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Revised Upper Cenozoic stratigraphy of the Dutch sector of the North Sea Basin: towards an integrated lithostratigraphic, seismostratigraphic and allostratigraphic approach

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Abstract

A revised Upper Cenozoic stratigraphic framework of the Dutch sector of the North Sea Basin is presented whereby offshore stratigraphic units are integrated or correlated with onshore units. The framework is based on an integrated stratigraphic approach that combines elements of lithostratigraphy, seismostratigraphy and allostratigraphy. Offshore formations are redefined in terms of seismofacies and lithofacies associations, and are differentiated on the basis of common genesis and stratigraphic position. These facies associations represent five major depositional environments, which occur in repetitive successions in the subsurface of the Netherlands: Marine, Coastal, Glacial, Fluvial, and Local Terrestrial. Five conceptual basin-wide bounding discontinuities are identified in the North Sea-Basin that span land and sea. They are represented by both seismostratigraphic and lithostratigraphic unconformities and interpreted as surfaces that formed as a result of North Sea Basin-wide changes in depositional systems. Their formation relates to sea level rise, continental-scale glaciations, and tectonic processes. The bounding discontinuities separate informal allostratigraphic groups of formations that have a grossly uniform geologic setting in common. While the allostratigraphic principles provide a view on the stratigraphy on the largest spatial and temporal scale, the genetic concept facilitates mapping on a local scale.

Keywords: Cenozoic stratigraphy, North Sea Basin, lithostratigraphy, seismostratigraphy, allostratigraphy

Introduction

Traditionally, in the Netherlands (Fig. 1) separate stratigraphic schemes were employed for Upper Cenozoic sediments on land and at sea. Offshore, a scheme was employed that combined lithostratigraphy and seismostratigraphy, whereas onshore a lithostratigraphic scheme with distinct elements of bio- and chronostratigraphy was used until 1998 (Table 1). The development of two stratigraphic schemes resulted from the application of different data acquisition techniques and stratigraphic principles. Increasingly complex applied geological issues require application of a three-dimensional geological model that integrates land and sea data (Rose, 2002; McMillan, 2002; De Mulder et al., 2003; De Mulder & Ritsema, 2003; Ebbing et al., 2003; Weerts et al., 2004). One comprehensive scheme for the Netherlands and the adjacent shelf (Fig. 2) enhances external and internal communication, without the usage of correlation tables. Derived geological products such as maps and cross sections show geological continuity rather than artificial boundaries between equivalent stratigraphic units on land and at sea. This is of fundamental importance when dealing with complex geological problems extending on and offshore. The integrated scheme supports the fact that land and sea geology belong to a single depositional system and will increase the understanding of the Mesozoic-Cenozoic geological framework of the North Sea Basin (Dutch Sector of the North Sea and the onshore Netherlands). In those cases when correlation is problematical, it will highlight geological interpretation problems. Integrating and correlating the offshore seismic-based stratigraphy with the onshore lithostratigraphic-based

Fig. 1. Location of the Netherlands and Dutch Sector of the North Sea. Positions of seismic lines P15 and E8.

scheme required an approach that integrated lithostratigraphic, seismostratigraphic and allostratigraphic principles. This new approach led to a revision of the existing stratigraphic framework of the Upper Cenozoic record. This paper is focused on the consequences for the stratigraphic subdivision offshore, a forthcoming paper will deal with the consequences for the stratigraphic subdivision onshore (Weerts et al., 2004).

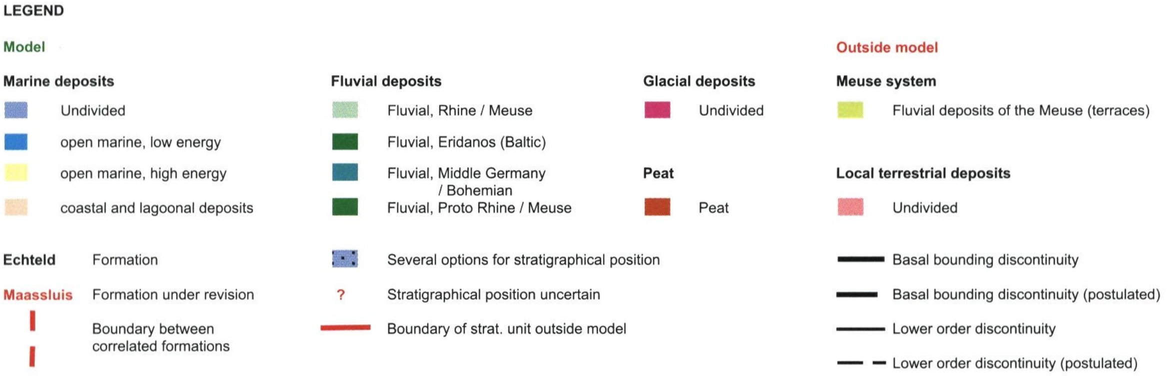
Onshore and offshore stratigraphic approaches

Onshore and offshore stratigraphic units differ fundamentally in that onshore they are based solely on borehole data (Fig. 3a, b), whereas offshore they are based on either a combination of borehole and seismic data or purely on seismic data (Fig. 3c, 4; Ebbing et al., 2003). Hence stratigraphic units of a correlated land-sea stratigraphy must be based on both types of data and must combine both stratigraphic approaches.

Offshore, two stratigraphic approaches are used for two different depth ranges below the sea bed because of differences in data acquisition systems used and available borehole data. Shallow strata subcropping within about 20 meters below the seafloor (mbsf) are surveyed with a 3.5 kHz single channel high resolution seismic system, leading to a vertical resolution between 0.3 and 0.5 m. For this depth range (0 - 20 mbsf) a relatively dense grid of boreholes is available for ground truthing. Deeper strata, subcropping between 20 and 2000 m below the seabed, are surveyed with a combination of 250 Hz single- and multi-channel high resolution seismic systems, leading to a vertical resolution between 3.5 and 7 m. Borehole data for this depth range is very scarce.

In the shallow subsurface, strata are classified on the basis of integrated lithostratigraphic and seismostratigraphic principles, leading to a 'lithoseismostratigraphy' (Table 1; Laban et al., 1984; Laban, 1995; Cameron et al., 1989b). Lithologic information is obtained by borehole data, and is used for ground-truthing the interpretation of seismic reflection data (Fig. 4a). In areas devoid of boreholes, stratigraphic interpretations are based only on seismic facies and stratigraphic position of individual units. In the deeper subsurface, strata are subdivided purely on seismostratigraphic principles sensu Mitchum et al. (1977) (Laban et al., 1984; Cameron et al., 1989a). As a result of low borehole density these seismostratigraphic units are only locally characterised lithologically by borehole data. Seismostratigraphic units or sequences, are bounded by unconformities and their lateral correlative conformities (Mitchum et al., 1977; Whittaker, 1999) (Fig. 3c, d, 4b). These units are differentiated on the basis of objectively identifiable seismic reflection criteria and do not involve the interpretative aspects of 'sequence stratigraphy' (sensu Van Wagoner et al., 1988, 1991; Emery & Meyers, 1998). Traditionally, the seismostratigraphic sequences are assigned formation status as basic mapping units.

Onshore, a dense network of borehole data is available and hence a lithostratigraphic approach has been adopted (Zagwijn & Van Staalduinen, 1975; Doppert et al., 1975). Recently, the 1975 classification has been revised (Ebbing et al., 1997, 1999, 2003; Weerts et al., 2000, 2004) according to international guidelines provided for lithostratigraphy by the International



Legend of Fig. 2.

