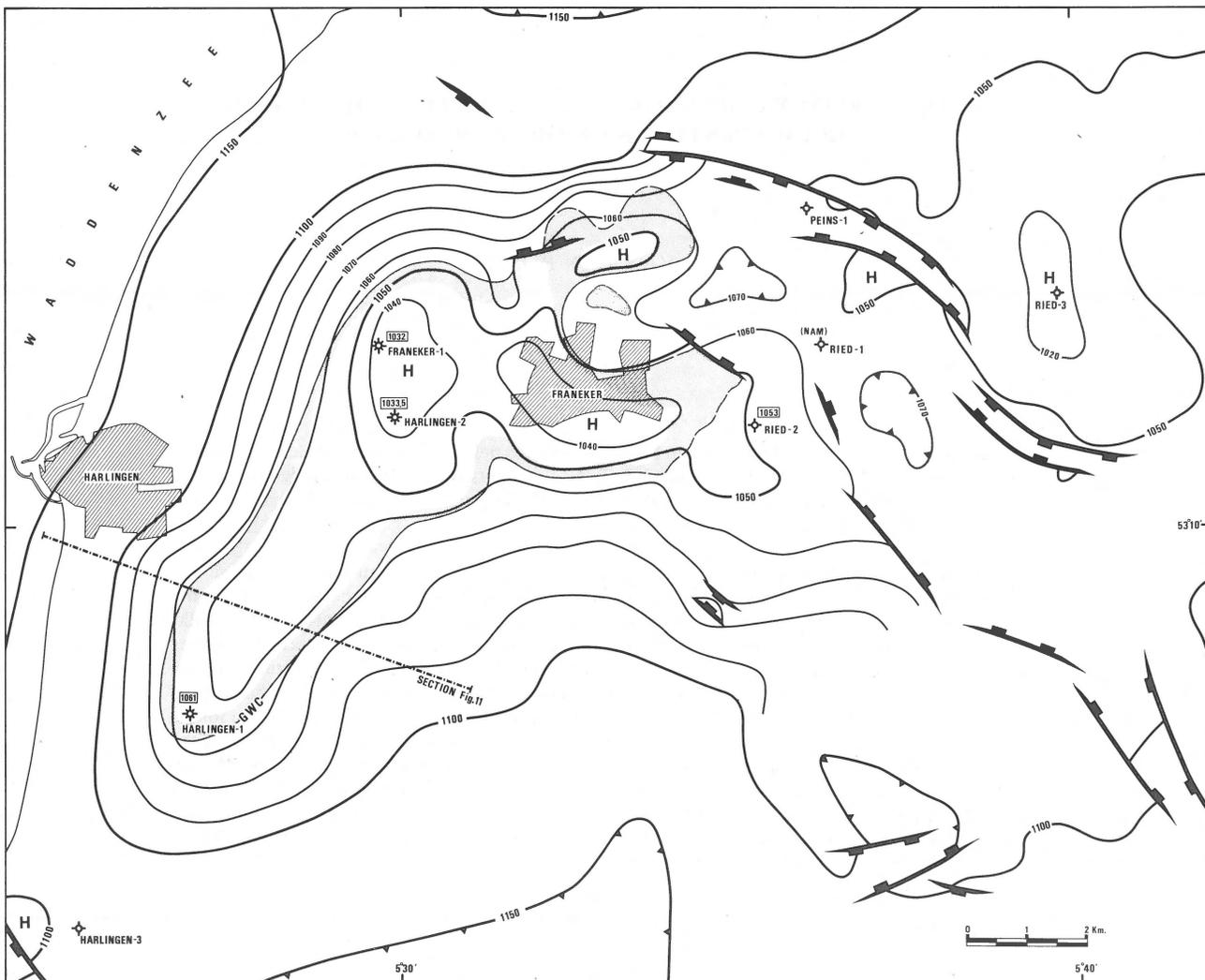
Fig. 2
Migrated seismic depth contour map base Tertiary. This map shows the structure of the eroded top of the Ommelanden Chalk. The Harlingen Field, as mapped from seismic, is indicated by a dotted signature. Its limit coincides approximately with the effective gas-water contact at a Sw of 90%, but does not entirely coincide with the depth contours. In the east and north it is very difficult to establish in parts where the structure is very flat. A seismic section through the field is shown in figure 11.

TENÇON ET AL., 1975). The well entered the chalk at −1061 m*. Strong gas showns (7% C_1, 5% C_2) were encountered while drilling the upper 30 m. Logs showed a 7 m thick interval with relatively high gas saturations in the upper part, which gradually decreased downward to the effective gas-water contact (water saturation = 90%) at −1068 m (Fig. 3). An open-hole test between −1063.5 m and −1093 m produced gas at a rate of 5000 m³/day, with a well-head pressure of 80 bar.

The first appraisal well, Harlingen-2, was drilled in 1965 near the culmination of the field (Fig. 2). It penetrated the chalk at −1033.5 m. Logs showed a gas-bearing interval with the gas saturations gradually decreasing from approximately 40% at the top to 10% at the effective GWC at`−1051.5 m

(Fig. 3). Subsequent production tests from the interval −1033.8 m to −1037.8 m flowed unstimulated at a rate of 50 000 m³ gas/day, with a well-head pressure of 43 bar. After acidizing, the well flowed gas at a rate of 65 000 m³/day with the same pressure. A second test programme was carried out in 1971, after the encouraging results of the chalk exploration in the Norwegian North Sea. However, stimulation by a combination of fracturing and acidizing did not result in a significant increase of the production rate and doubts remained whether the obtained flows could be maintained over a longer period.

A second appraisal well, Franeker-1, was drilled in 1978 near the culmination of the structure, 1320 m to the north of Harlingen-2 (Fig. 2). It penetrated the top of the chalk at −1031 m. Logs showed a gas column of 20 m, with a S_w of 43.9% at the top and the effective GWC at −1051 m (Fig. 3).

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* All depths in meters below NAP (= Dutch Ordnance Datum).

Without stimulation, the well flowed 22 000 m³ of gas in twenty hours from perforations between −1031.1 m and −1041.1 m, with a strong drawdown.

A test-production programme of more than one year, with an actual production period of five months, was carried out in 1978 and 1979. Production was from Harlingen-2, whereas Franeker-1 was used as an observation well. After stimulation, an average production rate of approximately 60 000 m³/day, with a well-head pressure of more than 50 bar, was maintained during the entire period. No water was produced. Total gas production was 9 020 000 m³. The feared pore collapse in the relatively weak granular framework of the chalk following decompression did not occur during the first few weeks or few months of production. Such a phenomenon is common in most chalk fields outside the North Sea Basin. Such pore collapse on a field-wide scale usually reduces production by approximately 80%. Pore collapse near the well, following the stimulation by fracturing and acidizing, did not happen either. The effects of this stimulation, which usually tends to decrease rapidly in fields in unfractured or little fractured chalk, lasted for the entire test period.

