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Towards an integrated land–sea stratigraphy of the Netherlands

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Abstract

The classification of rocks and sediments may be based on many types of stratigraphy; e.g. litho-, bio-, seismo-, chrono-, chemostratigraphy, and others. The boundaries of the various types of stratigraphy need not at all or seldom coincide. It is especially this last consideration that may cause problems, since this discrepancy in boundaries is very difficult to understand for those not professionally trained as geologists. Since TNO-NITG, as the Dutch Geological Survey, is an organisation for applied geosciences it is necessary that full notice is taken of this problem. A complete revision of the existing late Tertiary and Quaternary lithostratigraphy of the onshore part of the Netherlands, which was a mixture of various types of stratigraphies, was undertaken starting in 1997. At the same time the opportunity was taken to integrate this new scheme with the two other operational stratigraphies used by TNO-NITG. Important solutions in resolving some of the integration problems are outlined. An example of the relation between some of the newly established lithostratigraphic units with some of the seismostratigraphic ones used in the offshore part of the Netherlands is given. Finally an example of the implications of the new approach for the existing geological model is presented.

1. Introduction

From 9 to 11 April 2003 an international workshop on "Integrated Land–Sea Lithostratigraphic Correlation" was organised in Utrecht, The Netherlands by TNO-NITG. On this workshop several lectures were presented regarding the Quaternary stratigraphy. Amongst them were three presentations to announce the establishment of a new Land–Sea stratigraphy of the Netherlands (Ebbing, 2003; Weerts et al., 2003; Westerhoff, 2003). It was on this meeting that the Editor-in-Chief of Quaternary Science Reviews invited us to write an introductory paper with our view on this subject. We gratefully accepted his request. In this paper, we outline the rationale behind the new onshore Tertiary and Quaternary stratigraphy of The Netherlands, followed by an indication of its dominant principles, its relation to the two other existing Dutch stratigraphic schemes, the problems and solutions regarding the integration of land–sea stratigraphy and an example of the results of that integration process.

Full details of this and associated work will be published in a forthcoming special issue of the Netherlands Journal of Geosciences.

2. Motivation

For TNO-NITG and many others (e.g. Brenner and McHargue, 1988; Doyle and Bennett, 1998; McMillan, 2002) it is clear that a three-dimensional model of the subsoil is the most suitable format to make geological information accessible for the users. Within such a model the various rock or sediment layers with specific properties or attributes can be made spatially visible. Stratigraphy is used as a tool to help classifying the sediments and rocks that are of interest. It is here where the problems arise. A practical definition for stratigraphy given by Brenner and McHargue (1988) "*Stratigraphy is the study of rock distribution in four dimensions*" clearly elucidates the problem: time, being the fourth dimension, points to changes of the model through time.

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Time correlation, rock correlation, and bio correlation are approaches that we take in trying to decipher the four-dimensional relationships between rocks in separate locations. In doing this, we recognise both natural and artificial boundaries in order to organise rocks into a system that is simultaneously accurate and simplified (Brenner and McHargue, 1988). The natural and artificial boundaries that we recognise may be based on many types of stratigraphy: lithostratigraphy, biostratigraphy, chronostratigraphy, seismostratigraphy, chemostratigraphy, etc. The boundaries of units classified by the various types of stratigraphy need not at all or seldom coincide. It is especially this last consideration that causes problems, since this discrepancy in boundaries is very difficult to understand for those not professionally trained as geologists. It is for that reason that the three-dimensional model should be built on the basis of only one type of stratigraphy, to keep it intelligible for a broad category of users. Since the user interest lies generally in the properties and the possible use of the subsoil it is logical to opt for a model based on a lithostratigraphic classification scheme. Lithostratigraphy is the element of stratigraphy that deals with the description and systematic organization of the rocks of the Earth's crust into distinctive named units based on the lithologic character of the rocks and their stratigraphic relations (Salvador, 1994) (Fig. 1).

Although the existing lithostratigraphical classification scheme for late-Tertiary and Quaternary onshore deposits in The Netherlands (Zagwijn and van Staalduinen, 1975) was originally also intended to be purely lithostratigraphical, in practice it became a mixture of various kinds of stratigraphy. The knowledge of the geology of the Netherlands and the amount of available data (Fig. 2) has evolved since 1975. Furthermore, all available data at TNO-NITG was stored in a relational database (DINO) from the 1980s onward. By the end of the last century, the increased knowledge was robust enough to translate the scheme back into a purely lithostratigraphical classification scheme. Together with the DINO-database, this scheme is an important building block for an easily accessible three-dimensional model of the subsoil of the Netherlands. These considerations within TNO-NITG (Ebbing et al., 1997) have led to the revision of the existing lithostratigraphical classification scheme that was published by Zagwijn and van Staalduinen (1975). The revision is based on the lithostratigraphical principles established in the international guidelines by Hedberg (1976) and Salvador (1994), and extended to the whole Tertiary.

