

TERTIARY STRATIGRAPHY OF THE NETHERLANDS¹W. J. LETSCH² & W. SISSINGH²

ABSTRACT

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Analysis of stratigraphic relationships and depositional characteristics shows that the deposition of the Paleogene of The Netherlands was governed particularly by global cycles of (marine) transgressions and regressions. Shorelines generally lay in the south and southeast. Intercalated sands were derived from the Central European hinterland.

The depositional history of the Neogene is closely related to the development of the Lower Rhine Embayment and the Rhine River system. It also manifests the onset of the formation of the deltaic fan system which has characterized the onshore Netherlands since the early Pleistocene.

INTRODUCTION

Objective

Regional knowledge of the largely concealed Tertiary of The Netherlands is mainly based on information derived from the many onshore and offshore wells drilled by the Bataafse Petroleum Maatschappij (B.P.M.), the Nederlandse Aardolie Maatschappij (N.A.M.) and the Rijks Geologische Dienst (R.G.D.). Much of the gathered stratigraphic data is stored by computer, or otherwise, with N.A.M.

The objective of this study is to update the review of the Dutch Tertiary by KEIZER & LETSCH (1963) and VAN STAALDUINEN ET AL. (1979), and to supplement the pertinent stratigraphic nomenclature of N.A.M. & R.G.D. (1980) by outlining the areal distribution of the various rock-units. The current foraminiferal biostratigraphy of the Dutch Tertiary is therefore also reviewed. Foraminiferal biofacies have been studied for the evaluation of the environmental conditions of deposition.

The lithostratigraphic and biostratigraphic subdivision of some hundreds of onshore and offshore wells have been evaluated for this study. Additional information has been incorporated from literature.

Basinal setting

During the late Cretaceous and early Tertiary The Netherlands were subjected to the Subhercynian and Laramide

phases of tectonism. In the north and in the south tectonic movements seem to have been gentle. Only a small portion of the Cretaceous has been removed by erosion. In the extreme northern and southern areas, where early Paleocene (Danian) occurs, the Cretaceous and the Tertiary deposition was seemingly continuous. However, in the more central area of The Netherlands uplift and erosion was intense and that resulted in some regional peneplanation.

The early Paleocene overlapped this region from the north and from the south, and like during the Senonian, in a predominantly carbonate facies. However, towards the end of the early Paleocene rifting phase these carbonates were eroded and succeeded by clastics consisting predominantly of holomarine shelf clays and sands.

In The Netherlands some infra-basinal depressions and highs existed during the Cenozoic (PANNEKOEK, 1956). Infra-basinal shifting of these highs and lows has apparently occurred to such an extent that areas of major uplift or minor subsidence could ultimately become zones of minor uplift or major subsidence. In the north, halokinesis played a role and affected the configuration of Tertiary strata. The present-day depth contours of the base of the Tertiary of the North Sea Basin show a major depoaxis extending from the approximate northwest of the studied area, across the IJsselmeer Lake, into the Late Cenozoic Lower Rhine Embayment (Fig. 1).

The Tertiary of The Netherlands thus represents a tectonically mobile area of deposition, which is transitional between the deep North Sea Basin in the north and the epicontinental extension of this area into Belgium and France. Its preserved basinfill ranges generally in thickness from a few metres on the Mesozoic and Palaeozoic surfaces in the extreme southern and southeastern parts of The Netherlands to over 2 000 metres in the northern off-shore sector.

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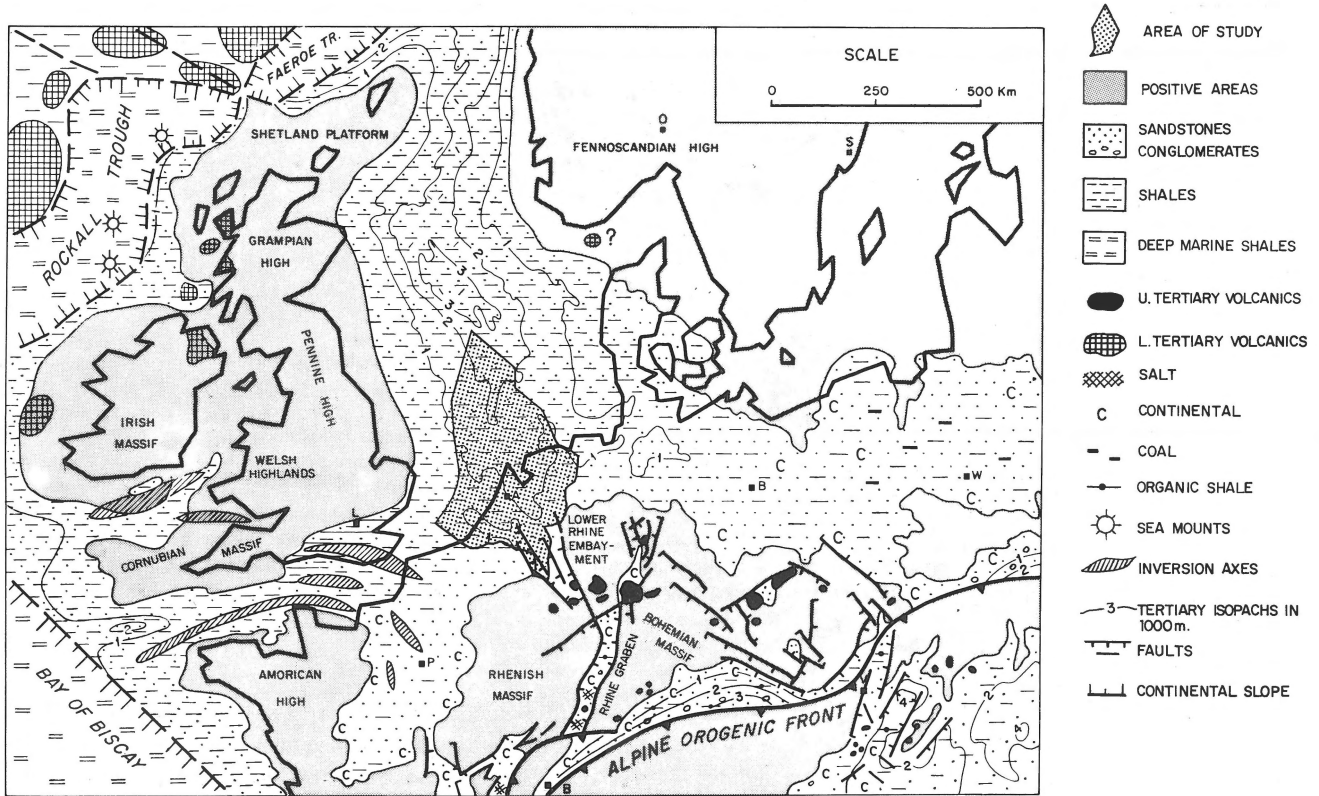


Fig. 1 Tertiary paleogeography of North-Western Europe and location of the area of study (based on Ziegler, 1978).

