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Revision of the 'Late Jurassic' stratigraphy of the Dutch Central North Sea Graben

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Abstract

The 'Late Jurasic' stratigraphy of the Dutch Central North Sea Graben is revised. The sediments, ranging in age from Callovian to Ryazanian, are grouped in two lithological units: the mainly non-marine Central Graben Group (with Lower Graben Sand, Middle Graben Shale, Upper Graben Sand, Puzzle Hole, and Delfland formations) and the distinct marine Scruff Group (with Kimmeridge Clay, Scruff Greensand, and Clay Deep formations). The latter two formations are new and are introduced formally.

Basic palynological and micropaleontological data are included to support age assignments of various formations. Several log correlations, range charts, distribution maps, facies maps and seismic sections are given to illustrate the stratigraphic framework. Finally, a synopsis of the geological history is presented, with special attention to sea-level changes and ensuing coastal developments, illustrating the relationships with the Danish and Norwegian sectors.

Introduction

The Central North Sea Graben can be regarded as the southern extension of the Central Graben (Fig. 1). According to Heybroek (1975), the graben appears to be a complicated block-faulted feature with maximum subsidence at its centre, flanked by intermediate blocks which step down from the bordering highs in the west, east and south (Fig. 1). Modern structural interpretations can be found in Clark-Lowes et al. (1987) and Van Wijhe (1987). The graben margins are usually coincident with linear, north-south oriented Zechstein salt piercements, but large salt domes and piercements also occur near the centre of the basin (Fig. 2). Since rifting was dominant in the Mid to Late Jurassic, the geological development of the area can be divided in pre-rifting, rifting, and post-rifting phases (see the chapter on the geological history).

Since the early Seventies, the stratigraphy of the Dutch Central North Sea Graben has consistently received attention from the Geological Survey of The Netherlands (RGD). This attention was not only justified by correlation problems between the sedimentary sequence in the northern and southern parts of the basin. The different and often conflicting opinions held by consultants and oil companies (see, for example, Heybroek 1975), also underscored the need to review the Central Graben stratigraphy.

In 1980 the Nederlandse Aardolie Maatschappij and the Rijks Geologische Dienst (NAM & RGD, 1980) published a monograph entitled Stratigraphic nomenclature of The Netherlands. Herngreen &

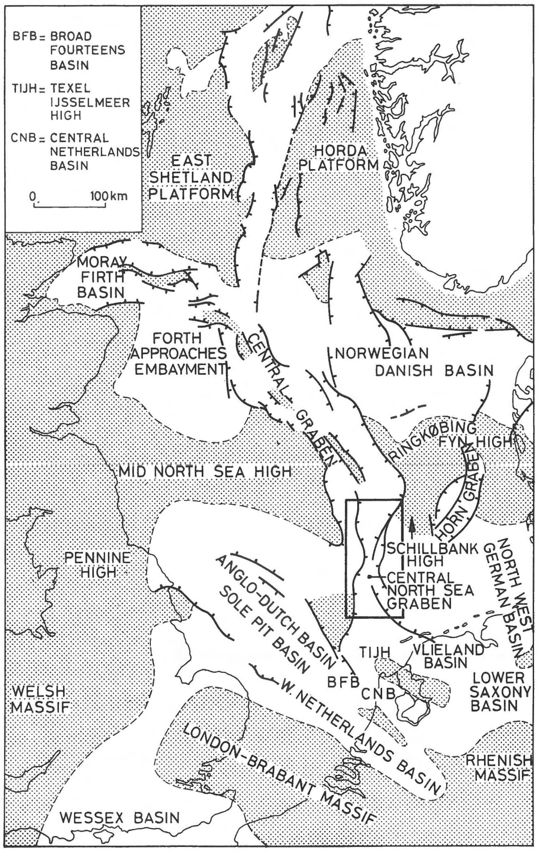

Fig. 1. Structural framework of the North Sea area (modified after Rawson & Riley; 1982).

De Boer (1985) showed that some of the data given by NAM & RGD for the 'Upper Jurassic' required re-interpretation in the light of new palynological evidence. The main conclusions from their study may be summarized as follows:
1. The Scruff (Green) Sand overlying the Main Kimmeridge Clay is Portlandian to Early Berriasian (Ryazanian). This lithostratigraphic unit, widely known as F18 Sand, Main Sand, etc., was not mentioned in NAM & RGD (1980).
2. The age of the Kimmeridge Clay deposits in the F3-3 reference well is not younger than Late Kimmeridgian. No evidence was found for a Portlandian and/or Berriasian (Ryazanian) age of the Kimmeridge Clay Formation in the boreholes mentioned by NAM & RGD (1980).
3. The organically rich clay above the Scruff Sand, which was provisionally indicated as Scruff Shale, is Berriasian (Ryazanian).
4. The Upper Kimmeridge Clay Member in the F11-2 reference well is of roughly Early Kimmeridgian age and not Kimmeridgian-Berriasian (Ryazanian) as pointed out in NAM & RGD (1980, p. 38) or indicated as Late Kimmeridgian in text-figure 9 of the same monograph.
5. Based on age dating and the depositional environment the Lower Kimmeridge Clay Member (NAM & RGD 1980) is considered to be equivalent to the restricted marine Middle Graben Shale Formation.
6. The Puzzle Hole Formation in reference well F11-2 is Middle to Late Oxfordian and not Early Kimmeridgian. The rapidly alternating sands and shales with minor coal seams in the southern part of the Central North Sea Graben show close resemblance to the Delfland strata.

After the presentation of the first results in September 1984 at the Symposium on Jurassic Stratigraphy in Erlangen, the RGD continued to carry out palynological and micropaleontological studies on Late Jurassic and Early Cretaceous sediments of the Dutch Central North Sea Graben. In dinoflagellate and sporomorph analyses emphasis was put on (side-wall) cores; the foraminiferal and ostracod work was mainly carried out on cuttings. During the last two years several of the questions which arose after the compilation of the revised rock stratigraphic diagram in Herngreen & De Boer (1985) were treated in more detail. These concern particularly:
1. the relationship between the Upper Graben Sand and the Puzzle Hole formations;
2. the age and development of strata equated with the Puzzle Hole sediments in the area south of F11;
3. a more accurate dating of the Scruff (Green) Sand and of some sand bodies in the Kimmeridge Clay and Middle Graben Shale formations; and
4. the distribution of the Scruff Shale, at present formally designated Clay Deep Formation.

It is now considered justified to give a formal description of some lithostratigraphic units used informally in Herngreen & De Boer (1985). This opportunity is also taken to present additional information on other formations described by NAM & RGD (1980) and to define a regrouping of some units.

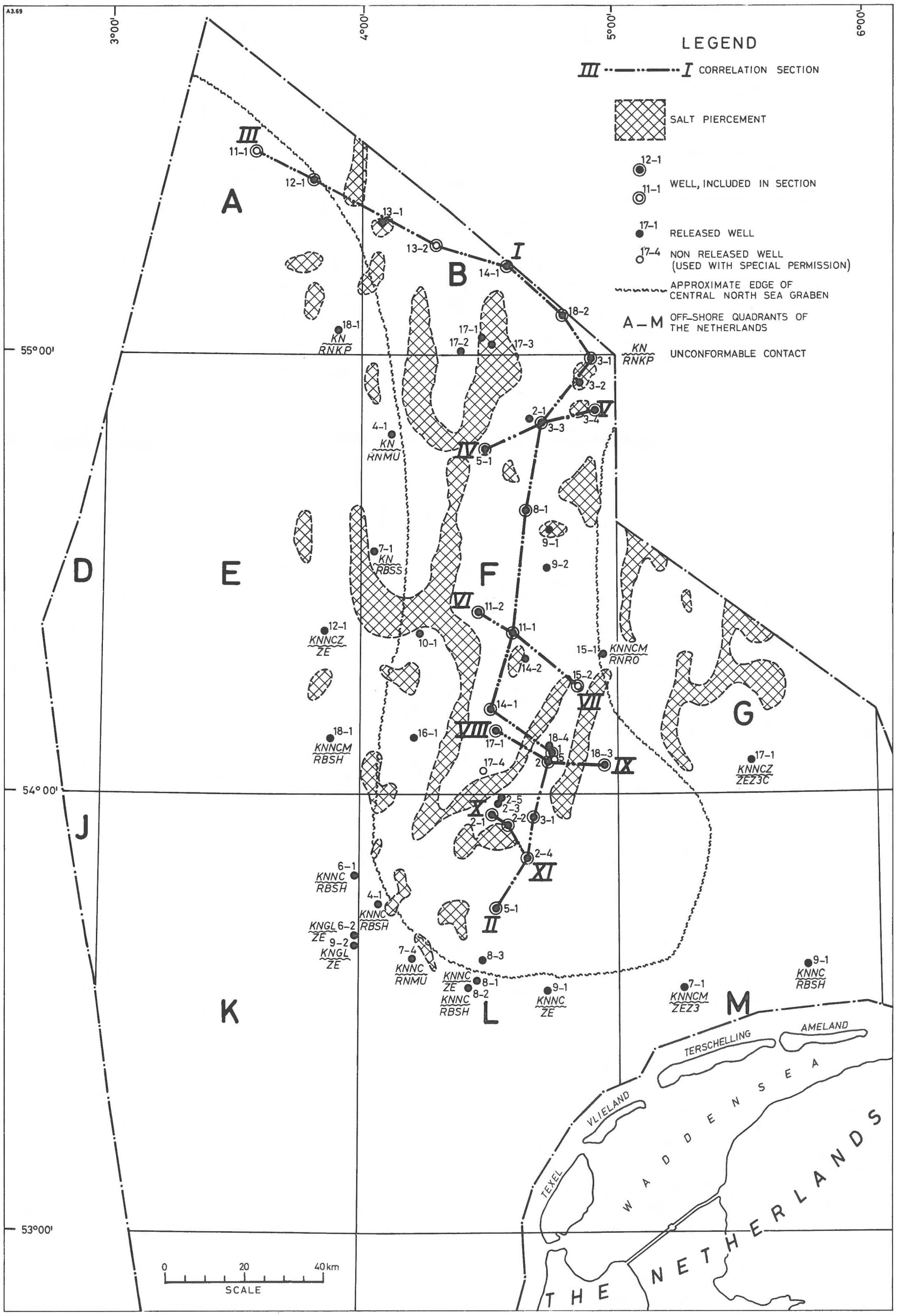

Fig. 2. General outline of the Dutch Central North Sea Graben, showing position of relevant drill-holes, cross-sections (Figs 18–22 and Encl. 1), salt domes and piercements.

Stratigraphy

All released wells of the area under study were included in the present report (see Fig. 2 for location of these wells). In a few cases, additional relevant information has been added for which permission for publication was obtained from the respective oil companies. Several log correlations through the Dutch Central North Sea Graben have been constructed and are presented in Encl. 1 and Figs 18–22. Finally, the lithostratigraphic units were tied to recent seismic data. A brief account of these results and a description of the seismic facies are given in the next chapter.

We will first discuss a number of problems concerning the dual interpretation of Kimmeridgian and Portlandian and the Jurassic-Cretaceous boundary.

ENGLAND		STANDARD AMMONITE ZONES	FRANCE	SOVIET UNION	
PORTLANDIAN	Late	lamplugi	PORTLANDIAN	Late	VOLGIAN
		preplicomphalus			
		primitivus			
	Early	'oppressus'		Middle	
		anguiformis			
		kerberus			
		okusensis			
		glaucolithus			
		albani			
KIMMERIDGIAN	Late	fittoni			
		rotunda			
		pallasioides			
		pectinatus		Early	
		hudlestoni			
		wheatleyensis			
		scitulus			
		elegans			
	Early	autissiodorensis	KIMMERIDGIAN	KIMMERIDGIAN	
		eudoxus			
		mutabilis			
		cymodoce			
		baylei			
OXFORDIAN		pseudocordata to cordatum	OXFORDIAN	OXFORDIAN	

Fig. 3. **Stratigraphy of the Kimmeridgian and Portlandian.**

Kimmeridgian and Portlandian

There is still considerable confusion about the meaning of the stage names Kimmeridgian and Portlandian (Fig. 3). Since the middle of the nineteenth century both terms have been used either with a 'British' meaning (*sensu anglico*) or in a continental sense (*sensu gallico*). In Britain, the Kimmeridgian spans the interval from the *baylei* Zone up to and including the *fittoni* Zone. The Portlandian extends from the *albani* Zone at the base to the *lamplughi* Zone at the top. In France, however, the base of the Portlandian, as established by d'Orbigny (1842–1851), is taken at the base of the *Gravesia* beds which are equated with the *elegans* Zone.

According to the recommendations and resolutions of the First and Second Jura Colloquia held in Luxembourg in 1962 and 1967 (Maubeuge 1964, 1970), the Kimmeridge stage has been defined by the following ammonoidal zones for both northern (Boreal) and southern (Mediterranean) Europe:

top : Zone à *Aulacostephanus autissiodorensis* (Boreal) and Zone à *Hybonoticeras beckeri* (Mediterranean)

base : Zone à *Pictonia baylei* (Boreal) and Zone à *Sutneria platynota* (Mediterranean)

Unfortunately, no decision was reached about the base and the name of the terminal Jurassic stage. If we were to use the term Portlandian in the original sense (in Britain it is customary to equate Portlandian with the Portland Beds and higher Jurassic strata), i.e., starting with the *albani* Zone and ending with the *lamplughi* Zone, a new stage would have to be introduced for the period between the *elegans* and *fittoni* zones. This confusing situation may explain the tendency in the northwestern European literature (e.g. Rawson & Riley 1982; Zeiss 1983) to use the subdivision into Oxfordian, Kimmeridgian (continental sense and Luxembourg) and Volgian. This classification has been added in the extreme right column in Fig. 3.

According to Cope (1985), the Soviet Union would now rather use the Tithonian than Volgian as their standard. However, Dr. V.A. Zakharov recently assured us that this statement is not correct (V.A. Zakharov pers. comm. 1987).

Here, the conventional North European or Boreal subdivision of the Late Jurassic into Oxfordian, Early and Late Kimmeridgian, and Portlandian will be used. This division is followed for reasons outlined in Herngreen & De Boer, 1985: to facilitate comparison with NAM & RGD 1980 and to tie in with the classical subdivision that is widely used by the northwest European stratigraphers.

Jurassic – Cretaceous boundary

The Portlandian standard ammonite zonation has been established by Wimbledon (in Cope et al. 1980) and is based on earlier schemes by Casey (1973) and Wimbledon & Cope (1978). Casey also proposed a subdividion of the Ryazanian stage for Britain. According to Wimbledon (1985), the *oppressus* Zone fauna is anomalous and he inferred a gap between the *primitivus* and *anguiformis* zones.

Zeiss (1983) discussed the ammonite sequences for the latest Jurassic-earliest Cretaceous; the zonation for the Berriasian in the Tethyan/Mediterranean realm is essentially based on Le Hégarat (1973). It has repeatedly been pointed out (e.g. Casey 1973; Hancock 1972; Rawson et al. 1978; Wimbledon 1985) that the Mediterranean Berriasian overlaps the terminal Jurassic stage. In other words, the Jurassic/Cretaceous boundary is drawn at a somewhat higher level in the Boreal realm than in the Tethyan/Mediterranean realm (see Fig. 4). Zeiss (1983) correlated the Tithonian/Berriasian boundary with the transition *oppressus/primitivus* zones. Cope (1985) placed this boundary at the topmost part of the *primitivus* Zone.

We support the usage of Portlandian as the name for the latest Jurassic stage. Moreover, we prefer to avoid a mixed Boreal (Portlandian) and Tethyan/ Mediterranean (Berriasian) terminology for intervals spanning the Jurassic/Cretaceous boundary. For this reason, we use Ryazanian as the earliest Cretaceous stage.

Lithostratigraphy

General:

In revising the 'Late Jurassic' sediments we have followed two directives:

1) All non-marine sediments are included in the Central Graben Group, whilst the marine sediments are grouped in the Scruff Group.

2) The original classification of NAM & RGD (1980) has been followed as much as possible. This implies that existing names for lithological units will be used in emended forms.

The lithological units will be discussed in stratigraphic order; see Fig. 5 for a general scheme. For details on the biozonation, the reader is referred to Encl. 2.