The well Ried-2, was drilled in 1980 to a deeper objective just to the east of the field (Fig. 2). It penetrated the top chalk at −1053 m, 2 m deeper than the GWC's encountered in Harlingen-2 and Franeker-1 (Fig. 3). No gas shows were encountered while entering the reservoir and logs showed the entire chalk to be tight and water bearing. A production test between −1054 m and −1089 m flowed at a rate of only 1.5 m³ of water per day.

Two smaller neighbouring structures were tested by the wells Harlingen-3 (1965) and Ried-3 (1980): both wells were dry (Fig. 2).

GENERAL GEOLOGY

The Harlingen Field is situated to the northeast of the inverted Texel-IJsselmeer High, in a rather unique position on the end of a pronounced structural nose (Fig. 4).

The oldest sediments penetrated in the area are the coal-bearing clastics of Westphalian age (Fig. 5; see also Fig. 11). Hercynian deformation phases faulted, uplifted and eroded these sediments. After deposition of the red clastics of the Upper Rotliegend Group (lithostratigraphic names by NAM & RGD, 1980) during the Middle Permian, approximately 900 m of evaporites and carbonates of the Zechstein Group were deposited (mainly salt). These evaporites are conformably overlain by red clastics of Early Triassic age.

Salt movements and tectonic deformation took place during the Jurassic, and might have started already during the Triassic. The associated erosion reduced the thickness of the remaining Triassic sediments in the Harlingen area to less than 200 m. Lacustrine and lagoonal shales of the Upper Delfland Formation (Latest Jurassic - Earliest Cretaceous) overlie the eroded Triassic surface unconformably. The upper
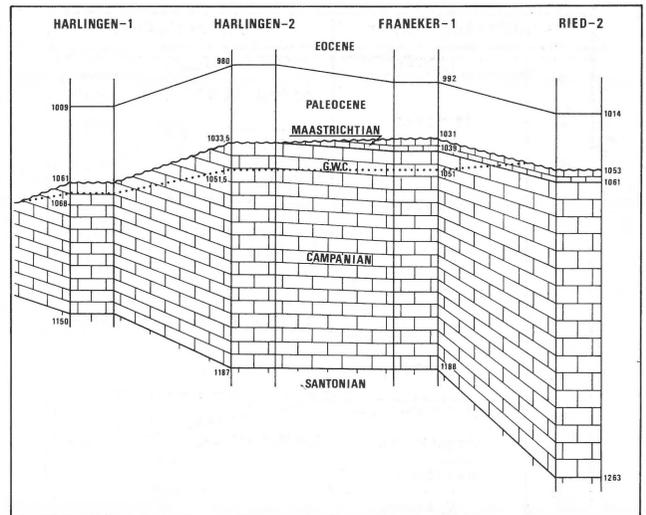

Fig. 3
Well correlation.

part is very rich in organic material.

A weak, but distinct angular unconformity separates the Upper Delfland Formation from the Vlieland Sandstone, the oldest marine Mesozoic deposit in the area. Clastic marine sedimentation continued during the remainder of the Early Cretaceous, with the organic-rich shales of the Vlieland Shale (Hauterivian-Early Aptian) and the marls of the Holland Formation (Late Aptian/Albian). Weakly developed, not very distinct unconformities developed at the base and in the middle of the Vlieland Shale, whereas a more distinct one occurs at the base of the Holland Formation.

Carbonate deposition started gradually with the argillaceous carbonates of the Texel Chalk Formation of Cenomanian age. Chalk was the predominant lithology during the remainder of the Late Cretaceous (Ommelanden Chalk Formation). A locally developed angular unconformity within the Ommelanden Chalk, approximately at the base of the Coniacian, represents the beginning of the basin inversion, which
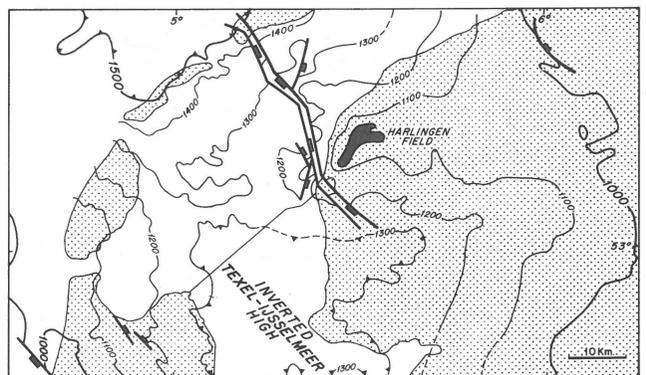

Fig. 4
Generalized regional depth map base Tertiary. The Harlingen Field is situated in a unique position at the end of a regional uplift of Oligocene/Miocene age.
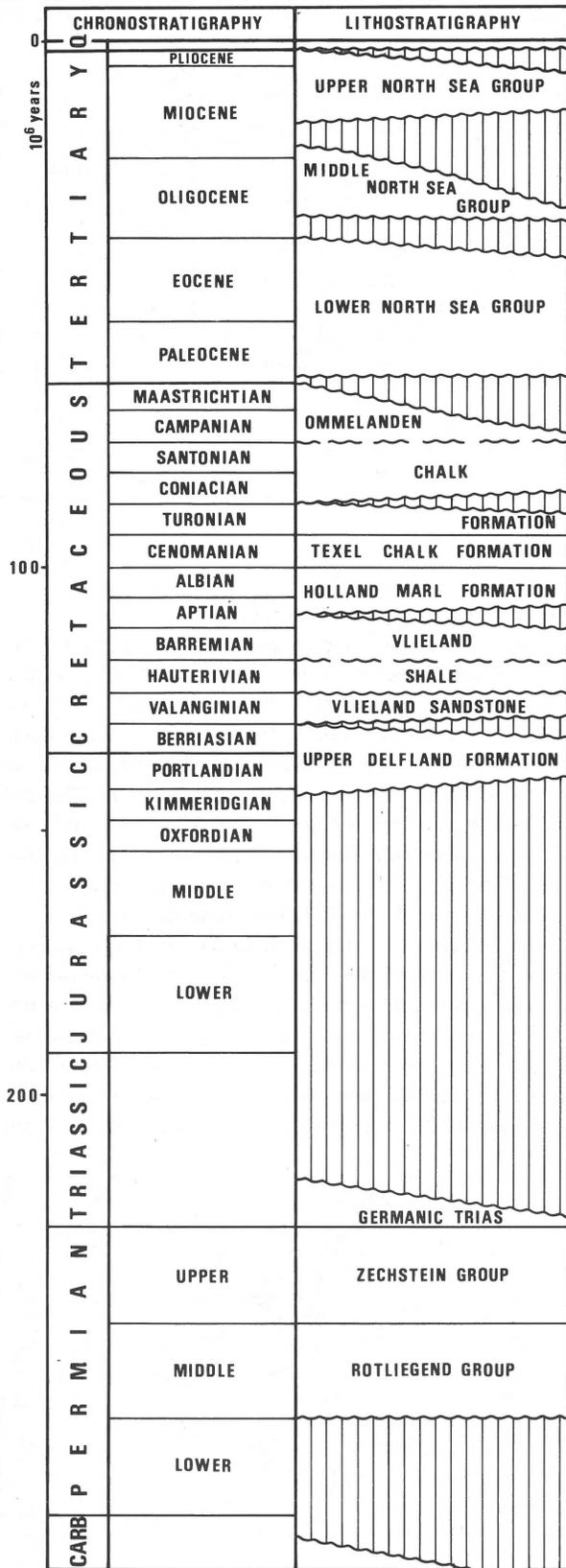
Fig. 5
Chrono- and lithostratigraphic units in the Harlingen area.