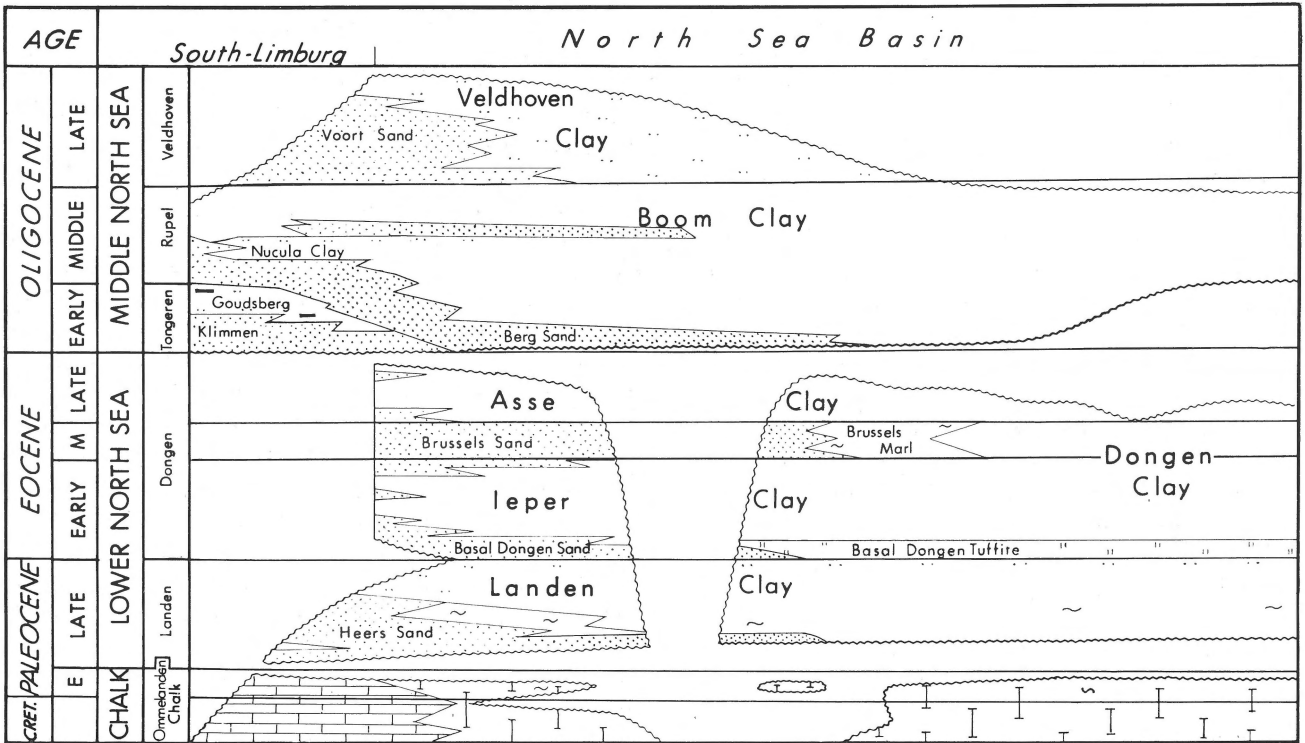


Fig. 2 Lithostratigraphic diagram of the Lower and Middle North Sea Groups in South-Limburg and adjacent northern areas.

LITHOSTRATIGRAPHY

N.A.M. & R.G.D. (1980) assign nearly all Cenozoic deposits of The Netherlands into three groups; viz. the Lower, Middle, and Upper North Sea Groups (Figs. 2, 3). These groups are assembled here into the North Sea Supergroup.

The more or less chalky strata at the base of the Tertiary sequence belong to the upper part of the Ommelanden Chalk Formation (Fig. 4). In the Province of Limburg these deposits are described as the Houthem Formation (FELDER, 1975). In the north, the discontinuous distribution of the formation is apparently related to the inversion of the southern part of the Central North Sea Graben (HEYBROEK, 1975).

The Lower North Sea Group ranges in age from Paleocene (post-Danian) to Eocene (Fig. 2) and comprises from the base upward the Landen Formation (Fig. 5) and the Dongen Formation (Figs. 6, 7). The boundary between the formations is usually equated with the Paleocene/Eocene boundary (VAN STAALDUINEN ET AL., 1979; N.A.M. & R.G.D., 1980). However, this boundary may be actually in the uppermost part of the Landen Formation, since Eocene ages for this rock-unit have been determined micropalaeontologically in the northeast (Province of Groningen).

The subdivision and mapping of the Eocene Dongen Formation (Figs. 6, 7) is based on foraminiferal biostrati-

graphic criteria. The sand members of the Landen and Dongen Formations all wedge out in more or less northwestern directions. Two Paleocene/Eocene depocenters are distinguishable: one in the north and one in the south. Both depocenters are separated by a northwest-southeast trending high located across the central Netherlands. Maps (Figs. 5, 6, 7) show uplift and intense, deep-cutting erosion in the central part of The Netherlands around the Eocene/Oligocene transition (see also Fig. 2). This erosion may be related to the Pyrenean phase of tectonism.

The Oligocene interval comprises the Middle North Sea Group. Within this group three formations are distinguished (from base to top): the Tongeren, Rupel and Veldhoven Formations (Figs. 2, 3).

The distribution of the Tongeren Formation has not been studied. In The Netherlands it is confined to the southern part of the Province of Limburg (see KUYL, 1975).

The distribution of the Rupel Formation and the basal Berg Sand Member is indicated in Fig. 8. The Nucula Clay Member has not been studied. Its occurrence in southern Limburg is discussed by KUYL (1975). The Rupel Formation has not been recognized in some restricted off-shore areas (Fig. 8). These apparent absences remain still unexplained. The formation is presently assumed to range in age from early Oligocene to middle Oligocene (VERBEEK, 1979; pers. comm. 1981).

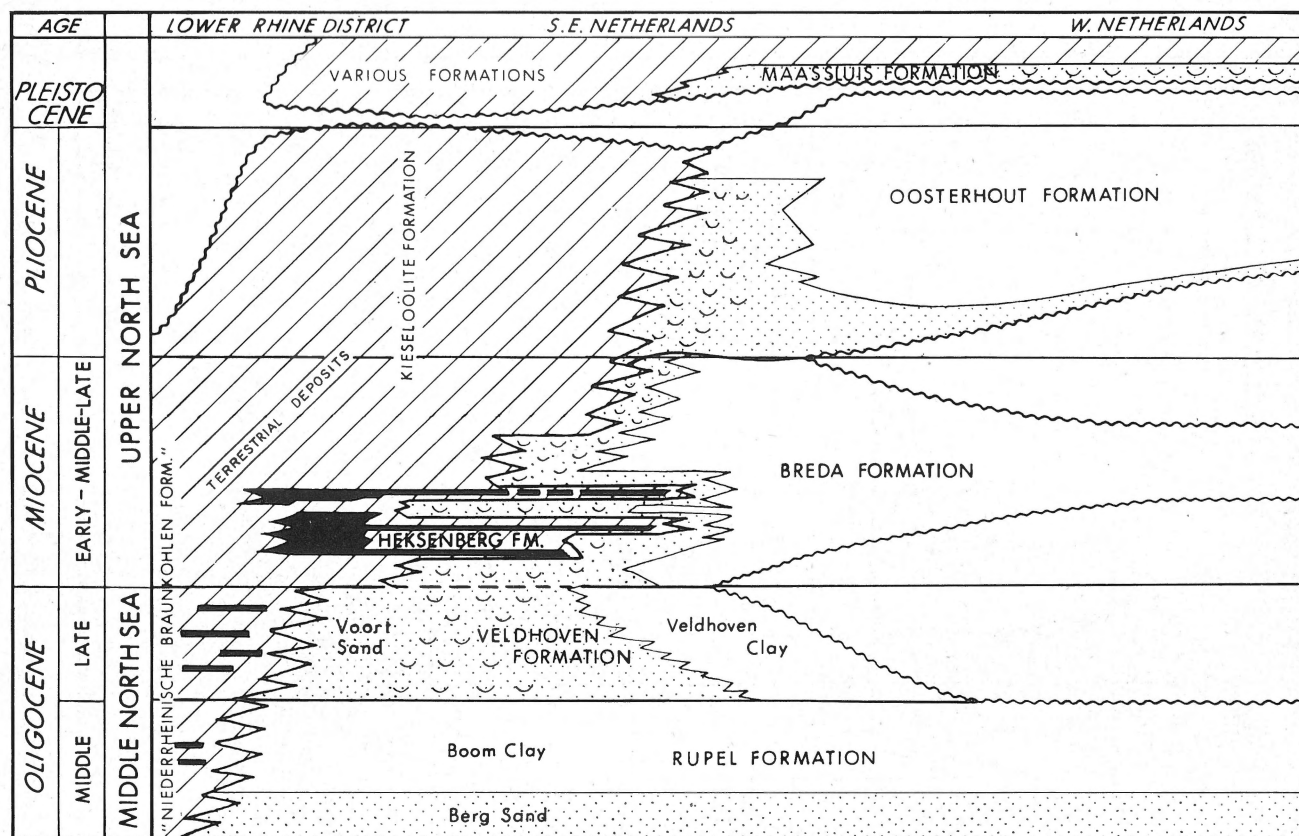


Fig. 3
Lithostratigraphic diagram of the Middle (p.p.) and Upper North Sea Groups in the Lower Rhine District and adjacent eastern and western areas.