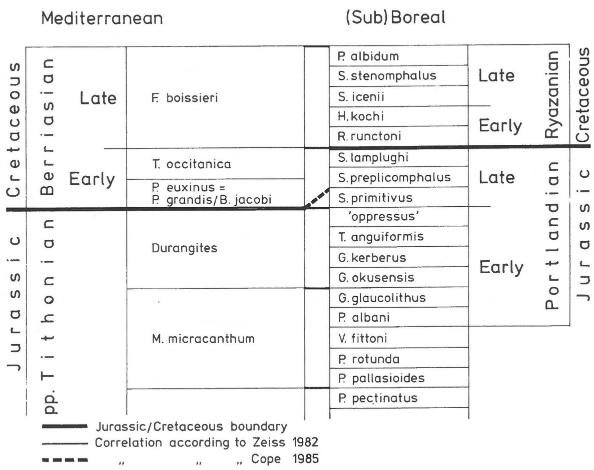

Fig. 4. Stratigraphic position of the Jurassic-Cretaceous boundary in the Boreal and Mediterranean areas.

Central Graben Group (CG): NAM & RGD (1980), emended

General – Traditionally, this Group comprises the Lower Graben Sand Formation, the Middle Graben Shale Formation and the Upper Graben Sand Formation. It is proposed here to add the Delfland Formation and the Puzzle Hole Formation to this Group.

Name – Name derived from the Central North Sea Graben (NAM & RGD, 1980).

Reference section – Well F3-3, 2547–3652 m, coord.: N 54° 50′ 45.5″, E 4° 42′ 29.3″ (Encl. 1). For the Delfland and Puzzle Hole successions, see the reference sections for these formations.

Definition – (emended after NAM & RGD, 1980). Group of formations deposited in a predominantly paralic environment and consisting of shales, sandstones, and coal seams. In the Dutch Central North

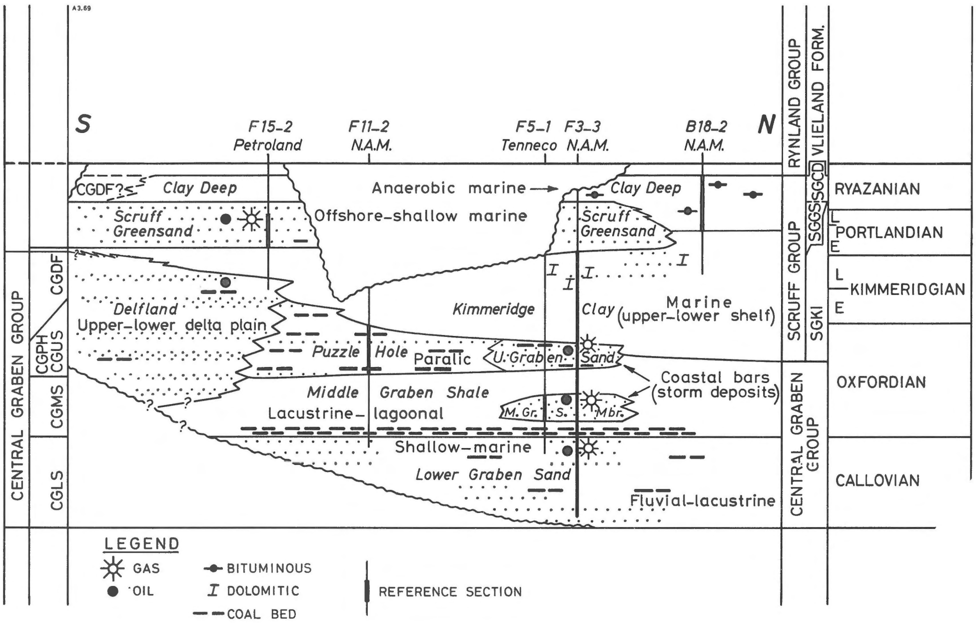

Fig. 5. **Rock stratigraphic diagram of the Central Graben and Scruff Groups, showing depositional environments and the occurrence of oil and gas in the various reservoir rocks.**

Sea Graben this succession unconformably overlies the Altena Group (generally the Aalburg Shale Formation and locally the Werkendam Shale Formation). In the Roer Valley Graben, the West Netherlands Basin, and the main part of the Broad Fourteens Basin, the Central Graben Group is situated between the marine sediments of the Altena and Rijnland Groups.

However, in the Central Netherlands and Vlieland Basins the Group overlaps sediments assigned to the Niedersachsen Group. In the Dutch Central North Sea Graben the Group interfingers with marine shales of the Kimmeridge Clay Formation of the Scruff Group.

Age – Callovian to Ryazanian.

Subdivision – five formations are distinguished, as follows:

Delfland Formation (CGDF)
Puzzle Hole Formation (CGPH)
Upper Graben Sand Formation (CGUS)
Middle Graben Shale Formation (CGMS)
Lower Graben Sand Formation (CGLS)

Lower Graben Sand Formation (CGLS). NAM & RGD (1980), emended.

Name – Named after the Central North Sea Graben (NAM & RGD, 1980).

Reference section – Well F3-3, 3090–3652 m; coord.: N 54° 50′ 45.5″, E 4° 42′ 29.3″ (NAM & RGD, 1980).

Definition – Section of greyish-brown, very fine to fine, well-sorted sandstones, occurring in beds generally less than 10 m thick, with intercalations of thin greyish-brown silty to sandy shales. The formation is generally carbonaceous with some distinct coal layers. The individual sandbodies display a rather restricted lateral extension. Especially in higher parts of this unit the gamma ray log pattern of these beds shows a generally coarsening upward sequence. The formation, which is confined to the Central Graben, ranges in thickness from 40 m to 562 m, with maxima attained in the SW (fault bounded) corner of block F3 (Fig. 6). The formation rests unconformably on strata of the Werkendam Shale Formation, the Aalburg Shale Forma-

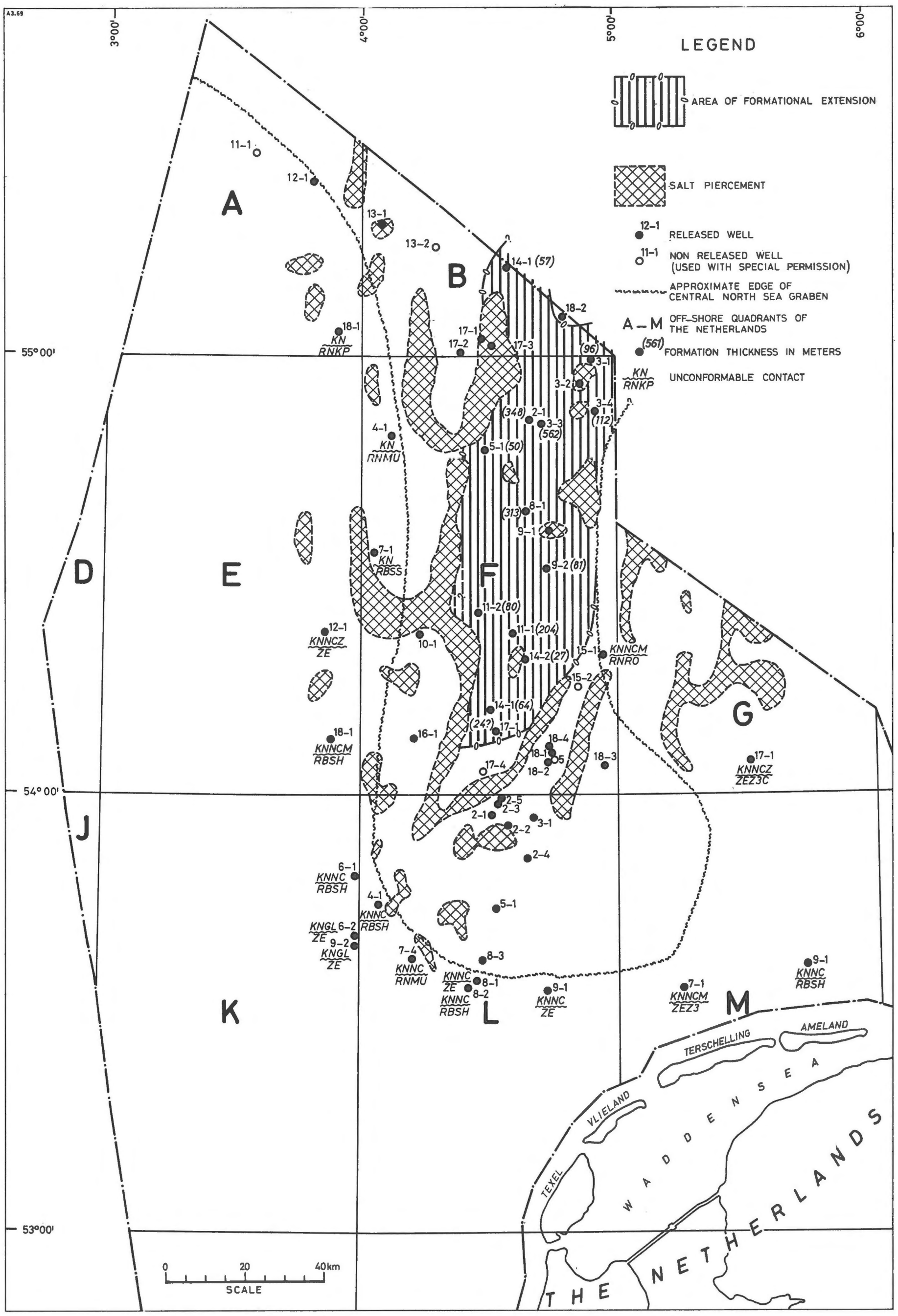

Fig. 6. Geographical distribution of Lower Graben Sand Formation.

tion, or the Upper Germanic Triassic Group. Occasionally, the underlying Werkendam Shale Formation may be developed in a coarse-grained oolitic facies, which makes the boundary between the two formations difficult to pick on the logs. The Lower Graben Sand Formation is conformably overlain by the Middle Graben Shale Formation. In the Danish part of the Central Graben the formation has also been recognized (Koch, 1983; Jensen et al., 1986 & Frandsen et al., 1987).

Age – Callovian, presumably not older than Middle Callovian. A Middle to Late Callovian age can be established on the basis of dinoflagellate associations. Significant species permitting a more precise dating are: *Acanthaulax senta, Ctenidodinium* spp. (a.o. *C. continuum, C. gochtii-kettonense* group, *C. sellwoodii-stauromatos* group), *Energlynia acollaris, Lithodinia jurassica, Meiourogonyaulax borealis, Pareodinia prolongata, Rigaudella aemula, Scriniodinum galeritum, Stephanelytron* spp., *Systematophora* spp., *Wanaea fimbriata,* and *W. thysanota.* There is a consistent presence of a characteristic sporomorph association with *i.a. Contignisporites* sp. 1. In other well-dated marine deposits, this species is not older than Middle Callovian. Samples from only two wells (F14-1: 2109–2115 m and F17-3: 2040 m) yielded a Middle or Middle to Late Callovian ostracod fauna the most characteristic representatives of which are *Fastigatocythere interrupta interrupta, Fuhrbergiella horrida horrida,* and *Lophocythere bipartita.*

Sedimentary history – The great variation in the thickness of the formation points to a differential subsidence with larger sediment accumulations in the more rapidly subsiding areas (e.g. F3-3).

Since no marine organisms occur in the lower part of the formation a fluvial origin seems the most likely here. This is consistent with the findings of Koch (1983), who interpreted the basal part of the J-2 unit to have been deposited in a braided river plain.

In the course of time deltaic conditions with occasional marine incursions started to prevail, as can be deduced from the sparse microfauna, rich dinoflagellate assemblages, and the log patterns. Coarsening upward sequences probably represent various channel-mouth bars, whereas clays formed as delta plain deposits.

There is great similarity with the Danish area where, according to Jensen et al. (1986), the formation was deposited 'in a marginal marine environment with strong fluvial influence, probably a delta with lagoons and interdistributary bays'.

Middle Graben Shale Formation (CGMS). NAM & RGD (1980), emended.

Name – Named after the Central North Sea Graben (NAM & RGD, 1980).

Reference section – Well F3-3, 2670–3090 m; co-ord.: N 54° 50′ 45.5″, E 4° 42′ 29.3″ (NAM & RGD, 1980).

Definition – Section of grey, locally very silty carbonaceous shales with some thin coal seams in the lowermost part of the formation. In the northern part of the F-quadrant (e.g. in F2, F3, and F5) a single thick sandstone bed may be intercalated. It is considered to have such a divergent development that we propose it to be a separate member called the Middle Graben Sand Member. The formation varies in thickness and its geographical distribution is limited to the northern part of the Central North Sea Graben (Fig. 7). According to Herngreen & De Boer (1985), the formation also comprises the Lower Kimmeridge Clay Member of NAM & RGD (1980). In the lower part of the formation some distinct coal seams occur. They are laterally extensive and form important lithostratigraphic markers. One such coal seam at the base of the formation reflects the contrast between the basal carbonaceous part of the formation and the underlying sands of the Lower Graben Sand Formation. Hence, the boundary between the two formations is placed at the base of this coal seam. Toward the north the formation is overlain by the Kimmeridge Clay Formation. In southern direction the formation is (in part) equivalent to the Puzzle Hole Formation. In the Danish part of the Central Graben the J4-unit as described by Koch (1983) displays a similar lithology, and therefore Jensen et al. (1986) and Frandsen et al. (1987) correctly assign the name Middle Graben Shale Formation to this unit.

Age – Early-Middle Oxfordian. The age determination based on dinoflagellates yields a latest Callovian-Middle Oxfordian age as indicated by *Acanthaulax senta, Leptodinium subtile, Polystephanephorus paracalathus, Scriniodinium crystallinum, Systematophora valensii, Systematophora* spp., *Wanaea fimbriata* and *W. thysanota.* Among the sporomorphs the frequent presence of the *Contig-*

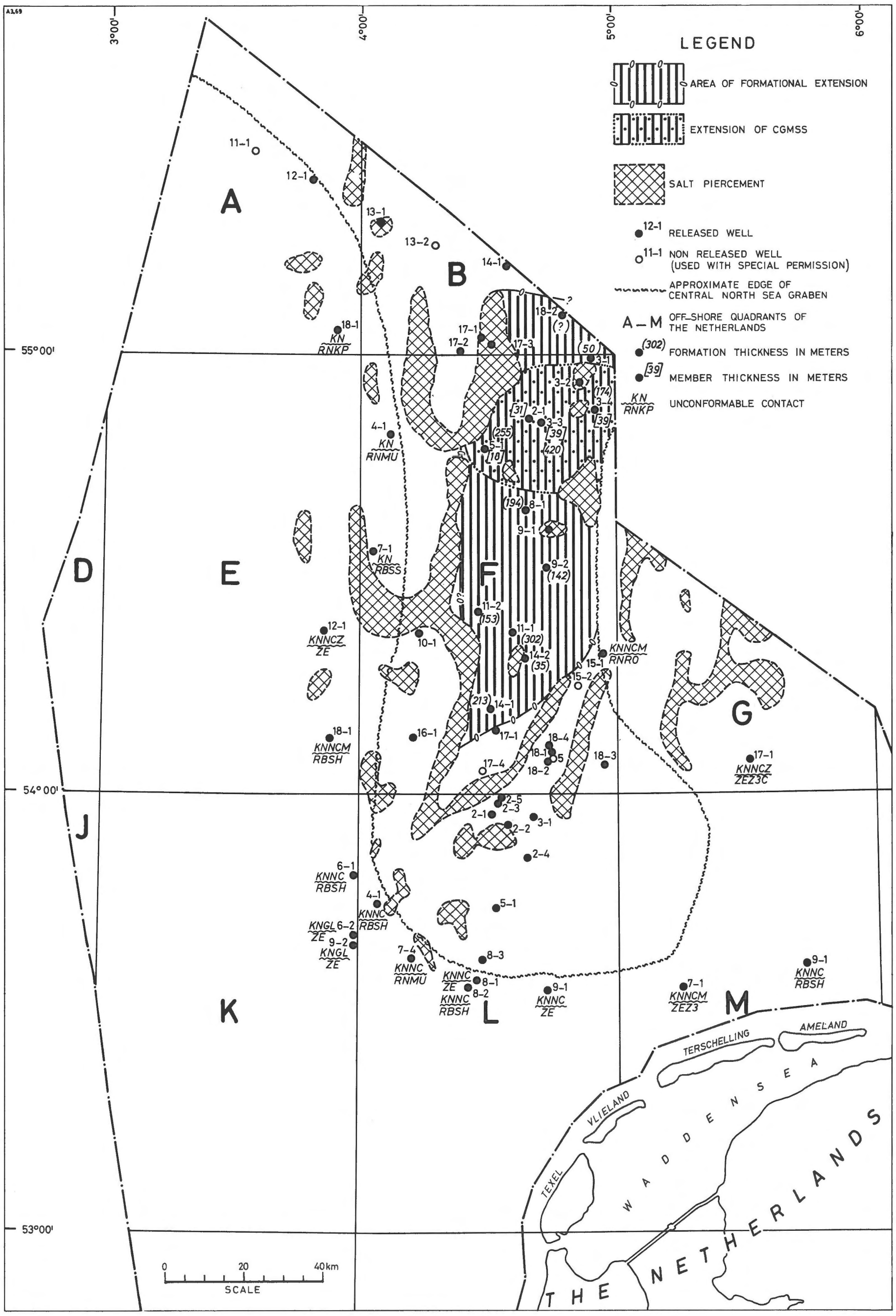

Fig. 7. Geographical distribution of Middle Graben Shale Formation.

nisporites sp. 1–3 complex can be noted. The formation is characterized by a typical ostracod assemblage (consisting of *Galliaecytheridea 'praedissimilis'*, *G. 'prae-postsinuata'*, *G. 'incurvata'*) which represents the Early-Middle Oxfordian.