culminated during the Laramide phase at the end of the Late Cretaceous. The accompanying erosion was less than in the southern and central parts of the country; it removed usually not more than the chalk of Maastrichtian age in the Harlingen area (Fig. 3). Concentrations of chert nodules and/or hard-grounds often accentuate these two unconformities. A third chert concentration is locally present in the upper part of the Santonian, a possible indication for some increased tectonic activity and erosion at that time.

Shales of the Landen Formation (Paleocene) overlie the eroded chalk unconformably. Clastic deposition continued uninterrupted during the Eocene (Dongen Formation), but renewed tectonic activity took place at the end of the period and resulted in the development of an angular unconformity at the base of the overlying clastic Middle North Sea Group (Middle Oligocene - Early Miocene). The first stage of structural closure of the Harlingen Field is probably of Early Oligocene age. Renewed tectonic activity occurred after the deposition of the Middle North Sea Group. This is illustrated by the presence of a weak but locally distinct angular unconformity at the base of the overlying clastic Upper North Sea Group (Middle Miocene - Recent).

RESERVOIR

Age

Micropalaeontological age determinations have established that the upper 8 m of the chalk in Franeker-1 and Ried-2 are probably of Early Maastrichtian age (Fig. 3). In Harlingen-2, microfossils characteristic for the top Upper Campanian have been found at the top of the reservoir. The Campanian is approximately 150 m thick in these three wells. More section is missing in Harlingen-1, where only approximately 85 m of Campanian has been preserved. Log correlation and inspection of seismic sections show that these differences were caused by erosion at the end of the Cretaceous. The truncated chalk surface is overlain by dark-coloured shales with Paleocene microfauna.

Environment of deposition

The microfossil content suggests an open-marine environment of deposition. The presence of a high percentage of intact coccoliths would suggest that the original depth of deposition may not have been much more than 70 m, the depth at which the coccoliths start disintegrating in modern environments (HANCOCK, in HARPER & SHAW, 1974). Later, HANCOCK (1975) suggested a depth range of 100-600 m, based on a large number of criteria. Seismic-stratigraphic analysis of a sigmoid-progradational sedimentary unit in the upper part of the Chalk directly to the northwest of the Harlingen Field indicates a water depth of approximately 250 m at the time of deposition.

Petrography

Cores taken in the reservoir in Franeker-1 show a relatively homogeneous lithological composition, except that slightly more fractured intervals exist in the upper part than in the lower part.

Macroscopically the sediments can be described as a very light beige chalk with thin, dark grey, locally greenish, sub-horizontal and wavy argillaceous partings (flasers) which give the rock a nodular appearance (Fig. 6). These flasers probably originated by preferential solution and are locally associated with penecontemporaneous fractures which probably originated by differential compaction. This suggests a very early post-depositional origin (HANCOCK, 1975). Locally the partings have developed into stylolites during a later stage of diagenesis, after the chalk had been lithified. The loss of volume by stylolites is not more than approximately 1.5%. A few small clay pebbles of the same colour as the flasers and a few disseminated, small, grey chert nodules, 1-2 cm in size, occur.
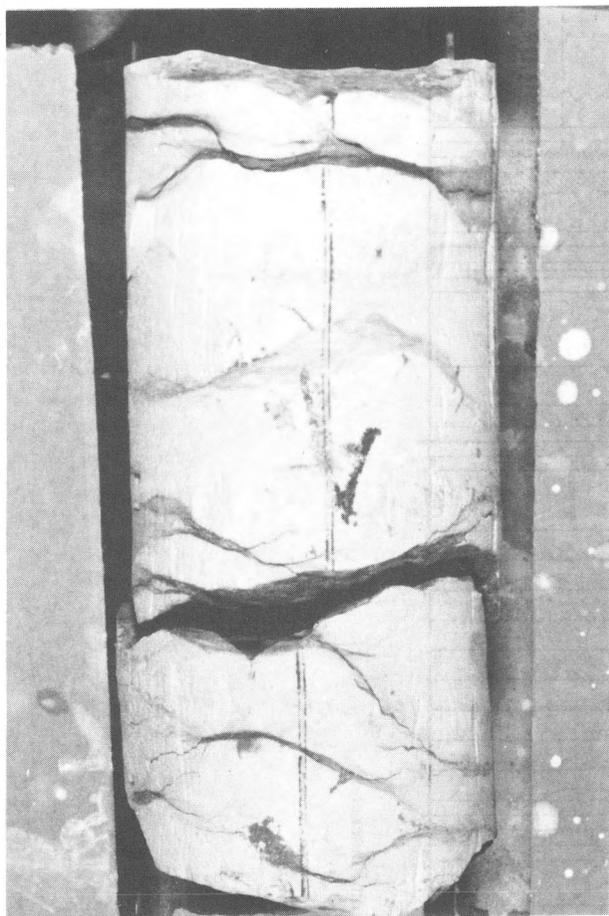

Fig. 6
Photograph of core no. 2 of the well Franeker-1 near −1048 m. Length of core segment 22 cm. Note the darker shale flasers with more or less nodular chalk fragments between them.

