buff coloured chalk, which is soft to moderately hard and in which the occurrence of flint and chert is common. The clay content is generally lesser than in the lower member.

Log characteristics: The Chalk-6 Unit is divided into two distinct intervals: a lower member and an upper member.

The gamma ray generally reads slightly higher values in the lower member than in the upper one. The sonic curve shows numerous high velocity peaks, reflecting the numerous flint beds throughout the entire unit. In the lower member the sonic values are considerably higher than in the upper member, which normally reads values equally low as in the upper part of Unit-5.

Boundaries: The lower boundary is identical to the upper boundary of the Chalk-5 Unit.

The upper boundary to the 'North Sea Marl' is gradual, showing an increase from constantly low gamma ray values and a decrease in the sonic velocities. Where the 'North Sea Marl' is missing, the change is very abrupt. The boundary is defined at the point where the gamma ray and sonic values change to higher and lower values respectively.

Distribution: The Chalk-6 Unit has been recorded in all Danish wells (fig. 29) and, together with the equivalent Ekofisk Formation, this chalk sequence has a wide distribution, being recognized in the Dutch, German, English, Norwegian, and Danish sectors of the central North Sea.

Geological age: The Chalk-6 Unit has recently been dated by means of planktonic foraminifera. These datings point to a Danian age exclusively. Previous datings pointed to a slight time transgressive nature for the Unit.

Detailed studies of the Chalk-6 Unit show that the boundary between the upper and the lower member falls within the *G. daubjergensis* Zone. The upper member may be divided into three subzones, one of which is apparently related to a characteristic log marker. The age of the top of the Chalk-6 Unit varies due to erosion of the chalk (fig. 30).

Depositional environment: The planktonic foraminifera point to outer neritic marine conditions. The recorded thickness of the Chalk-6 Unit in the Central Graben points to a slightly higher rate of subsidence in the northern part (fig. 29). Local variations seem to be less pronounced than in previous periods and the effect of halokinesis has decreased, as verified by a relatively thick sequence of the Chalk-6 Unit on top of salt structures.

Source rock potential: The upper member contains only a small amount of organic matter and is immature. Although the lower member may contain relatively more organic matter, it has never reached a mature stage.

Reservoir potential: The lower member has a fair primary porosity and a fairly low permeability (chapter 9), but it is nevertheless a reservoir rock. The fairly high clay content causes poor production characteristics due to fairly low permeability, unless fractured. The upper member has a good reservoir potential, and high hydrocarbon saturations have often been encountered within this member.

Sealing potential: The presence of clay lamina and chert beds within the lower member may occasionally render the Unit a sealing potential.

3.7 Cenozoic excl. Danian limestone

By Finn Nyhuus Kristoffersen & Inger Bang

During the Quaternary and Tertiary a regional subsidence took place resulting in a large depositional basin, the axis of which coincides with the central part of the present North Sea. Thick Tertiary and Quaternary series were deposited, consisting mainly of clays with an increasing amount of sand upwards. The upper part of the series is particularly uninfluenced by deeply seated structures or by major tectonic activities (fig. 36).

North Sea Marl *(informal name)*

The North Sea Marl may be correlated to the unnamed marl unit in the Norwegian Central North Sea mentioned as an equivalent to the Maureen Formation of the Montrose Group (Deegan & Scull 1977), in the Norwegian Central North Sea.

Type section: The Danish E-1 well, 6725-6735' b.KB.

Reference sections: In the Danish Central Graben the following wells characterize the Unit: N-1 (6839-6897' b.KB), P-1 (9504-9580' b.KB), Q-1 (9971-10072'

b.KB), Adda-1 (6841-6866' b.KB), and L-1 (6548-6732' b.KB) outside Central Graben.

Thickness: The thickness varies from 56 m in the L-1 well to less than one meter in the A-2 well, where the Unit mostly occurs as matrix between chalk nodules (fig. 32).

Parts of the Unit seem to be missing in some wells.

Lithology: Marl, greyish-green; calcareous clay, light to dark grey or greyish-green; and chalk, clayey, light grey to green, often with a high content of pyrite.

The type section shows a very condensed but apparently complete series, which has been cored. The lithology is from top: clay, greyish-green, calcareous, grading downwards into slightly shaly marl, and limestone, light greenish-grey, clayey.

Log characteristics: The gamma ray pattern shows diversity depending on the lithology (clay content).

Boundaries: The top of the Unit is defined by a maximum on the gamma ray readings below which generally lower values can be found, together with corresponding higher values on the sonic velocity. There often seems to be a gradual change to the underlying Chalk-6 Unit, and the boundary is then defined on the gamma ray at the transition to the more homogenous limestone of the Chalk-6 Unit.

Distribution: The Unit has been found in most wells and seems to be distributed over major parts of the Danish Central Graben apart from a few structures (fig. 32).

Geological age: The age is Late Danian-Early Selandian. The biostratigraphy is established on the basis of planktonic foraminifera and forms 3 successive assemblages in the *S. triloculionides* Zone.