Another important innovative point is that the new scheme is dynamic. New evidence or altered scientific views will be incorporated on a regular basis. In this way future major revisions are not required, thus avoiding very time-consuming and expensive tasks. Thanks to the internet such an update can be made fairly easily and the results can be available for the users. The new scheme is presented on the TNO-NITG website (http://nitg.tno.nl/ned under the link DINO*loket*) and will be updated once a year.

3. Dominant principles

The new stratigraphical classification scheme for the onshore Tertiary and Quaternary deposits is strictly lithostratigraphical and it follows the international guidelines of Hedberg (1976) and Salvador (1994).

The scheme has a hierarchical structure, consisting of one group and several subgroups, formations, members and beds. The formation is the central unit of any lithostratigraphical classification scheme. According to the mentioned guidelines, formations, defined on the basis of lithology alone, are the only formal units into which the stratigraphic column should be classified. Lithostratigraphical units are samples of rocks or sediments that are defined and recognised on the basis of their (macroscopic) observable and distinctive lithologic properties or combination of lithologic properties and their stratigraphic relations (Salvador, 1994, pp. 31–32). Lithology and stratigraphic relation (or position) alone do not provide adequate explanations for all the properties of a sediment body. Properties such as (pressure) stability, porosity, internal variability and spatial distribution are also determined by syn- and postgenetic processes. Thus, along with observable lithologic properties and stratigraphic position the genesis and source of the deposits play an important a role in the new scheme. Moreover, sediment bodies with the same genesis and source generally have a continuous spatial distribution, although their original integrity may be lost by subsequent erosion or tectonics.

The dominant requirement of the lithostratigraphical classification always remains, however, that genesis and sediment-source must have an expression in macroscopic clearly visible differences in lithological properties and/or stratigraphic position of the sediments in cores or outcrops.

4. Relation to other existing Dutch stratigraphic schemes

The preliminary results of the revision were presented in the TNO-report NITG 00-95-A (Weerts et al., 2000). Following this, a decision was made to integrate this preliminary lithostratigraphic scheme into a more general stratigraphic scheme for the whole geological domain of the Netherlands.

In relation to this effort it is important to realise that Van Adrichem Boogaert and Kouwe (1993–1997) compiled a stratigraphic nomenclature of the Netherlands, for the deeper parts of the subsurface in relation

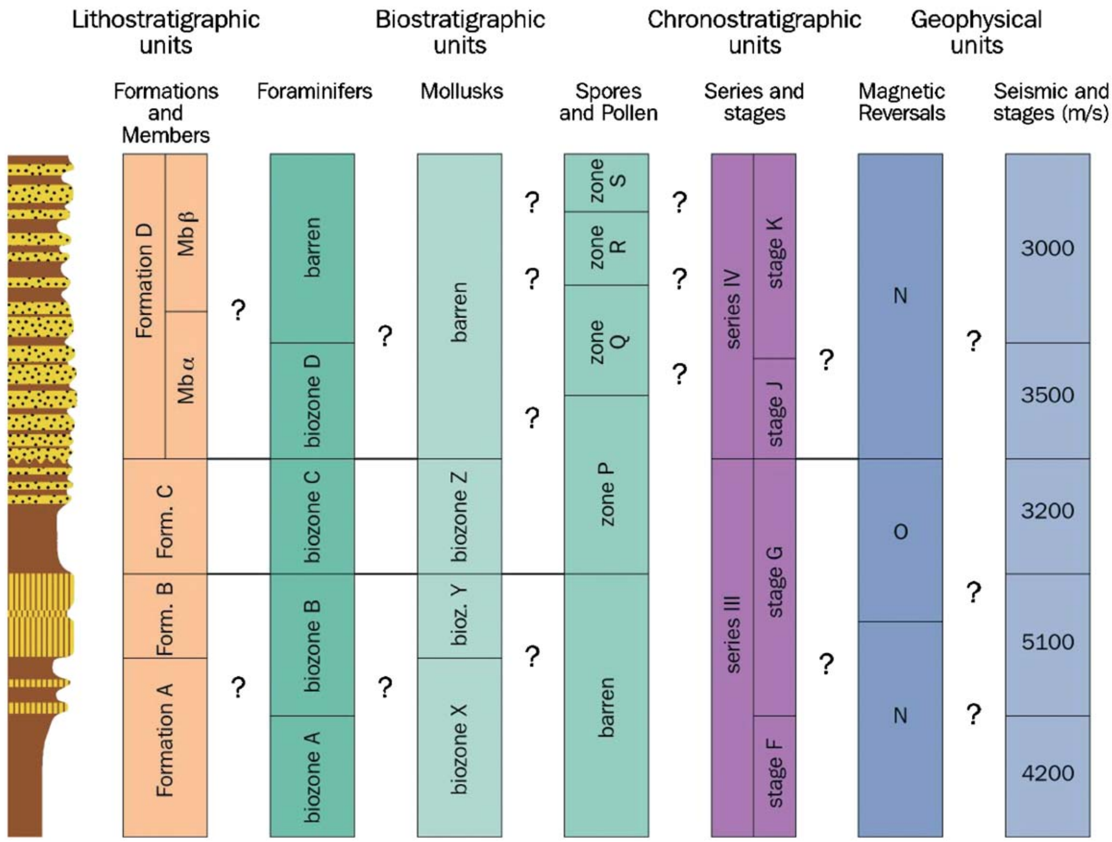

Fig. 1. Position of the stratigraphic boundaries based on different rock properties (litho-, bio, chronostratigraphy and geophysics) in a stratigraphic sequence (after Salvador, 1994).

