DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2003/72

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# Lithostratigraphy of the Palaeogene siliciclastic sediments in the Danish North Sea sector

by

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## Abstract

As a result of a lihological, sedimentological and biostratigraphic study of recently drilled exploration wells in the Danish sector and a restudy of data from previous wells sections, the lithostratigraphic framework for the siliciclastic Palaeogene sediments of the Danish North Sea sector is revised. The sediment package from the top Chalk surface through the Mid-Miocene log and seismic marker is subdivided into 7 formation containing 11 new members. Vaale, Lista, Sele, Fur, Balder, Horda and Lark Formations of previously published lithostratigraphic schemes are adequate for a subdivision of the Danish sector at formation level and are retained virtually unchanged herein. Bor is a new sandstone member of the Vaale Formation. The Lista Formation is subdivided into the three new mudstone members Vile, Ve and Bue and the three new sandstone members Gerd, Idun and Rind are described from the formation. Sif is a new sandstone member of the Sele Formation. Nana is a new sandstone member of the Horda Formation. The two new sandstone members Freja and Dufa are established in the Lark Formation. Type and reference sections are erected for the new members, and Danish reference sections are established for the formations. The biostratigraphy and palaeoenvironmental setting of the formations is described and a correlation with Danish onshore sections suggested.

## Introduction

The understanding of the lithostratigraphy of the siliciclastic Palaeogene sediments in the Danish North Sea Sector (Fig. 1a) has been greatly improved following a considerable number of wells drilled since the discovery of the Siri Field in 1995. Many of the new wells have been drilled in search for oil reservoirs in sand bodies of Paleocene–Eocene age. Yet the lithostratigraphy available builds on data sets from previous generations of wells drilled with deeper stratigraphic targets with little or no interest for the overlying siliciclastic Palaeogene sediment package. A revised lithostratigraphy needs to be established on the basis of the new knowledge acquired. This has been the main aim of the present work.

The lithostratigraphy presented herein (Fig. 2) has its genetic base at the top Chalk Group surface. Although the uppermost formation of the Chalk Group, the Ekofisk Formation, is of Early Paleocene (Danian) age and therefore belongs to the Palaeogene Period, the present study does not deal with that formation. The reason for this omission is that the Ekofisk Formation, like the rest of the Chalk Group, represents an entirely different sedimentary regime, far from that of the overlying siliciclastic sediments both by nature, depositional mechanism and host basin configuration. The top of the study section is constituted by the Mid-Miocene Unconformity; a basin-wide erosional surface that separates two thick and very different sediment packages, the Oligocene–middle Miocene Hordaland Group and the Mid-Miocene to Recent Nordland Group.

The lithostratigraphy proposed herein is based on the analysis of petrophysical logs and cuttings samples from a large number of wells and core sections. Lithostratigraphic well correlation is supported by a detailed biostratigraphic analysis based on a reassessment of a large number of biostratigraphic reports encompassing both micropalaeontological and palynological data. Furthermore, the biostratigraphy is supplemented by results from preparations of new sample material from North Sea wells. The resulting well correlation has been matched with results from interpretation of key seismic sections.

All of the widespread Palaeogene mudstone units in the North Sea have been previously established with Norwegian or British type wells. In the present work, Danish reference wells have been established for these units, and lithological descriptions have been updated to cover the appearance of these units in the Danish sector. Many of the sandstone bodies recently discovered in the Danish sector have a limited spatial distribution and are probably sourced from other areas than their contemporaneous counterparts in the Norwegian and British sectors and are most likely not in contact with them. These units have therefore been established as new in the Danish sector, and have been assigned Danish type and reference sections.

Oil companies operating in the North Sea have collected a substantial amount of lithostratigraphic data on the Palaeogene succession. In particular, a detailed lithostratigraphy for the Paleocene sand and clay successions in the Danish and

Norwegian sector has been developed. This work has introduced a number of informal lithostratigraphic units that have subsequently found their way into academia and geological survey organisations. It has been the aim during the present work to formally define these new units. This has been done maintaining their original names whenever feasible.

It has not been the aim of this work to provide a sequence stratigraphic model for the Palaeogene sediments in the North Sea; for this the reader is referred to the encompassing works of Michelsen et al. (1992, 1995, 1998), Mudge and Bujak (1994, 1996a,b), Neal et al. (1994) and Danielsen et al. (1997). The aim has in stead been to provide a clear and concise nomenclature for the post-Chalk Group Palaeogene succession in the Danish sector, as well as providing a straightforward guide for identification of the sediment bodies within it. The present contribution does not attempt to review the petroleum-related aspects of the Palaeogene succession either. Information about this may be found e.g. in the annual reports from the Danish Energy Authorities.

## Previous work

The Permian to Recent lithostratigraphy of the North Sea area was described in two pioneering stratigraphic works: Rhys (1974) provides an overview of the extend and contents of the North Sea basin and gives a first, brief description of the Palaeogene sediments. Deegan and Scull (1977) compiles a detailed lithostratigraphic subdivision and lithological description for the central and Northern North Sea (Figs 3,4). The work of Deegan and Scull (1977) has formed the backbone of all subsequent lithostratigraphic schemes for the area, including that of the present contribution.

In a volume edited by Michelsen (1982), Bang and Kristoffersen (1982) suggested a lithostratigraphy for the Danish sector of the Central Graben area. In that volume, the post-chalk sediment package was subdivided into 7 units. The Palaeogene was subdivided into 5 units: North Sea Marl and Cen-1–4 (Fig. 4). It was not stated if the units were at group or formation level. The boundaries of the CEN-units coincide with the major formation boundaries of Deegan and Scull, but the contents of some of the units of Bang and Kristoffersen differ from that of the formations established by Deegan and Scull (Fig. 4). Although more detail had gone into description and interpretation of the CEN units, they have not found as much use as the formations of Deegan and Scull (1977).

Hardt et al. (1989) published a revised lithostratigraphy for the Palaeogene and Neogene of the Norwegian North Sea in a volume edited by Isaksen and Tonstad (1989) (Fig. 4). That contribution formalised for the first time the considerable number of sandstone bodies observed in the Palaeogene of the North Sea. It may be noticed, that many of the names of the sandstone units established by Hardt et al. (1989) have found use also in the Danish sector as they have been thought to be correlatable with the Norwegian units in a broad sense.

Mudge and Copestake (1992a,b) presented a revised Palaeogene stratigraphy for the outer Moray Firth and northern North Sea. In their papers they retained and redefined the Moray Group and Montrose Group of Deegan and Scull (1977), established for the outer Moray Firth-Forties area, and abandoned the Rogaland Group. The authors also reduced the various sandstone formations that occur in the two groups to member status. Furthermore, and most importantly, they allowed for a greater influence of biostratigraphical data in the characterisation of the various lithostratigraphic units; an approach which is also followed herein. However, as the stratigraphic scheme of Mudge and Copestake does not cover the Central and eastern North Sea, it is not shown in Fig. 3.

Knox and Cordey (1992) edited 6 comprehensive volumes dedicated to establish a joint nomenclature for the British North Sea. The Palaeogene of the Central and northern North Sea was dealt with in a contribution by Knox and Holloway (1992). In their large format atlas the Palaeogene lithostratigraphic scheme was updated with focus on the British and Norwegian Central and northern North Sea. Their lithostratigraphic scheme is shown in Fig. 4. The authors followed Mudge and Copestake (1992a) in abandoning the Rogaland Group of Deegan and Scull (1977), and maintained Mudge and Copestake's revised definition of the Montrose and Moray groups also for the Central

North Sea. However, a change in the definition of the boundary between the Lista and Sele Formation was introduced (see the Sele and Lista chapters of the lithostratigraphy section herein for comments on this). The thick and hitherto undivided Hordaland Group was subdivided into two new groups, a lower Stronsay Group and an upper Westray Group, each containing a proximal and a distal formation. As the proximal sandstone formations of the two new groups are absent in the Danish sector, the above subdivision of the Hordaland Group of Deegan and Scull (1977) is not retained herein. However, the two distal formations of Knox and Holloway (1992), the Horda Formation and Lark Formation that together constitute the bulk of the Palaeogene in the Danish North Sea sector are retained (Figs 2,3,4).

Building on on new, high-resolution seismic surveys new stratigraphic work focused on a sequence stratigraphic subdivision of the Palaeogene sediment package in the North Sea. The Danish sector was thoroughly treated in a series of publications from a working group at the University of Aarhus (*e.g.* Michelsen et al., 1992, 1995, 1998; Michelsen, 1993; Danielsen et al., 1997; Huuse and Clausen, 2001). The result of that work was a subdivision of the Palaeogene sediment package into five genetic units (six if the Early to Mid Neogene sediments also covered by the present work is included) (Fig. 4). Sequence stratigraphic contributions covering the larger North Sea basin including the British and Norwegian sectors are *e.g.* Mudge and Bujak (1994, 1996a,b) and Neal et al. (1994).

## Offshore and onshore lithostratigraphic nomenclature

Many lithostratigraphical schemes correlate the Danish onshore stratigraphic succession with the North Sea succession (for the most recent and thorough correlations see Heilmann-Clausen, 1995 and Michelsen et al., 1998). Clearly, there is a high degree of lithological similarity between the onshore and offshore successions, and for many of the units there can be little doubt that the onshore and offshore counterparts are identical. The nomenclatural status for the Danish onshore succession is, however, quite varied: many units have been coined before requirements to lithostratigraphic nomenclature were established, other fulfil these requirements, and yet other are still informal units. If identity between an onshore and an offshore unit can be demonstrated beyond doubt, the situation arises where the name of the onshore units could be argued to have seniority over an offshore unit (*e.g.* Holmehus Formation over Ve Member). Likewise, names of North Sea units could be argued to have seniority over onshore units (e.g. Balder/Sele Formations over Ølst Formation). In order to acknowledge the traditional distinction between North Sea and Danish onshore stratigraphic nomenclature, the two sets of nomenclature are kept separate herein. It is believed that this facilitates communication between users of the nomenclature. Whenever possible, comments are given in the text to explain the relation between offshore and onshore Danish stratigraphic nomenclature (Fig. 2).

## Material

The lithostratigraphic subdivision herein represents the combined results from a study of petrophysical logs, biostratigraphy and seismic profiles, inspections of cuttings samples and cored sections. Petrophysical logs from 70 wells in the Danish sector have been scrutinised, predominantly gamma ray and sonic logs, but also resistivity and density logs and in a few wells sp logs have been used. The location of the wells studied is shown in Fig. 1a. Five log panels (Enclosures 1-5) constitute the backbone of the log correlation. The location of the 5 correlation lines is shown on Fig. 1b. Biostratigraphical reports from 29 wells have been reassessed in order to support well correlation, and biostratigraphic sample suites from 11 wells have been prepared at the Geological Survey of Denmark and Greenland (GEUS) in order to further enlighten the biostratigraphic event succession. The resulting optimum downhole succession of biostratigraphic key events is shown in Fig. 5a–c; its correlation with international and North Sea biozones is shown in Fig. 6a–c. The seismic surveys CGD85, DK-1, RTD81-RE94, UCG96 and UCGE97 have been used to verify the obtained well correlation and to further determine the spatial distribution of stratigraphic units in areas with only scattered well coverage. The location of key seismic sections illustrated herein is shown in Fig. 1c. Inspection of cuttings samples from 16 key wells supplemented with sedimentological studies of cored intervals from 23 wells have formed the basis for the lithological and sedimentological descriptions of the individual units.

## Chronostratigraphy and biostratigraphy

The bio-events selected for correlation and dating of the lithostratigraphic units are shown in Fig. 5a–c; biostratigraphic zonations used are shown in Fig. 6a–c. The events used are mainly first downhole occurrences (FDO) of planktic and benthic foraminiferids and dinoflagellate cysts. The events occur consistently within the study area. Most of the material studied consists of cuttings samples, only few core samples have been used. The use of last downhole occurrence (LDO) is hampered due to downhole caving in cuttings samples. Correlation between the bio-events and the standard chronostratigraphy of Berggren *et al.* (1995) is mainly based on Hardenbol *et al.* (1998).

The creation of a new biozonation has not been attempted as existing zonation charts were found adequate. The zonations by King (1983, 1989) covering planktic and benthic microfossils and the dinoflagellate cyst zonation of Mudge and Bujak (1996a, b) (Figs 5a–c,6a–c) were established specifically for the North Sea area and are adapted herein. The rather coarse dinoflagellate cyst zonation of Costa and Manum (1988) was erected for NW Europe; the revision of that zonation by Köthe (1990) was based on North German data and is used herein. The zonal boundaries in Figs 5 and 6 are correlated with geochronology based on the biochronostratigraphic chart provided by Hardenbol *et al.* (1998). In a few cases the correlation of zonal boundaries and bioevents to geochronology has been revised according to new data (see comments below).

*Paleocene*

The base of the Selandian and Thanetian stages have yet to be formally established, but according to the International Subcommission on Palaeogene Stratigraphy both the proposed GSSPs (Global Stratotype Section and Point) will be placed in the Zumaya section (northern Spain). The GSSP of the base of the Selandian will be close to the P2/P3a or P3a/P3b foraminiferid zone boundaries, while the GSSP for the Thanetian will be at the base of Magnetochron C26n (Schmitz, 2002). Concerning the

Danian/Selandian boundary, Hardenbol *et al.* (1998) followed the interpretation by e.g. Hansen (1968), Berggren and Miller (1988) and Berggren *et al.* (1995) and placed the base of Selandian at the lowest occurrence of the planktic foraminiferid *Morozovella angulata*, which defines the base of Zone P3a.

The top of the Danian has been placed based on local events because many of the microfossil species that characterise the Danian-Selandian boundary interval in the probable future type section area (Zumaya, Spain, in the Tethys realm) including *M. angulata*, are absent or rare in the North Sea. Some of the commonly used markers in the North Sea include the FDO of the yet undescribed dinoflagellate species *Spiniferites "magnificus"* (e.g. Mudge and Bujak, 1996), the FDO of the dinoflagellate *Danea californica* (Heilmann-Clausen, 1994), the FDO of common Paleocene calcareous foraminiferids, the highest occurrences of the planktic foraminiferid species *Subbotina trivialis* and *Globanomalina* cf. *compressa* (e.g. Mudge and Bujak, 2001) and the FDO of abundant specimens of the nannoplankton species *Praeprinsius dimorphosus* (Varol, 1998).

*Eocene*

A GSSP for the base of the Eocene (Paleocene-Eocene boundary) has recently been approved by the ICS at the lowermost and most conspicuous of a series of $C^{13}$ isotope excursions (CIE) in the Dababiya section in Luxor, Egypt (Gradstein and Ogg, 2002). The CIE is related to a global thermal maximum and has been dated 55.5 Ma (Berggren and Aubrey, 1996). The CIE has been correlated with dinoflagellate biostratigraphy and coincides with the sudden proliferation of the dinoflagellate genus *Apectodinium* (Knox, 1996; Crouch *et al.* , 2000, 2001; Heilmann-Clausen and Schmitz, 2000). Other marker events for the Paleocene-Eocene boundary include the "Benthic Foraminiferal Extinction Event" (BEE) (Aubrey, 2001). The BEE is also a cosmopolitan event known both from e.g. the North Sea, the Tethys area (e.g. Monechi *et al.*, 2000) and North America (Cramer *et al.*, 2000). In the Danish onshore area the CIE and the sudden proliferation of *Apectodinium* has been recognised in the laminated Stolle Klint Clay in the lowermost part of the Haslund Member of the Ølst Formation (Heilmann-Clausen and Schmitz, 2000). In the Danish North Sea area the proliferation of *Apectodinium* is in the lowermost part of the Sele Formation.

*Oligocene*

The Massignano section in eastern central Italy has been ratified as the GSSP for the Eocene/Oligocene (Priabonian/Rupelian) boundary. The boundary was placed at the highest occurrence of the planktic foraminiferid genera *Hantkenina* and *Cribrohantkenina* (see papers in Premoli-Silva *et al.*, 1988), which is located immediately above the P17/P18 (planktic foraminiferid zones) boundary *sensu* Berggren *et al.* (1995). Hantkeninids have not been observed from the North Sea area in the present study and alternative zonal markers have therefore been used. In the North Sea, the planktic foraminiferid *Globigerinatheka index* and the benthic *Cibicidoides truncanus* have their FDOs in the Late Eocene, a little below the Eocene/Oligocene boundary (King, 1989). Palynologically, the lowest occurrence of *Glaphyrocysta semitecta* and the highest occurrence of *Areosphaeridium diktyoplokum* are good markers for the earliest Oligocene in the Mediterranean area (Brinkhuis and Biffi, 1993). Together with the two foraminferids *G. index* and *C. truncanus*, the dinoflagellate *A. diktyoplokum* serves as a useful marker for the interval around the Eocene/Oligocene boundary in the North Sea.

The boundary between the dinoflagellate cyst zones D14 and D15 (Köthe, 1990) is defined by the FDO of *Rhombodinium draco* and the LDO of *Tuberculodinium vancampoae*. The latter is not useful in the present study due to the risk of caving. The FDO of *Rhombodinium draco* occurs in the Rupelian (30.24Ma) according to Hardenbol *et al.* (1998), while Köthe (1990; 1996) correlated this event with the Chattian. This discrepancy may be due to diachronism, reflecting palaeoceanographic and palaeoenvironmental changes within the seaway connecting the Tethys with the Northwest European Tertiary Basin (Pross 2001). The uncertainty caused by the possible diachronism of this zonal boundary is indicated in Fig. 6c with a slanted line.

The correlation of the FDO of *Wetzeliella gochtii* with chronostratigraphy is problematic. According to Hardenbol *et al.* (1998) this event is located in the Rupelian in NW Europe, while it is located in the Chattian in the Mediterranean area. Recently, Pross (2001, Fig. 1) showed that the FDO of *W. gochtii* is diachronous, and that its stratigraphic highest occurrence is found in the northernmost localities of the Northwest European Tertiary Basin. According to the studies referred to by Pross (2001, fig. 1), the FDO of *W. gochtii* varies from the lower part of the nannoplankton zone NP23 (mid Rupelian) for localities in the southern Upper Rhine Graben to the uppermost part of NP24 (lower Chattian) for localities in Belgium and northern Germany. It is therefore inferred that the FDO of *W. gochtii* in the present study indicates a lower Chattian stratigraphic level (Fig. 5c).

*Miocene*

The Palaeogene-Neogene System Boundary coincides with the Oligocene-Miocene Series boundary. The GSSP for this boundary is located in the Lemme-Carrosio section in the Piemonte Basin, Italy. The stratigraphic highest occurrence of *Distatodinium biffi* and the lowest occurrence of the dinoflagellate cyst species *Ectosphaeropsis burdigalensis*, both located closely below the boundary, are useful markers in the North Sea area (albeit safe use of the latter event is restricted to cored sections). Additional palynological markers in the North Sea area include the stratigraphic highest occurrences of the dinoflagellate genera *Chiropteridium* and *Deflandrea* that are both located closely above the boundary.

The planktic foraminiferid *Paragloborotalia kugleri* has its lowest occurrence 2 m above the Oligocene/Miocene boundary in the Lemme-Carrosio section, where it marks the base of the M1a Zone of Berggren *et al.* (1995). This species has not been encountered in the present study and the precise location of the boundary is not easily established in the North Sea based on microfossil evidence. Useful microfossil events that characterise the lowermost Miocene include the FDO of the diatom *Aulacodiscus insignis quadrata* (small morphotype, =diatom sp. 3 of King, 1983, 1989) and the FDO of the benthic foraminiferid *Brizalina antiqua* (King, 1989). The FDO of the planktic foraminiferid *Paragloborotalia nana* marks penetration to Chattian strata.

# Lithostratigraphy

## Rogaland Group (Deegan and Scull, 1977) emend. Hardt *et al.*, 1989

In the Central North Sea, the Rogaland Group encompasses the succession of Paleocene to Early Eocene marlstones and mudstones that overlies the Chalk Group (Deegan and Scull, 1977). The Rogaland Group itself is overlain by the mudstones of the Hordaland Group. In the Danish sector, the Rogaland Group is represented by the formations Vaale (=Våle of Hardt *et. al*, 1989), Lista, Sele and Balder (Fig. 7), the location of the correlation line is shown in Fig. 1d. Hardt *et al.* (ibid.) added three new sandstone units (Ty Formation, Hermod Formation and Meile Member) to the Rogaland Group. Although these sandstone units are broadly comparable to contemporaneous sandstone units in the Danish sector, the latter have a different provenance than that of the three units described from the Norwegian sector and they are not contiguous with them. Thus, the sandstone units in the Danish sector are described as new members herein.

**Comments.** In the Siri submarine canyon system (hereafter Siri Canyon), in the northern part of the Danish sector, concordant and discordant post-depositional sandstone intrusions occur in the surrounding mudstones. In some wells intrusive sandstones constitute up to 30 % of the total sandstone thickness. The sands have predominantly intruded the Ve Member (new member of the Lista Formation, see below), but are generally present at all levels in the Rogaland Group (Fig. 8a,b). The petrography of the intrusive sandstones is similar to that of the *in situ* sandstones and they are therefore most probably sourced from the latter. Most of the intrusive sandstones are only a few mm thick, but they may reach a thickness of 5 m. The intrusives are usually massive, but occasionally a faint lamination is present, especially at the top of the beds. In some wells the intrusive sandstones are chlorite cemented. Most of the intrusive sandstones bodies are separated by *in situ* mudstones, but they may also occur in intervals showing multiple intrusions. The boundaries to the host rock are slight to very irregular or wavy, and in places discordant. Small intrusions into the host rock (apophyses) are common. The intrusion of sand was mainly sub-horizontal, parallel to the bedding, and most of the intrusive bodies can be classified as sills.

In the Nini-3 cores, the Vile and Ve members of the Lista Formation are particularly rich in intrusive sandstones; the intrusions increase in number and thickness upward through the Vile Member to terminate in a large intrusive complex in the Ve Member (Fig. 9). Commonly, large amounts of mudstone clasts are present in the sandstones and in the intrusive complex in the Nini-3 well. When present, they may constitute from a few percent up to 90 % of the volume of the host sandstone. They are most abundant in the upper parts of the beds. The clasts range in size from a few mm to wider than the core diameter. Most of the clasts are angular, often with delicate protrusions. Most clasts are aligned parallel to the bounding planes of the intrusive sandstone body. In thick intrusions, flow banding and de-watering structures are occasionally present.

## Vaale Formation (Hardt *et al.*, 1989)

The Vaale Formation was established by Hardt *et al.* (1989) for marls with interbedded claystones, limestones and silt- and sandstone stringers that overlie the Chalk Group in the central and northern North Sea. The presence of a marly succession on top of the Chalk Group was previously mentioned by Deegan and Scull (1977) and treated informally as an equivalent to the more coarse-grained Maureen Formation in the UK Sector. Kristoffersen and Bang (1982) established the North Sea Marl for an exclusively marly and calcareous unit equivalent to the unnamed Maureen-equivalent unit of Deegan and Scull (1977). Although the description of the North Sea Marl fulfils the requirements for a formal description of a lithostratigraphic unit (formation) they stated that their unit was only informally established. As doubt therefore may be raised whether the unit has a formal status or not, and as results from subsequent drilling in the Danish sector has clarified that the unit needs a definition that allows for the presence of sandstones, it is considered herein that the Vaale Formation of Hardt *et al.* (1989) serves as a better name for the unit in the Danish Sector. For ease of use, the orthography of the formation name is changed from Våle to Vaale, replacing the exclusively Danish-Norwegian letter "å" with a double "a", which may be pronounced in the same way (as in "open").

**Type well.** Norwegian (N) well 1/3-1, 3258–3209 m below KB.

**Danish reference wells.** E-8X, 2060.3–2057.0 m below KB (Fig. 10); Siri-1, 2186.5–2156.3 m below KB (Fig. 11).

**Distribution and thickness.** The Vaale Formation is present throughout the North Sea Basin, except in a few areas where its absence is due to non-deposition or erosion. It is absent on intra-basinal highs (Hardt *et al.*, 1989) and in parts of the Siri Canyon where the Rogaland Group overlies the Chalk Group with an erosional unconformity. Towards the East, in the Danish Basin onshore Denmark, the Vaale Formation passes into the lithologically similar Kerteminde Marl. Its thickness varies from 0 to 48 m in the Danish North Sea sector. An isochore map of the Vaale Formation is shown in Fig. 12.

**Lithology.** Light grey to greenish grey, heavily bioturbated marlstones dominate the formation. In the Siri Canyon, the marls are interbedded with turbidite sandstones. Thin sandstone intrusions are present locally. The marl-sand interbedded succession in the Siri Canyon is established as a new member herein (Bor Member, see below).

**Macro- and ichnofossils.** Fragments of shelly macrofossils are present, but rare. The Vaale Formation is heavily bioturbated. Trace fossils in the Formation include *Chondrites* spp., *Phycosiphon* spp., *Planolites* spp. and *Zoophycos* spp. *Thalassinoides* spp. is only present locally.

**Lower boundary.** In most wells in the Danish Sector the boundary between the Chalk Group and the marlstones of the Vaale Formation is diffuse and difficult to position exactly (Fig. 13). On the petrophysical logs, the boundary is placed where the stable, low gamma ray response characteristic of the Ekofisk Formation starts to increase uphole and the high sonic readings likewise characteristic of the latter formation starts to decrease upwards. The change in the log pattern may be stepwise with each step represented by a small increase in gamma ray response and decrease in sonic reading. In most wells in the Siri Canyon there is erosional contact between the Chalk Group and the Vaale Formation and the formation boundary is sharp.

**Upper boundary.** Same as the lower boundary of the Lista Formation.

**Log characteristics.** From its base to its top, the Vaale Formation is characterised by an overall steady increase in gamma ray response, combined with an overall steady decrease in sonic readings. When the Bor Member sandstones are present, blocky log signatures of higher gamma ray response and sonic readings interrupt this trend.

**Depositional environment.** Over most of the Danish Sector the marlstones of the Vaale Formation comprise hemipelagic deposits and deposits from diluted turbidity currents. The foraminiferid fauna of the Vaale Formation is characterised by common calcareous taxa. Taxa belonging to the neritic "Midway-type" fauna are especially common. The planktic/benthic-ratio varies from approximately 1:1 in some areas to a total dominance of calcareous benthic foraminiferids in other areas. The microfauna composition indicates that the Vaale Formation was deposited in an open marine, outer neritic and periodically upper bathyal palaeoenvironment. The bottom conditions were predominantly oxic with periods of dysoxia. The indications from the microfauna is supported by the trace fossil assemblage, which indicates water depths of at least 200 m combined with oxic to dysoxic bottom conditions. In the Siri Canyon, where thin turbidites are frequent in the Vaale Formation, gravity flow played a major role during the deposition of the formation.

**Age.** Selandian.

**Biostratigraphy.** The Ekofisk Formation, which directly underlies the Vaale Formation, contains in its uppermost part the FDO of the planktic foraminiferid *Globoconusa daubjergensis*. Thus, the base of the Vaale Formation may be picked at the FDO of that species. The FDO of the yet undescribed taxon *"Spiniferites magnificus"* is an intra-Vaale marker. The FDO of the dinoflagellate *Alisocysta reticulata* marks a level in the middle to lower part of the Vaale Formation. *Alisocysta reticulata* is consistently present in the lowest part of the Kerteminde Marl, onshore Denmark, but absent from strata above. The oldest part of the Kerteminde Marl is coeval with the Lellinge Greensand which occurs onshore Denmark and in Storebælt

(Thomsen, 1994). The FDO of *A. reticulata* is therefore an important intra-Vaale as well as intra-Kerteminde Marl marker. Calcareous microfossil events within the Vaale Formation include the FDO of *Subbotina trivialis*, and common *Stensioeina beccariformis* and a downhole increase in the diversity of planktic foraminiferids.

**Correlation.** The Vaale Formation is equivalent with the Lellinge Greensand and the Kerteminde Marl Formations onshore Denmark. Of the two latter formations, the Lellinge Greensand is the older and has a more restricted distribution (in Sjælland and in Storebælt only). The Vaale Formation correlates with the lower Maureen (M1) of Knox and Holloway (1992).

## Bor Member (new)

The name Bor Member is given to sandstone-marlstone interbeds that occur within the Vaale Formation, or at its base or top. The unit was recognised by a stratigraphic working group at Statoil Norway in the mid 90's and informally named "Borr Member", under which name it has been subsequently recognised in company reports. The unit is formally described herein with its name maintained.

**Type well.** Danish (DK) well Augusta-1, 2963.4–2941.3 m below KB (Fig. 14).

**Reference well.** DK well Cecilie-1, 2319.4–2285.0 m below KB (Fig. 15).

**Etymology.** Named after Bor, the father of Odin. The name "Borr Member" for this stratigraphic unit was first used by a working group at Statoil Norway.

**Distribution and thickness.** The Bor Member has been encountered in the Siri Canyon mouth as well as in the nearby wells Tabita-1, Augusta-1 and Cleo-1 (Fig. 16a). It reaches a thickness of up to 23 m.

**Lithology.** The Bor Member encompasses olive green, partly calcite cemented sandstones, interbedded with Vaale Formation marlstones. The sandstones are very fine to fine-grained and well-sorted (Fig. 17). Rounded and translucent quartz grains dominate, but the contents of glaucony grains is high (20–25 %). Mica and pyrite concretions are present in small amounts. Angular chalk and claystone clasts occur locally in the sandstones.

**Macro- and ichnofossils.** Not observed.

**Boundaries.** The boundaries to the marlstones of the Vaale Formation, the mudstones of the Lista Formation or the chalks of the Ekofisk Formation are sharp and characterised by prominent shifts on the gamma ray and sonic logs.

**Log characteristics.** The Bor Member sandstones are best identified on the density log where they appear with a blocky pattern with density values significantly lower than that of the surrounding marlstones. On the gamma ray log the member is characterised by a blocky log signature with only small-scale increasing or decreasing intervals and with values clearly higher than those of the surrounding marlstones.

**Depositional environment.** The sandstones of the Bor Member were deposited from highly concentrated gravity flows deposited in a sub-tidal, bathyal environment.

**Age.** Selandian.

**Correlation.** The Bor Member has no lithological correlative onshore Denmark. It is possibly contemporaneous with the lower part of the Maureen Formation.

## Lista Formation (Deegan and Scull, 1977)

The Lista Formation was established by Deegan and Scull (1977) for the widespread non-tuffaceous, non-laminated mudstones that overlie the marls of the Vaale Formation. Herein, the Lista Formation is subdivided into six units, which are proposed as new members. Three are mudstone units: Vile Member, Ve Member and Bue Member; these have widespread distribution in the North Sea and can be correlated with Danish onshore exposures. In the Siri Canyon, fine-grained sandstones occur within each of the three mudstone units. These sandstones are proposed as three new members: Gerd Member for the sandstones in the Vile Member, Idun Member for the sandstones in the Ve Member, and Rind Member for the sandstones in the Bue Member.

**Type well.** N well 2/7-1, 2917.5–2872.5 m below KB.

**Danish reference wells.** E-8X, 2057.0–2027.6 m below KB (Fig. 10); Cleo-1, 2821.0–2765.5 m below KB (Fig. 18).

**Distribution and thickness.** The Lista Formation is present throughout the North Sea Basin, except in a few areas where it has been removed by erosion. In the Danish Sector, its thickness varies from 0 to 108 m. An isochore map of the total thickness of the Lista Formation is shown in Fig. 19.

**Lithology.** Dark coloured, predominantly greyish, greenish or brownish, non-laminated to faintly laminated, tuffaceous to non-tuffaceous mudstones. In the Siri Canyon, glauconic, massive sandstone layers and injected sandstone bodies occur in the Lista Formation.

**Macro- and ichnofossils.** Macrofossils have not been reported from the formation. The Lista Formation is moderately to heavily bioturbated.

**Lower boundary.** In most wells where the transition has been cored, the boundary between the light-coloured marls of the Vaale Formation and the dark-coloured, non-calcareous Vile Member (lowest mudstone member of the Lista Formation) is sharp. However, in other cores, as well as in Danish onshore sections, the boundary is gradual. On the gamma ray log the boundary is picked at a sharp upward shift to a higher response level than that of the underlying Vaale Formation marls. Usually, this level can be identified on the sonic log as well as at a velocity minimum. Above this minimum, the sonic readings increase slightly.

**Upper boundary.** Same as the lower boundary of the Sele Formation (see comment section below for further details on the Sele-Lista formation boundary).

**Log characteristics.** Both the gamma ray and the sonic log through the Lista Formation are characterised by moderate to big fluctuations about a relatively stable mean value generally higher than that of the underlying Vaale Formation, but lower than that of the overlying Sele Formation. In wells where mudstone facies dominate the Lista Formation, the log pattern can be subdivided into three parts. The three parts reflect the succession of three mudstone units, established as new members herein. See description of individual members below for details.

**Depositional environment.** The Lista Formation consists predominantly of hemipelagic mudstones and was probably deposited from very diluted turbidity currents and from suspension deposition from turbidite flows.

The microfaunal composition indicates a relatively open marine, upper to possibly middle bathyal depositional setting with oxic to dysoxic bottom conditions. This is based on the presence of a rich agglutinated foraminiferid fauna dominated by tubular suspension feeders (especially *Rhabdammina* spp.) together with epifaunal and infaunal detritivores (*e.g. Haplophragmoides* spp. and *Spiroplectammina spectabilis*). The relative abundance of tubular suspension feeders seems to be higher in wells in the Siri Canyon than in wells outside the Canyon. This may indicate slightly increased palaeodepths in the Siri Canyon than outside.

**Age.** The Lista Formation is Selandian to Thanetian (Upper Paleocene). The Selandian-Thanetian boundary may be placed in the lower part of the Ve Member, above the top of the Vile Member (new members, see below) and close to the FDO of the dinoflagellate *Palaeoperidinium pyrophorum*.

**Biostratigraphy.** The FDO of *Isabelidinium*? *viborgense* is an important intra-Lista and intra-Vile marker. The FDO of a diverse calcareous benthic foraminiferid fauna and an influx of radiolaria characterises the interval around the Vile Member-Ve Member boundary. The FDO of the dinoflagellate *P. pyrophorum* is in the lower part of the Ve Member in the Siri Canyon. Elsewhere, the event occurs at the top of the Vile Member or below it or above it (see details about the occurrence of that event in the Correlation section of the Vile Member section below). The FDO of the dinoflagellate *Alisocysta margarita* is located close to, but below, the top of the Ve Member. The FDO of an acme of the dinoflagellate *Areoligera gippingensis* characterises the middle part of the Ve Member. The last downhole occurrence (LDO) of the dinoflagellate *Apectodinium augustum* and of an acme of the genus *Apectodinium* occur in the lowermost part of the Sele Formation. These events are therefore useful markers for a level close to, but above the Lista-Sele Formation boundary, but are difficult to pick precisely on cuttings material. There is no FDOs directly at the boundary level, but he FDO of the short-ranged species *A. augustum* is close to, but above, the base of the overlying Sele Formation and may be used as an approximation for the Lista-Sele Formation boundary. Additional boundary markers are the reappearance of rare agglutinated foraminiferids downhole from the uppermost part of the Lista Formation.

**Correlation.** The Lista Formation may be correlated with the following succession of upper Paleocene units from onshore Denmark: Æbelø formation (informal mudstone unit), Holmehus Formation (Heilmann-Clausen *et al.*, 1985) and Østerrende Clay (informal mudstone unit) (Heilmann-Clausen, 1995).

**Comments.** The concept of the Lista formation used herein follows the original definition by Deegan and Scull (1977). It deviates from that of Knox and Holloway (1992) with respect to the position of the upper boundary of the formation (i.e. the base of the Sele Formation). That boundary was defined by Deegan and Scull at the contact between "non-laminated, non-tuffaceous shales" (Lista Formation) and "laminated tuffaceous shales" (Sele Formation) (Deegan and Scull, 1977, p. 34). This boundary definition is also followed by Mudge and Copestake (1992a,b), but differs from that used by Knox and Holloway (1992), who placed the boundary at the contact between "grey-green and green-grey, blocky, bioturbated claystones" (Lista Formation) and "dark grey fissile mudstones" (Sele Formation) (Knox and Holloway, 1992, p. 46). The Lista-Sele boundary *sensu* Knox and Holloway is below that of Deegan and Scull

(1977). The boundary concept of Knox and Holloway implies that a sediment package of grey, fissile, but non-laminated mudstones (the "non-laminated, non-tuffaceous shales" of Deegan and Scull, 1977) is incorporated in the Sele Formation where it constitutes the basal Sele unit S1a (Knox and Holloway, 1992). Following the boundary concept of Deegan and Scull (1977), the same unit is herein maintained in the Lista Formation as its topmost unit. It is further formalised as a new member herein (Bue Member, see below).

## Vile Member (new)

The name Vile Member is given to the widespread, dark olive-grey to dark grey, non-calcareous, swelly, fissile, smectite-rich mudstones that constitute the basal part of the Lista Formation. The unit was recognised by a stratigraphic working group at Statoil Norway in the mid 90's and informally named "Vile Formation", under which name it has been subsequently recognised in company reports. The latter name is maintained herein, but its status has been changed from (informal) formation to member.

**Type well.** DK well Siri-3, 2102.6–2072.6 m below KB (Fig. 20).

**Reference wells.** DK well E-8X, 2057.0–2042.7 m below KB (Fig. 10); DK well Cleo-1, 2812.0–2792.4 m below KB (Fig. 18).

**Etymology.** Named after Vile, the brother of Odin. The name was first used for this stratigraphic unit by a working group at Statoil, Norway.

**Distribution and thickness.** The sediments of the Vile Member have been recognised from a large number of wells in the Danish and Norwegian sectors of the Central North Sea, and the unit probably has a basinal distribution. However, it apparently lacks in a few wells in the Siri Canyon (Siri-1, Siri-1b and Connie-1) due to erosion. Over most of the Danish sector its thickness varies between 0 and 30 m. It greatest thickness is reached in the Siri Canyon. Strata similar to the Vile Member are known from wells and outcrops onshore Denmark under the name "Æbelø Formation" (see Correlation section). The latter formation is present in that area until the erosional boundary towards the Northeast.

**Lithology.** Dark olive-grey to dark grey, non-calcareous, swelling, smectitic, fissile mudstones. Thin silicified layers occur in the Vile Member. Calcite is commonly present as small nodules or larger concretions. In the Siri Canyon, small pyrite concretions and silty, very fine-grained glauconic sandstone or siltstone laminae are locally present in the Vile Member. The laminae have sharp bases, are normally graded and are parallel to the bedding in the mudstones. They are less than 1 cm thick and show parallel lamination.

In the Siri Canyon, the Vile Member is interbedded by thick, very fine to fine-grained well-sorted sandstone layers. These sandstone layers are established as a new member herein (Gerd Member, see below). Concordant or discordant, post-depositional sandstone intrusions are locally present; they are very common in the cored succession of the Nini-3 well. In the lower part of the Vile Member, the intrusives are only a few mm thick, but they increase in number and thickness towards the top of the member (Figs 21,22). In the upper part of the member, the intrusives are up to 60 cm thick. Top-bed rip-down mudstone clasts as described by Stow and Johansson (2000) are common (Fig. 22). The sandstone intrusions are either unconsolidated or cemented by calcite or non-calcitic carbonates. Fossil wood fragments are present, but rare.

**Macro- and ichnofossils.** The Vile Member is moderately to heavily bioturbated. Ichnogenera in the member include *Chondrites* spp., *Phycosiphon* spp., *Planolites* spp., and *Zoophycos* spp.

**Lower boundary.** Same as the lower boundary of the Lista Formation.

**Upper boundary.** Same as the lower boundary of the Ve Member.

**Log characteristics.** In most wells there is a gradual slight increase in gamma ray response up through the Vile Member accompanied with a slight decrease in sonic readings.

**Depositional environment.** The mudstones of the Vile Member are hemipelagic deposits, whereas the thin sandstone and siltstone laminae are interpreted as deposits of low-density turbidity currents. The faint lamination in the mudstones is interpreted as being mainly of biogenic origin, whereas the thin, graded mudstone laminae suggest deposition from very diluted turbidity currents. The depositional mechanism probably was a combination of sedimentation from diluted muddy turbidite currents, suspension from turbidity flows and air-born dust from onshore areas. The presence of *Zoophycos* spp. suggests water depths of at least 200 m (Bottjer and Droser, 1992).

**Age.** Selandian.

**Biostratigraphy.** The base of the Vile Member is marked by the downhole reappearance of planktic foraminiferids. The FDO of the dinoflagellate *Palaeoperidinium pyrophorum* marks the top of the Member in the Danish North Sea sector outside the Siri Canyon, but is situated below the top of the Vile Member in the Siri Canyon.

**Correlation.** Onshore Denmark, the Vile Member is represented by a unit of grey clay with silica- and carbonate-cemented layers. This unit was first described by Bøggild (1918) who named it Æbelø Formation. The unit was re-described by Heilmann-Clausen *et. al* (1985) and Heilmann-Clausen (1995). The dinoflagellate stratigraphy of the Æbelø Formation (as "grey clay" unit) at its type locality was provided by Heilmann-Clausen (1985).

The upper boundary of the Vile Member and the Æbelø Formation seems to be moderately diachronous both in the Danish onshore area and in the Danish North Sea sector, based on the FDO of the dinoflagellate *P. pyrophorum*. This event is located at the upper boundary of the Vile Member in the Central North Sea outside the Siri

Canyon, but below it in the Siri Canyon. In Jylland, the event is located above the equivalent onshore boundary (*i.e.* the boundary between the Æbelø Formation and the Holmehus Formation) (Heilmann-Clausen, 1985), but below it in south-eastern Denmark (Heilmann-Clausen, 1992). Moreover, the Vile Member is characterised by increasing diversity of benthic foraminiferids and radiolaria in a downhole direction from the top of the member.

## Gerd Member (new)

The name Gerd Member is given to sandstones that interbed with the Vile Member. The Gerd Member overlies the Vile Member or the Vaale Formation, or the Ekofisk Formation where the Vaale Formation is absent. Hardt *et al.* (1989) recognised a pure sandstone unit directly underlying the Lista Formation mudstones in the South Viking Graben and named it Ty Formation. The Ty Formation may, partly or entirely, be contemporaneous with the Gerd Member, but is not contiguous with it and has a different source area. In order to appreciate the different distribution and provenance of the sandstone unit encountered in the Danish sector it is proposed as a new member herein.

**Type well.** DK well Nini-3, 1803.0–1794.3 m, 1780.2–1764.1 m below KB (Fig. 23).

**Reference well.** DK well Cecilie-1, 2277.8–2242.3 m below KB (Fig. 15).

**Etymology.** Named after Gerd, the wife of Frej.

**Distribution and thickness.** The Gerd Member has only been encountered in the Siri Canyon and it may be restricted to that area (Fig. 16a). It reaches a thickness of up to 40 m.

**Lithology.** The sandstones of the Gerd Member are olive green to greenish green, very fine to fine-grained and well sorted (Fig. 24). Petrologically, rounded and translucent quartz grains dominate, but the contents of glaucony grains is high (15-20 %). The sandstones are olive green to greenish green due to the high contents of glauconies.

Mica and small pyrite concretions are present in small amounts. Angular chalk and claystone clasts occur locally in the sandstones. The sandstones are partly calcite cemented.

**Macro- and ichnofossils.** Not observed.

**Boundaries.** The boundaries to the mudstones of the Vile Formation, the marlstones of the Vaale Formation or the chalks of the Ekofisk Formation are sharp and characterised by prominent shifts in gamma response, sonic readings and on the density log.

**Log characteristics.** The Gerd Member is best identified on the density log where it is characterised by conspicuously lower density values than those of the surrounding mudstones. The gamma ray response is closely similar to that of the underlying Vaale Formation, but slightly lower than the response of the Vile Member. This makes it feasible to identify even minor sand units of the Gerd Member from mudstone beds of the Vile Member. Each larger sand unit may show upward decreasing or increasing gamma ray response. These trends do not seem to be related to grain size variations, judged from observations of the cores.

**Depositional environment.** The sandstones of the Gerd Member were deposited from highly concentrated gravity flows, but post-depositional liquefaction and fluidisation were the main mechanisms behind the present appearance of the Gerd Member sandstones.

**Age.** Selandian.

**Correlation.** There are no correlative units to the Gerd Member onshore Denmark. The Gerd Member may be partly or entirely contemporaneous with the Ty Formation of Hardt *et al.* (1989) and sandstone units in the upper part of the Maureen Formation (M2) referred to as the "Maureen Sandstone Member" (informal unit) in completion reports (*cf.* Knox and Holloway, 1992).