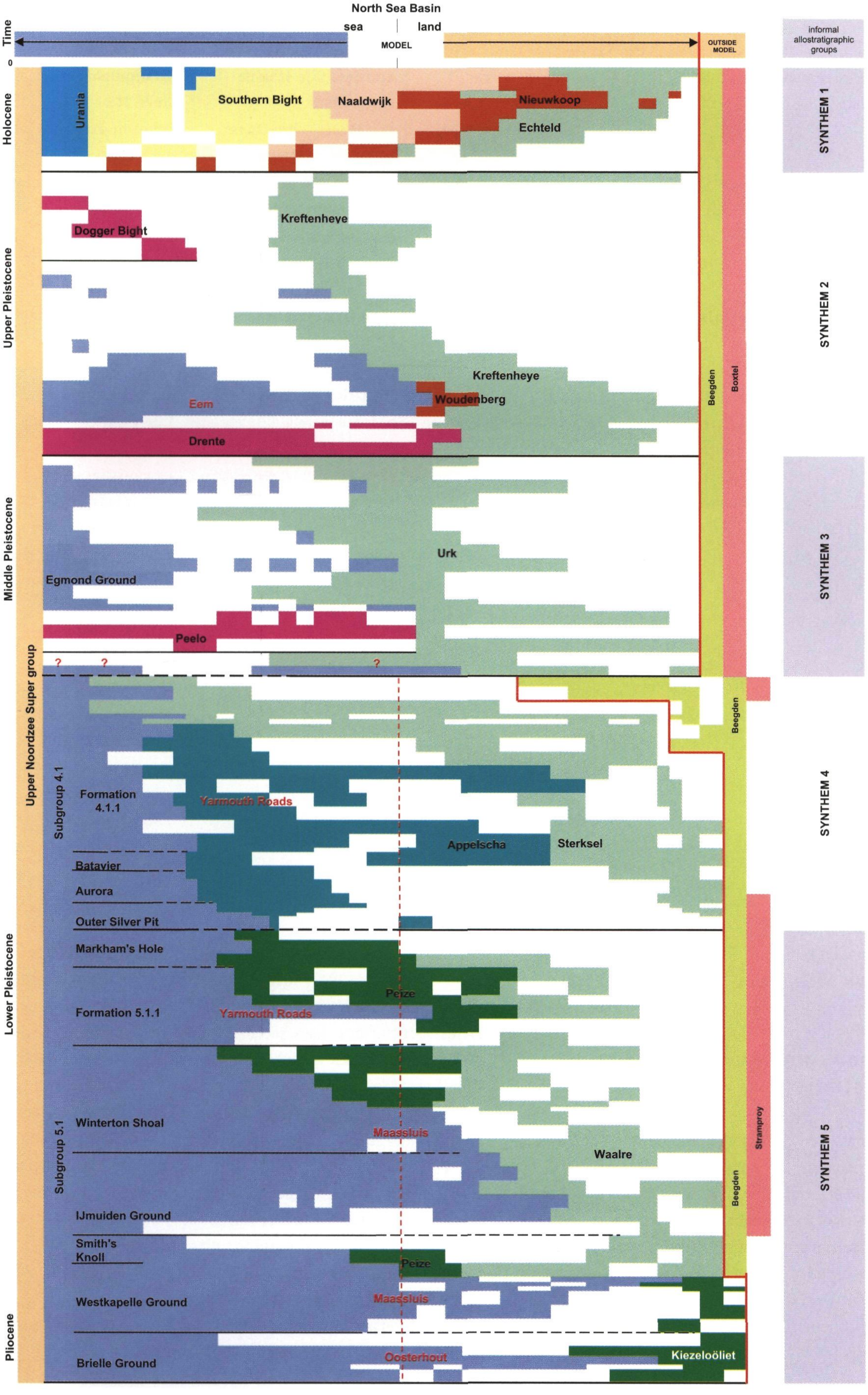


Fig. 2. Integrated stratigraphic model.

Table 1. Leading principles of different stratigraphic approaches employed in the past and currently in the integrated land-sea stratigraphic scheme.

Stratigraphic schemes employed until 2003 Upper Cenozoic strata			**Stratigraphic scheme since 1993 Palaeozoic – pre-Upper Cenozoic strataUpper**	**Stratigraphic scheme since 2003 Cenozoic strata**
Offshore stratigraphy (Oele, 1971; Laban et al., 1984; Laban, 1995)	**Onshore stratigraphy (1974 - 1998)** (Zagwijn & Van Staalduinen, 1974; Doppert et al., 1974)	**Onshore stratigraphy (1998-2003)** (Ebbing et al., 1997, 1999, 2003; Weerts et al., 2000, 2004)	**Onshore and offshore stratigraphy (1993 - recent)** (Van Adrichem Boogaert & Kouwe eds., 1993)*	**Land-sea stratigraphy** (Ebbing et al., 2003; Weerts et al., 2004; this paper)
Lithoseismostratigraphy *shallow strata* Formations and members are differentiated on the basis of lithology using seismic data as an interpolation aid.	**Litho(geneto)stratigraphy** Formations, members and beds are differentiated on the basis of lithology and genesisbased on boreholes. In addition elements of bio- and chonostratigraphy were employed.	**Litho(geneto)stratigraphy** Formations, members and beds are differentiated on the basis of lithology and genesis based on boreholes.	**Lithostratigraphy** Formations, members and beds are mainly differentiated on the basis of lithology and gamma log characteristics. Locally lithostratigraphy is combined with seismostratigrapy and biostratigraphy, and are sequence stratigraphic principles applied.	**Integrated stratigraphy** *shallow strata* Formations are differentiated on the basis of litho- and seismo-facies associations and stratigraphic position, members and beds on the basis of lithological and seismic criteria.
Seismostratigraphy *deep strata* Formations and members are differentiated on the basis of unconformities and seismic facies.				**Land Sea Correlation** *deep strata* Conceptual bounding discontinuities enable correlation of deeper offshore seismostratigraphic units with onshore lithostratigraphic units.

* Available on http://www.nitg.tno.nl/nomenclator/nl/start/introduction/home.html

Subcommission on Stratigraphic Classification (ISSC) of the International Union of Geological Sciences (IUGS) (Salvador ed., 1994).

Integration and correlation of offshore and onshore stratigraphy

Integration of seismo- and lithostratigraphic interpretations is realized for the shallow subcropping strata offshore by redefining the basic stratigraphic unit, formation, in terms of both litho- and seismofacies associations (see below). In the deeper subsurface, seismostratigraphic units are correlated with onshore formations based on common genesis and stratigraphic position of bounding discontinuities. In the stratigraphic model, this type of correlation is indicated by a vertical indented red line (Fig. 2).

Formations form the basic mapping units: they constitute the primary building blocks of the stratigraphic framework. Rather than being defined in purely lithostratigraphic terms as in Salvador (1994), formations are redefined more extensively to include both genetic and seismic criteria in terms of facies associations (see section 2.2.2. in Reading & Levell, 1996). These facies associations represent five major depositional environments, which occur in repetitive successions in the subsurface of the Netherlands: Marine, Coastal, Glacial, Fluvial, and Local Terrestrial (Table 2). In the integrated scheme, offshore and onshore deposits of a particular depositional environment at the same stratigraphic level belong to the same formation. The integration of shallow offshore stratigraphic units with stratigraphic units onshore is facilitated by the high vertical resolution of shallow seismic data and relatively high borehole control.

Deeper seismic formations (seismostratigraphic sequences) are however not yet integrated with formations onshore. This is due to three factors: 1) seismic formations are delimited by extensive seismic unconformities that often are poorly, or not, recorded in the borehole-based record onshore (Fig. 4; Fig. 3 in Ebbing et al., 2003); 2) single seismic formations, being unconformity bounded may contain parts of several onshore formations and vise versa (Fig. 3a, 3d); 3) onshore, with increasing depth, there is ample control on the geometry of deeper units as the density of boreholes decreases dramatically with depth. However, correlation of seismic formations with onshore formations is possible based on the common stratigraphic position of basal bounding discontinuities (Fig. 3b, 3d). Such correlation is enabled by the redefinition of onshore formations in terms of facies associations, whereby basal bounding discontinuities of onshore formations may coincide with offshore seismic sequence boundaries. The transition of one depositional system into another (e.g. Eridanos system replaced by Middle German and Bohemian river system) is both reflected in major seismic unconformities of sequence boundaries offshore and by lithological disconformities at which major regional changes in lithofacies associations and/or provenance take place. When stratigraphic problems exist with the correlation of stratigraphic units, they are placed in a temporary informal subgroup class (Van Leeuwen et al., 2004). When these problems are resolved the sediments of the subgroup will be placed in one or more new formations or become part of a broader formation.

Constructing the integrated stratigraphic model

Based on integration of lithological and seismic data and correlation of offshore and onshore formations a stratigraphic model for the North Sea Basin is compiled. The stratigraphic model is denoted a 'model', in the conceptual sense, as it is based on empirical data combined with geological insight. The model is compiled from geological profiles, time-space diagrams and based on current insights into the extent and genesis of strata (Fig. 5; Van Leeuwen et al., 2004). Three geological profiles (Fig. 6a and figs. 193, 205 in Westerhoff et al., 2003b) constitute the empirical basis of the stratigraphic reference model. These geological profiles are strategically positioned across the Netherlands and the adjacent shelf so that they