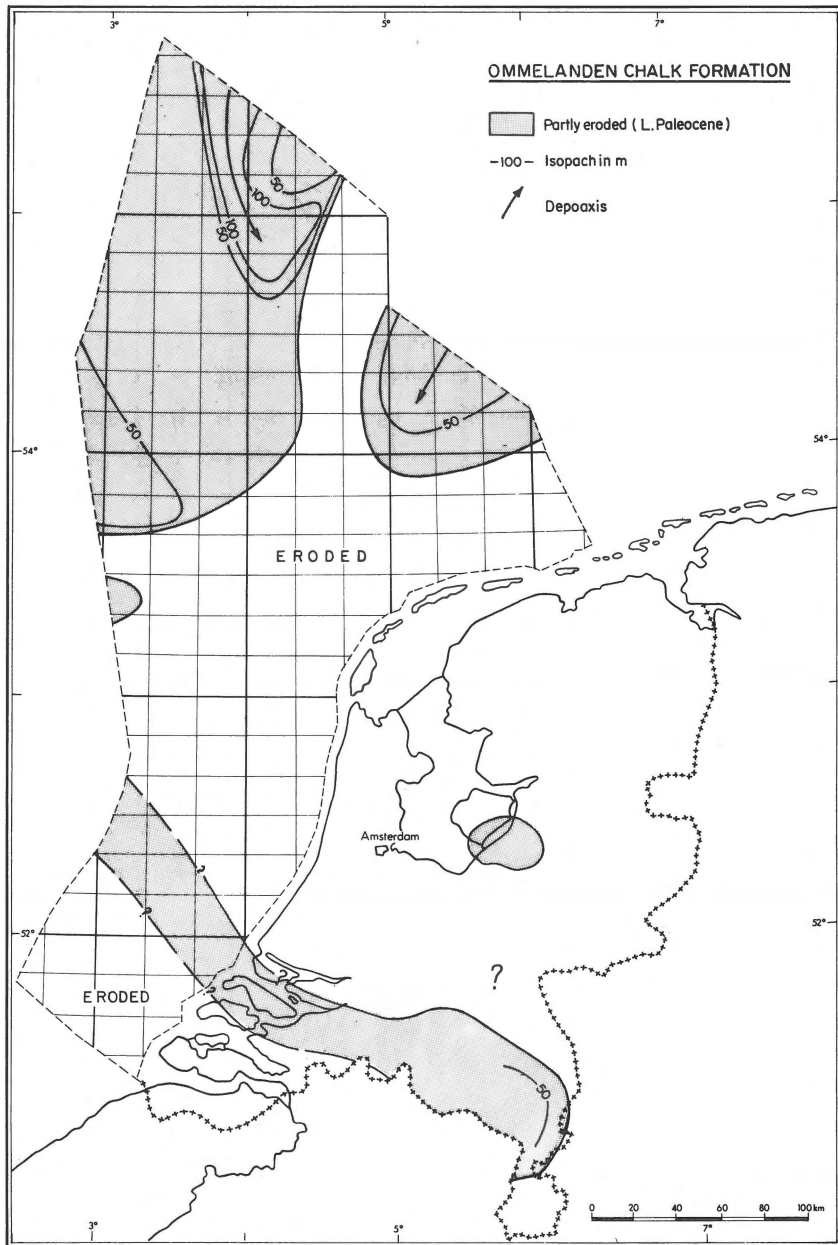


Fig. 4
Distribution of the Ommelanden Chalk Formation (Lower Paleocene part).

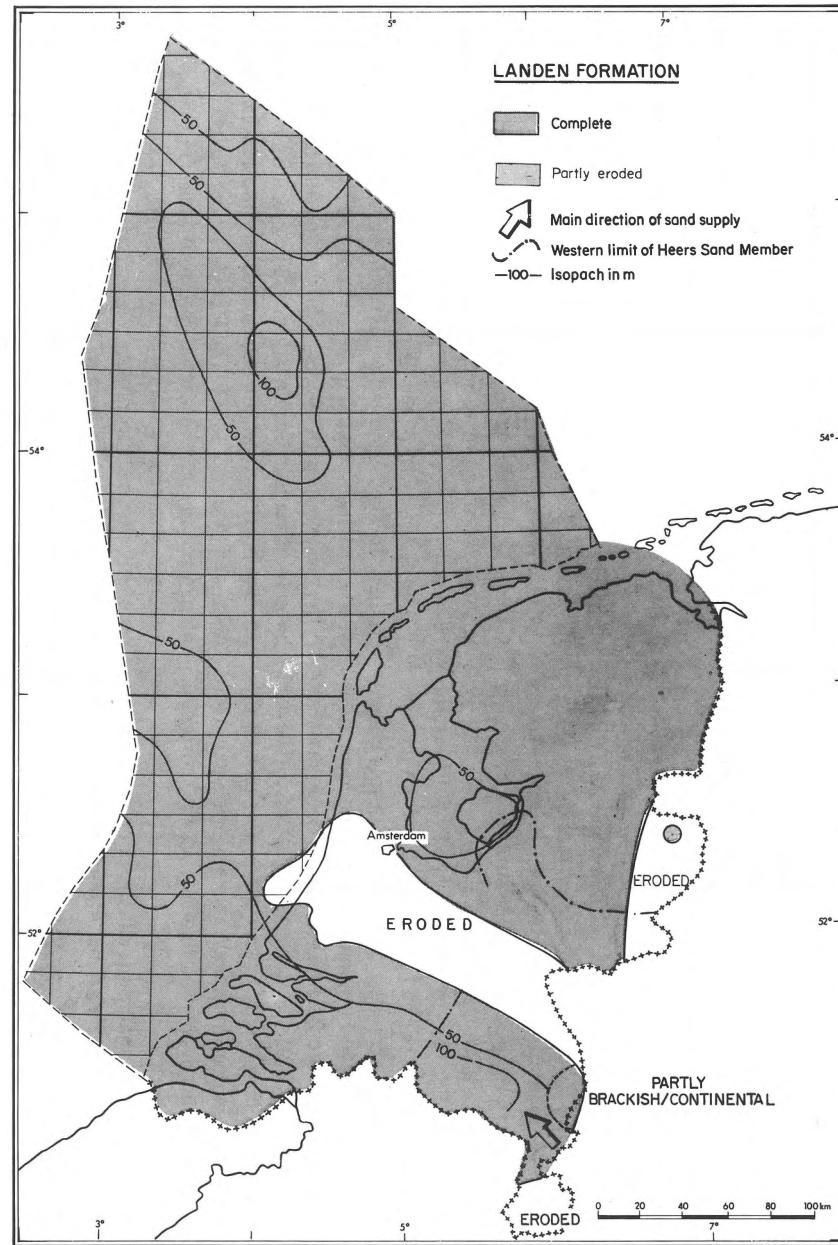


Fig. 5
Distribution of the Landen Formation (Upper Paleocene).