## Ve Member (new)

The name Ve Member is given to widespread green, bluish green, reddish brown and brown mudstones occurring in the middle part of the Lista Formation, overlying the dark grey-coloured mudstones of the Vile Member. The presence of the unit was recognised in the North Sea as the Holmehus Formation by Heilmann-Clausen *et al.* (1985), who gave no further details, and by Danielsen and Thomsen (1997); the latter authors indicated its presence in several wells. The name Holmehus Formation is herein proposed reserved for the onshore correlative to the Ve Member. The unit was also recognised by a stratigraphic working group at Statoil Norway in the mid 90's and informally named "Ve Formation" under which name it has been subsequently recognised in company reports. The latter name is maintained for the unit herein, but its status has been changed from (informal) formation to member.

**Type Well.** DK well Augusta-1, 2911.8–2902.6 m below KB (Fig. 14).

**Reference wells.** DK well E-8X, 2042.7–2030.3 m below KB (Fig. 10); DK well Cleo-1, 2792.4–2777.6 m below KB (Fig. 18).

**Etymology.** Named after Ve, brother of Odin. The name was first used for this stratigraphic unit by a working group at Statoil, Norway.

**Distribution and thickness.** The sediments of the Ve Member have been recognised from a large number of wells in the Danish and Norwegian sector of the Central North Sea, and the unit probably has a basinal distribution. Its thickness varies from 0 to 16 m in the Danish sector. Strata similar to the Ve Member are known from wells and outcrops onshore Denmark as the Holmehus Formation (Heilmann-Clausen *et al.*, 1985), and the unit is present in that area until the erosional boundary towards the Northeast (see Correlation).

**Lithology.** The Ve Member consists of alternating or mottled green, bluish green, reddish brown and brown mudstones. Mottled, purple coloured intervals are also present locally. The middle part of the member is often characterised by a thick dark reddish brown to chocolate brown interval. The Ve Member mudstones are non-calcareous and rich in smectite. Pyrite and carbonate concretions occur frequently. A weak biogenic lamination may sometimes be observed in cores. Ash layers, previously reported from the correlative Holmehus Formation by Nielsen and Heilmann- Clausen (1988) are also present in the Ve member, but are rare. Only very little organic material is present in the member. In the Siri Canyon, the Ve Member is interbedded by thick, very fine to fine-grained, well-sorted sandstone units. These sandstone layers are established as a new member herein (Idun Member, see below). In the Siri Canyon, the Ve Member hosts sandstone intrusions.

**Macro- and ichnofossils.** The mudstones of the Ve Member are heavily bioturbated. The most common trace fossils are *Phycosiphon* spp. and *Zoophycos* spp. *Chondrites* spp. and *Planolites* spp. are present but rare.

**Lower boundary.** The lower boundary to the Vile Member is placed at the first appearance of greenish, bluish or reddish-brown mudstones above the olive-grey to dark grey mudstones of the Vile Member. The colour change from the Vile to the Ve mudstones is often gradual and may be difficult to pick precisely, especially so when only cuttings samples are available. However, at the colour transition a gamma ray spike separates an interval with an increasing gamma ray response (below) from an interval of decreasing gamma ray response (above). In the absence of clear indication of the boundary level from colour change, the gamma spike at the shift from increasing to decreasing gamma ray response mentioned above may be used as marker for the boundary to the Vile Member.

**Upper boundary.** Same as the lower boundary of the Bue Member.

**Log characteristics.** The gamma ray response generally has a decreasing trend through the Ve Member, as opposed to the increasing trend through the underlying Vile Member. The sonic log is smooth and relatively stable through the Ve Member compared with the sonic pattern of the Vile Member. The log pattern of the Ve Member differs from that of the overlying Bue Member in having a lower gamma ray response level.

**Depositional environment.** The deposition of the mudstones of the Ve Member was controlled by hemipelagic sedimentation and sedimentation from diluted turbidites. The occurrence of the trace fossil *Zoophycos* spp. indicates a water depth of at least 200 m (Bottjer and Droser, 1992). The overall high degree of bioturbation and the greenish, bluish and reddish brown colours together suggest oxygenated bottom conditions.

**Age.** Selandian to Thanetian.

**Biostratigraphy.** In the Danish North Sea sector, the dinoflagellate *P. pyrophorum* has FDO at the base of the member in areas outside the Siri Canyon. In the Siri Canyon the event occurs below the base of the Ve Member, in the upper part of the Vile Member. The dinoflagellate assemblage from the Ve Member is rich in specimens of *A. gippingensis*.

**Correlation.** The Ve Member correlates with the Holmehus Formation (Heilmann-Clausen *et al.*, 1985), onshore Denmark and is lithologically indistinguishable from that formation (Heilmann-Clausen *et al.*, 1985).

## Idun Member (new)

The name Idun Member is given to sandstone units in the Ve Member in the Siri Canyon. Hardt *et al.* (1989) recognised an impure sandstone unit in the Lista Formation in the South Viking Graben and named it Heimdal Formation. The Heimdal Formation may be partly contemporaneous with the Idun Member, but is not contiguous with it and has another source area. In order to appreciate the different distribution and provenance of the sandstone unit encountered in the Danish sector it is proposed as a new member herein.

**Type well.** DK well Connie-1, 2367.8–2354.0, 2347.9–2332.6 m below KB (Fig. 25).

**Reference well.** DK well Siri-2, 2205.5–2127.0 m below KB (Fig. 26).

**Etymology.** Named after Idun, the goddess of youth.

**Distribution and thickness.** The Idun Member is known from the Siri Canyon only, and it may be restricted to that area (16b). It reaches a thickness of up to 179 m in the well Siri-2.

**Lithology.** The Idun Member consists of very fine to fine-grained, well-sorted sandstones (Fig. 27). Petrologically, rounded and translucent quartz grains dominate, but the contents of glaucony grains is high (15-25 %). The sandstones are olive green to greenish green due to the high contents of glauconies. Mica and small pyrite concretions are present in small amounts. Angular chalk and claystone clasts occur locally in the sandstones. The sandstones are partly calcite cemented. In the Nini and Siri wells the sandstones occur in thick amalgamated successions over- and underlain by Ve Member mudstones, whereas in the Connie-1 well the Idun Member is interbedded with Ve Member mudstones.

**Macro- and ichnofossils.** Not observed.

**Boundaries.** The boundaries between the sandstones of the Idun Member and the mudstones of the Ve Member are sharp and characterised by prominent shifts on both the gamma ray and sonic log. The Vile Member is absent from the Siri-1, Siri-1B and Connie-1 wells and an erosive unconformity separates the Idun Member sandstones from the marlstones of the Vaale Formation.

**Log characteristics.** The Idun Member is characterised by a blocky, upward decreasing gamma ray and density log pattern. Intervals with an overall constant gamma ray pattern may be further partitioned by many small-scale increasing or decreasing gamma ray cycles.

**Depositional environment.** The sandstones of the Idun Member were deposited from highly concentrated gravity flows. Post-depositional liquefaction and fluidisation have been the main mechanisms behind the present appearance of the Idun Member sandstones.

**Age.** Thanetian.

**Correlation.** There are no correlative units to the Gerd Member onshore Denmark. The Idun Member may be contemporaneous with the lower part of the Heimdal Formation of Hardt *et al.* (1989) and with the sandstones of the Lower Balmoral Sandstone and the tuffite of the May Sandstone Member of Knox and Holloway (1992).

## Bue Member (new)

The name Bue Member is given to the light to dark grey and greyish black mudstones that occur above the variegated mudstones of the Ve Member.

**Type well.** DK well Augusta-1, 2902.6–2893.7 m below KB (Fig. 14).

**Reference wells.** DK well E-8X, 2030.3–2027.6 m below KB (Fig. 10); DK well Cleo-1, 2777.6–2765.5 m below KB (Fig. 18).

**Etymology.** Named after Bue, the son of Odin and Rind.

**Distribution and thickness.** The sediments of the Bue Member have been recognised from a large number of wells in the Central North Sea, and the unit probably has a basinal distribution. Its thickness varies from 0 to 18 m in the Danish sector.

**Lithology.** The Bue Member consists of light to dark grey and greyish black mudstones. The mudstones are generally rich in smectite. The mudstones are sometimes thinly interbedded with very fine to fine-grained sandstone laminae, siltstones and mudstones. The sandstone laminae are less than two cm thick, have sharp bases, are normally graded and show parallel lamination (Fig. 28). Small calcite and siderite concretions are occasionally present. Moderately to heavily bioturbated intervals are interbedded with non-bioturbated intervals. Occasionally, tuff layers are present. In the Siri Canyon, the Bue Member is interbedded by thick, very fine to fine-grained well-sorted sandstone units. These sandstones are established as a new member herein (Rind Member, see below).

**Macro- and ichnofossils.** The trace fossils recognised in the Bue Member are *Planolites* spp., *Phycosiphon* spp., *Thalassinoides* spp. and rare *Zoophycos* spp.

**Lower boundary.** The transition from the Ve Member to the Bue Member is gradual and therefore difficult to position precisely. It may be placed where mottled green, bluish green, reddish brown and brown mudstones give way to grey mudstones. On the petrophysical log this transition is seen as a shift from decreasing to increasing gamma ray response or as an abrupt increase in gamma ray response.

**Upper boundary.** The upper boundary of the Bue Member coincides with the upper boundary of the Lista Formation and with the lower boundary of the Sele Formation, except where the Rind Member (new member, see below) sandstones constitute the top of the Bue Member.

**Log characteristics.** The gamma ray response is generally higher in the Bue Member than in the underlying Ve Member but lower than that of the overlying Sele Formation.

**Depositional environment.** The normally graded sandstone laminae indicate that deposition of the Bue Member took place from diluted low-density turbidity currents in a general sediment-starved environment. The small coarsening-upwards cycles may represent either small distal lobes or levee deposits of deep-water channel-sandstones.

**Age.** Thanetian.

**Biostratigraphy.** There is no biostratigraphic marker at the Ve-Bue boundary. However, the boundary is bracketed by the stratigraphic succession of the FDO of *A.*

*margarita* (occurring in the Ve Member) followed uphole by the FDO of an impoverished assemblage of benthic agglutinating foraminiferids (in the lower part of the Bue Member). The LDO of the dinoflagellate *Apectodinium augustum* and the coeval LDO of an acme of the genus *Apectodinium* in the lowermost part of the overlying Sele Formation are useful events for locating the Bue Member-Sele Formation boundary. There is no FDO event at the top of the Bue Member, but the FDO of the short-ranged dinoflagellate *A. augustum*, located in the lower part of the overlying Sele Formation may be used as an approximation of the Bue Member-Sele Formation boundary.

**Correlation.** The unit correlates with the "Østerrende Clay", an informal unit described by Heilmann-Clausen (1995) and with the S1a sub-unit of Sele (Knox and Holloway, 1992; see discussion in Comment section under Lista Formation for further details). The boundary between the Ve and the Bue Members can be correlated lithostratigraphically with the, likewise gradual, boundary between the Holmehus Formation and the Østerrende Clay onshore Denmark. A similar lithostratigraphic correlation was shown by Knox (1997, fig. 3).

## Rind Member (new)

The name Rind Member is given to sandstone units in the Bue Member in the Siri Canyon. Hardt *et al.* (1989) recognised an impure sandstone unit in the Lista Formation in the South Viking Graben and named it Heimdal Formation. The Heimdal Formation may be partly contemporaneous with the Idun Member, but is not contiguous with it and has another source area. In order to appreciate the different distribution and provenance of the sandstone unit encountered in the Danish sector it is proposed as a new member herein.

**Type well.** DK well Connie-1, 2329.9–2292.8 m below KB (Fig. 25).

**Reference well.** DK well Sandra-1, 2066.3–2004.8 m below KB (Fig. 29).

**Etymology**. Named after Rind, wife of Odin.

**Distribution and thickness.** The Rind Member has only been encountered in the Siri Canyon, and it may be restricted to that area (Fig. 16c). It reaches a thickness of 62 m.

**Lithology.** The Rind Member consists of very fine-grained, well-sorted sandstone (Fig. LI-13). Petrologically, rounded and translucent quartz grains dominate, but the contents of glaucony grains in the very fine to fine-grained size fraction is high (15-25 %). The sandstones are olive green to greenish green due to the high contents of glauconies. Mica and small pyrite concretions are present in small amounts. Angular chalk and claystone clasts occur locally in the sandstones. The sandstones are partly calcite cemented.

**Macro- and ichnofossils.** Not observed.

**Boundaries.** The boundaries between the sandstones of the Rind Member and the mudstones of the Bue Member are sharp and characterised by prominent shifts on both the density and sonic logs. It is difficult to identify the boundaries on the gamma ray log alone.

**Log characteristics.** The Rind Member is most easily recognised on the density log where it shows either a blocky or a serrate pattern where sandstone units and sandstone beds with low density are separated by beds of Bue Member mudstones with high density. The gamma ray log shows a low-amplitude serrate pattern. This pattern does not reflect alternating sand or mudstones.

**Depositional environment.** The sandstones of the Rind Member were deposited from highly concentrated gravity flows, but post-depositional liquefaction and fluidisation have been the main mechanisms behind the present appearance of the Rind Member sandstones.

**Age.** Thanetian.

**Correlation.** There are no correlative units to the Rind Member onshore Denmark. The Rind Member may be contemporaneous with higher parts of the Heimdal Formation of Hardt *et al.* (1989) and with the Upper Balmoral Sandstone of the May Sandstone Member of Knox and Holloway (1992).

## Sele Formation (Deegan and Scull, 1977)

The Sele Formation was established by Deegan and Scull (1977) for the dark grey to greenish grey, laminated and carbonaceous, tuffaceous, montmorillonite-rich shales and siltstones that overlie the non-laminated and non-tuffaceous shales of the Lista Formation in some areas, or arenaceous sediments belonging to a variety of different units in other areas. The original concept of the contents of the Sele boundary is followed herein. This implies that the base of the Sele formation is located at the base of the "laminated tuffaceous shales" that overlie the "non-laminated, non-tuffaceous shales" of the Lista Formation (Deegan and Scull, 1977, p. 34) (see Comment section under the Lista Formation above for further details). In the Danish sector, sandstone units occur in the Sele Formation; these are established as a new member, the Sif Member, herein.

**Type well.** UK well 21/10-1, 2100–2131 m below KB.

**Danish reference wells.** Siri-1, 2073.7–2048.1 m below KB (Fig. 11); Tabita-1, 2958.8–2941.4 m below KB (Fig. 30).

**Distribution and thickness.** The Sele Formation is recognised from the central and northern North Sea and it probably has a basinal distribution. In the Danish Sector, its thickness varies from 5 to 54 m. An isochore map of the total thickness of the Sele Formation is shown in Fig. 31.

**Lithology.** The Sele Formation consists of dark grey to black mudstones with intervals of lamination and with thin tuff layers. It contains three or more m-thick conspicuously laminated intervals where dm-thick black mudstone beds alternate with lighter coloured mudstone beds (Fig. 32). The laminated intervals are enriched in organic material and Uranium, and have a high gamma ray response. The darkest and most organic-rich interval is found in the basal part of the formation. The light coloured beds have sharp upper and lower boundaries and lack grading whereas the black beds are normally graded. Both bed types are characterised by mm-scale lamination internally (Fig. 32). Occasionally, the mm-scale laminae of the black intervals are normally graded, whereas the mm-scale laminae of the light coloured intervals normally lack grading. The mudstones of the Sele formation show an overall upward increase in the silt fraction and in the upper half of the formation the mudstones may be interbedded with thin, very fine-grained sandstone laminae and sandstone beds. The sandstone laminae and thin beds are up to 12 cm thick, normally graded and display parallel lamination. (Fig. 33). Locally, graded tuff laminae less than 1 cm thick are present in the formation. In cores, the tuff laminae have a light purple colour. Small calcite concretions are present, but rare. In the Siri Canyon, the Sele Formation is interbedded with sandstones or it grades upward into a succession of thinly interbedded sandstones and mudstones. The sandstone units in the Siri Canyon are proposed herein as a new member of the Sele Formation named Sif Member (see below).

**Macro- and ichnofossils.** Fish scales and skeleton fragments are common in cores from the Sele Formation. Bioturbation is very rare, but *Chondrites* spp. has been observed locally.

**Lower boundary.** When the Sele Formation overlies the mudstones of the Bue Member (Lista Formation), the boundary is characterised by a change from light to dark grey and greyish black non-laminated mudstones of the Bue Formation to dark grey to black laminated mudstones of the Sele Formation. On the gamma ray log, this change is marked by a conspicuous uphole shift to consistently higher gamma ray readings. This uphole gamma ray shift is situated closely below the base of the lowermost of several prominent gamma ray spikes in the Sele Formation. When the basal part of the Sele Formation contains sandstone of the Sif Member (see below) the base of the Sele Formation is picked at the base of the Sif Member. If the Sif Member overlies Rind

Member sandstones of the Lista Formation without any intercalating Bue Member mudstones, the Lista-Sele boundary is difficult to pick with certainty on lithology alone.

**Upper boundary.** Same as the lower boundary of the Balder Formation.

**Log characteristics.** The Sele Formation is characterised by high gamma ray readings throughout (the highest average gamma ray response of the entire Palaeogene succession) and includes at least two prolific gamma excursions, one at the base and one at the top of the formation. The most pronounced spike is found near or at the base of the formation, in the laminated mudstones. Between the high levels at the top and at the base there is an interval with depressed gamma readings. The sonic readings are high at the base of the formation but decrease to lower values towards the top of the formation.

**Age.** The lowermost part of the Sele formation is of Thanetian age; the remainder of the formation is of Ypresian age (See discussion in the Chronostratigraphy and Biostratigraphy Chapter for further details on the Paleocene-Eocene boundary).

**Biostratigraphy.** The LDO of an acme of the dinoflagellate genus *Apectodinium* and the coeval LDO of the short-ranged dinoflagellate *A. augustum* mark a level slightly above the base of the Sele Formation. The FDO of an influx of the dinoflagellate *Cerodinium wardenense* marks a level in the upper part of the Sele Formation. The FDO of an influx of the diatoms *Fenestrella antiqua* and *Coscinodiscus morsianus* is located in the uppermost part of the Sele Formation (Mitlehner, 1996).

The Sele Formation is generally characterised by high numbers of spores and pollen.

**Depositional environment**. The mudstones of the Sele Formation represent a mixture between pelagic fall-out and diluted, low-density, mud turbidites. The well-laminated character of the sediment, the high contents of organic material and Uranium, and the general lack of trace fossils indicate starved sedimentation under dysoxic to anoxic bottom conditions. The laminated mudstones contain few or no foraminiferids, but diatoms are common. The two observations in combination indicate a high nutrient level in the water mass and dysoxic to anoxic bottom conditions.

The tuffs of the Sele Formation are evidence of extensive volcanism in the region. The significant extinction of the benthic microfaunas during the deposition of the Sele Formation was most likely caused by a very effective isolation of the North Sea Basin (Schmitz *et al.*, 1996). The restriction and isolation of the basin was a result of a sea level fall, possibly combined with (or caused by) tectonic uplift (Knox *et al.*, 1981). Based on microfossils, the palaeoenvironment has been suggested to be upper bathyal with a palaeodepth of around 300 m (Mitlehner, 1996). However, the palynomorph assemblage indicates a much shallower environment characterised by a massive influx of terrestrial palynomorphs. On balance, it is believed that the Sele Formation was deposited in a marginal marine environment under considerable influx from terrestrial source areas.

**Correlation.** The Sele Formation approximately correlates with the Haslund Member (Heilmann-Clausen *et al.*, 1985) of the Ølst Formation (Heilmann-Clausen *et al.*, 1985) and with the equivalent, locally developed diatomitic Knudeklint Member of the Fur Formation (Pedersen and Surlyk, 1983) in Northwest Jylland (Danielsen and Thomsen, 1997).

The lower part of the Sele Formation, consisting of laminated, dark grey to black mudstones, is known from throughout the North Sea (Hardt *et al.*, 1989, Knox and Holloway, 1992). It correlates with the S1b unit of Knox and Holloway, 1992) and with the informal unit Stolle Klint Clay, which constitutes the lower part of the Haslund Member of Ølst Formation, onshore Denmark (Heilmann-Clausen, 1995). The lower boundary of the Sele Formation correlates precisely (both litho- and biostratigraphically) with the boundary between the Østerrende Clay and the Haslund Member of the Ølst Formation. The upper part of the Sele Formation may be correlated with the upper part of the Ølst Formation, onshore Denmark (Heilmann-Clausen *et al.*, 1985).

**Comments.** The Carbon Isotope Excursion that defines the Paleocene-Eocene boundary (see Chronostratigraphy and biostratigraphy chapter) coincides with a sudden proliferation of the dinoflagellate genus *Apectodinium* (Knox, 1996; Crouch *et al.*, 2000, 2001; Heilmann-Clausen and Schmitz, 2000). Onshore Denmark these event both take place at the base of the Stolle Klint Clay in the lowermost part of the Haslund Member of the Ølst Formation (Heilmann-Clausen and Schmitz, 2000). In the North Sea area the proliferation of *Apectodinium* occurs shortly above the base of the Sele Formation as defined by Deegan and Scull (1977), directly below the lowest of a series of prominent gamma spikes (see eg. Knox, 1996). Hence, the mentioned gamma spike may be used as an approximation for the Paleocene-Eocene boundary in the North Sea.

## Sif Member (new)

The name Sif Member is given to a sandstone unit within the Sele Formation encountered in the Siri Canyon. Hardt *et al.* (1989) recognised a pure sandstone unit within the Sele Formation in the South Viking Graben and named it Hermod Formation. The Hermod Formation may be contemporaneous with the Sif Member, but is not contiguous with it and has another source area. In order to appreciate a different distribution and provenance of the sandstone unit encountered in the Danish sector it is proposed as a new member herein.

**Type well.** DK well Siri-3, 2066.5–2036.2 m below KB (Fig. 20).

**Reference well.** DK well Nini-3, 1712.4–1700.6 m below KB (Fig. 23).

**Etymology.** Named after Sif, wife of Thor.

**Distribution and thickness.** The Sif Member has a restricted distribution in the Siri Canyon in the northern part of the Danish sector (Fig. 16c). It reaches a thickness of up to 30 m.

**Lithology.** The Sif member consists of fine-grained to very fine-grained, olive green to greenish grey, well-sorted, quartz-rich sandstones that occur encased in Sele Formation mudstones (Fig. 34). Rounded and translucent quartz grains dominate the mineralogical assemblage, but the content of glaucony grains is high (15–25 %). Mica and small pyrite concretions are present in small amounts. Angular chalk and mudstone clasts occur locally in the sandstones. Locally, the sandstones are partly cemented by calcite and chlorite. The member usually includes one thick unit composed of amalgamated sandstones and a number of thinner sandstone beds interbedded with Sele Formation mudstones.

**Boundaries.** The boundaries to the mudstones of the Sele or Lista Formations are sharp and characterised by prominent shifts on the gamma ray and sonic log.

**Log characteristics.** The Sif Member is clearly defined on the gamma ray log by a blocky pattern of intermediate response level. This is in contrast to the normally high gamma ray response level of the lower Sele Formation. A gradual upward decrease in gamma ray response seen in the lower part of the Sif Member in the well Nini-3 (Fig. 23) does not reflect grain-size change, judged from core examination. Densities in the Sif Member are lower than those of the adjacent Sele Formation.

**Biostratigraphy.** The Sif Member is characterised by abundance of *A. augustum*.

**Depositional environment.** The Sif Member sandstones were deposited from highly concentrated gravity flows. Post-depositional liquefaction and fluidisation have been the main mechanisms determining the present character of the Sif Member. Primary sedimentary structures are common in the Sif Member in the Sandra-1 well, indicating that the member has experienced less post-depositional liquefaction and fluidisation in that area.

**Correlation.** The Sif Member is possibly contemporaneous with the Forties Sand (Knox and Holloway, 1992) of the British Central Graben (=Hermod Formation of Hardt *et al.*, 1989).

## Fur Formation (Pedersen and Surlyk, 1983)

The Fur Formation is a marine diatomite with numerous ash layers, established from a coastal cliff exposure onshore Jylland, Denmark by Pedersen and Surlyk (1983). The characteristic lithology of the Fur Formation was subsequently recognised in cuttings samples from three wells located in the north-eastern part of the Danish North Sea and in one well in the Norwegian sector by Thomsen and Danielsen (1995) and Danielsen and Thomsen (1997). The formation was shown to exist in a narrow belt parallel to the southern coast of Norway. Onshore Denmark, west of the Limfjorden area, it reaches a thickness of 15 m, but it is considerably thinner in the North Sea. It reaches a thickness of 15 m in the Inez-1 well, but is only 3–4 m in the neighbouring C-1 and K-1 wells. On the petrophysical logs, the formation is identified on its low gamma ray response and sonic readings within intervals of generally higher values of the surrounding mudstones of the Sele and Balder Formations (Danielsen and Thomsen, 1997). In two of the Danish wells from where the Fur Formation has been encountered (Inez-1 and C-1), the diatomite is located in the Balder Formation; in the third well (K-1) it is located in the Sele Formation (Danielsen and Thomsen, 1997).

As the formation has a very limited distribution in the North Sea and as it is already described adequately in the literature both from its onshore and offshore sections, the Fur Formation is not further dealt with herein.

## Balder Formation (Deegan and Scull, 1977)

Deegan and Scull (1977) established the Balder Formation for the variegated fissile and laminated shales separating the Sele and Horda Formation. The formation is present throughout the Danish North Sea where it consists of dominantly medium grey mudstones overlying the dark grey mudstones of the Sele Formation and underlying the fissile greenish grey mudstones of the Horda Formation.

**Type well.** N well 25/11-1, 1705–1780 m below KB.

**Danish reference wells.** Mona-1, 2945.0–2930.8 m below KB (Fig. 35). Siri-3, 2016.8–1998.8 m below KB (Fig. 20).

**Distribution and thickness.** The Balder Formation extends over most of the central and northern North Sea. However, it lacks in the Danish well S-1 (Michelsen *et al.*, 1998). In the Danish sector outside the latter well, its reaches a thickness of more than 20 m in the Siri-3 and Frida-1 wells in the western part of the Danish sector and 20 m in Gwen-2 in the northern part of the Danish Central Graben. The Balder Formation thins to less than 5 m towards the Southwest and to less than 10 m in the eastern part of the Danish sector. An isochore map of the Balder Formation is shown in Fig. 36.

**Lithology.** The Balder Formation is composed of laminated, dominantly grey, fissile shales with inter-bedded dark and light grey, purple, buff and green sandy tuffs. The tuffs are normally graded and less than 5 cm thick. Locally the tuff beds are slumped. The tuffs may contain vertical lightning-shaped cracks filled with calcite. The cracks may extend up to 20 cm out from the base and top of the layers. The cracks commonly penetrate tuff layers above and below. Similar cracks have been reported from the Balder Formation in the Grane Field, Norwegian North Sea sector (Haaland *et al.*, 2000). Sandstone beds, interpreted as intrusive sandstone bodies, occur occasionally in the Balder Formation

**Macro- and ichnofossils.** Macrofossils not observed. The Balder Formation is non-bioturbated to moderately bioturbated.

**Lower boundary.** The contact to the underlying Sele Formation is gradational or occasionally sharp. When gradational, it is placed where the tuff layers become prominent. On the petrophysical logs, the lower boundary is identified at a significant uphole decrease in gamma ray response accompanied by an increase in sonic readings.

**Upper boundary.** Same as the lower boundary of the Horda Formation.

**Log characteristics.** The Balder Formation is characterised by a relatively high gamma ray response level at its base and top with very low values in the middle part of the formation. The decrease and subsequent increase of gamma response up through the section is normally gradual but relatively steep. The gamma motif is mirrored by a gradual increase in sonic readings commencing at the formation base, culminating in maximum values at or slightly below the level of minimum gamma ray response, followed by a gradual decrease towards the top of the formation where the lowest sonic reading is reached. The gamma and sonic motif together creates a characteristic barrel-shaped log motif in a log panel.

**Subdivision.** Knox and Holloway (1992) subdivided the Balder Formation into a lower Unit B1 and an upper Unit B2 based on the degree of lamination and the abundance of tuff layers (the B1 unit being laminated and having abundant tuffs, the B2 being poorly laminated with few tuff layers). The B2 unit is absent from Danish North Sea wells northeast of, and including, the Cecilie-1 well.

**Age.** The Balder Formation is Early Ypresian.

**Biostratigraphy.** Calcareous benthic foraminiferids are virtually absent from the Balder Formation. Penetration to the Balder Formation from above is indicated by a sudden drop in absolute abundance of that fossil group. The diatom *Fenestrella antiqua* characterises the formation and has FDO closely below the top of the Balder Formation. Palynologically, the lower boundary to the Sele Formation is marked by the FDO of an influx of the dinoflagellate *Cerodinium wardenense*. The dinoflagellate *Hystrichosphaeridium tubiferum* becomes common downhole from the lowermost part of the overlying Horda Formation and *Deflandrea oebisfeldensis* becomes common downhole from the upper part of the Balder Formation. Thus, the two events bracket the upper boundary of the Balder Formation.

**Depositional environment.** A restricted marine, upper bathyal palaeoenvironment with dysoxic to anoxic bottom conditions may be suggested for the Balder Formation. This is based on the scarcity of calcareous microfossils and agglutinating foraminiferids combined with common to abundant siliceous microfloras and –faunas, especially diatoms. Contrary to the overlying Horda Formation, the Balder Formation is characterised by abundant terrestrial palynomorphs. This palynofacies further supports a restricted (marginal) marine setting for the deposition of the formation.

The tuffs within the Balder Formation were deposited from the settling of pyroclastics in a marine environment. A petrographical and geochemical study of the Balder Formation in the Grane Field, Norwegian North Sea sector, shows that the tuffs can be classified as representing sub-alkaline basalts and basaltic andesites of intra-plate origin (Haaland *et al.*, 2000). The tuffs are similar to the contemporaneous Lower Basalts in East Greenland, the Rockall Trough and the Middle Series of the Faeroe Islands, all linked to the opening of the North Atlantic (Haaland *et al.*, 2000). The volcanic phase took place at 55-52 Ma.

**Correlation.** Although the B2 subunit of Knox and Holloway (1992) apparently lacks from wells in the north-eastern part of the Danish sector, both subunits can be correlated to strata onshore Denmark (although the B2 unit is very thin). The Unit B1 correlates approximately with the Værum Member of the Ølst Formation, in Jylland and, in NW Jylland, the contemporaneous Silstrup Member of the Fur Formation. The lower boundary of the Værum and Silstrup Members is placed at ash layer No. +1 in the tephrachronology of Bøggild (1918). The ash chronology is not identified in the type section of the Balder Formation and the precise correlation of the lower boundary is therefore uncertain. However, judged from the abundance of thick ash-layers in the Balder Formation and the scarcity of ash layers in the underlying Sele Formation, it is likely that the base of the Balder Formation may approximately correlate with ash layer no. +1, i.e. with the base of the Værum and Silstrup Members.

Unit B2 probably correlates with the Knudshoved Member of the Røsnæs Clay Formation. This member has a very restricted distribution in NW Jylland where it overlies the Silstrup Member of the Fur Formation. The Knudshoved Member consists of a lower, dark grey, pyritic clay unit rich in pyritised diatoms, and an upper, rather different, greenish clay unit (Heilmann-Clausen, 1982). Only a few, thin volcanic ash layers are present in the member (Håkansson and Sjørring, 1982). On lithological indication, it is suggested that at least the lower, pyritic, part of the Knudshoved Member may be correlated with the upper, tuff-poor Unit B2 of the Balder Formation.

## Hordaland Group (Deegan and Scull, 1977)

The Hordaland Group was established by Deegan and Scull (1977) for the light grey to brown, soft, fissile, marine shales with thin limestone streaks that overlie the Balder Formation of the Rogaland Group and underlie the undifferentiated Nordland Group. Knox and Holloway (1992) replaced the Hordaland Group with two: a lower Stronsay Group dominated by grey-green mudstones and an upper Westray Group dominated by grey-brown mudstones. In the central North Sea, and in most of the Danish Sector, each of the two groups is dominated by a single formation. The Horda Formation (Knox and Holloway, 1992) constitutes the bulk of the Stronsay Group and the Lark Formation (Knox and Holloway, 1992) constitutes the bulk of the Westray Group. Due to the limited number of formations present in the Hordaland Group in the Danish sector and to the largely similar lithology (both are marine mudstones), herein we maintain the Hordaland Group of Deegan and Scull (1977) with its two basinal formations Horda and Lark of Knox and Holloway (1992). Sandstone units occur at many levels in the Hordaland group along the basin margin in the Norwegian and British sectors, and have been established as formations or members (Deegan and Scull, 1977; Knox and Holloway, 1992). Sandstone units also occur in the Horda and Lark Formations along the basin margin in the Danish sector. These sandstones are described as new members of the Horda and Lark Formations herein.

## Horda Formation (Knox and Holloway, 1992)

The Horda Formation was established by Knox and Holloway (1992) for the basinal mudstone-dominated facies of their Westray Group (lower part of the Hordaland Group of Deegan and Scull, 1977 and Hardt *et al.*, 1989). In the Danish sector, the Horda Formation is characterised by fissile, greenish grey mudstones and claystones. The

Horda formation overlies the predominantly grey mudstones of the Balder Formation and underlies the non-fissile greenish grey to brownish grey mudstones of the Lark Formation.

**Type well.** UK well 22/1-1A, 1992-2379.5 m below KB.

**Danish reference wells.** Mona-1, 2930.8–2363.5 m below KB (Fig. 37); Siri-1, 2037.9–1916.5 m below KB (Fig. 38).

**Distribution and thickness.** The Horda Formation extends over the central and northern North Sea and is present in all wells in the Danish North Sea Sector. However, a part of the Horda Formation is lacking in the eastern wells R-1 and S-1 (Michelsen *et al.*, 1998). An isochore map of the Horda Formation is shown in Fig. 39. It reaches a thickness of 906 m in the Central Graben well Tordenskjold-1, but thins towards the East and Southeast to less than 100 m, with 9 m in the well Ida-1 and 4 m in the well S-1 being minimum values recorded from wells. The overall thinning of the Horda Formation towards the south-east is shown in Fig. 40a. Figure 40b shows the conspicuous thinning of the formation towards the Northeast.

**Lower boundary.** The base of the Horda Formation is placed at an uphole change from the laminated, predominantly grey mudstones with inter-bedded sandy tuffs of the Balder Formation to the non-laminated, greenish grey or red-brown mudstones and claystones of the basal part of the overlying Horda Formation. The Balder-Horda Formation boundary is somewhat subtle and often difficult to pick on petrophysical logs. On the sonic log, the base of the Horda Formation is picked where a gradual decrease in the upper part of the underlying Balder Formation is succeeded by relatively stable, but somewhat lower readings. Where the Nana Member (new member of the Horda Formation) overlies the Balder Formation directly, the boundary is characterised by a transition to a succession of mudstone-intercalated sandstone laminae.

**Upper boundary.** Same as the lower boundary of the Lark Formation.

**Lithology.** The dominant lithology of the Horda Formation is greenish-grey to greyish-green mudstone and claystone. Subordinate limestone benches and thin layers of black claystone occur at some levels in the formation. In many wells, particularly in the Central Graben, the lowermost 20–50 m of the Horda Formation consists of red-brown mudstone and claystone. This lithology is apparently lacking in the eastern wells of the area. A sandstone body within the Horda Formation has been encountered in the well Floki-1 in the northern part of the Danish Sector. This sandstone is established herein as a new member (Nana Member, see below).

**Macro- and ichnofossils.** Macrofossils not observed. The Horda Formation is moderately to strongly bioturbated.

**Log characteristics.** The Horda Formation is characterised by having an overall stable gamma ray and sonic log motif with a lower gamma ray response than that of the underlying Balder Formation and the overlying Lark Formation. In a few wells, the base of the Horda Formation has a relatively high gamma ray response level, which decreases to lower and more stabile values over a short interval. The sonic readings decrease slightly upwards from the base of the Horda Formation. In wells from the central and western part of the Danish Central Graben, the log break between the Horda Formation and the overlying Lark Formation is relatively subtle, whereas wells in the eastern part of the Danish Central Graben and wells East of that area show a conspicuous log break at the formation boundary.

**Subdivision.** On a seismic section, a three-fold subdivision of the Horda Formation is often feasible (Fig. 40b), the location of the seismic section of the figure is shown in Fig. 1c). This subdivided was already noted by Knox and Holloway (1992). In some central Graben wells, this subdivision may be recognised, based on shifts in log pattern on both gamma ray and sonic log (Fig. 37). In many wells where this subdivision can be recognised the three units are separated by subtle peaks on the gamma ray log. In the Danish wells studied, the subdivision apparently lacks pronounced lithological expression. Knox and Holloway (1992) noticed that the top of the lower of the three units is close to the FDO of the dinoflagellate *Eatonicysta ursulae*, and the top of the middle unit is close to the FDO of the foraminiferid *Spiroplectammina spectabilis*. This is supported by observations from the present study.

**Age.** The Horda Formation is Ypresian to earliest Rupelian and thereby spans all of the stages in the Eocene Epoch. A small hiatus seems to separate the base of the formation from the top of the underlying Balder Formation. The age of the top of the Horda Formation varies laterally: in wells to the East and North, the top is as old as Lutetian, whereas it is earliest Rupelian in Central Graben wells. This age distribution indicates that the top of the Horda Formation is diachronous, younging in a south-westerly direction. This is possibly due to increased erosion or longer intervals of non-deposition towards the north-east in the basin.

**Biostratigraphy.** The lowermost part of the Horda Formation contains the FDOs of the planctic foraminiferid *Subbotina* ex. gr. *linaperta*, which occurs abundantly, and the dinoflagellates *Dracodinium condylos*, *Deflandrea oebisfeldensis* and *Phelodinium magnificum*, indicating an early Ypresian age. In wells to the North and East od the Danish sector, the top of the Horda formation contains *Eatonicysta ursulae*, indicating an age as old as Lutetian. Central Graben wells contain the downhole succession of one or more of the dinoflagellate cyst events FDO *Areosphaeridium diktyoplokum,* FDO *A. michoudii,* FDO *Cerebrocysta bartonense* and FDO *Heteraulacacysta porosa* from the top of the formation, indicating an age as young as earliest Rupelian.

**Depositional environment.** The lower part of the formation contains microfauna significantly different from that of the underlying Balder Formation. The basal 5–40 m of the Horda Formation is characterised by a diverse foraminiferid fauna of both calcareous benthics and planktics (*e.g. Subbotina* ex. gr. *linaperta*) together with agglutinated foraminiferids. This indicates that the depositional setting was open marine, bathyal and with oxic bottom conditions.

The upper part of the Horda Formation is characterised by an abundant and diverse agglutinated foraminiferid fauna. Calcareous foraminiferids are very sparse or absent. The assemblage of *Rhabdammina discreta*, *Haplophragmoides* spp., *Recurvoides* spp.

and *Usbekistania charoides* indicate that the upper part of the Horda Formation was deposited in an upper bathyal palaeoenvironment with dysoxic bottom conditions. Radiolaria occur commonly in several narrow intervals, the lowest of which is slightly above the top of the lower, oxic part of the formation. The occasional influxes of radiolaria throughout the upper part of the formation suggest that deeper marine conditions became established periodically.

Palynofacies in the Horda Formation is generally dominated by a rich dinoflagellate assemblage with dispersed terrestrial matter (phytoclasts, spores and pollen) as a minor component, indicating an open marine environment with only limited influx from surrounding terrestrial areas.

**Correlation.** The Horda Formation can largely be correlated with the succession of Røsnæs Clay Formation (Heilmann-Clausen *et al.*, 1985), Lillebælt Clay (Heilmann-Clausen *et al.*, 1985), Søvind Marl Formation (Heilmann-Clausen *et al.*, 1985) and Viborg Formation (Christensen and Ulleberg, 1973), onshore Denmark. A hiatus is present between the Røsnæs Clay Formation and the underlying Ølst Formation.

The red-brown mudstones and claystones near the base of the Horda Formation in the central North Sea can be observed with only small lithological and thickness variations in the Danish onshore area. Here they constitute the Røsnæs Clay Formation and the lower part of the Lillebælt Clay Formation. The lower part of the Røsnæs Clay is calcareous.

The overlying main body of greenish and greyish mudstones of the North Sea succession can also be correlated with deposits onshore Denmark. The lower part of it has a similar lithology as that of the upper part of the Lillebælt Clay Formation and is of similar age. The upper part of the Horda Formation in the North Sea is represented by grey marls in onshore sections; the Søvind Marl Formation.

## Nana Member (new)

The name Nana Member is given to a sandstone unit that occurs close to the base of the Horda Formation in a restricted area in the northern part of the Danish sector.

**Type well.** DK well Floki-1, 1793.4–1731.3 m below KB (Fig. 42).

**Reference well.** The new member is only known from its type well.

**Etymology.** Named after Nana, wife of Balder.

**Distribution and thickness.** The Nana Member is only known from the Floki-1 well in the northern part of the Danish sector. As the unit currently cannot be identified on seismic sections, its distribution outside the Floki-1 well is unknown. Its thickness in the Floki-1 well is 62 m.

**Lithology.** The Nana member consists of greenish grey, fine-grained, immature sandstone with glauconies.

**Macro- and ichnofossils.** Not observed.

**Boundaries.** The boundaries to the mudstones of the Horda Formation are sharp and characterised by prominent shifts in gamma and sonic response.

**Log characteristics.** The Nana Member is characterised by a conspicuous blocky signature on the gamma ray, sonic and density logs. Gamma ray responses are lower than those of the surrounding Horda Formation.

**Age.** Ypresian, based on the age of the Horda Formation mudstones that overlie the Nana Member.

**Depositional environment.** The Nana Member sandstone is probably deposited from concentrated gravity flows, based on its similarity with the other fine-grained sand bodies in the area.

**Correlation.** The Nana Member is possibly contemporaneous with the Frigg Sandstone in the Norwegian sector (Hardt *et al.*, 1989).

## Lark Formation (Knox and Holloway, 1992)

The Lark Formation was established by Knox and Holloway (1992) for the brownish grey mudstone-dominated facies of their Westray Group (upper part of the Hordaland Group of Deegan and Scull, 1977; Hardt et al, 1989) overlying the more variable association of green-grey mudstones, silty mudstones or sandstones of the Horda Formation and underlying the grey, sandy and shelly mudstones and siltstones of the Nordland Group of Deegan and Scull (1977) (Knox and Holloway, 1992). The upper and lower boundary of the Lark Formation can be easily recognised in the Danish sector, both lithologically and on petrophysical logs. However, the lithology of the formation is more variable than that given in the original description. The Lark Formation can be subdivided into four mudstone packages in the Danish Sector; these units are characterised informally herein. The Lark Formation contains two sandstone units, established herein as the Dufa Member and Freja Member.

**Type well.** UK well 21/10-4, 1867-1217 m below KB.

**Danish reference wells.** Mona-1, 2363.5–1598.3 m below KB (Fig. 43); Siri-1, 1916.5–819.3 m below KB (Fig. 44).

**Distribution and thickness.** The Lark Formation extends over the central and northern North Sea area and is present in the entire Danish North Sea Sector. Its depocenter is in the north-western part of the Danish sector, along the eastern boundary of the Danish Central Graben where it reaches a thickness of 1194 m in the Siri-3 well. The Lark Formation thins towards the East and West to a thickness of 389 m in the Tordenskjold-1 well and 240 m in the S-1 well. The eastern and southern limit of the formation is not known due to insufficient seismic and well coverage. An isochore map of the Lark Formation is shown in Fig. 45.

**Lower boundary.** The base of the Lark Formation is marked by a change from flaky, micro-fissile, greenish-grey mudstone of the Horda Formation to non-fissile, crumbly, greenish-grey mudstone. In wells outside the Central Graben, the change in lithology at the formation boundary is characterised by a significant increase in gamma ray response. In Central Graben wells, the base of the Lark Formation is marked by a slight increase in gamma ray response to a consistently higher level than that of the underlying Horda Formation. Although the actual increase in gamma readings may be limited in these wells, the offset is usually sharp and well defined. On the sonic log, the transition from Horda Formation to Lark Formation is characterised by a transition from a stable sonic signature to one characterised by numerous fluctuations.