The Unit may occasionally contain reworked foraminifera. They derive from different parts of the Chalk-6 Unit but never, as mentioned from the Norwegian North Sea sector, from the Cretaceous formations.

Depositional environment: The planktonic foraminifera indicate uniform oceanic conditions (high salinity, open marine) while the benthonic foraminifera seem to show a great variation, from near littoral on some structures to deeper water facies.

Source rock potential: Poor and immature for oil generation.

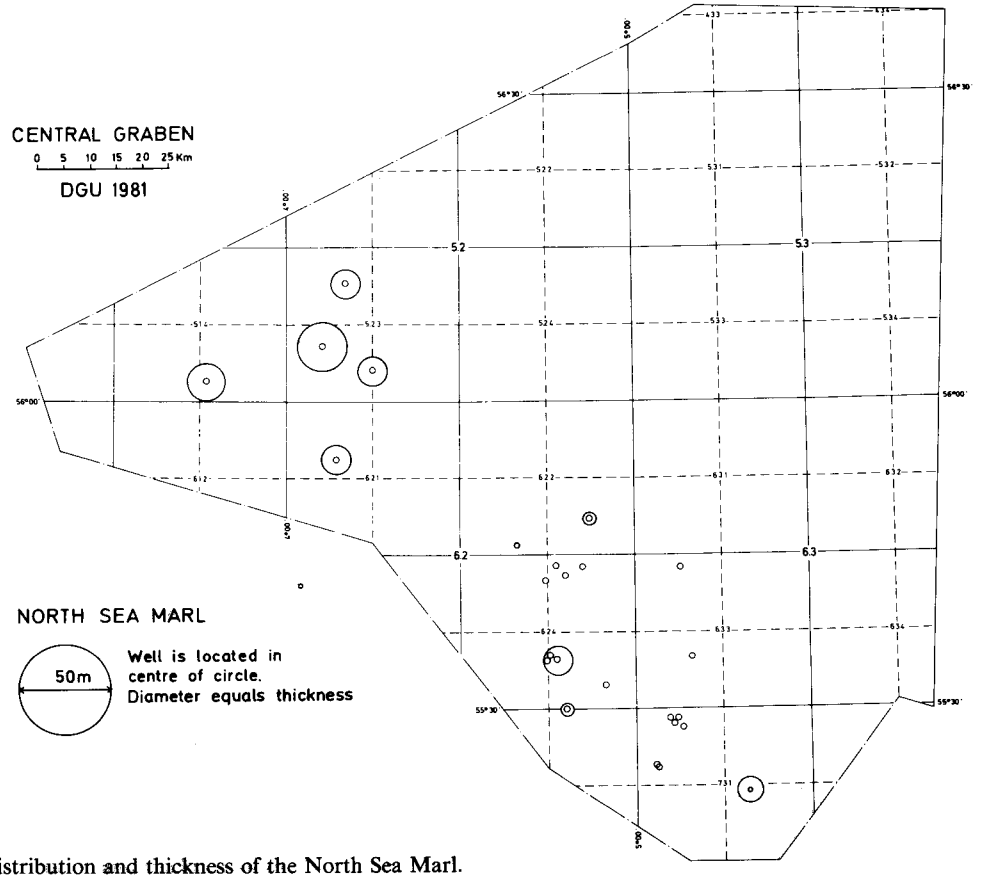

Fig. 32: Distribution and thickness of the North Sea Marl.

Reservoir potential: Hydrocarbon shows have been found within the Unit in: E-1, I-1, N-1, T-1, U-1, Adda-1, and B-1.

Sealing potential: Generally poor but some of the clay layers may act as sealing beds.

CEN-1 Unit *(informal name)*

The Unit includes Selandian non-calcareous clays. It may correspond to the Norwegian Lista Formation (Deegan & Scull 1977).

Type section: The Danish E-1 well, 6683-6725' b.KB.

Reference sections: In the Danish Central Graben the following wells characterize the Unit: A-2 (5898-5950' b.KB), P-1 (9282-9504' b.KB), and Q-1 (9790-9971' b.KB).

Thickness: The Unit has a varying thickness from 3 to 68 m (fig. 33).

Lithology: Clay and shale, non-calcareous, mostly red-brown, greenish-grey and grey, but other colours occur, with subordinate layers of silt or sandstone (in the P-1, Q-1, and W-1 wells). Beds of diagenetically formed limestone (? dolomite) have been found in a few wells.

In the type well, the cored section consists of shale, red-brown; with clay, greyish-green (6688-6703'); shale, brownish grey with red-brown and greenish parts (6703-6708'); there is no recovery from 6708-6727'.

Log characteristics: The gamma ray readings are higher in the top and bottom, and the Unit can best be characterized by its boundaries.

Boundaries: The upper boundary is well defined at the base of the beds with volcanic tuff corresponding to the base of the gamma ray peaks mentioned under the CEN-2 Unit. The lower boundary is defined at a maximum of the gamma ray readings below which a change to generally lower values occur.