Certain intervals are fractured, especially in the upper 8 m, i.e. in the chalk of Maastrichtian age. These intervals are 30-50 cm thick and contain usually (approximately 90%) sub-vertical fractures. The number of fractures gradually decreases toward −1049 m (i.e., approximately the GWC). A second fractured interval occurs between −1059 and −1061 m. It appears that the fracture density (and also stylolite density) is highest in intervals with a high percentage of bioclastic debris, i.e. in the most competent beds.

Microscopically the rock can be described as a wackestone which locally grades into a lime mudstone. It contains a pelagic fauna with locally some benthonic elements. The pelagic fauna consists mainly of speciments of Globigerinidae and, less abundant, of *Globotruncana* and Heterohelicidae, locally abundant sponge spiculae, rather rare specimens of *Stomiasphaera* and *Pithonella,* pelagic echinoderms and belemnite rostrums. The benthonic fauna consists of rather regularly distributed echinoderms, rare bryozoans, small shell fragments, a few mainly arenaceous benthonic foraminifera and *Inoceramus* fragments (Fig. 7).

The reservoir is composed of 96-99% calcite, 1-4% quartz and 0-2% clay, figures comparable with those for the Ekofisk Field (HARPER & SHAW, 1974; Fig. 7).

Investigation of samples under the electron microscope reveals that the chalk matrix is largely composed of coccoliths, i.e. rings of tablet-shaped calcite particles, 7 to 20 of which make up the globular exoskeleton (coccosphere) of calcareous algae of the class Haptophyceae (HANCOCK, 1975). A remarkable high percentage of intact coccoliths occurs, especially in the upper 9 m of the section, i.e. in the reservoir of Maastrichtian age (Fig. 8). The latter is due to the relatively little compaction in that interval. Calcite crystals, formed by recrystallization, occur below −1050 m, i.e. approximately below the GWC (Fig. 9).

A petrographical study of Ried-2 demonstrated that rocks of the same age as those in the gas-bearing interval in Franeker-1 contain less intact coccoliths, less fracturing, more compaction, more calcite crystals and cement, and locally a higher argillaceous content. This type of sediment is comparable to that below the GWC in Franeker-1.

Poroperms

Porosity visible in thin sections occurs in Franeker-1 above −1048 m and it appears to have developed by dissolution and fracturing. Dissolution pores vary in size between 30 and 300 μm and are concentrated near the fractures. Both types of porosity combined constitute only approximately 5% of the rock volume. More fracturing and leaching, as in the Ekofisk Field, could enhance permeabilities ten- to hundred-fold (HARPER & SHAW, 1974).

Matrix porosity is almost entirely formed by intact coccoliths or coccolith fragments. Values of up to 38% have been measured in the upper 9 m where many intact coccoliths with a diameter of 3-10 μm occur. Values as low as 24% have been

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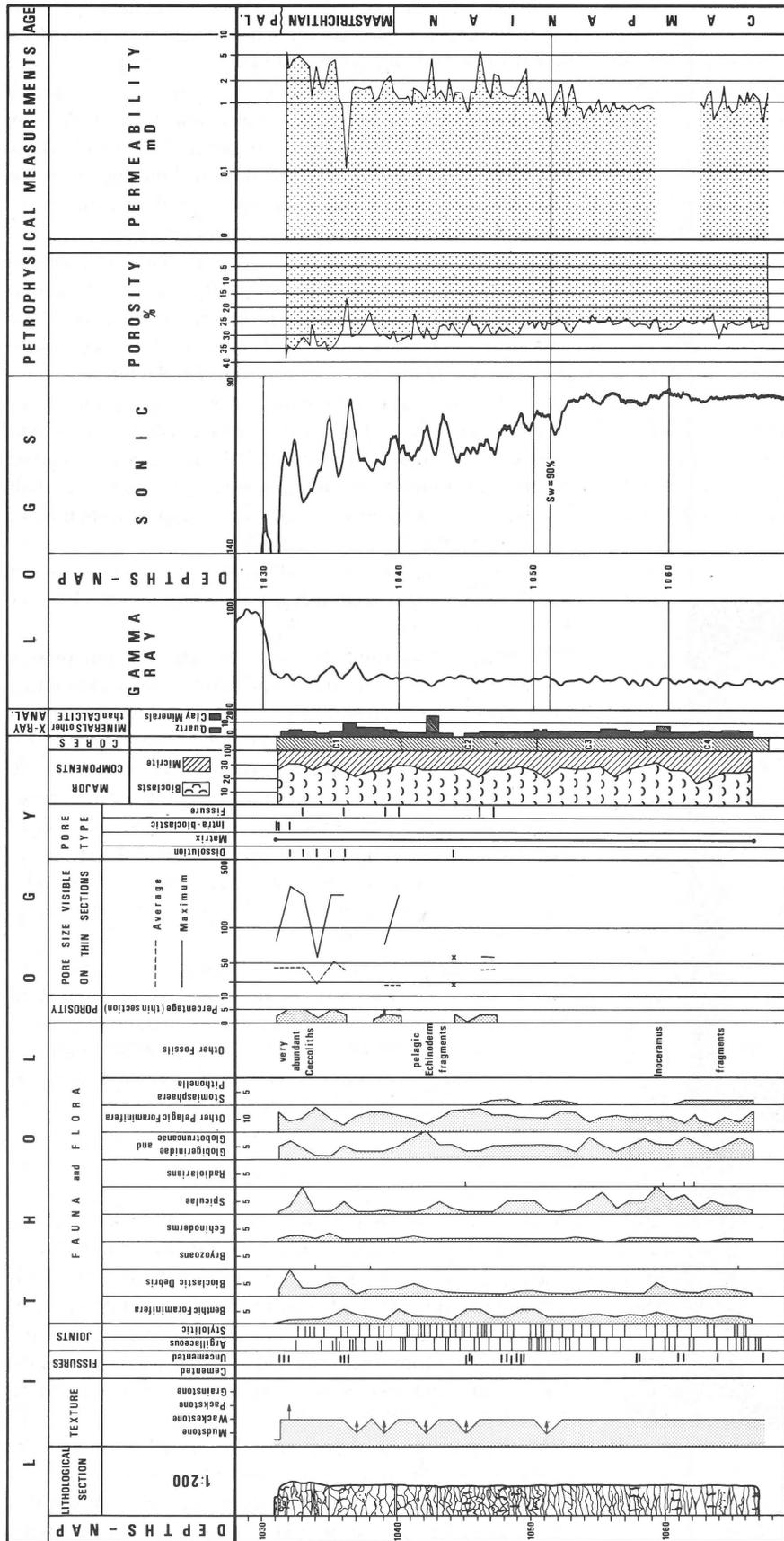