**Upper boundary.** The top of the Lark Formation (*i.e.* the base of the Nordland Group) is at a distinct high gamma ray peak. Above the distinct gamma ray peak there is a 20-40 m thick interval of elevated gamma ray response in the basal part of the Nordland Group. In the majority of wells studied herein, the top of the Lark formation is located directly at or closely below the top of a beige-grey mudstone unit. Therefore, the top of the latter unit may serve as a convenient approximation for the top of the Lark Formation. The beige-grey mudstone unit underlies medium grey to dark grey mudstones of the Nordland Group, characterised by intervals with shell-hash and coarse-grained sands.

**Lithology.** The lower third to half of the Lark Formation is dominated by dark greenish grey, crumbly, non-fissile mudstones, in some wells with subordinate intervals of brownish grey mudstones. This lower part of the formation also contains layers of white or reddish brown carbonates in its upper part. The upper half to two thirds of the Lark Formation is dominated by light to dark brownish grey mudstones with subordinate intervals of greenish grey mudstones in its lower part. The uppermost 50–100 m of the formation consists of beige-grey to beige-brown mudstones. Minor sand bodies occur in the upper part of the Lark Formation and at its very top in many wells in the eastern and northern part of the Danish Sector, two separate fine- to coarse-grained quart-rich sandstone intervals occur within the Lark Formation. The sandstone intervals are established as the new Dufa and Freja members herein (see below).

**Macro- and ichnofossils.** Macrofossils not observed. The Lark Formation is moderately to strongly bioturbated.

**Log characteristics.** The lower part of the Lark Formation is characterised by an overall stable gamma ray log signature. The upper part of the Lark Formation has an unstable gamma ray log signature. This change in gamma ray log signature coincides approximately with the change from lithologies dominated by greenish-grey mudstones to lithologies dominated by light to dark brownish grey mudstones. From the base of the Lark Formation and to its top, the sonic readings are relatively stable, with an overall-increasing trend. In wells from the eastern and northern part of the Danish sector, where minor sandstone layers become frequent towards the top of the formation, the gamma ray and sonic log pattern is serrated.

**Subdivision.** On seismic sections the Lark Formation may be subdivided into four main units, herein numbered Lark 1 through 4 from the base up (Fig. 46a,b; the location of the seismic section of the figure is shown in Fig. 1c). This subdivision may be recognised on petrophysical logs also (Fig. 47, the location of the correlation line is shown in Fig. 1d). The four units are bounded by five surfaces: Top Horda Marker, Lark 2 Marker, Lark 4 Marker, Upper Oligocene Unconformity (UOU Marker) and Top Lark Marker. Apart from the lowest unit (Lark 1) all units can be recognised over the entire study area.

*Lark 1 Unit* (Figs 46a,b;47;48a): The unit has been recognised in the north-eastern part of the Danish Sector only. It is bounded downwards by the Top Horda Marker and upwards by the Lark 2 Marker. On the gamma ray log the Lark 1 unit is characterised by a slight concave signature, going from relatively high gamma ray response level at the base, over a gamma ray low half way through the unit to increase approximately to the starting response level. On seismic sections it is characterised by downlapping reflectors. Lithologically it consists predominantly of greenish grey mudstones but includes also beige brown and dark grey mudstones. Its termination to the west and south is difficult to define precisely on the basis of log and biostratigraphy only. Figure 48a shows an isochore map of the Lark 1 unit. The unit is probably identical to Sequence 4 of Michelsen *et al.* (1998).

*Lark 2 Unit* (Figs 46a,b;47;48b): The unit is recognised over the entire Danish sector. It is bounded downwards by the Lark 2 Marker in the north-eastern part of the area, where it is underlain by the Lark 1 Unit, and by the Top Horda Marker elsewhere. It is bounded upwards by the Lark 4 Marker, or by the UOU Marker in the Central Graben area where the UOU and Lark 4 markers cannot be separated on the seismic sections. On the gamma ray and sonic logs the unit is characterised by a stable log signature with the indications on the gamma ray log of up to three slightly concave successions with signatures similar to that that characterises the Lark 1 unit. The lithology is characterised by dark beige-grey to greenish grey mudstones, greenish colours becoming dominant towards the top of the unit. An isochore map of the Lark 2 unit is shown in Fig. 48b.

*Lark 3 Unit* (Figs 46a,b;47;48c): The unit is encountered in the northern part of the Danish sector, East of the Central Graben. The unit cannot be discerned on logs or on seismic sections in the Central Graben area. It is bounded downwards by the Lark 4 Marker and upwards by the UOU Marker. The interval is characterised by stable gamma ray and sonic log signature. The lithology consists almost invariably of dark greenish grey mudstones. An isochore map of the Lark 3 unit is shown in Fig. 48c.

*Lark 4 Unit* (Figs 46a,b;47;48d): The unit is recognised over the entire Danish sector. The Lark 4 unit is bounded downwards by the UOU Marker and upwards by the Top Lark Marker. The interval is characterised by a slightly more unstable gamma ray and sonic log signature that those of the underlying units. The lithology is dominated by brown to beige brown mudstones, but in some wells an interval of greenish grey mudstones occur in its lower part. In wells to the East and North, minor sandstone layers intercalate with the mudstones in the Lark 4 unit; the sandstones become frequent towards the top of the unit in this area. An isochore map of the Lark 4 unit is shown in Fig. 48d.

**Age.** The Lark Formation is Bartonian to Serravallian (Upper Eocene to Middle Miocene) with Eocene sediments being present in the Lark 1 unit only. Lark 1 unit is Bartonian to lower Rupelian with its oldest base farthest to the North and East and with its base younging towards the South and West. A small hiatus, encompassing a part of the Bartonian stage, seems to separate the Lark Formation from the underlying Horda Formation in the North and East of the Danish sector. Lark 2 unit is Rupelian. Lark 3 unit is Rupelian in its lower part and Chattian in its upper part. The Rupelian/Chattian boundary is located in the upper part of the unit. The Chattian/Aquitanian (Oligocene/Miocene) boundary is located close to or at the base of the interval with brownish grey mudstones, coinciding with or closely above the UOU Marker. A hiatus is sometimes indicated at that unconformity by a number of coinciding biostratigraphic tops. The boundaries between the stages Aquitanian/Burdigalian, Burdigalian/Langhian and Langhian/Serravallian are all located in the Lark 4 unit, in the interval dominated by brownish-grey and beige-grey mudstones. The uppermost part of the Lark Formation is in the lower part of the Serravallian Stage.

**Biostratigraphy.** Farthest to the North and East the base of the formation includes the downhole succession of FDO *A. diktyoplokum,* FDO *A. michoudii* and FDO *H. porosa,* indicating a Bartonian age for the basal Lark Formation. The base of the Lark Formation is significantly younger in the Central Graben area where it contains FDOs characteristic of the middle and lower Rupelian Stage: *Phtanoperidinium amoenum, P. comatum* and *Achilleodinium biformoides*. The Top of the Lark Formation is bracketed by a number of easy recognisable bio-events. The uppermost part of the Lark Formation contains one or more of the events: FDOs of the benthic foraminiferids *S. subdehiscens, Asterigerina staeschei, Elphidium inflatum, Uvigerina tenuipustulata,* the FDOs of the planctic foraminiferids *Globorotalia praescitula, Globigerina angustiumbilicata* and *Alabamina tangentialis*, and the FDO of the dinoflagellate *Apteodinium spiridoides.* The lowermost part of the overlying Nordland Group contains one or more of the events: the FDOs of the benthic foraminiferid *Uvigerina hemmoorense,* the calcareous dinoflagellate cysts *Bolboforma metzmacheri*, *B. spiralis* and *B. clodiusi* and the organic walled dinoflagellate cyst *Spiniferites pseudofurcatus*.

**Depositional environment.** Based on seismic interpretation the Lark 1 unit represents a south and westward progradation of mudstones in an open marine environment. The Lark Formation displays significant microfaunal differences internally. The vertical (stratigraphic) faunal dissimilarities are, as a rule, more pronounced than the lateral. In general terms, the lowermost Bartonian to lowermost Rupelian part of the formation (Lark 1 unit) is characterised by abundant agglutinated foraminiferids dominated by *Rhabdammina discreta* and similar tubular taxa together with *Haplophragmoides* spp. and *Recurvoides* spp. The microfaunal composition indicates that the Lark 1 unit in many places was deposited in a dysoxic, upper bathyal palaeoenvironment.

The succeeding, mainly lower Rupelian to Chattian, middle part of the formation (Lark units 2 and most of Lark 3 unit) is characterised by increasing abundance and diversity of calcareous benthic and planktic foraminiferids. The relative proportion of agglutinating, calcareous planktic and benthic foraminiferids vary considerably from well to well. The calcareous planktic/benthic ratio is usually low, but in a few restricted intervals it may reach 1:2 or even 1:1. The mixed nature of the foraminiferid assemblages within the middle part of the Lark Formation indicates open marine, well-oxygenated bottom conditions in an outer neritic palaeoenvironment in most areas, with some lateral variations. A neritic setting for the Lark Formation is supported by the generally low planktic/benthic ratios in most intervals.

The upper part of the Lark Formation (upper Chattian to Serravallian, uppermost Lark 3 and Lark 4 unit) is generally poor in agglutinated foraminiferids and calcareous benthic foraminiferids dominate the microfossil assemblage. Epifaunal and shallow infaunal foraminiferids are more common than deep infaunal taxa, indicating continued well-oxygenated sea-bottom conditions during this interval. In general, the microfaunal composition in the upper part of the formation suggests that this part was deposited in a neritic, probably middle neritic palaeoenvironment in most areas of the Danish Sector, with some local variations.

The palynofacies assemblage of the Lark Formation is generally characterised by abundant dispersed terrestrial matter (phytoclasts, spores and pollen) indicating considerable influence from nearby land areas. However, the sediments were deposited in an open marine environment, based on the presence of a rich dinoflagellate assemblage. Successive pulses of progradation and backstepping of the palaeo-coastline is reflected in stratigraphic variations in relative abundance of terrestrial palynomorphs within the Lark Formation.

**Correlation.** The lowermost Lark 1 unit probably correlates with the upper part of the Søvind Marl Formation and the Viborg Formation, onshore Denmark. Intervals of Rupelian to lower Chattian age of Lark Unit 3, belonging to the NP 23 and NP 24 nannoplankton zones may be correlated with the onshore Danish Branden Clay (Ravn, 1906) based on lithological similarities and biostratigraphy (see Heilmann-Clausen, 1995 for discussion of the age of the Branden Clay). Intervals within the Lark Formation, at the Chattian-Aquitanian boundary may be correlated with the two lowermost, clay-rich units of the Vejle Fjord Formation, Brejninge Clay and Vejle Fjord Clay (Larsen and Dinesen, 1959). King (1994) correlated the two latter units with the NSB 8c Zone of King (1983) based on benthic foraminiferid biostratigraphy. This zone straddles the Oligocene-Miocene boundary and the boundary between the Lark Unit 3 and 4. The uppermost part of the Lark Formation possibly correlates with the onshore Arnum Formation (Sorgenfrei, 1958) and Hodde Formation (Rasmussen, 1961).

**Comments.** The log-based definition of the top of the Lark Formation is identical with its definition in the UK type well. In the north-western part of the Danish Sector, in the wells Nini-1, Vanessa-1, Cecilie-1, Upper Miocene sediments rest unconformably on the Lark Formation, and a portion of the uppermost Lark Formation is missing, probably due to erosion. Thus, in this area the top of the formation is more difficult to identify on petrophysical logs, but is clearly indicated on biostratigraphical data.

## Dufa Member (new)

The name Dufa Member is given to a thick sandstone unit that occurs within the Lark Formation in the northern and eastern part of the Danish sector.

**Type well.** DK well Inez-1, 697.1–485.5 m below KB (Fig. 49).

**Reference well.** DK well F-1, 337.5–324.3 m below KB (Fig. 50).

**Etymology.** Named after Dufa, daughter of Ægir and Ran and goddess of the sea.

**Distribution and thickness.** The Dufa Member is present in the north-eastern part of the Danish sector (Figs 51, 52), the location of the seismic section of Fig. 52 is shown in Fig. 1c). In the type well, the Dufa Member consists of 2 major sandstone units with thickness of 73 m (lower sandstone unit) and 120 m (upper sandstone unit). The two sandstone units are separated by a 20 m thick layer of Lark Formation mudstones. Towards the East, post-Palaeogene uplift and erosion has eroded the sediments away. Towards the North, the lower sandstone body has probably shaled out, whereas the upper sandstone body is present in the F-1X well (Fig. 52). The Dufa member is not present in wells west of the F-1X.

**Lithology.** The lower, relatively thin, aggrading sandstone unit predominantly consists of very fine- to fine-grained greenish-brown, muddy sandstone with mudstone stringers in its lower part. The upper, thicker and overall upward fining sandstone unit consists of medium- to coarse-grained, quartzitic, relatively pure sand with intervals rich in glauconies.

**Macro- and ichnofossils.** Not observed.

**Boundaries.** The boundaries to the mudstones of the Lark Formation are sharp and characterised by prominent shifts in gamma and sonic.

**Log characteristics.** The member is characterised by an overall blocky gamma ray log signature. In the type well, the lower part of the Dufa Member shows the presence of a number of 5–10 m thick sandstone units with a generally upward coarsening blocky gamma ray log signature. The sand units are separated by intervals of higher gamma ray response. The upper part of the Dufa Member is characterised by one large blocky interval with minor gamma ray spikes.

**Subdivision.** In the type well (Inez-1), the Dufa Member can be subdivided into two sandstone units separated by Lark Formation mudstones.

**Age.** The member is of Rupelian to ?Aquitanian age. In the type well, claystones directly below the Dufa Member belong to the Lark 1 Unit and yield a Priabonian age and claystones above the member are Aquitanian. However, there is no firm evidence for an age older than Rupelian in the Dufa Member.

**Depositional environment.** The Dufa Member sandstones represent deltaic, shallow marine deposits, and was probably deposited in pulses during a relative sea level low in the Rupelian-Aquitanian interval.

**Correlation.** On biostratigraphic evidence, the upper sandstone unit of the Dufa Member may be broadly contemporaneous with the Freja Member (new member, see below) further to the west. The Danish onshore succession has a hiatus between the Branden Clay of Rupelian to Chattian age and the Vejle Fjord Formation of Chattian to Aquitanian age, and safe correlation with the Danish onshore section is currently not feasible.

## Freja Member (new)

The name Freja Member is given to the fine- to coarse-grained sandstones that occur within the upper part of the Lark Formation in the northern part of the Danish Sector. The Freja Member consists of up to three sandstone layers, separated by thin layers of Lark Formation mudstone.

**Type well.** DK well Francisca-1, 1840.7–1559.8 m below KB (Fig. 53).

**Reference well.** DK well Frida-1, 1623.5–1487.7 m below KB (Fig. 54).

**Etymology.** Named after Freja, First wife of Odin and goddess of love and fertility.

**Distribution and thickness.** The Freja Member is present in the northern, central part of the Danish sector and is known from the wells Frida-1, Francisca-1 and Cecilie-1 (Figs 51,55), the location of the seismic section of Fig. 55 is shown in Fig. 1c). The Freja Member is absent to the North and to the East, in the wells Nini-1 and Vanessa-1. In its type well, the Freja Member spans a stratigraphic interval of 280 m and consists of three sandstone units, separated by two intervals of Lark Formation mudstones. The uppermost unit is 100 m thick, the middle unit is 30 m thick and the lower unit is 115 m thick. In the Cecilie-1 well, the member span 150 m and encompasses two sandstone units, in the Frida-1 well one sandstone unit is present with a thickness of 130 m.

**Lithology.** In its type well, the lowermost unit of the Freja member and the lower half of the middle unit consists of quarzitic sandstone with many mudstone beds, becoming less muddy in the upper part of the middle unit which is dominated by very fine- to fine-grained sandstone. The upper unit consists of relatively pure quarzitic, very fine-grained sandstone.

**Boundaries.** The boundaries to the surrounding Lark Formation mudstones are sharp and characterised by prominent shifts in gamma ray and sonic log response.

**Log characteristics.** The Freja Member has an overall blocky gamma ray log signature. In the type well the Freja Member can be divided into three units, each with a blocky gamma ray log pattern. The lower unit can be split into a number of smaller units with blocky or mainly upward increasing gamma ray log signature separated by abundant gamma ray highs. In comparison, the two upper units have a consistent low gamma ray log pattern with few gamma ray log spikes. The mudstone-dominated interval separating the three units generally has high gamma ray values; however, thin sandstone units with upward decreasing gamma ray values intercalate the upper mudstone dominated interval.

**Age.** The Freja Member in its type well is Chattian to Aquitanian, with its base possibly as old as Rupelian. In the Frida-1 well, it is entirely Chattian.

**Depositional environment.** Sandy turbidite deposits dominate the 75 metres of core available from the Freja Member in the Francisca-1 well. The sandy parts of the Freja Member can be subdivided into successions, each representing a transition from sand-dominated turbidites to overlying open slope deposits. The lower part of these successions consists of thick- and thin-bedded turbidite sands deposited in submarine channels and proximal levee environments. The upper part of the turbidite successions shows a transition through normally graded turbidites deposited in slightly more distal levee environments and minor turbidite channels, to mainly silty turbidite deposits that represent distal levee and fan fringe environments and the transition to open slope. The source of the sand is probably a marginal marine shelfal environment, judged by the abundance of the acritarch *Paralecaniella indentata* in the Freja Member (Dybkjær, 2003, this Volume).

**Correlation.** The upper part of the Freja Member in the Frida-1 well correlates with the Brejning Clay of the Vejle Fjord Formation (Larsen and Dinesen, 1959).

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## Figure captions

Fig. 1a. Well location map showing all wells used in the study.

Fig. 1b. Position of log panels shown as enclosures 1–5.

Fig. 1c. Position of seismic sections shown as Figs 40a,b, 46a,b, 52 and 55.

Fig. 1d. Position of log correlations shown as Figs 7, 41 and 47.

Fig. 2. Revised stratigraphic column for the Palaeogene of the Danish North Sea sector.

Fig. 3. Stratigraphic correlation between key lithostratigraphic schemes for the Central and Eastern North Sea, group level.

Fig. 4. Stratigraphic correlation between key lithostratigraphic schemes for the Central and Eastern North Sea, formations and members, formations and members.

Fig. 5a. Paleocene chronostratigraphy and biostratigraphy. The chronostratigraphy is based on the scheme of Berggren *et al.* (1995). The majority of the selected microfossil and dinoflagellate events are chronologically placed according to the age estimates by Hardenbol *et al.* (1998, chart 3). In the microfossil event column, the planktic foraminiferid events have been written in normal, benthic foraminiferids in italics and diatoms and radiolarians are underlined. The microfossil events are correlated with the biostratigraphic zonation of King (1989), and - together with the dinoflagellate events - further correlated with the main lithostratigraphic units.

Fig. 5b. Eocene chronostratigraphy and biostratigraphy. Explanation as in Fig. 5a.

Fig. 5c. Oligocene and Lower to Middle Miocene chronostratigraphy and biostratigraphy. Explanation as in Fig. 5a.

Fig. 6a. Correlation of selected Paleocene biostratigraphic standard biozones and North Sea biozones. The standard biozones are adopted from Berggren and Miller (1988) with later revisions of Berggren *et al.* (1995) (planktic foraminiferids) and from Martini (1971) (nannoplankton). The correlation follows the scheme by Hardenbol *et al.* (1998). The North Sea biozones, which serve as a biostratigraphical base for the present

paper, are adopted from King (1989) (foraminiferids) and Costa and Manum (1988), Köthe (1990) and Mudge and Bujak (1996) (dinoflagellates).
Fig. 6b. Correlation of selected Eocene biostratigraphic standard biozones and North Sea biozones. Explanation as in Fig. 6a.
Fig. 6c. Correlation of selected Oligocene and Lower to Middle Miocene biostratigraphic standard biozones and North Sea biozones. Explanation as in Fig. 6a.

Fig. 7. Log panel illustrating relative uniform thicknesses of the Rogaland Group formations in Danish Central Graben. Wells included are Kim-1, Mona-1, Cleo-1, Gulnare-1 and E-8x.

Fig. 8. Core log from Vaale and Lista Formations in Cecilie-1 showing intrusive sandstone complex.

Fig. 9. Core photo, intrusive sandstone complex in the Ve Member in Cecilie-1.

Fig. 10. E-8X, Danish reference well for the Vaale Formation and Lista Formation. Reference well for Vile Member, Ve Member and Bue Member.

Fig. 11. Siri-1, Danish Reference well for the Vaale Formation and the Sele Formation.

Fig. 12. Isochore map of the Vaale Formation in the Danish North Sea sector.

Fig. 13. Core photo of the Ekofisk Formation-Vaale Formation boundary in the well Augusta-1.

Fig. 14. Augusta-1, type well for the Bor Member, Ve Member and Bue Member.

Fig. 15. Cecilie-1, reference well for the Bor Member and Gerd Member.

Fig. 16a. Distribution of the Bor Member and Gerd Member sandstones in the Siri submarine Canyon system.

Fig. 16b. Distribution of the Idun Member sandstones in the Siri submarine Canyon system.

Fig. 16c. Distribution of the Rind Member and Sif Member sandstones in the Siri submarine Canyon system.

Fig. 17. Core log of Bor Member sandstone in the well Augusta-1.

Fig. 18. Cleo-1, Danish reference well for the Lista Formation and reference well for Vile Member, Ve Member and Bue Member.

Fig. 19. Isochore map of the Lista Formation in the Danish North Sea sector.

Fig. 20. Siri-3, type well for Vile Member and Sif Member, and Danish reference well for the Balder Formation.

Fig. 21. Core log showing intrusive sandstones in Vile and Ve Members in the well Nini-3.

Fig. 22. Core photos showing sandstone intrusions, flow banding and top bed rip-down clasts in the Vile and Ve Members in the well Nini-3.

Fig. 23. Nini-3, type well for the Gerd Member, reference well for the Sif Member.

Fig. 24. Core log of Gerd Member sandstones in the well Nini-3.

Fig. 25. Connie-1, type well for the Idun Member and the Rind Member.

Fig. 26. Siri-2, reference well for the Idun Member.

Fig. 27. Core log of Idun Member and Rind Member sandstones in Connie-1.

Fig. 48a. Isochore map of Lark Formation sub-unit Lark 1.

Fig. 48b. Isochore map of Lark Formation sub-unit Lark 2.

Fig. 48c. Isochore map of Lark Formation sub-unit Lark 3.

Fig. 48d. Isochore map of Lark Formation sub-unit Lark4.

Fig. 49. Inez-1, type well for the Dufa Member.

Fig. 50. F-1, reference well for the Dufa Member.

Fig. 51. Isochore map of the Lark Formation showing the distribution of the Dufa Member and the Freja Member.

Fig. 52. Composite seismic section RTD81-RE94-45/RTD81-RE94-09 showing the outline of the Dufa Member. The GR logs from the wells Inez-1 and F-1 are inserted. The location of the seismic line is shown on Fig. 1c.

Fig. 53. Francisca-1, type well for the Freja Member.

Fig. 54. Frida-1, reference well for the Freja Member.

Fig. 55. Composite seismic section DK1–5623A RE94/DK1–0448B RE94 with the Freja Member outlined and the Francisca-1 Gr log inserted. The location of seismic section is shown on Fig. 1c.

## Enclosures

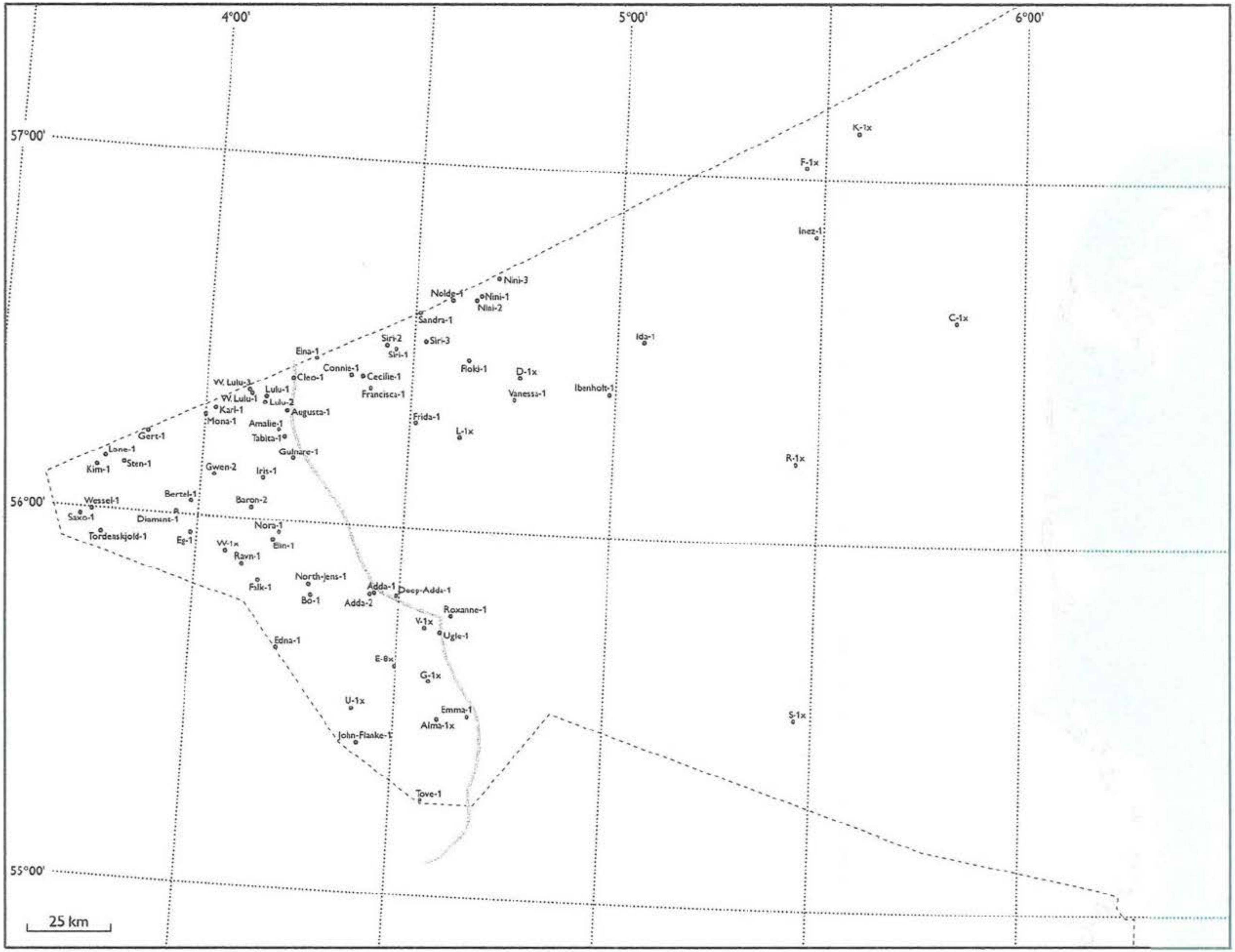
Enclosure 1. East-West trending log panel Saxo-1–Inez-1. Stratigraphic interval: top Chalk Group to Top Lark Formation. Base line: top Horda Formation. The vertical scale is 1:4000.

Enclosure 2. North-South trending log panel West Lulu-3–Tove-1. Stratigraphic interval: top Chalk Group to Top Lark Formation. Base line: top Horda Formation. The vertical scale is 1:4000.

Enclosure 3. North–South trending log panel Lone-1–John Flank-1. Stratigraphic interval: top Chalk Group to Top Lark Formation. Base line: top Horda Formation. The vertical scale is 1:4000.

Enclosure 4. North-South trending log panel Nini-3–John Flank-1. Stratigraphic interval: top Chalk Group to Top Lark Formation. Base line: top Horda Formation. The vertical scale is 1:4000.

Enclosure 5. North-South trending log panel K-1–S-1. Stratigraphic interval: top Chalk Group to Top Lark Formation. Base line: top Horda Formation. The vertical scale is 1:4000.



4°00'
5°00'
6°00'
57°00'
56°00'
55°00'
25 km
K-1x
F-1x
Inez-1
C-1x
Nini-3
Nolde-1
Nini-1
Nini-2
Sandra-1
Ida-1
Siri-2
Siri-1
Siri-3
Elna-1
Floki-1
D-1x
Connie-1
Cleo-1
Cecilie-1
Francisca-1
Vanessa-1
Ibenholt-1
W. Lulu-3
Lulu-1
W. Lulu-1
Lulu-2
Karl-1
Augusta-1
Mona-1
Frida-1
Amalie-1
L-1x
Gert-1
Tabita-1
Lone-1
Gulnare-1
R-1x
Kim-1
Sten-1
Gwen-2
Iris-1
Bertel-1
Wessel-1
Baron-2
Saxo-1
Diamant-1
Nora-1
Tordenskjold-1
Eg-1
W-1x
Elin-1
Ravn-1
North-Jens-1
Falk-1
Adda-1
Deep-Adda-1
Bo-1
Adda-2
Roxanne-1
V-1x
Ugle-1
Edna-1
E-8x
G-1x
U-1x
Emma-1
S-1x
Alma-1x
John-Flanke-1
Tove-1


Fig.1a

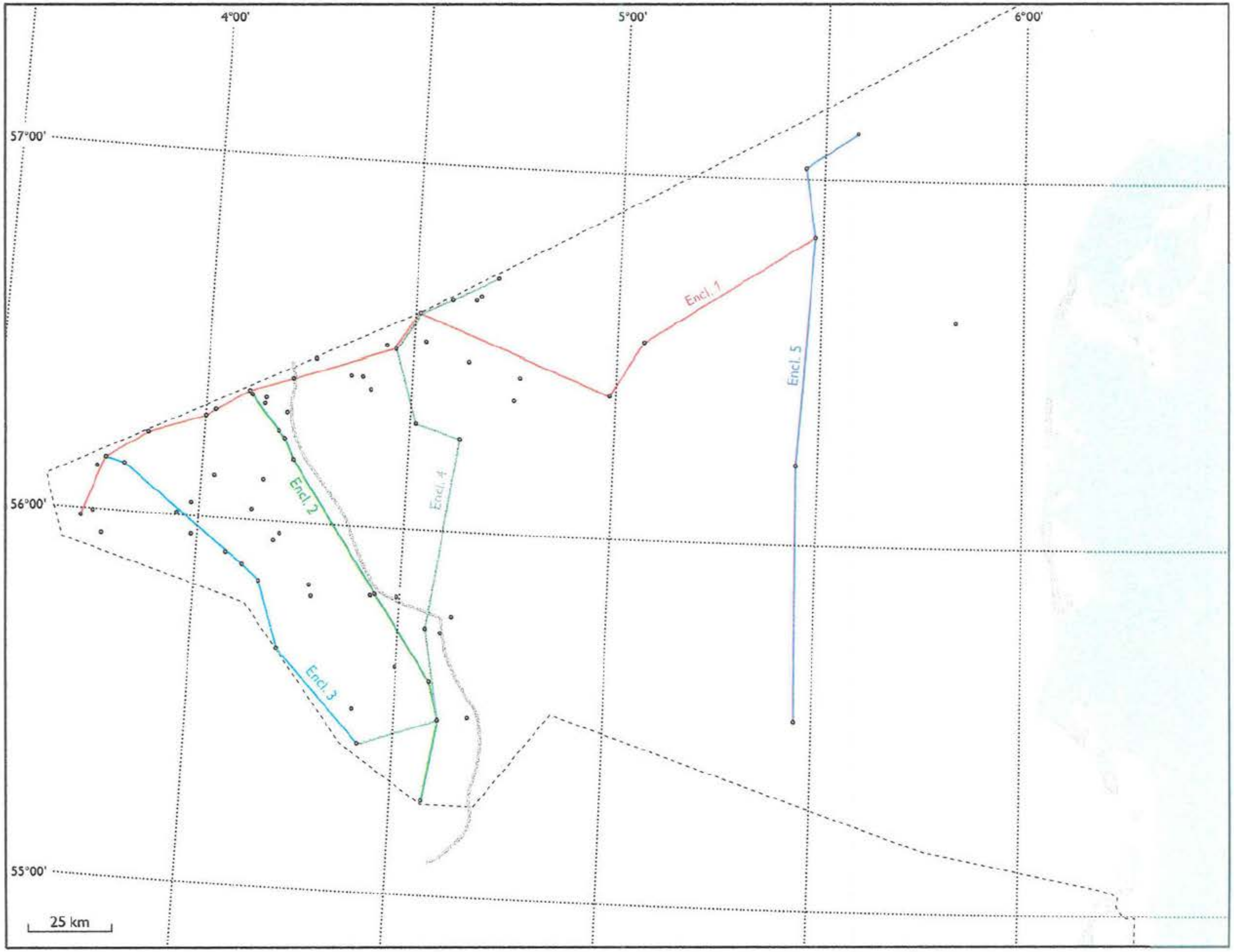

4°00'
5°00'
6°00'
57°00'
56°00'
55°00'
Encl. 1
Encl. 2
Encl. 3
Encl. 4
Encl. 5
25 km

Fig.1b

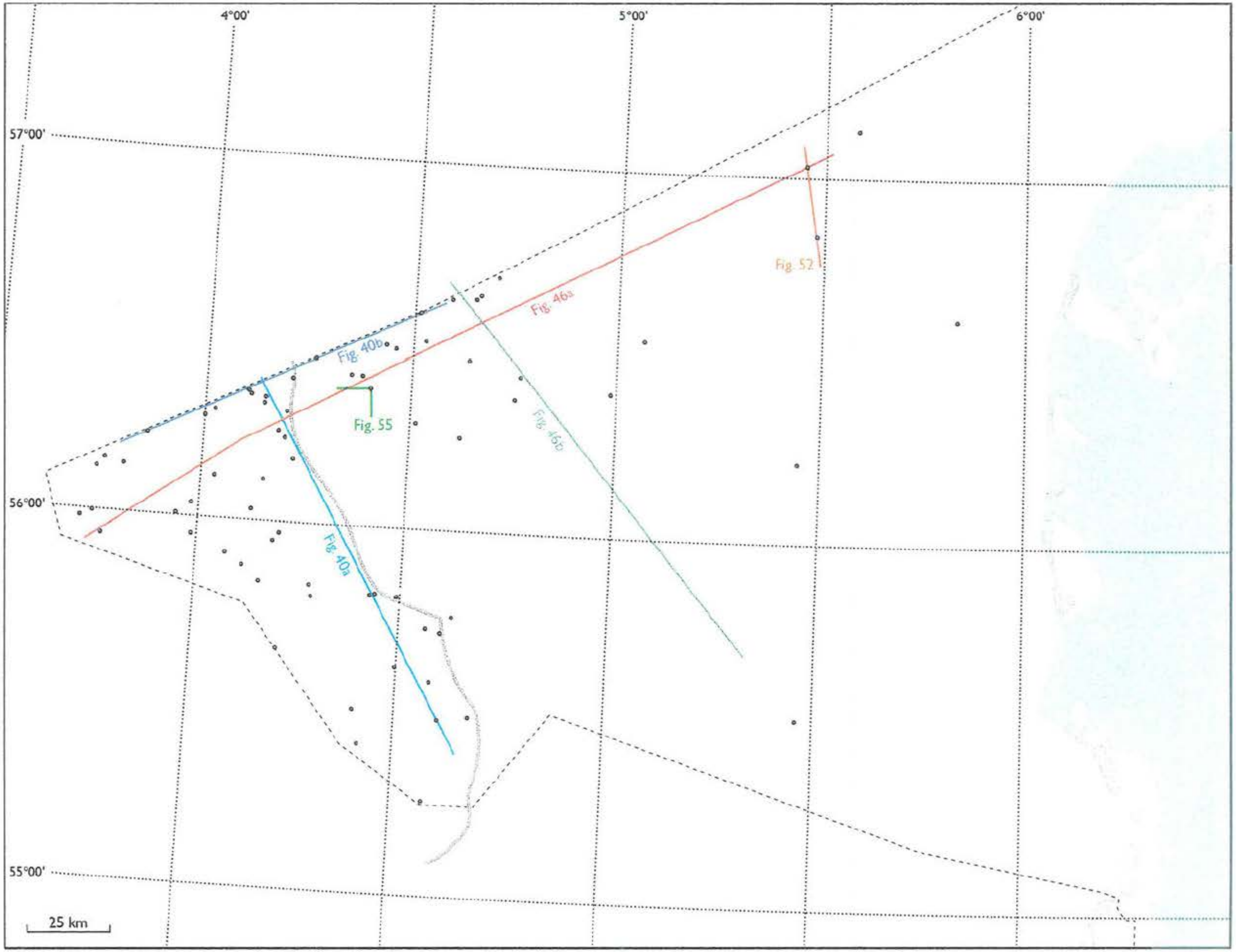

4°00'
5°00'
6°00'
57°00'
56°00'
55°00'
Fig. 40b
Fig. 46a
Fig. 52
Fig. 55
Fig. 46b
Fig. 40a
25 km

Fig.1c

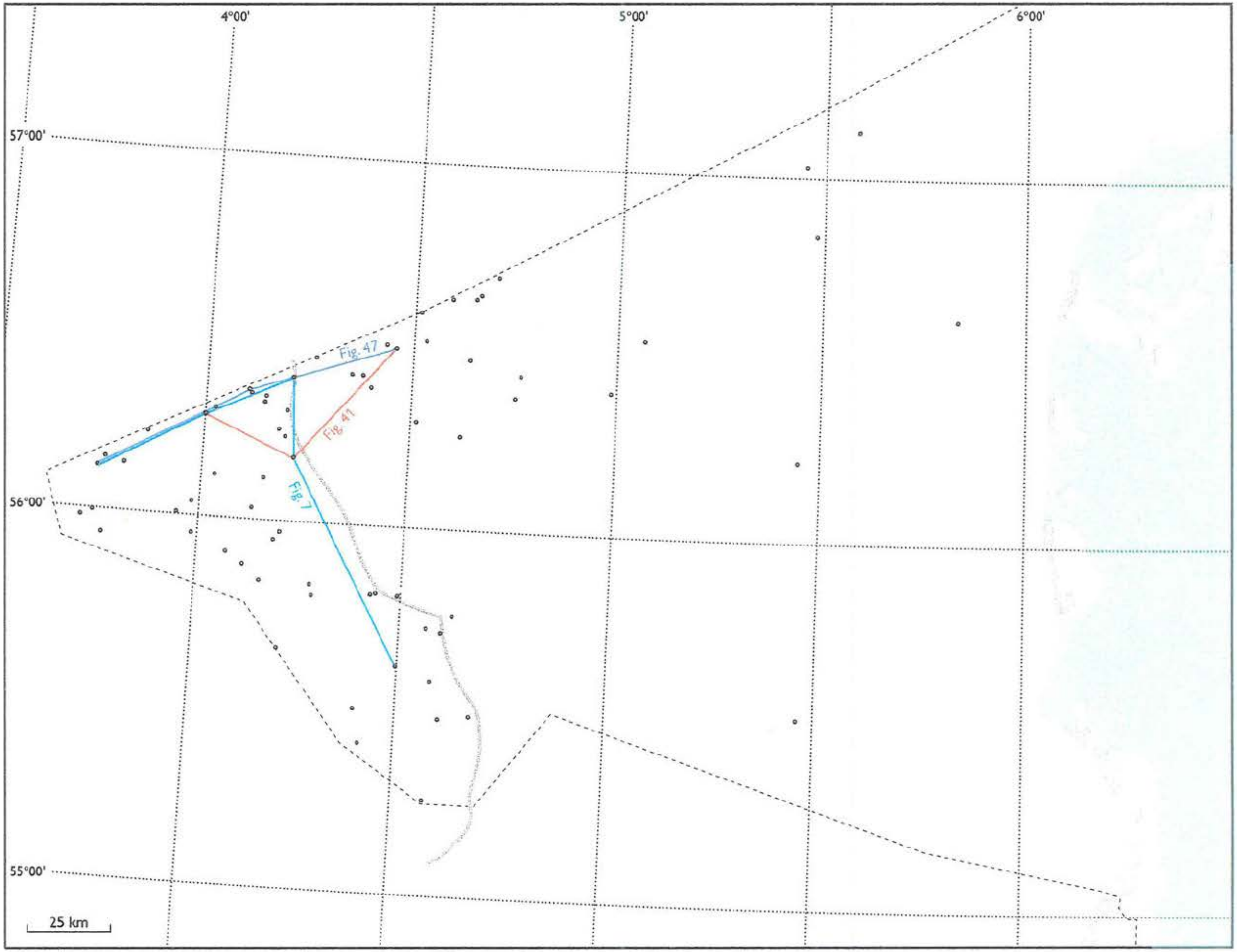



Fig.1d

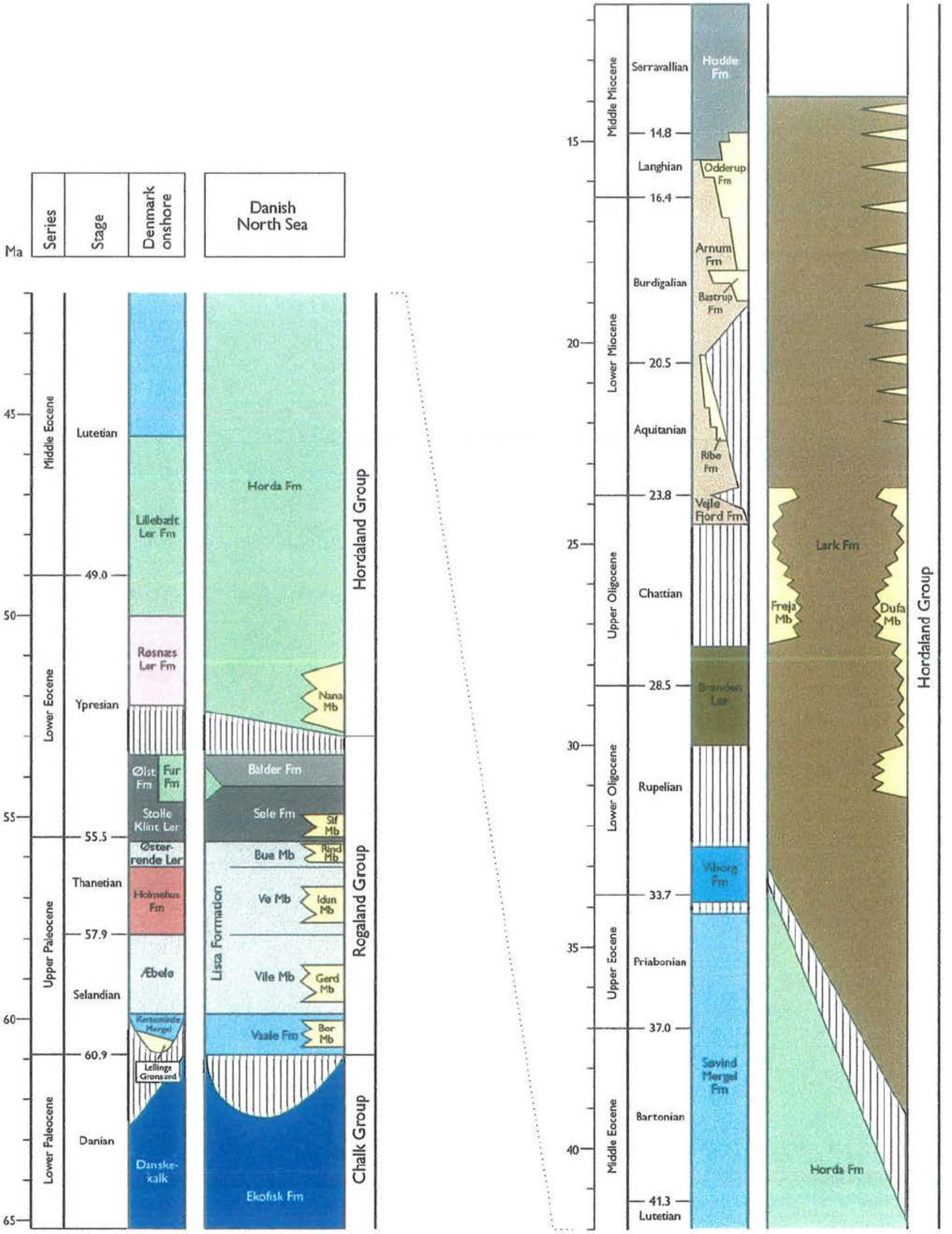
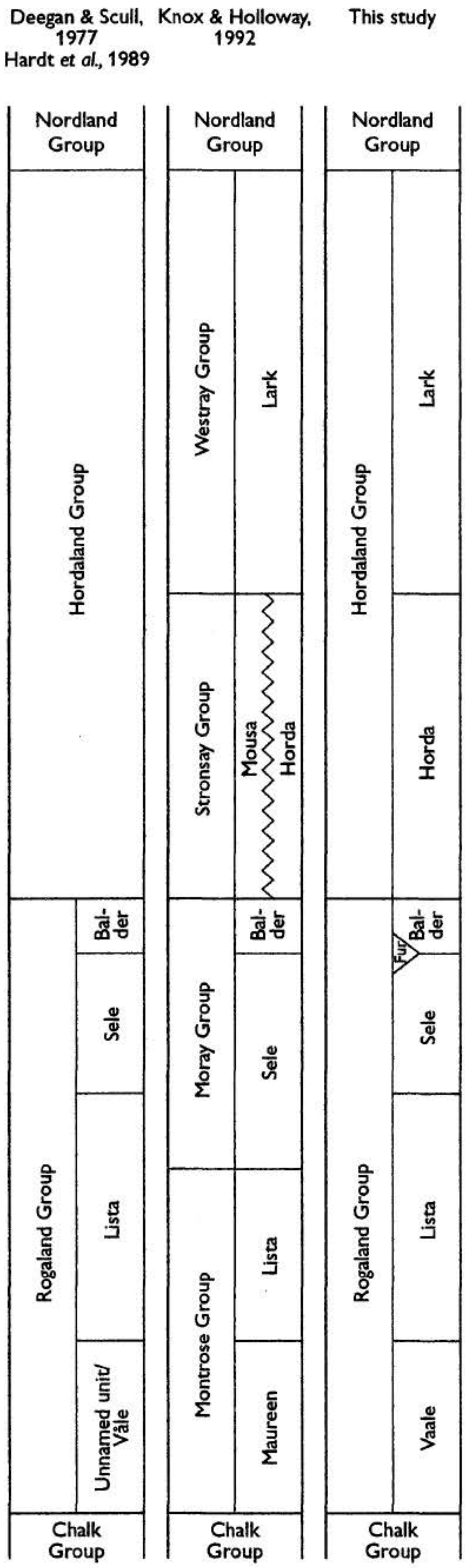