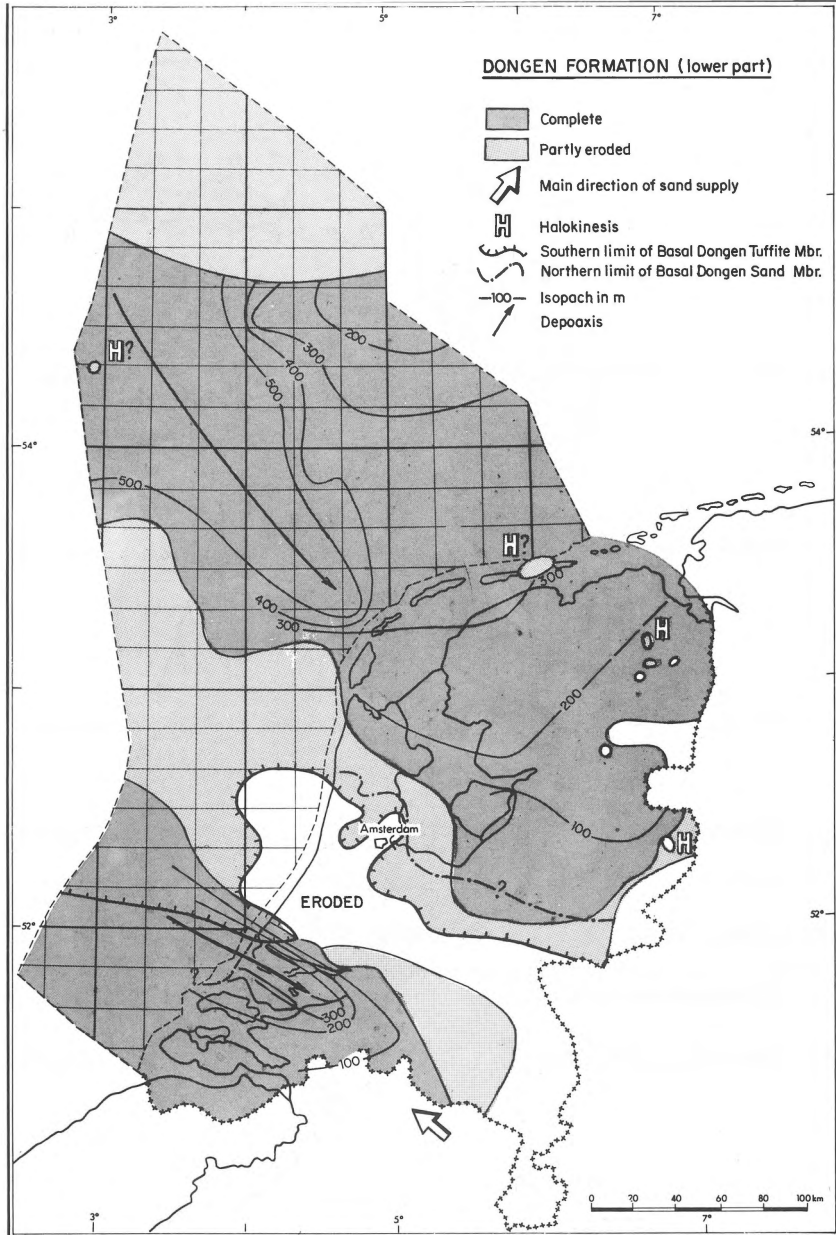


Fig. 6
Distribution of the Dongen Formation (Lower Eocene).

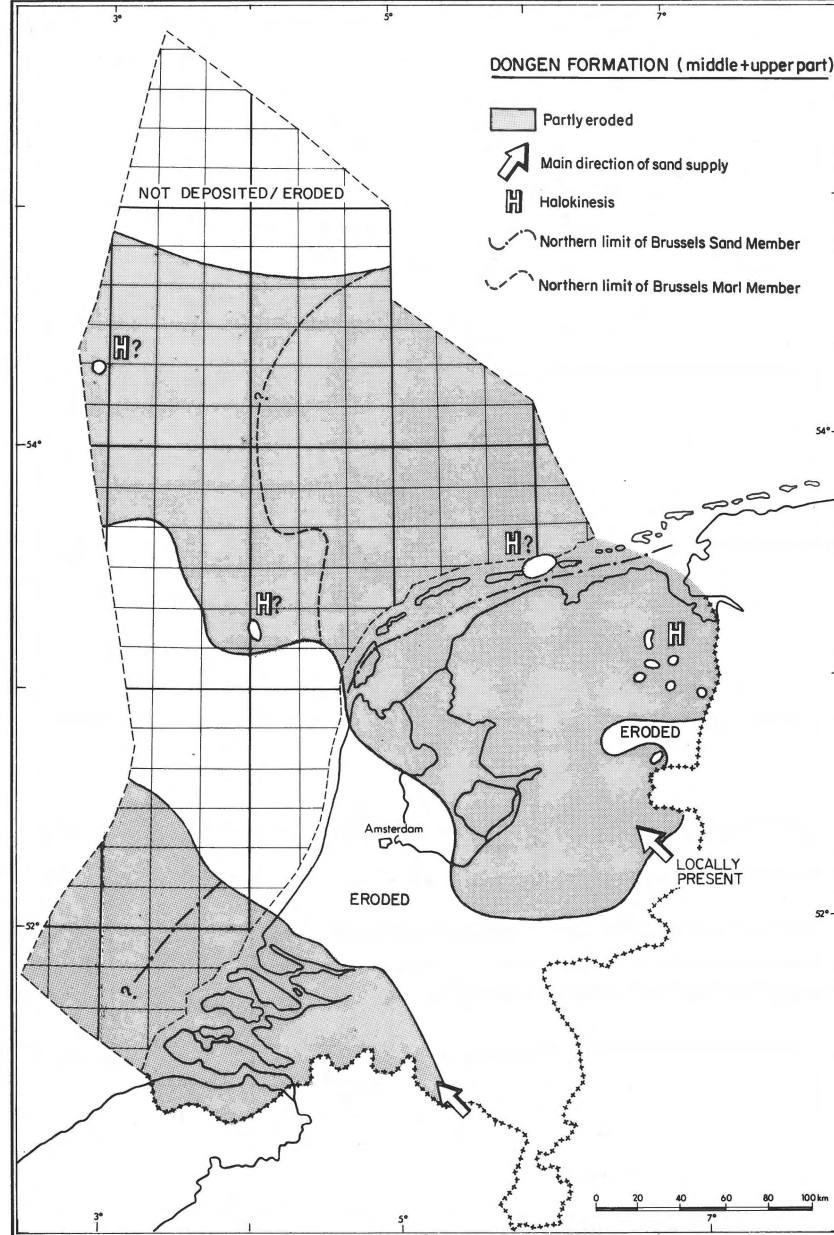


Fig. 7
Distribution of the Dongen Formation (Middle/Upper Eocene).

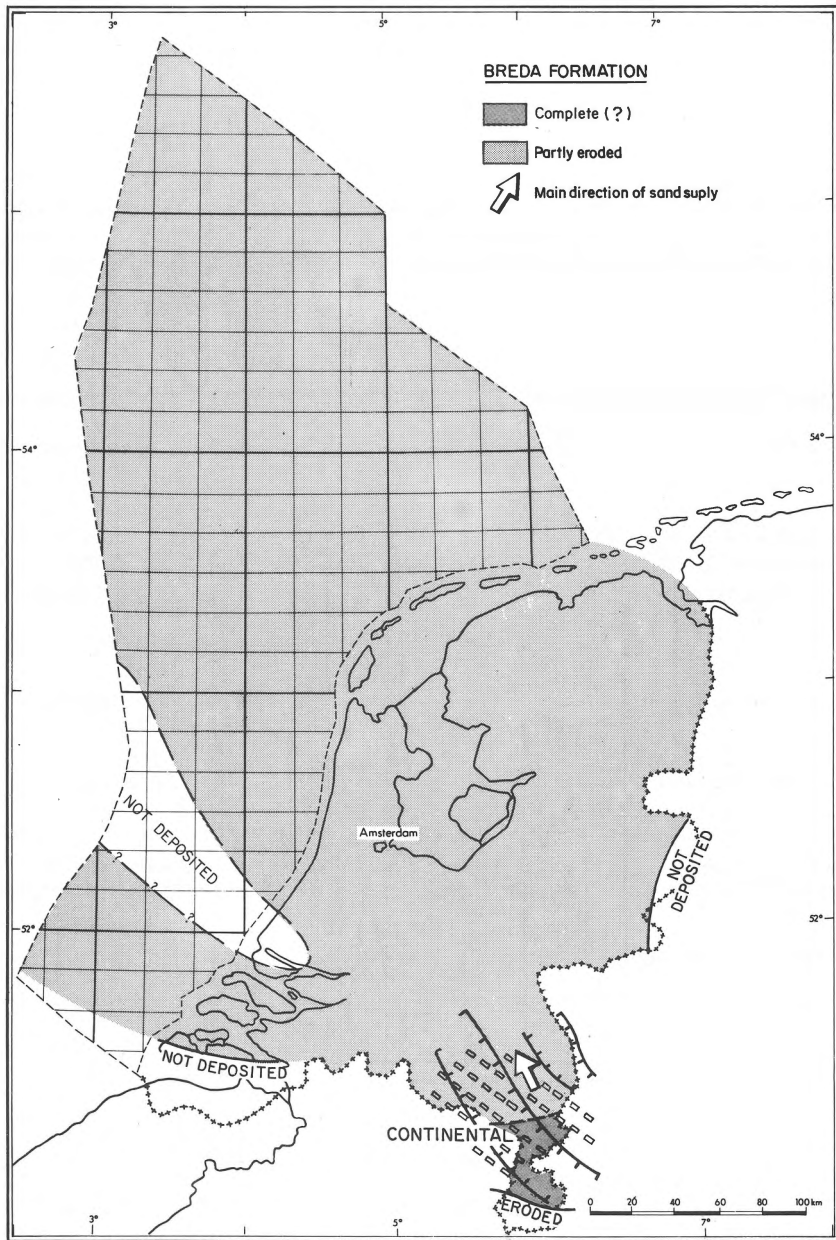


Fig. 10
Distribution of the Breda Formation (Miocene).