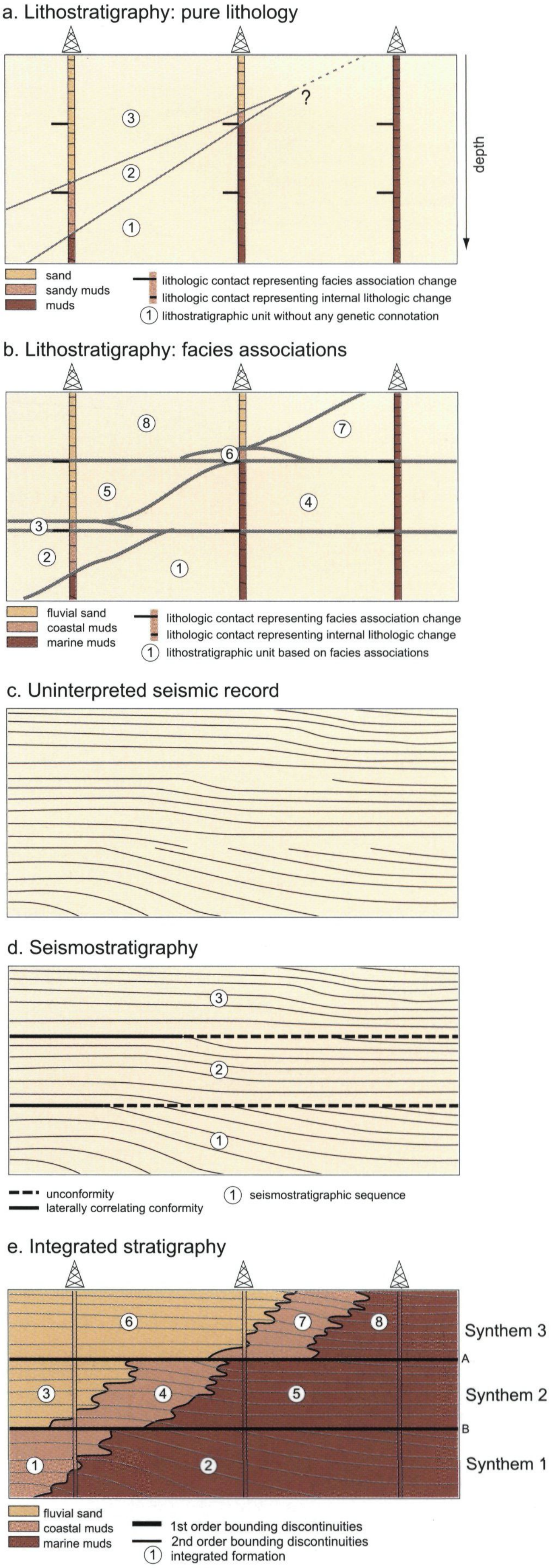


Fig. 3. Stratigraphic approaches (schematized). a. Theoretically, pure lithostratigraphic approaches, not using facies association concepts and not using discontinuity concepts, may lead to oversimplified lithostratigraphic models. Based on a few boreholes (offshore) distinction between minor (internal lithologic contacts) and major stratigraphic breaks (bounding discontinuities between facies associations) can not always be made; b. Lithostratigraphy, involving facies associations and major discontinuities, leads to a more realistic stratigraphic model; c. Un-interpreted seismic record; d. Seismostratigraphy, sequences identified on the basis of major unconformities may be identical to bounding discontinuities of facies associations identified at b; e. Integrated seismic and lithostratigraphy including allostratigraphic elements may lead to a more realistic stratigraphic model.

Table 2. Integrated Upper Cenozoic stratigraphic units subcropping in the North Sea Basin. Note that stratigraphic units listed in the column 'Old stratigraphic names' are not always identical to the new units.

Integrated land-sea stratigraphical units present offshore		*Old names of stratigraphical units used offshore*
Southern Bight Formation	Open marine deposits	*not differentiated*
Bligh Bank Member		*Bligh Bank Formation*
Terschellinger Bank Member		*Terschellinger Bank Member*
Buitenbanken Member		*Buitenbanken Formation*
Indefatigable Grounds Member		*Indefatigable Grounds Formation*
Urania Formation	Low energy open marine deposits	*not differentiated*
Western Mud Hole Member		*Western Mud Hole Member*
Well Hole Member		*Well Hole Formation*
Naaldwijk Formation	Marine-coastal deposits	*not differientiated*
Wormer Member		*Banjaard Formation*
Bergen Bed		*not differentiated*
Velsen Bed		*Elbow Formation*
Nieuwkoop Formation	Sedentary deposits	*not differentiated*
Basal Peat Bed		*Elbow Formation*
Echteld Formation	Fluvial deposits (Rhine Meuse)	*not differientiated*
Boxtel Formation	Local terrestrial deposits	*Twente Formation*
Dogger Bight Formation	Glacial deposits	*not differentiated*
Botney Cut Member		*Botney Cut Formation*
Dogger Bank Member		*Dogger Bank Formation*
Volans Member		*Volans Formation*
Bolder Bank Member		*Bolder Bank Formation*
Well Ground Member		*Well Ground Formation*
Oosterdok Bed		*not differentiated*
Eem Formation	Marine deposits	*Eem Formation*
Brown Bank Member		*Brown Bank Formation*
Kreftenheye Formation	Fluvial deposits (Rhine Meuse)	*Kreftenheye Formation*
Drente Formation	Glacial deposits	*not differentiated*
Schaarsbergen Member		*Molengat Formation*
Gieten Member		*Borkum Riff Formation*
Uitdam Member		*Cleaver Bank Formation*
Boxtel Formation	Local terrestrial deposits	*not differentiated*
Drachten Member		*Tea Kettle Hole Formation*
Egmond Ground Formation	Open marine deposts	*Egmond Ground Formation*
Peelo Formation	Glacial deposits	*Swarte Bank Member*
Juister Rif Member		*Juister Rif Member*
Niewolda Member		*not differentiated in the past*
Boxtel Formation	Local terrestrial deposits	*not differentiated*
Middelrug Member		*Middelrug Formation*
Urk Formation*	Fluvial deposits (Rhine Meuse)	*not differentiated*
Formation 4.1.1.	Predominantly low energy open-marine deltaic, delta top and fluvial deposits (Rhine, Middle German and Bohemian)	*Yarmouth Roads Formation*
Alkaid Member		*Alkaid Member*
Batavier Formation	Low energy open-marine deposits	*Batavier Formation*
Aurora Formation		*Aurora Formation*
Outer Silver Pit Formation	Marine deltaic, delta top and fluvial deposits (Middle German - Bohemian systems)	*Outer Silver Pit Formation*
Markams Hole Formation	Predominantly low energy open-marine deltaic, delta top and fluvial deposits (Eridanos, German, Rhine and Meuse)	*Markams Hole Formation*
Formation 5.1.1.		*Yarmouth Roads Formation*
Winterton Shoal Formation		*Winterton Shoal Formation*
IJmuiden Ground Formation		*IJmuiden Ground Formation*
Smith Knoll Formation	Low energy open-marine prodelta deposits (British systems)	*Smith Knoll Formation*
Westkapelle Ground Formation	Marine prodelta and delta-front, delta-top and fluvial deposits (Eridanos, German, Rhine and Meuse)	*Westkapelle Ground formation*
Brielle Ground Formation		*Brielle Ground Formation*

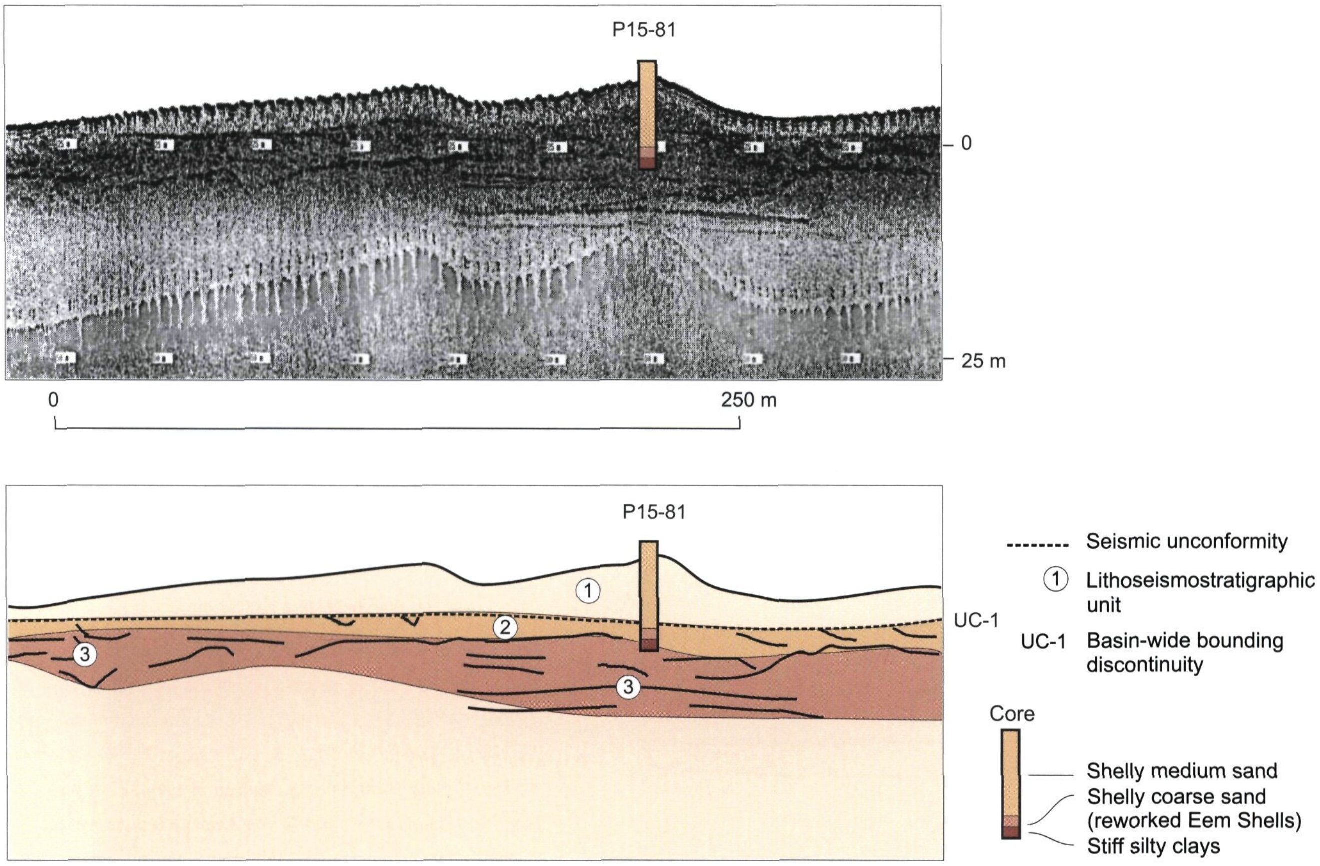


Fig. 4a. Lithoseismostratigraphy. Stratigraphic units are defined by seismic facies, seismic unconformities and borehole data. Line P15, approx. 52°10', 3°46' (see Fig. 1). 1. Southern Bight Formation- Bligh Bank Member; 2. SBF-Buitenbanken Member; 3. Eem Formation-Brown Bank Member. North Sea Basin-wide bounding discontinuities represented by seismic unconformities: UC-1. Unconformity at the base of the Southern Bight Formation. UC-1 formed in response to Holocene climatic amelioration and sea level rise.

cover the regional variability of the depositional systems. The profiles provide insight in the local stratigraphic position of formations. Adjoining time-space diagrams, show the presumed or derived age of the deposits across the profile (Fig. 6b). The stratigraphic model is ideally generated by the projection of several superimposed 2-dimensional time-space diagrams.