Distribution: The Unit seems to cover most of the Danish Central Graben (fig 33).

Geological age: The age is Selandian (Paleocene). The top of the Unit contains diatoms (*Coscinodiscus* sp.) succeeded by a (mostly poor) fauna of arenaceous foraminifera with *Spiroplectammina spectabilis*. It is often interrupted by a zone dominated by radiolaria.

Depositional environment: The sediments and the fossil content indicate deposition below the calcite compensation depth: Marine, bathyal.

Source rock potential: Poor. Studies of a few well sections show an immature stage for oil generation.

Reservoir potential: Hydrocarbon shows have been seen within the Unit in the E-1, E-2, H-1, M-1, T-1, Adda-1, and Ruth-1 wells.

Sealing potential: Generally good, due to the relatively homogenous clay series.

CEN-2 Unit *(informal name)*

The Unit is a very important chronostratigraphic marker, since it contains a widely distributed volcanic tuff series. It is easily recognized on the gamma ray log and is easily mapped on the seismic sections in at least the Norwegian, Danish, and British Central Graben areas.

The CEN-2 Unit is equivalent to the Sele and Balder Formations to the north of the Danish sector (Degan & Scull 1977), but a subdivision into the two formations has not yet been possible in the Danish Central Graben area.

A possible correlation to the volcanic ash series of onshore Denmark has not yet been studied.

Type section: The Danish E-1 well, 6640-6683' b.KB.

Reference sections: The following Danish well sections characterize the Unit: A-2 (5823-5898' b.KB), H-1 (6620-6670' b.KB), and M-1 (5787-5832' b.KB).

Thickness: The thickness is 13 m in the type section. The general thickness is 20 m (fig. 33).

Lithology: In the type section the Unit comprises greenish-grey, dark grey, and greyish-black claystones with numerous interbedded volcanic ash layers. The greyish-black claystone occurs mainly as finely laminated claystones. Part of the ash series has been cored in two Danish Central Graben wells: E-1 and A-2. There seems, however, to be some discrepancies with respect to the stratigraphic position of the laminated claystone which, in the E-1 well is found in the top of the CEN-2 Unit, while in the A-2 well is described from the bottom. In a number of wells the ditch