Fig. 7
Core description Franeker-1.

observed in the more compacted part below −1050 m, which almost entirely consists of more compacted coccolith fragments with pore sizes varying between 1 and 2 μm. These values are similar to those measured in the Ekofisk Field (VAN DEN BARK & THOMAS, 1981; HARPER & SHAW, 1974). Average
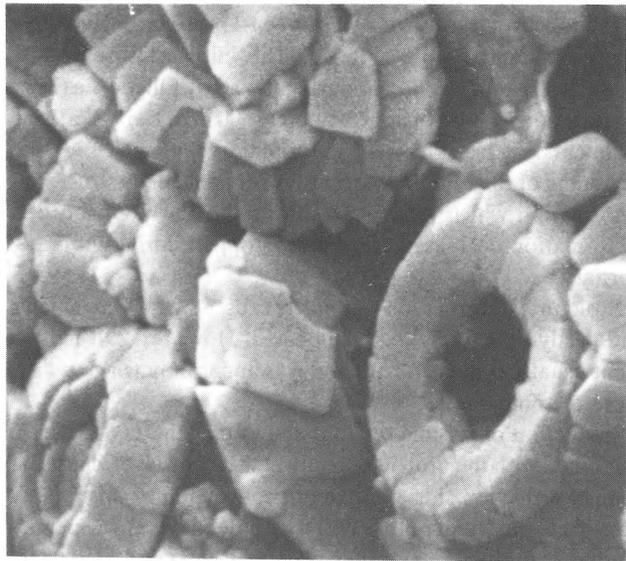
porosities in the gas-bearing interval in Franeker-1 are 28.3%. Those in Harlingen-2 are slightly better: 30.5%. Average porosities in Ried-2 are comparable with those in the water-bearing interval in Franeker-1 and Harlingen-2.

The slightly enhanced fracture and dissolution porosity in the upper part of the reservoir has probably been caused by the development of small fractures in the relatively compact sediment rich in organic debris. Along such fractures porewaters could enter and cause some dissolution.

Permeabilities range from 8 mD at the top to 0.7 mD below −1050 m, 1.5 mD being the average. These values also compare well with values measured in slightly or unfractured reservoirs in the Ekofisk Field (HARPER & SHAW, 1974). Permeabilities are low in comparison with the relatively high porosities. This may be explained by the very small size of the connections between the pores which are less than 0.5 μm. This figure is reduced to less than 0.1 μm below the GWC and in the well Ried-2. The porosity/permeability plot (Fig. 10) is typical of a pure chalk.

Gas saturations

The GWC has been taken at S_w = 90%. The highest gas saturations occur at the top of the reservoir (43.9% in Harlingen-2; 40.1% in Franeker-1). The average gas saturation for the entire gas-bearing interval ranges from 32.3% in Harlingen-2 to 28% in Franeker-1. These observations suggest that the gas column of the Harlingen Field is technically a transition zone.

Fig. 8
Scanning electron microscope photograph of the chalk reservoir in Franeker-1 near −1040 m (10 000 ×). Porosity = 31.8%, permeability = 2.5mD. This photograph of the formation above the gas-water contact shows a high percentage of intact coccoliths and limited calcite overgrowths.
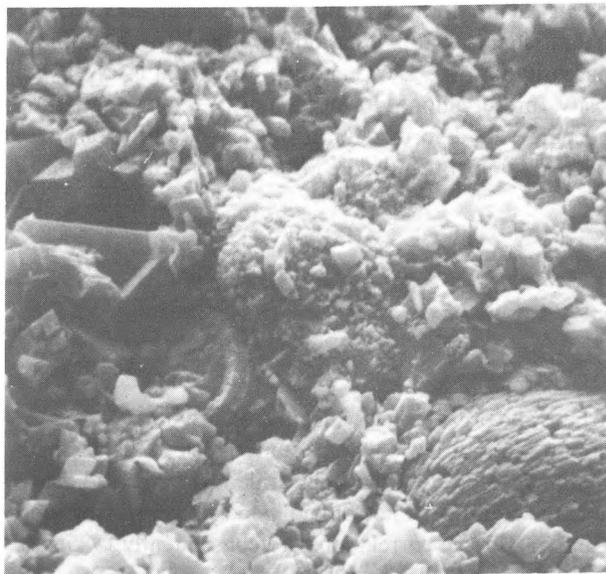

Fig. 9
Scanning electron microscope photograph of the chalk in Franeker-1 near −1053 m (2000 ×). Porosity = 25.9%, permeability = 0.5mD. This photograph of the formation below the gas-water contact shows less intact coccoliths, more calcite overgrowths and secondary large blocky calcite crystals.
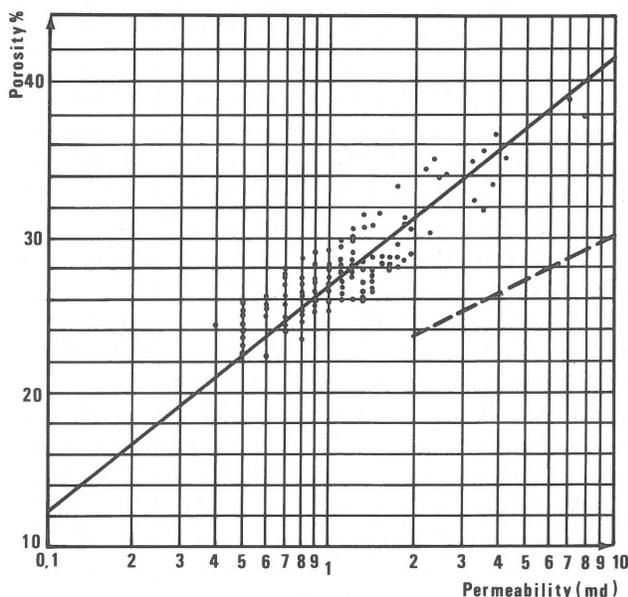

Fig. 10
Porosity/permeability relationship based on core analyses in the upper part of the chalk of Franeker-1 (dots). The drawn line represents the correlation for a pure chalk, the broken line that of a calcarenitic chalk (Scholle, 1977).