Five North Sea Basin-wide bounding discontinuities are identified that form the basis of informal allostratigraphic synthems (Fig. 2; see discussion). In the Upper Cenozoic record the significance and stratigraphic position of these discontinuities is derived on an *a posteriori* basis from the spatial and stratigraphic distribution of mapped formations (see discussion). Transparency of stratigraphic problems within the reference model is maintained by the usage of signs and classes (Fig. 2).

Key elements

Although the integration process required revision of some stratigraphic principles, its classification of mappable stratigraphic units (i.e. formation rank and lower) remains largely based on the guidelines for lithostratigraphy of the ISSC/IUGS (Salvador ed., 1994). Key elements of this stratigraphic approach include that stratigraphic units (Fig. 5):

1. are based on macroscopic lithologic criteria;
2. are based on geometry and architectural elements;
3. have a specific stratigraphic position;
4. have relevance for applied mapping;
5. are well-defined mappable units;
6. occur in a hierarchical scheme;
7. have stratotype descriptions.

Being an applied and user-focussed scheme, stratigraphic units of formation and lower rank are defined in terms of objectively defined macroscopically, readily recognisable lithologic criteria (Hedberg ed., 1976; NACSN, 1983; Salvador ed., 1994; Van Leeuwen et al., 2004). Sediments are lithologically described according to a referenced core description manual developed by TNO-NITG (Bosch, 2000). This institutional guideline is based on internationally recognised and nationally defined sediment classification schemes, such as Munsell scale for sediment colour (Oyama & Takehara, 1967), grain size scale of Folk (1954), NEN 5104 (1989) and roundness scale of Powers (1953). As stratigraphic units of the integrated scheme may be mapped by seismic techniques, macroscopic

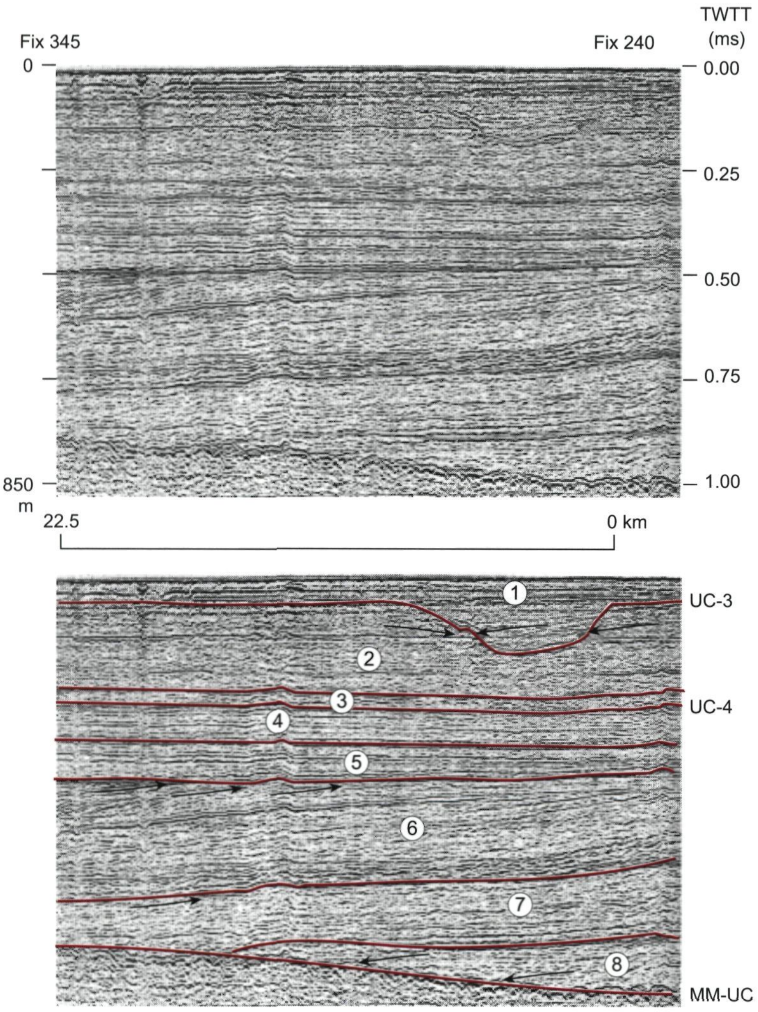


Fig. 4b. Seismostratigraphy. Formations are distinguished mainly on the base of seismic unconformities (UC). Line E8, approx. 54°32', 3°35' (see Fig. 1). 1. Peelo Formation and younger; 2. Formation 4.1.1; 3. Outer Silver Pit Formation; 4. Markhams Hole Formation; 5. Winterton Shoal Formation; 6. IJmuiden Ground Formation; 7. Westkapelle Ground Formation; 8. Brielle Ground Formation. UC-3: Unconformity at the base of the Peelo Formation. UC-4: Conformity at the base of the Outer Silver Pit Formation. MM-UC: Mid Miocene Unconformity coincides in this profile with the sedimentary discontinuity at the base of the Brielle Grounds Formation.

criteria include seismic criteria such as seismic internal reflection configuration, geometry of seismic structures and reflection amplitude (Reading & Levell, 1996; Whittaker, 1998). Seismic data may provide further important information on architectural elements (cf. Miall, 1985), which are crucial for the interpretation of depositional environments.

Integrated land-sea stratigraphy is based on hierarchical stratigraphic units, with the formation as the basic mapping unit, and members and beds as units of lower order, generally with smaller geographic distribution and more homogeneous lithologies (Hedberg ed., 1976; NACSN, 1983; Salvador ed., 1994). Well-defined stratotype descriptions are provided for each formation and are described according to the guidelines of the IUGS (Salvador ed., 1994).

Revision of the stratigraphic subdivision of the Dutch sector of the North Sea

Below an overview is given of the consequences of the implementation of the integrated stratigraphy for the Upper Cenozoic record in the Dutch Sector of the North Sea (Table 2). The new approach led to changes in the hierarchy of older stratigraphic units. When on land and sea stratigraphic units co-existed, which denoted equivalent stratigraphic units but with a different name or stratigraphic hierarchy, the unit with the best defined stratotype has been maintained to denote the integrated stratigraphic unit.

Marine facies associations, shallow subsurface

The marine facies associations in the Netherlands comprise sediments that were deposited in shallow clastic (shelf) seas at water depths generally less than 200 m (Johnson & Baldwin, 1996). In the setting of the Southern North Sea this environment includes seismically defined delta-top, deltafront and prodelta facies (Westerhoff et al., 2003b).

All shelly and sandy marine units which have a high-energy open marine genesis in common (i.e. beds mobilised by wave action or tidal currents) are grouped in the newly established Southern Bight Formation (Van Leeuwen et al., 2004). They include former Holocene formations: the Bligh Bank, Buiten Banken, Indefatigable Ground and the Terschellinger Bank (Cameron et al., 1984a; Harrison et al., 1987) which are all down-graded to members or beds. Muddy sediments of the low-energy open marine environments are grouped in the Urania Formation (Van Leeuwen et al., 2004). It consists of the former

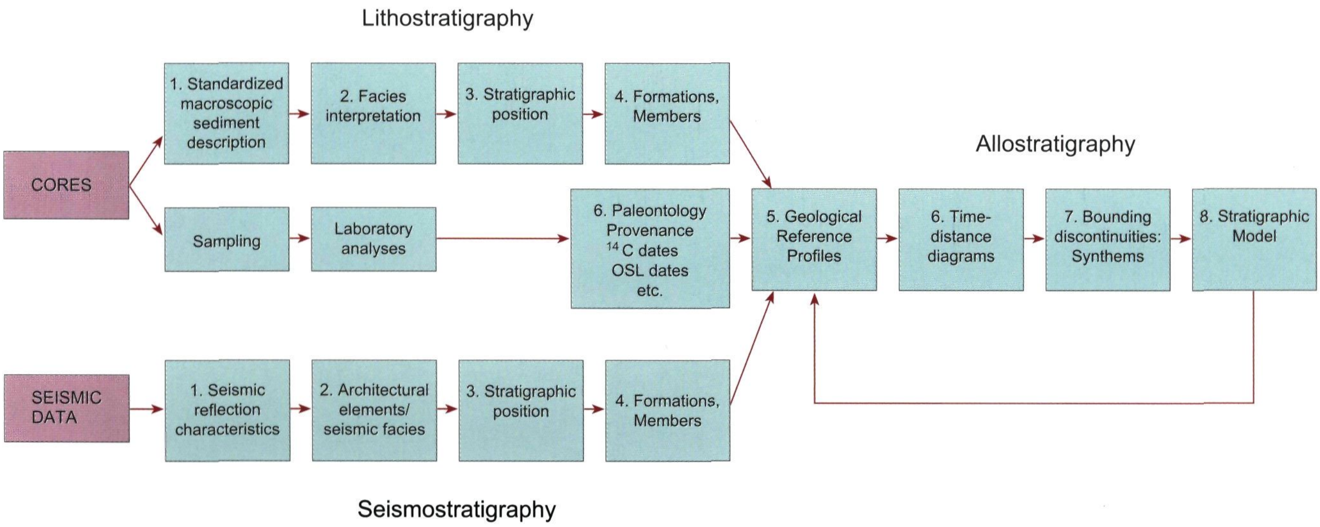


Fig. 5. Flow diagram showing the process of stratigraphic classification of the integrated approach. (1) Observations obtained from boreholes and seismic data, form the basis for stratigraphic classification, seismic and lithological units are grouped in (2) facies associations. Their stratigraphic position and extension warrant the (3) stratigraphic hierarchical status of the unit (4) and their position within the geological reference profile (5). Palaeontological and dating information may provide information on the time-space position of units within the 'time-space diagrams' (6). Based on the derived profiles major bounding discontinuities are identified (7). From the profiles the 'stratigraphic reference model' is constructed (8). This model is annually updated, resulting in an iterative classification process.