Ma
Series
Stage
Denmark onshore
Danish North Sea
Middle Eocene
Lower Eocene
Upper Paleocene
Lower Paleocene
Lutetian
Ypresian
Thanetian
Selandian
Danian
49.0
55.5
57.9
60.9
Lillebælt Ler Fm
Røsnæs Ler Fm
Ølst Fm
Fur Fm
Stolle Klint Ler
Østerrende Ler
Holmehus Fm
Æbelø
Lellinge Grønsand
Danskekalk
Horda Fm
Nana Mb
Balder Fm
Sele Fm
Sif Mb
Bue Mb
Rind Mb
Ve Mb
Idun Mb
Vile Mb
Gerd Mb
Vaale Fm
Bor Mb
Lista Formation
Ekofisk Fm
Hordaland Group
Rogaland Group
Chalk Group
Middle Miocene
Lower Miocene
Upper Oligocene
Lower Oligocene
Upper Eocene
Middle Eocene
Serravallian
Langhian
Burdigalian
Aquitanian
Chattian
Rupelian
Priabonian
Bartonian
Lutetian
14.8
16.4
20.5
23.8
28.5
33.7
37.0
41.3
Hodde Fm
Odderup Fm
Arnum Fm
Bastrup Fm
Ribe Fm
Vejle Fjord Fm
Viborg Fm
Søvind Mergel Fm
Lark Fm
Freja Mb
Dufa Mb
Horda Fm
Hordaland Group

Fig.2



Deegan & Scull, 1977
Hardt et al., 1989
Knox & Holloway, 1992
This study
Nordland Group
Hordaland Group
Rogaland Group
Unnamed unit/ Våle
Lista
Sele
Bal-der
Chalk Group
Westray Group
Lark
Stronsay Group
Mousa
Horda
Moray Group
Montrose Group
Maureen
Fur
Vaale


Fig.3

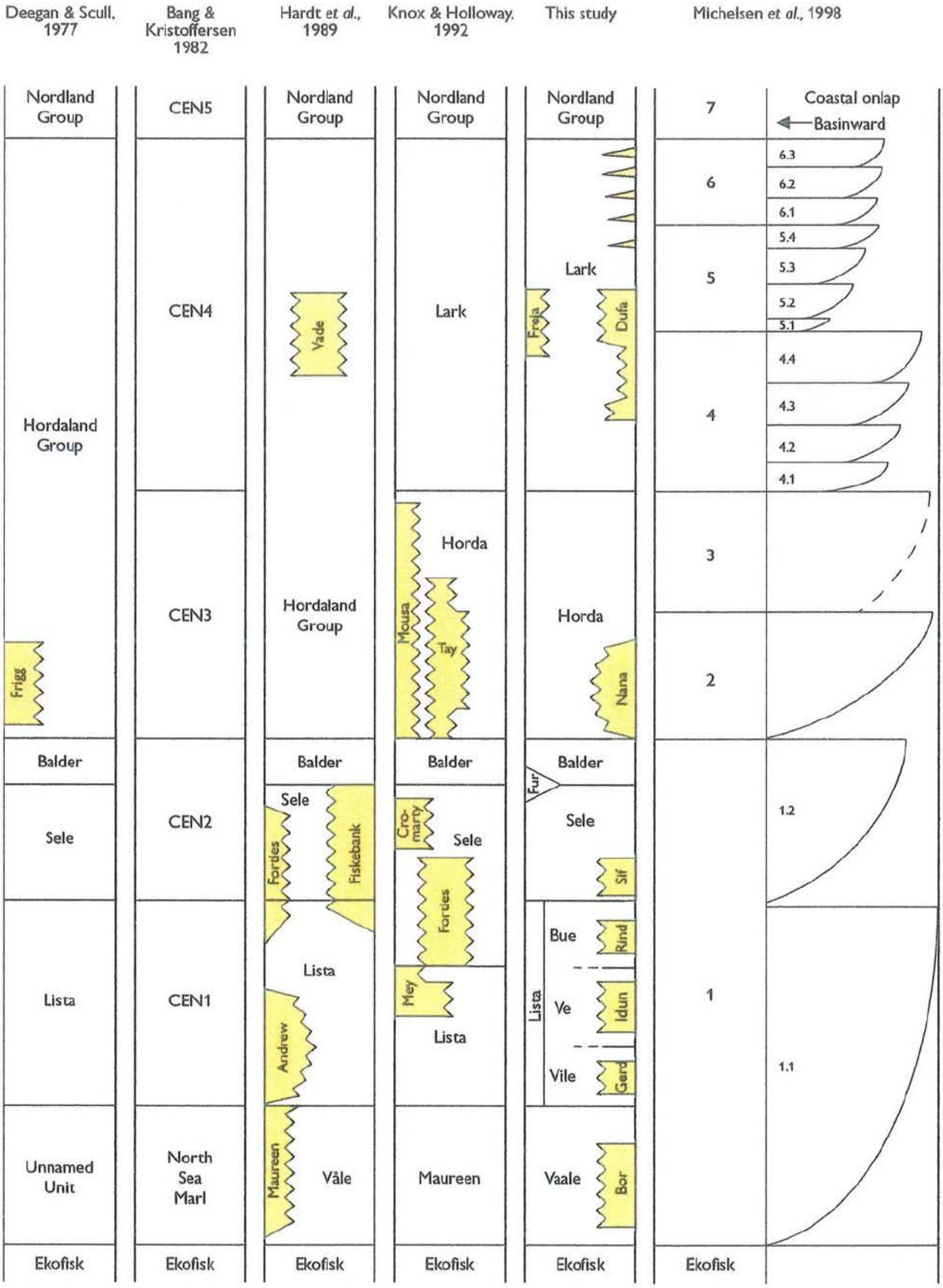
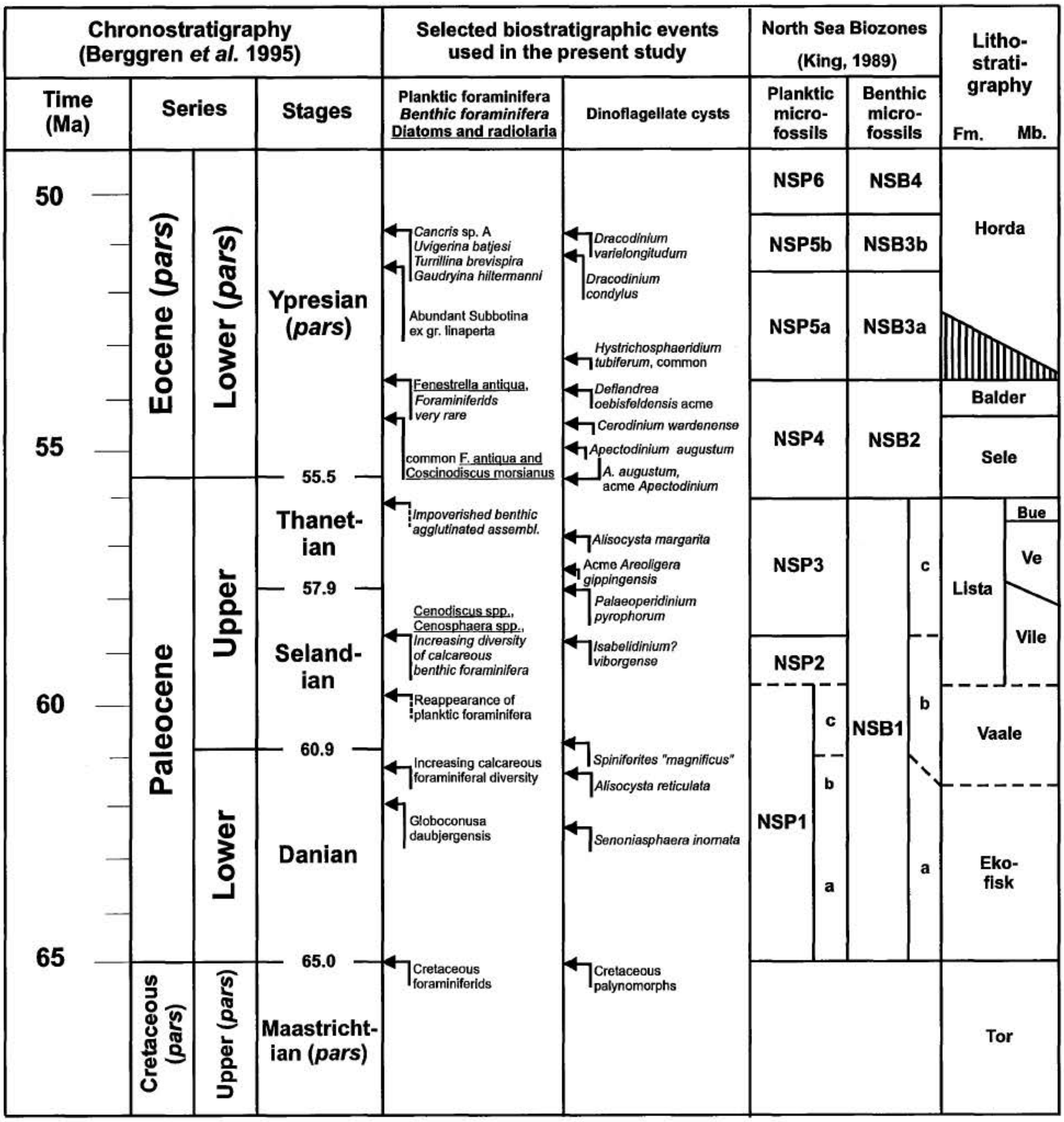
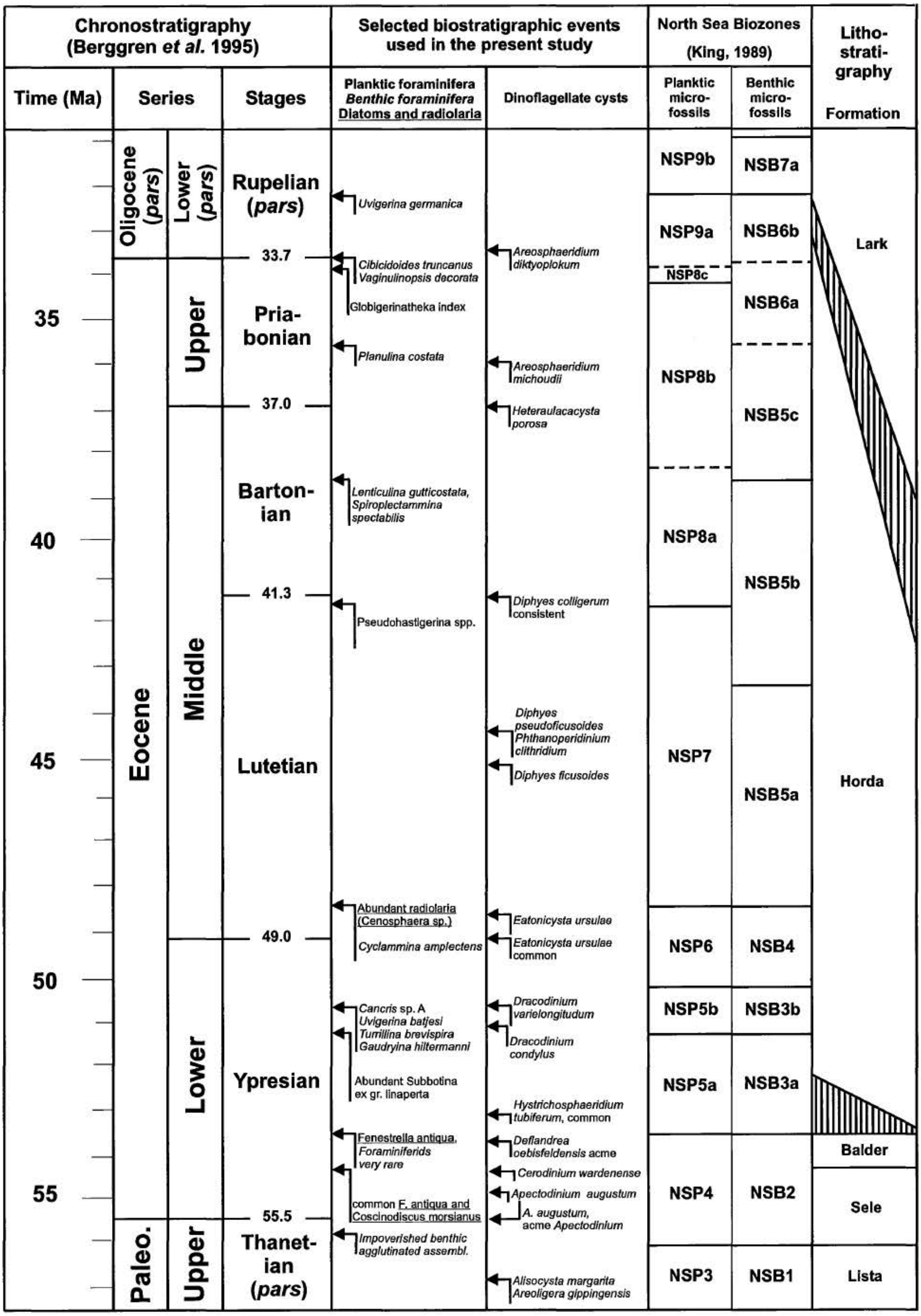

Deegan & Scull, 1977
Bang & Kristoffersen 1982
Hardt et al., 1989
Knox & Holloway, 1992
This study
Michelsen et al., 1998
Nordland Group
CEN5
Nordland Group
Nordland Group
Nordland Group
7
Coastal onlap
Basinward
6.3
6
6.2
6.1
5.4
Lark
5.3
5
5.2
CEN4
Vade
Lark
Freja
Dufa
5.1
4.4
4.3
4
Hordaland Group
4.2
4.1
Horda
3
Mousa
CEN3
Hordaland Group
Horda
Tay
Frigg
Nana
2
Balder
Balder
Balder
Balder
Fur
Sele
Fiskebank
Cro-marty
1.2
Sele
CEN2
Sele
Sele
Forties
Sif
Forties
Bue
Rind
Lista
Lista
CEN1
Mey
Ve
Idun
1
Lista
Lista
Andrew
Vile
Gerd
1.1
Unnamed Unit
North Sea Marl
Maureen
Våle
Maureen
Vaale
Bor
Ekofisk
Ekofisk
Ekofisk
Ekofisk
Ekofisk
Ekofisk

Fig.4



Chronostratigraphy (Berggren et al. 1995)
Selected biostratigraphic events used in the present study
North Sea Biozones (King, 1989)
Litho-strati-graphy
Time (Ma)
Series
Stages
Planktic foraminifera
Benthic foraminifera
Diatoms and radiolaria
Dinoflagellate cysts
Planktic micro-fossils
Benthic micro-fossils
Fm.
Mb.
50
55
60
65
Eocene (pars)
Lower (pars)
Paleocene
Upper
Lower
Cretaceous (pars)
Upper (pars)
Ypresian (pars)
55.5
Thanet-ian
57.9
Seland-ian
60.9
Danian
65.0
Maastricht-ian (pars)
Cancris sp. A
Uvigerina batjesi
Turrilina brevispira
Gaudryina hiltermanni
Abundant Subbotina ex gr. linaperta
Fenestrella antiqua,
Foraminiferids very rare
common F. antiqua and Coscinodiscus morsianus
Impoverished benthic agglutinated assembl.
Cenodiscus spp.,
Cenosphaera spp.,
Increasing diversity of calcareous benthic foraminifera
Reappearance of planktic foraminifera
Increasing calcareous foraminiferal diversity
Globoconusa daubjergensis
Cretaceous foraminiferids
Dracodinium varielongitudum
Dracodinium condylus
Hystrichosphaeridium tubiferum, common
Deflandrea oebisfeldensis acme
Cerodinium wardenense
Apectodinium augustum
A. augustum, acme Apectodinium
Alisocysta margarita
Acme Areoligera gippingensis
Palaeoperidinium pyrophorum
Isabelidinium? viborgense
Spiniferites "magnificus"
Alisocysta reticulata
Senoniasphaera inornata
Cretaceous palynomorphs
NSP6
NSB4
NSP5b
NSB3b
NSP5a
NSB3a
NSP4
NSB2
NSP3
NSP2
NSP1
NSB1
a
b
c
Horda
Balder
Sele
Lista
Bue
Ve
Vile
Vaale
Eko-fisk
Tor


Fig. 5a



Chronostratigraphy (Berggren et al. 1995)
Selected biostratigraphic events used in the present study
North Sea Biozones (King, 1989)
Litho-strati-graphy
Time (Ma)
Series
Stages
Planktic foraminifera
Benthic foraminifera
Diatoms and radiolaria
Dinoflagellate cysts
Planktic micro-fossils
Benthic micro-fossils
Formation
35
40
45
50
55
Oligocene (pars)
Lower (pars)
Eocene
Upper
Middle
Lower
Paleo.
Upper
Rupelian (pars)
33.7
Pria-bonian
37.0
Barton-ian
41.3
Lutetian
49.0
Ypresian
55.5
Thanet-ian (pars)
Uvigerina germanica
Cibicidoides truncanus
Vaginulinopsis decorata
Globigerinatheka index
Planulina costata
Lenticulina gutticostata, Spiroplectammina spectabilis
Pseudohastigerina spp.
Abundant radiolaria (Cenosphaera sp.)
Cyclammina amplectens
Cancris sp. A
Uvigerina batjesi
Turrilina brevispira
Gaudryina hiltermanni
Abundant Subbotina ex gr. linaperta
Fenestrella antiqua, Foraminiferids very rare
common F. antiqua and Coscinodiscus morsianus
Impoverished benthic agglutinated assembl.
Areosphaeridium diktyoplokum
Areosphaeridium michoudii
Heteraulacacysta porosa
Diphyes colligerum consistent
Diphyes pseudoficusoides
Phthanoperidinium clithridium
Diphyes ficusoides
Eatonicysta ursulae
Eatonicysta ursulae common
Dracodinium varielongitudum
Dracodinium condylus
Hystrichosphaeridium tubiferum, common
Deflandrea oebisfeldensis acme
Cerodinium wardenense
Apectodinium augustum
A. augustum, acme Apectodinium
Alisocysta margarita
Areoligera gippingensis
NSP9b
NSP9a
NSP8c
NSP8b
NSP8a
NSP7
NSP6
NSP5b
NSP5a
NSP4
NSP3
NSB7a
NSB6b
NSB6a
NSB5c
NSB5b
NSB5a
NSB4
NSB3b
NSB3a
NSB2
NSB1
Lark
Horda
Balder
Sele
Lista

Fig. 5b

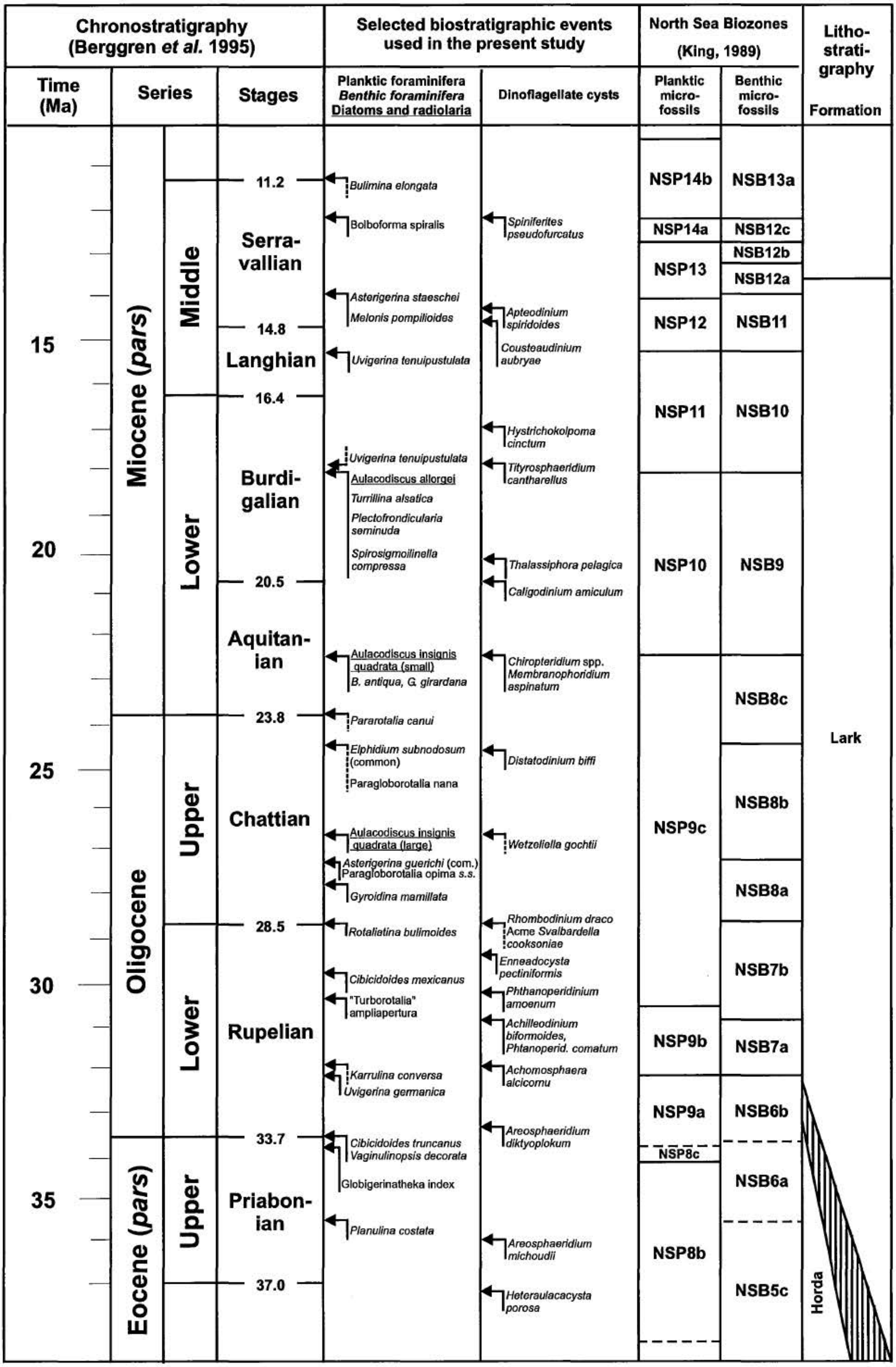

Chronostratigraphy (Berggren et al. 1995)
Selected biostratigraphic events used in the present study
North Sea Biozones (King, 1989)
Litho-strati-graphy
Time (Ma)
Series
Stages
Planktic foraminifera
Benthic foraminifera
Diatoms and radiolaria
Dinoflagellate cysts
Planktic micro-fossils
Benthic micro-fossils
Formation
15
20
25
30
35
Miocene (pars)
Oligocene
Eocene (pars)
Middle
Lower
Upper
Lower
Upper
11.2
Serra-vallian
14.8
Langhian
16.4
Burdi-galian
20.5
Aquitan-ian
23.8
Chattian
28.5
Rupelian
33.7
Priabon-ian
37.0
Bulimina elongata
Bolboforma spiralis
Asterigerina staeschei
Melonis pompilioides
Uvigerina tenuipustulata
Uvigerina tenuipustulata
Aulacodiscus allorgei
Turrilina alsatica
Plectofrondicularia seminuda
Spirosigmoilinella compressa
Aulacodiscus insignis quadrata (small)
B. antiqua, G. girardana
Pararotalia canui
Elphidium subnodosum (common)
Paragloborotalia nana
Aulacodiscus insignis quadrata (large)
Asterigerina guerichi (com.)
Paragloborotalia opima s.s.
Gyroidina mamillata
Rotaliatina bulimoides
Cibicidoides mexicanus
"Turborotalia" ampliapertura
Karrulina conversa
Uvigerina germanica
Cibicidoides truncanus
Vaginulinopsis decorata
Globigerinatheka index
Planulina costata
Spiniferites pseudofurcatus
Apteodinium spiridoides
Cousteaudinium aubryae
Hystrichokolpoma cinctum
Tityrosphaeridium cantharellus
Thalassiphora pelagica
Caligodinium amiculum
Chiropteridium spp.
Membranophoridium aspinatum
Distatodinium biffi
Wetzeliella gochtii
Rhombodinium draco
Acme Svalbardella cooksoniae
Enneadocysta pectiniformis
Phthanoperidinium amoenum
Achilleodinium biformoides,
Phtanoperid. comatum
Achomosphaera alcicornu
Areosphaeridium diktyoplokum
Areosphaeridium michoudii
Heteraulacacysta porosa
NSP14b
NSP14a
NSP13
NSP12
NSP11
NSP10
NSP9c
NSP9b
NSP9a
NSP8c
NSP8b
NSB13a
NSB12c
NSB12b
NSB12a
NSB11
NSB10
NSB9
NSB8c
NSB8b
NSB8a
NSB7b
NSB7a
NSB6b
NSB6a
NSB5c
Lark
Horda

Fig. 5c

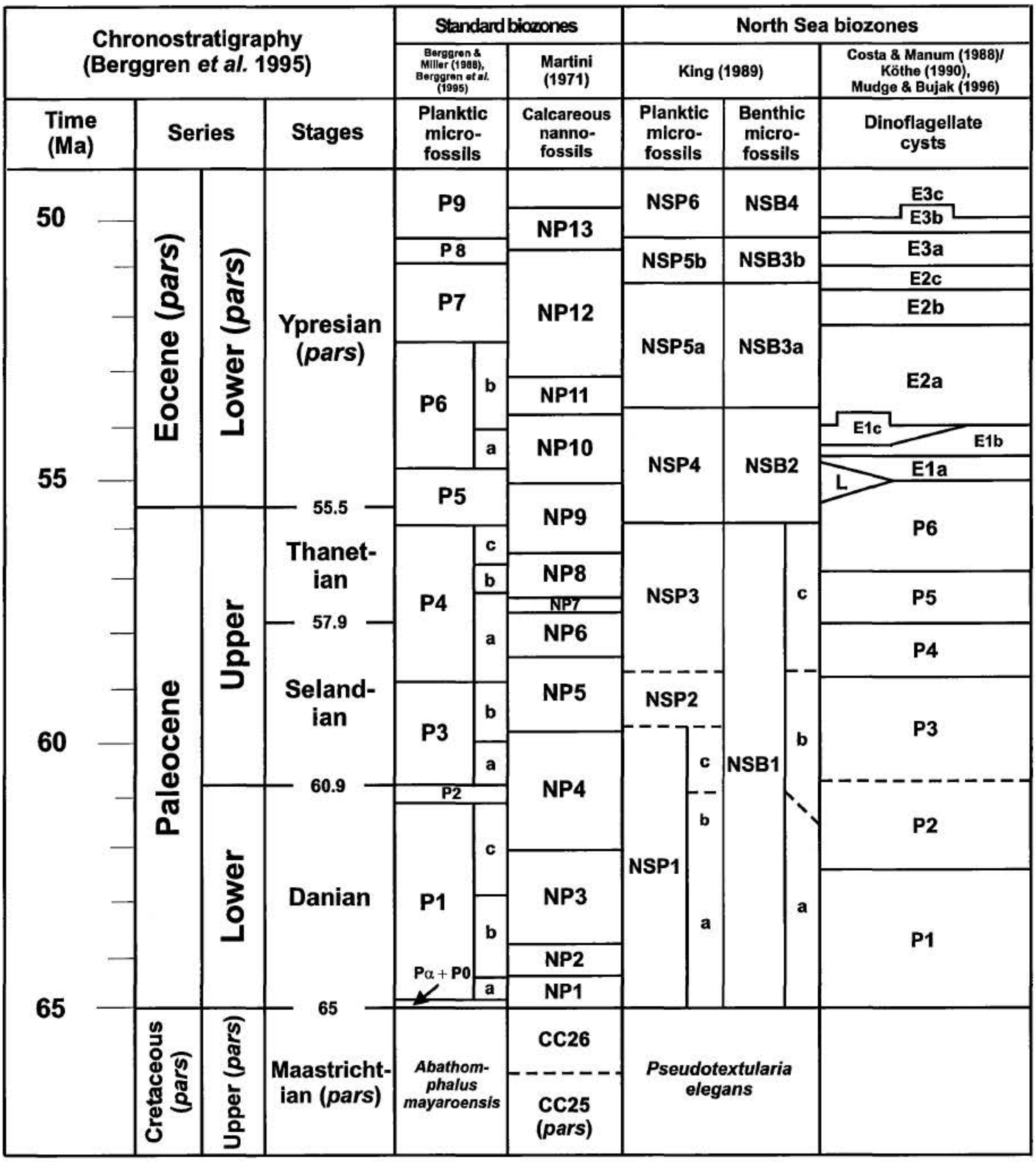
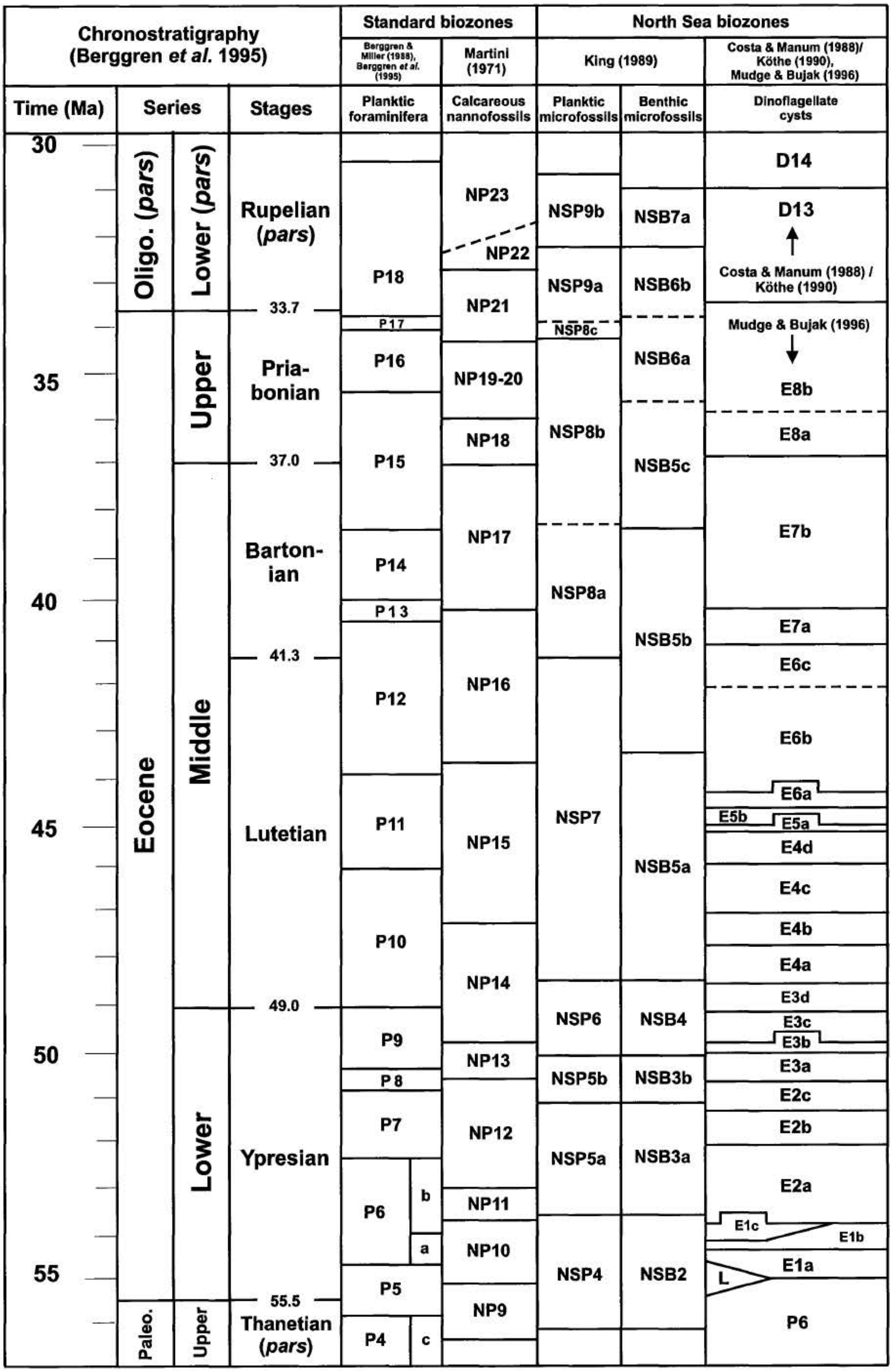
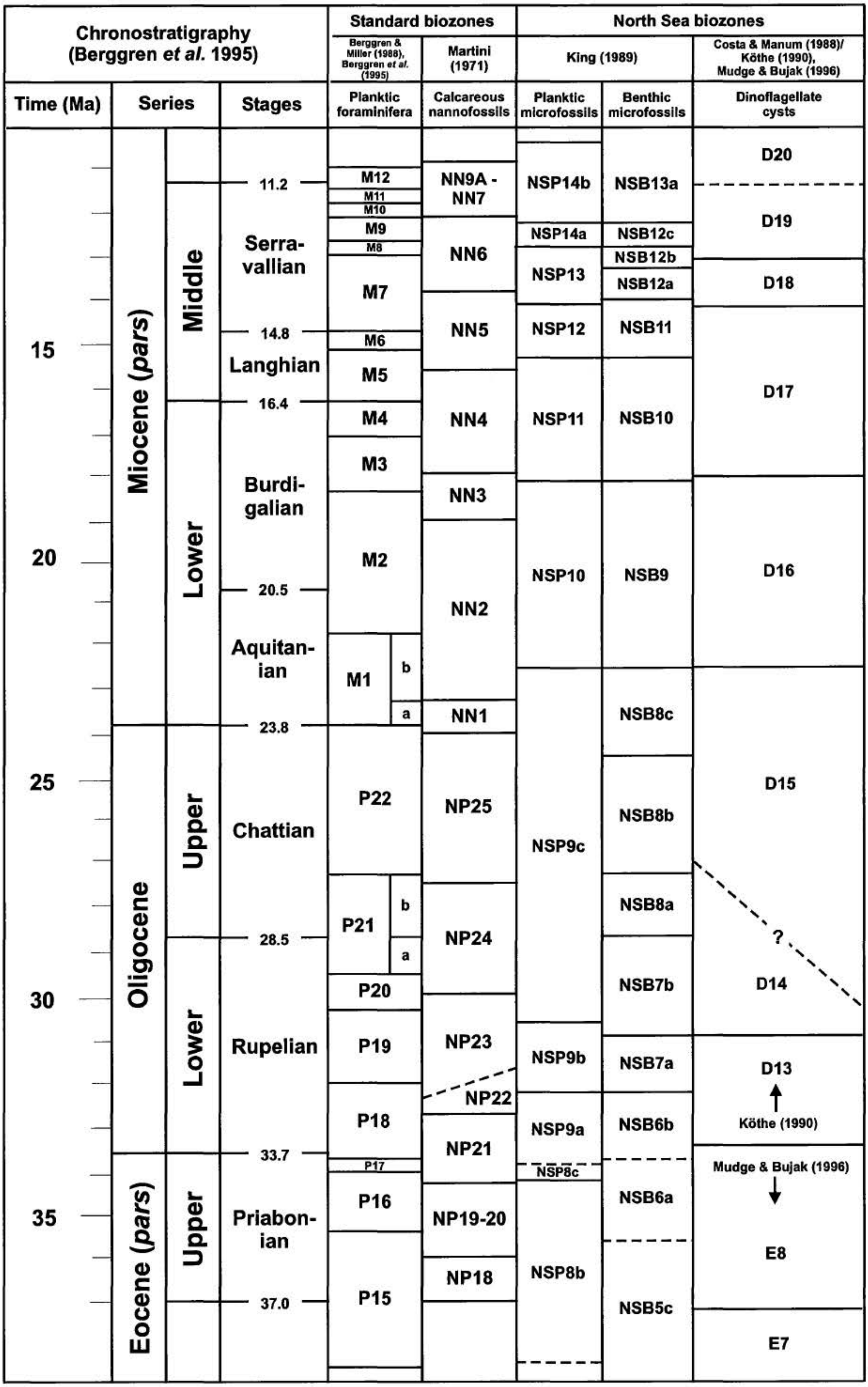

Chronostratigraphy (Berggren et al. 1995)
Standard biozones
North Sea biozones
Berggren & Miller (1988), Berggren et al. (1995)
Martini (1971)
King (1989)
Costa & Manum (1988)/ Köthe (1990), Mudge & Bujak (1996)
Time (Ma)
Series
Stages
Planktic micro-fossils
Calcareous nanno-fossils
Planktic micro-fossils
Benthic micro-fossils
Dinoflagellate cysts
50
55
60
65
Eocene (pars)
Lower (pars)
Paleocene
Upper
Lower
Cretaceous (pars)
Upper (pars)
Ypresian (pars)
55.5
Thanet-ian
57.9
Seland-ian
60.9
Danian
65
Maastricht-ian (pars)
P9
P8
P7
P6
a
b
P5
P4
c
b
a
P3
b
a
P2
P1
c
b
a
Pα + P0
Abathom-phalus mayaroensis
NP13
NP12
NP11
NP10
NP9
NP8
NP7
NP6
NP5
NP4
NP3
NP2
NP1
CC26
CC25 (pars)
NSP6
NSP5b
NSP5a
NSP4
NSP3
NSP2
NSP1
c
b
a
Pseudotextularia elegans
NSB4
NSB3b
NSB3a
NSB2
NSB1
c
b
a
E3c
E3b
E3a
E2c
E2b
E2a
E1c
E1b
E1a
L
P6
P5
P4
P3
P2
P1

Fig. 6a



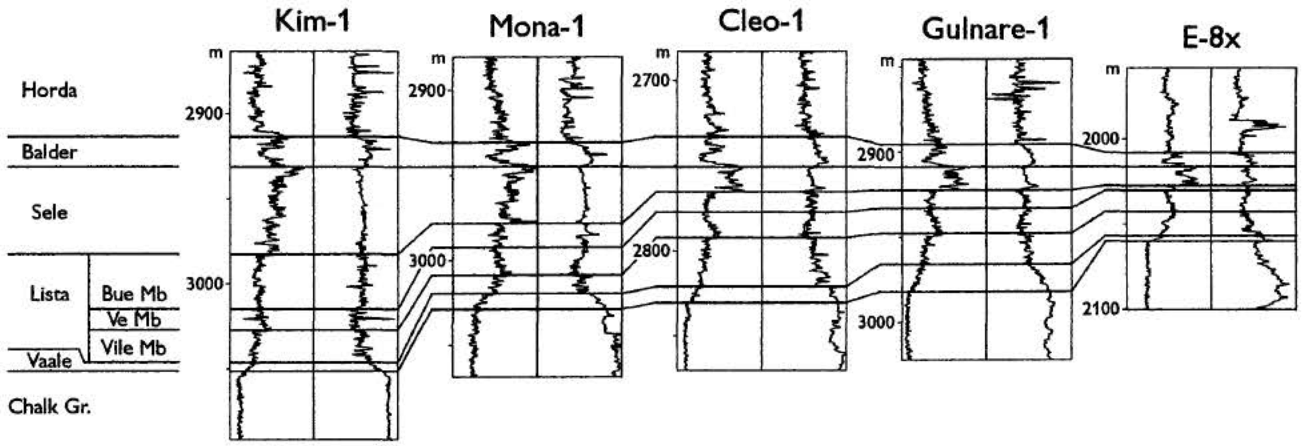
Chronostratigraphy (Berggren et al. 1995)
Standard biozones
North Sea biozones
Berggren & Miller (1988), Berggren et al. (1995)
Martini (1971)
King (1989)
Costa & Manum (1988)/ Köthe (1990), Mudge & Bujak (1996)
Time (Ma)
Series
Stages
Planktic foraminifera
Calcareous nannofossils
Planktic microfossils
Benthic microfossils
Dinoflagellate cysts
30
35
40
45
50
55
Oligo. (pars)
Lower (pars)
Eocene
Upper
Middle
Lower
Paleo.
Upper
Rupelian (pars)
33.7
Pria-bonian
37.0
Barton-ian
41.3
Lutetian
49.0
Ypresian
55.5
Thanetian (pars)
P18
P17
P16
P15
P14
P13
P12
P11
P10
P9
P8
P7
P6
b
a
P5
P4
c
NP23
NP22
NP21
NP19-20
NP18
NP17
NP16
NP15
NP14
NP13
NP12
NP11
NP10
NP9
NSP9b
NSP9a
NSP8c
NSP8b
NSP8a
NSP7
NSP6
NSP5b
NSP5a
NSP4
NSB7a
NSB6b
NSB6a
NSB5c
NSB5b
NSB5a
NSB4
NSB3b
NSB3a
NSB2
D14
D13
Costa & Manum (1988) / Köthe (1990)
Mudge & Bujak (1996)
E8b
E8a
E7b
E7a
E6c
E6b
E6a
E5b
E5a
E4d
E4c
E4b
E4a
E3d
E3c
E3b
E3a
E2c
E2b
E2a
E1c
E1b
E1a
L
P6


Fig. 6b



Chronostratigraphy (Berggren et al. 1995)
Standard biozones
North Sea biozones
Berggren & Miller (1988), Berggren et al. (1995)
Martini (1971)
King (1989)
Costa & Manum (1988)/ Köthe (1990), Mudge & Bujak (1996)
Time (Ma)
Series
Stages
Planktic foraminifera
Calcareous nannofossils
Planktic microfossils
Benthic microfossils
Dinoflagellate cysts
15
20
25
30
35
Miocene (pars)
Oligocene
Eocene (pars)
Middle
Lower
Upper
Lower
Upper
11.2
Serra-vallian
14.8
Langhian
16.4
Burdi-galian
20.5
Aquitan-ian
23.8
Chattian
28.5
Rupelian
33.7
Priabon-ian
37.0
M12
M11
M10
M9
M8
M7
M6
M5
M4
M3
M2
M1
b
a
P22
P21
b
a
P20
P19
P18
P17
P16
P15
NN9A - NN7
NN6
NN5
NN4
NN3
NN2
NN1
NP25
NP24
NP23
NP22
NP21
NP19-20
NP18
NSP14b
NSP14a
NSP13
NSP12
NSP11
NSP10
NSP9c
NSP9b
NSP9a
NSP8c
NSP8b
NSB13a
NSB12c
NSB12b
NSB12a
NSB11
NSB10
NSB9
NSB8c
NSB8b
NSB8a
NSB7b
NSB7a
NSB6b
NSB6a
NSB5c
D20
D19
D18
D17
D16
D15
?
D14
D13
Köthe (1990)
Mudge & Bujak (1996)
E8
E7