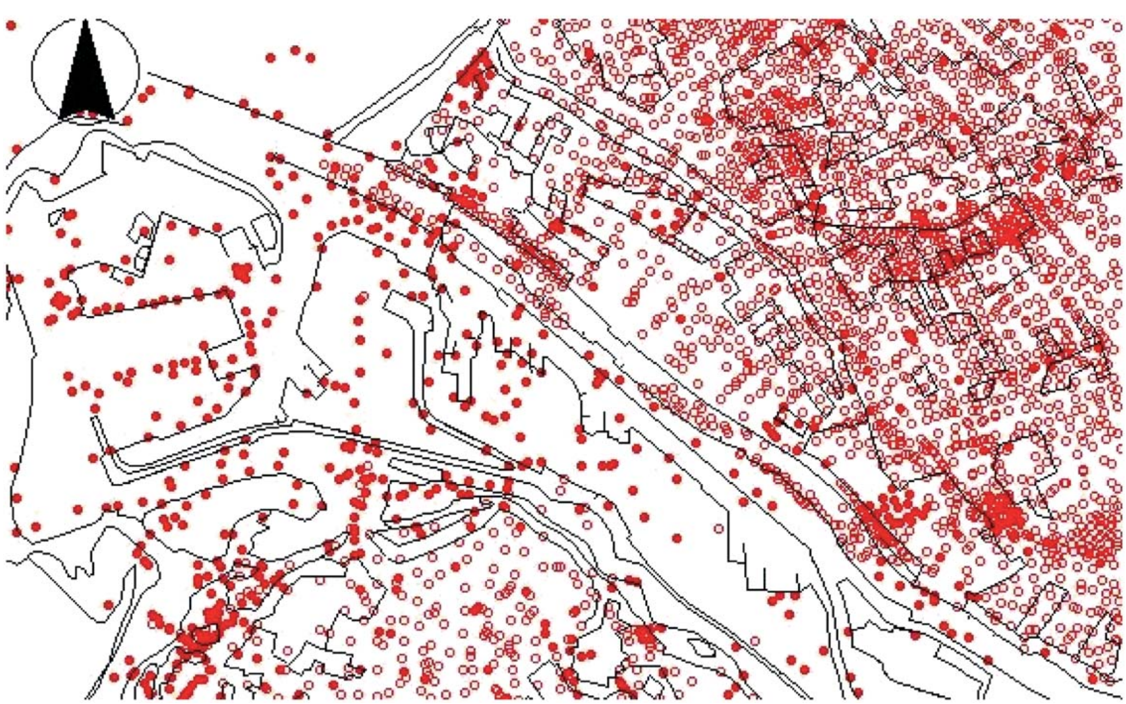

Fig. 2. Available data in the DINO-database in a small area in the western part of the Netherlands. Closed dots: boreholes of intermediate depth (10's to 100's of meters). Open dots: shallow boreholes (5–15 m). The size of the area is approximately 12×20 km.

to oil and gas exploration. This compilation was also meant to be a lithostratigraphic scheme. Since their compilation is based on a limited amount of exploration core-descriptions and seismic lines, biostratigraphy and seismostratigraphy play an important role in the definition of the units, although lithology is a central theme in their stratigraphic interpretation (van Leeuwen et al., 2000).

The Marine Geology Department of TNO-NITG on the other hand depends for their stratigraphy very strongly on seismostratigraphy. Their stratigraphic units are recognised as seismostratigraphic units, based on discontinuities, with a lithologic description (Long et al., 1988; Laban, 1995).

The differences in approach between the three Dutch stratigraphic schemes led to the conclusion that one fully integrated classification based solely on lithostratigraphy is impossible. Nevertheless there must exist a stratigraphic relationship between the three classification schemes used by TNO-NITG, since the different stratigraphic units recognised do not "know" whether they have a litho-, bio-, chrono-, or seismostratigraphic nature. They all contain, rocks and/or sediments that interrelate. So, the integrated stratigraphic scheme of the Netherlands that is presently under construction relies on lithostratigraphic, seismostratigraphic and biostratigraphic criteria, depending on the part of the domain. Lithostratigraphic criteria prevail for the Quaternary deposits on the mainland. A combination of litho- and seismostratigraphic criteria is used for the Quaternary deposits in the Dutch sector of the North Sea. Tertiary deposits are also classified by a combination of litho- and seismostratigraphic criteria. Older deposits are mainly classified by a combination of bio- and seismostratigraphic criteria. This approach is more or less dictated by the available data in different parts of the domain. It should be emphasised that the integrated stratigraphic scheme is not yet complete.