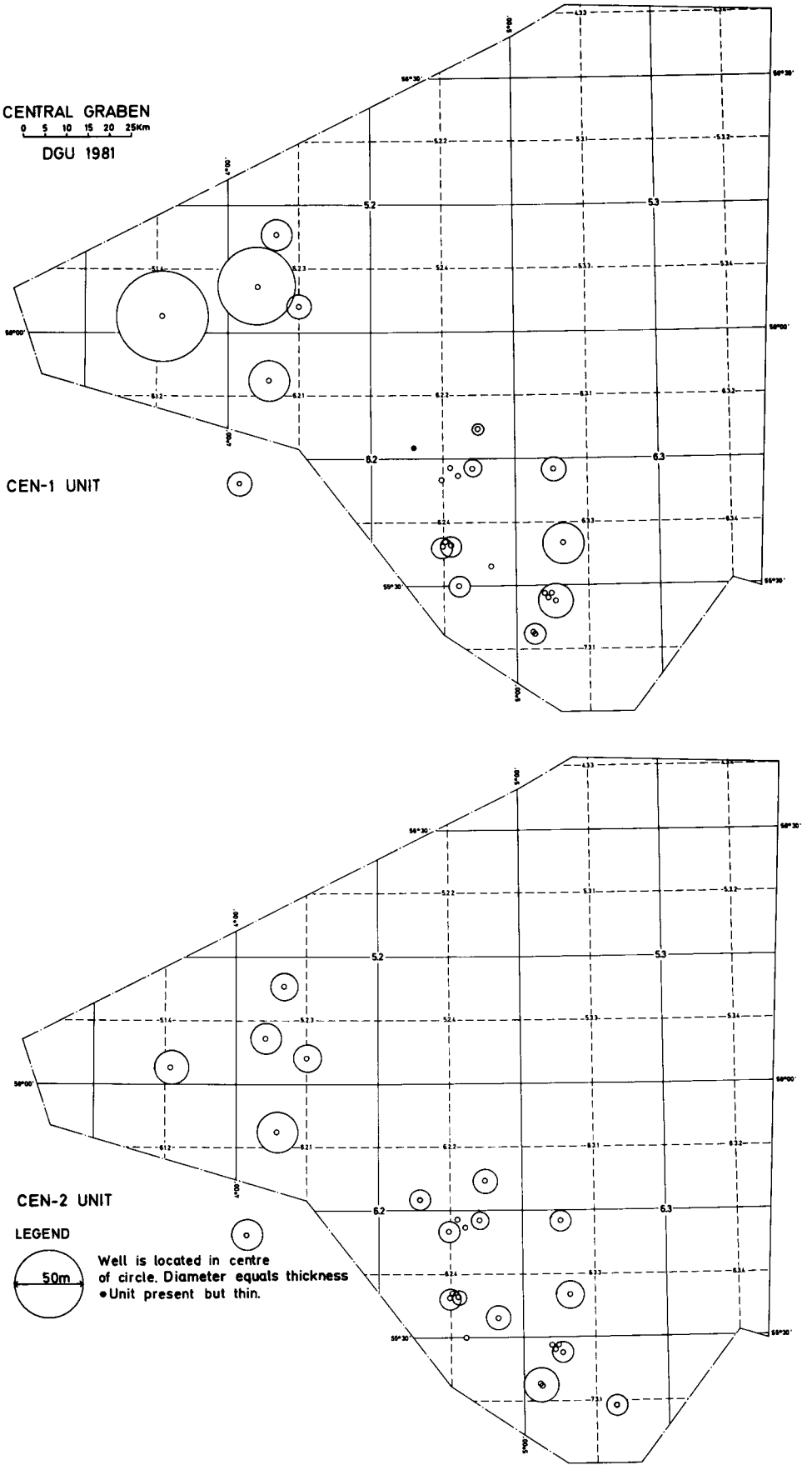

Fig. 33: Distribution and thickness of a) the CEN-1 Unit and b) the CEN-2 Unit.

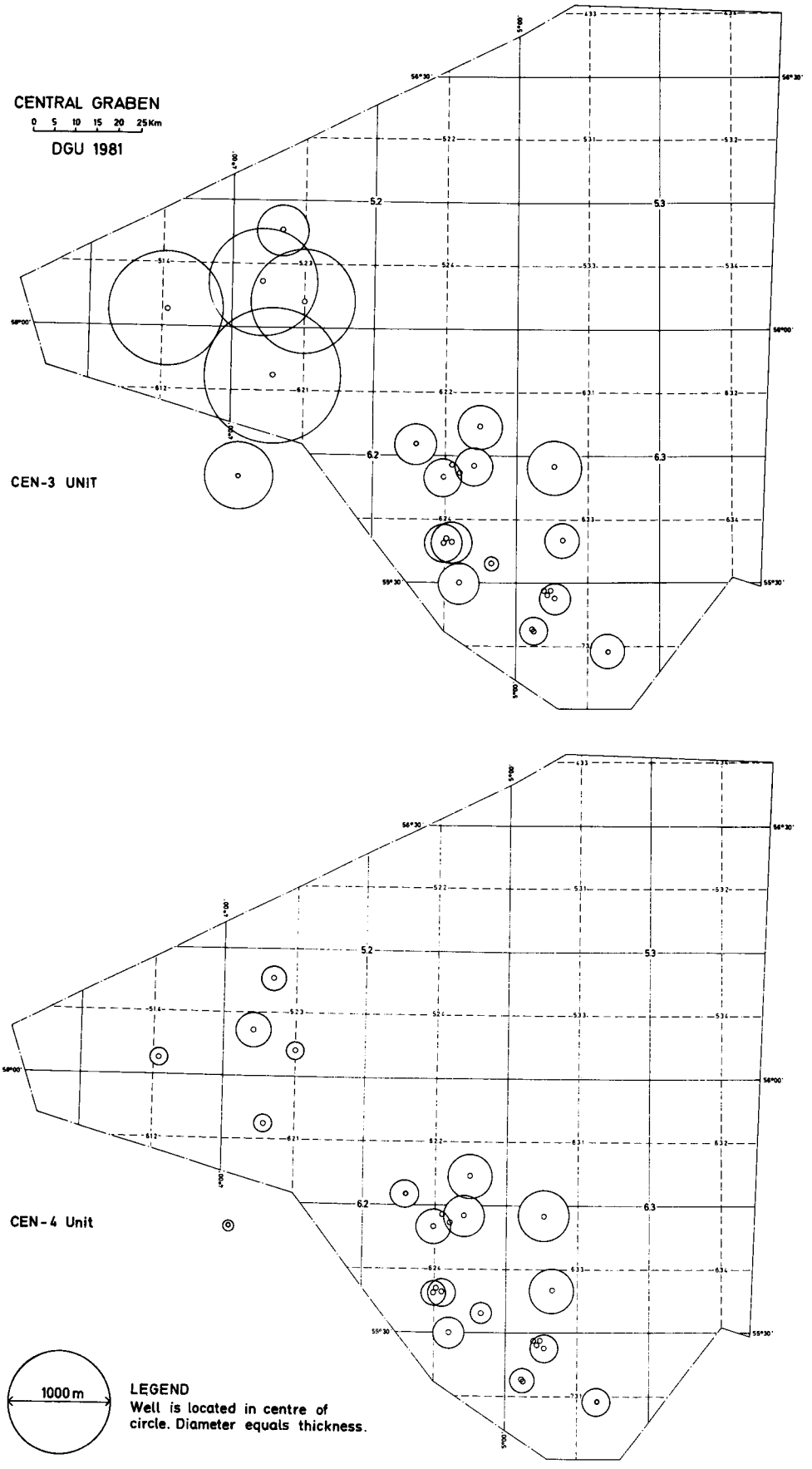

Fig. 34: Distribution and thickness of a) the CEN-3 Unit and b) the CEN-4 Unit.