Sedimentary history – Herngreen & De Boer (1985) concluded to a paralic depositional environment for the formation. The coal layers in the lower part of the formation were formed in swamps with large geographical extensions. The shales between these coals are distinctly marine, which points to preservation of the marine environment established during sedimentation of the top of the Lower Graben Sand Fm. Higher in the formation, only terrestric associations occur with locally very high numbers of the fresh water algae *Botryococcus*. This and the sporadic presence of dinoflagellates in that part of the formation seem to point to lacustrine-coastal lagoonal conditions. Similar conditions existed in the Danish area (cf. Jensen et al., 1986).

Subdivision – Within the Middle Graben Shale Formation, one member called the Middle Graben Sand Member (CGMSS) has been defined. When present, this member separates an upper part (CGMSU) of the Middle Graben Shale Formation from its lower part (CGMSL). We feel, however, that it would be redundant to assign formal member status to these units, and refer to the present description of the Middle Graben Shale Formation for the general description of these informal units.

Middle Graben Sand Member (CGMSS). New member.

Name – Named after the Central North Sea Graben.

Reference section – Well F5-1, 2628–2646 m; co-ord.: N 54° 47′ 10.7″, E 4° 29′ 14.6″ (Fig. 8).

Definition – Section of buff, fine-medium, moderately sorted sandstone (up to 20 m thick) with calcareous cement. Its base is usually characterized by a high carbonaceous content. This sandstone unit has a rather lenticular configuration and is confined to the F3-F5 area (see Fig. 7). The gamma ray log shows a generally coarsening upward trend. The top and base of the member are characterized by distinct log breaks defining the contacts with the under- and overlying non-calcareous shales of the Middle Graben Shale Formation.

Age – Early-Middle Oxfordian; based on its position within the Middle Graben Shale Formation.

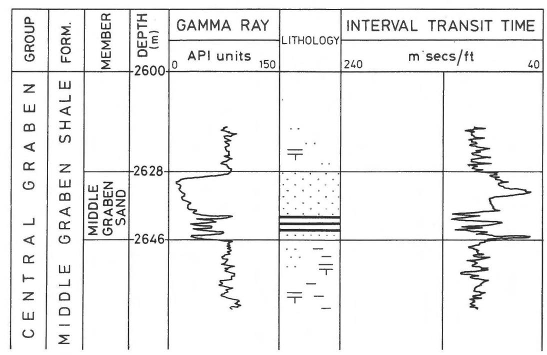

Fig. 8. Reference section of Middle Graben Sand Member; well F5-1, 2628–2646 m.

Sedimentary history – Based on log patterns and its geographical extension, it is assumed that the number represents a local barrier bar and/or deltaic mouth bar build up.

Upper Graben Sand Formation (CGUS). NAM & RGD (1980), emended.

Name – Named after the Central North Sea Graben (NAM & RGD, 1980).

Reference section – Well F3-3, 2547–2670 m; co-ord.: N 54° 50′ 45.5″, E 4° 42′ 29.3″ (NAM & RGD, 1980).

Definition – Two intervals of greyish-brown, very fine – fine grained, carbonaceous sandstones, separated by a silty shale section. In our concept the formation represents a basal tongue of the Puzzle Hole Formation. The formation attains a maximum thickness of 123 m in well F3-3. Its geographical extent is restricted to blocks F3 and F5 and the transition to the Puzzle Hole Formation takes place at the boundary between blocks F5 and F8 (see Fig. 9).

Generally, the formation conformably overlies the Middle Graben Shale Formation and pinches out in the Kimmeridge Clay Formation toward the north. Consequently, the upper limit of the formation is also marked by the contact of its sandy beds with the shales of the Kimmeridge Clay Formation.

Age – Middle-Late Oxfordian. In the type section

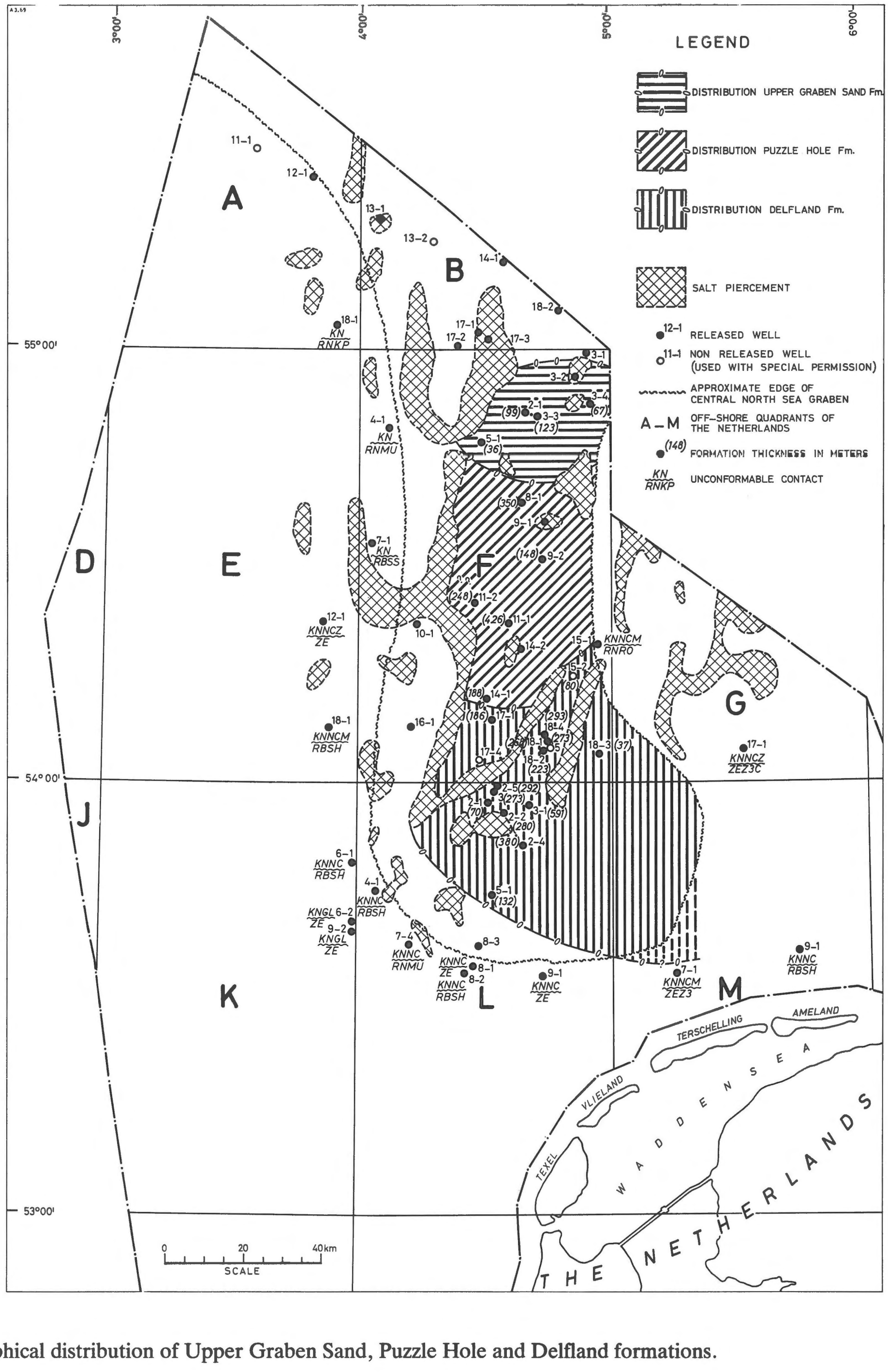

Fig. 9. Geographical distribution of Upper Graben Sand, Puzzle Hole and Delfland formations.

this age is based solely on superposition. A definite late Middle-Late Oxfordian age could be established from dinoflagellates in well F3-4 (in the cored interval from 2755.4–2777.5 m). Among the diagnostic forms are *Ellipsoidictyum* sp., *Glossodinium dimorphum,* and *Leptodinium arcuatum.* The top occurrence of *Systematophora valensii* has been recorded in this formation. Among the sporomorphs the first representatives of the *Concavissimisporites-Impardecispora* complex can be noted. The few ostracods found in this formation show more resemblance to assemblages from the underlying Middle Graben Shale Formation than to those of the overlying marine sediments of the Kimmeridge Clay Formation.

Sedimentary history – The sand-bodies of the Upper Graben Sand Formation represent several coastal bars and/or deltaic mouth bars, separating the paralic Puzzle Hole realm from the marine Kimmeridge Clay facies. Recent palynofacies studies have even suggested that some of these sands were storm generated.

Puzzle Hole Formation (CGPH). NAM & RGD (1980), new combination.

Name – Named after the Puzzle Hole Bank in the Dutch northern offshore region (NAM & RGD, 1980).

Reference section – Well F11-2, 2149–2397 m; co-ord.: N 54° 24′ 54.6″, E 4° 27′ 38.8″ (NAM & RGD, 1980).

Definition – Regular alternation of light brownish-grey silty carbonaceous claystones, argillaceous siltstones with thin sandstone beds, and very frequent coal seams (10 to 20 seams per 100 m section). Particularly toward the south the sandstone beds display a typical fining upward character. NAM & RGD (1980) considered the Puzzle Hole Formation to be a silty-sandy tongue within the Kimmeridge Formation, as part of the Scruff-Group. Because of its predominantly terrestric-paralic character we have placed the Puzzle Hole Formation in the Central Graben Group. Geographically, the formation occupies an intermediate position between the Delfland Formation, into which it grades toward the south, and the Upper Graben Sand Formation in the north (Fig. 9). The latter is thought to be a northern tongue of the Puzzle Hole Formation. The transition to the Delfland Formation is rather gradual and takes place in the southern part of the F quadrant. The Puzzle Hole Formation displays a typical 'nervous' pattern on both gamma ray and sonic logs due to the rapid alternation of thin sandstones, siltstones, claystones, and coal seams, by which it differs from the Delfland and Upper Graben Sand Formations. These formations have thicker sand beds with fewer intercalated coal seams. The Puzzle Hole Formation partially overlies the Middle Graben Shale Formation but to the south it rests unconformably on the Altena Group. Due to the removal of the Kimmeridge Clay Formation by erosion over large areas, the Puzzle Hole Formation is often covered unconformably by basal sediments of the Rijnland Group.

Age – Late Oxfordian-Early/Late Kimmeridgian. According to NAM & RGD (1980) the formation has an Early Kimmeridgian age, but Herngreen & De Boer (1985) have already pointed out that this age determination was based on a misconception. The top of the formation seems to become younger toward the south. By the use of ostracods, the basal part of the Puzzle Hole Formation in well F8-1 can be dated as Late Oxfordian and the same age was found for the top of the formation in the reference section F11-2 (*Pseudocordatum* Zone). These ages are confirmed by the palynological findings. The above-mentioned intervals in F8-1 and F11-2 display a marine character (an uncommon facies in the Puzzle Hole Formation) with a rich dinoflagellate association in F11-2. Characteristic forms are *Gonyaulacysta jurassica* (abundant), *Ctenidodinium chondrum, Hystrichosphaerina orbifera, Occisucysta monoheuriska,* and *Systematophora.* Among the sporomorphs, *Trilites minutus* and representatives of the *Contignisporites* complex occur.

Sedimentary history – The sediments of the Puzzle Hole Formation were deposited in a paralic (lower delta plain) environment. In this facies the coals were formed in numerous swamps.

Delfland Formation (CGDF). NAM & RGD (1980), status novum and extended.

Name – Named after the polder authority of Delfland in the province of Zuid-Holland (NAM & RGD, 1980).

Reference section – Well Nieuwerkerk-1, 968–1942 m; coord.: N 51° 57′ 00.2″, E 4° 37′ 32.4″ (NAM & RGD, 1980).

Additional reference section – Well F18-1, 2417–2690 m, coord.: N 54° 5′ 54″, E 4° 44′ 32″ (Encl. 1).

Additional reference section – Well K15-1, 1559–2270 m, coord.: N 53° 13′ 28.2″, E 3° 53′ 47.6″ (NAM & RGD 1980).

Definition – Sequence of rapidly alternating sands, siltstones, and shales, with some coal beds and with common lignitic matter. The siltstones and shales are generally multi-coloured (grey, green, beige, and pink) and become increasingly reddish-mottled toward the south. The gamma ray log pattern of the sandbeds shows a change from predominantly coarsening upward in the north (F17) to predominantly fining upward in the south (L & K quadrants). In the original concept of NAM & RGD (1980) the rank of Group had been assigned to this formation. Its traditional subdivision into Lower Delfland, Fourteens Clay and Upper Delfland formations was mainly based on the fact that they considered the Fourteens Clay to be a major marine intercalation between the Lower and Upper Delfland formations. Herngreen & De Boer (1985) pointed out that the Fourteens Clay in the type well K15-1 distinctly showed terrestrial assemblages and only a restricted marine influence at the top of the formation. This does not justify the threefold subdivision proposed by NAM & RGD (1980). Moreover, the subdivision seems to be a local phenomenon. We favour the concept of an undivided Delfland Formation with the Fourteens Clay (CGDFF) as a member of this formation (see NAM & RGD (1980) for more information on type section, etc.). We realize that in the Delfland Formation other lithostratigraphic units with member rank may be recognized in other basins, but it would take us beyond the scope of the present paper to deal in detail with this formation outside the Central North Sea Graben.

Age – Oxfordian – Ryazanian. A Kimmeridge age can be attributed to the Formation in the F18-L2-L3 area. In F17-4, however, an Oxfordian age, and probably even a Middle Oxfordian age, can be established on the basis of palynological data. Ostracod assemblages are similar to those usually found in the Middle Graben Shale, and thus confirm this age determination. This implies that the Delfland Formation in the southern part of the Central North Sea Graben is distinctly older than the original type section K15-1 (of NAM & RGD) in the Broad Fourteens Basin. Sporomorphs from the basal part of the formation (F17-4) are similar to the Oxfordian assemblages from the Middle Graben Shale Formation and the Upper Graben Sand Formation. The Late Kimmeridge associations are very well developed in F18-2 and F18-5; they show first occurrences of the *Trilobosporites bernissartensis* group, *Pilosisporites* spp., and *Kraeuselisporites* sp., and last appearance of *Lycopodiacidites irregularis*.

Sedimentary history – The sediments of the Delfland Formation mainly represent upper to lower delta plain deposits. Occasional high frequencies of *Botryococcus* point to local lacustrine conditions.

Scruff Group (SG): NAM & RGD (1980), emended.

General – According to the original definition of NAM & RGD (1980) the Scruff Group consists of the Kimmeridge Clay Formation and the Puzzle Hole Formation. We propose in this report that the Puzzle Hole Formation be transferred to the Central Graben Group. In addition, we introduce two new formations, which are included in the Scruff Group: the Scruff Greensand Formation and the Clay Deep Formation.

Name – Named after the offshore Upper Scruff Bank, which lies adjacent to the reference well F3-3 (NAM & RGD, 1980).

Reference section – Well F3-3, 1628 to 2547 m; coord.: N 54° 50′ 45.5″, E 4° 42′ 29.3″ (NAM & RGD, 1980; emended).

Additional reference section – Well F3-1, 2265 to 2810 m; coord.: N 54° 59′ 40″, E 4° 54′ 18″ (Encl. 1).