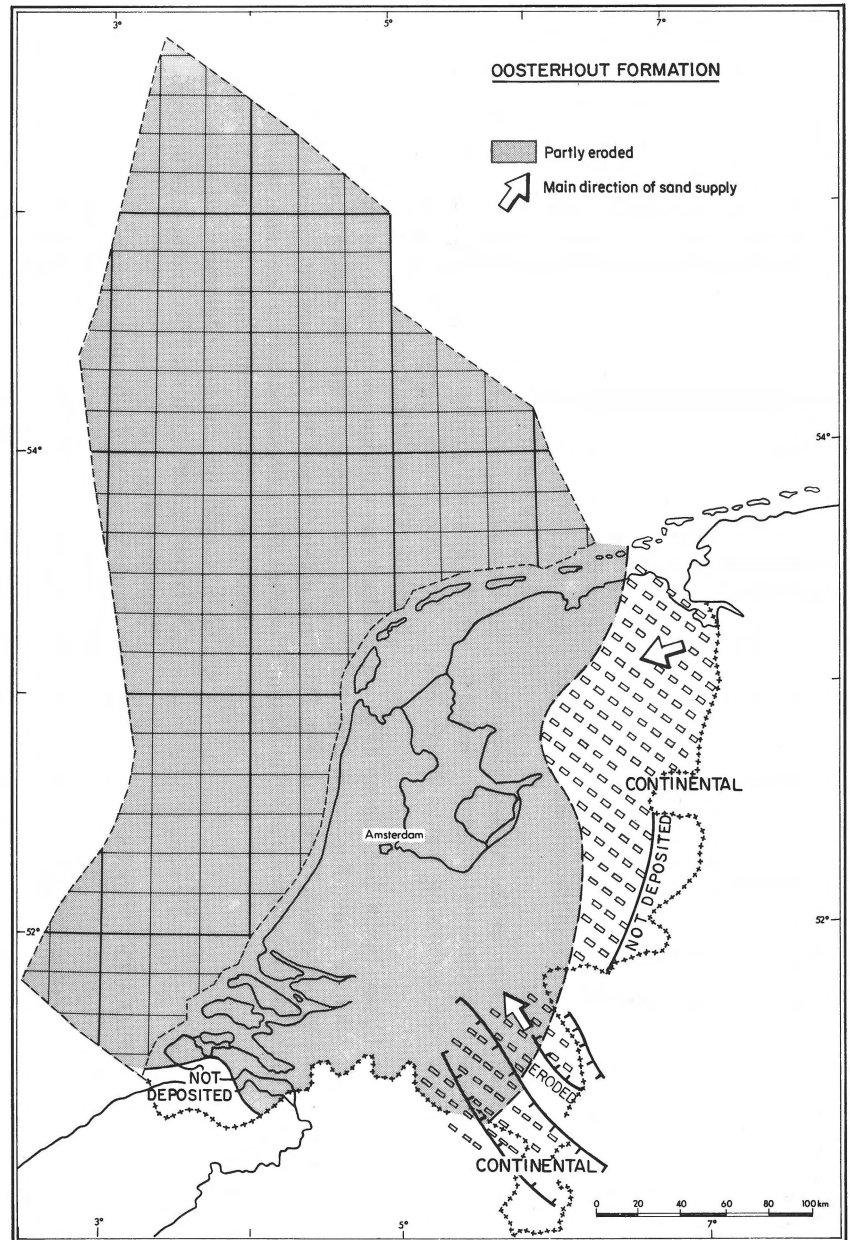


Fig. 11
Distribution of the Oosterhout Formation (Pliocene).

The distribution of the Veldhoven Formation (Fig. 9), as well as that of the Rupel Formation, suggests that uplift and erosion close to the Oligocene/Miocene boundary was less effective in the southeast of The Netherlands than elsewhere in the area of study. The southeastern region was uplifted around the Eocene/Oligocene transition but became an area of major subsidence during the Oligocene. Significant accumulations of sediments took place in the Peel area (approx. 51°N-6°W; compare Figs. 7 and 8) and the area became gradually part of the subsiding part of the tectonic complex of the Lower Rhine Embayment.

The two main sand members of the Middle North Sea Group tend to pinch out in a northwesterly direction similar to the sand members of the underlying Lower North Sea Group.

The post-Oligocene Upper North Sea Group (Fig. 3) includes the essentially Miocene Breda Formation (Fig. 10) and the essentially Pliocene Oosterhout Formation (Fig. 11). These rock-units are unconformably superimposed in most of the study areas.

SEDIMENTARY CYCLES

The Early Tertiary depositional record of the uppermost part of the Chalk Group and the Lower North Sea Group has been severely affected by erosion induced by Laramide and Pyrenean tectonic movements. Similarly, 'Savian' erosion probably reduced the record of the Middle North Sea Group over a large part of The Netherlands. In Fig. 12 a lithostratigraphic model for these groups is presented. It shows a cyclic sequence of holomarine clays alternating with marginal

marine to lagoonal sands and clays on top of generally early Paleocene Ommelanden Chalk. An essentially identical sequence for the Paleogene in a partly more pronounced basin fringe setting is recognizable further to the south in Belgium (Fig. 13). Both these sequences are interpreted as representing eight transgressive-regressive cycles of sedimentation (cycles I-VIII) (cf. HARDENBOL & BERGGREN, 1978). They correspond to global cycles of relative changes in sea level and correlate with the Cenozoic cycle chart of VAIL & MITCHUM (1979) (Figs. 12, 13). Contrary to the cycle chart of the latter authors it is not possible to recognize in our area of study an additional (third-order) subdivision within the cycles II (TP 2) and V (TE2).

The Late Tertiary depositional record involves the Upper North Sea Group. In the southeastern Netherlands this record reflects four sedimentary cycles (cycles IX-XII) (cf. GLIESE & HAGER, 1978) of which the Heksenberg Formation represents two cycles (IX and X). The transgressive parts of these cycles contain the pronounced brown coal deposits known as the Morken and Frimmersdorf seams. The third Neogene cycle (XI) occupies the remaining Miocene, while the fourth one (XII) commenced near the Pliocene base of the Oosterhout Formation (Fig. 3).

In the absence of adequate biostratigraphic-chronostratigraphic control it is not possible to correlate this sequence of Neogene cycles with the geochronometric cycle chart of VAIL & MITCHUM (1979). However, the late Miocene is recorded as a period of overall regressive sedimentation and the initial deposition of Pliocene sediments is, as in VAIL & MITCHUM (1979), also transgressive. It is probable that the older Neogene cycles (IX and X) have a predominantly local significance and are both related to the geological evolution of the Lower Rhine Embayment.

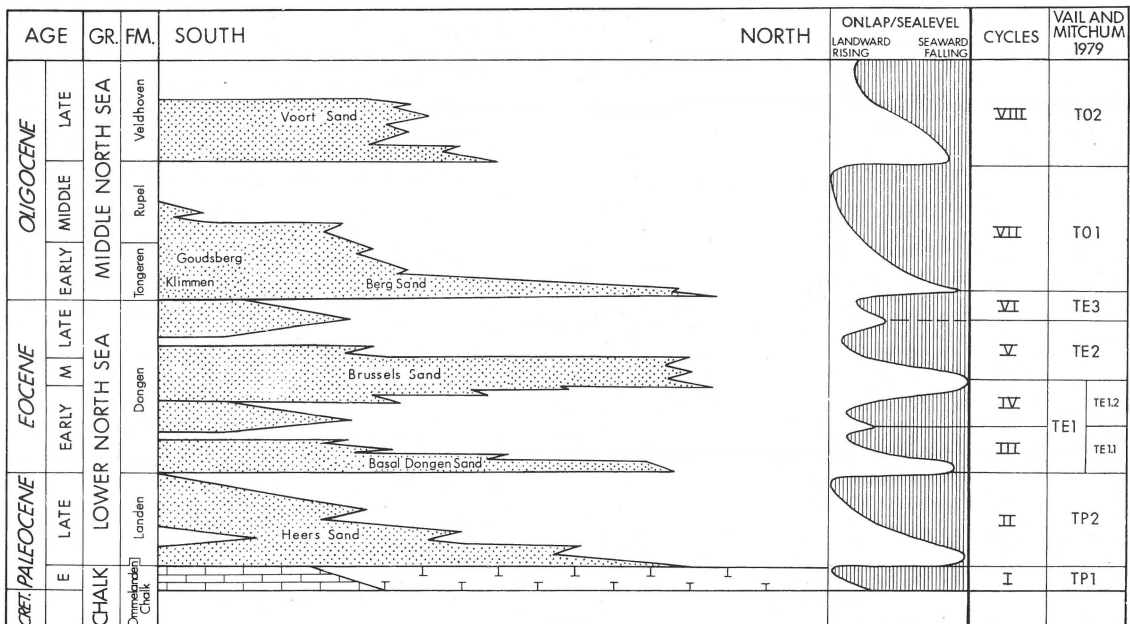


Fig. 12
Cycle chart for the Paleocene of The Netherlands.