5. Integration of Tertiary and Quaternary land–sea stratigraphic units

To illustrate the different stratigraphic approaches in different parts of the domain an introductory background to the common practise of geological mapping on- and offshore within The Netherlands is given below. At the same time we list some of the methods used to overcome the problems of correlating between the two almost completely different stratigraphic schemes that are presently still used in the mapping process. For more specific and detailed information and references the reader is referred to the forthcoming special issue of the Netherlands Journal of Geosciences that is due to be published in 2004.

To show the differences in approach for on- and offshore geological mapping a general characterisation of the basis for on- and offshore mapping is summarised below.

(1) Onshore mapping of Tertiary and Quaternary deposits is based on:
  (a) Many boreholes (approximately 400,000). Descriptions of the cores are available in a relational database (DINO);
  (b) Lithostratigraphical classification of the cores, since the required information (1a) is available and is the one most suitable in applied studies;
  (c) Much lithological detail, because of the vast amount of good quality boreholes (1a);
  (d) A good time-control, because of the many existing high quality biostratigraphic and absolute dating results;
  (e) A poor boundary and spatial control; because outcrops in The Netherlands are almost absent. Continuous lateral information is extremely scarce. Lateral boundaries of the units are nearly always inferred from point-information.

(2) Offshore mapping is based on:
  (a) Relatively few, dominantly shallow, boreholes;
  (b) Seismostratigraphic data, since offshore seismics are a relatively cheap and powerful tool;
  (c) Some direct lithological detail in the first 10 m below seabed, obtained from the few boreholes available (2a) and very little direct lithological detail on deposits buried deeper;
  (d) A poor time-control, because of the lack of enough high quality biostratigraphic and absolute dating (2a);
  (e) A good boundary and spatial control, since this is one of the big advantages of using especially high-resolution seismics.

In an idealised cross section the subdivision in units according to the above-mentioned mapping constrains for on- and offshore mapping leads to two different interpretations of that cross section.

5.1. Onshore mapping

With the aid of the available borehole information and the dominant principles mentioned earlier a classification into lithostratigraphic units is possible in this "geological" cross section. Based on the genetic environments alone, this would result in five different lithostratigraphic units, following the legend indicated in Fig. 3. Generally, the macroscopic differences between coastal marine and shallow marine are not distinct enough in core descriptions to be useful as boundary indicators. If data is limited to core-descriptions, a subdivision into only four major genetic types (deep marine, shallow and coastal marine, terrestrial/fluvial, glacial) remains. Each of these types can be subdivided further into lithostratigraphic units. In The Netherlands, a fifth genetic type is added: locally to regionally deposited fluvial sediments and peat, with superimposed aeolian deposits. This is possible because of the high resolution of the data that form the base of the geological model of The Netherlands.

5.2. Offshore mapping

This same cross section now treated as a "seismic" cross section (Fig. 4) will result in a large number of possible seismostratigraphic units, based on reflectors and the termination of reflectors in on- and offlaps. Between the dominant reflectors (often important discontinuities) typical seismostratigraphic lithofacies can often be recognised. These act as a kind of unique spatial fingerprint for a distinct seismostratigraphic unit.

5.3. Integration

The challenge is to combine these two different stratigraphic interpretations of the same cross section in one integrated coherent general stratigraphic scheme. To achieve this goal, we propose the following solution (Laban et al., 2003):

(1) To combine the best of both worlds, namely:
   (a) Use the seismostratigraphy (especially offshore) as a tool for boundary and spatial control;
   (b) Use the lithostratigraphy (especially onshore) for sediment characterization;
(2) Look for the most important seismic discontinuities and coinciding lithologic breaks;
(3) Use lithofacies as a common factor. Since, by using the mentioned genetic types within the lithostratigraphic scheme, lithofacies is indirectly incorporated in that scheme, while lithofacies as a spatial genetic fingerprint can relatively easy be recognised on seismic lines;
(4) Accept differences in spatial dimension within hierarchically equal stratigraphic units. So, for example, an offshore formation may occupy a substantially larger spatial part of the general stratigraphic scheme than an onshore formation. This holds both for a purely quantitatively way (size) as for time within the chronostratigraphic record.
(5) Additional information regarding e.g. chrono-, bio- or chemostratigraphy can be added to the general stratigraphic scheme, but should never be used as classification criteria.