Fig. 6c



Kim-1
Mona-1
Cleo-1
Gulnare-1
E-8x
Horda
Balder
Sele
Lista
Bue Mb
Ve Mb
Vile Mb
Vaale
Chalk Gr.
m
2900
3000
2700
2800
2000
2100


Fig.7

Cecilie-1

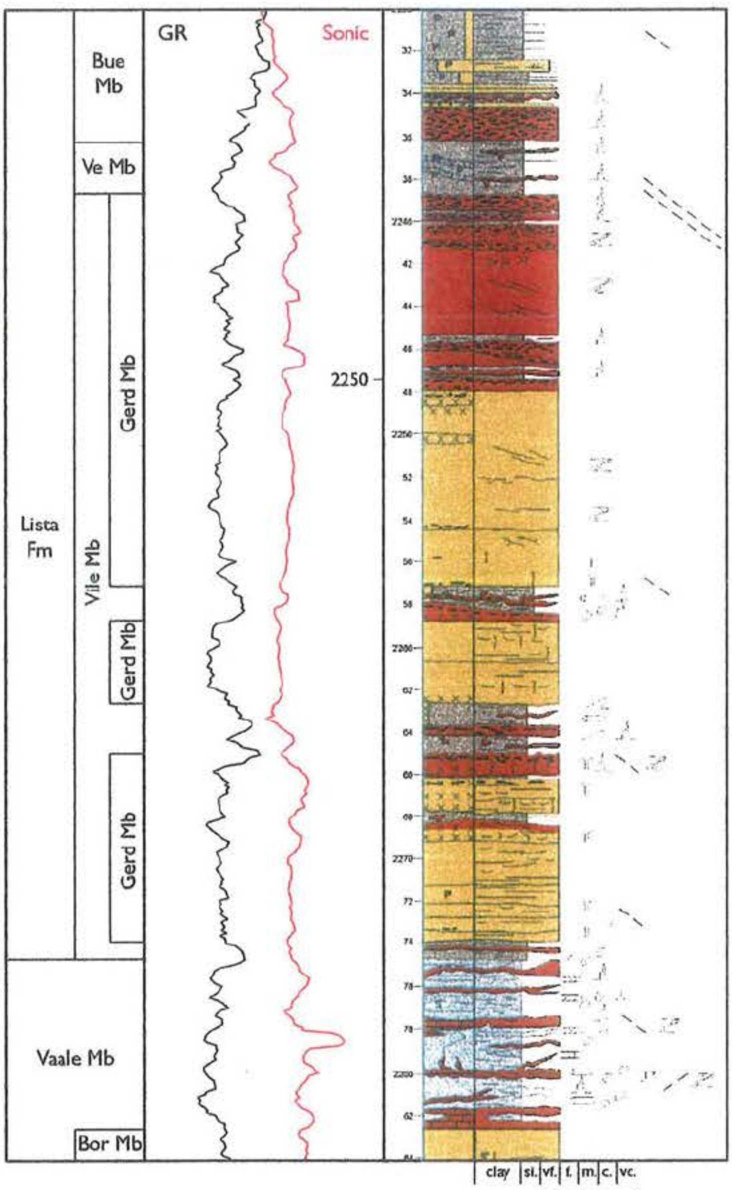



Fig.8a

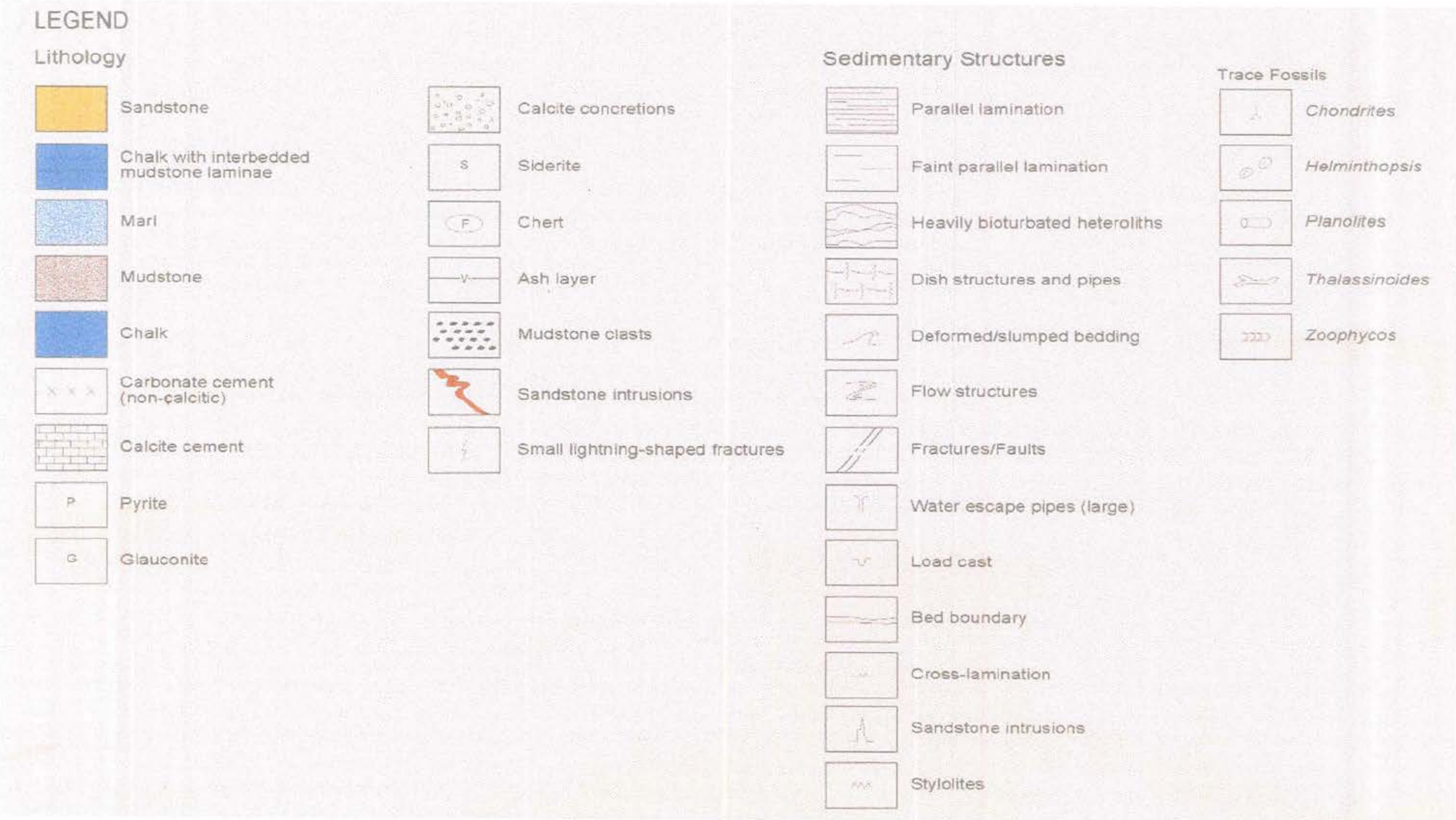

LEGEND
Lithology
Sandstone
Chalk with interbedded mudstone laminae
Marl
Mudstone
Chalk
Carbonate cement (non-calcitic)
Calcite cement
P
Pyrite
G
Glauconite
Calcite concretions
S
Siderite
F
Chert
V
Ash layer
Mudstone clasts
Sandstone intrusions
Small lightning-shaped fractures
Sedimentary Structures
Parallel lamination
Faint parallel lamination
Heavily bioturbated heteroliths
Dish structures and pipes
Deformed/slumped bedding
Flow structures
Fractures/Faults
Water escape pipes (large)
Load cast
Bed boundary
Cross-lamination
Sandstone intrusions
Stylolites
Trace Fossils
*Chondrites*
*Helminthopsis*
*Planolites*
*Thalassincides*
*Zoophycos*

Fig.8b

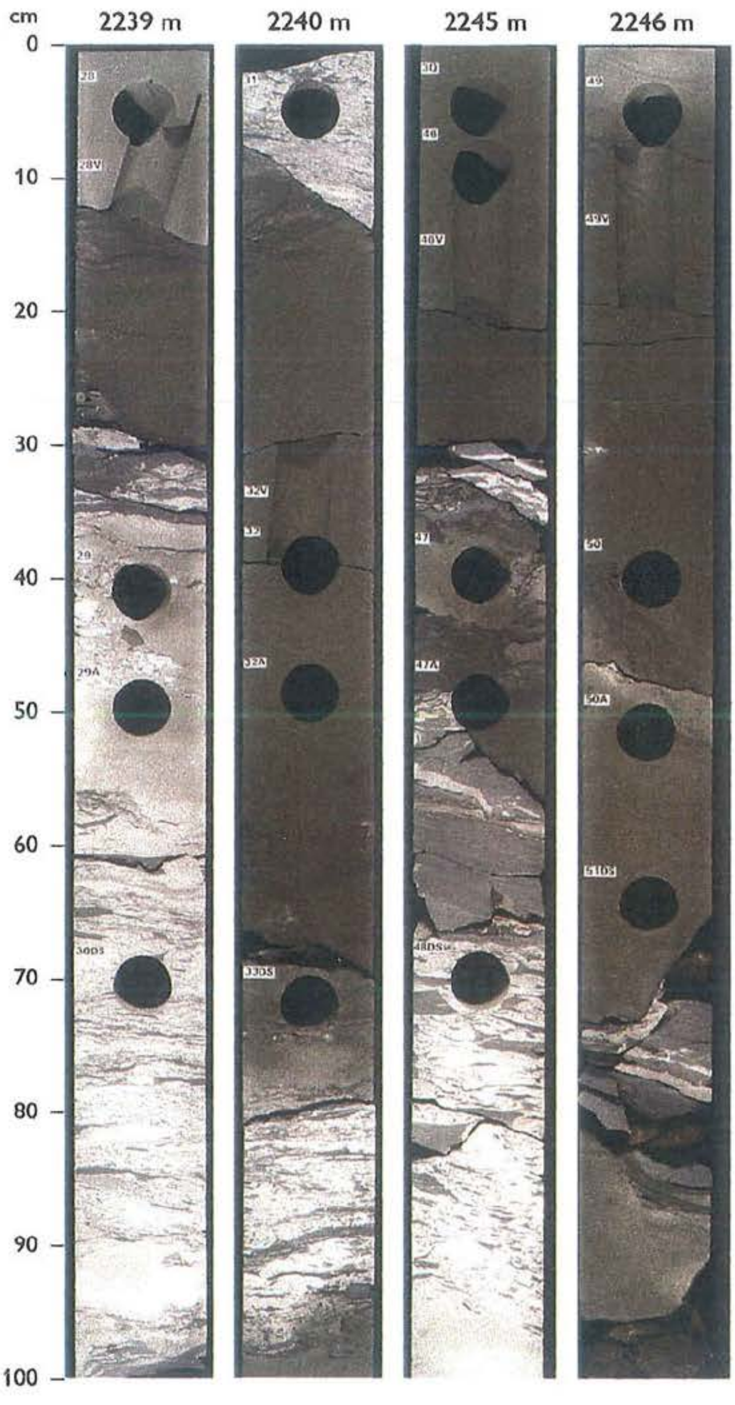
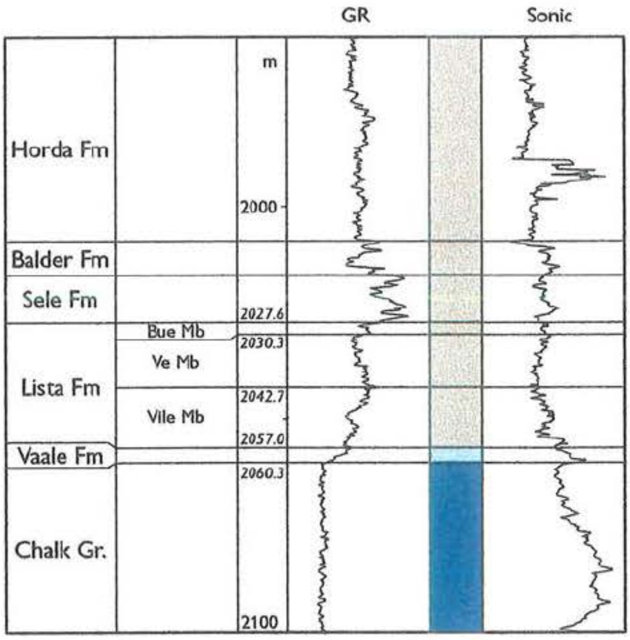



Fig.9

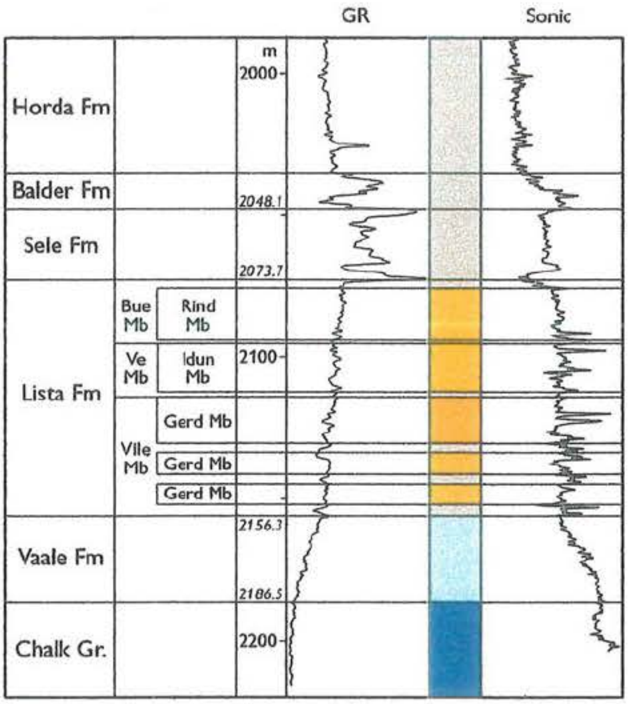
E-8x



GR
Sonic
m
Horda Fm
2000
Balder Fm
Sele Fm
2027.6
Bue Mb
2030.3
Ve Mb
Lista Fm
2042.7
Vile Mb
2057.0
Vaale Fm
2060.3
Chalk Gr.
2100


Fig.10

Siri-1



GR
Sonic
m
2000
2048.1
2073.7
2100
2156.3
2186.5
2200
Horda Fm
Balder Fm
Sele Fm
Lista Fm
Bue Mb
Rind Mb
Ve Mb
Idun Mb
Vile Mb
Gerd Mb
Gerd Mb
Gerd Mb
Vaale Fm
Chalk Gr.


Fig.11

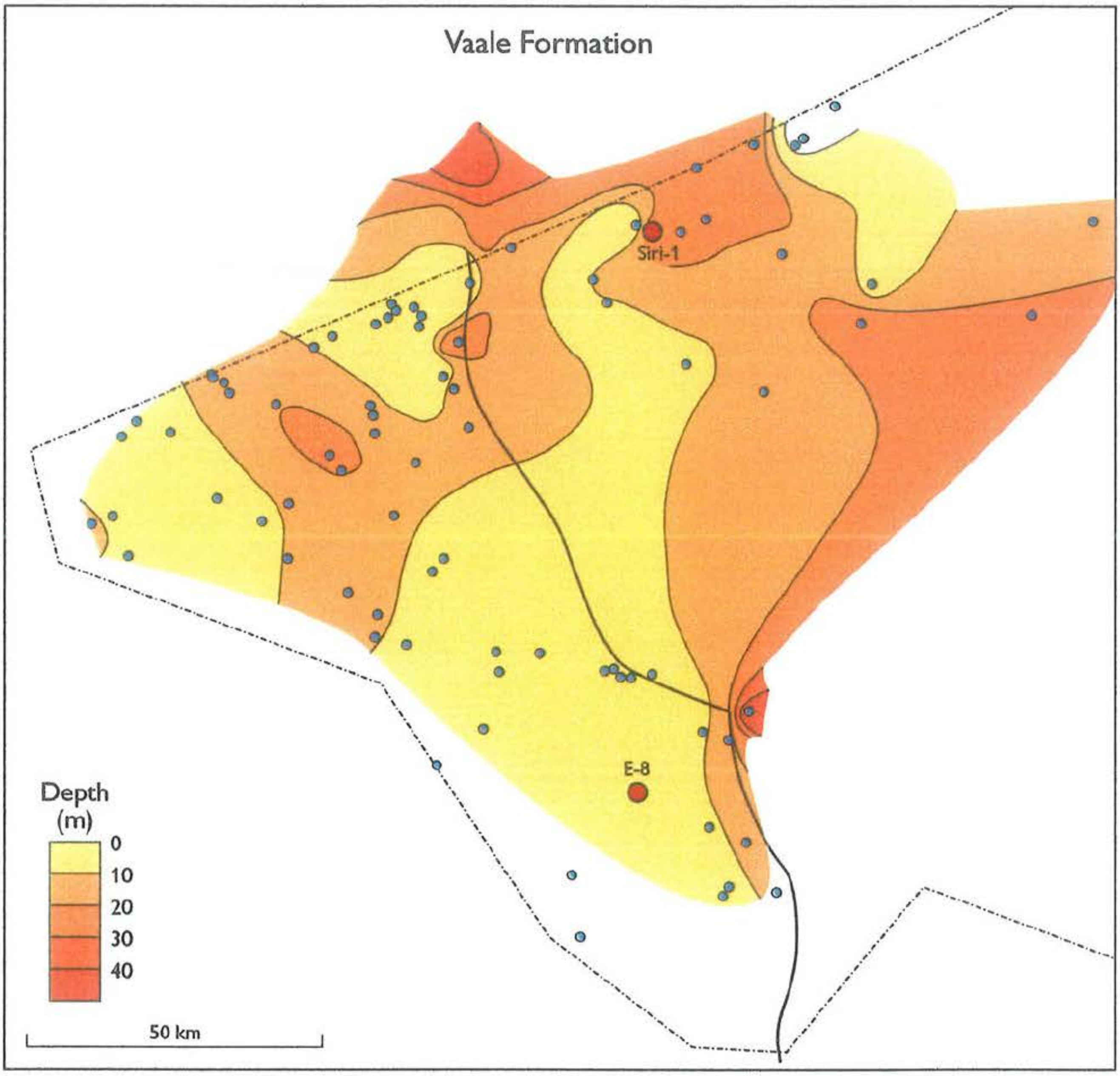



Fig.12

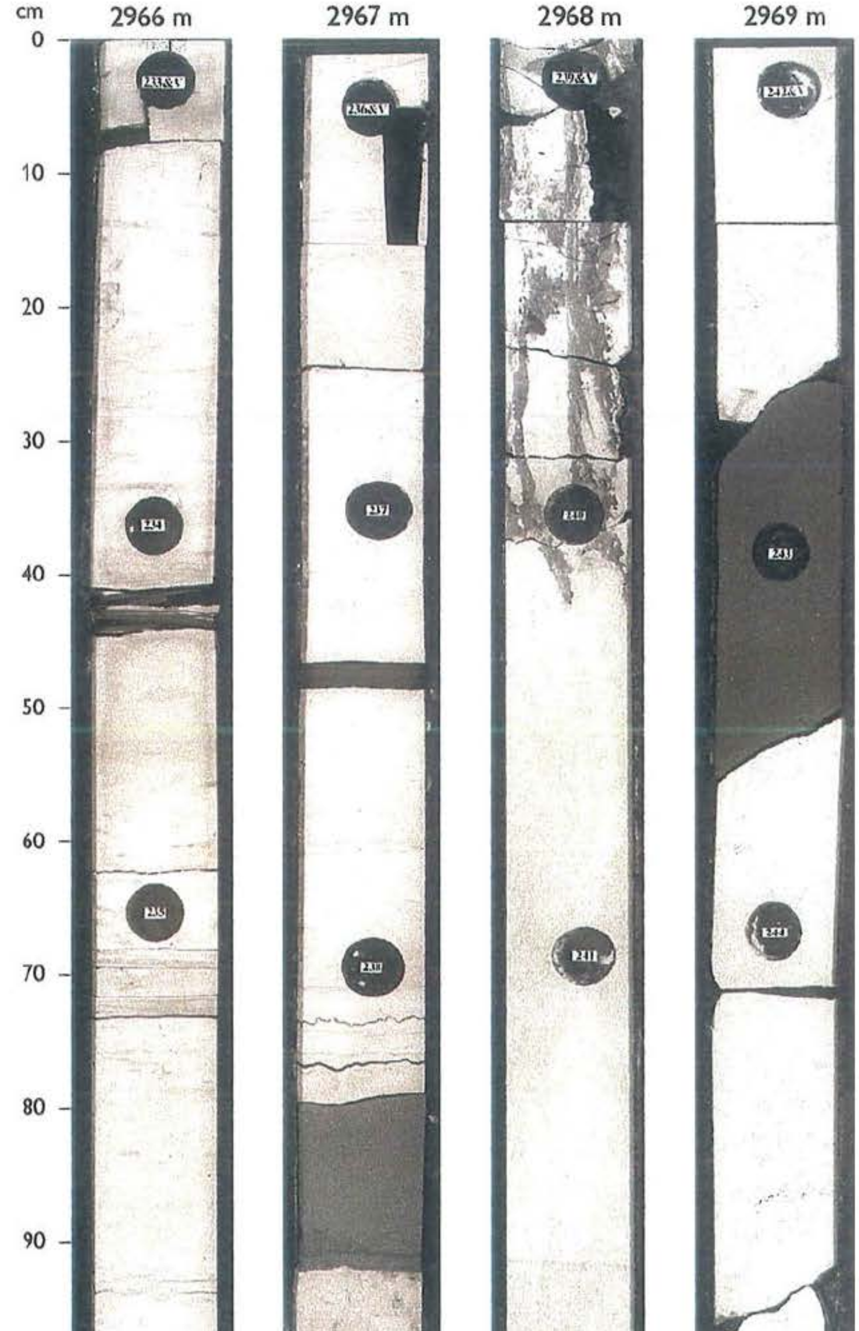



Fig.13

## Augusta-1

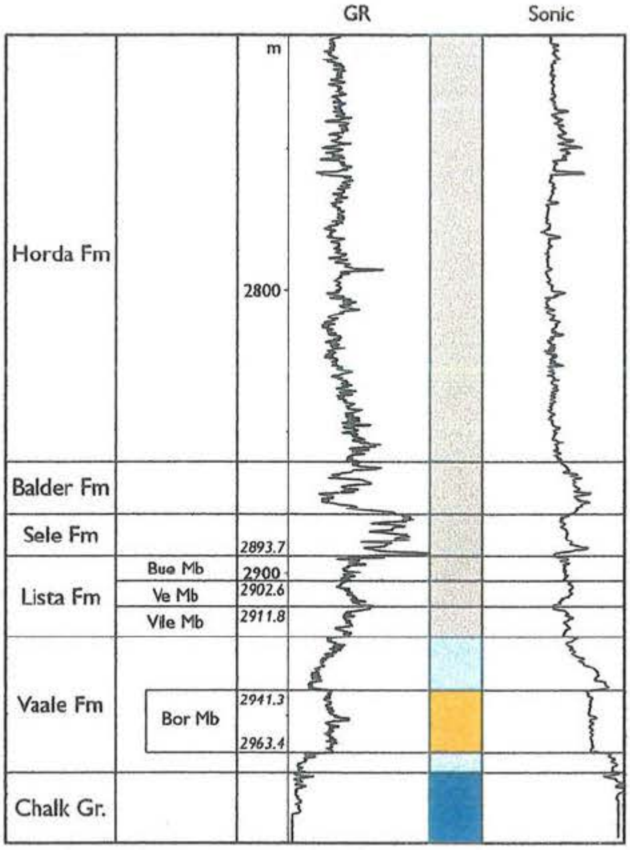



Fig.14

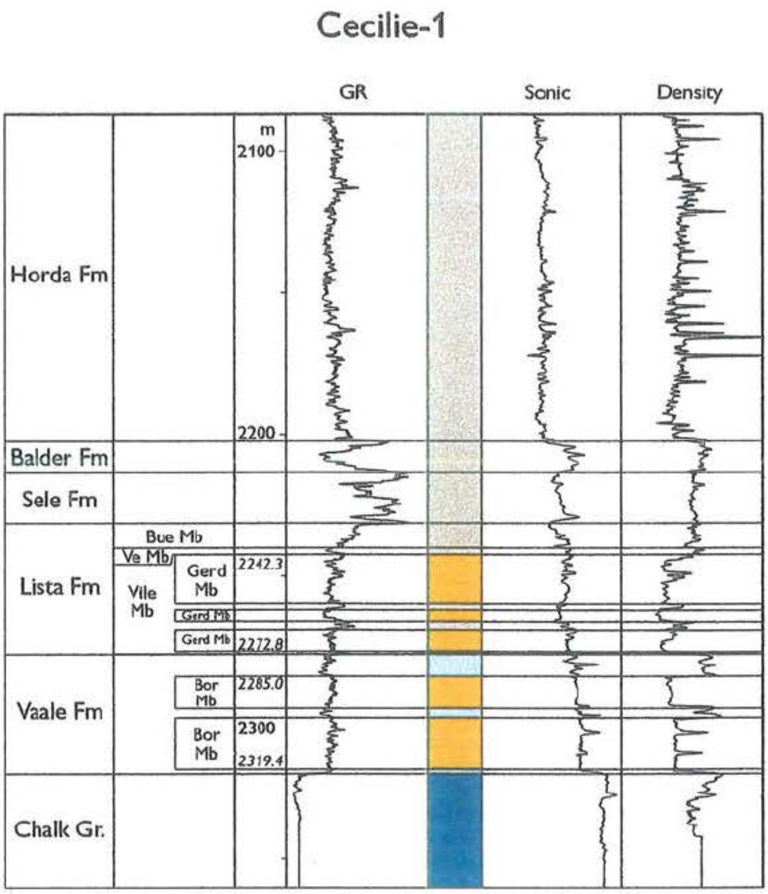
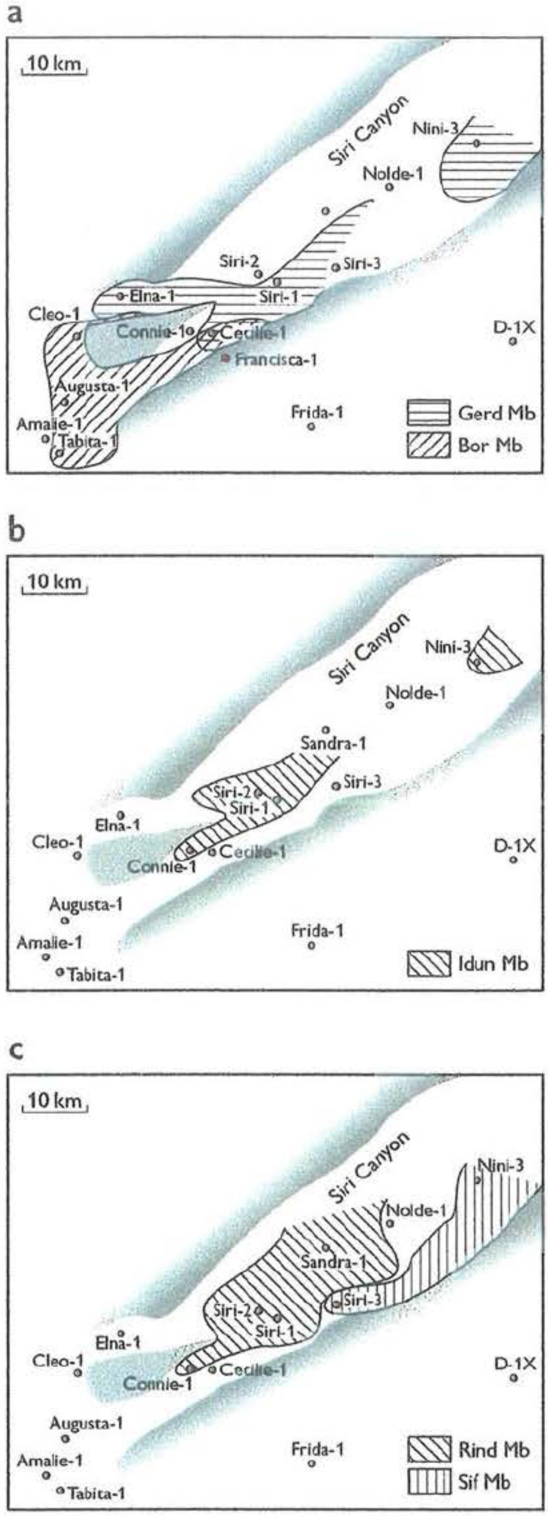

Cecilie-1
GR
Sonic
Density
m
2100
2200
Horda Fm
Balder Fm
Sele Fm
Lista Fm
Bue Mb
Ve Mb
Vile Mb
Gerd Mb
Gerd Mb
Gerd Mb
2242.3
2272.8
Vaale Fm
Bor Mb
2285.0
Bor Mb
2300
2319.4
Chalk Gr.

Fig.15

a
b
c


10 km
Siri Canyon
Nini-3
Nolde-1
Siri-2
Siri-3
Elna-1
Siri-1
Cleo-1
Connie-1
Cecilie-1
Francisca-1
D-1X
Augusta-1
Amalie-1
Tabita-1
Frida-1
Gerd Mb
Bor Mb
Sandra-1
Idun Mb
Rind Mb
Sif Mb


Fig.16

# Augusta-1

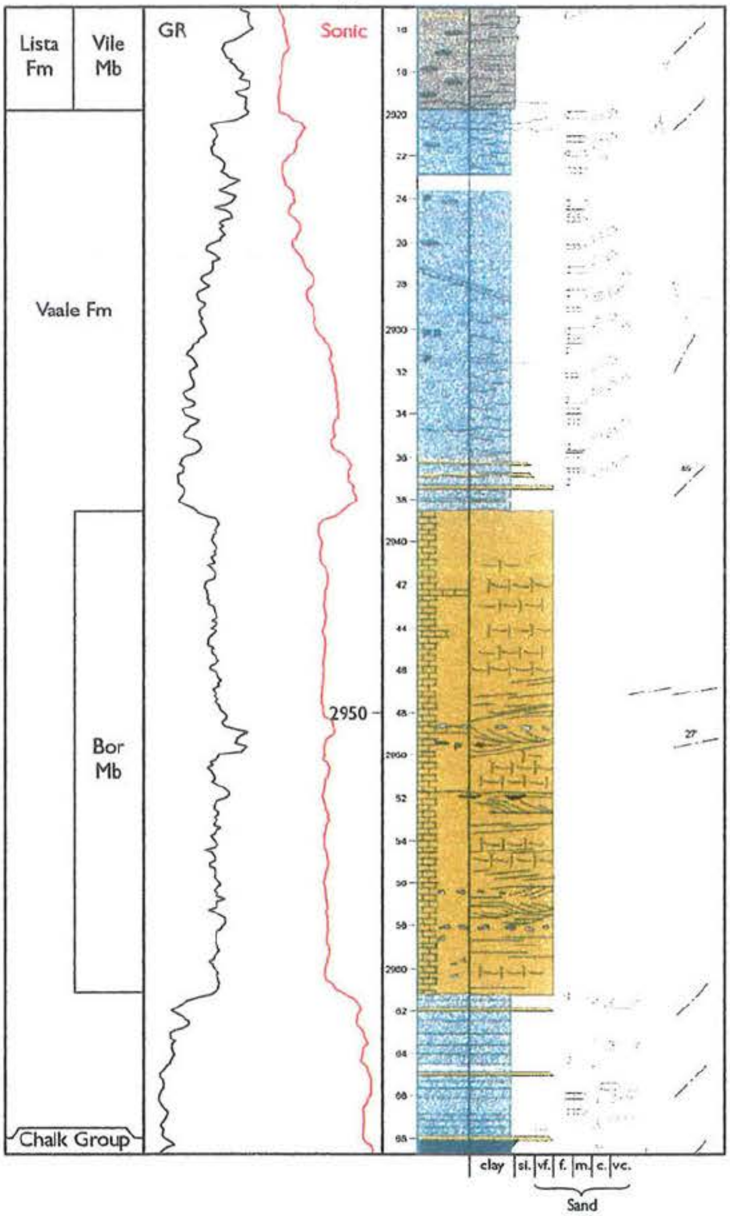



Fig.17

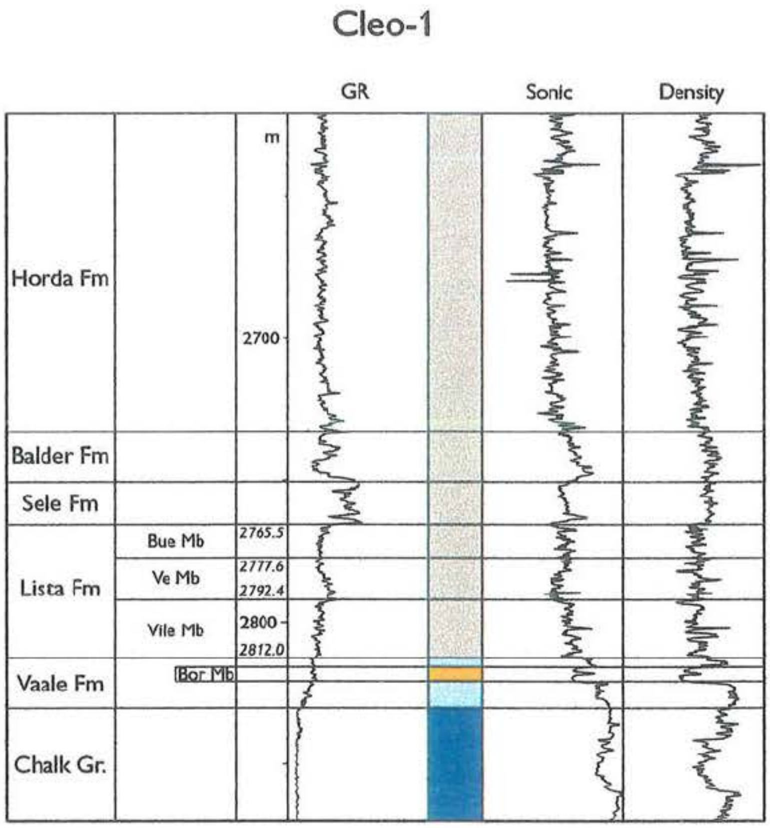

Cleo-1
GR
Sonic
Density
m
Horda Fm
2700
Balder Fm
Sele Fm
Bue Mb
2765.5
2777.6
Ve Mb
2792.4
Lista Fm
Vile Mb
2800
2812.0
Bor Mb
Vaale Fm
Chalk Gr.

Fig.18

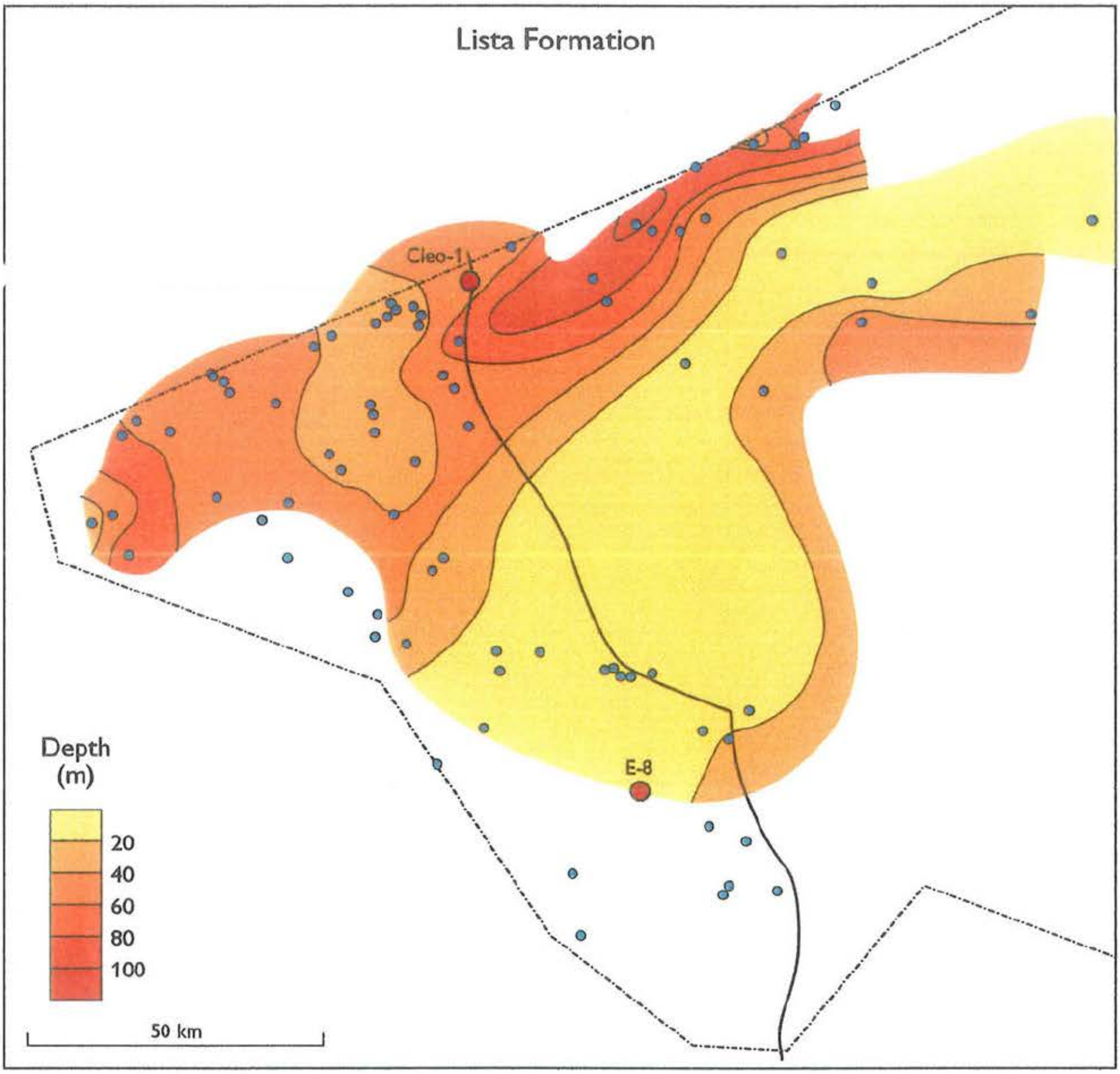
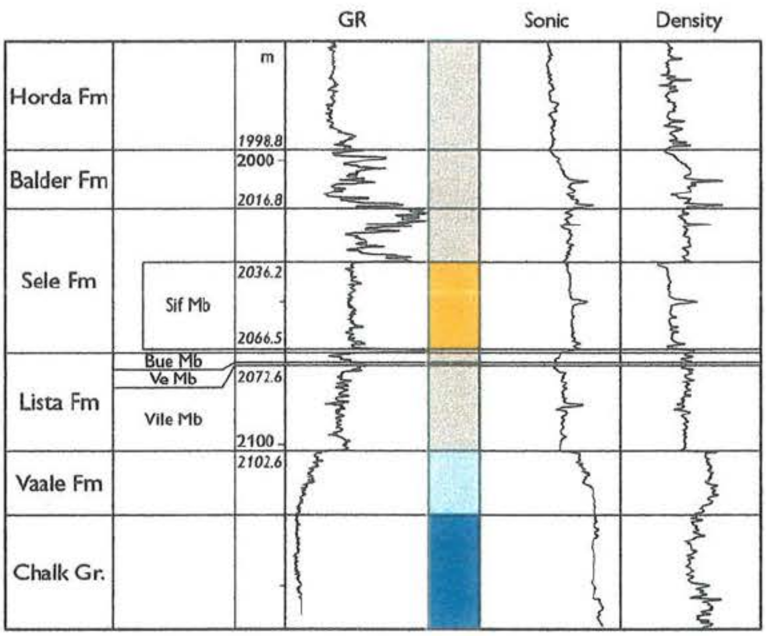



Fig.19

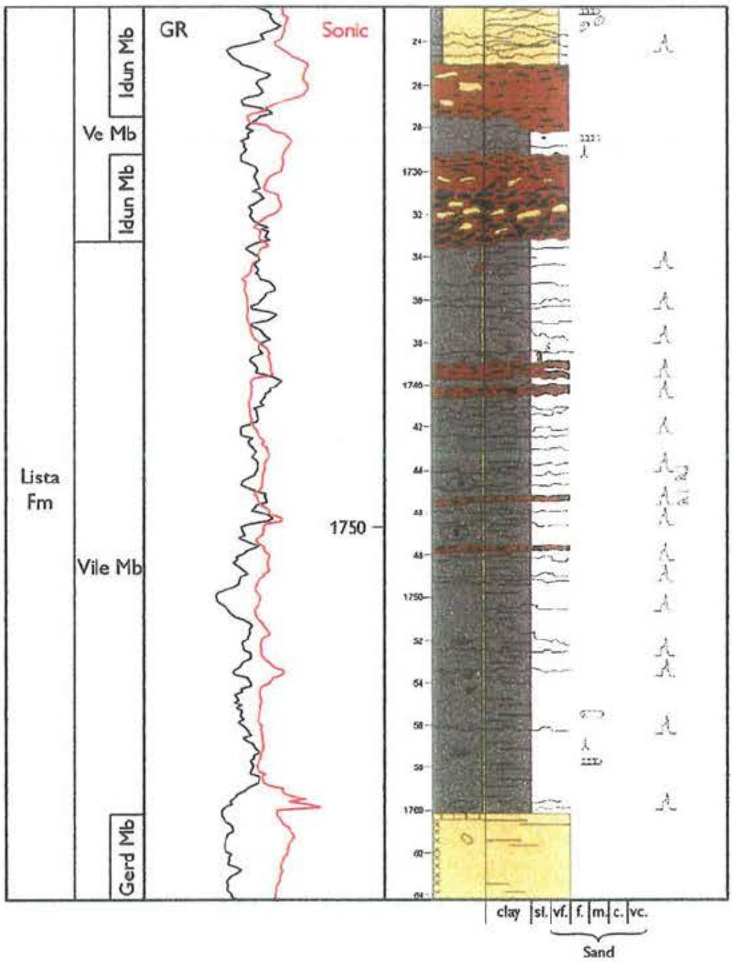
Siri-3



GR
Sonic
Density
m
Horda Fm
1998.8
2000
Balder Fm
2016.8
Sele Fm
2036.2
Sif Mb
2066.5
Bue Mb
Ve Mb
2072.6
Lista Fm
Vile Mb
2100
2102.6
Vaale Fm
Chalk Gr.