FORAMINIFERAL BIOSTRATIGRAPHY

As yet microfossil biostratigraphy of the Dutch Tertiary is based mainly on benthonic foraminifera. So far very little attention has been paid to planktonic microfossil groups, such as calcareous nannoplankton and microplankton. Partly for this reason correlations of benthonic foraminiferal zones with the standard chronostratigraphic scale are best considered as tentative and in need of confirmation by means of the biostratigraphic evaluation of other fossil groups.

Eleven foraminiferal zones and subzones are recognized (Figs. 14, 15). Most of these units correspond in essence with those defined by DOPPERS (1975, 1980) and DOPPERS ET AL. (1979). Persistent variations in palaeo-environmental conditions exclude the possibility to define meaningful range zones. The primary characteristics of the assemblage zones and subzones are indicated in figure 15.

A new unifying system of zonal Foraminifera Tertiary (FT) codes is introduced to standardize the biostratigraphic scheme, since it corresponds to elements of the Dutch (FA-FJ) zonation of DOPPERS (1975) and of the (BFN) subdivision of DE MEUTER & LAGA (1977) established for the Neogene of Belgium (Fig. 14). The zonation is most applicable to the onshore Tertiary of The Netherlands and northern Belgium.

STRATIGRAPHIC RELATIONSHIPS

Paleogene stratigraphic relationships are reviewed in figure 16. Notably, a discrepancy in nomenclature exists involving the relative position of the Rupelian/Chatian boundary.

Based on benthonic foraminiferal criteria this boundary is determined by Dutch and other stratigraphers by means of the first appearance level of *Stainforthia schreibersiana*, the extinction level of *Rotaliatina bulimoides* and, to a lesser extent, by the disappearance of *Ammobaculites humboldti*. The first occurrence of *S. schreibersiana* is generally found at (or just above) the boundary between the Rupel Formation and the Veldhoven Formation, while the last occurrences of *R. bulimoides* and *A. humboldti* are reported at (or some distance below) the top of the Rupel Formation. These biostratigraphic events thus straddle the boundary between the cycles VII and VIII.

This latter level is correlated with the boundary between the cycles TO1 and TO2.1 of VAIL & MITCHUM (1979) since that boundary is the only one in the late Oligocene which is marked by a similarly pronounced regressive phase. The top of the *R. bulimoides* subzone and both cycle boundaries are therefore equated at the 29 Ma level. This correlation is supported by calcareous nannoplankton biostratigraphy, which indicated that the extinction level of *R. bulimoides* and the first appearance level of *S. schreibersiana* virtually coincide with the 29 Ma NP23/NP24 boundary (J. W. CHR. DOPPERS & J. W. VERBEEK, pers. comm. 1981). VAIL ET AL. (1977) and VAIL & MITCHUM (1979) placed the TO1/TO2.1 boundary at the 30 Ma and 32 Ma level, respectively. A difference in age in the order of magnitude of two or three million years with the 32 Ma Rupelian/Chatian boundary (cf. HARDENBOL & BERGGREN, 1978) is consequently assumed by these authors. This assumption is not followed here. We assume that the Rupelian/Chatian boundary corresponds with the base of cycle TO2.1 close to the 29 Ma level.

AGE	GR.	FM.	SANDS/CLAYS	BEDS	FORMATION	ONLAP/SEALEVEL		CYCLES	VAIL AND MITCHUM 1979
						LANDWARD RISING	SEAWARD FALLING		
OLIGOCENE	LATE	Veldhoven	SANDS OF VOORT		VOORT			VIII	TO2
	MIDDLE		BOOM CLAY NUCULA CLAY SANDS OF BERG		RUPEL				
	EARLY	Tongeren	VARIOUS HORIZON OF HOOGBUTSEL SANDS AND CLAYS	UPPER TONGEREN LOWER TONGEREN	TONGEREN			VII	TO1
MIDDLE	Dongen	SANDS OF ASSE CLAY OF ASSE SANDS OF LEDE/WEMMEL		ASSE LEDE					
EARLY		SANDS OF BRUSSELS		BRUSSELS			VI	TE3	
M		SANDS OF AALTER SANDS OF VUERZELE SANDY CLAY OF ANDERLECHT EQUIVALENT	UPPER PANISEL LOWER PANISEL	PANISEL					
Eocene	EARLY	Dongen	CLAYS OF ROUBAIX/ROMCO SANDS OF MONS - EN PÉVELE MORLANWELZ MEMBER CLAYS OF IEPER		IEPER			IV	TE1
	EARLY		SANDS OF OOSTENDE SANDS OF LANDEN SANDS OF ERQUELINNES SANDS OF GRANDGLISE CLAYS OF LOUVIL MARLS OF GÉLINDE SANDS OF ORP	UPPER LANDEN LOWER LANDEN	LANDEN				
CRET. PALEOCENE	LATE	Landen						III	TE11
	E				MONS				
CHALK		Ommelanden Chalk						I	TP1

Fig. 13

Cycle chart for the Paleocene of Belgium.

EPOCHS	AGES	DOPPERT 1975, 1980		DE MEUTER & LAGA 1977		THIS PAPER		PRIMARY DATUM INDICATORS
PLEISTOCENE	FA	ELPHIDIELLA HANNAI-CRIBRONION EXCAVATUM ASS-ZONE	FA 1	AMMONIA-QUINQUE-LOCULINA SUBZONE				
		TEXTULARIA DECRESCENS-BULMINA ACULEATA ASS-ZONE	FB					
PLIOCENE	FB	BUCELLA-CASSIDULINA SUBZONE	FA 2		BFN 6	ELPHIDIELLA HANNAI-CRIBRONION EXCAVATUM ASS.ZONE		
					BFN 5	CIBICIDES LOBATULUS PEAK ZONE		
MIOCENE PLIOCENE	FC	SIPHOTEXTULARIA SCULPTURATA	FC 1	DENTALINA CASSIDULINA SUBZONE	BNF 4	FLORILLUS BOUEANUS-MONSPELIENSIS PSEUDOTEPIDA ASS.ZONE	FT 9	SIPHOTEXTULARIA SCULPTURATA ZONE
MIOCENE	late	UVIGERINA HOSIUSI ASS.ZONE	FC 2	ELPHIDIUM-GLOBIGERINA SUBZONE	BNF 3	UVIGERINA HOSIUSI DEURNENSIS-ELPHIDIUM ANTONINUM ASS.ZONE	FT 8	ELPHIDIUM ANTONINUM ZONE
		ASTERIGERINA-STAESCHEI-UVIGERINA TENUIPUSTULATA ASS.-ZONE	FD		BNF 2	UVIGERINA TENUIPUSTULATA-ELPHIDIUM INFLATUM ASS.ZONE	FT 7	ELPHIDIUM INFLATUM ZONE
		STEINFORTHIA SCHREIBERSIANA SIGMOMORPHINA REGULARIS ASS.-ZONE	FE 1	ROTALIA-TRIFARINA SUBZONE	BNF 1	TRIFARINA GRACILIS RUGULOSA-ELPHIDIUM UNGERI ASS.ZONE	FT 6	ASTERIGERINA STAESCHEI ZONE
OLIGOCENE	late	ALMAENA CRIBRONION S.Z.	FE 2					
		ASTERIGERINA SUBZONE	FE 3					
		ROTALIA BULMINOIDES - CIBICIDES UNGERIANUS ASS. - ZONE	FF					
OLIGOCENE	middle	SCUTULORIS OBLONGUS-ASTERIGERINA BARTONIANA ASS. - ZONE	FG					
		ROTALIA BARTONIANA ZONE	FT 4					
EOCENE	late	VAGULINOPSIS DECORATA PSEUDOHASTIGERINA MICRA ASS.-ZONE	FH 1	NUMMULITES EPNIDES SUBZONE				
		PLANULINA CIBICIDES SUBZONE	FH 2					
		ANOMALINA YPRESIENSIS GAUDRYINA HILTERMANNI ASS. - ZONE	FI					
PALEOCENE	late	BULMINA TRIGONALIS HAPLOPHRAGMOIDES EGGERI ASS. - ZONE	FJ					
		PARAROTALIA GLOBIGERINI - FORMIS - ROTALIA SAXORUM ASS. - ZONE	FK					
PALEOCENE	early							

Fig. 14
Correlation chart of Tertiary foraminiferal biozonations.