Preservation of porosity and permeability

Chalk has a much higher initial porosity than most other carbonates, because its particles are composed of stable low-magnesium calcium carbonate (less than 5% Mg; HANCOCK, 1975), which does not recrystallize during early diagenesis. Most other carbonates are composed of aragonite, a meta-stable form of calcium carbonate which is converted to calcite under increasing pressure (HARPER & SHAW, 1974). Recent work suggests that sparse cementation in chalk results indirectly from the retention of a sufficiently high Mg/Ca ration in the pore fluids to impede extensive pressure solution. Dissolution of low Mg calcium calcite grains can then only occur when sufficient linear pressure (250-1000 atm) is applied to increase calcite solubility (by the overburden). At a depth of 1000 m, the amount of calcite derived through pressure solution can represent 0.5-5% of the rock volume.

It has been demonstrated in the previous chapters that poroperms in the gas-bearing part of the reservoir of the Harlingen Field are considerably better than in the water-bearing part. VAN DEN BARK & THOMAS (1981) have suggested that preservation of porosity in the Ekofisk Field (Norwegian North Sea) may have been caused by either (1) the early introduction of hydrocarbons into the reservoir, (2) overpressure, (3) the early introduction of Mg-rich pore fluids, (or a combination of those phenomena). Early introduction of hydrocarbons in the Harlingen Field took place probably shortly after the Early Oligocene, when part of the structural closure developed. These hydrocarbons have probably reduced the entry of pore waters and therefore partly prevented solution transfer of calcite (VAN DEN BARK & THOMAS, 1981). Recrystallized calcite crystals have indeed only been found below the GWC (Fig. 8). The Harlingen Field is also overpressured (see section on Reservoir Dynamics). This may have reduced the differential stresses at the grain contacts and overpressuring could also explain the observed better preservation of intact coccolith skeletons, the reduced compaction, and the reduced cementation caused by pressure solution in the gas-bearing zone, compared with the water-bearing part of the reservoir. The presense of Mg-rich pore fluids in the early stages of diagenesis is difficult to prove.

Both overpressures and hydrocarbon saturations in the Harlingen Field are considerably lower than in the Ekofisk Field, whereas the age of early trap formation and the introduction of hydrocarbons into the reservoir may have been comparable (see next section). This could explain the slightly lower poroperms in the Harlingen Field compared to those in the Ekofisk Field.

STRUCTURE

The Harlingen Field is situated on an L-shaped anticline, the long part of which has a NNE-SSW direction (Fig. 2). The structural closure, which coincides largely, but not entirely,

with the field outline, measures approximately 24 km². The slight curvature of the anticline was not sufficient to induce significant fracturing at the crest, which is known from the more strongly folded Ekofisk Field.

An angular unconformity developed at the end of the Cretaceous. Beds below this unconformity dip to the east to northeast (Fig. 11). The latter explains the decreasing erosion of the top Cretaceous from Harlingen-1, via Harlingen-2, to Franeker-1 and Ried-2 (Fig. 3). The initial closure of the eroded top chalk developed during the Early Oligocene (Fig. 11), after deposition of approximately 500 m of Early Tertiary sediments. A last phase of deformation took place at the beginning of the Middle Miocene and enhanced the structural deformation which took place during the Early Oligocene. Deformation decreased and finally stopped during the Late Tertiary.

Structural deformation was partly caused by salt movement and partly directly by tectonic phases. However, salt movement usually coincided with and was apparently triggered by these tectonic phases.

Inspection of seismic sections shows that the GWC itself, combined with the drop in porosity at the same level, caused a distinct reflection (Fig. 11). Depth conversion of this reflection confirmed that the GWC was indeed 17 m deeper in Harlingen-1 than in Harlingen-2 and Franeker-1. No such reflection occurs on the section through the dry well Ried-2. An isopach map of the interval between the reflection representing the top of the reservoir and the one representing the GWC (Fig. 12) confirmed the heights of the gas columns encountered in the three wells drilled on the field. Strangely enough, the reflection representing the GWC is not flat, but weakly structured. Its structural shape is in between the structural shape at top reservoir level and the horizontal. Apparently both the GWC and the associated interval with porosity preservation, formed shortly after the Early Oligocene, were deformed during the last deformation phase at the beginning of the Middle Miocene, resulting in *a folded GWC*.

HYDROCARBONS

Source rocks

Coal beds and organic-rich shales in the Carboniferous are the most important, if not only, gas source rock in the northern Netherlands. However, the wells drilled by Petroland in and around the Harlingen Field did not penetrate the Carboniferous and gas-source correlations are consequently lacking in this area.

Dark-coloured carbonates and marine shales in the Zechstein Group have some potential for oil generation. Although mature, they lack the quality for generation of hydrocarbons in any major quantity here. Dark-coloured lacustrine and lagoonal shales in the upper part of the Upper Delfland
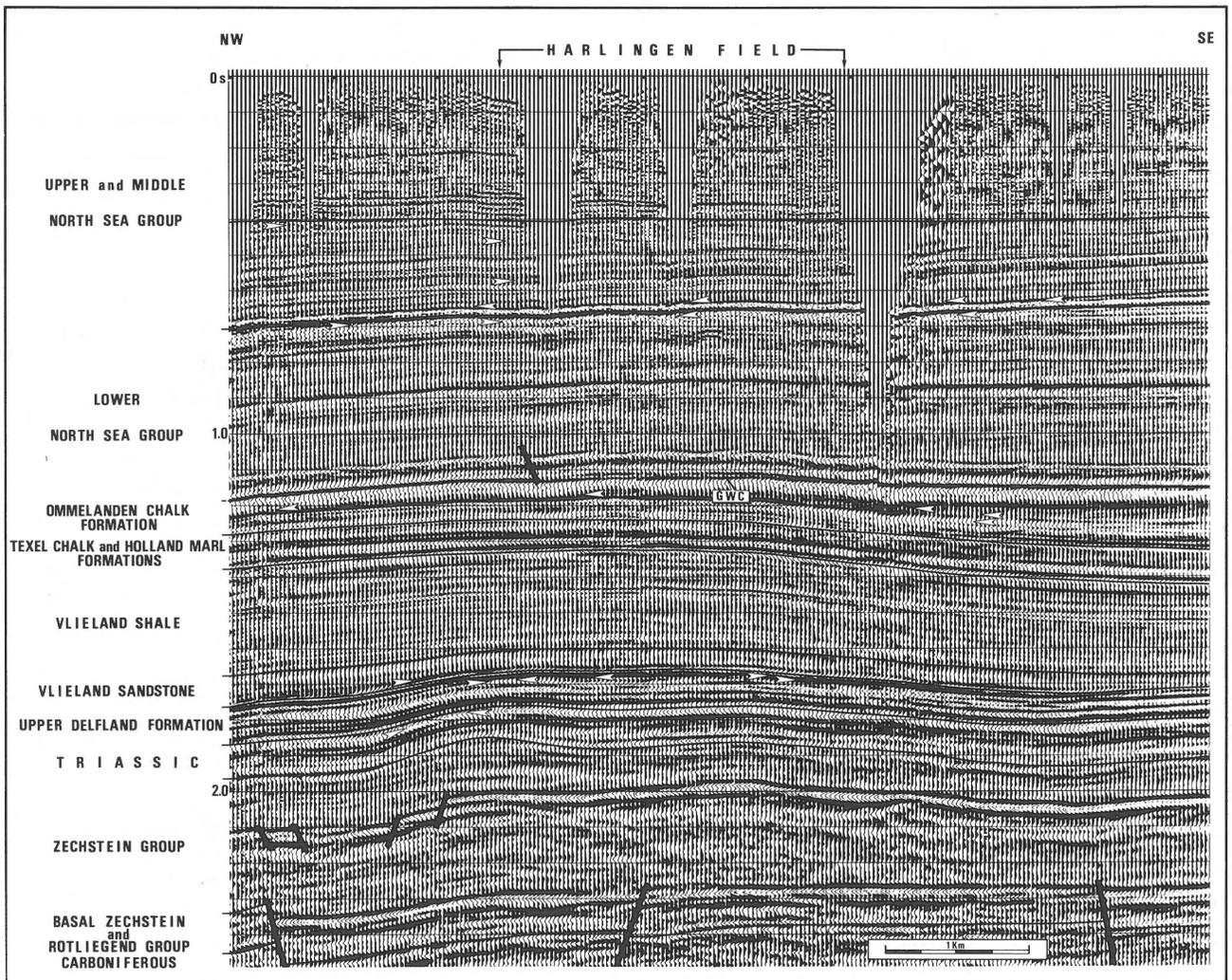
Fig. 11
Seismic section through the southern part of the Harlingen Field. Its location is given on figure 2. This section shows that the structure did not develop before the start of the deposition of the Middle North Sea Group (Middle Oligocene). A double reflection developed at the top of the Ommelanden Chalk Formation at the location of the folded gas reservoir.