Fig.20

Nini-3



Lista Fm
Idun Mb
Ve Mb
Idun Mb
Vile Mb
Gerd Mb
GR
Sonic
1750
clay
sl.
vf.
f.
m.
c.
vc.
Sand


Fig.21

cm
1725 m
1726 m
1727 m
1730 m
1731 m
1732 m
0
10
20
30
40
50
60
70
80
90
100
128
128V
129
127


Fig.22

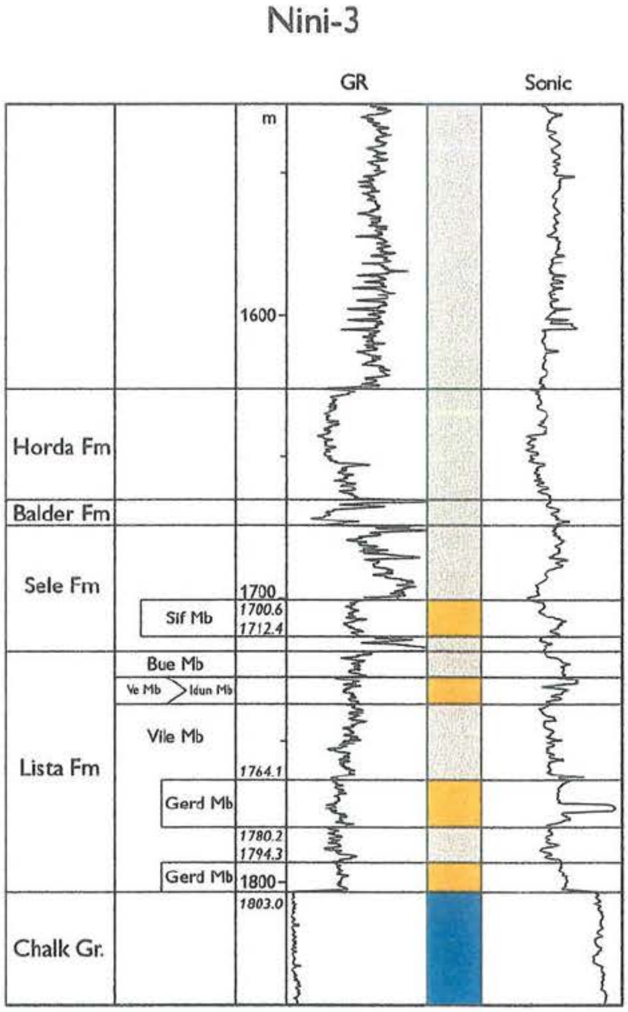
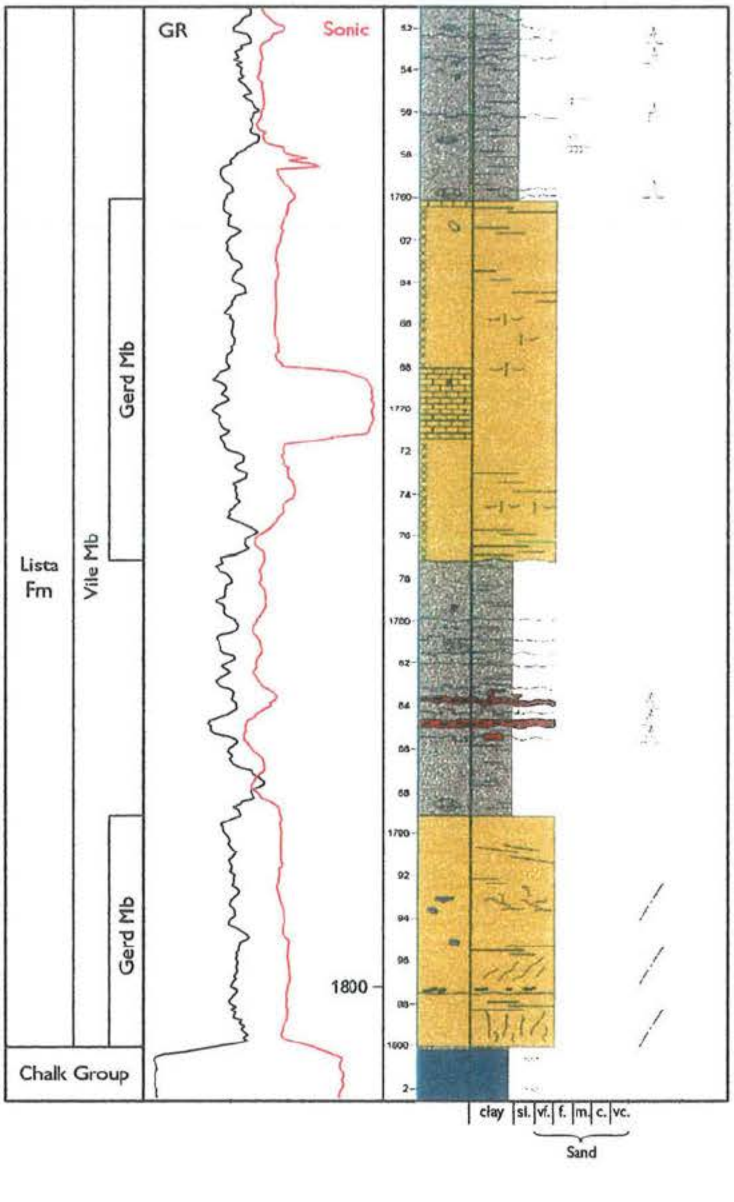

Nini-3
GR
Sonic
m
1600
Horda Fm
Balder Fm
Sele Fm
1700
Sif Mb
1700.6
1712.4
Bue Mb
Ve Mb
Idun Mb
Vile Mb
Lista Fm
1764.1
Gerd Mb
1780.2
1794.3
Gerd Mb
1800
1803.0
Chalk Gr.

Fig.23

## Nini-3



GR
Sonic
Lista Fm
Vile Mb
Gerd Mb
Gerd Mb
Chalk Group
1800
clay
sl.
vf.
f.
m.
c.
vc.
Sand


Fig.24

# Connie-1

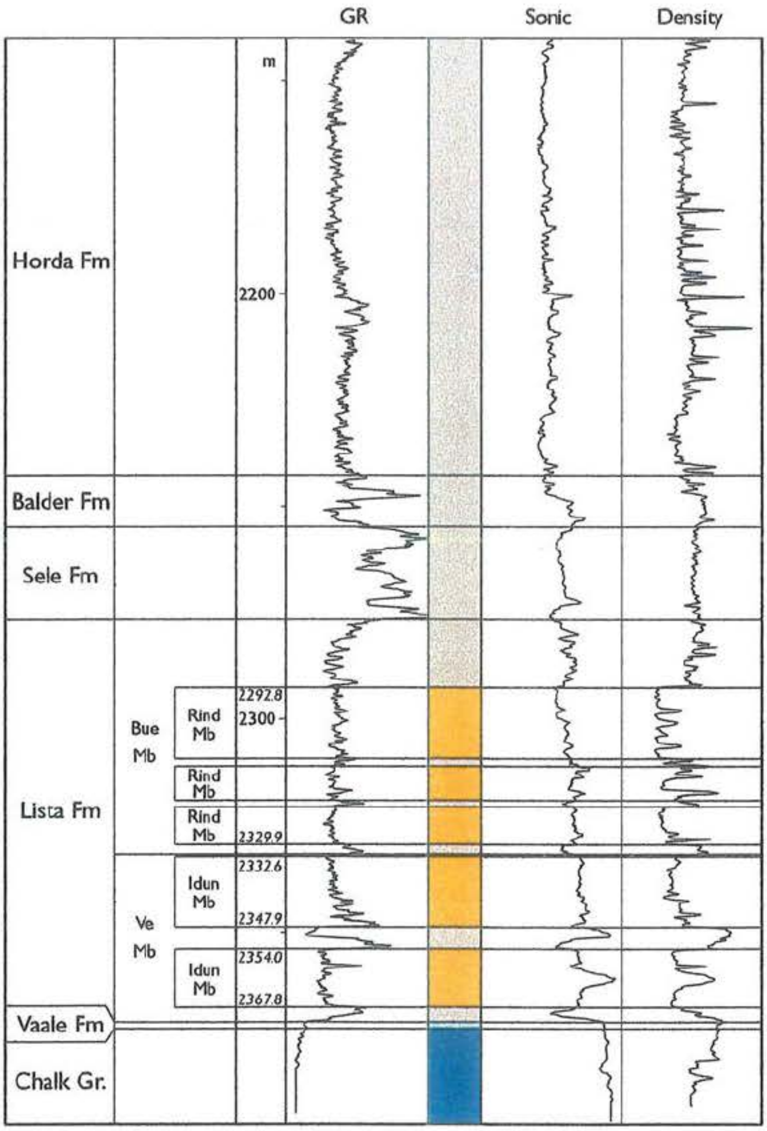



Fig.25

# Siri-2

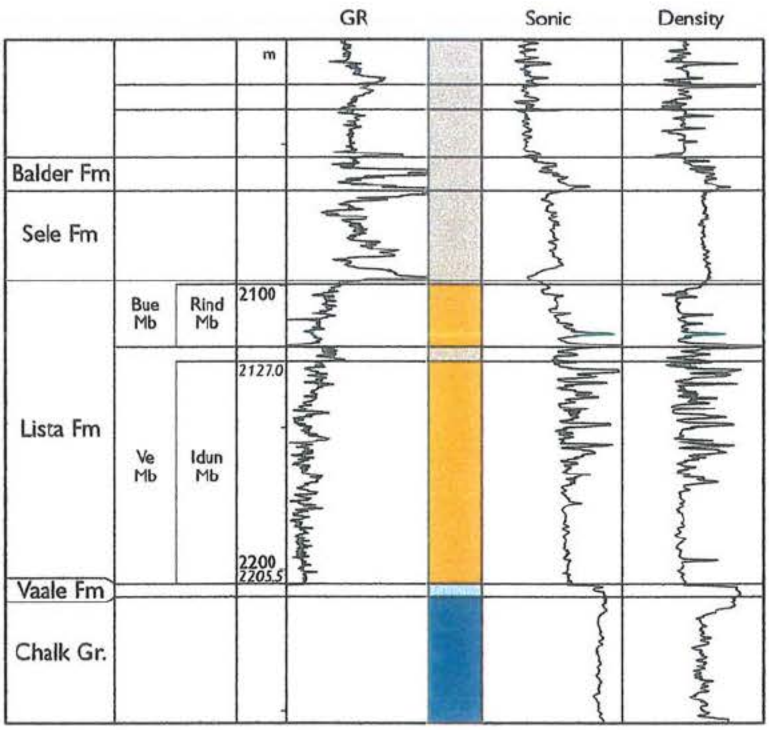

GR
Sonic
Density
m
Balder Fm
Sele Fm
Lista Fm
Vaale Fm
Chalk Gr.
Bue Mb
Rind Mb
Ve Mb
Idun Mb
2100
2127.0
2200
2205.5

Fig.26

## Connie-1

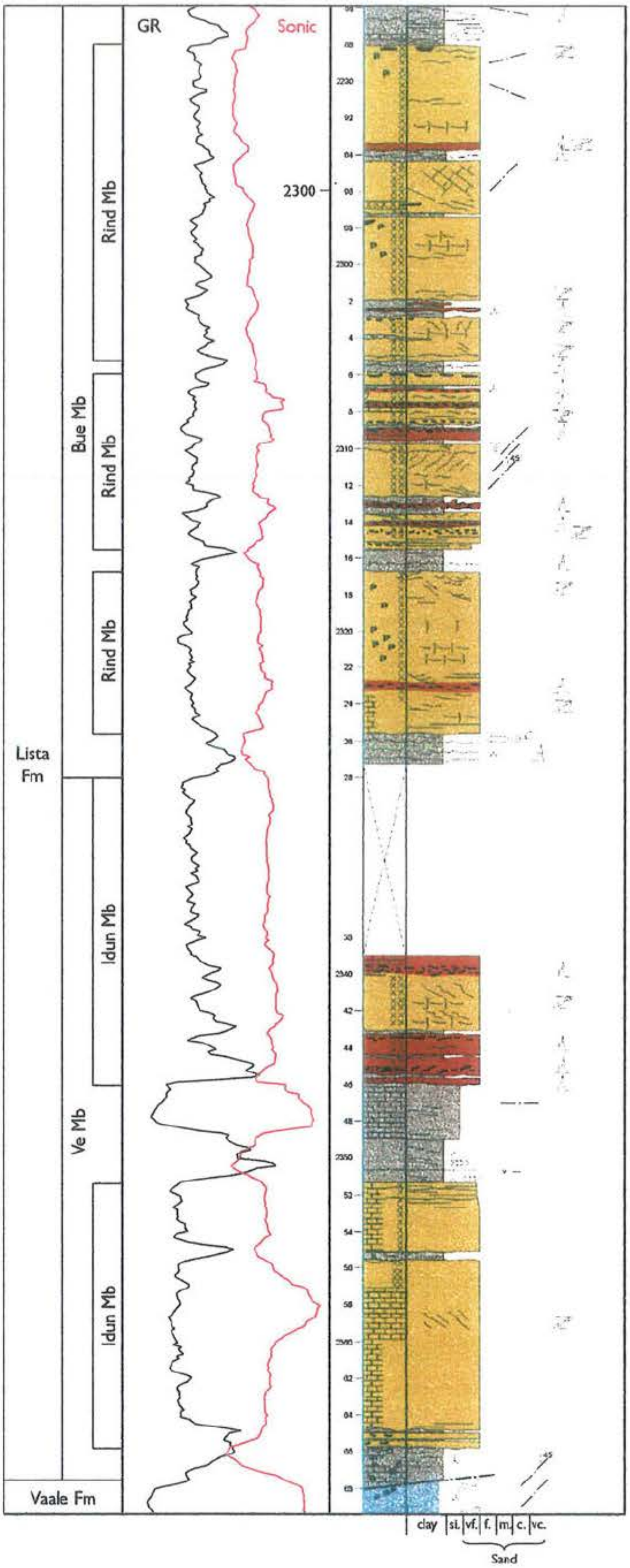



Fig.27

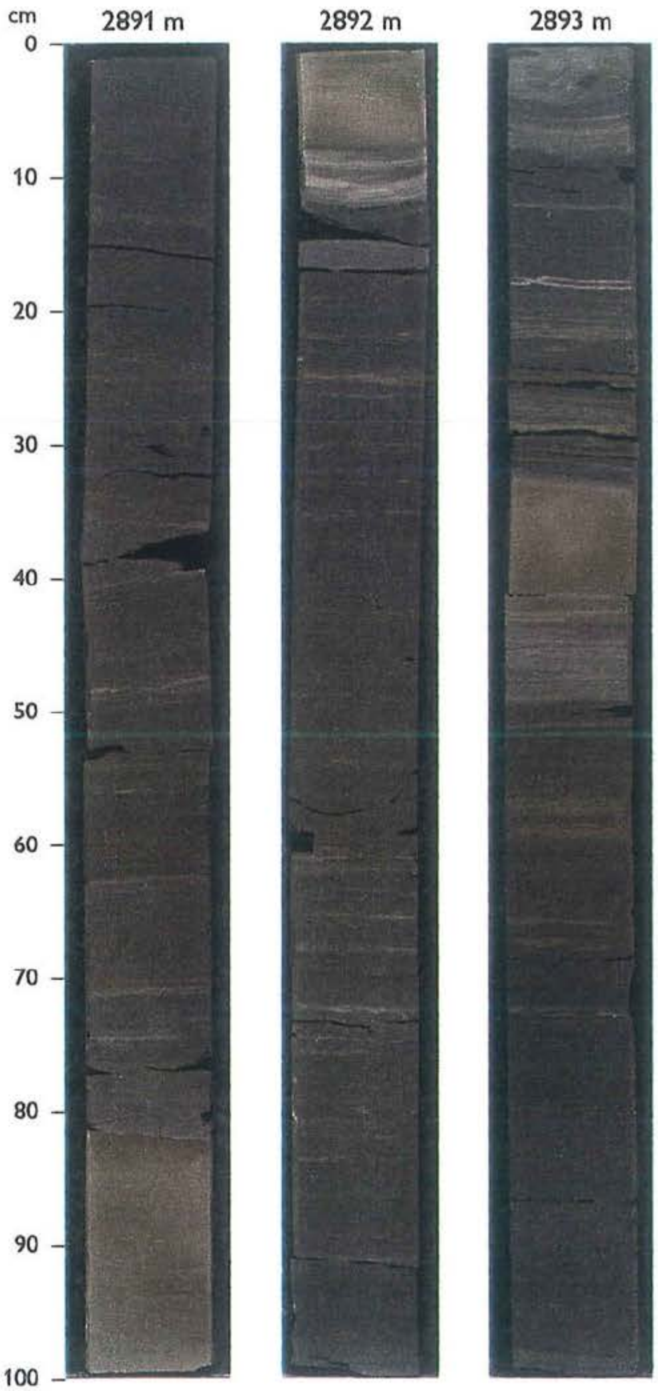



Fig.28

# Sandra-1

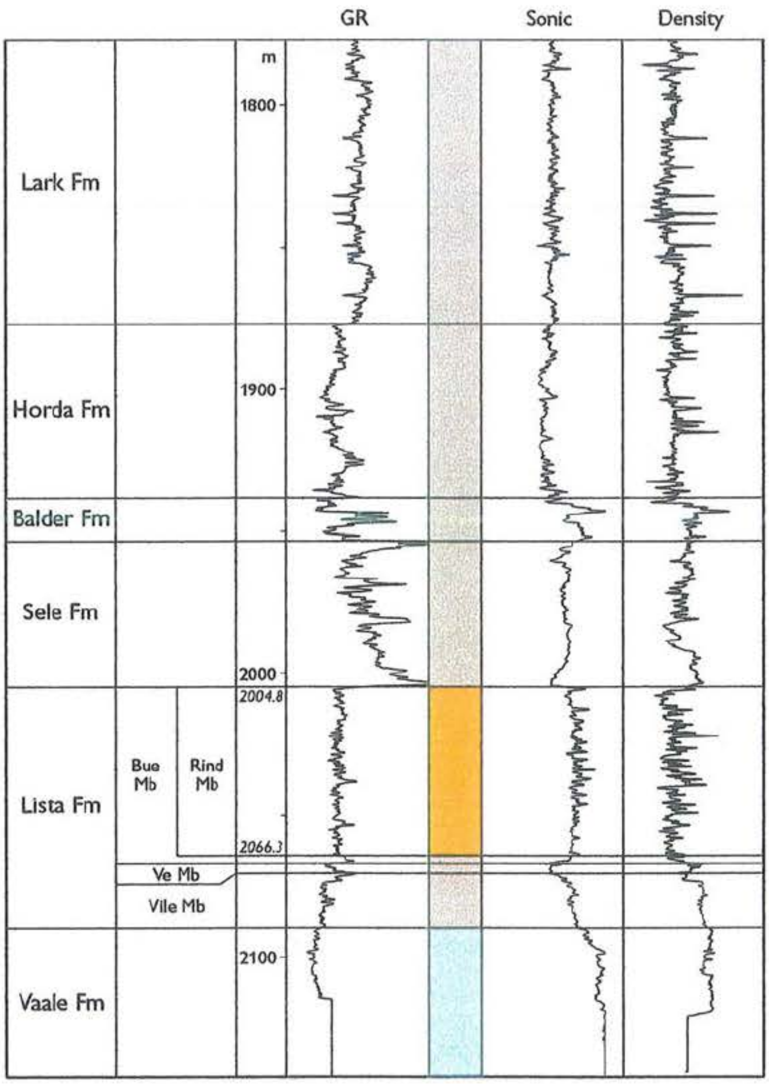



Fig.29

## Tabita-1

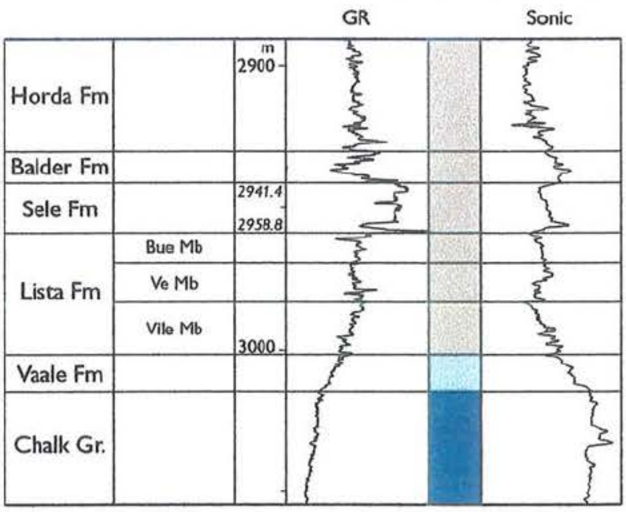



Fig.30

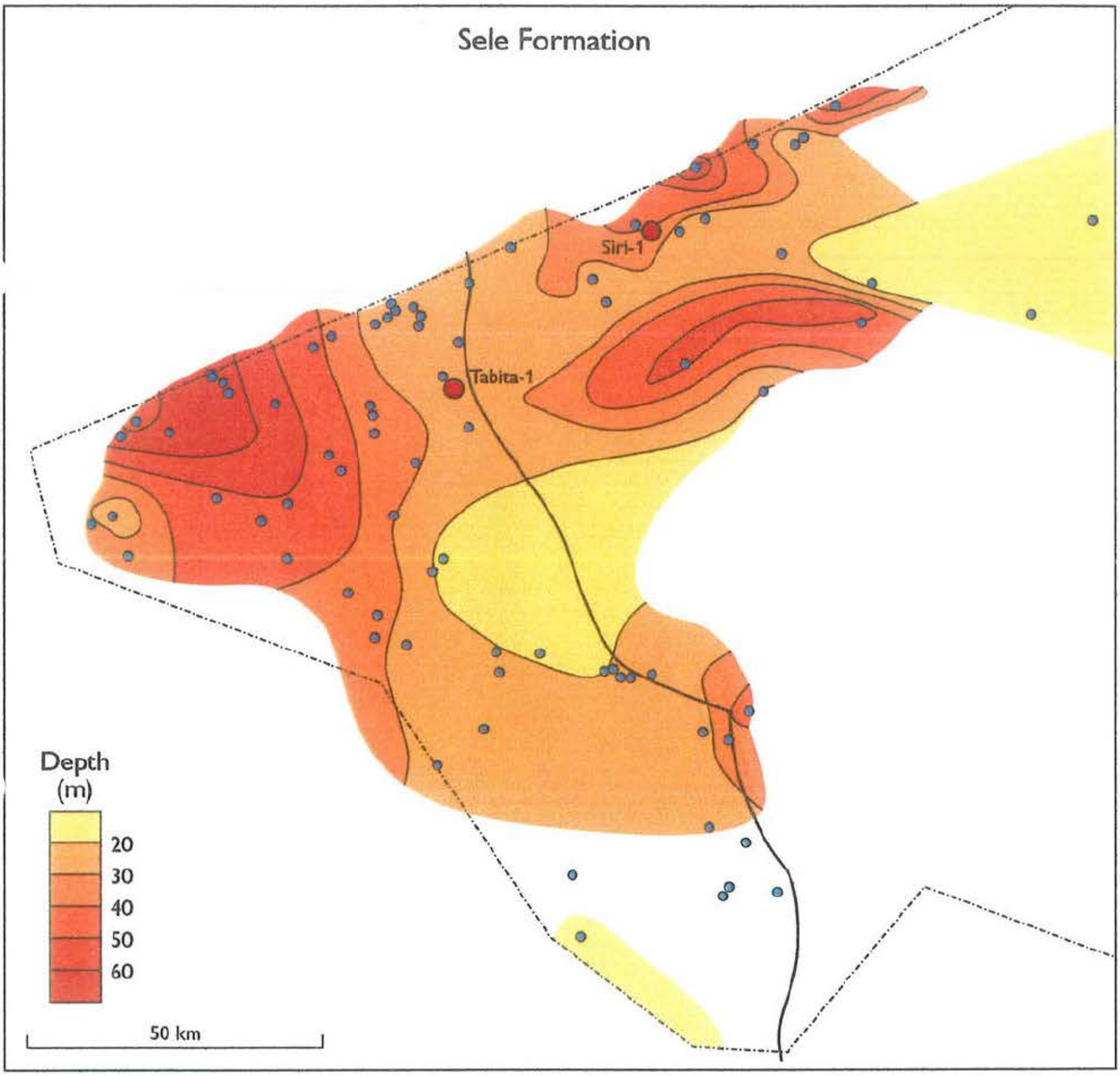



Fig.31

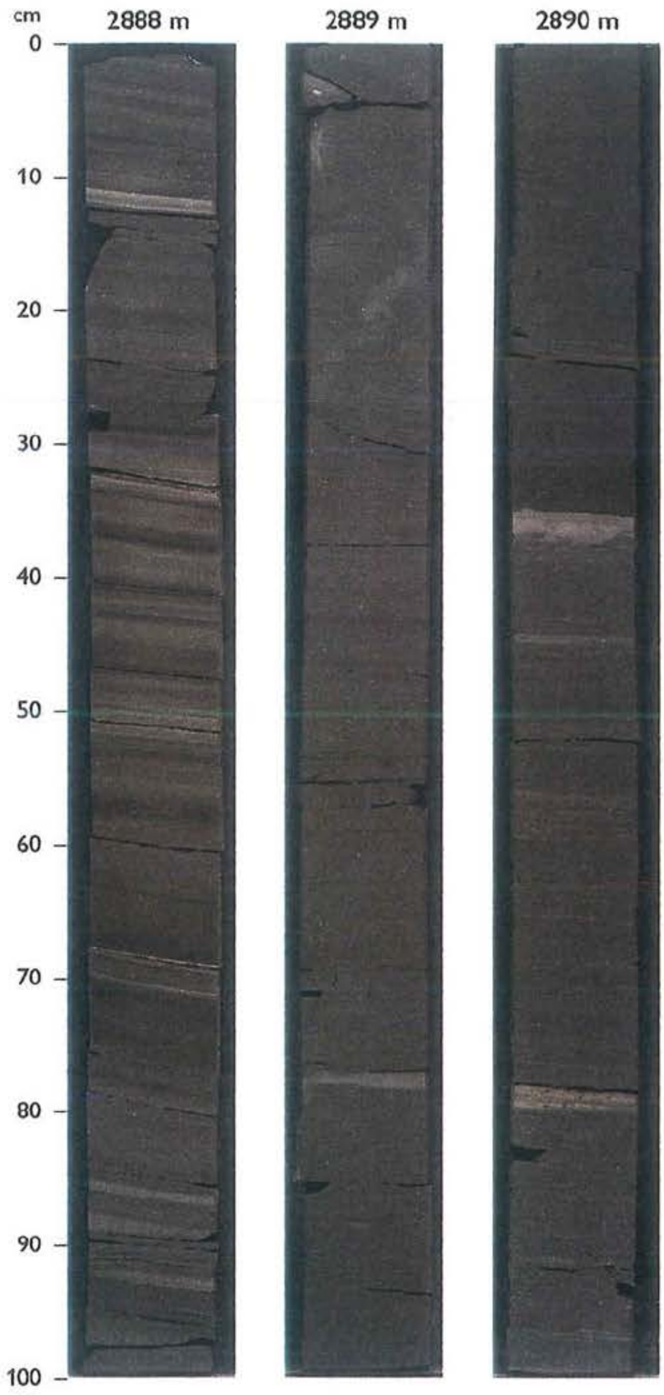



Fig.32

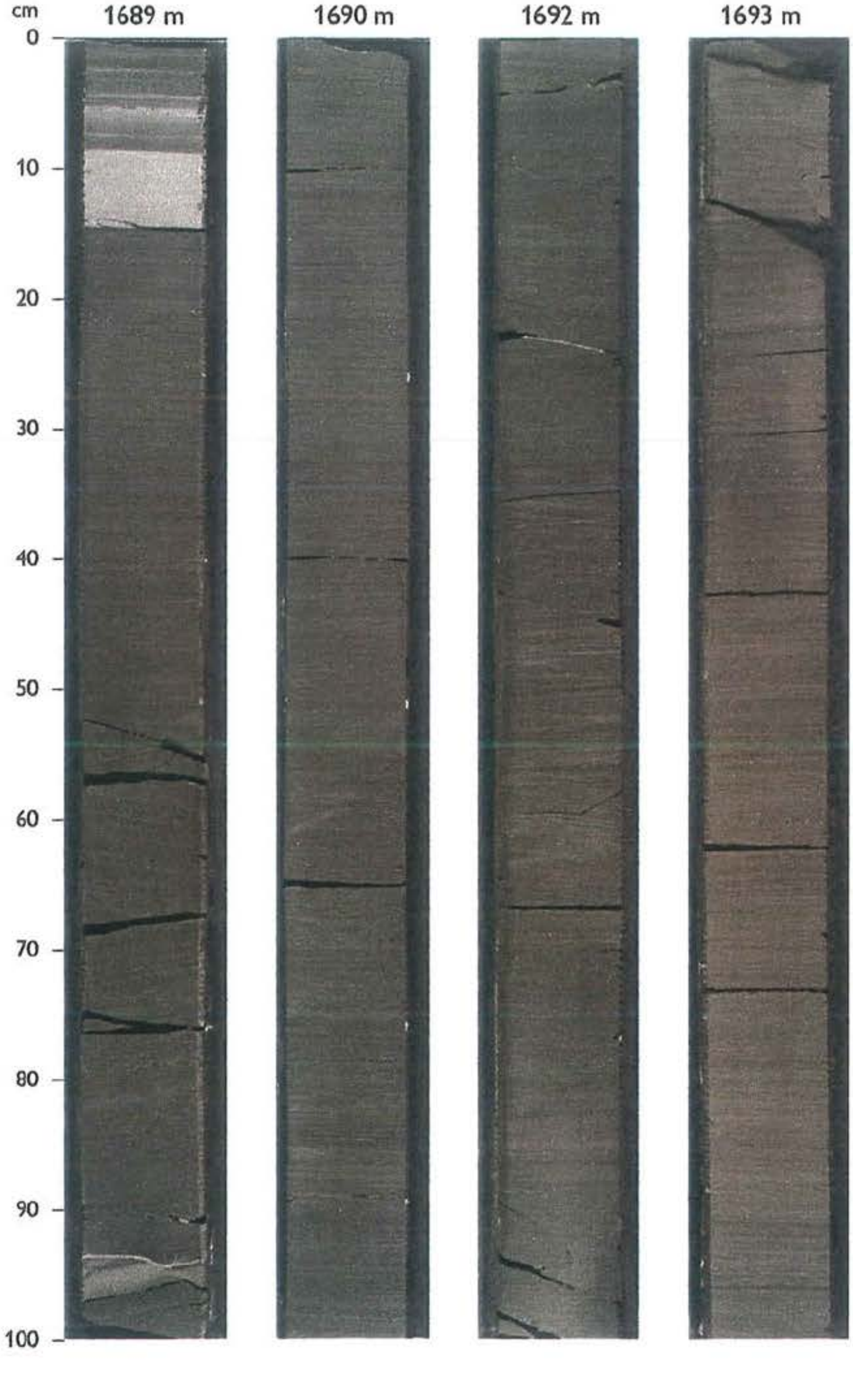
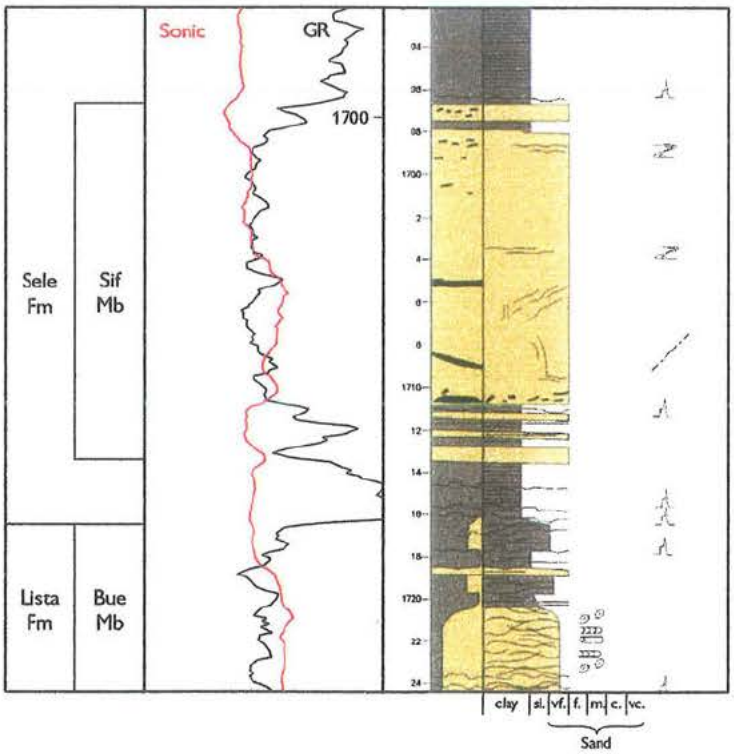



Fig.33

Nini-3



Sele Fm
Sif Mb
Lista Fm
Bue Mb
Sonic
GR
1700
clay
sl.
vf.
f.
m.
c.
vc.
Sand


Fig.34

Mona-1

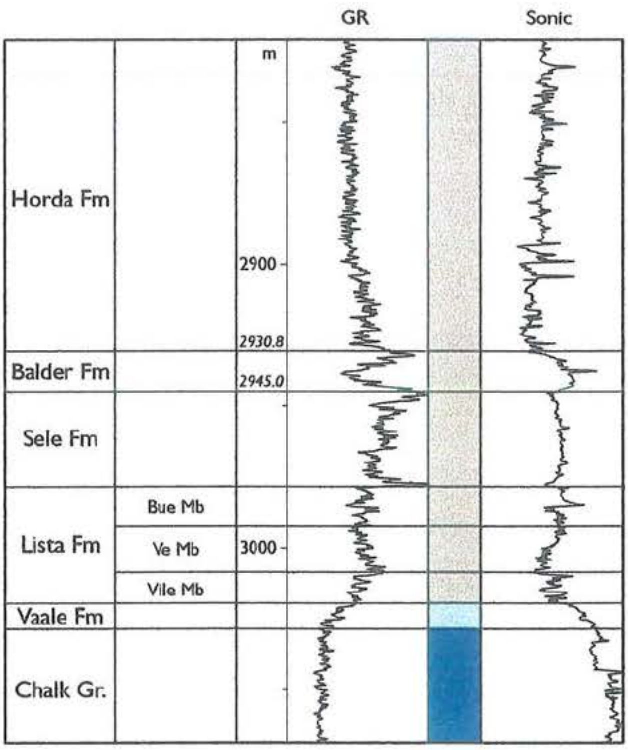

GR
Sonic
m
Horda Fm
2900
2930.8
Balder Fm
2945.0
Sele Fm
Bue Mb
Lista Fm
Ve Mb
3000
Vile Mb
Vaale Fm
Chalk Gr.

Fig.35

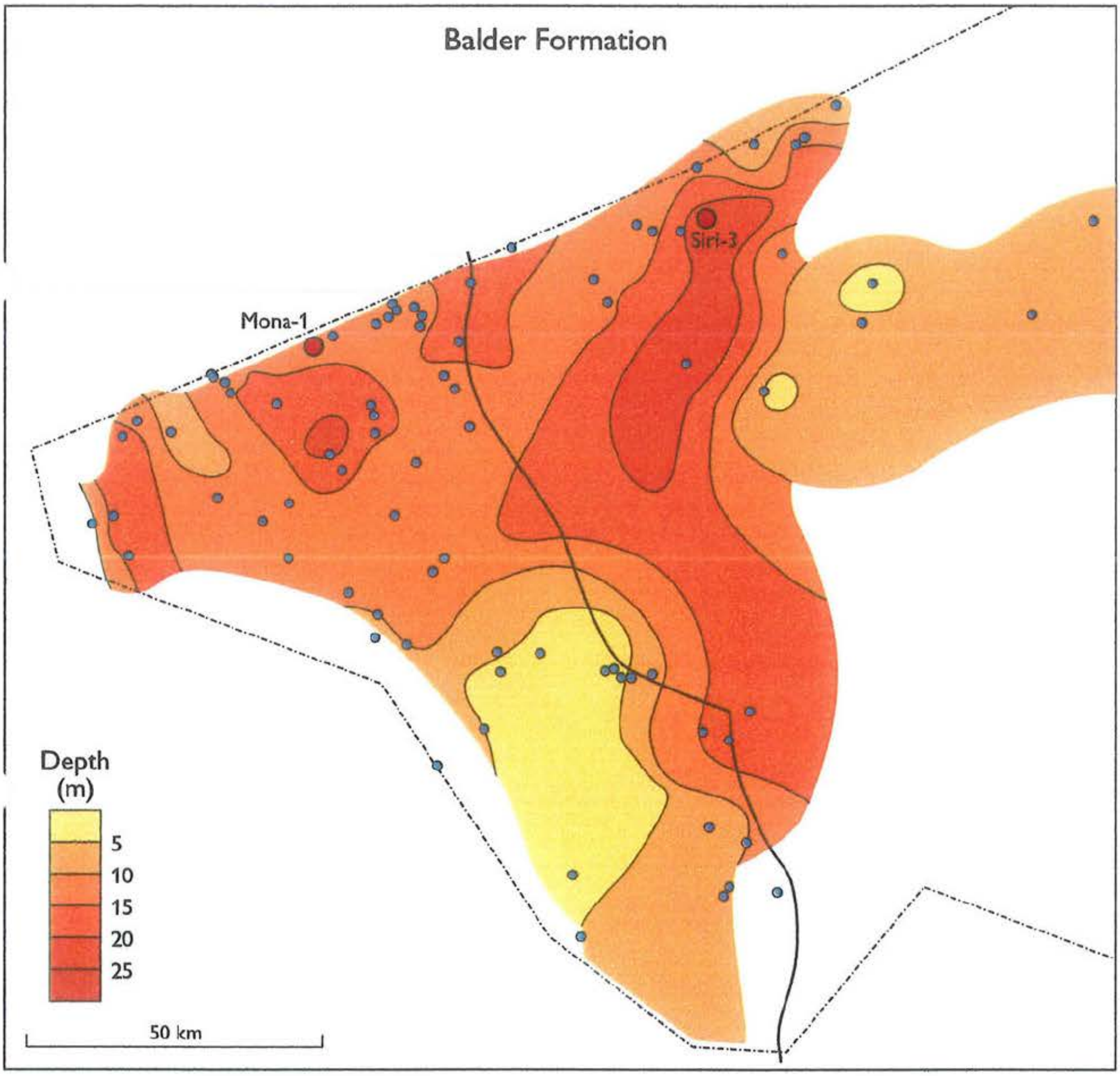
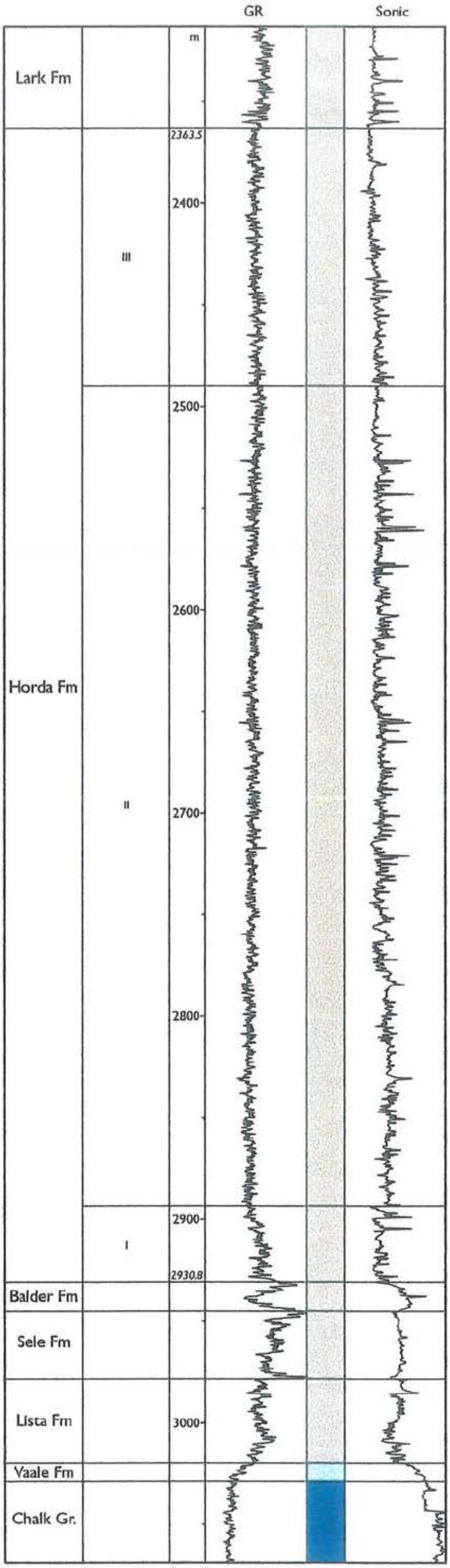



Fig.36

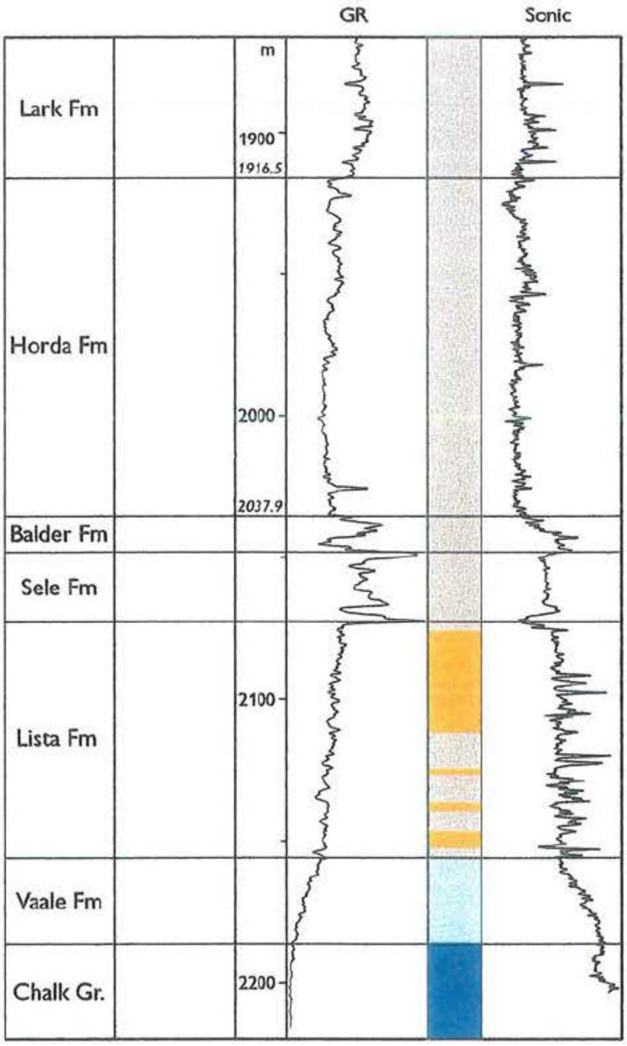
# Mona-1



GR
Sonic
m
Lark Fm
2363.5
2400
III
2500
2600
Horda Fm
II
2700
2800
2900
I
2930.8
Balder Fm
Sele Fm
Lista Fm
3000
Vaale Fm
Chalk Gr.