Well Hole Member and Western Mud Hole Members (Harrison et al., 1987) which are maintained at member status. The 'Nieuw Zeeland Gronden Formation' (Cameron et al., 1984a) is abolished as it combined sediments that formed in both low and high energy marine environments.

Within the Middle and Upper Pleistocene sequence two formations based on marine facies associations are recognised: the Eem Formation and the Egmond Ground Formation. The Eem Formation, which comprises shelly sands and marine clay, was already integrated as a land-sea formation in the past (Laban et al., 1992). The Brown Bank Formation, comprising partly consolidated silty clays and fine sands representing regressive marine and terrestrial sediments (Oele, 1971; Cameron et al., 1984b, 1989b), is down-graded to member status as part of the Eem Formation. The Egmond Ground Formation, comprising shelly fine sands, is currently only recognised offshore as stratigraphically third last marine incursion (Oele, 1971; Cameron et al., 1984b, 1989b).

Coastal facies associations, shallow subsurface

Coastal facies include a wide range of sub-environments: foreshore sediments, tidal deltas, tidal channel fills, beaches and beach-dunes (Reading & Collinson, 1996). These sub-environments are grouped together as they represent elements of a dynamic sediment transport system, whereby sand in the foreshore regions may be transported in tidal delta and foreshore areas, and onshore on beaches ultimately forming dunes. The open marine tide-dominated parts of estuarine environments such as the mouth of the Rhine and Scheldt estuaries are included in the coastal facies associations as long as their marine genesis can be inferred from sediments and macrofossils. Where sediments and fossils of the landward parts of the estuaries are dominated by the fluvial signal, they are included in fluvial facies associations (Van Leeuwen et al., 2004).

The Naaldwijk Formation comprises all Holocene sandy and clayey coastal plain deposits (Westerhoff et al., 2003b; Weerts et al., 2004). The Banjaard Formation (Ebbing, 1992) is abolished as the deposits are integrated in the Naaldwijk Formation which has a well-defined equivalent stratotype section on land (Weerts, 2003; Weerts et al., 2004). The Elbow Formation, comprising lagoonal clays, was established as a lithostratigraphic unit at sea by Oele (1969), even though its lithostratigraphic equivalent was identified on land as the Velsen Bed of the former Calais Member in the Westland Formation. Oele (1969) pointed out that the Calais Member was defined in chronostratigraphic terms to include sediment younger than 8000 yrs and as the clays offshore predated this age they could not be correlated. With the abolishment of the Calais Member and the redefinition of the Velsen Bed as part of the Naaldwijk Formation (Ebbing et al., 1997; Weerts, 2003; Weerts et al., 2004) the possibility was created to integrate the Elbow Formation in the Velsen Bed as a diachronous lithostratigraphic unit. The Velsen Bed, representing lagoonal clays, forms blankets in patches in major parts of the North Sea shelf. The Bergen Bed represents marine interbedded clays and fine sands deposited below the wave base in a coastal setting (Westerhoff et al., 1987; Weerts, 2003; Weerts et al., 2004). Peats which were part of the Elbow Formation in the past are now distinguished separately as Nieuwkoop Formation (Weerts & Busschers, 2003).

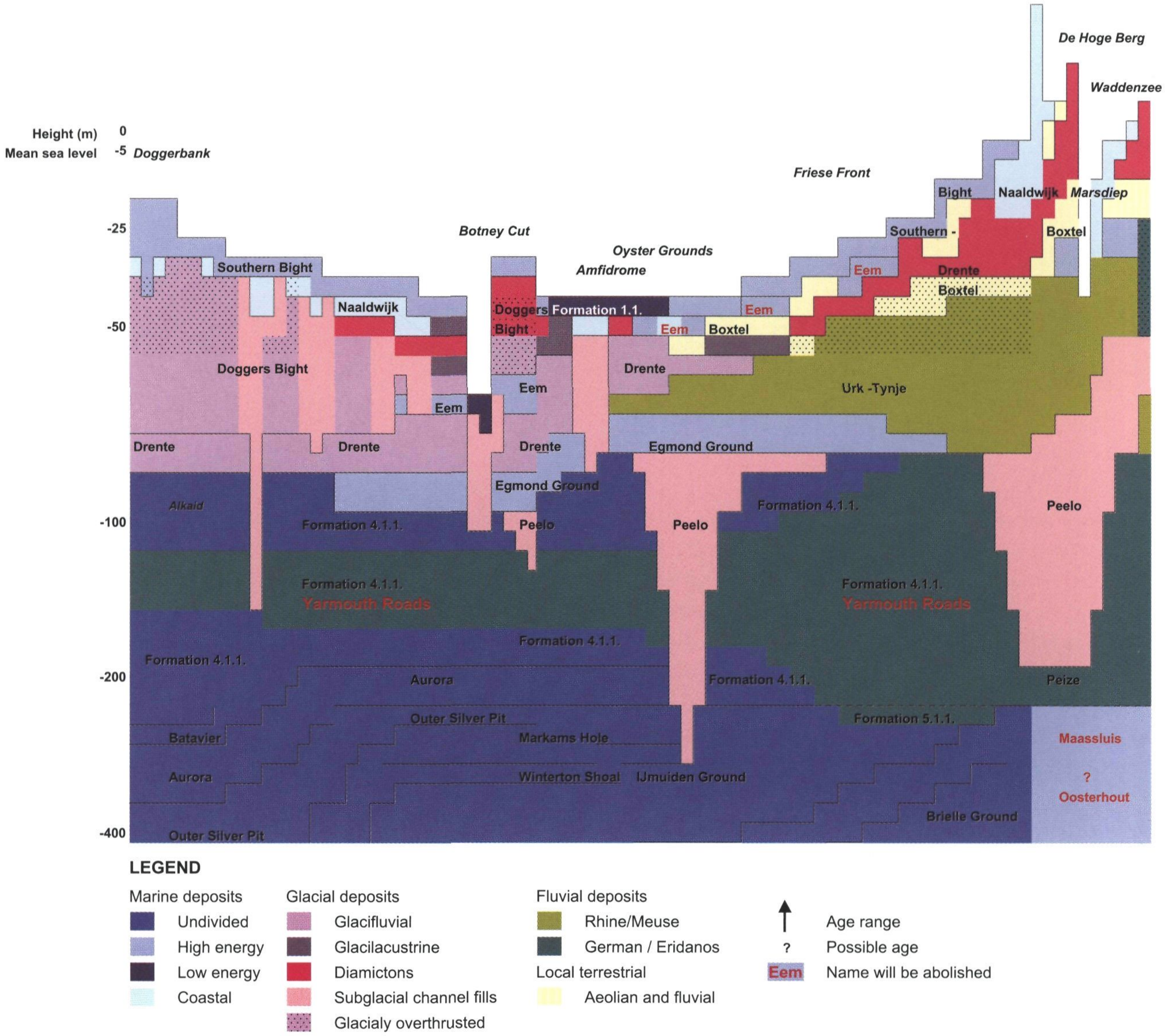


Fig. 6a. Example of geological profile providing a cross sectional view on the local stratigraphic position of formations along a line across Dutch sector of the North Sea. These profiles constitute the empirical basis of the stratigraphic reference model.

Fluvial facies associations, shallow subsurface

Fluvial facies associations include a wide range of sub-environments including floodplains, channel fills, oxbow channel fills, and crevasse splays (Collinson, 1996). The fluvial facies associations also include the landward part of estuarine environments (fresh water tidal deposits). Based on clast provenance and architecture, fluvial formations are distinguished on the basis of the river system (Eridanos, Western German and Bohemian systems, Rhine-Meuse) that formed the deposits (Gibbard, 1988; Overeem, 2002; Westerhoff et al., 2003b; Van Leeuwen et al., 2004).