Definition (emended after NAM & RGD, 1980) – Group of formations deposited in a predominantly marine environment. Most of this group rests conformably on several formations of the Central Graben Group. The sediments of the Rijnland Group usually unconformably overlie the Scruff Group.

Age – Late Oxfordian – Ryazanian.

Subdivision – Three formations are distinguished as follows:

Kimmeridge Clay Formation (SGKI)
Scruff Greensand Formation (SGGS)
Clay Deep Formation (SGCD)

Kimmeridge Clay Formation (SGKI). NAM & RGD (1980), emended.

Name – Name derived from the British stratigraphic nomenclature where it is applied to similar clayey deposits which are wide-spread in the general North Sca rcgion (NAM & RGD, 1980).

Reference section – Well F3-3, 1780–2547 m; co-ord.: N 54° 50′ 45.5″, E 4° 42′ 29.3″ (NAM & RGD, 1980; emended).

Definition – 'In the northern part of the Central North Sea Graben, the Formation is a sequence of medium to dark olive-grey, generally silty shales with numerous thin dolomite streaks (expressed on wire-line logs with a characteristic peaked appearance). Fossil fragments are common in lenses; lignite particles occur frequently. Towards the south, the carbonate streaks and the olive hue gradually disappear. Furthermore, the shales become increasingly silty to sandy' (from NAM & RGD, 1980). In the northern part of the area a twofold division can be made of the formation. The upper part is characterized by the presence of numerous dolomitic beds, whereas the lower part is predominantly clayey. In seismic sections from this area (e.g. Fig. 14) a slight intraformational unconformity coincides with the boundary between these lithologies. The formation rests conformably on the sediments of the Central Graben Group. Generally, the formation is conformably overlain by the Scruff Greensand Formation. North of F3, where the latter formation is not present, the Clay Deep Formation locally rests conformably on the Kimmeridge Clay Formation. The twofold lithological division, as described by us, can also be noted in the Danish part of the Central Graben. There, the Upper and Lower units are named respectively, Farsund and Lola Formation (Jensen et al., 1986). In our new concept the formation corresponds with the Main Kimmeridge Clay as described by Herngreen & De Boer (1985). The same authors also discarded the subdivision into the Upper and Lower Kimmeridge Member of NAM & RGD (1980). Figure 10 shows the geographical distribution of the formation. We agree with the argumentation put forward by Doré et al. (1985), who dealt with the problems in connection with correlation of the Kimmeridge Clay Formation and the Humber Group from the type areas in England with several North Sea basins. In this respect we had two options: 1) to extend the Humber Group into the Dutch area and reject the Scruff Group; or 2) to introduce a new name for the Kimmeridge Clay Formation in the Dutch area (as Jensen et al. 1986 have done in the Danish area).

Both solutions would have been stratigraphically correct, but at this moment we prefer to follow NAM & RGD (1980) and use well-established formation names rather than adopt a new nomenclature.

Age – Late Oxfordian-Berriasian (NAM & RGD, 1980). In the type section F3-3 this age does not seem to be appropriate, since the age of the top of the Kimmeridge Clay in that well is near the Kimmeridgian-Portlandian boundary (see Herngreen & De Boer, 1985). An earliest Portlandian and latest Kimmeridgian age could be established in F3-1 from side-wall samples from the sandy interval 2427–2510 m. The age determinations based on micropaleontology and palynology are in good agreement. The Kimmeridge Clay Formation is generally characterized by a rich dinoflagellate association. Some species with stratigraphic significance are *Cannosphaeropsis thula, Ctenidodinium chondrum, C. culmulum, C. panneum, Egmontodinium polyplacophorum, Epiplosphaera bireticulata, Gochteodinia mutabilis, Gonyaulacysta jurassica, 'Gonyaulacysta' longicornis, Histiophora ornata, Leptodinium arcuatum/eumorphum, L. subtile, Muderongia* sp.A in Davey 1982, *Occisucysta balia, 'Oligosphaeridium pulcherrimum'*-acme, *Scriniocassis dictyota, Scriniodinium crystallinum, S. inritibilum, S. luridum,* and *Stephanelytron* spp. In the holomarine facies there are strongly selected sporomorph assemblages, dominated by bisaccates

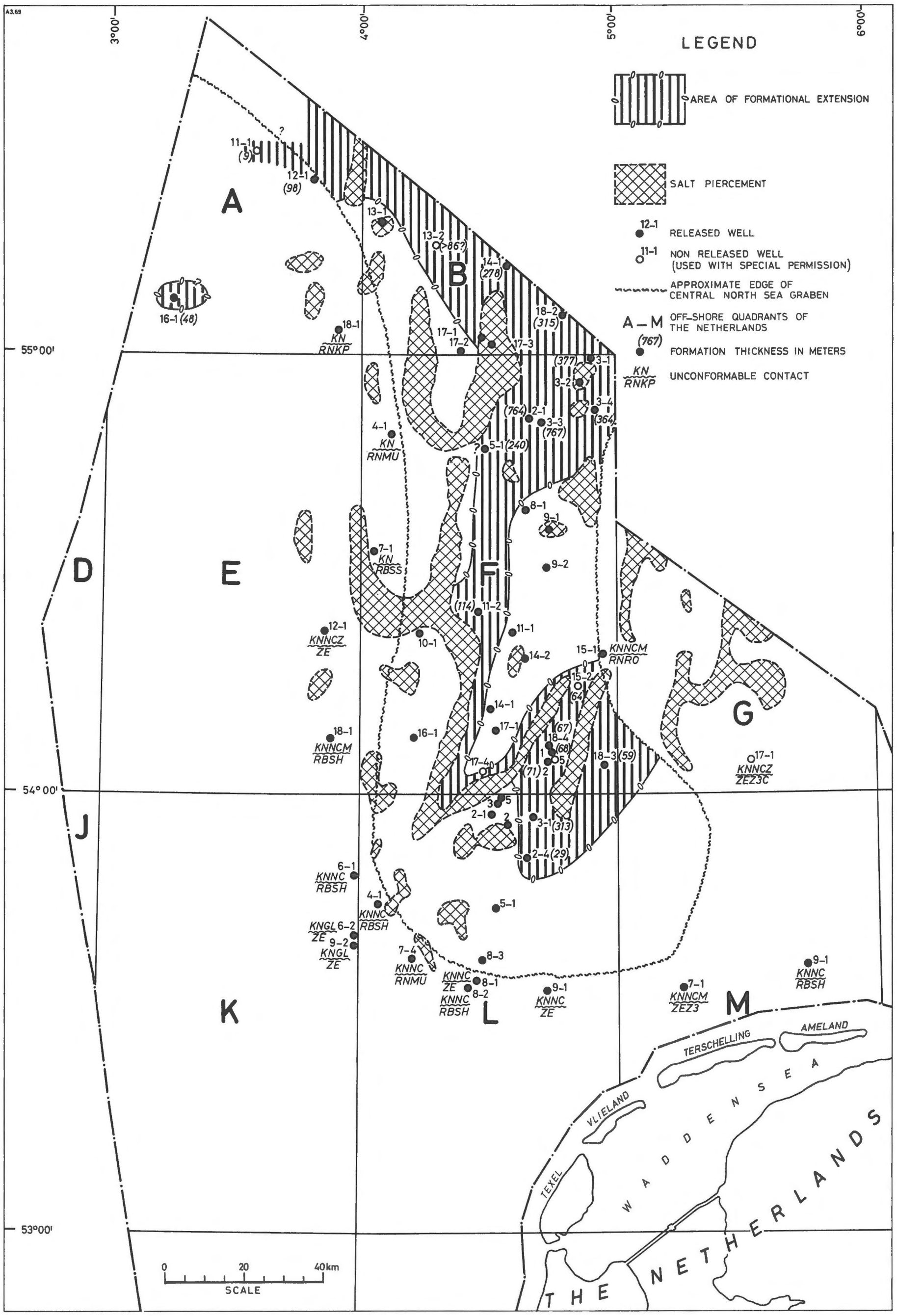

Fig. 10. Geographical distribution of Kimmeridge Clay Formation.

and *Calliasporites*. Micropaleontologically, two marine associations can be distinguished within the Kimmeridge Clay Formation. The upper part of the formation bears the ostracods *Galliaecytheridea compressa* and *G. spinosa* and the foraminifer *Saracenaria triquetra,* whereas the lower part is characterized by the ostracods *Galliaecytheridea dissimilis, G. gracilis, G. dorsetensis, Macrodenti-*

na cicatricosa,* and *Epipleura eleonorae.*

Sedimentary history – The sediments of the Kimmeridge Clay Formation were deposited in an upper to lower shelf environment with increasing terrestrial influence toward the south. In the northern area the lower clayey unit may reflect deposition in a tranquil, deep environment whereas the dolomitic beds in the overlying unit suggest that the area became shallower.

Scruff Greensand Formation (SGGS). New formation.

Name – Named after the Upper Scruff Bank near Well F3-3.

Reference section – Well F15-2, 3021–3276 m; coord.: N 54° 14′ 18.54″, E 4° 50′ 44.86″ (Fig. 11).

Additional reference section – Well F18-1, 2193–2350 m; coord.: N 54° 5′ 54″, E 4° 44′ 32″ (Encl. 1).

Definition – Section of light grey to greyish-green, very fine – fine, well-sorted massive sandstone. The formation generally has a very high glauconite content and shows varying amounts of argillaceous matter. Large amounts of sponge spiculae sometimes form a conspicuous constituent of the upper part of the formation. The general configuration of the formation varies from distinct massive to sheet-like. The formation has a large extension in the Central North Sea Graben but does not reach its northern part (e.g. B18-2) (Fig. 12). The formation onlaps on the flanks of the adjacent highs, probably overstepping them locally. This suggests that we are dealing with a complex of numerous individual sandbodies which were stacked and coalesced. In the type area the formation conformably overlies the Kimmeridge Clay Formation but on the flanks it may rest unconformably on the Zechstein erosional surface. Toward the south (e.g. L5-2), biostratigraphic and seismic data suggest an unconformable contact between the Scruff Greensand Formation and the underlying Delfland Formation. There seems to be a conformable contact with the overlying part of the Clay Deep Formation (e.g. L3-1 and F3 block). When the Clay Deep Formation is absent the sediments of the Rijnland Group are found to rest unconformably on the Scruff Greensand. The formation was not mentioned in NAM & RGD (1980) and since then several names such as the Scruff Sand (Herngreen & De Boer, 1985), F18 Sand, Main Sand, and Vlieland Sand have been used to denote this unit.

F15-2 (PETROLAND)

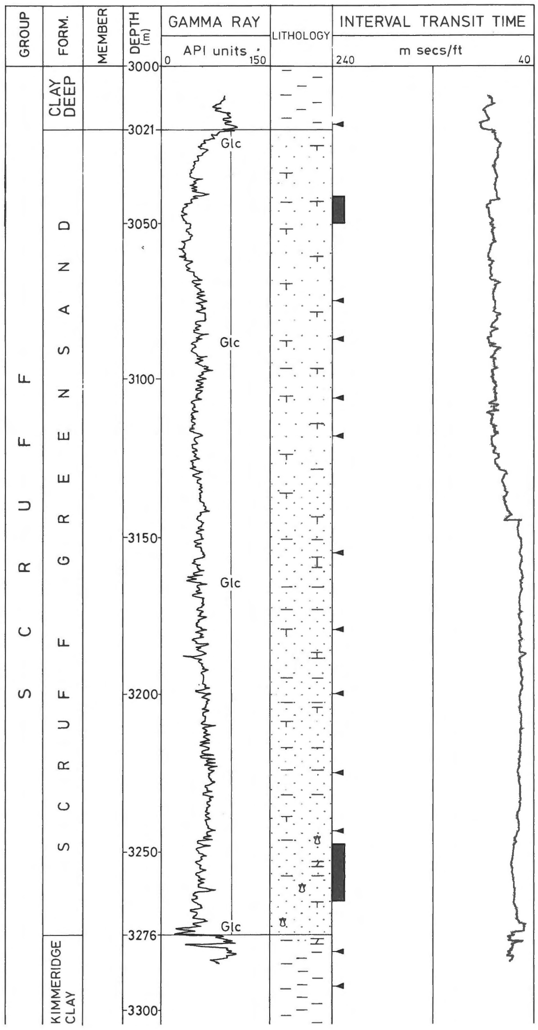

Fig. 11. Reference section of Scruff Greensand Formation; well F15-2, 3021–3276 m (by courtesy of Petroland B.V.).

Age – Portlandian-Early Ryazanian. This age is based on palynology and superposition, since no microfauna has been encountered yet in the formation. The reference section in F15-2 is character-

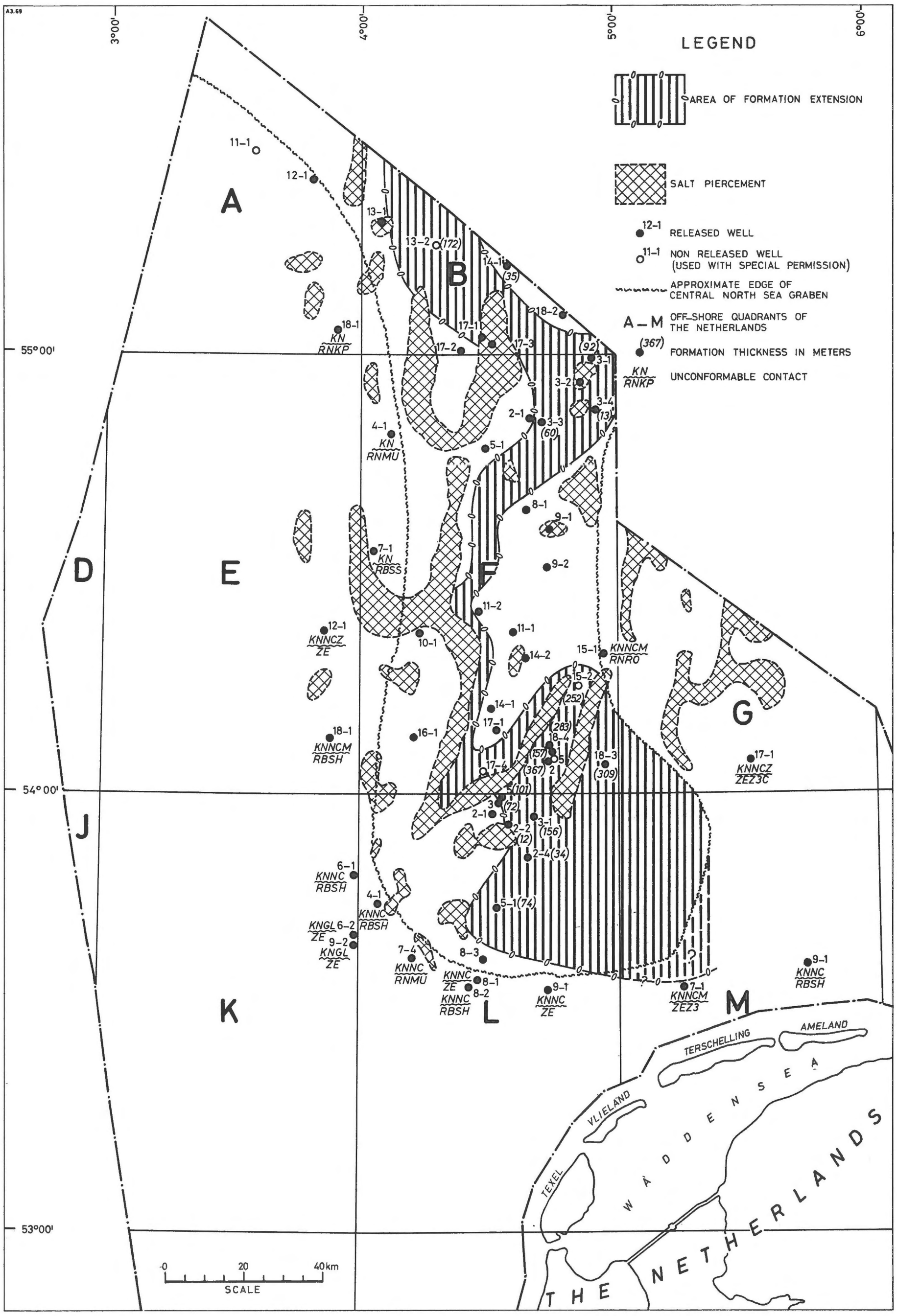

Fig. 12. Geographical distribution of Scruff Greensand Formation.

ized by a rich dinoflagellate association which made the following age determination possible. Two cores (no. 1 at 3042–3050.87 m and no. 2 at 3248–3266.5 m) and eight side-wall samples between 3075 and 3243 m were examined.