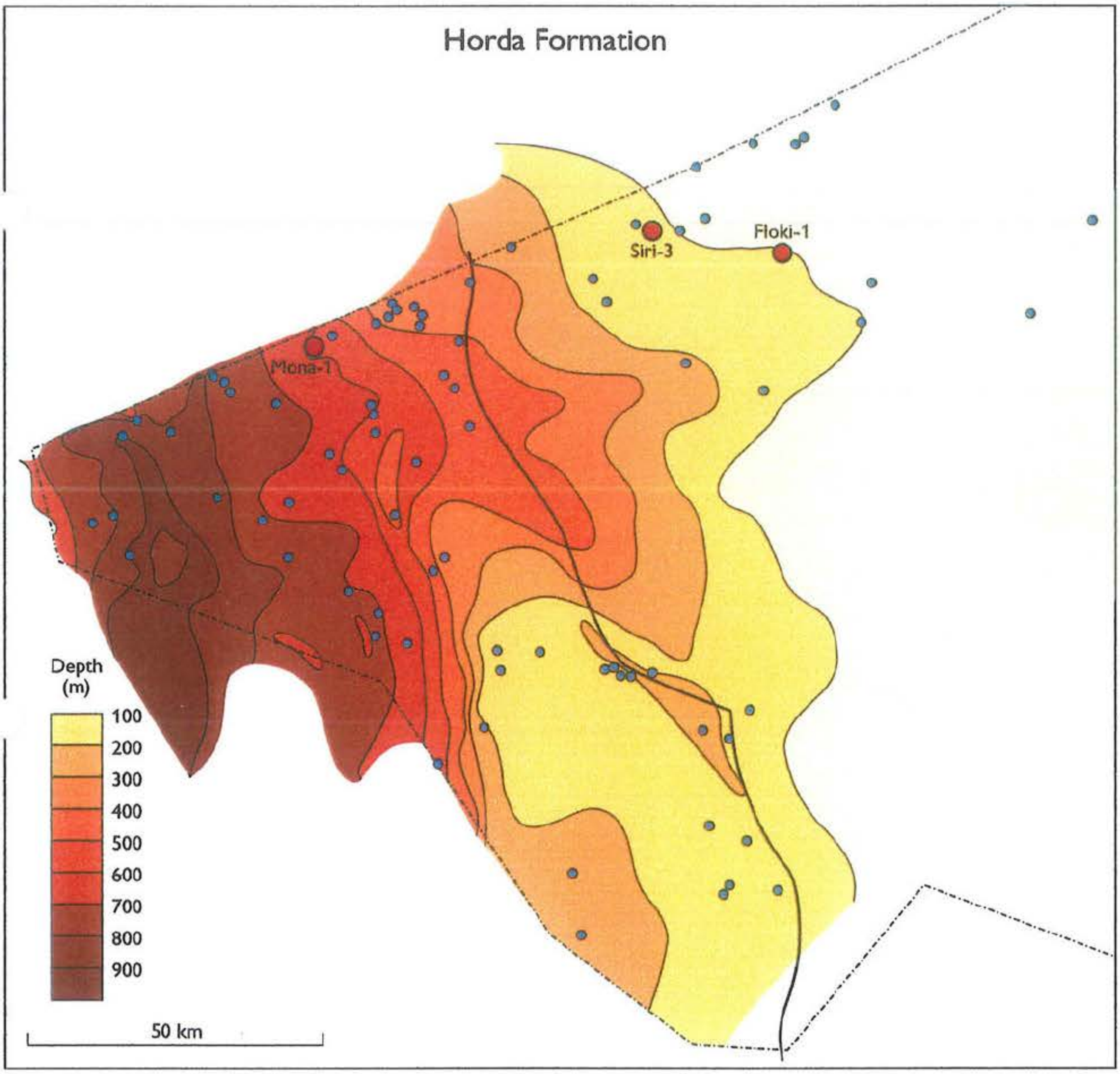

Fig.37

## Siri-1



GR
Sonic
m
Lark Fm
1900
1916.5
Horda Fm
2000
2037.9
Balder Fm
Sele Fm
Lista Fm
2100
Vaale Fm
Chalk Gr.
2200


Fig.38



Horda Formation
Siri-3
Floki-1
Mona-1
Depth
(m)
100
200
300
400
500
600
700
800
900
50 km


Fig.39

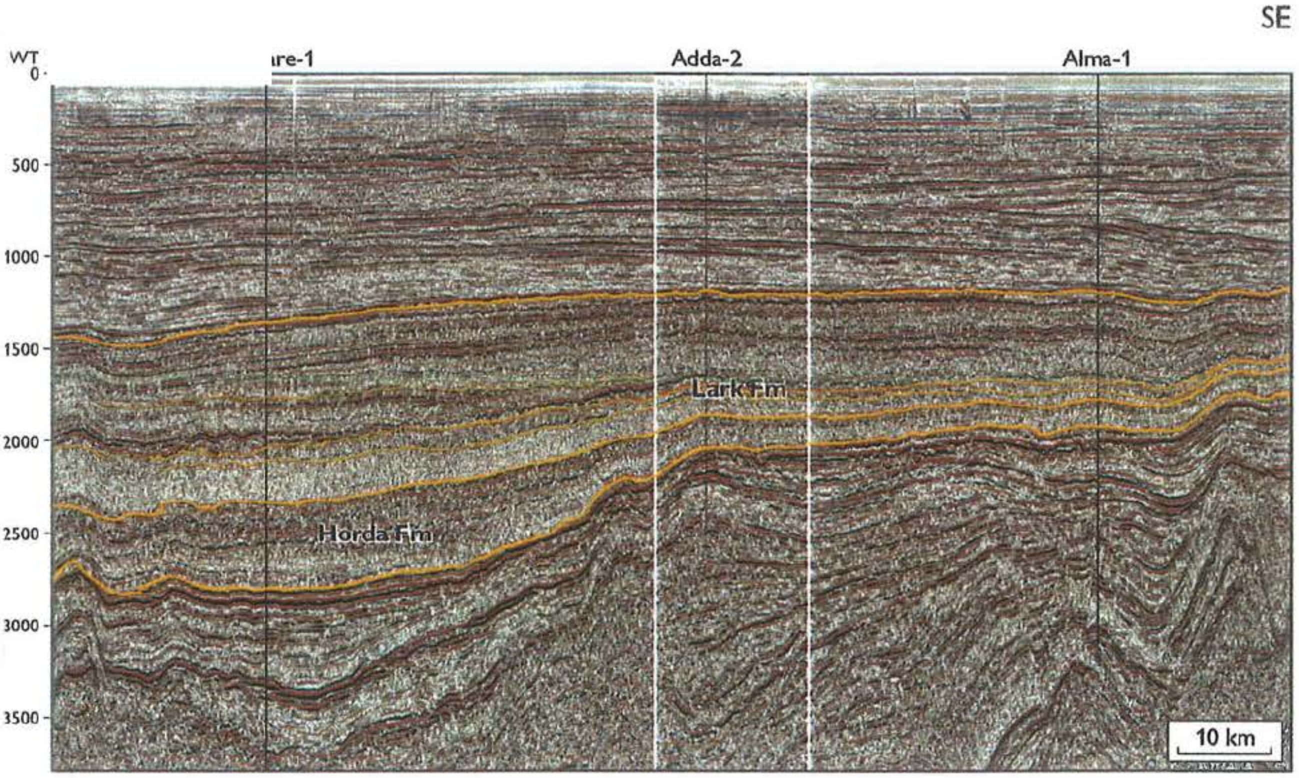

SE
WT
0
500
1000
1500
2000
2500
3000
3500
ıre-1
Adda-2
Alma-1
Lark Fm
Horda Fm
10 km

Fig.40a

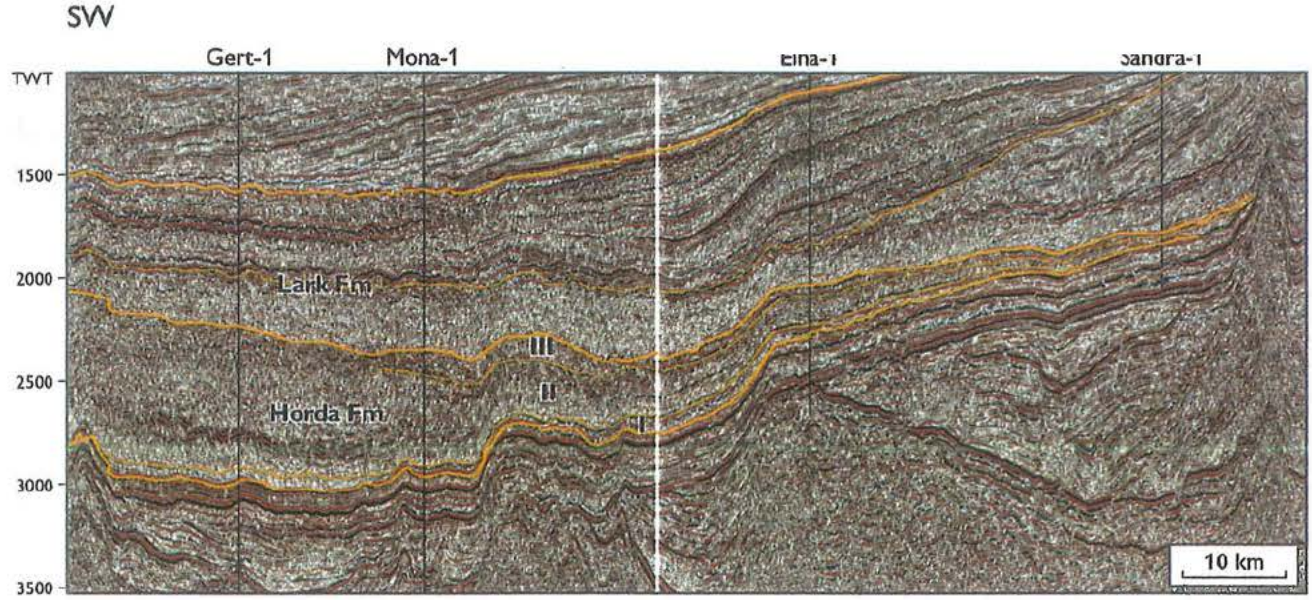

SW
Gert-1
Mona-1
Elna-1
Sandra-1
TWT
1500
2000
2500
3000
3500
Lark Fm
III
II
I
Horda Fm
10 km

Fig.40b

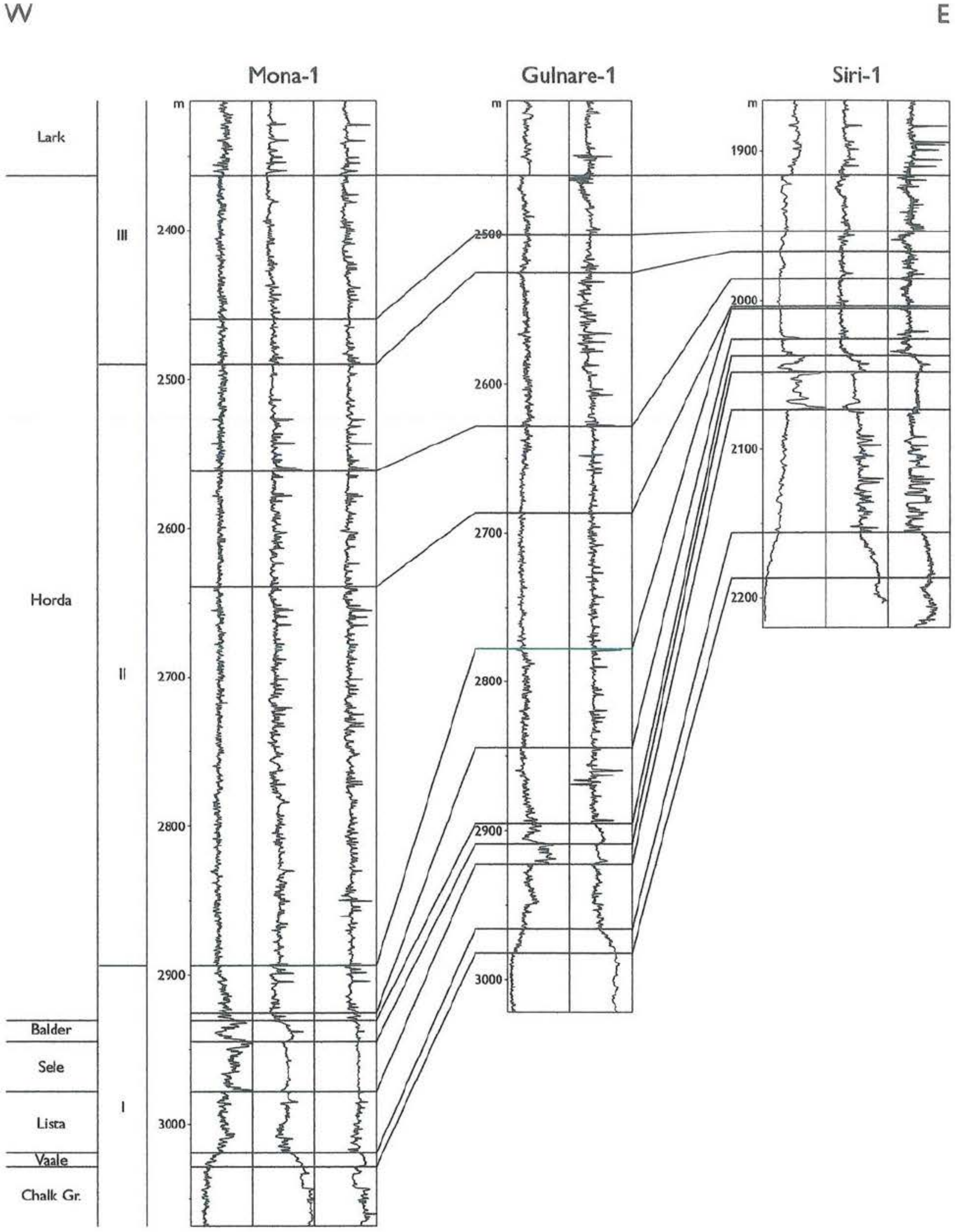

W
E
Mona-1
Gulnare-1
Siri-1
Lark
Horda
Balder
Sele
Lista
Vaale
Chalk Gr.
III
II
I
m
2400
2500
2600
2700
2800
2900
3000
1900
2000
2100
2200

Fig.41

## Floki-1

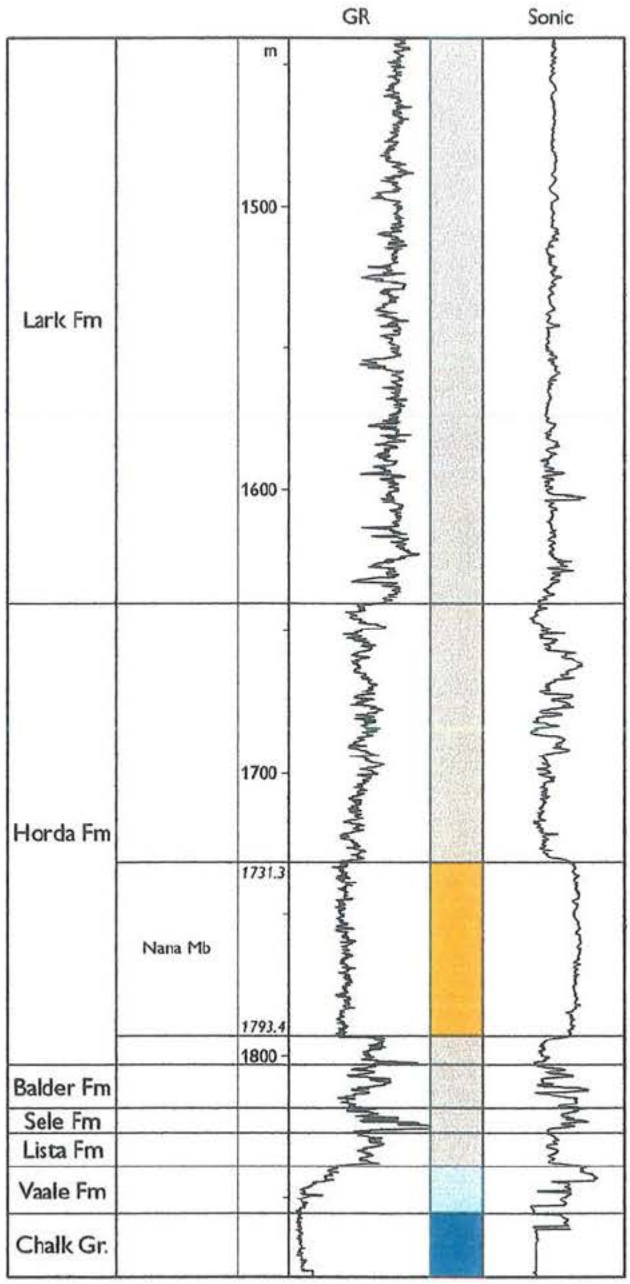
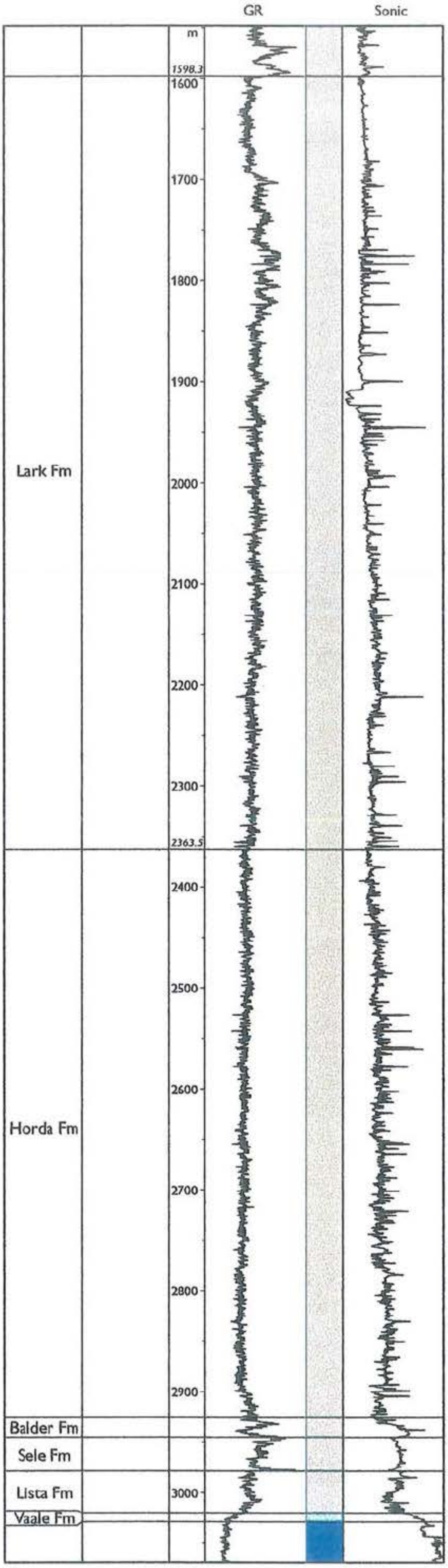



Fig.42

# Mona-1



GR
Sonic
m
1598.3
1600
1700
1800
1900
2000
2100
2200
2300
2363.5
2400
2500
2600
2700
2800
2900
3000
Lark Fm
Horda Fm
Balder Fm
Sele Fm
Lista Fm
Vaale Fm


Fig.43

Siri-1

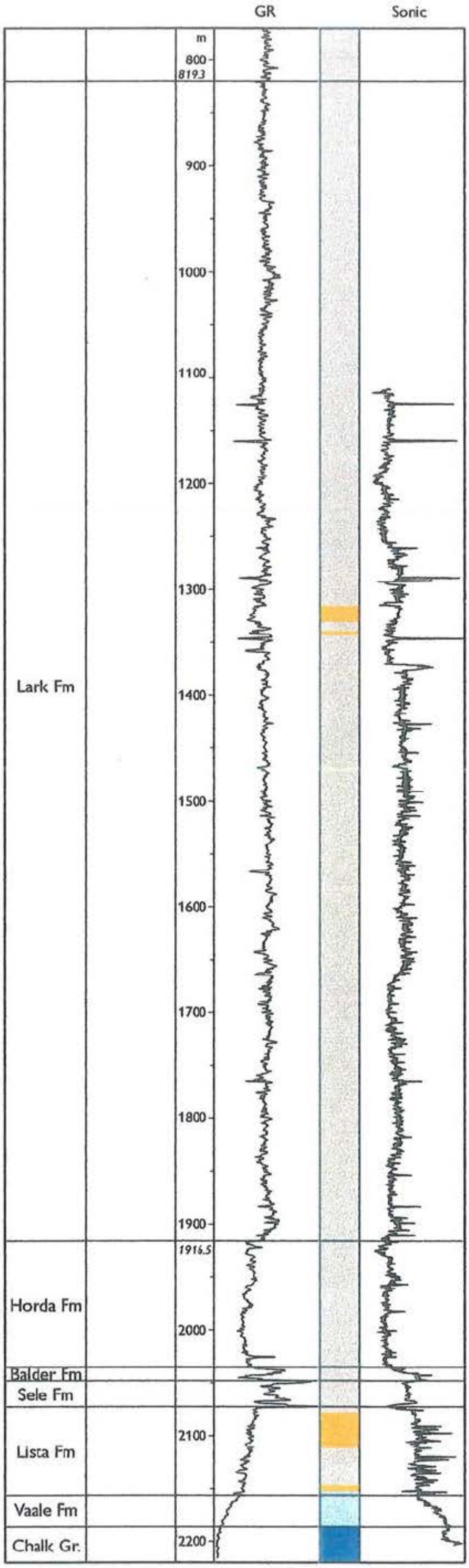

GR
Sonic
m
800
819.3
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
1916.5
2000
2100
2200
Lark Fm
Horda Fm
Balder Fm
Sele Fm
Lista Fm
Vaale Fm
Chalk Gr.

Fig.44

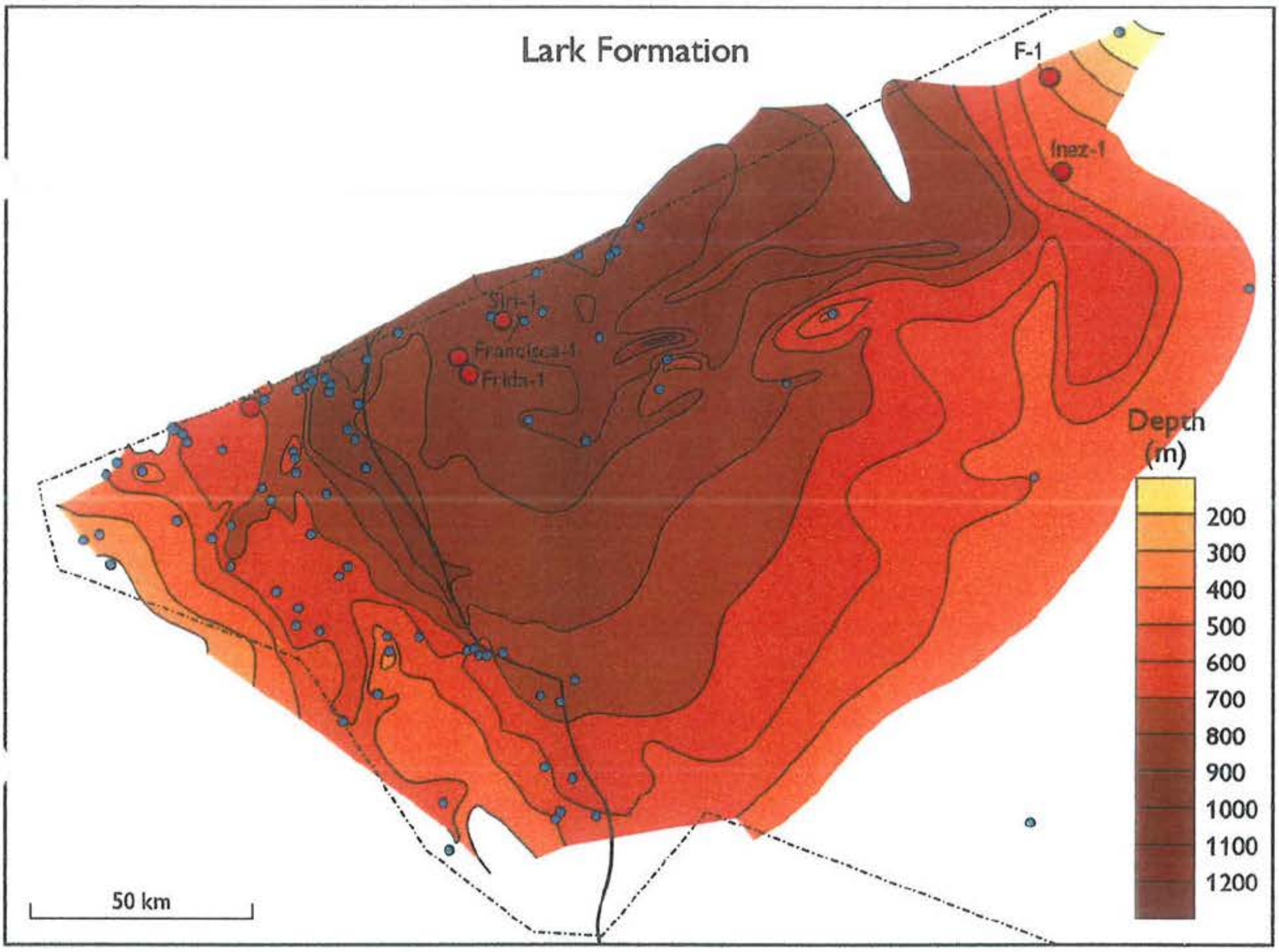
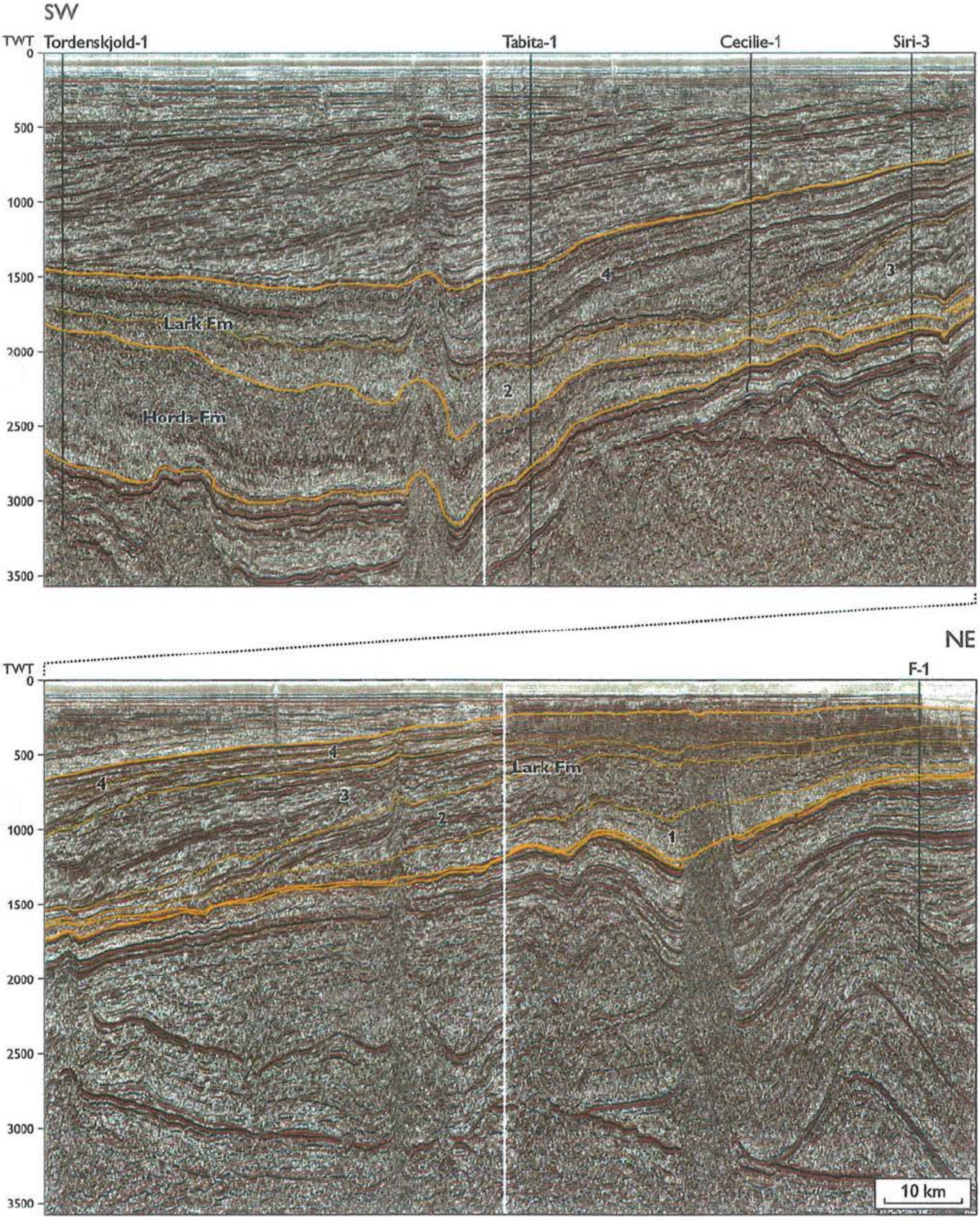

Lark Formation
F-1
Inez-1
Siri-1
Francisca-1
Frida-1
Depth (m)
200
300
400
500
600
700
800
900
1000
1100
1200
50 km

Fig.45



SW
TWT
Tordenskjold-1
Tabita-1
Cecilie-1
Siri-3
0
500
1000
1500
2000
2500
3000
3500
4
3
Lark Fm
2
Horda Fm
NE
TWT
F-1
0
500
1000
1500
2000
2500
3000
3500
4
4
Lark Fm
3
2
1
10 km


Fig.46a

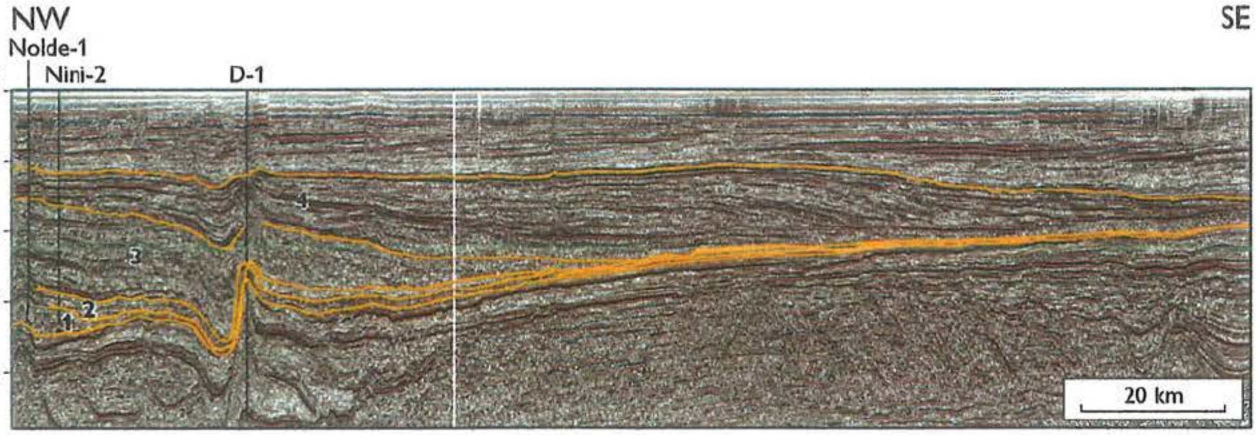



Fig.46b

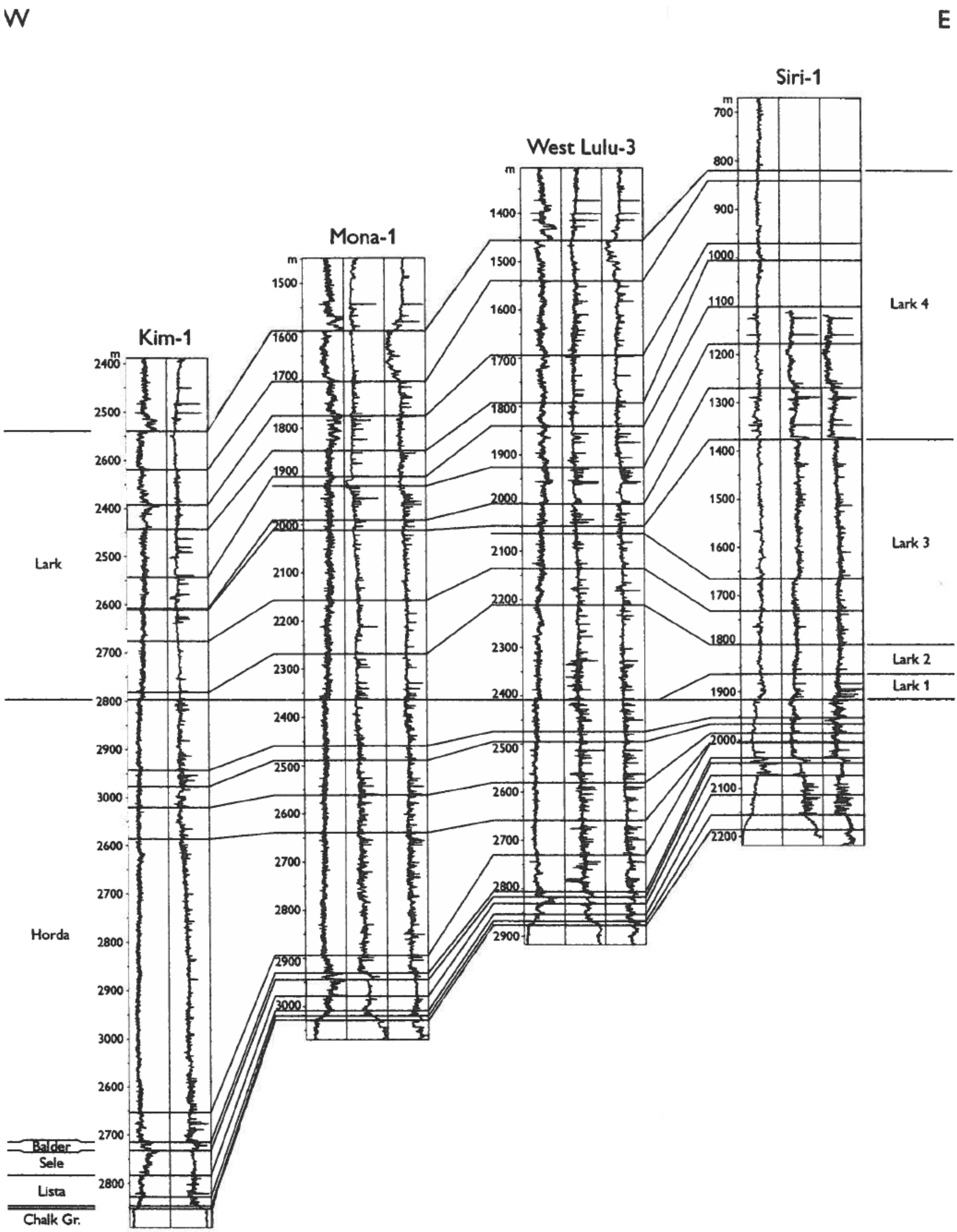

W
E
Kim-1
Mona-1
West Lulu-3
Siri-1
Lark
Horda
Balder
Sele
Lista
Chalk Gr.
Lark 4
Lark 3
Lark 2
Lark 1