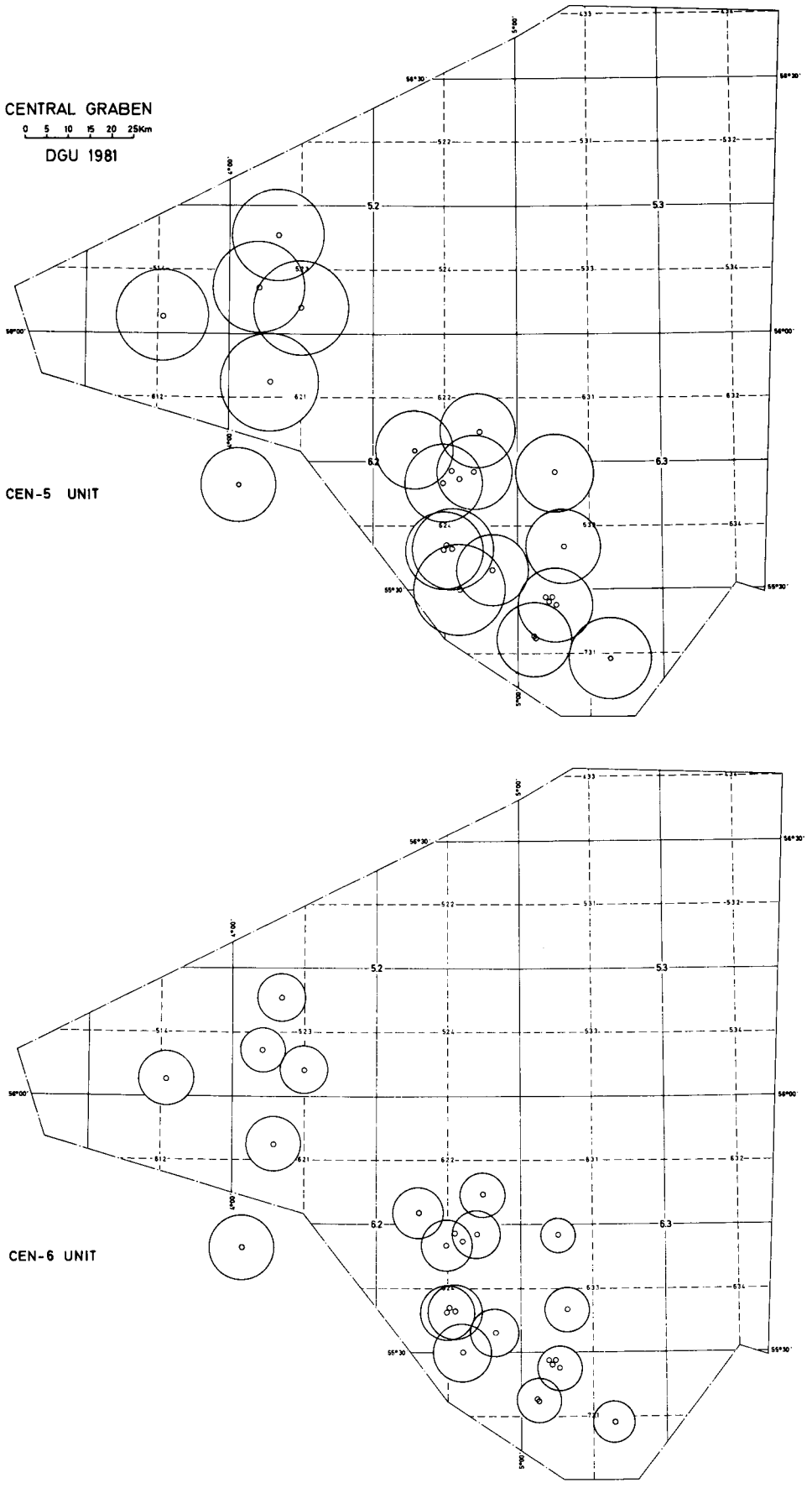

Fig. 35: Distribution and thickness of a) the CEN-5 Unit and b) the CEN-6 Unit. – For legend, see fig. 34.

sample descriptions indicate that the laminated claystone occurs below the ash layers, that is in the lower part of the CEN-2 Unit. Thin layers of sandstone occur frequently.

Log characteristics: The CEN-2 Unit is easily recognized from the gamma ray readings. It is typically a narrow section delimited upwards and downwards by distinct peaks with high gamma ray.

Boundaries: The lower boundary lies between the reddish-brown claystone of the CEN-1 Unit and the laminated claystone.

The upper boundary lies between the dark grey claystones of the CEN-2 Unit and the reddish-brown claystone which typically seems to make up the basal section of the CEN-3 Unit.

Distribution: The volcanic ash series is widely distributed within the North Sea Basin and is found in all Danish Central Graben wells (fig. 33).

Geological age: Foraminifera are very rare in this Unit and they are all long-range forms. Pyritized diatoms are frequent. Based on the presence of the ash series, the Unit is referred to a Late Paleocene - Early Eocene age.