The samples from core 1 are poor in fossils; they contain for example *Cannosphaeropsis thula* and *Gochteodinia villosa,* indicating an indifferent late

Early Portlandian-pre *albidum* Late Ryazanian age. Because Late Jurassic and Early Cretaceous marker species are missing a more precise dating cannot be given, but the presence of some types of *Cribroperidinium* makes a Portlandian age plausible.

The side-wall samples between 3075 and 3118 m yielded the following time-stratigraphically significant dinoflagellates: *Dingodinium spinosum, Egmontodinium expiratum, E. polyplacophorum, Gochteodinia villosa, G. virgula, Occisucysta balia,* and *Perisseiasphaeridium insolitum.* This association indicates late Early Portlandian (*kerberus* and *anguiformis* zones). Downhole the assemblages gradually become older. *Glossodinium dimorphum* appears at 3118 m. The transition to the *okusensis* Zone is marked by the top occurrence of *Gochteodinia mutabilis* at 3155 m. Other index species include *Muderongia* sp.A at 3200 m and *Senoniasphaera jurassica* with its top occurrence in this sample. The side-wall cores at 3225 and 3243 m and sampling material from core 2 show *Ctenidodinium culmulum, C. panneum, Glossodinium dimorphum, Gochteodinia mutabilis* and *Senoniasphaera jurassica,* indicating a latest Kimmeridgian-earliest Portlandian age.

A Late Portlandian age could be established in core samples 1997–2021 m of L3-1 with *Gochteodinia virgula* and *Batioladinium.*

Among the sporomorphs representatives of *Cicatricosisporites* are consistently present in low numbers in the Portlandian; a remarkable increase, both quantitatively and in diversity, can be noted in the Ryazanian. The top occurrence of *Kraeuselisporites tubbergensis* is in the Portlandian; *Parvisaccites radiatus* appears near the Kimmeridgian-Portlandian boundary.

Sedimentary history – The Scruff Greensand Formation was deposited in a shallow marine environment as a complex of barrier sands which in the course of time were partly reworked and coalesced into transgressive sheet sands.

Clay Deep Formation (SGCD). New formation.

Name – Named after the Clay Deep, a depression situated at about N 55°, E 4° in the Dutch northern offshore region.

Reference section – Well B18-2, 2225–2357 m; coord.: N 55° 5′ 35.4″, E 4° 47′ 48.6″ (Encl. 1).
Additional reference section – Well F3-1, 2265–2335 m; coord.: N 54° 59′ 40″, E 4° 54′ 54.18″ (Encl. 1).

Definition – Grey, brownish-grey to black shales usually with an increasing amount of silt toward the base. The shales are generally rather bituminous, but locally less organic matter may be present. Lithologically, the formation differs from the Kimmeridge Clay Formation by the absence of well developed dolomite stringers. Generally, the formation is of rather uniform thickness (max. ± 131 m) throughout the area studied (Fig. 13). The amount of silt and sand particles increases toward the south, whereas the bituminous character decreases in that direction. The formation conformably overlies the Scruff Greensand Formation in the F3 block and toward the south (e.g. L3-1). North of F3 the formation rests conformably on the Kimmeridge Clay Formation. The contact between the two formations is well marked on gamma ray logs, since the bituminous ('hot') shales of the Clay Deep Formation have a distinctly higher radioactivity. The formation is often unconformably covered by sediments of the Rijnland Group which are generally more sandy and less carbonaceous. Herngreen & De Boer (1985) informally called it the Scruff Shale Formation.

Equivalent 'hot shales' outside the Dutch sector are oil prone in varying degrees (e.g. Barnard & Cooper, 1981; Cornford, 1984). Two examples are the Tau 'hot shale' Member of the Borglum Formation of the Fiske sub-basin and the Mandal Formation in the adjacent Norwegian sector of the Central Graben (cf. Cornford, 1984). Jensen et al. (1986) describe a similar unit (informally named 'Hot unit') from the Danish Central Trough, which they consider to be patchily developed as a 'hot' organic rich facies of the Kimmeridge Clay.

Age – Late Early Portlandian – Ryazanian, pre-

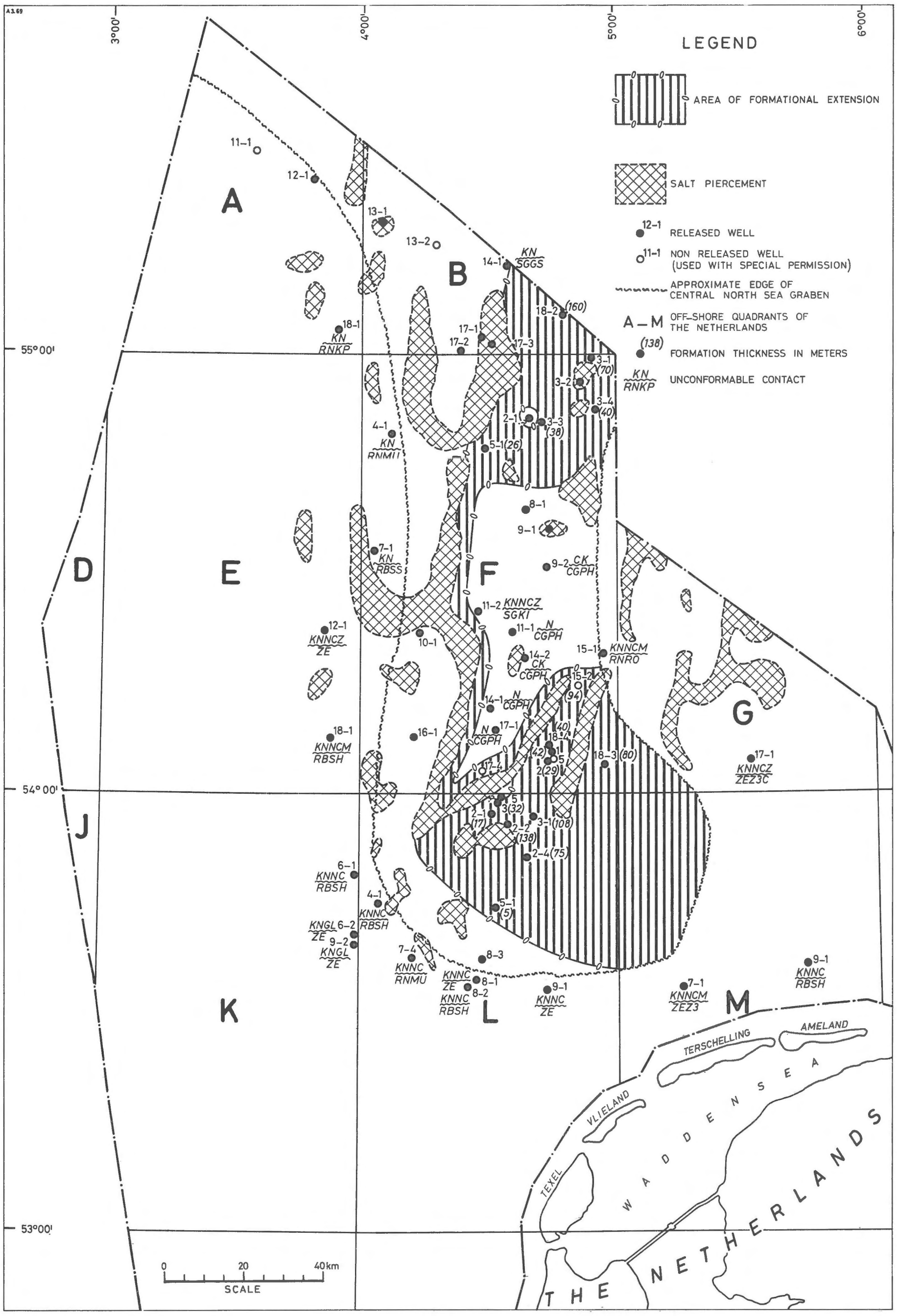

Fig. 13. Geographical distribution of Clay Deep Formation.

albidum Zone. From the reference section B18-2, core 2242–2260 m and four side-wall samples between 2279 and 2343 m were examined. The eight core samples contain for example *Batioladinium radiculatum, Gochteodinia villosa* subsp. *multifurcata, Gonyaulacysta* sp. A/B plexus (Davey, 1979; 1982) and *Oligosphaeridium diluculum* indicating a pre-*albidum* Late Ryazanian age. Side-wall samples 2279 and 2288 m are rich in dinoflagellates. Time-significant species include *Batioladinium radiculatum, B.* cf. *varigranosum* (Davey, 1982), *Cannosphaeropsis thula, Egmontodinium expiratum/torynum, Gonyaulacysta* sp. A (2288 m) and B (2279 m), and *Occisucysta* sp. A in Davey (1979; recently described as *Tehamadinium daveyi*) representing a Ryazanian (2288 m) and Late Ryazanian (2279 m) age. Sample 2304 m shows a rich, although timestratigraphically non-conclusive Portlandian/Ryazanian, dino-assemblage. Neither uppermost Jurassic nor lowermost Cretaceous marker types were recognized; some representatives of *Batioladinium* suggest Jurassic/Cretaceous transitional strata. Next sample 2343 m shows a distinct late Early Portlandian association with *i.a. Cribroperidinium* sp. A in Davey (1982), *Ctenidodinium panneum, Dingodinium spinosum, Egmontodinium polyplacophorum* (common), *Gochteodinia villosa* and *G. virgula* (very common).

Elsewhere, e.g. F3-3, F15-2, and L3-1 a (Late) Ryazanian age could be demonstrated for the Clay Deep Fm. Diagnostic forms include *B. radiculatum, E. torynum,* and *Gonyaulacysta* sp. B.

Characteristic elements of the microfauna are the foraminifer *Haplophragmoides infracalloviensis* and the ostracods *Galliaecytheridea* cf. *volgaensis, G. teres* and *Mandelstamia sexti.*

Sedimentary history – The Clay Deep Formation in the northern part of the graben was deposited in a marine environment with little or no water circulation, causing euxinic (anaerobic) conditions favourable for the formation of organic-rich, bituminous shales. Toward the south (e.g. F18 and L3) open marine conditions prevailed.

Biostratigraphy

A total account of the biostratigraphy in this review article would take too much space. Details on the micropaleontology and palynology will be dealt with in a future publication. For the sake of brevity, the reader is referred to Encl. 2.

The palynomorph zonation schemes are based exclusively on cored material and side-wall samples. Dinoflagellate zones are defined by top-occurrence (first appearance downhole) of the nominate species. In general this zonation can be correlated with information from the British Isles, for instance with a scheme established by Woollam & Riding (1983). In the southern part of the Central North Sea Graben fewer marine intervals occur, and sporomorphs are used for dating and comparison. The limits of the sporomorph zones are less precisely known than those of the dinoflagellate zones. In general, they cannot be drawn at the standard ammonite levels, but they represent a (sub)stage accuracy. Nevertheless, some major boundaries in the sporomorph scheme could be adequately dated with dinoflagellates in marine incursions. Several zonal markers represent new, in-house, species and/or genera.

Ostracods and foraminifera of the Central Graben formations show little correspondence with those described from equally old strata in England or Continental Europe. Marine intercallations provided the framework in which faunas from restricted marine or non-marine environments could be placed.

Biozonation is based mainly on ostracods; foraminifera play only a minor role in the area. Nodosariae are present in marine intervals, as well as some species of *Epistomina* and a few arenaceous forms. Paralic facies may yield *Ammodiscus* species, sometimes in great numbers. Assemblages dominated by the ostracod genus *Cypridea,* that are of common occurrence in the transitional Jurassic-Cretaceous fresh-to-brackish water deposits in all parts of the world are not present. The genus *Cypridea,* is only represented by an early form *C. valdensis praecursor.*

Within the Central Graben area, relatively minor local variations in depositional environments gave rise to distinct microfaunal communities. As a result, some of the assemblages recognized in this study have coincident ranges.

The ranges of assemblages presented in Encl. 2 are based on material from drill cuttings; due to caving they are less accurate than would have been the case if cores had been used. Since this means that total ranges are not always precisely known, the bars have been left open-ended.

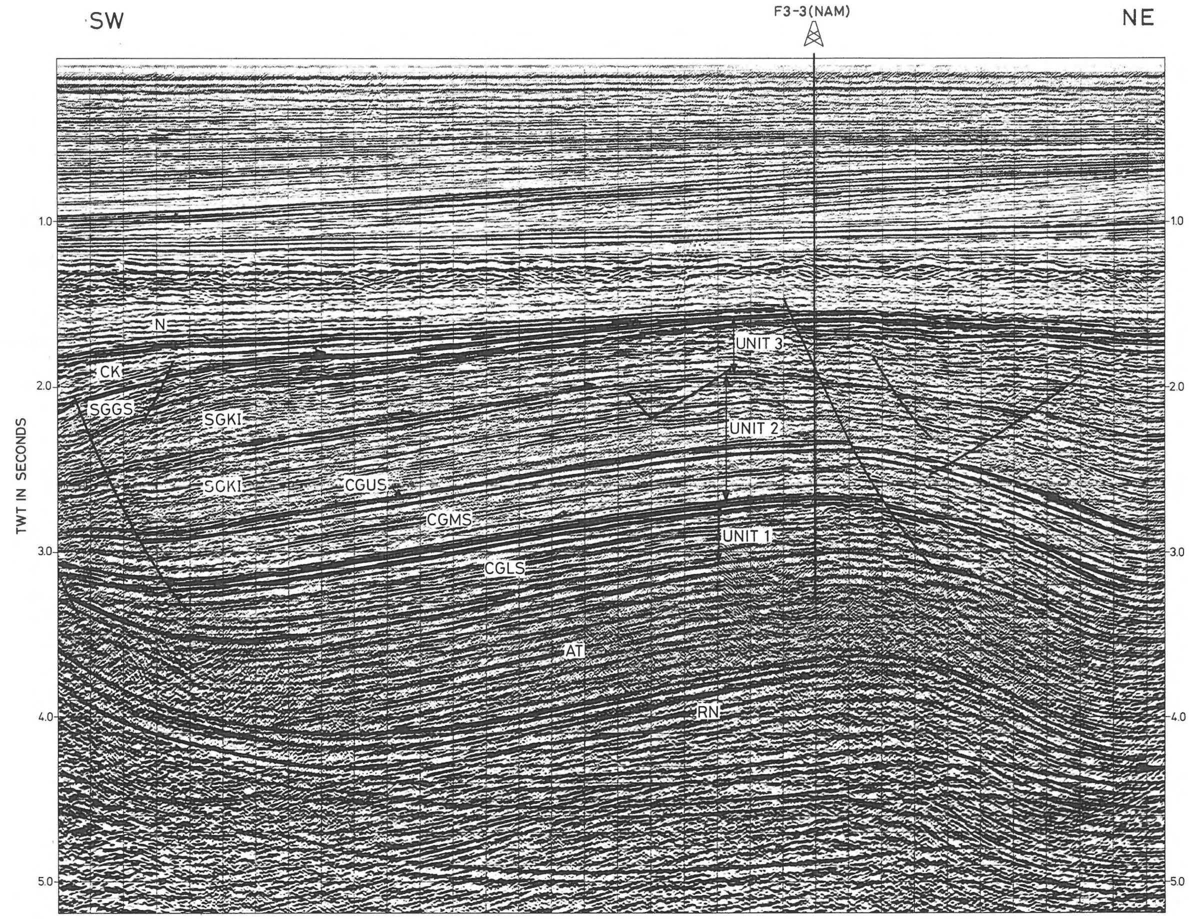

Fig. 14. Seismic section, Dutch Central North Sea Graben, showing sediment succession through well F3-3 and character of seismic facies units 1–3. RN = Upper Germanic Trias, AT = Altena Group (Early-Late Jurassic), CGLS = Lower Graben Sand Fm., CGMS = Middle Graben Shale Fm., CGUS = Upper Graben Sand Fm., SGKI = Kimmeridge Clay Fm., SGGS = Scruff Greensand Fm., CK = Chalk Group (Late Cretaceous), N = Tertiary (by courtesy of Mobil Producing Netherlands Inc.).

Seismic facies description

The Callovian – Ryazanian sediments of the Dutch Central North Sea Graben can be considered to be one seismic sequence with only minor internal seismic unconformities. The base of the complete sequence is formed by the Callovian unconformity. The top may be formed either by the conformable contact with the Valanginian, or by one of the unconformities corresponding to the bases of the Rijnland Group, the Chalk, or the Tertiary.