Formation (Fig. 5) have potential for oil and gas generation, but lack sufficient maturity: vitrinite-reflectance values vary from approximately 0.37% in the upper part to 0.47% in the lower part of the source-rock interval. Marine shales of the Vlieland Shale have some potential for oil and gas generation but they are even less mature than the shales of the Upper Delfland Formation.

Composition

Gas obtained from the upper chalk reservoir in Franeker-1 has the following composition:

Methane	: 95.79%	Density (air=1)	: 0.573
Ethane	: 0.54%	Caloric value	: 9238 Kcal/m
Higher hydrocarbons	: 0.06%		(= 38661 x 10^3 J)
Nitrogen	: 3.61%	δ^{13}C (methane)	: −31.1‰ PDB

The composition of this very dry, but relatively pure hydrocarbon gas is quite different from that of the gas encountered in the Lower Cretaceous in the same area and in the rest of the Leeuwarden concession (COTTENÇON ET AL., 1975). The latter gas is less dry (approximately 3% ethane and higher hydrocarbons) and contains much more nitrogen (up to over 20%). The gas is only slightly heavier (δ^{13}C = −28.5‰ PDB).

Origin

One could explain these differences in several ways. A different source rock could be present, but it has been explained in the previous section that no major mature gas source rocks exist in the post-Carboniferous section. The methane in the Late Cretaceous gas constitutes 99.4% of the total hydrocarbons, whereas it constitutes only 96.1% in the Early Cretace-
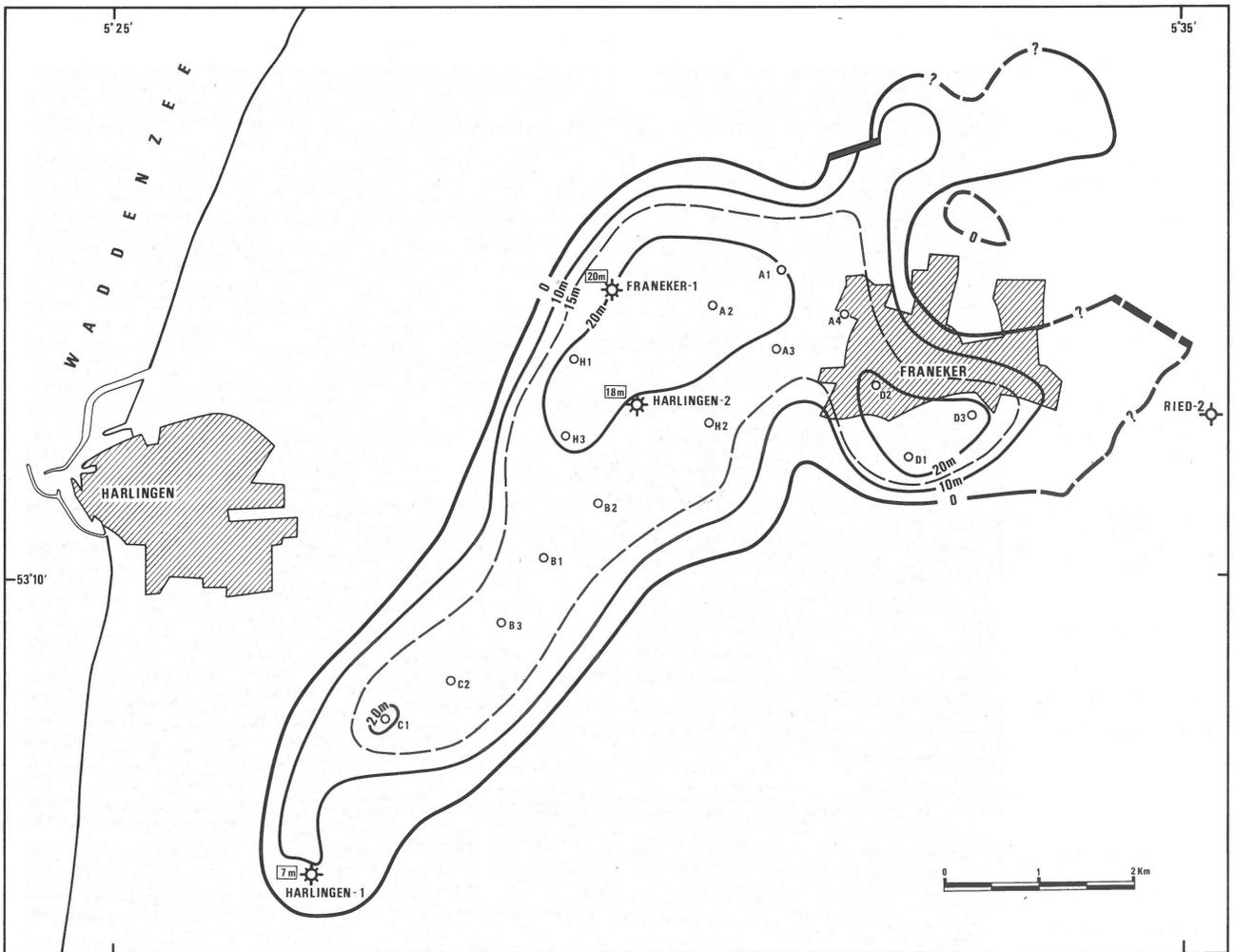
Fig. 12
Provisional isopach map of the gas reservoir. This map is based on seismic data (Fig. 11) and well data. The limit of the field coincides approximately with a water saturation of 90%. Future appraisal wells (A1, C2, D1) and development wells are shown.