Fig.47

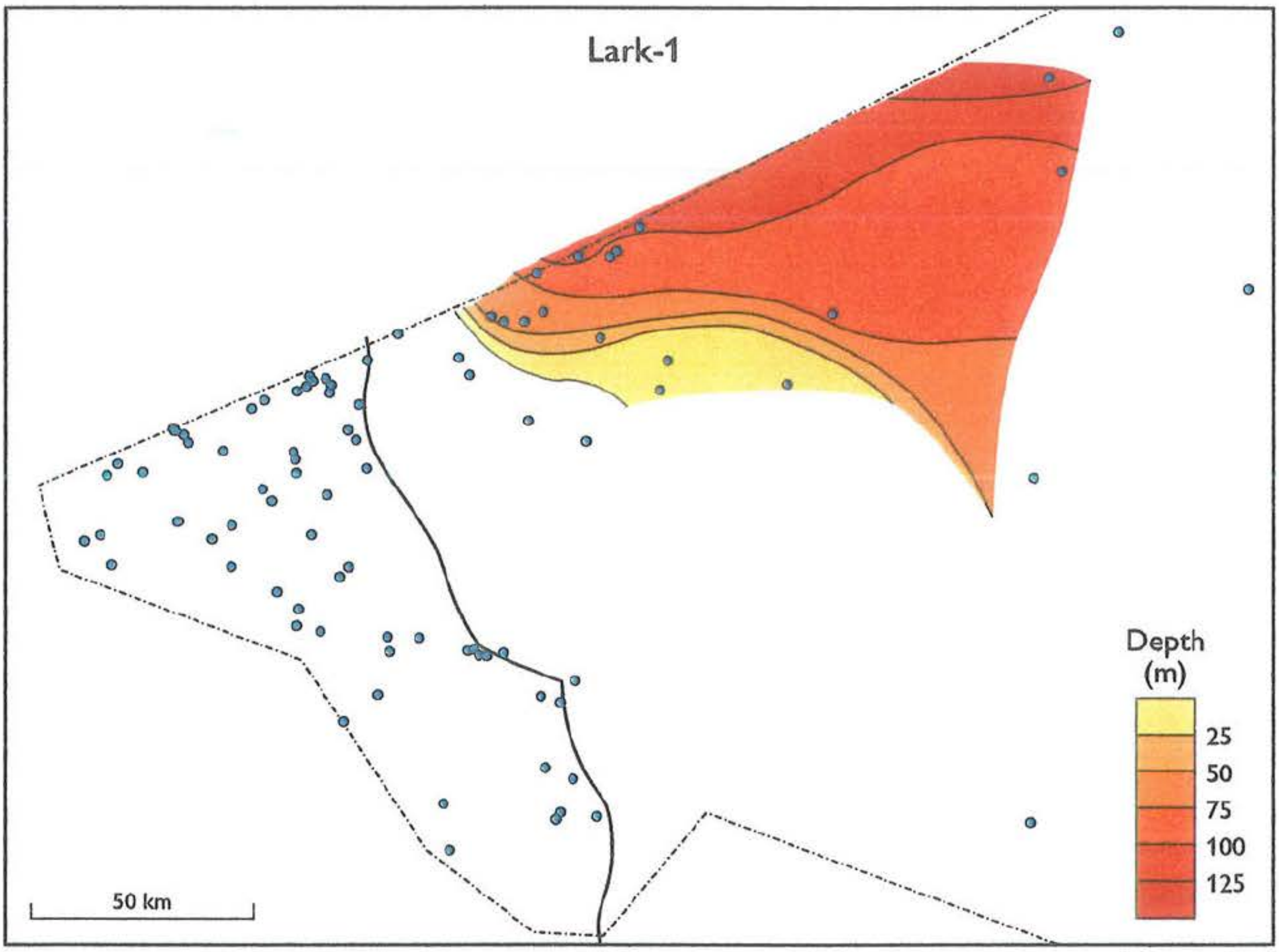



Fig.48a

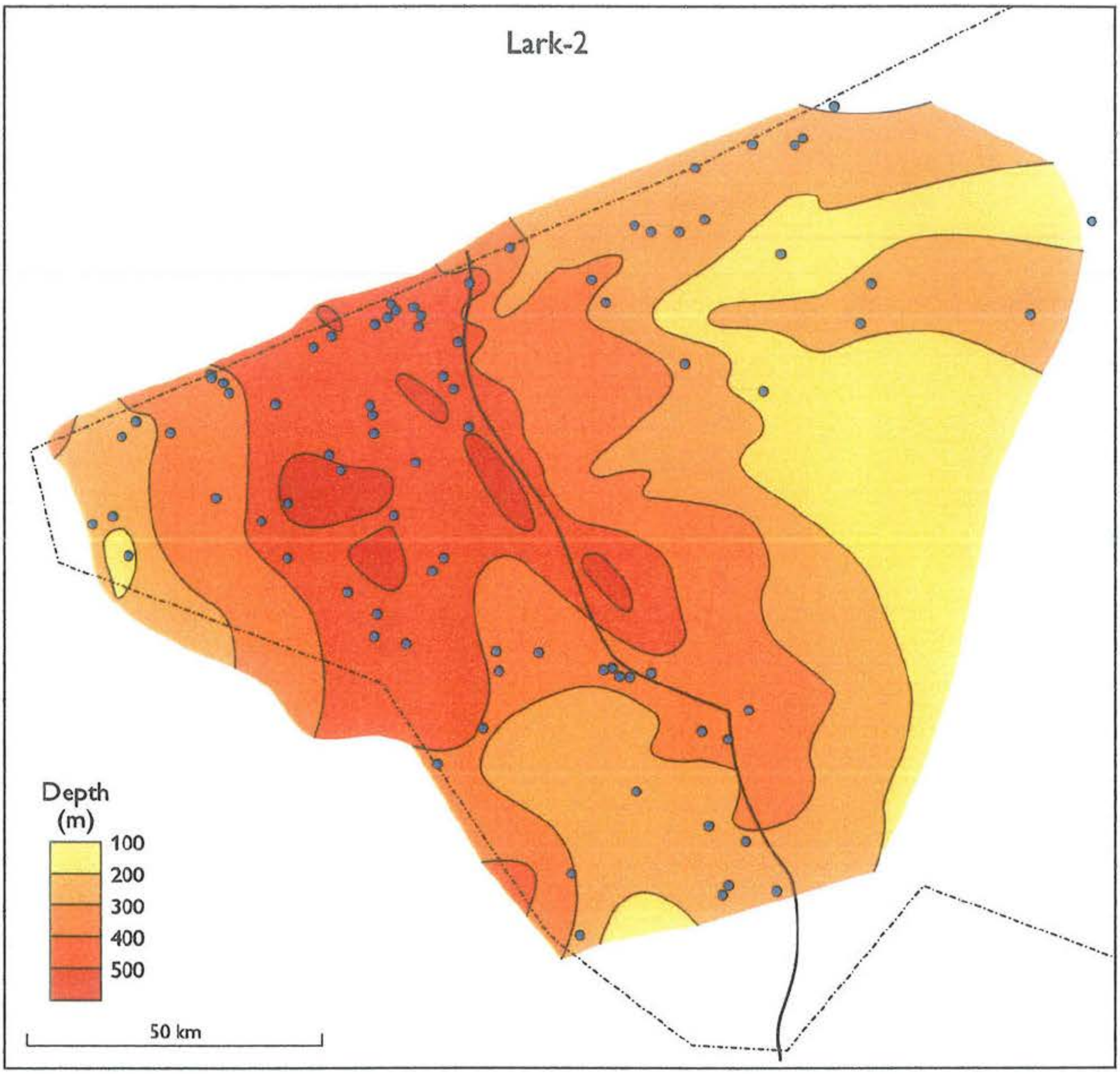



Fig.48b

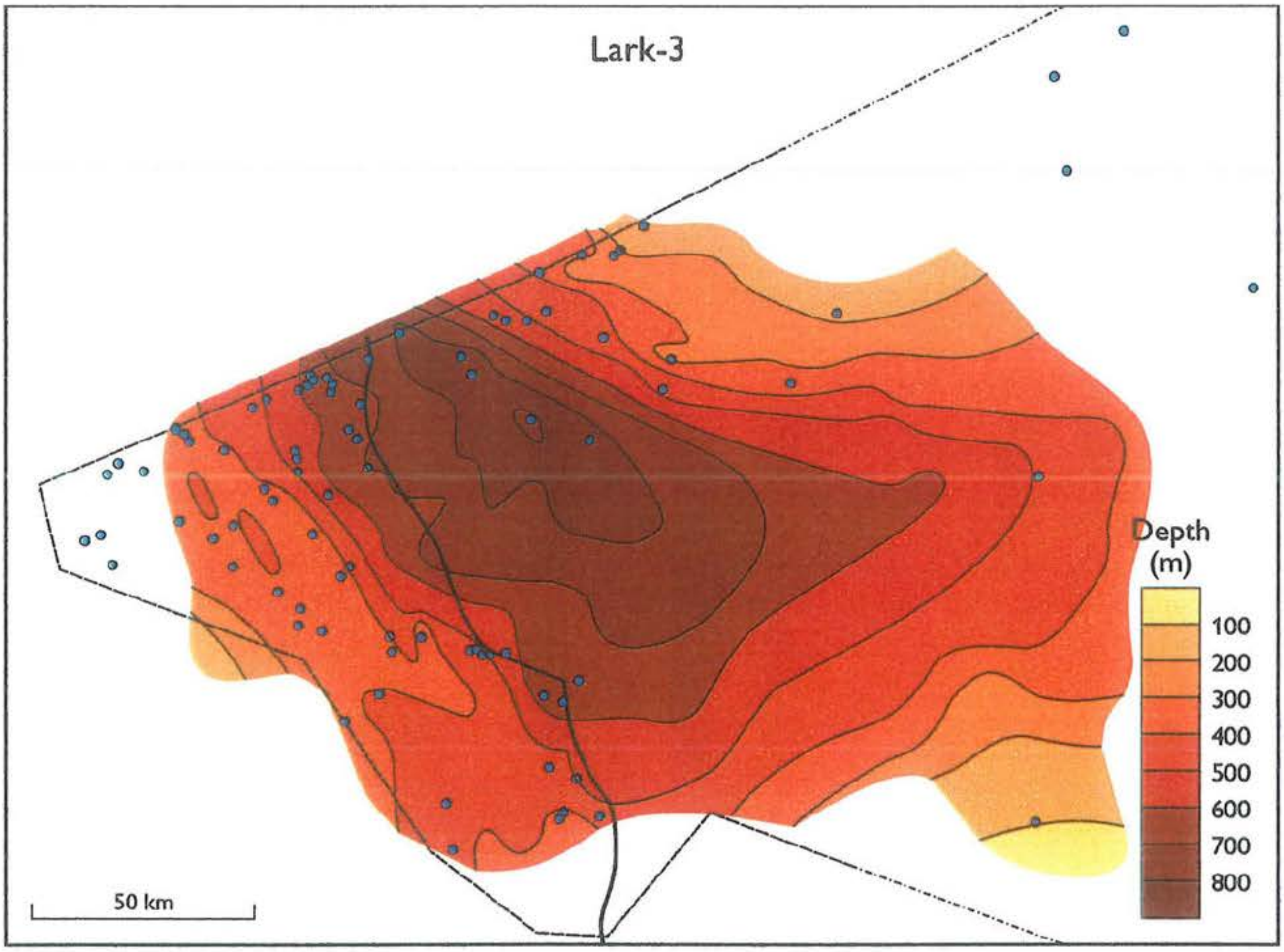



Fig.48c

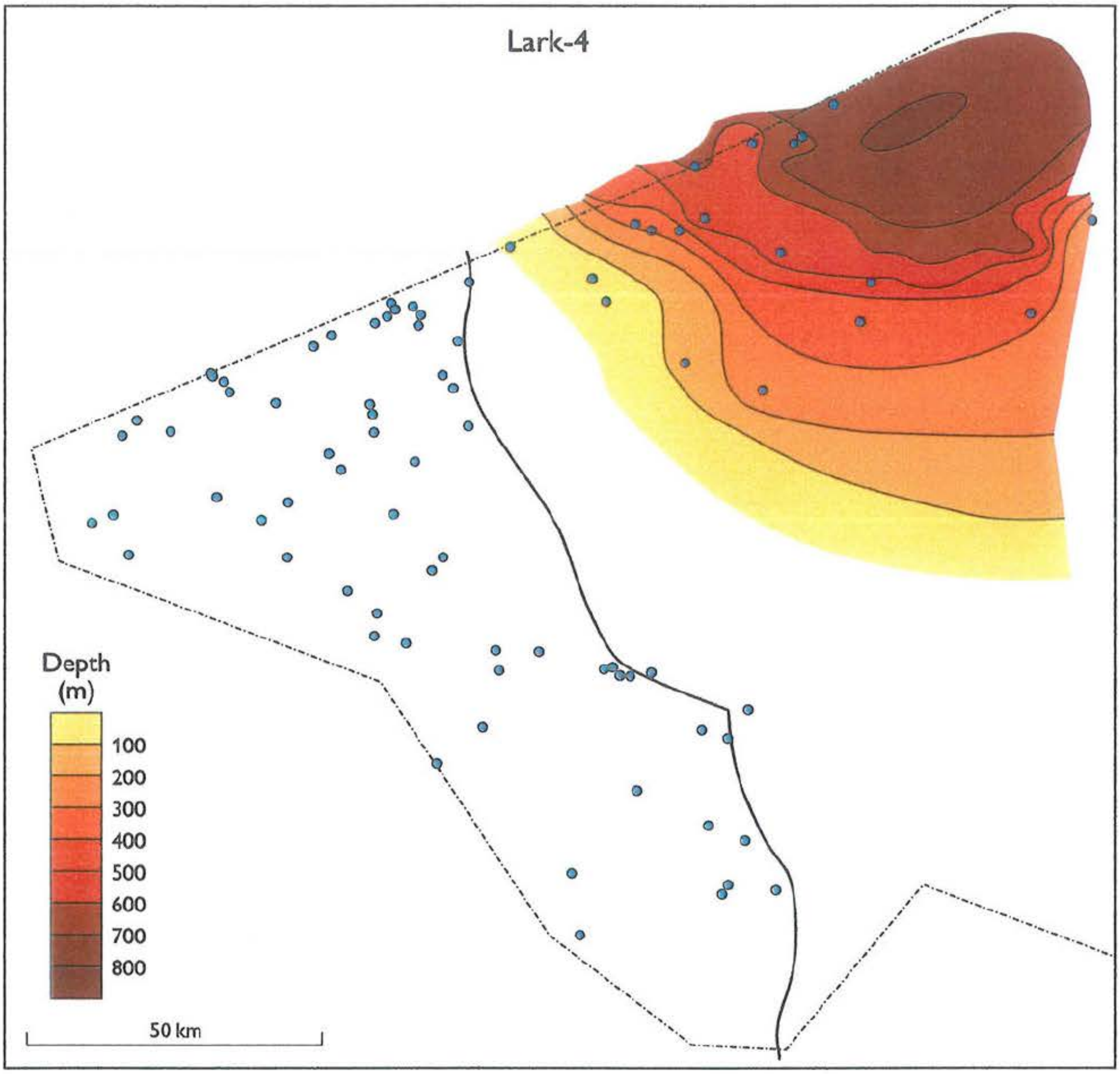



Fig.48d

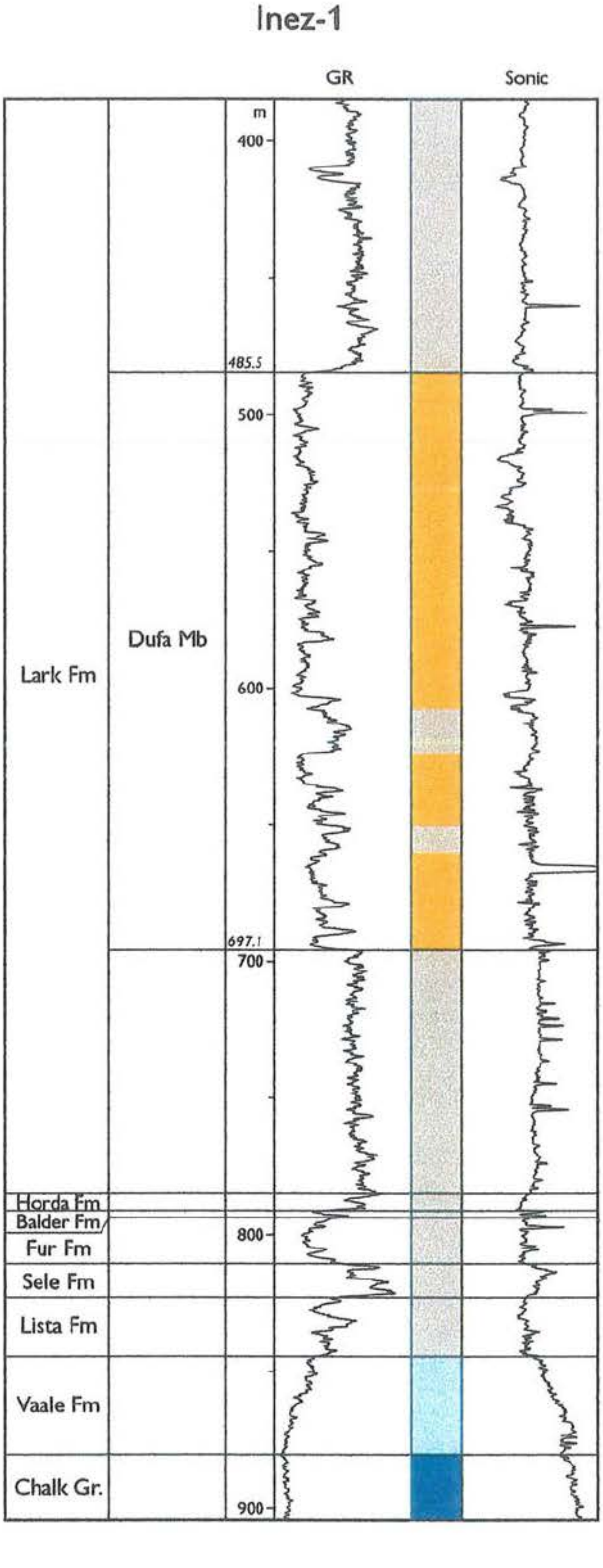

Inez-1
GR
Sonic
m
400
485.5
500
600
697.1
700
800
900
Lark Fm
Dufa Mb
Horda Fm
Balder Fm
Fur Fm
Sele Fm
Lista Fm
Vaale Fm
Chalk Gr.

Fig.49

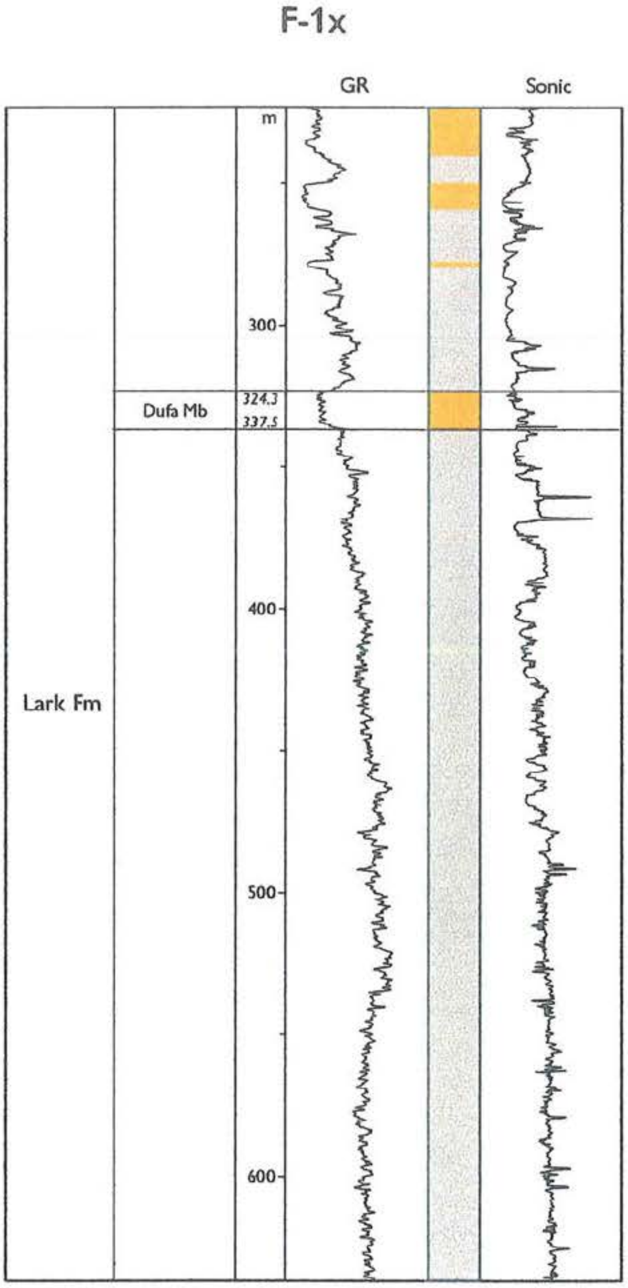



Fig.50

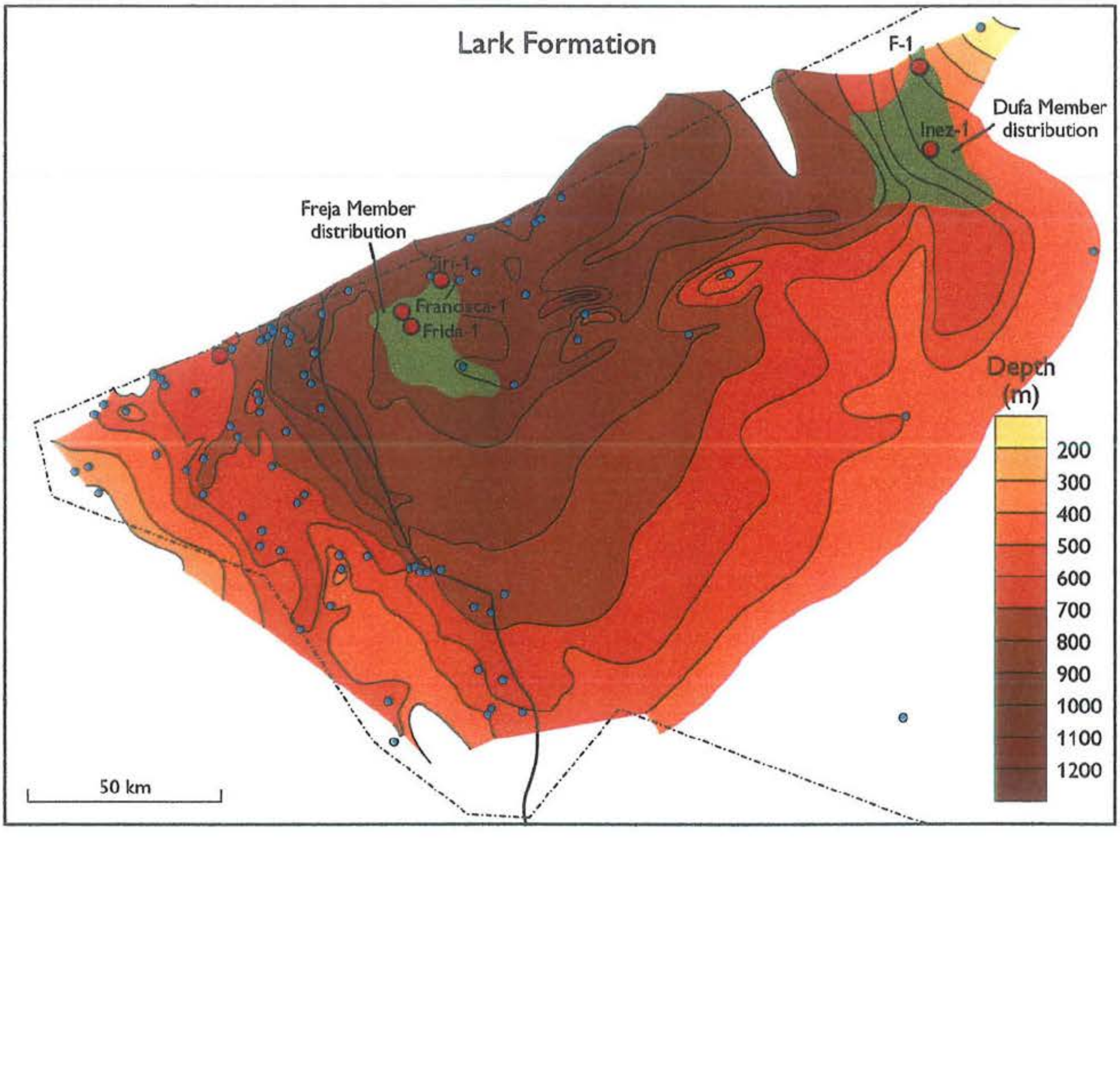

Lark Formation
F-1
Dufa Member
distribution
Inez-1
Freja Member
distribution
Siri-1
Francisca-1
Frida-1
Depth
(m)
200
300
400
500
600
700
800
900
1000
1100
1200
50 km

Fig.51

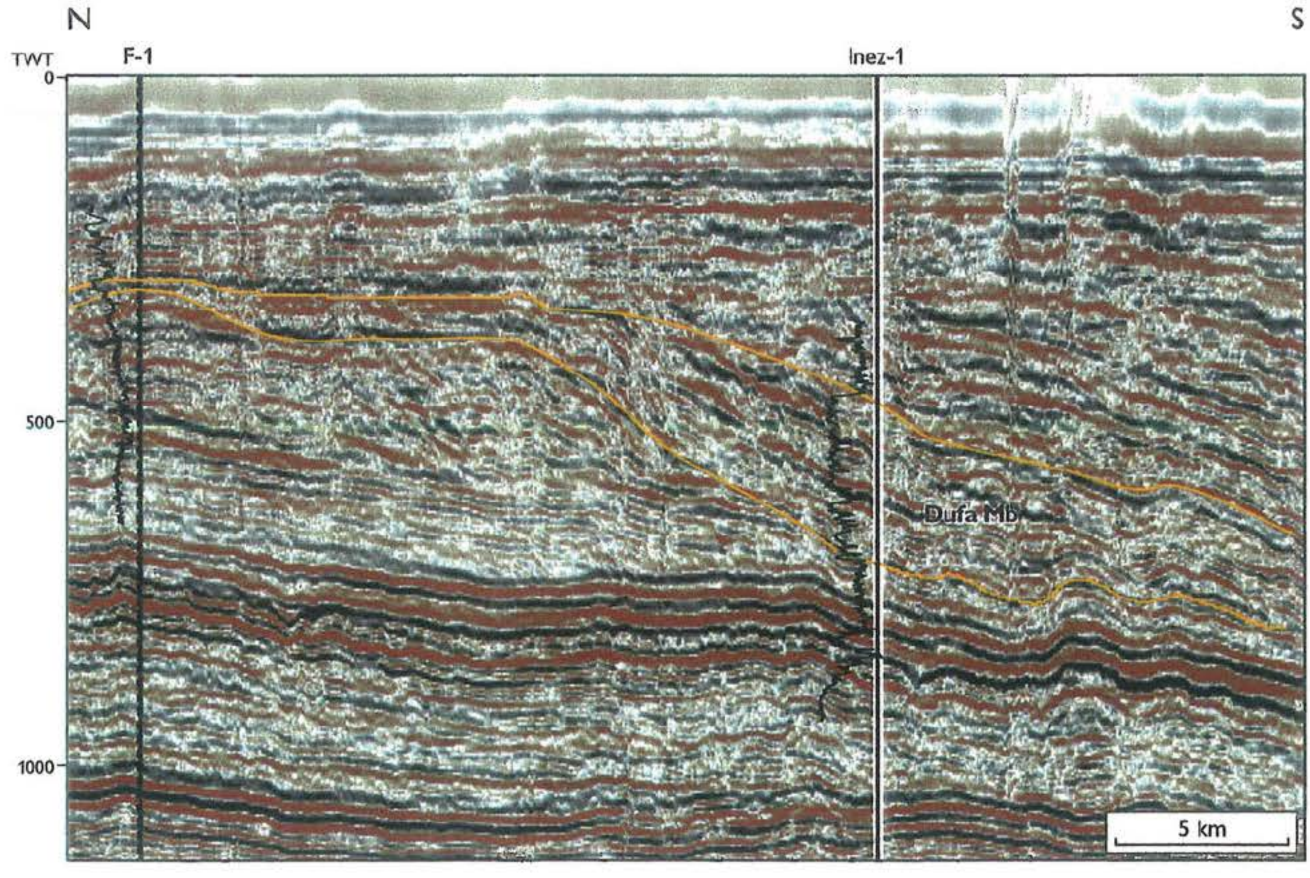



Fig.52

# Francisca-1

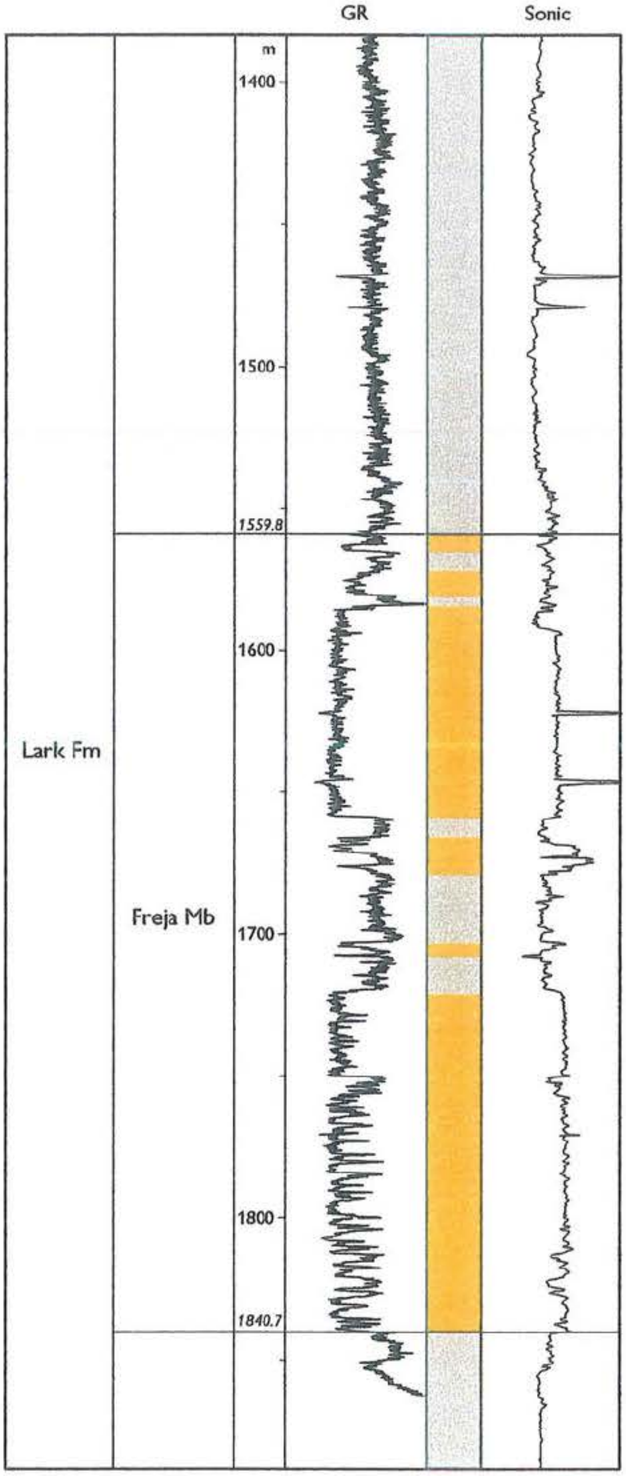



Fig.53

## Frida-1

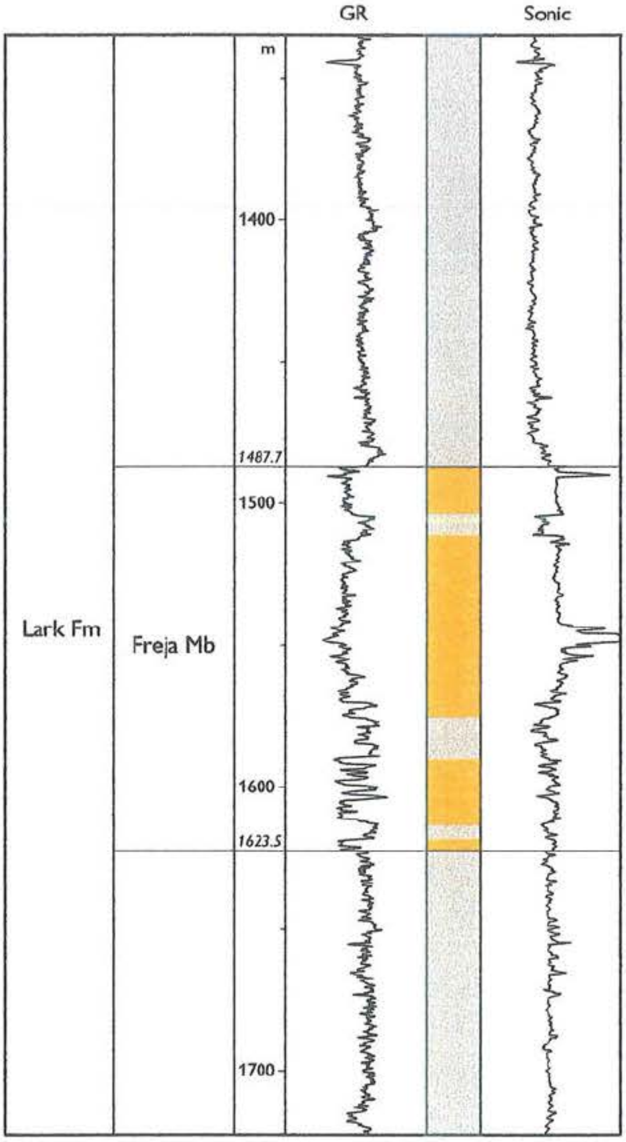



Fig.54

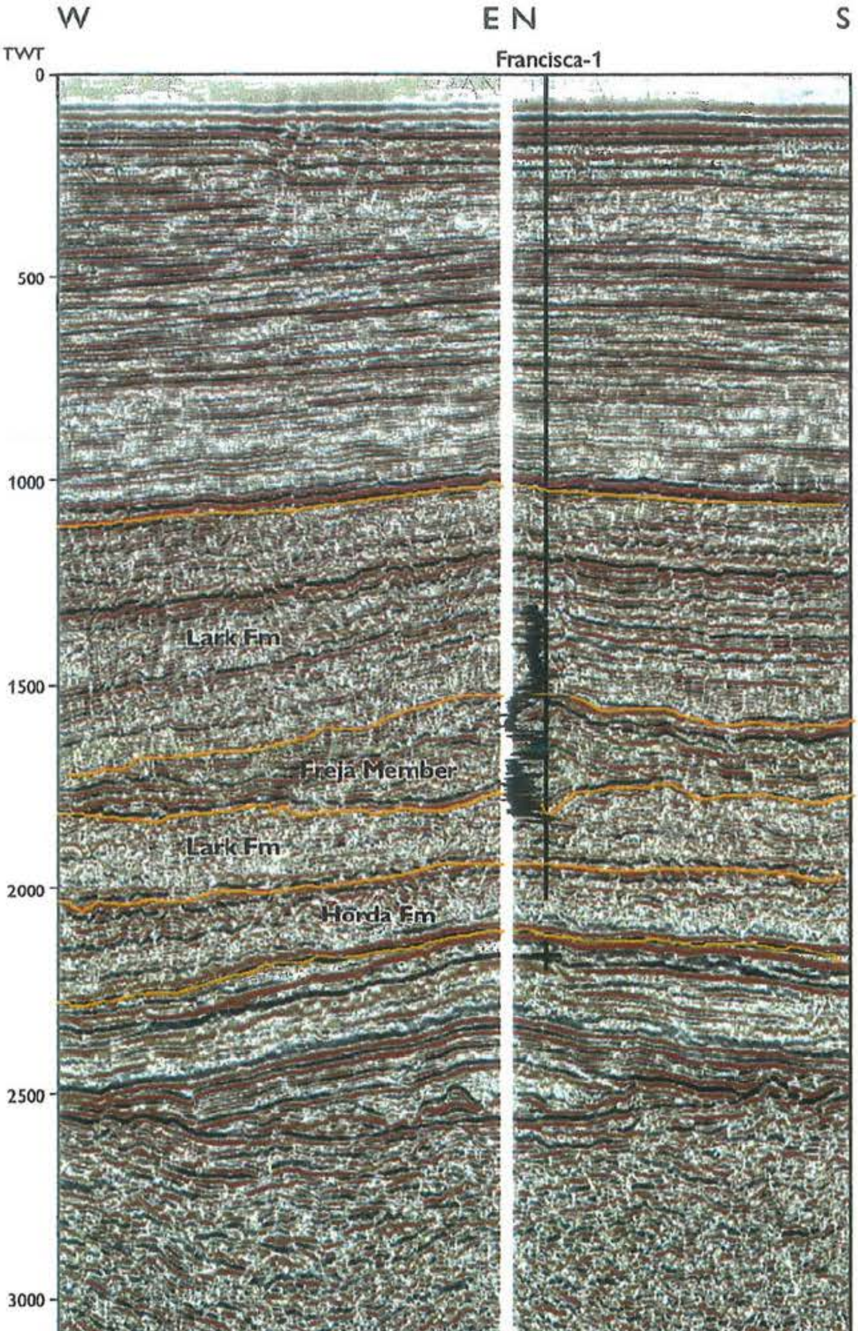
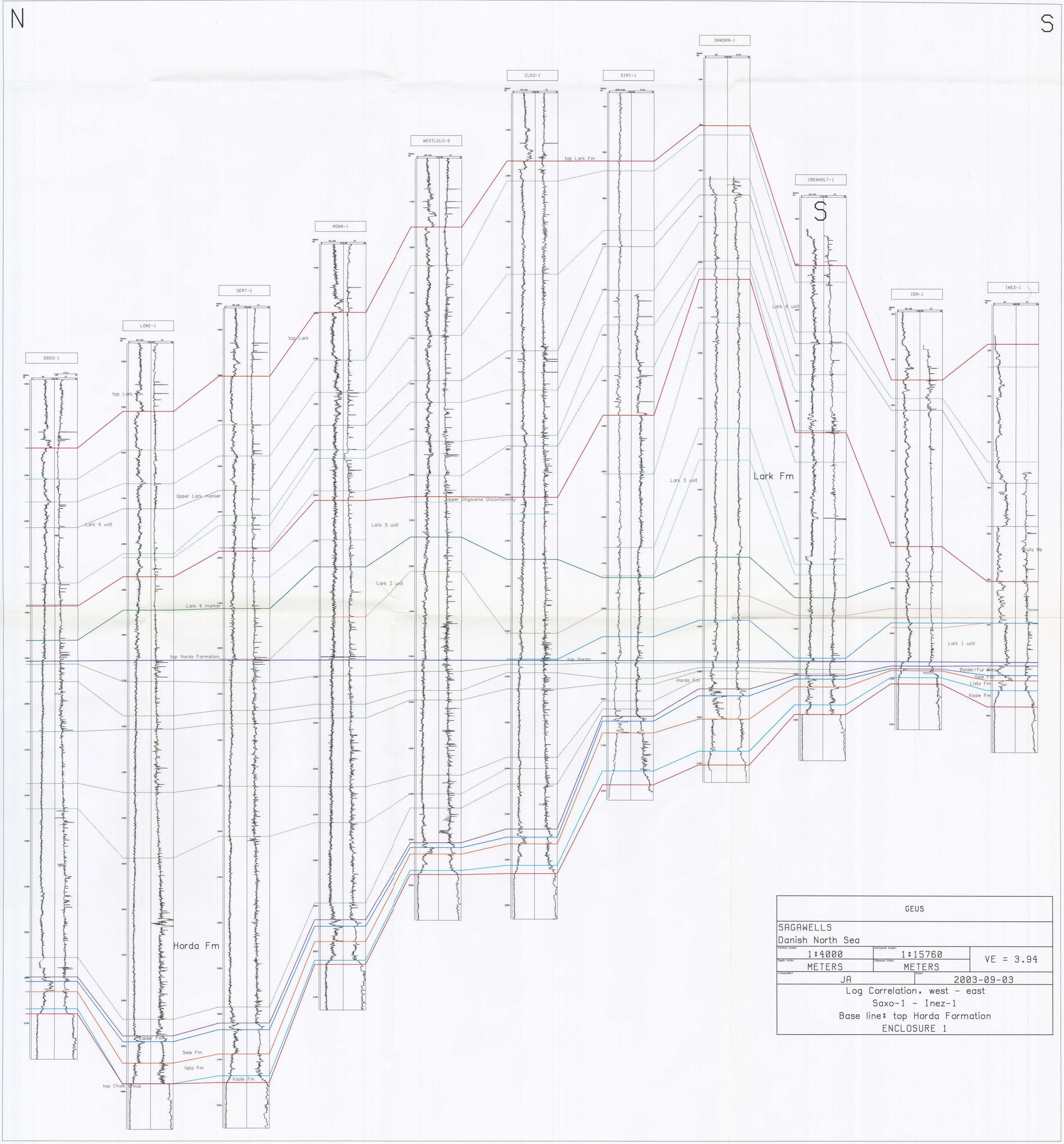
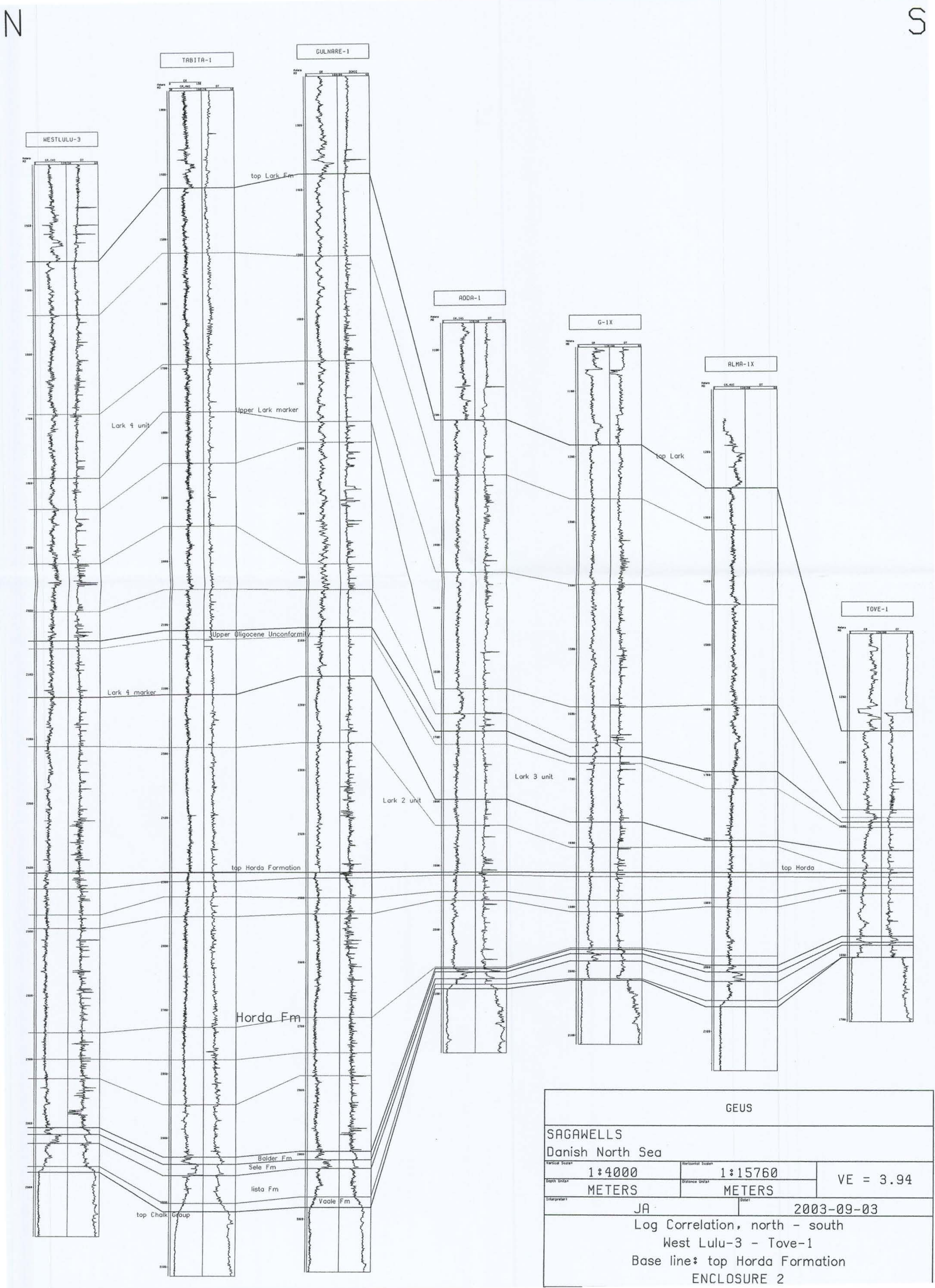

W
E N
S
TWT
Francisca-1
0
500
1000
1500
2000
2500
3000
Lark Fm
Freja Member
Lark Fm
Horda Fm
2 km

Fig.55

**Enclosure 5**


N
S
SAXO-1
LONE-1
GERT-1
MONA-1
WESTLULU-3
CLEO-1
SIRI-1
SANDRA-1
IBENHOLT-1
IDA-1
INEZ-1
top Lark Fm
top Lark
Upper Lark marker
Lark 4 unit
Lark 4 marker
Lark 3 unit
Lark 2 unit
Lark 1 unit
Lark Fm
Upper Oligocene Unconformity
top Horda Formation
top Horda
Horda Fm
Balder Fm
Balder/Fur Fms
Sele Fm
lista Fm
Lista Fm
Vaale Fm
Dufa Mb
top Chalk Group
GEUS
SAGAWELLS
Danish North Sea
1:4000
1:15760
METERS
METERS
VE = 3.94
JA
2003-09-03
Log Correlation, west - east
Saxo-1 - Inez-1
Base line: top Horda Formation
ENCLOSURE 1




GEUS

SAGAWELLS

Danish North Sea

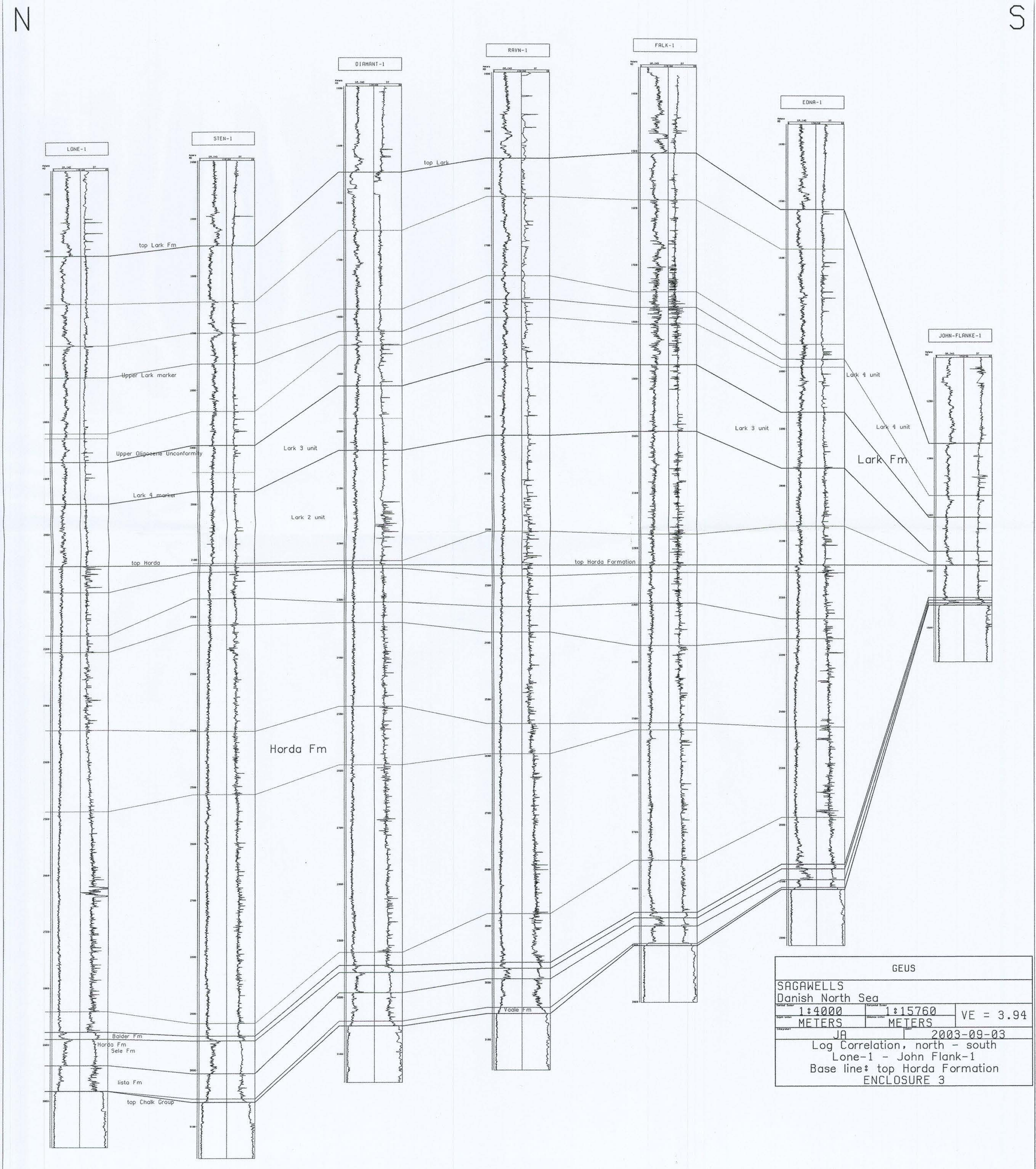
| Vertical Scale: | Horizontal Scale: | |
|---|---|---|
| 1:4000 | 1:15760 | VE = 3.94 |
| Depth Units: METERS | Distance Units: METERS | |
| Interpreter: JA | Date: 2003-09-03 | |

Log Correlation, north - south

West Lulu-3 - Tove-1

Base line: top Horda Formation

ENCLOSURE 2

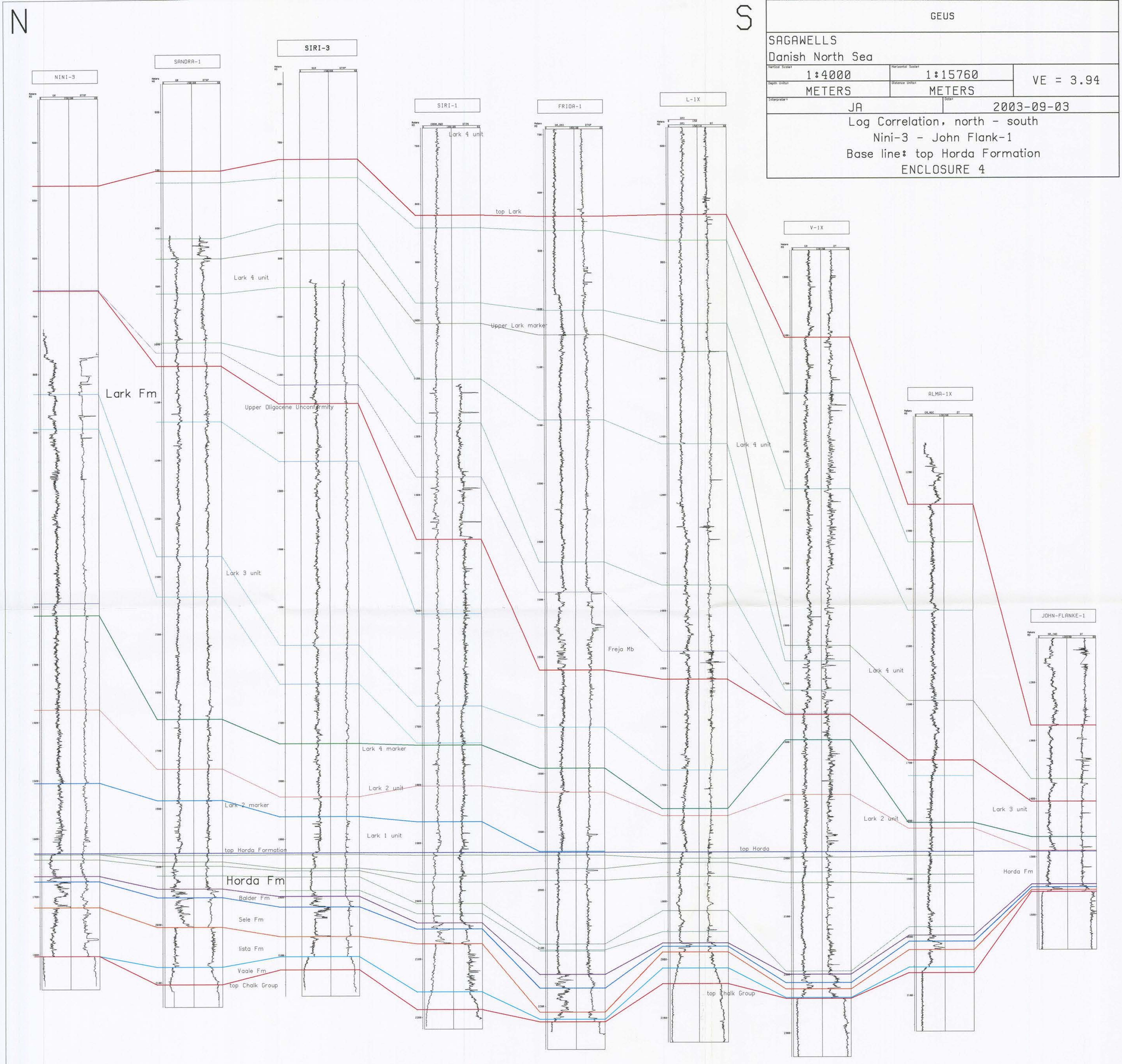



GEUS

SAGAWELLS
Danish North Sea

| | | |
|---|---|---|
| 1:4000 METERS | 1:15760 METERS | VE = 3.94 |
| JA | 2003-09-03 | |

Log Correlation, north - south
Lone-1 - John Flank-1
Base line: top Horda Formation
ENCLOSURE 3


N
S
GEUS
SAGAWELLS
Danish North Sea
1:4000
1:15760
METERS
METERS
VE = 3.94
JA
2003-09-03
Log Correlation, north - south
Nini-3 - John Flank-1
Base line: top Horda Formation
ENCLOSURE 4
NINI-3
SANDRA-1
SIRI-3
SIRI-1
FRIDA-1
L-1X
V-1X
ALMA-1X
JOHN-FLANKE-1
Lark Fm
Lark 4 unit
top Lark
Upper Lark marker
Upper Oligocene Unconformity
Lark 3 unit
Freja Mb
Lark 4 marker
Lark 2 unit
Lark 2 marker
Lark 1 unit
top Horda Formation
top Horda
Horda Fm
Balder Fm
Sele Fm
lista Fm
Vaale Fm
top Chalk Group

GEUS

SAGAWELLS
Danish North Sea

| Vertical Scale: 1:4000 | Horizontal Scale: 1:15760 | VE = 3.94 |
|---|---|---|
| Depth Units: METERS | Distance Units: METERS | |
| Interpreter: JA | Date: 2003-09-03 | |

Log Correlation, north - south
K-1 - S-1
Base line: top Horda Formation
ENCLOSURE 5