As Vail et al. (1977) showed, reflections within a seismic sequence parallel stratal surfaces and have the same chronostratigraphic significance as stratal surfaces. Consequently, all primary reflections recognized within the sequence represent chronostratigraphic surfaces and do not necessarily correspond to the lithostratigraphic boundaries as defined in this article. Despite this problem, an attempt has been made to link our lithostratigraphic horizons with seismic data from the studied area. Furthermore, we were able to follow characteristic seismic events over significant distances. Notwithstanding the presence of local lateral changes and diachronous lithostratigraphic boundaries, a general description of seismic facies units can be presented. The latter consist of one or more lithostratigraphic units. According to Mitchum et al.

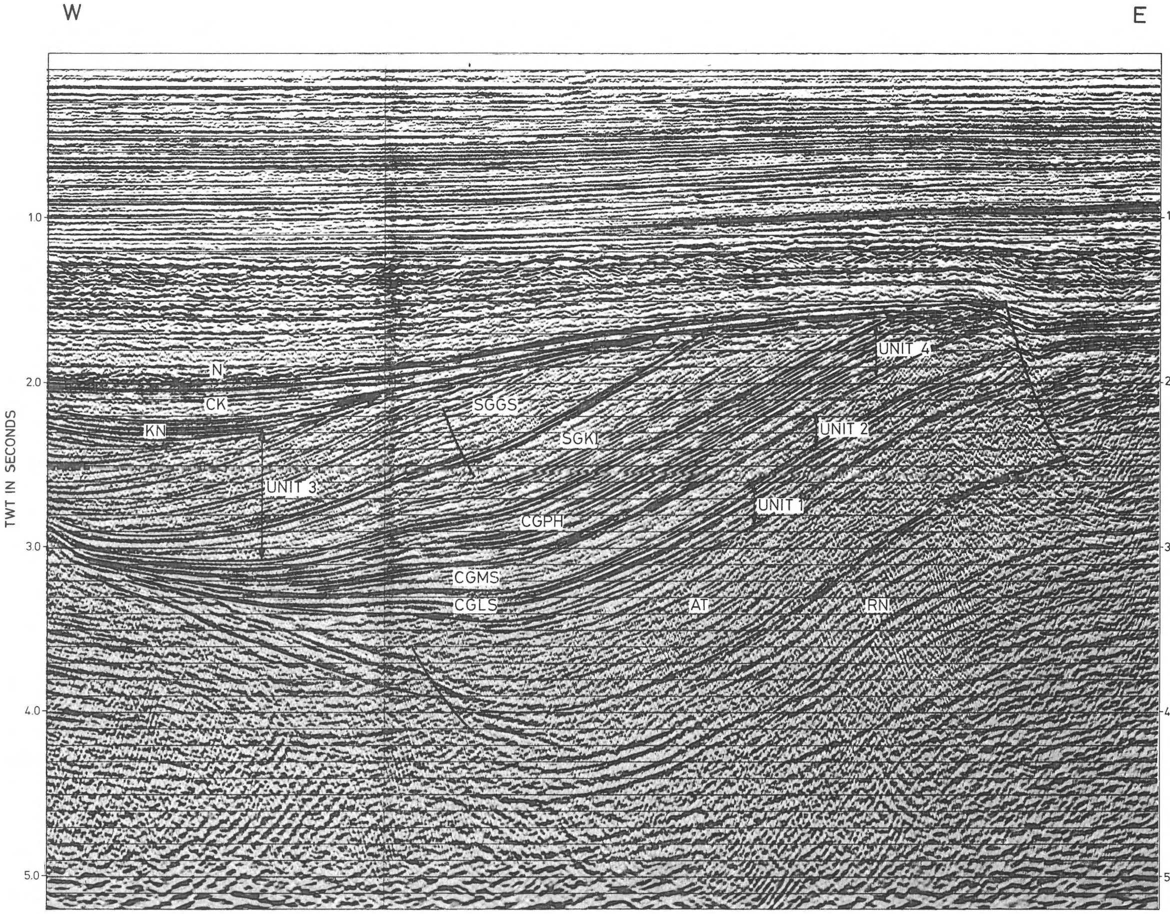

Fig. 15. Seismic section, Dutch Central North Sea Graben, showing character of seismic facies units 1–4. RN = Upper Germanic Trias, AT = Altena Group (Early-Late Jurassic), CGLS = Lower Graben Sand Fm., CGMS = Middle Graben Shale Fm., CGPH = Puzzle Hole Fm., SGKI = Kimmeridge Clay Fm., SGGS = Scruff Greensand Fm., KN = Rijnland Group (Early Cretaceous), CK = Chalk Group (Late Cretaceous) (by courtesy of Western Geophysical Co.).

(1977), a seismic facies unit is characterized by the following parameters: internal reflection configuration, seismic amplitude, frequency, reflector continuity, and interval velocity. Hence, these parameters should define a facies unit which is distinctive from adjacent units.

The following seismic facies units within the Callovian-Ryazanian sequence can be recognized (see Figs 14 & 15):

Unit 1 – Corresponding to the Lower Graben Sand Fm. This unit is characterized by high-amplitude parallel reflections with relatively low frequency and medium continuity. At its top, however, there is a distinct event indicated by two very high amplitudes and very high continuity reflections which can be followed over large distances.

Unit 2 – Corresponding to the sequence consisting of the Middle Graben Shale Fm., Upper Graben Sand Fm., and the lower part of the Kimmeridge Clay Fm. Occasionally a slight intra-Kimmeridge Clay unconformity can be identified which separates this unit from the upper part of the Kimmeridge Clay Fm. That upper part displays a different seismic facies and it onlaps the lower part of the Kimmeridge Clay. The unit is characterized by mostly low amplitude, high frequency parallel reflectations which are extremely continuous. Due to extremely low amplitudes, the unit locally is seismically transparent. Of the two relatively higher amplitude reflectors one can be easily tied to the bases of the Upper Graben Sand, the other one to the Kimmeridge Clay.

Unit 3 – Corresponding to the upper part of the Kimmeridge Clay and the Scruff Greensand Fm. At the top of this unit the Clay Deep Fm. may be included, but this formation is usually too thin to be seismically recognizable. The unit has low amplitude, medium to high continuity, and high frequency reflectors which can be either parallel or divergent.

Unit 4 – Corresponding to the Puzzle Hole and Delfland formations. This unit is very characteristic and easily recognizable because of its many closely spaced, high amplitude, and relatively low frequency reflectors. These reflectors have either low continuity when they form a subparallel configuration or medium continuity when they are parallel.

Geological history

Prior to the rifting phase, predominantly continental sediments were deposited during the Carboniferous, Permian, and Triassic. Evaporites were formed in the Zechstein. Marine sedimentation started in the latest Triassic with the onset of the large transgressive phase known as the Rhaetian transgression which continued into the Early Jurassic. With a minor unconformity the sediments of the Altena Group overly the Upper Germanic Trias Group. This unconformity is referred to as the Early Cimmerian event. During the Early Dogger another tectonic pulse known as the Mid Cimmerian phase truncated the Early Jurassic section (Ziegler, 1977).

With the opening of the Central North Sea Graben during the Callovian, sediments started to be deposited on the eroded surfaces of the Aalburg Shale and Werkendam Formations. Based on the description of the Bathonian – Callovian (and questionable Bajocian) deltaic-coastal section from the Lulu-1 well in the Danish Central Trough (Frandsen, 1986), we assume that the opening may have occurred earlier in the north than in the Dutch sector further south. This configuration seems consistent with the Bajocian – Bathonian paleogeographical map of Ziegler (1982b). This map does not indicate sedimentation for the area of the Central North Sea Dome. Deposition of the Lower Graben Sand Formation started in approximately mid-Callovian times and initially took place under fluvial and lacustrine conditions. In the course of time these conditions became deltaic and marginally marine. Differential subsidence of the area during this period was responsible for the widely differing thicknesses of the formation. The Callovian transgressive trend, which correlates well with the documented sea level changes of Hallam (1978, 1981, 1984) and Vail & Todd (1981), declines at the beginning of the Oxfordian. At that time extensive vegetated swamps came into existence, as shown by the carbonaceous shales and coal seams of the Middle Graben Shale Formation. The majority of the Middle Graben Shale deposits reflect stable conditions in a lagoonal setting.

A clearly regressive development can be noted during the Middle Oxfordian, as indicated by the progradation of the Puzzle Hole Formation and the Upper Graben Sand Formation. This corresponds with a shift of the coastline from south to north under influence of the regressive trend. There seems to be a close relationship between this Mid-Oxfordian regression and the age of the Zuidwal volcanism (144 ± 1 M.a. cf. Dixon et al., 1981). This is in accordance with the findings of Cloetingh et al. (1987), which underline the congruence between sea level fluctuations and the paleostress field in the North Sea region. According to their concept, 'periods of gradual increase in sea level are associated with times of more gradual build-up of tension and stretching, while the lowering of sea level is associated with discrete rifting episodes'.

The next transgressive sequence started in the Late Oxfordian with the onset of the marine sedimentation of the Kimmeridge Clay Formation. The marine influence introduced by this second transgression can also be observed in the contemporaneous Upper Graben Sand Formation of F3-4.

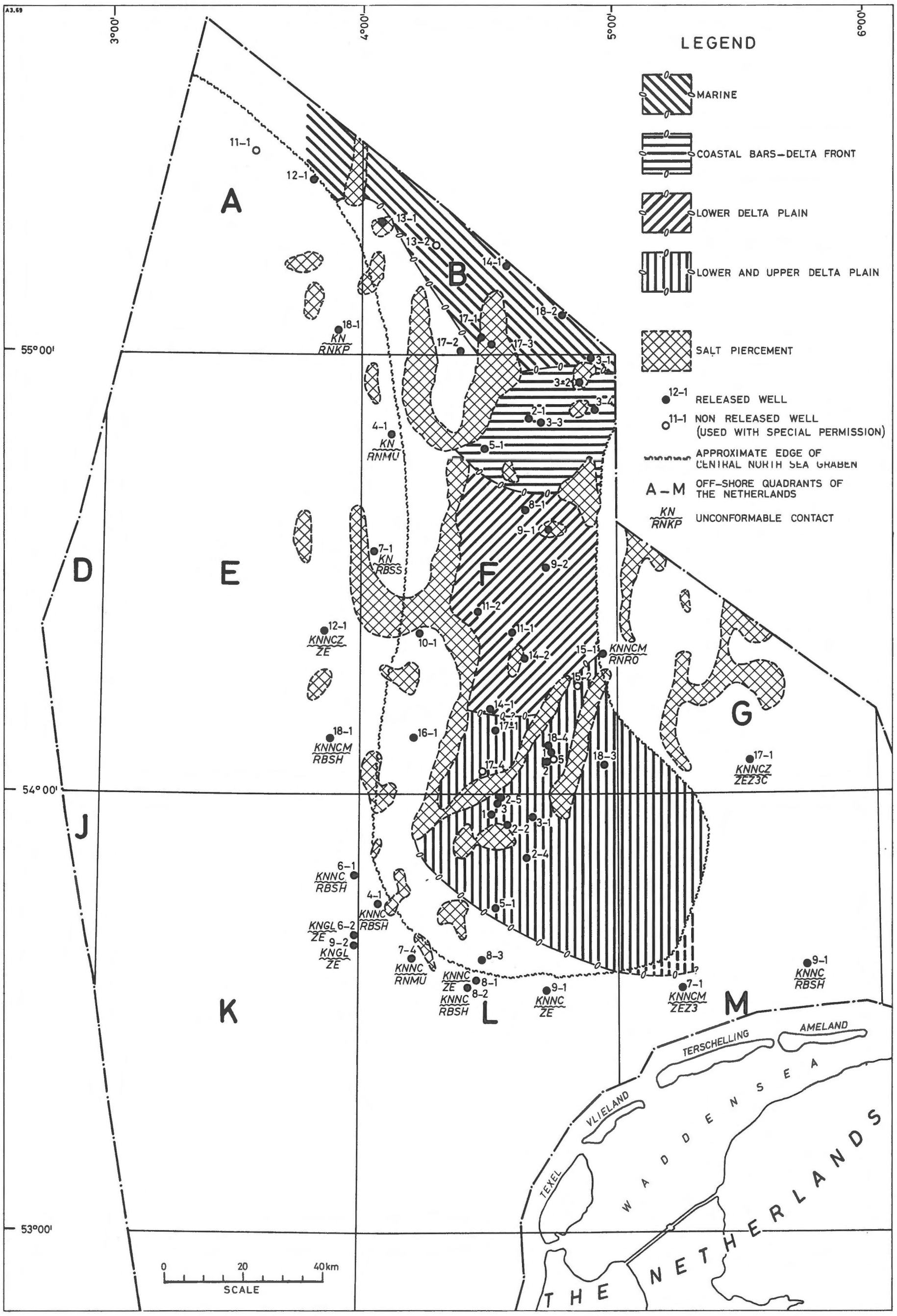

Fig. 16. Facies map for Middle-Late Oxfordian times.

The north-south direction of the transgression is indicated by the progressively younger age of the base of the Kimmeridg Clay Formation noted when correlating F3-3 via F11-2 with the F18 and L2 area.

A paleogeographic map of the area at this time (Fig. 16) shows from south to north: the lower and upper delta plains with deposition of the Delfland Formation (e.g. L2-F17), the paralic environment

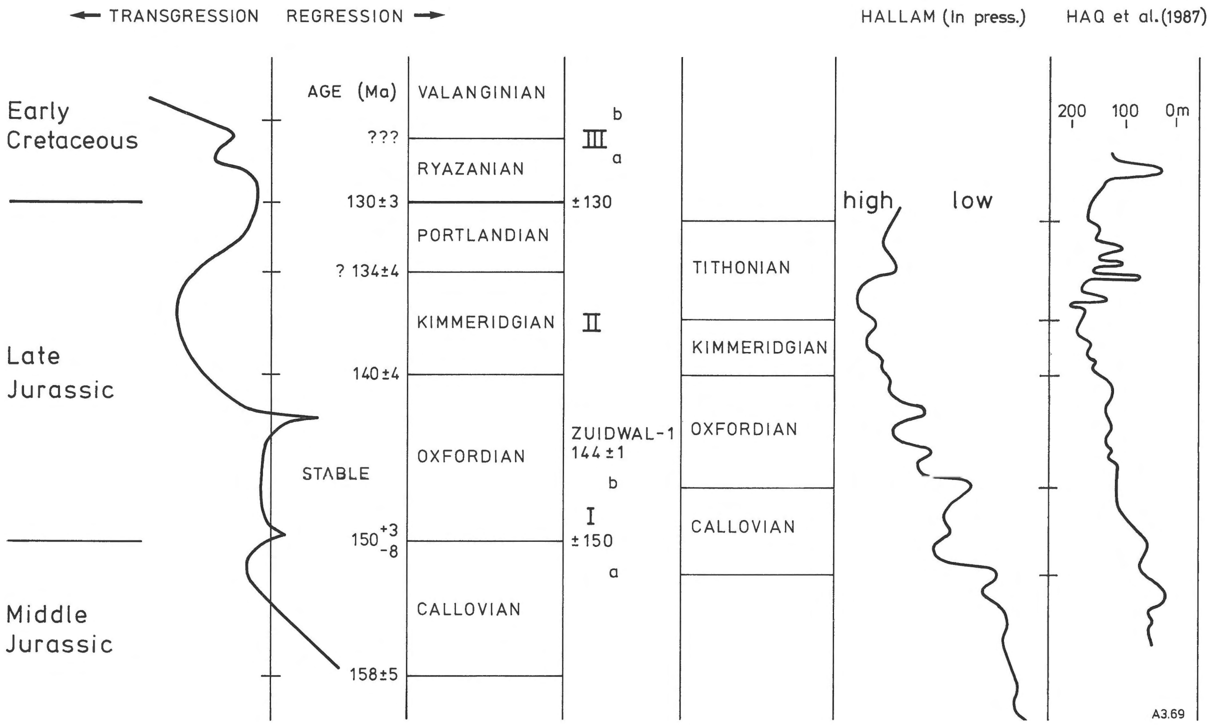

Fig. 17. Late Jurassic-Earliest Cretaceous sea-level curve for the Dutch Central North Sea Graben, with similar curves determined by Hallam (In press) and Haq et al. (1987). Absolute ages after Kennedy & Odin (1982); dating of the Zuidwal Volcanism according to Dixon et al. (1981).

with increasing marine influences reflected by sediments of the Puzzle Hole Formation (F11-2, F11-1 to F8-1), the coastal barrier complex and storm deposits represented by the Upper Graben Sand Formation (F5-1 and F3-3) and the shallow marine environment with sedimentation of the Kimmeridge Clay Formation (B14-1 and B18-2).