Depositional environment: Possibly a marine, bathyal environment with contemporaneous volcanic activity.

Source rock potential: Poor. Studies of a few well sections show an immature stage for oil generation.

Reservoir potential: Poor. Diminutive hydrocarbon shows are referred to thin layers of siltstone and volcanic ash.

Sealing potential: Good, due to well-developed claystone series.

CEN-3 Unit *(informal name)*

The basal reddish-brown claystone of the CEN-3 Unit may correlate with the Early Eocene Røsnæs clay of onshore Denmark. The superjacent silty claystones are equivalent to the Lillebælt Formation, the Søvind Formation, the Viborg Formation, and possibly to the Late Oligocene Branden Clay.

Comparison with Norwegian units has not yet been attempted because lithologic subdivisions have not been carried out in the Norwegian Middle and Late Tertiary.

Type section: The Danish U-1 well, 5870-7195' b.KB.

Reference sections: The following Danish well sections are regarded as characteristic: E-1 (5460-6640' b.KB) and W-1 (5600-9850' b.KB).

Thickness: The thickness is 404 m in the type section; the general thickness is 3-400 m in the southern Central Graben and 11-1200 m in the northern (fig. 34).

Lithology: The sediments of this Unit are predominantly greenish-grey and grey, more or less silty claystones, which become slightly brownish in the uppermost part. The basal layers are typically reddish-brown claystones. Numerous thin limestone layers are present throughout the Unit, perhaps most frequently in the lower part.

Log characteristics: The gamma ray readings show generally gently upwards increasing values through the interval, with some significant increase uppermost in the Unit. This sharp change to higher gamma ray readings may possibly correspond to a lithologic change from greenish-grey to darker and more greyish claystone uppermost. Close to the base of the Unit, a narrow interval shows relatively high gamma ray values. This is a characteristic marker horizon, which at present cannot be referred to any specific lithological feature.

Boundaries: The lower boundary is at the change from the dark grey claystones with high gamma ray values in the CEN-2 Unit, to the basal reddish-brown claystone in the CEN-3 Unit. The upper boundary is defined at the top of a log motif with two rounded gamma ray peaks, which might be very difficult to identify in some wells. This feature is best demonstrated in the Danish W-1 well, whereas it is indistinct in the type section. The boundary is between greenish-grey and grey claystones below, and somewhat darker and slightly brownish claystones above, in the CEN-4 Unit.

Distribution: The Unit is widely distributed in the North Sea Basin, and is present in all Danish Central Graben wells (fig. 34).

Geological age: The rather abundant foraminiferal species are mainly long-ranging arenaceous forms. The very rare calcareous benthonic and planktonic species refer the Unit to an Early Eocene - Late Oligocene age.

Depositional environment: The foraminiferal fauna and the fine-grained sediment suggest a deposition in a marine bathyal environment. The depocentre is situated in the northern part of the Danish Central Graben area and in the adjacent Norwegian Central Graben area, where thicknesses exceed 1000 metres, more than three times the thicknesses in the southern part of the Danish Central Graben area.

Source rock potential: Poor. Studies from a few well sections show an immature stage for oil generation.

Reservoir potential: The numerous thin layers of limestone constitute a rather limited reservoir potential.

Sealing potential: Good, due to the thick claystone series.

CEN-4 Unit *(informal name)*

The CEN-4 Unit is equivalent to the micaceous clay and sand formations of Upper Oligocene and Lower to Middle Miocene age in Jylland, where these marine and non-marine formations interfinger. In particular, the Middle Miocene Hodde Formation seems in some respects comparable with the upper part of the CEN-4 Unit.

A comparison with Norwegian formations has not been possible because only the oldest part of the Norwegian Tertiary has been subdivided.

Type section: The Danish M-1 well, 4015-4900' b.KB.

Reference sections: The following Danish wells are regarded as characteristic sections: U-1 (4870-5870' b.KB), V-1 (3860-5553' b.KB), and W-1 (5050-5600' b.KB).

Thickness: The CEN-4 Unit has a thickness of 270 m in the type section, and the general thickness is 200-400 m (fig. 34).

Lithology: In the type section the Unit is a dark greyish-brown, non-calcareous and micaceous clay or claystone, which becomes more greyish towards the base. In the northern part of the Danish Central Graben area, these dark claystones seem to be replaced by light grey, rather sticky claystones. Thin layers of siltstone are frequent.

Log characteristics: Based on the gamma ray it seems possible to divide the Unit into two subunits. The gamma ray readings are generally on a slightly lower level in the upper part than in the lower part of the Unit. At present, however, this difference has not succesfully been related to lithological features.

Boundaries: There is an indistinct transition from the greenish claystones of CEN-3 to the brownish claystones of the present Unit. As already mentioned, the lower boundary has been very difficult to determine on the basis of wire line logs. However, it has been possible to identify two gently rounded peaks on the gamma ray curve in the top of the CEN-3 Unit. These peaks are best developed in W-1.