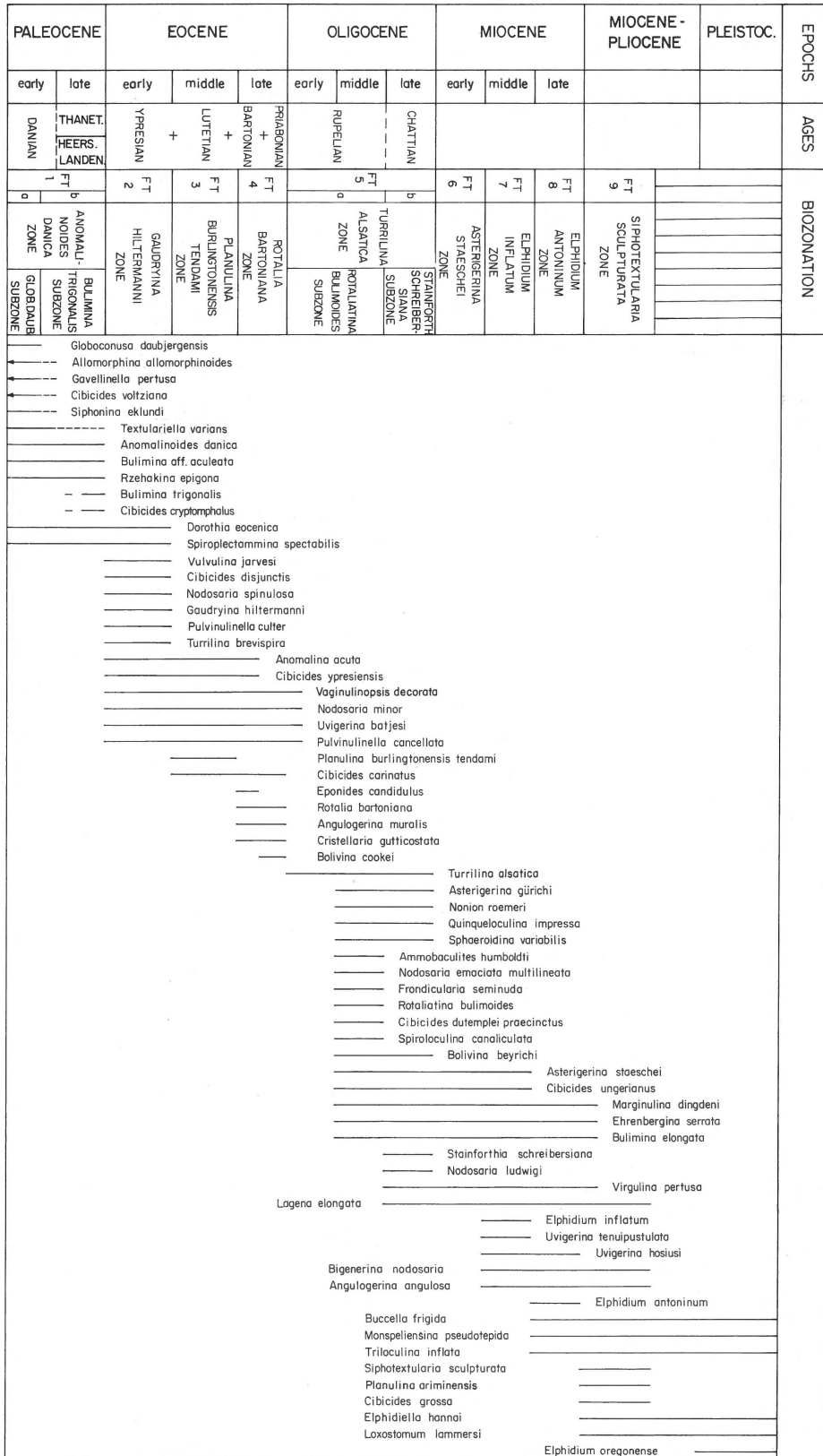


Fig. 15
Range chart of Tertiary foraminiferal marker species.

CHRONOSTRATIGRAPHY		BIOSTRATIGRAPHY		LITHOSTRATIGRAPHY		CYCLES		VAIL AND MITCHUM 1979		
EPOCHS		AGES		(SUB) ZONE		GROUPS		FORMATIONS		
M.								SUPER CYCLES		
								CYCLES		
								STANDARD AGES		
OLIGOCENE	LATE	CHATTIAN	b	ASTERIGERINA STAESCHELI ZONE	MIDDLE NORTH SEA	BREDA	III	TM1	AQUITANIAN 24	
	MIDDLE	RUPELIAN	c	TURRILINA ALSATICA ZONE		VELDHOVEN	XIII	Td	TO2	CHATTIAN
	EARLY					TONGEREN	XVII	Tc	TO1	
Eocene	LATE	PRIABONIAN + BARTONIAN	FT4	BOITALIA BARTONIANA ZONE	LOWER NORTH SEA	DONGEN	VI	TE3	37	
	MIDDLE	LUTETIAN	FT3	PLANULINA BURLINGIENSIS TENDAMI ZONE		IX		Tb	TE2	40
	EARLY	YPRESIAN		FT2		GAURDYRNA HILTERMANNI ZONE	III	Tg	TE1	44
							IV		TE1	49
PALEOCENE	LATE	THANETIAN + HEERSIAN	b	ANOMALI-INDUS DANICA ZONE	CHALK	LANDEN	II	TP2	51.5	
	EARLY	DANIAN	c	SILININA TRIGONALIS SUBZONE		OMMELANDEN CHALK	I	Kc	TP1	60
									TP2	65

Fig. 16
Correlation chart of Paleogene stratigraphic relationships.

DEPOSITIONAL HISTORY

Paleogene

The deposition of the Paleogene sequence of The Netherlands, including its off-shore sector, has been governed particularly by global cycles of marine transgressions and regressions in a basin with ancient shorelines generally to the south and southeast from the area under consideration (BATJES, 1958; KAASSCHIETER, 1961). During the earliest Paleocene (Danian) Ommelanden Chalk was transgressively deposited in the southern Netherlands. In this depocenter the sea transgressed approximately from the west to the east, while seemingly overlapping Cretaceous strata that belong to the same formation (KEIZER & LETSCH, 1963). More or less friable, light-coloured limestones with 'hardgrounds' and glauconitic layers were laid down in relatively shallow marine, neritic environments. In relatively off-shore environments chalky carbonates were concurrently deposited. This latter lithofacies is strongly dominant in the northern off-shore sector of The Netherlands.

Much of the Paleocene Ommelanden Chalk was eroded during the Laramide phase of tectonism (Figs. 2, 4). After this regressive period, sedimentation resumed in exclusively clastic facies (Fig. 2), when regional subsidence began as a result of tensional forces related to additional opening of the North Sea Rift (ZIEGLER, 1978).

The oldest of the clastic formations is the Landen Formation. This largely transgressive rock-unit was deposited when the sea rapidly re-occupied the area of study from the north. The sea seems to have covered the entire area of The Netherlands, including the central region which, according to the isopachs, separated two depocenters: one in the extreme south and one in the north (Fig. 5).

The basal Heers Sand consists of glauconitic, calcareous sands intercalated with clay beds, which in the Peel area

overlay non-marine clays and sands with browncoal. The marine sands which are characterized by *Cyprina morrisi* and *Turritella imbricata* are transgressive. They are laterally replaced and upwards succeeded by the Landen Clay, a sequence of grey marls and calcareous clays laid down in shallow marine environments of deposition. The main direction of supply for the sands of the Heers Sand Member was from the southeast, the source being the Central European hinterland. A short regressive phase terminated the deposition of the Landen Formation.

The following sedimentary cycle initiated the deposition of the Dongen Formation, which quickly covered the entire area of study (Figs. 6, 7). Two depocenters with maximal rates of subsidence can be distinguished: one in the north and one in the southwest (Fig. 6). The northern one forms part of the North-German-Danish Basin, while the southern one was connected with the coeval marine depositional domain covering northern France, Belgium and southern England.