Three integrated formations with fluvial facies associations of Rhine-Meuse origin are distinguished in the Holocene and Middle/Upper Pleistocene deposits offshore. They are: the Echteld Formation, the Kreftenheye Formation, and the Urk Formation. The Echteld Formation comprises the mixed clay and sand deposits of the Rhine and Meuse that were deposited during Holocene sea level rise (Weerts & Busschers, 2003; Weerts et al., 2004). It represents the stratigraphically uppermost Rhine Meuse sediments, lying on top of the Kreftenheye Formation. The bulk of the Kreftenheye Formation includes coarse gravelly sands of the Rhine-Meuse system, which overlie the Urk Formation or the Eem Formation. The Kreftenheye Formation was already part of an integrated formation (Laban et al., 1992), but has its stratotype locality on land (Busschers & Weerts, 2003). It was deposited from Saalian time until the end of the Weichselian. The Urk Formation includes Rhine-Meuse sediments at the next lower stratigraphic level and has been only recently identified in cores offshore. It comprises Middle Pleistocene Rhine-Meuse deposits and also has its stratotype onshore (Bosch et al., 2003).

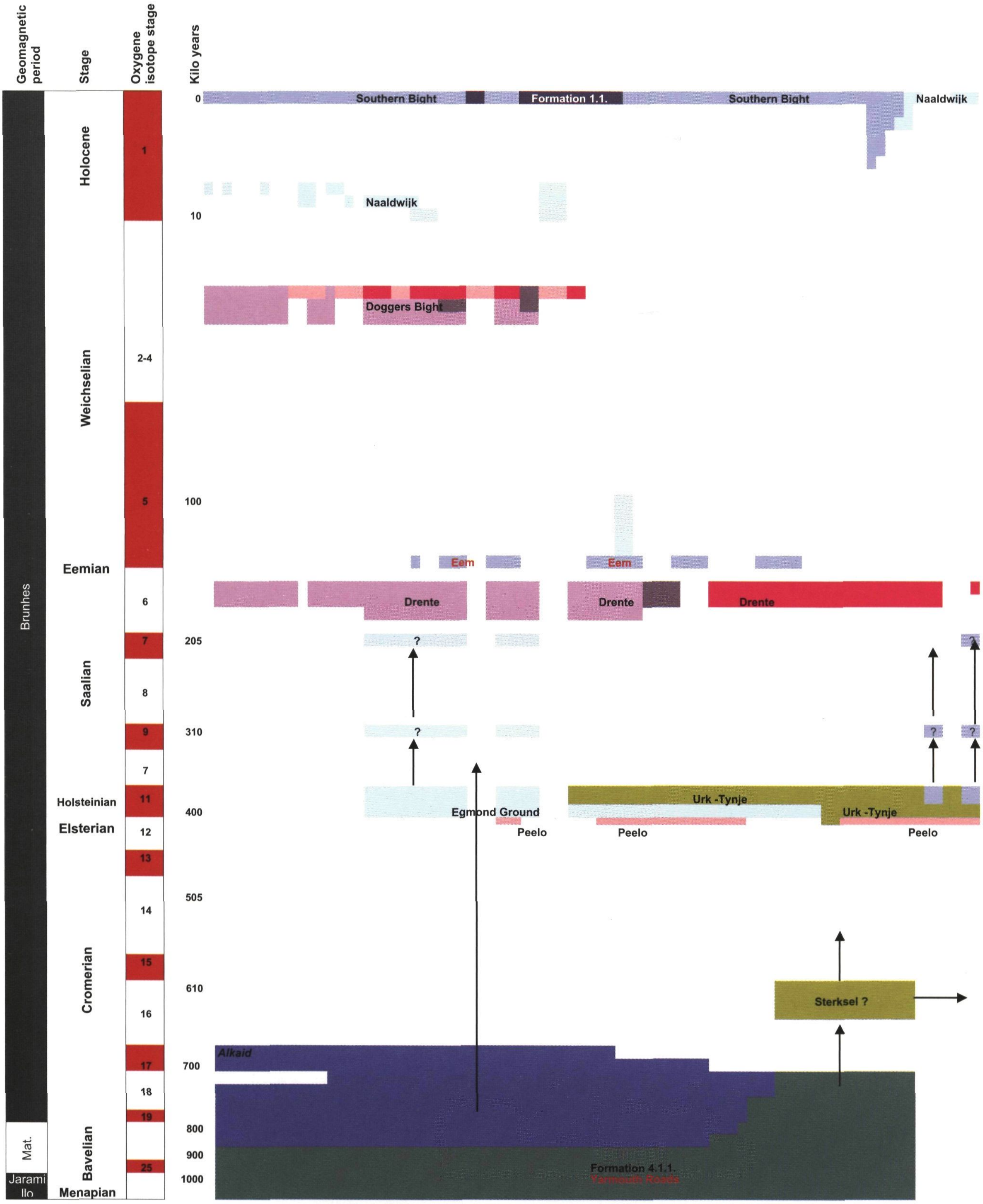


Fig. 6b. The geological profiles are accompanied by time-space diagrams, which show the presumed or derived age of the deposits across the profiles with their uncertainties. Such profiles and diagrams empirically constrain the stratigraphic reference model.

Glacial facies associations, shallow subsurface

Glacial facies associations include subglacial, supraglacial, proglacial, glacifluvial, glacilacustrine and glacimarine sediments (Miller, 1996). Within the Pleistocene succession, three glacial formations are differentiated: the Dogger Bight Formation, the Drente Formation and the Peelo Formation. The Dogger Bight Formation is a newly established formation that includes the stratigraphically youngest (Weichselian) glacial deposits, which overlie marine sands of the Eem Formation (Van Leeuwen et al., 2004). It comprises former formations which are now downgraded to members: glacilacustrine clays of the Dogger Bank Member, glacifluvial sands of the Well Ground Member, glacial valley fills of the Botney Cut Member, tills of the Bolders Bank Member and the youngest glacial valley fills of the Volans Member (Laban, 1995).

The Drente Formation comprises the second oldest glacial deposits that overlie fluvial sands of the Urk Formation and underlie marine sands of the Eem Formation. The sediments were deposited during the Saalian glaciation. The stratotype section of the Drente Formation is located on land (Bakker et al., 2003). The name Borkum Rif Formation (Laban & Mesdag, 1996; Laban, 1995), representing tills of Saalian age recognized in boreholes and seismic data off-shore, is abolished and the former formation is integrated as Gieten Member in the Drente Formation. Glacilacustrine deposits of the former Cleaver Bank Formation (Cameron et al., 1986) are integrated in the Uitdam Member and glacifluvial deposits of the former Molengat Formation (Laban & Mesdag, 1996; Laban, 1995) are integrated in the Schaarsbergen Member (Bakker et al., 2003).

The Peelo Formation comprises the third oldest glacial deposits that overlie and incise fluvial deposits of the Veenhuizen Member of the Urk Formation and Appelscha Formations and the former Yarmouth Roads (4.1.1) Formation. The formation underlies marine deposits of the Egmond Ground Formation and is partly overlain by the Tynje Member of the Urk Formation. The glacial deposits are ascribed to the Elsterian glaciation. It comprises the integrated and abolished Swarte Bank Formation (Cameron et al., 1986), which included the fill of glacial valley geometries recognized in seismic data and offshore boreholes. This former formation is now integrated in the Nieuwolda Member (Ebbing, 2003). The Peelo Formation also comprises the Juister Rif Member, an Elsterian till identified offshore (Laban & Mesdag, 1996; Laban, 1995).

Local terrestrial deposits, shallow subsurface

Local terrestrial deposits include all terrestrial deposits except from coastal, glacial and fluvial depositional environments. They generally represent deposits that have no or poor North-Sea basin-wide stratigraphic significance throughout the Upper Cenozoic Era, due to poor stratigraphic resolution, regional confinedness (small scale) and discontinuous occurrence. They comprise aeolian deposits, deposits of small fluvial systems (brooks and minor tributaries), local terrace deposits and peats (Weerts et al., 2000). These sediments are grouped as a separate class within the integrated land-sea stratigraphic scheme and occupy a position outside the stratigraphic reference model represented by vertical columns that are bounded by red lines (Fig. 3c). Because these smaller scale systems typically were reactivated during successive stages of the Cenozoic, their deposits may form locally thick sedimentary stacks without significant internal facies change, making their precise stratigraphic position unsure.

Two members and one formation comprising local terrestrial deposits are recognised in Upper Pleistocene strata. Within the integrated scheme the Boxtel Formation represents a new formation that includes all aeolian sediments that stratigraphically overlie Formation 5.1.1, the Sterksel and Appelscha Formations (Schokker et al., 2003). The Twente Formation (Cameron, 1984a, Laban et al., 1992; Laban, 1995) comprising periglacial deposits of Weichselian age, is formally abolished, and replaced by the Boxtel Formation as its definition included chronostratigraphic elements (Schokker, 2003; Schokker et al., 2003). Several facies in the Twente Formation are replaced by members of the Boxtel Formation (e.g. cover sands: Wierden Member, brook deposits: Tilligte Member). Offshore the unit can be stratigraphically distinguished as underlying the Southern Bight Formation and overlying Dogger Bight and Eem Formations.

The Drachten Member is part of the Boxtel Formation and comprises all local terrestrial deposits that underlie glacial deposits of the Drente Formation. It includes the former fine sandy Tea Kettle Hole Formation (Laban, 1995). The Middelrug Member (Laban & Mesdag, 1996) comprises aeolian sands and small scale local fluvial deposits underlying the Egmond Ground Formation. This formation is not recognised on land.