The upper boundary is at the base of a distinct gamma ray marker. This boundary coincides with the upper boundary of the zone with 'overpressured shales'.

Distribution: The CEN-4 Unit is widely distributed in the central North Sea area and is found in all Danish Central Graben wells (fig. 34).

Geological age: Based on the investigations of foraminiferal fauna, a Late Oligocene age is proposed for the lower part of the Unit. The fauna are very different from those known from the corresponding formations in Jylland, and only few forms have been recorded from both areas. One of these, *Plectofrondicularia seminuda*, seems to be characteristic for the younger Oligocene in the North Sea area.

While the lower part of the CEN-4 Unit shows an almost pure arenaceous foraminiferal fauna, the upper part contains a calcareous fauna with numerous planktonic species. Many of these are indicative of an Early to Middle Miocene age.

Depositional environment: The CEN-4 Unit has been deposited in an open marine and outer sublittoral environment.

Source rock potential: Poor. Studies of a few well sections show an immature stage for oil generation.

Reservoir potential: Poor. A number of diminutive hydrocarbon shows are recorded in thin siltstone layers.

Sealing potential: This homogenous claystone series probably has good sealing potentials.

CEN-5 Unit *(informal name)*

The CEN-5 Unit can be correlated with the Late Miocene Gram Formation and the micaceous clay and

silt series of supposed Pliocene age in southwestern Jylland.

Comparisons with Norwegian formations has not been attempted since a lithological subdivision of the younger Tertiary and Quaternary series has not yet been carried out in the Norwegian central North Sea area.

Type section: The Danish N-1 well, 2028-4633' b.KB.

Reference section: The following Danish well sections are found to be characteristic: E-1 (1695-4200' b.KB) and M-1 (1585-4015' b.KB).

Thickness: The CEN-5 Unit has a thickness of 794 m in the type section, and the general thickness is 700-900 m (fig. 35).

Lithology: Grey, occasionally micaceous, silty clay predominates in the lower part of the Unit. Intercalations of micaceous sand and silt are frequent. Towards the top of the Unit, the amount of sand and silt increases. A rather thick gravelly sand bed forms the uppermost part.

Log characteristics: The gamma ray readings are generally on a medium level, but with an upwards increasing number of oscillations, reflecting the presence of graded beds towards the top.

Boundaries: The lower boundary is defined at the base of a distinct marker with high gamma ray values. This marker is typically composed of two gamma ray peaks.

The upper boundary is at the top of the thick gravelly sand bed characterized by low gamma ray values. It appears to be a sharp boundary towards the clayey bed above.

Distribution: The CEN-5 Unit is widely distributed in the Danish North Sea area and it is found in all Danish Central Graben wells (fig. 35).

Geological age: The Unit is referred to Upper Miocene and Pliocene. By means of foraminifera, the lower part is correlated with the Upper Miocene Gram Formation. Differences in the fauna are regarded as reflecting different depositional environments.

For the upper part, a Pliocene age is proposed, based on faunal correlation to Pliocene strata known from the Netherlands.

Depositional environment: The alternation between silty clay and sand beds, the numerous graded beds which appear from the gamma ray readings, and the open marine, sublittoral foraminiferal fauna, give the impression that the CEN-5 Unit was deposited in a delta front in the subsiding North Sea Basin.

Source rock potential: Probably poor. Studies in a few well sections point to an immature stage for oil generation.

Reservoir potential: The uppermost gravelly sand of Pliocene age has good reservoir potential. Gas accumulations are frequently met with in these beds and give rise to the 'bright spots' on the seismic sections.

Inferior hydrocarbon shows are related to thin layers of limestone or siltstone close to the lower boundary.

Sealing potential: The sealing potential is generally poor in the Pliocene sand, but good in the Miocene clay sequence.

CEN-6 Unit *(informal name)*

The Unit comprises mainly marine sediments. Glacial deposits known from onshore Denmark have not been recognized within the Unit.

Comparison with Norwegian units has not been attempted since a lithological subdivision of the younger Tertiary and Quaternary has not yet been carried out in the Norwegian central North Sea area.

Type section: The Danish E-1 well, 245-1695' b.KB.

Reference sections: The following Danish wells have characterizing sequences: A-2 (263-1675' b.KB) and H-1 (274-1942' b.KB).

Thickness: The Unit has a thickness of 442 m in the type section, and the general thickness is 400-500 m (fig. 35).

Lithology: Silt, sand, and gravel alternate with grey silty clays. Shell fragments and lignite occur frequently.

Log characteristics: The basal part is characterized by relatively high gamma ray readings reflecting a basal clay bed. The superjacent part shows strongly oscillating gamma ray readings corresponding to interbedded sand and clay layers.

Boundaries: The lower boundary is very distinct on

the gamma ray, changing very abruptly from low values in the sand uppermost in the CEN-5 Unit, to high values in the basal clay bed of the CEN-6 Unit. The upper boundary is represented by the sea floor.

Distribution: The Unit is widely distributed within the Danish North Sea region and is found in all Danish Central Graben wells (fig. 35).