6. Example: lithostratigraphical classification of deposits in the Holocene coastal and alluvial plain

The Holocene deposits in the coastal and alluvial plain are present in a "coastal prism" that formed due to the Holocene sea-level rise. This wedge-shaped sediment

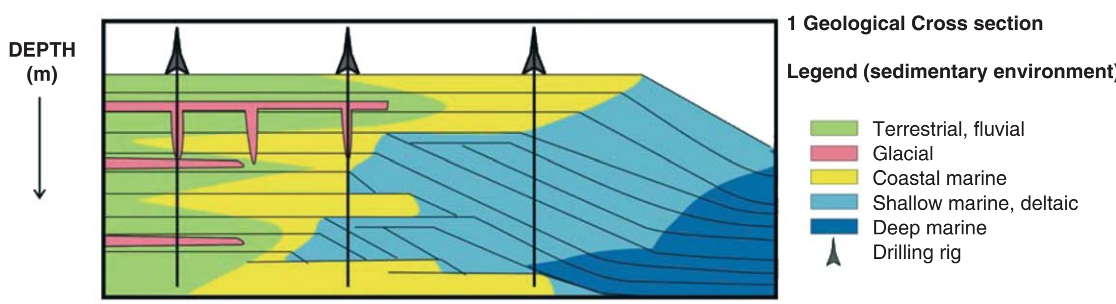

Fig. 3. "Geological" cross-section, interpreted from lithological data from drilling rigs (adapted after Milton, 1996).

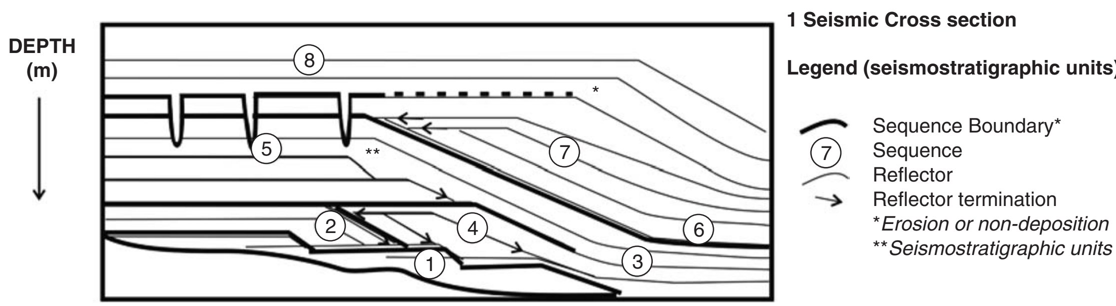

Fig. 4. "Seismic" cross-section, interpreted from seismic data (adapted after Milton, 1996). Note that the location of the section is identical to that of Fig. 3.

body consists of marine coastal siliclastic deposits, fluvial siliclastic deposits and peat. It reaches a maximum thickness of ~25 m near the present coast in the western part of the Netherlands (exclusive the dune sands). Offshore, shallow marine siliclastic deposits cover the seafloor, generally they are less than 10 m thick. Usually, the base of the Holocene deposits can easily be established in core-descriptions, because of the lithologic contrast with the underlying deposits.

Following the lithogenetic approach outlined above, this leads to a classification of four formations:

- the Echteld formation, comprising all clastic fluvial deposits in the alluvial plain;
- the Nieuwkoop formation, consisting of peat;
- the Naaldwijk formation, coastal and back-barrier clastic marine sediments;
- the Southern Bight formation, comprising marine reworked deposits at the seafloor of the Dutch sector of the North Sea.

Deposits of the Echteld, Nieuwkoop and Naaldwijk formations interdigitate over large areas in the coastal prism. Nevertheless, we choose to classify the deposits in three formations because of their different lithologic properties. A prerequisite for successful mapping of these deposits at the formation-level is the availability of a large amount of data. In the Dutch situation, over 100,000 core-descriptions are available in the coastal and alluvial plain what enables us to classify and map the deposits at the formation level. In cases where the amount of data is insufficient to apply the genetic approach, one might choose to classify the coastal prism as one formation with several litho-genetic components.

Fig. 5 shows the position of two cross-sections. Section A1–A2 is positioned in the coastal and alluvial plain in west-central Netherlands, section B1–B2 in the northern part of the present coastal plain. Fig. 6 shows the deposits in section A1–A2, Fig. 7 its lithostratigraphical interpretation.

In the western part of the Netherlands, Holocene clastic marine and fluvial deposits are present. The latter have been deposited predominantly by the river Rhine. Following our genetic approach, all fluvial clastic deposits in the alluvial and coastal plain are assigned to one formation; the Echteld formation (Fig. 7). No members are discerned in this formation. Several informal lithogentic units can be identified, following Berendsen (1982, 1984) and Berendsen and Stouthamer (2001). The cross-section of Fig. 6 only shows a division into sandy channel deposits and clayey overbank deposits. The peat is also assigned to one formation: the Nieuwkoop formation. Peat formation in the western part of the coastal plain in the Netherlands became widespread after the coastal barriers closed around 5000 BP. In Fig. 6 this is still visible by the