Peat strata are classified separately within the local terrestrial sediments class. The basal peat layer that lies at the base of Holocene strata has a basin-wide stratigraphic significance. Offshore it was part of the former Elbow Formation (Oele, 1969) that comprised lagoonal clays and basal peat and is now assigned to the Nieuwkoop Formation as the Basal Peat Bed (Weerts & Busschers, 2003). Older peat layers and brown coal layers occur locally on a small scale (e.g. Eemian peats of the Woudenberg Formation see Weerts et al., 2003) but generally do not form mappable units.

Marine Formations in the deeper subsurface

Below, seismostratigraphic marine units are correlated to fluvial and marine stratigraphic units identified in onshore cores. The Yarmouth Roads Formation (Cameron et al., 1984b, 1989a) comprising both marine and fluvial facies, is split into two formations, which are provisionally named Formation 4.1.1 and 5.1.1 (Fig. 2). The formation can no longer be maintained, because it contains a major seismic unconformity, rendering its formation status invalid (Van Leeuwen et al., 2004). Formation 4.1.1 includes both marine and fluvial facies. Its upper part is to a large extent obscured by multiple effects. The formation is represented onshore by Rhine-Meuse deposits of the Sterksel Formation and Western German-Bohemian deposits of the Appelscha Formation (Bosch, 2003; Westerhoff, 2003; Westerhoff et al., 2003b). In the outermost northern part of the Dutch Sector of the North Sea the Alkaid Member is present within Formation 4.1.1, representing fully marine deposits (Jeffery et al., 1991). The Batavier, Aurora and Outer Silver Pit Formations are all open marine deposits, in seismic data onlapping deeper-marine pro-delta units (Cameron et al., 1986; Jeffery et al., 1989).

The Markham's Hole Formation (Cameron et al., 1986) represents the youngest stage of distal deeper marine pro-deltaic deposition generated by the Eridanos fluvial system (Overeem, 2002; Westerhoff et al., 2003a). The top is marked by a major unconformity truncating open marine seismic deltaic facies. This unconformity is represented with the stratigraphic reference model by a North Sea bounding discontinuity separating synthem 4 and 5. Formation 5.1.1 comprises open marine seismic deltaic facies and fluvial deposits of the Eridanos and Rhine-Meuse system, which are onshore part of respectively the Peize and Waalre Formations (Overeem, 2002; Westerhoff, 2003; Westerhoff et al., 2003b; Westerhoff & Weerts, 2003). The Winterton Shoal Formation is dominated by open marine seismic facies (Cameron et al., 1984b, 1989a), but in its top Baltic (Eridanos) and Middle German fluvial units correlate with the Peize and Waalre Formations onshore. The IJmuiden Ground Formation comprises mainly open marine deposits but in the southernmost part of its extension also includes proto-Rhine and Meuse deposits (Cameron et al., 1984b, 1989a; Laban et al., 1992), correlative to the onshore Waalre Formation (Westerhoff et al., 2003b).

The Smith's Knoll Formation represents a clastic wedge, which prograded from the British mainland (Cameron et al., 1984b, 1989a). The Westkapelle Ground Formation, comprises marine deltaic seismic facies and in its southernmost extent fluvial Rhine and Meuse deposits correlating with Peize Formation onshore (Cameron et al., 1984b, 1989a, Westerhoff et al., 2003b). The Brielle Ground Formation lastly comprises well-developed open marine seismic deltaic facies representing westward marine progradation of the combined Baltic (Eridanos) and Rhine systems (Overeem, 2002; Cameron et al., 1984b, 1989a) that correlate with the Kiezelooliet Formation.

Discussion

Allostratigraphic elements

In both lithostratigraphy and allostratigraphy, subdivision is based on major changes in sediment properties across mappable bounding surfaces. Where lithostratigraphy focuses on the sediments themselves, allostratigraphy involves the initiations and terminations of sedimentation, however, without the requirement of knowing the actual processes that cause them (article 58 f. in NASCN, 1983; Salvador ed., 1994: p. 45). Therefore, the two approaches are both purely descriptive and can be ideally used side by side, depending on available data sets (borehole information, seismic data, or a combination of the two) (Fig. 3e) (Van Leeuwen et al., 2004). As explained earlier, a lithofacies definition of formations enables correlation of basal bounding discontinuities of seismic sequences with those of onshore formations, as a means to integrate offshore seismostratigraphic units with onshore lithostratigraphic units.

From the stratigraphic model North Sea Basin-wide bounding discontinuities spanning land and sea can be identified. These can be interpreted allostratigraphically as surfaces that formed as a result of North Sea Basin-wide events that led to major changes in lithofacies and seismofacies affecting both onshore and offshore strata (Van Leeuwen et al., 2004). These surfaces formed by erosion, non-deposition or changes of depositional processes. They generally represent polygenetic and diachronous bounding surfaces between stratigraphic units and are represented by both seismic unconformities (*sensu* Mitchum et al., 1977) and lithological unconformities (*sensu* Salvador ed., 1994 chapter 6). Their origin relates to geologic processes that led to basin-wide changes in deposition and include climatic change, sea level rise, basin-wide glaciations, and tectonic processes. They may mark the transition from one depositional system into another.

Bounding discontinuities can be used for allostratigraphic classification whereby stratigraphic hierarchy is based on the scale of their extent. In contrast to its usage in a sequence stratigraphic context (e.g., Von Wagoner et al., 1988, 1990), the allostratigraphic concept does however not require knowledge about the genesis of the discontinuities (article 58 f. in NASCN, 1983; Salvador ed., 1994: p. 45) and therefore can be used to objectively classify sediments. Groups of formations separated by basal bounding discontinuities are comparable to the 'synthem' in Salvador ed. (1994) or 'alloformation' in NACSN (1983). These groups combine several formations that were deposited under grossly uniform depositional environmental conditions by single depositional systems. In the integrated stratigraphic scheme these groups can only be identified and interpreted on an *a posteriori* basis: they can be recognized after having established an integrated stratigraphic model (Fig. 5) (Van Leeuwen et al., 2004). Whereas the integrated stratigraphic model presented here is based on formations as primary building blocks (Fig. 2), synthems may be regarded as informal secondary building blocks (Fig. 3e).

The informal status of the synthems and allostratigraphic discontinuities warrants that they have no stratigraphic significance. Shifts in their position or changes in composition (formations) as a result of new insights or data should have no effects on formation level or group level. When considered stable they may give rise to form new formal stratigraphic units that comprise fully integrated seismic and lithology-based stratigraphic units.

Defined as such allostratigraphic bounding discontinuities and synthems may provide insight in the stratigraphy of the North Sea Basin on the largest spatial and temporal scale including the adjoining hinterlands. Conceptual synthems in the Upper Cenozoic stratigraphic framework provides continuity in approach between the Upper Cenozoic and older partly sequence stratigraphic-based schemes (cf. Van Adrichem Boogaert & Kouwe, 1993).

Allostratigraphic bounding discontinuities and synthems in the North Sea Basin

In the Upper Cenozoic record basin-wide discontinuities and synthems are difficult to identify as a result of geological processes occurring during this epoch leading to a fragmentary record (glaciations and related regional low- and high-sea level stands), data inadequate to directly identify large scale discontinuities (borehole data, multiple problems), and, at greater depths, inadequate borehole data density onshore. Based on the occurrences within the stratigraphic model some general genetic patterns of the bounding discontinuities and corresponding synthems can be inferred.

The uppermost discontinuity (the base of Synthem 1) formed as a result of a change in depositional conditions due to climatic amelioration (Fig. 7a, Zagwijn, 1994). In response to the climate amelioration at the end of the Weichselian, sea level rose leading to marine erosion of the exposed sea bed (Jelgersma, 1961, 1979). This erosion led to a major unconformity which is identifiable across much of the North Sea Basin at the base of the Southern Bight Formation (Fig. 2; 4a). In the coastal regions and inland this bounding discontinuity is present at the base of the Naaldwijk and Nieuwkoop Formation. On land, rivers changed from predominantly braided to meandering, which led to reduced sediment budgets and the transport of finer materials as recorded in the Echteld Formation (Weerts et al., 2003b; Westerhoff et al., 2003a).

The base of Synthem 2 is formed by a discontinuity at the base of glacial deposits (Drente Formation) and locally represents a lithologic unconformity between fluvial deposits (Urk and Kreftenheye Formation). The discontinuity represents the presence of an ice sheet affecting depositional processes in the entire North Sea Basin during the Saalian (Fig. 7b). Climatic deterioration led to the expansion of an ice sheet onto the northern part of the continental shelf and onshore parts of the Netherlands. Glacial sediments were deposited, and glacial remoulding of parts of the Netherlands generated relief. The course of the main fluvial system of the Rhine and Meuse forced to the west by the ice margin. Climatic deterioration during both Weichselian and Saalian, and erratic suites introduced at the ice margin, resulted in a facies shift of the Rhine-Meuse depositional systems.

A third discontinuity, which forms the base of Synthem 3; is offshore present within Formation 4.1.1 below the base of glacial valley fills and onshore at the base of the Urk Formation (Fig. 2; 4b). Onshore, towards the east, a major discontinuity is represented by a hiatus at the base of the Urk Formation comprising Rhine-Meuse sediments (Fig. 7c). In addition, deposits of Middle German and Bohemian fluvial systems are absent in the Dutch part of the North Sea Basin. Though in places well defined, in the northern part of the North Sea the discontinuity is sometimes hard to trace. Offshore, unconformities associated with Elsterian glacial channel fills, extent across much of the North Sea Basin. Outside the region of the glacial valleys they can not yet be tied to stratigraphic units and onshore their basal extent is unknown, hence they are regarded here as second order discontinuity.