Geological age: Foraminifera occur abundantly in the lower part of the Unit, while they are rare or absent above. The restricted number of foraminiferal species recorded points unambiguously to a Pleistocene to recent age. The lower bed with abundant foraminifera is referred to the Early Pleistocene (Icenian).

Depositional environment: The alternating sand and silty clay layers, the frequency of lignite and megaspores, and the common accumulations of shells point to marine, littoral to inner sublittoral environments related to a delta front in the subsiding North Sea Basin.

Source rock potential: Poor. Studies in a few well sections indicate an immature stage for oil generation.

Reservoir potential: Good in unconsolidated porous sand layers.

Sealing potential: Poor in the intraformational parts. The lower clay layer may probably act as a seal for hydrocarbon accumulations in the unit below.

4.0 Formation temperatures

By Peter Klint Jensen

Borehole temperatures have been studied to evaluate the natural temperature field of the geological formations (fig. 37). Formation temperature and time are main factors affecting maturation of source rocks and should, therefore, be compared with maturation measurements. Furthermore, temperature gradients through sedimentary sequences provide information about relationships between their heat conductivities, and this can be used to extrapolate temperatures measured in wells to the surrounding rock masses.

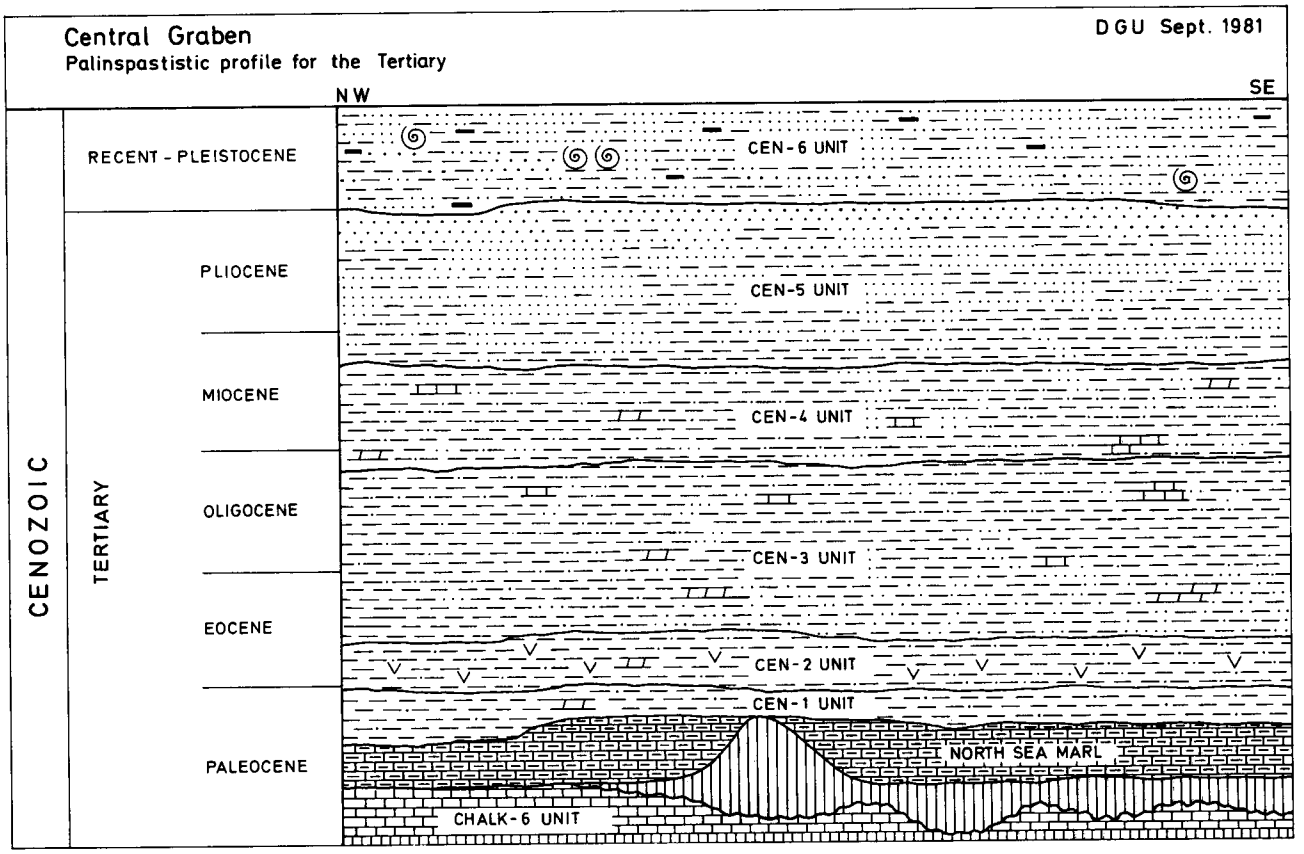

Fig. 36: Palinspastic profile of the Cenozoic deposits. For legend, see fig. 3.