The Basal Dongen Sand of this formation is glauconitic and assumed to be rather comparable with the Heers Sand. Maximum thickness occurs in the east. Its main direction of supply is therefore also interpreted to be from the approximate southeast. Towards the north the Basal Dongen Tuffite was deposited as a lateral equivalent of the Basal Dongen Sand. This tuffaceous clay is generally rich in pyritized frustules of *Coscinodiscus*-type diatoms, and its deposition is related to early Eocene anorogenic vulcanism, occurring in the Rockall-Faeroe Trough and the present-day Skagerak area (ZIEGLER, 1978) (Fig. 1).

Both basal members are overlain by the Ieper Clay, a sequence of dark grey and greenish, generally glauconitic clays. In the southern Netherlands these clays are very silty and contain sand stringers suggesting continuing sediment supply from southerly and easterly directions. The dominant occurrence of arenaceous foraminifera indicates restricted, brackish to shallow marine conditions of deposition for the basal beds of the Ieper Clay. In southern areas subjacent clays yield richer and more diversified foraminiferal assemblages with planktonic foraminifera. These intervals were apparently laid down in normal marine depositional environments, probably with water depths generally not exceeding 100-200 metres. A mid-Eocene regression culminated with the deposition of the Brussels Sand, a glauconitic and calcareous sandstone with nummulites. These beds were most probably deposited in shallow marine environments under tropical conditions (KAASSCHIETER, 1961).

Overall transgressive deposition of the Asse Clay represents a late Eocene southward penetration of the sea. At the Eocene/Oligocene transition Pyrenean tectonism caused uplift and erosion of the Asse Clay throughout the area of study. Major uplift occurred in the central part of The Netherlands, where erosion cut deeply down and removed even the basal strata of the Landen Formation in a roughly northwest-southeast trending region (Figs. 2, 5).

Post-Pyrenean sedimentation commenced with the deposition of the Tongeren Formation and the Rupel Formation.

The Tongeren Formation consists of a shallow marine sequence of fine-grained, micaceous sands (Klimmen Member), overlain by lagoonal to terrestrial clays containing some sand and brown coal beds (Goudsberg Member). In The Netherlands these were deposited only in the southern part of the Province of Limburg (see KUYL, 1975). Deposition of the early/middle Oligocene Rupel Formation began in the southern and northeastern regions with the Berg Sand; elsewhere in the north directly with the Boom clay, which later transgressed southwards over the Berg Sand (Figs. 5, 8). The Berg Sand is a fine-grained rock-unit with a very poor foraminiferal assemblage. It is assumed to be mainly a transgressive shoreline deposit. The Boom Clay consists of brownish fossiliferous clays with septaria, and was deposited in normal marine, relatively off-shore shelf environments. BOEKSCHOTEN (1963, 1967) and BROUWER (1977) assumed that depositional depths ranged from 150 metre to over 300-500 metre (Grashoek). However, new fossil data and reinterpretation of old fossil evidence suggests that bathyal depositional depths for the Boom Clay are unlikely. It seems most likely, at least in the south, that the prevailing environment of deposition had a water depth of less than 100-150 metres.

The climate was more or less subtropical (VAN DEN BOSCH ET AL., 1975; see also VANDENBERGHE, 1978 and ROCHE & SCHULER, 1979). Accumulation of the Rupel Formation seems to have been maximal in the Peel area (Fig. 8). Following the very effective Pyrenean uplift in the central Netherlands an Oligocene depocenter developed in the southeastern part of this uplifted region. This development is considered to be related to the tectonism that led to the formation of the Lower Rhine Embayment.

Towards the end of the middle Oligocene regression the deposition of the Rupel Formation terminated. The succeeding sedimentary cycle deposited the sandy and silty clays of the Veldhoven Formation, which in the south commenced with the Voort Sand. These shallow marine sands rapidly pinch out in a northerly direction, where they are replaced by the grey Veldhoven Clay (Figs. 2, 9). 'Savian' erosion close to the Oligocene/Miocene transition, however, removed most of this formation. Its present-day, rudimentary distribution is considered to be related to syndimentary tectonics in the Peel depocenter.

Neogene

Deposition of the Neogene sequence is closely related to the evolutionary development of the Lower Rhine Embayment and the Rhine river system as elements of the Central European hinterland, at least as far as the sequence in the southeastern part of The Netherlands is concerned. The depositional record also manifests the onset of the formation of the deltaic fan system so characteristic for the onshore Netherlands since early Pleistocene times.

Throughout The Netherlands and its offshore sector, Miocene deposition started with the Breda Formation, a sequence of clays and sands, which represents marine sedi-

mentation resumed after the 'Savian' regressive phase (Figs. 3, 10). Late Oligocene block faulting and tilting in the southeastern Netherlands resulted during the earliest Miocene in a mobile northwest-southeast trending fault system which included in the Peel area the Central Graben (in the southwest), the Peel Horst and the Venlo Graben (in the northeast), and the Lower Rhine Embayment in Germany (Fig. 1; see also ZAGWIJN & DOPPERT, 1978). This fault system became thus part of a megafault zone extending from the Rhine Graben through the Rhine and Central North Sea Grabens to beyond the Viking Graben in the northern North Sea (ZIEGLER, 1978; ORTLAM, 1981). In the Dutch part of this subsiding fault system the Breda Formation comprised transgressive shelly shoreline deposits, apparently conformable on top of the Veldhoven Formation, whilst further to the west holomarine clays were deposited unconformably on top of the Veldhoven Formation. The thickness of the formation is quite variable. The areas of main accumulation are the Central Graben and the area presently occupied by the southern IJsselmeer Lake (ZAGWIJN & DOPPERT, 1978).

An early Miocene regression in the southeastern Netherlands shifted the shoreline of the Lower Rhine Embayment towards the northwest and initiated the deposition of the early/middle Miocene Heksenberg Formation. This rock-unit consists of continental sands including two transgressive brown coal deposits, viz. the Morken and Frimmersdorf seams. Laterally, these continental strata interfinger with glauconitic shoreline deposits of the Breda Formation.

The basic pattern of this early/middle Miocene intertonguing (Fig. 3) reflects two cycles of shoreline migration in the southeastern Netherlands. Late Miocene deposition of the Breda Formation was essentially regressive and occurred probably in fairly shallow (100 m) water depths and under moderate to subtropical climatic conditions (VAN DEN BOSCH ET AL., 1975). In the southeast this regression is marked particularly by the continental gravels and sands of the Kieseloölite Formation, a paleogeographically restricted deltaic fan deposit.

Early/middle Miocene subsidence in the southeastern fault system gave rise to a Pre-Rhine river in the Lower Rhine Embayment. The drainage system of this ancestor of the present-day Rhine was probably confined to the northern slope of the Slate Mountains. The Pre-Rhine was replaced during the overall regressive late Miocene period by a Primitive Rhine which cut through the Slate Mountains and connected the Upper Rhine Graben into the Lower Rhine Embayment (GLIESE & HAGER, 1978). Deposition of terrestrial strata then progressed northwestwards, but remained restricted to the southeast. After a tectonic phase, which widely eroded the Breda Formation during the Miocene/Pliocene transition, the final Neogene sedimentary cycle began with the deposition of sandy shoreline deposits, including shelly 'Coralline Crag', and light-coloured, more or less sandy clays belonging to the Oosterhout Formation. During all of the Pliocene period marine conditions prevailed throughout the area of study, with the exception of the eastern areas (Fig. 11).

Continental sedimentation of the Kieseloölfte Formation related to the Primitive Rhine remained restricted to the southeast. In other eastern areas the Scheemda Formation was deposited (Fig. 11). It consists of more or less deltaic sands with gravel and clay beds which were laid down by rivers draining the Fennoscandian High and the northern regions of Germany. The areal distribution of the Pliocene sea remained essentially unchanged during the earliest Pleistocene when the very shallow marine Maassluis Formation was unconformably deposited on top of the Oosterhout Formation after a short-lasting tectonic-glacioeustatic phase of sea level change. A succeeding rapid and drastic regression of the sea moved the shoreline westward and finally caused a complete retreat of the marine realm out of the on-shore Netherlands. It established an early Pleistocene (late Tiglian) Rhine river system within a deltaic fan system as essentially still exist today (DOPPERT & ZAGWIJN, 1978).

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