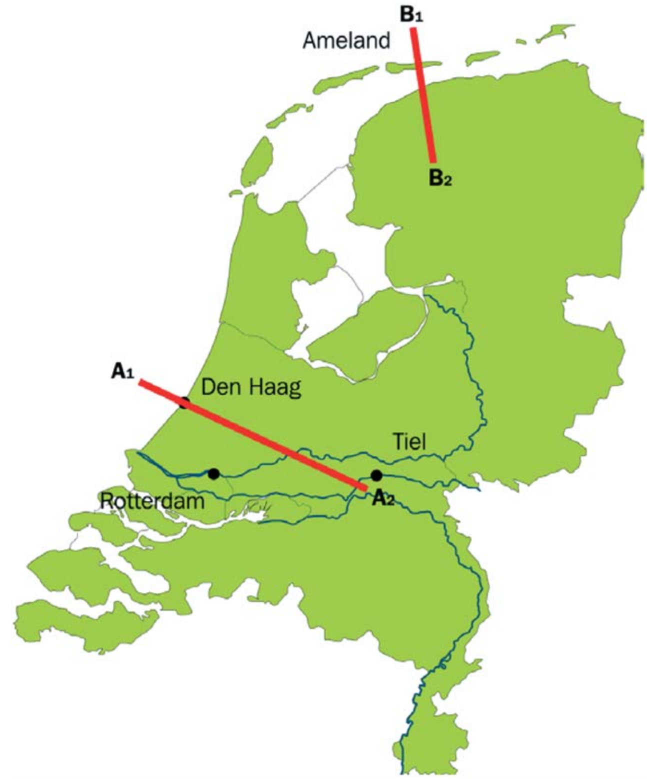

Fig. 5. The position of the cross-sections A1–A2 and B1–B2.

presence of a peat layer between the lower and upper mud flat deposits. Four lithofacies units are present in the coastal marine and back-barrier deposits in the western part of the coastal plain; sandy channel point-bar and tidal flat deposits, mud flat deposits, beach and shoreface sand and dune sand. Fig. 8 shows that these deposits are all assigned to one formation: the Naaldwijk formation. This formation is subdivided into several members, based on the lithological properties of the deposits. This is in contrast with the ''litho'' stratigraphical framework by Zagwijn and van Staalduinen (1975), where the (often presumed) age of the deposits formed the basis of the classification of members in the Holocene coastal formation (the Westland formation).

In the western part of the coastal plain, four members are discerned (see Fig. 7). Classification of the (upper) Walcheren Member and the (lower) Wormer Member, both consisting of sandy channel point-bar and tidal flat deposits and mud flat deposits is possible here because of the presence of a continuous peat layer between them. Only in places where large sandy channels of the Walcheren Member are present, the peat has eroded. In those cases, it is difficult to establish the base of the Walcheren Member. Offshore, shallow seismics can help elucidate very vividly the spatial distribution and infilling of these channels, tidal flats and mud flats.