ous gas. One would have to add more than five times the volume of pure methane to the Early Cretaceous gas to obtain the composition of the Late Cretaceous gas. This observation confirms that it is unlikely that gas from different sources has been added to the original gas.

Fractioning of the gas on its migration path from the Lower Cretaceous to the top of the Upper Cretaceous is a second possibility. This interpretation has been proposed for several other areas, but it is difficult to prove. Anyway, the gas in the Vlieland Sandstone of the nearby Zuidwal Field (Fig. 1), contains only 1.26% N_2 and almost 6.5% of higher hydrocarbons and this difference cannot be explained by vertical fractioning (COTTENÇON ET AL., 1975).

A third possibility is that the different types of gas were generated either at different times from the same Carboniferous source rock in a different stage of maturity, from Carboniferous source rocks of different composition, or from a combination of these possibilities. The author prefers this third theory. The ^{13}C contents of the gases do not contradict it: the difference in ^{13}C content is too small to state that the higher gas is derived from less mature source rock (STAHL, 1973) or that the lighter gas is the product of differential migration (BARTENSTEIN ET AL., 1971).

Age of gas generation

This discussion also shows that establishment of the time(s) of generation is a complex problem. The presence of weak magnetic anomalies under two ridges to the East of the Harlingen Field, which originated at the end of the Berriasian, suggests the presence of magmatic bodies of the same age. Their intrusion may have caused maturation of the Carboniferous source rocks. No firm evidence for a later stage of maturation exists.

RESERVOIR DYNAMICS

The prolonged test-production showed that the field can be produced for a long period (five months) at a rate of approximately 60 000 m³/d and at a well-head pressure of over 50 bar, without either water production, an appreciable pressure drop, or a rise of the gas-water contact. An interference test between Harlingen-2 and Franeker-1 suggested full communication between beds of different age. Pore collapse, very common after a production period of a few weeks or a few months in many other unfractured chalk fields, did not occur: neither on a field scale due to pressure release, nor near the borehole due to fracturing and/or acidizing. The full effects of the stimulation lasted for the entire test period.

Pressure measurements showed the reservoir to be over-pressured: 143 bar for a hydrostatic pressure of 100 bar.

Comparison of permeabilities calculated from the test-production data with those measured in the cores show that the former are equal or lower than the latter. This suggests that the fractures present in certain more competent intervals apparently did not enhance effective permeability.

The GWC is not flat and depends strongly on reservoir quality (see section Structure): the GWC in Harlingen-1 lies 17 m deeper than in Harlingen-2 and Franeker-1 and seismic data shows it to be folded. The anticlinal shape of the base of the gas has been explained by early migration of the gas into a flatter, early stage of the structure. This reduced diagenesis within the gas column, whereas poroperms were strongly reduced below the gas column. Subsequent deformation enhanced the curvature of the existing anticline and gently folded the base of the gas. These observations explain why no water was produced during the test production: the gas is located in permeable formation whereas the water is situated in the tight formation. Consequently, pure gas drive is expected during the entire production life of the field.

RESERVES

Calculations based on previously discussed analyses of poroperm data, gas saturations, gas composition, pressure data and the reservoir isopach map have shown that the Harlingen Field may have reserves in the range of 2.5 to 4.5 × 10^9 m³ of gas in place (0°C, 1 atm). This information, combined with the data obtained during the test-production, has shown that approximately 50% of this gas will be recoverable and that economic exploitation of the Harlingen Field may be feasible.

DEVELOPMENT PROGRAMME

The development programme will start with the acquisition of a few additional seismic lines over some of the provisional future well locations in order to complete the existing seismic grid which has an approximate distance of 1250 m between lines. The first three development wells (A1, D1 and C2: Fig. 2) will further define the shape of the curved base of the gas. Subsequently, these wells and the existing wells Harlingen-2 and Franeker-1 will be used for the initial production phase which will last for approximately two to three years. The information obtained to predict the middle- and long-term dynamic behaviour of the field will be used to confirm or, if necessary, to re-evaluate the information obtained during the test-production in 1978/1979. The next phase is planned to start approximately two to three years after the start of the initial production period with the drilling of approximately 7 development wells. Based on the results of these wells, the last phase (6 development wells) is envisaged to start two years later.

It is not excluded that one or more 'horizontal' wells will be drilled if well performance remains below the expected levels. Such wells have been drilled by Elf Aquitaine in the shallow limestone reservoir in Lacq, southern France. Lacq-90, for example, was drilled horizontally at a depth of approximately 600 m at an angle of 88° to 92° and over a distance of approximately 130 m. To increase productivity, the permeability-height product (Kh) must be increased. Stimulation increases (K), whereas a horizontal well increases (h). Such wells would make it possible to increase the production, keep a low drawdown in the well and avoid water coning.

It has not been decided yet whether the gas from the Harlingen Field, and the gas from a few small gas fields in the Lower Cretaceous in the same area, will be treated and compressed in the Harlingen/Franeker area or in the existing treatment/compression plant of the Leeuwarden Field in Garijp, situated 30-35 km to the east of the Harlingen Field.

CONCLUSION

It seems necessary to have an early formation of closure and migration of hydrocarbons, probably before the Middle Oligocene, to preserve the minimum permeability necessary to produce at economic rates from an unfractured chalk reservoir in the southeastern part of the North Sea Basin. Careful production from such a reservoir in the Harlingen Field has prevented the feared pore collapse, common in many other unfractured chalk fields.

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