Our biostratigraphic data suggest that in the southern part of the Central North Sea Graben (e.g. F18-1, F18-2, L2-2, and L2-4) the Delfland sediments are not older than Kimmeridgian. On these grounds it may be postulated that opening of the graben in this area only started in the Kimmeridgian. Moreover, the marine influence of the second transgression could be observed here around the Kimmeridgian-Portlandian boundary. An important interruption of the otherwise tranquil marine sedimentation of the Kimmeridge Clay Formation is formed by the apparently high-energy conditions in which the Scruff Greensand Formation was deposited. The latter formation represents a complex of barrier sands which in time became partially reworked and coalesced into transgressive sheet sands overstepping the graben margins and covering adjacent areas. Recently, Spencer et al. (1986) discussed the complex genesis of similar Late Jurassic sands in the Central Graben of Norway. These sands may have been storm generated, as Bailey et al. (1981) suggested and accumulated in topographic depressions on downfaulted graben margins. Spencer et al. (1986) postulated that halokinetic movements may also have played an important role. In the northernmost part of the Central North Sea Graben (e.g. B18-2) no Scruff Greensand is developed and pelitic sedimentation continued into the Late Ryazanian. The depositional environment locally became rather restricted and the ensuing anoxic conditions favoured the formation of the bituminous 'hot shales' of the Clay Deep Formation. Rawson & Riley (1982) attributed the

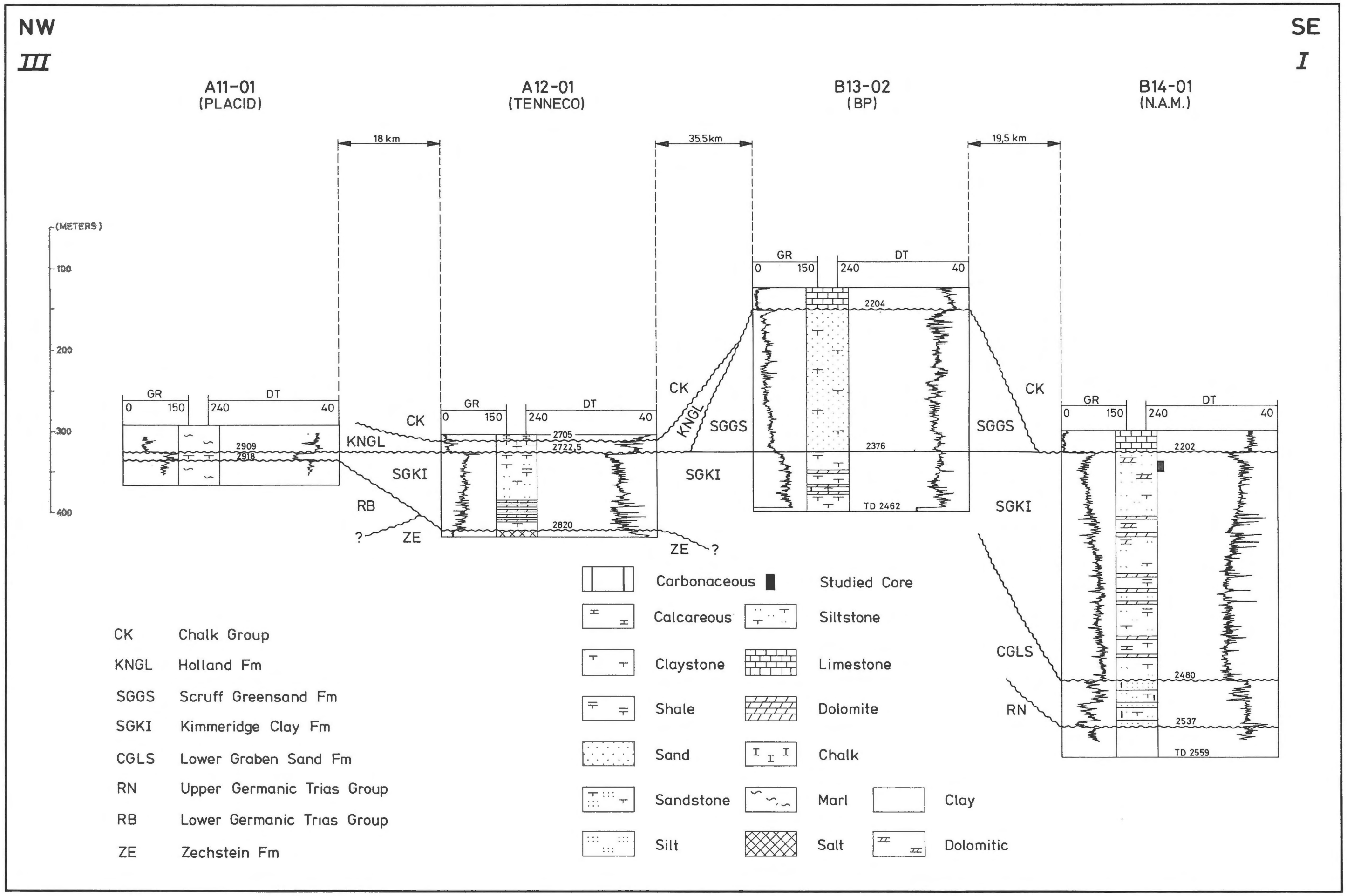

Fig. 18. Section III-I. This northernmost cross-section shows the limited development of the Late Jurassic strata. The position of the section is marked in Fig. 2. Note the thinning of the Kimmeridge Clay in NW direction and the local presence of Scruff Greensand in B13-2.

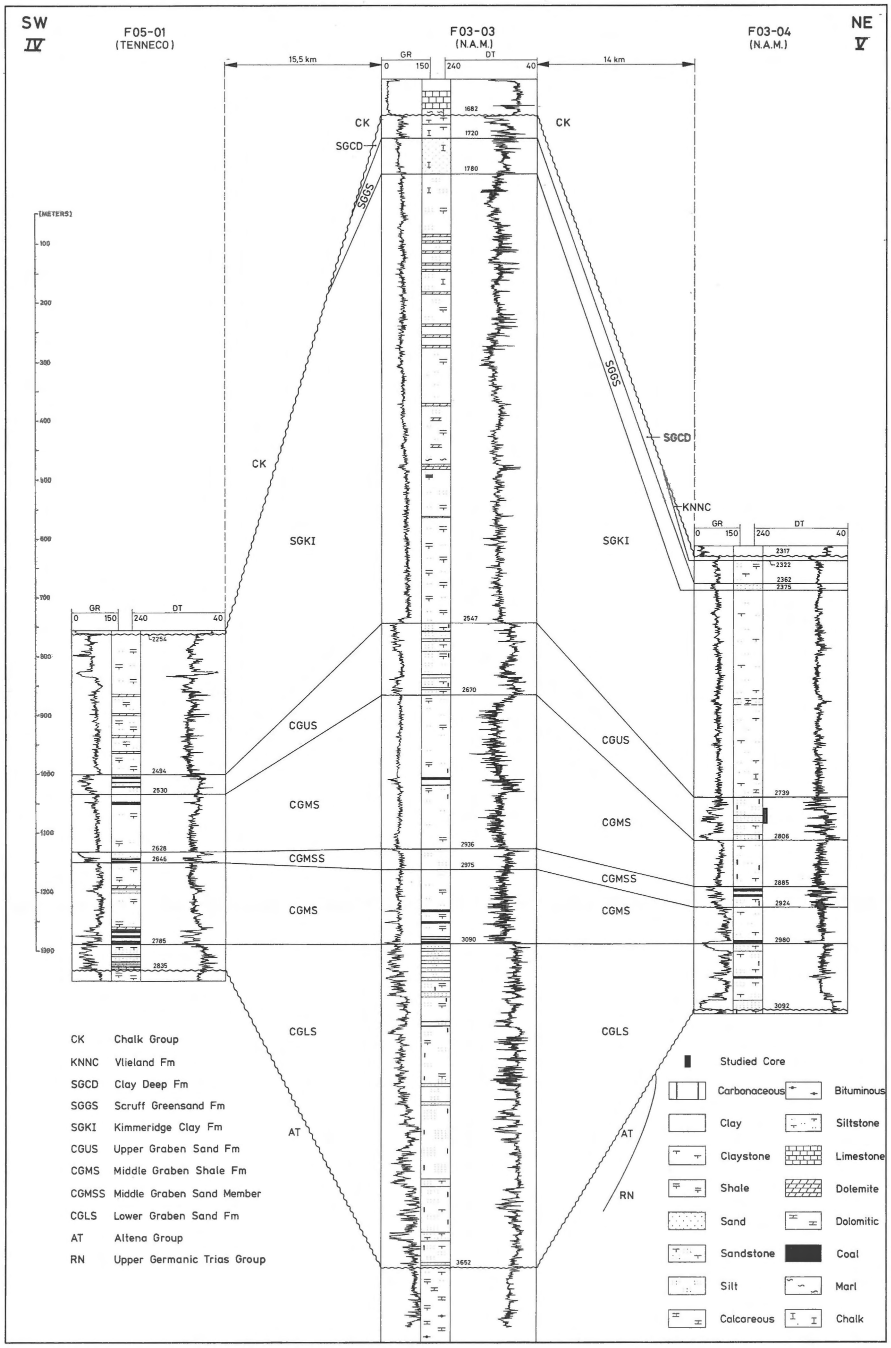

Fig. 19. Section IV-V. Correlation of Late Jurassic strata in the northern part of the F-quadrant. The position of the section is marked in Fig. 2. In F3-3 the various formations reach a remarkable thickness. The Middle Graben Sand Member and the Upper Graben Sand Formation are consistently present in this area.

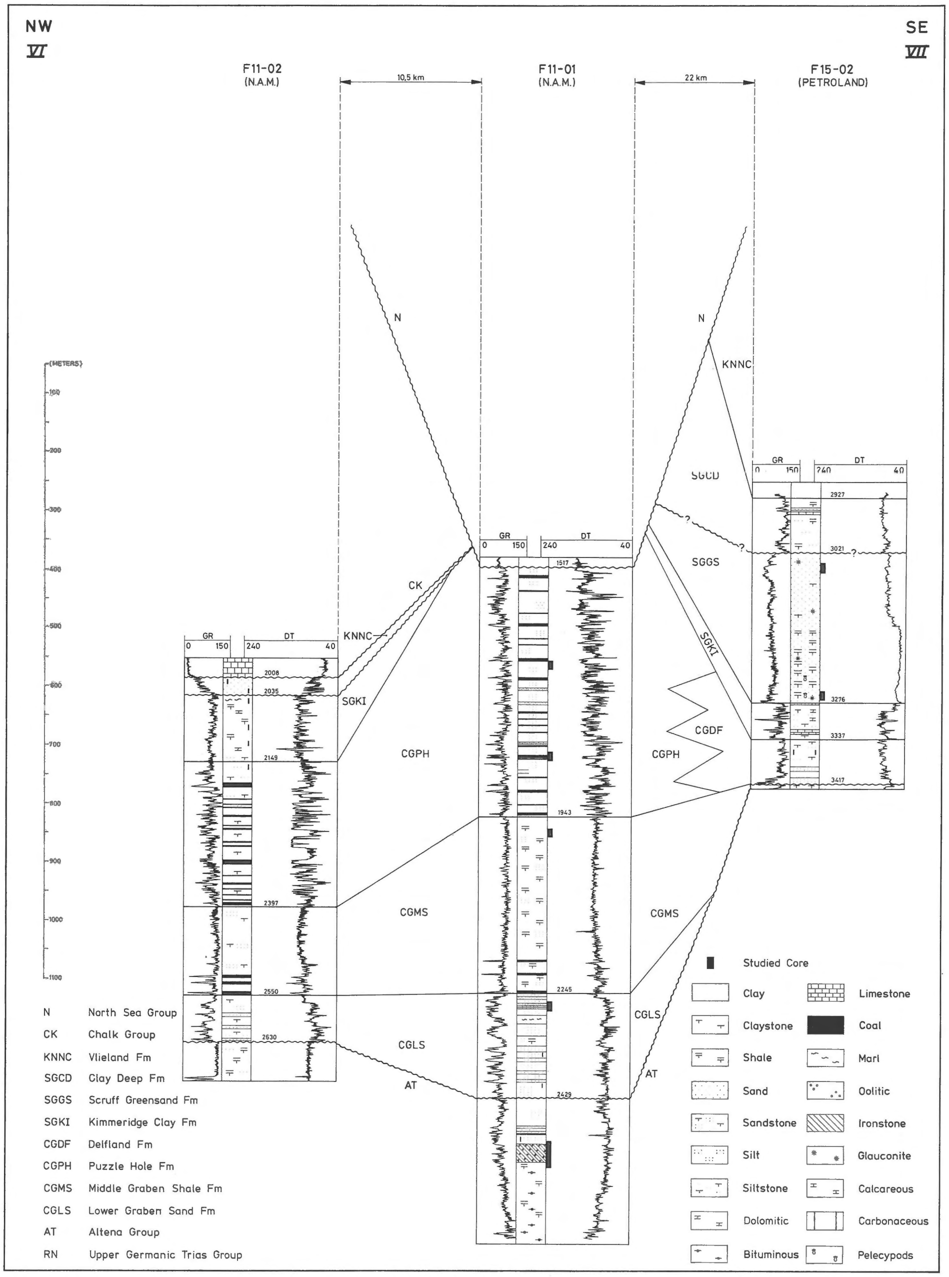

Fig. 20. Section VI-VII. Correlation of Late Jurassic strata in the F11-F15 area. The position of the section is marked in Fig. 2. The Central Graben Group is rather completely developed. Note the typical log pattern of the Puzzle Hole Formation (due to the numerous coal beds) and the presence of the well-marked coal beds at the base of the Middle Graben Shale Fm.

anoxic shales, which were formed under conditions of stagnant water circulation, to 'tectonically controlled basin enclosure'. The Clay Deep Formation represents one of the southernmost occurrences of the Kimmeridge Clay 'hot shale' facies of Barnard & Cooper (1981) in the North Sea area. Due to both shallower burial depths and decreasing organic matter, the formation becomes less mature in

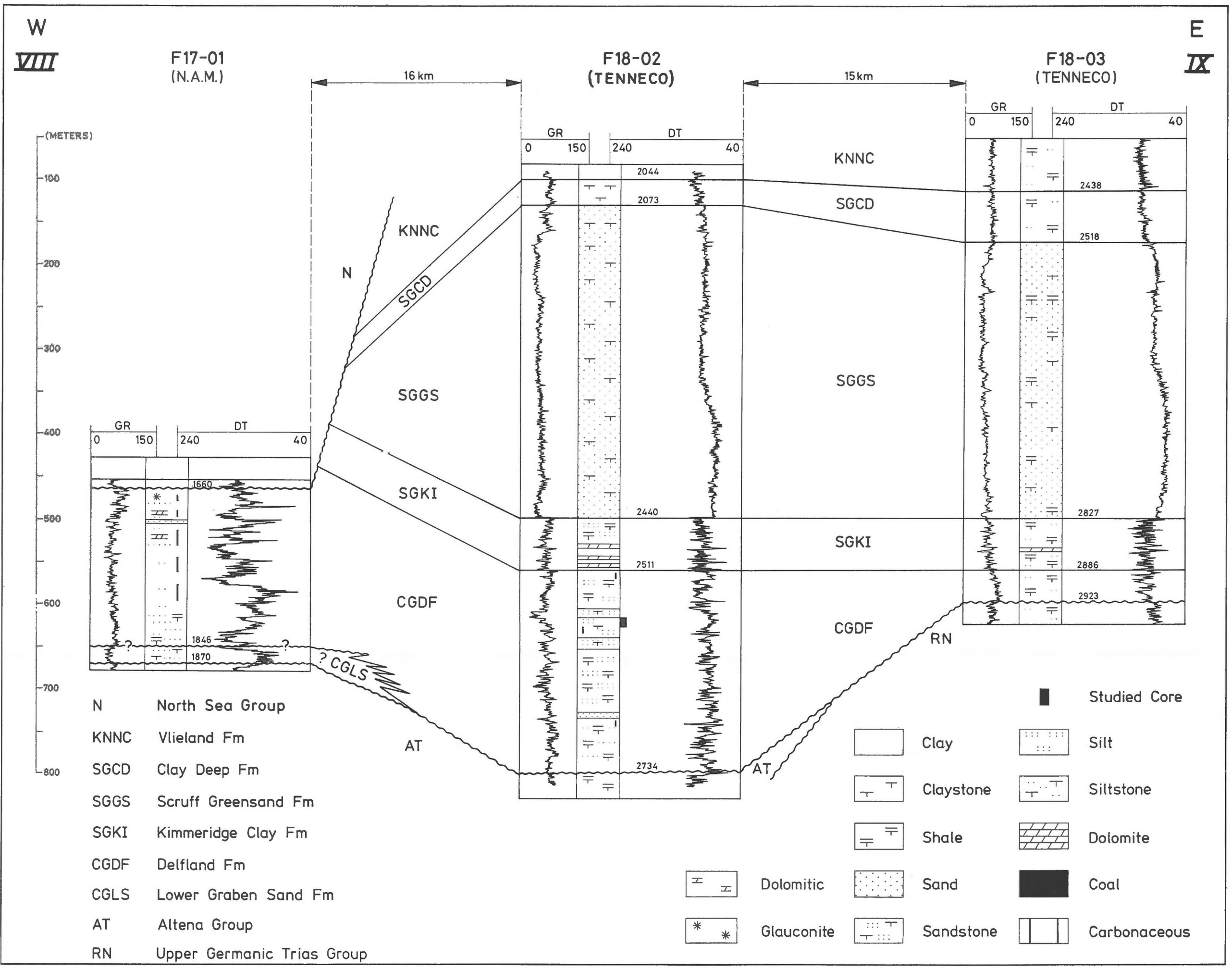

Fig. 21. Section VIII-IX. Correlation of Late Jurassic strata in the F17-F18 area. The position of the section is marked in Fig. 2. The Puzzle Hole Fm. of the F11 and F14 area has changed laterally into the Delfland Fm. Note the conspicuous thickness of up to several hundreds of meters of the Scruff Greensand Fm. The Clay Deep Fm. is hardly bituminous in this area and may be recognized by its slightly higher gamma ray readings.

the southern part of the Central North Sea Graben. We consider the deposition of the Clay Deep Formation on the Scruff Greensand Formation to be a transgressive development (phase 3a, Fig. 17).