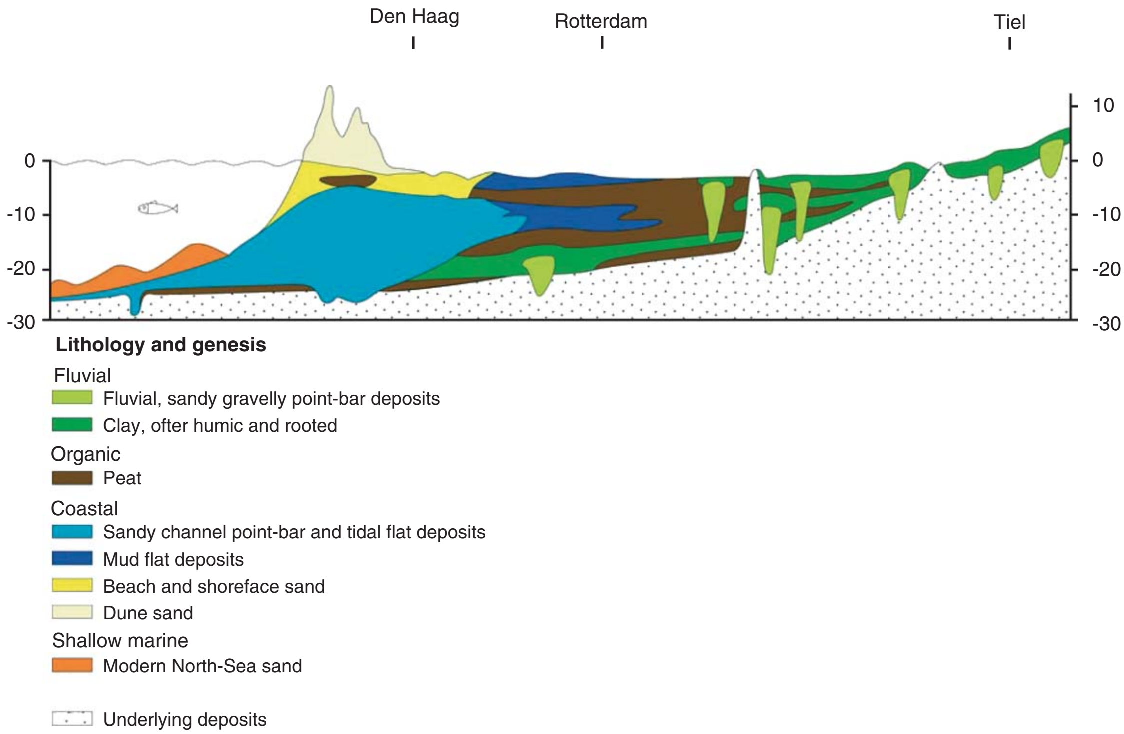

Fig. 6. Holocene deposits in cross-section A1–A2 (adapted after Berendsen, 1996; Cleveringa, 2000).

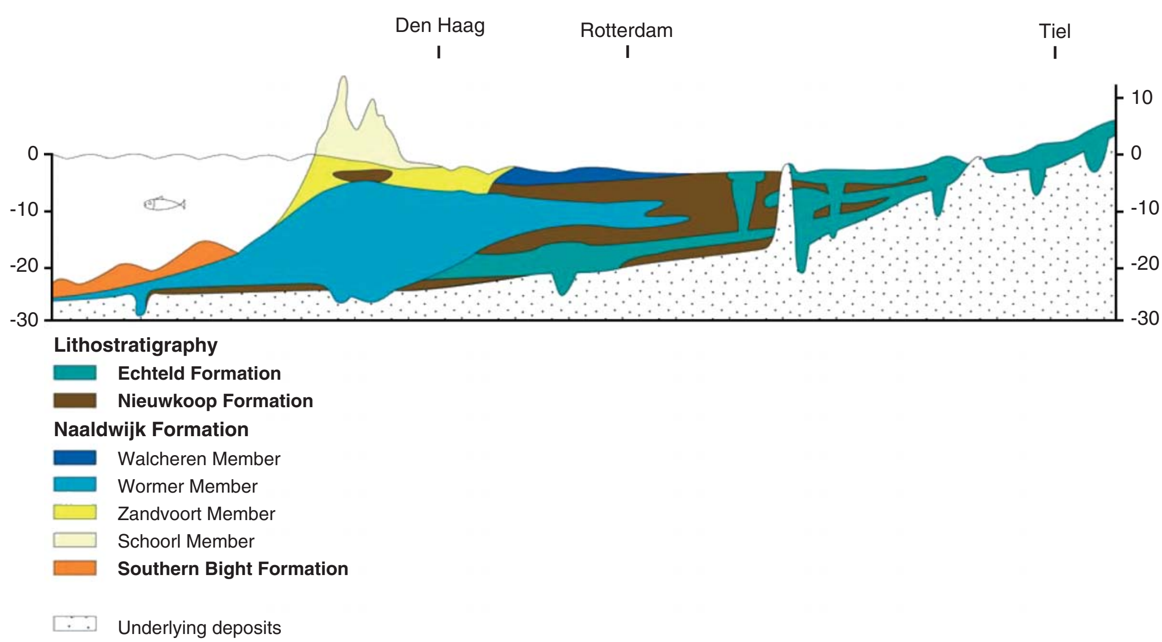

Fig. 7. Lithostratigraphical interpretation of Section A1–A2.

Finally, in the westernmost part of the section, modern North Sea sand is present at the seafloor. This sand is assigned to the Southern Bight formation. Often the base of this formation can be easily identified and mapped using shallow seismics. Within this formation, several members are discerned, based on the lithologic assemblage of the deposits. Laban et al. (2003) give a short list of the members in this formation.

Fig. 8 shows a simplified cross-section through the coastal plain in the northern part of the Netherlands. Two differences with respect to the west-central Netherlands are striking; (1) the absence of large-scale clastic fluvial deposits and (2) the limitation of the occurrence