The fourth discontinuity, the base of Synthem 4; is defined onshore by the termination of the Eridanos fluvial system in this area (Overeem, 2002) followed by the dominance of Middle German and Bohemian fluvial sedimentation represented by the Appelscha Formation (Fig. 7d). Offshore the base of the Outer Silver Pit Formation, which forms a major unconformity truncating the Markham's Hole Formation, is taken as the offshore equivalent of the onshore discontinuity marking the termination of the Baltic fluvial system. The discontinuity is poorly defined.

The base of Synthem 5 is formed by a well defined discontinuity, which coincides with the onset of deposition of the major Eridanos fluvial system in the Dutch part of the North Sea Basin (Fig. 7e, Overeem, 2002). Synthem 5 is represented by distal marine prodelta and delta facies of the Brielle Ground Formation, which onshore correlate with the marine Maassluis and Oosterhout Formations, as well as the overlying fluvial Peize Formation (Westerhoff et al., 2003 b).

Major unconformities between the seismostratigraphic formations in synthems 4 and 5 (Fig. 4b) probably represent autocyclic delta-lobe switching (Cameron et al., 1993). These unconformities are considered of a lower order than those formed by allocyclic processes, as they do not signify basin-wide changes in facies associations, and are therefore more difficult to identify onshore (Fig. 2). Other smaller scale discontinuities that occupy only parts of the North Sea Basin, such as below the Weichselian glacial deposits can also not be used for basin-wide correlation. The evidence they are based upon is either too fragmentary to allow for basin-wide correlation or the events that led to their development did not lead to basin-wide facies association changes. They may however be correlated to paleo-ecological changes in the basin, information that is not used in the present stratigraphic model.

The stratigraphic positions of basin-wide bounding discontinuities at the base of Synthems 3; 4 and 5 correspond with respectively unconformities C, B, and A identified by Zagwijn & Doppert (1975).

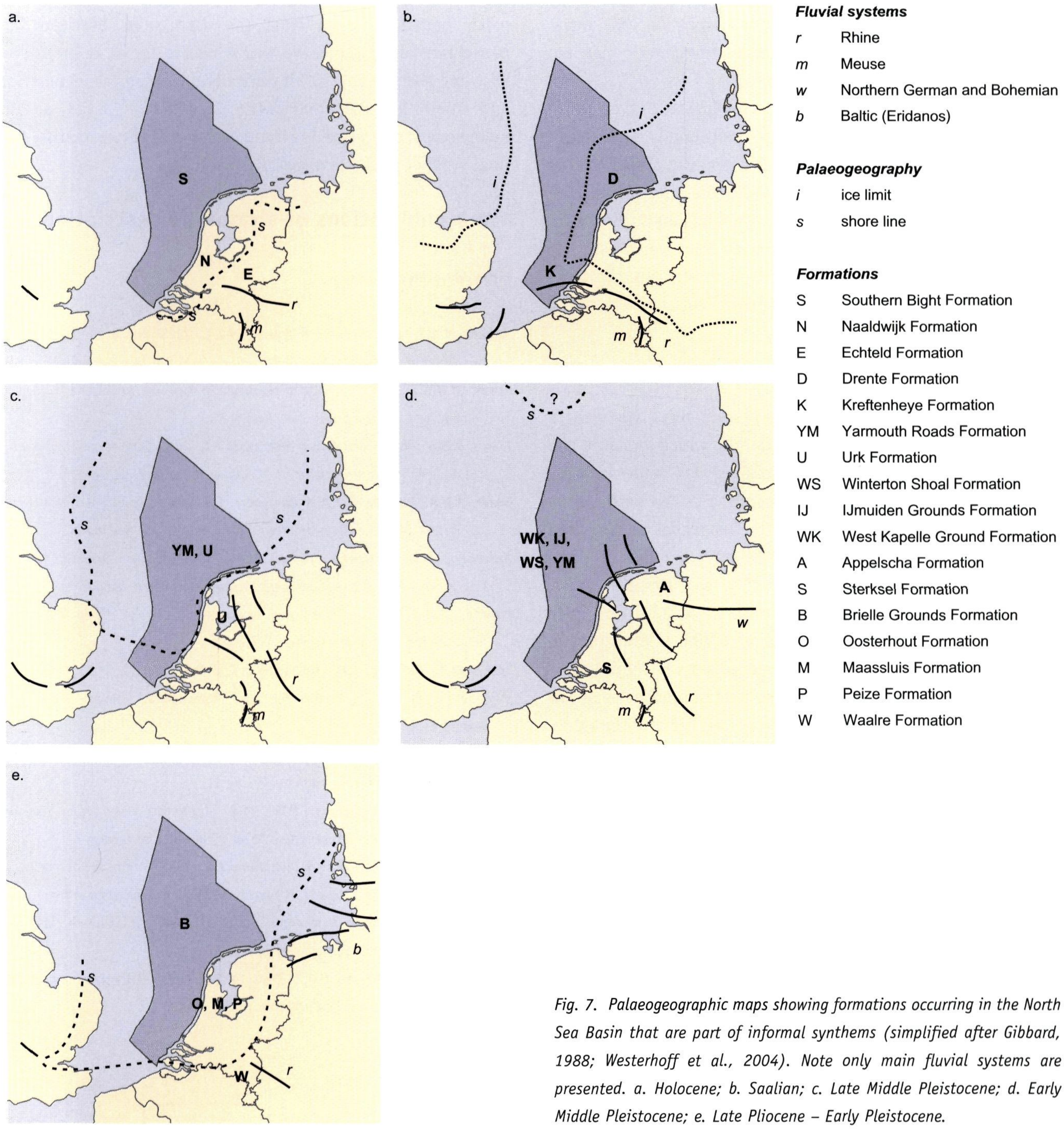


Fig. 7. Palaeogeographic maps showing formations occurring in the North Sea Basin that are part of informal synthems (simplified after Gibbard, 1988; Westerhoff et al., 2004). Note only main fluvial systems are presented. a. Holocene; b. Saalian; c. Late Middle Pleistocene; d. Early Middle Pleistocene; e. Late Pliocene – Early Pleistocene.

A rationale

The international guidelines of the ISSC do not allow genetic nor allostratigraphic criteria to play a role in lithostratigraphic based classification (Salvador et al., 1996). However, increasingly complex applied geological issues require application of a three-dimensional geological model that integrates land and sea data (Rose, 2002; McMillan, 2002; De Mulder et al., 2003; Ebbing et al., 2003). In practice, stratigraphic correlation is always based on geological interpretation, because there is no interpolation and extrapolation possible between boreholes without having a geological model in mind. Thus, implicitly, genesis and allostratigraphic principles always play an important role in stratigraphic schemes. The genetic component in the stratigraphic classification is represented by the use of facies associations, instead of pure lithological criteria sensu Salvador ed. (1994). Facies associations enable integration of stratigraphic units that are defined based on different data acquisition techniques. This approach allows integration of seismic facies, which rely on geometrical aspects of strata, with facies associations based on macroscopic sediment properties in cores (Fig. 5). Further it allows for the correlation of basal bounding discontinuities of deeper seismostratigraphic units with onshore lithostratigraphic units. The allostratigraphic principles provide a view on the stratigraphy on the largest spatial and temporal scale, whereas the genetic concept facilitates mapping on a local scale.

It is noteworthy that the British Geological Survey (BGS) already proposed a revision of its traditionally lithostratigraphic classification towards a 'lithogenetic' classification, which has many aspects in common with the Dutch integrated stratigraphic approach (McMillan & Hamblin, 2000; McMillan, 2002) and as part of this classification Rose (in press) has developed an independent scheme using essentially the same stratigraphic building blocks as proposed here.

Concluding remarks

An integrated stratigraphic model is presented for the offshore and onshore regions of the Netherlands, which replaces the separate stratigraphic schemes that existed. The model includes all Upper Cenozoic formations subcropping in the Netherlands and the adjacent continental shelf. The model is compiled from representative land-sea correlated geological cross sections and time-space diagrams (Fig. 6). Offshore stratigraphic units in the shallow subsurface (0-20 mbsf) are fully integrated with onshore units, deeper offshore stratigraphic units (more than 20 mbsf) are correlated with onshore units.

In the process of combining these stratigraphic schemes an approach has been developed that combines lithostratigraphic, seismostratigraphic and allostratigraphic principles. Formations are represented by facies associations, which are defined by environmental interpretations of lithologically and seismically defined macroscopic criteria. Members and beds are exclusively defined by macroscopic lithologic criteria, partly based on seismic facies interpretation.

Five conceptual allostratigraphic groups and bounding discontinuities provide a view on the stratigraphy on the largest spatial and temporal scale, whereas the detailed genetic approach allows stratigraphic classification on a local mapping scale. Using a combined lithostratigraphic, seismostratigraphic and allostratigraphic approach allows the integration of the Upper Cenozoic land-sea stratigraphic scheme with the Palaeozoic-Lower Cenozoic scheme (Van Adrichem Boogaert & Kouwe, 1993).

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