During the latest Ryazanian and continuing into the Early Cretaceous, a rapid transgression of the Vlieland Formation occurred. Several authors have pointed to the regionally abrupt lithological change and the large hiatus around the Jurassic-Cretaceous boundary. This level is generally called Late Cimmerian unconformity or base Cretaceous unconformity (e.g. Heybroek, 1975; NAM & RGD, 1980; Ziegler, 1975; Ziegler, 1978). Anderson et al. (in: Michelsen 1982) picture a regional NW European 'Late Cimmerian' tectonic phase, accompanied by a significant sea level drop but they interpreted this as a general submarine unconformity with continuing sedimentation. According to Ziegler (1982a, b), it is a eustatic lowering of the sea level which manifests itself regionally as a regression. We think that there are distinct hiatuses at the margin of the Central North Sea Basin but

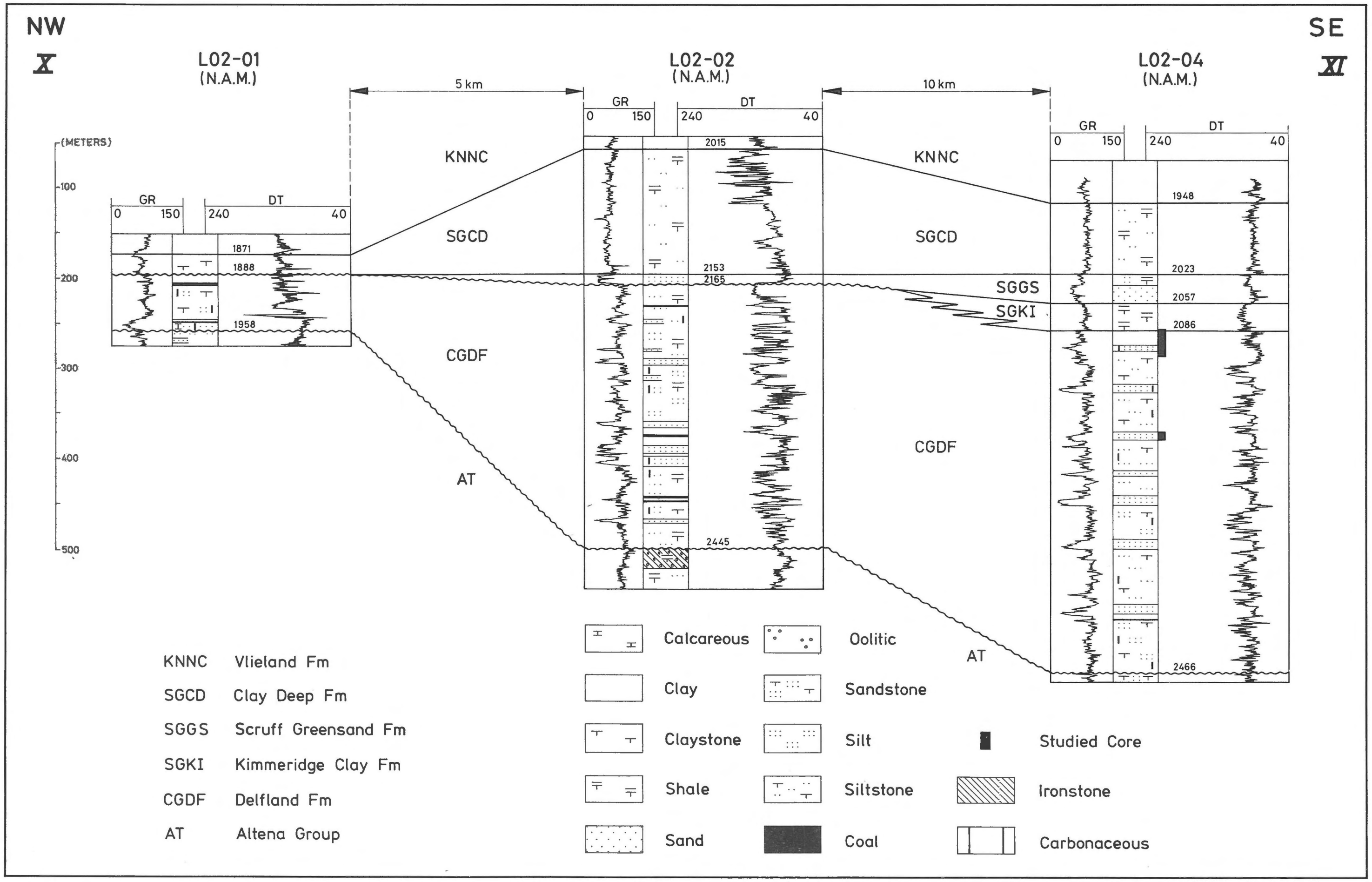

Fig. 22. Section X-XI. Southernmost cross-section of Late Jurassic strata. The position of the section is marked in Fig. 2. Note the well-developed Delfland Fm., characterized by a rapid alternation of sandstone, clayey beds, and a few coal beds. The Kimmeridge Clay and Scruff Greensand wedge out rapidly toward the flanks of the graben, and the Clay Deep directly overlies the Delfland Fm. (L2-1).

that overall the sedimentation was continuous. There is a conspicuous facies change from the anaerobic conditions of the Kimmeridge Clay to the well-oxygenated bottom conditions of the Vlieland Formation. This is in line with the findings of Rawson & Riley (1982), who see the Kimmeridge Clay – Valhall Formation boundary as an isochronous facies change rather than a regional unconformity. Very recently, Vejbaek (1986) reached the same conclusion, i.e., that a major unconformity at the base of the Valanginian in the northern North Sea, as claimed by Vail & Todd (1981), cannot be recognized as such in the Danish Central Trough.

In the Late Cretaceous, differential subsidence of the Graben ended and the 'Chalk sea' transgressed across the entire North Sea region. The major inversion at the end of the Cretaceous and the beginning of the Tertiairy, caused by the Subhercynian and Laramide compressional events, occurred in a number of pulses. The general uplift resulted in removal of the Late and Early Cretaceous and part of the Late Jurassic sequence. This succession is truncated at increasingly deeper levels toward the axis of inversion. Additionally, halokinesis also played an important role in disrupting the pattern of basin subsidence and sedimentation. Finally, in the Late Paleocene or Early Eocene, inversion movements ceased and the area was covered by a thick sequence of Tertiary marine clastics.

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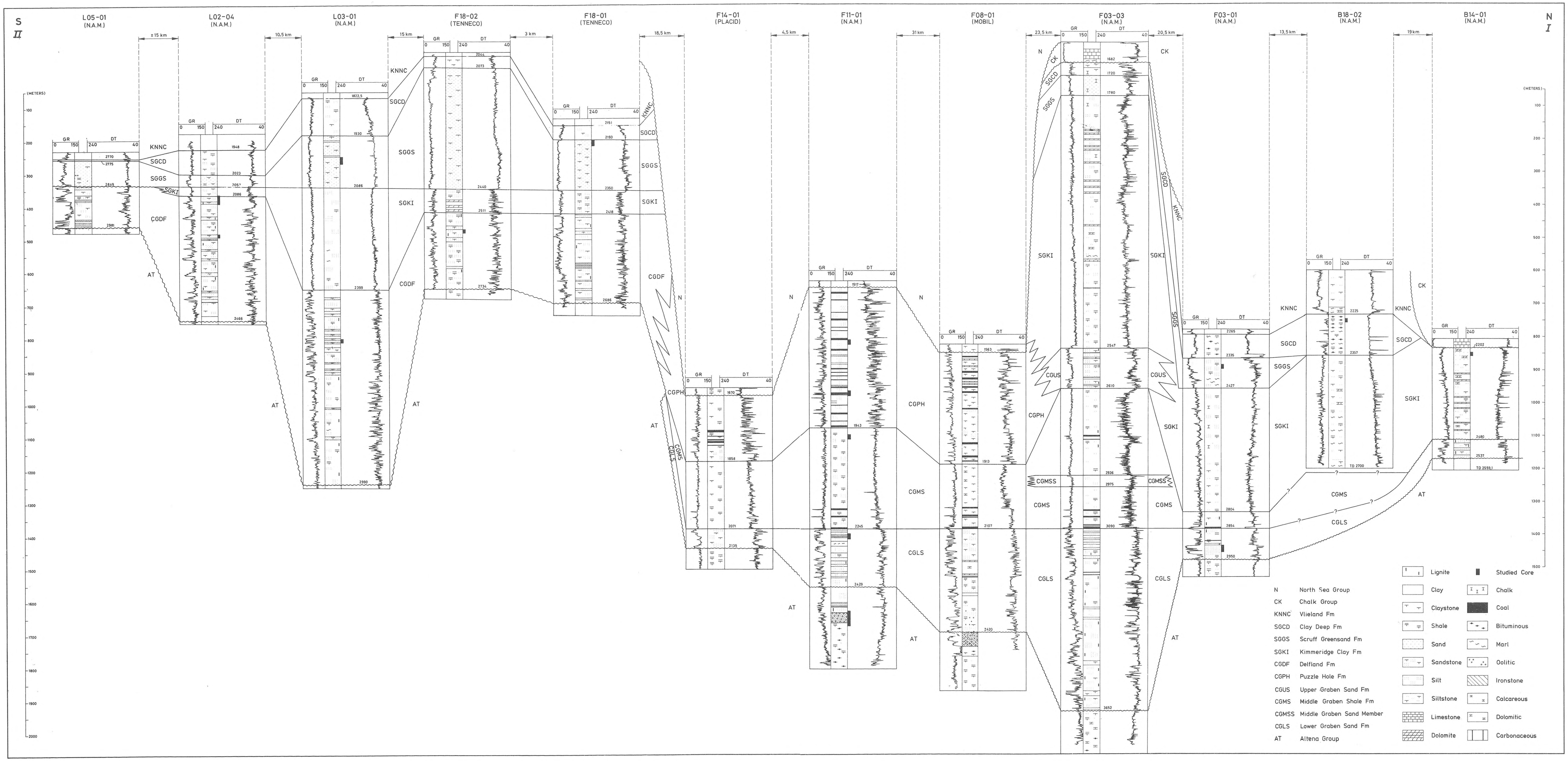
Errata added in prove

Fig. 6. Thickness of CGLS in F11-1 should read 184 instead of 204.

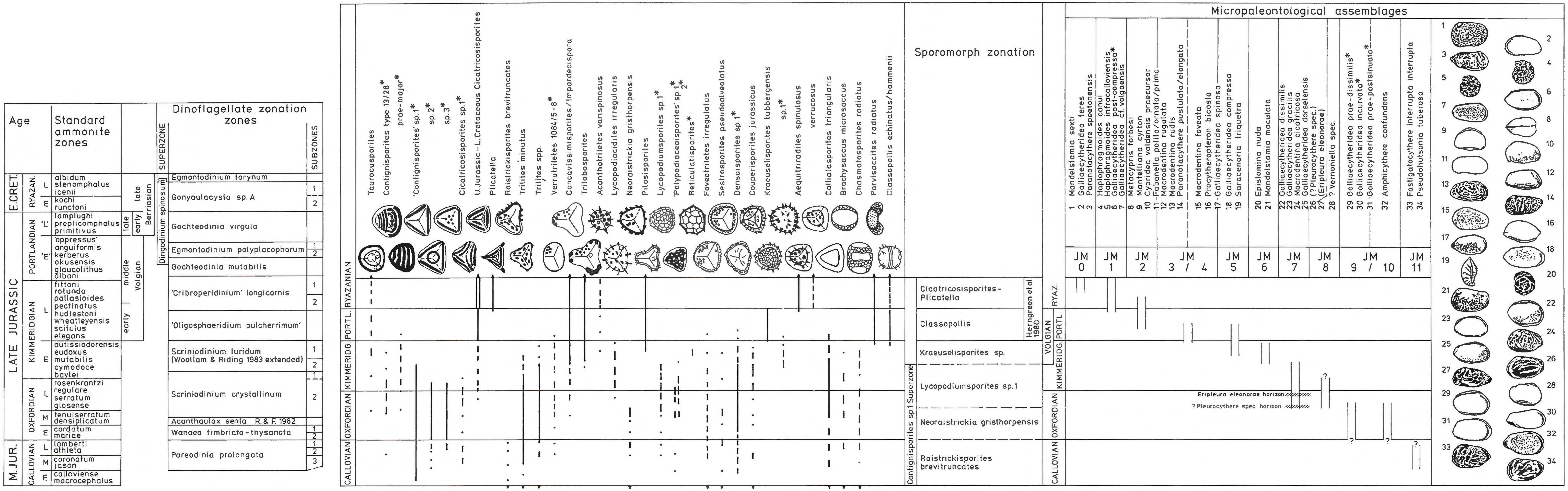
Fig. 9. Thickness of CGPH in F14-2 is 54.

Fig. 11. Delete side-wall core at ± 3180 m.

Fig. 12. Thickness of SGGS in B14-1 should read 0 instead of 35.



Encl. 1. Section I-II. North-South log correlation through the Central North Sea Graben. In the northernmost part of the section (B14-1) the Kimmeridge Clay is present. This formation is overlain in B18-2 and F3-1 by the bituminous Clay Deep. In the F3 area the entire Callovian-Ryazanian sequence comprising the Lower Graben Sand, Middle Graben Shale, Upper Graben Sand, Kimmeridge Clay, Scruff Greensand, and Clay Deep may be encountered. In the lower part of the Middle Graben Shale the newly established Middle Graben Sand Member is present. Southward, the Upper Graben Sand grades into the Puzzle Hole, i.e., in F8-1 and F11-1. South of F14-1 the Puzzle Hole in turn grades into the Delfland Fm. In addition, most of the other formations become thinner or even wedge out. Hence, the southern area is characterized by a generally well-developed Delfland Fm. overlain by either Kimmeridge Clay, Scruff Greensand, or Clay Deep formations.



Encl. 2. Biostratigraphic zonation based on dinoflagellates, sporomorphs, ostracods and foraminifera. The limits of the sporomorph and micropaleontological zones are not known as precisely as those of the dinoflagellates and represent a (sub)stage accuracy.