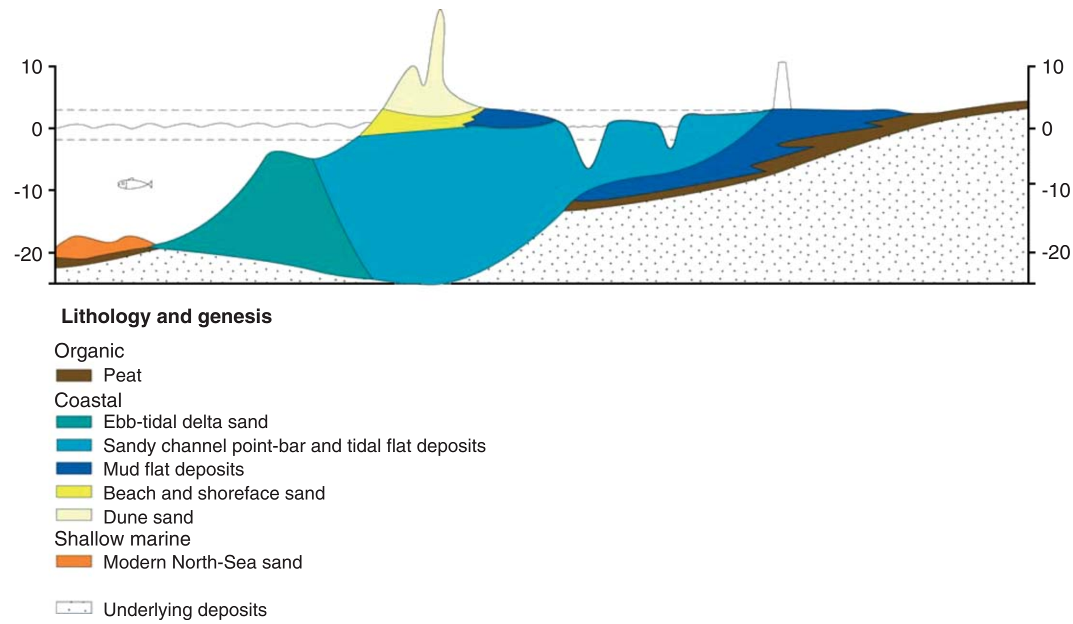

Fig. 8. Holocene deposits in cross-section B1–B2 (adapted after Van der Spek, 1994).

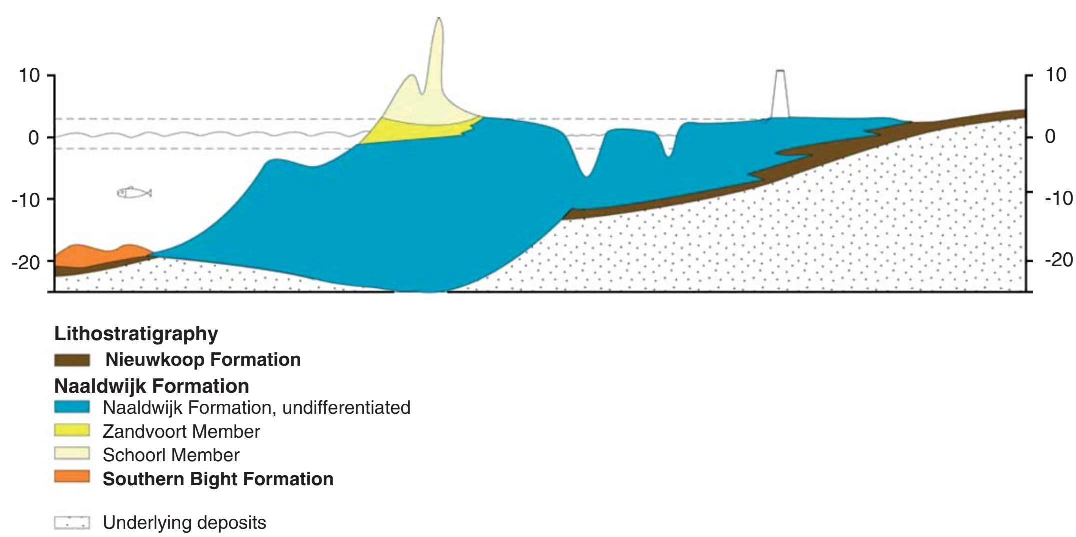

Fig. 9. Lithostratigraphical interpretation of Section B1–B2.

of peat to the base of the coastal prism. In this part of the coastal plain, only three formations are present: the Nieuwkoop formation (peat), the Naaldwijk formation (clastic coastal and back-barrier deposits) and the Southern Bight formation (modern North Sea sand at the seafloor). Within the Naaldwijk Formation, only two members are discerned here (Fig. 9). Because of the virtual absence of intercalated peat in the back-barrier deposits, the Walcheren and Wormer members are not discerned in this region. The absence of intercalated peat here is the consequence of the different coastal development during the Holocene in this region compared to the development of the western Netherlands (Van der Spek, 1994; Beets and Van der Spek, 2000). In the western Netherlands, the coastal barriers formed a closed coast between ~5000 and 2000 BP, thus enabling large-scale peat formation behind the barriers. This does not happen in the northern Netherlands. Here, the coast always remained open and peat formation was limited to the outermost landward fringe of the coastal plain.

7. Conclusions

If the geological model for a certain region is considered relatively stable and enough objective lithological information exists, it is possible to deal with that region lithostratigraphically in a very rigorous way. This leads to a sound basis for a three-dimensional model of the subsoil especially designed for applied studies. It also provides the possibility to integrate other stratigraphic schemes adopted in the same geological domain. The example from the Holocene deposits in the coastal and alluvial plain shows that the chosen lithostratigraphical approach works well. This is of course partly due to the presence of the deposits at or relatively near the surface. Data become more scarce at depth. As a consequence, the deeper a formation the less subdivsions. Finally, the developments in the Information Technology of the past decades have made it possible to incorporate new knowledge and data in both the scheme and the model efficiently in a way that is accessible to the users.

Acknowledgements

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