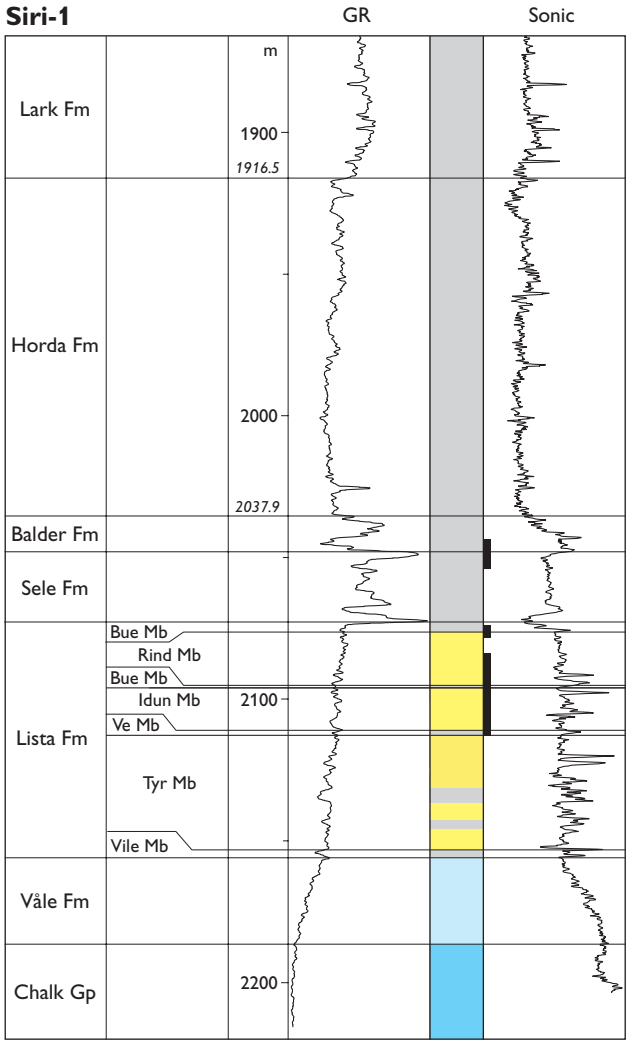


Fig. 47. Siri-1, Danish reference well for the Horda Formation. Black bars show cored sections.

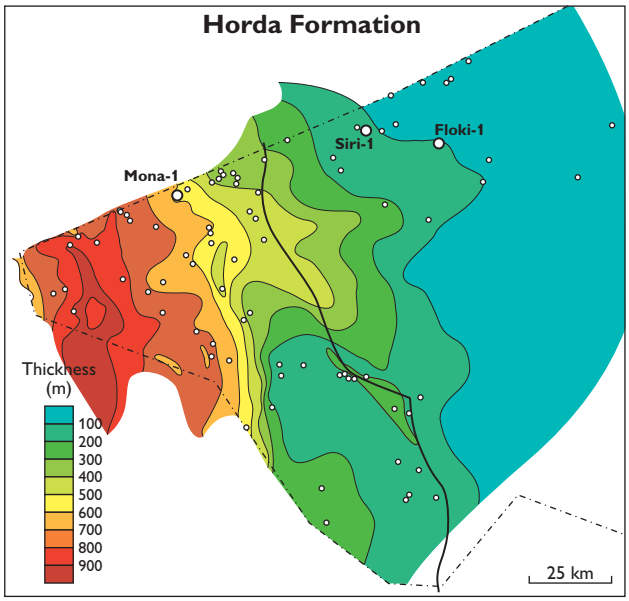


Fig. 48. Isochore map of the Horda Formation in the study area. The positions of the two Danish reference wells for the Horda Formation, Mona-1 and Siri-1, are indicated on the map. The position of Floki-1, the type well for the Hefring Member, is also indicated.

pyritic part of the Knudshoved Member may correlate with the upper, tuff-poor unit B2 of the Balder Formation.

Stronsay Group

Knox & Holloway (1992) replaced the Hordaland Group of Deegan & Scull (1977) with two new groups: the Stronsay Group succeeded by the Westray Group (Fig. 3). The two groups together comprise the light grey, green and brown coloured, soft, fissile, marine shales with thin limestone streaks that overlie the Rogaland Group and underlie the Nordland Group. These groups each contain two formations, one representing sandy shelf lithofacies and the other representing basinal mudstone lithofacies. In the central North Sea, and in the Danish sector, the Stronsay Group is represented by its mudstone facies, the Horda Formation (Knox & Holloway 1992). Sandstone units of varying thickness occur at many levels in the Stronsay and Westray Groups along the basin margin in the Norwegian and British sectors, and many of these have been defined as formations or members (Deegan & Scull 1977; Hardt *et al.* 1989; Knox & Holloway 1992). A sandstone unit also occurs in the Horda Formation on the Ringkøbing–Fyn High in the Danish sector and is described here as a new member (Hefring Member).

Horda Formation

History. Knox & Holloway (1992) established the Horda Formation for the greenish grey basinal mudstone facies of their Stronsay Group that overlies the grey tuffaceous mudstones of the Balder Formation and underlies the greenish grey to brown mudstones of the Lark Formation (Knox & Holloway 1992).

Type well. British sector well 22/1-1A, 2379.5–1992 m MDKB.

Danish reference wells. Mona-1, 2930.8–2363.5 m MDKB (Fig. 46); Siri-1, 2037.9–1916.5 m MDKB (Fig. 47).

Distribution and thickness. The Horda Formation extends over the central and northern North Sea and is present in

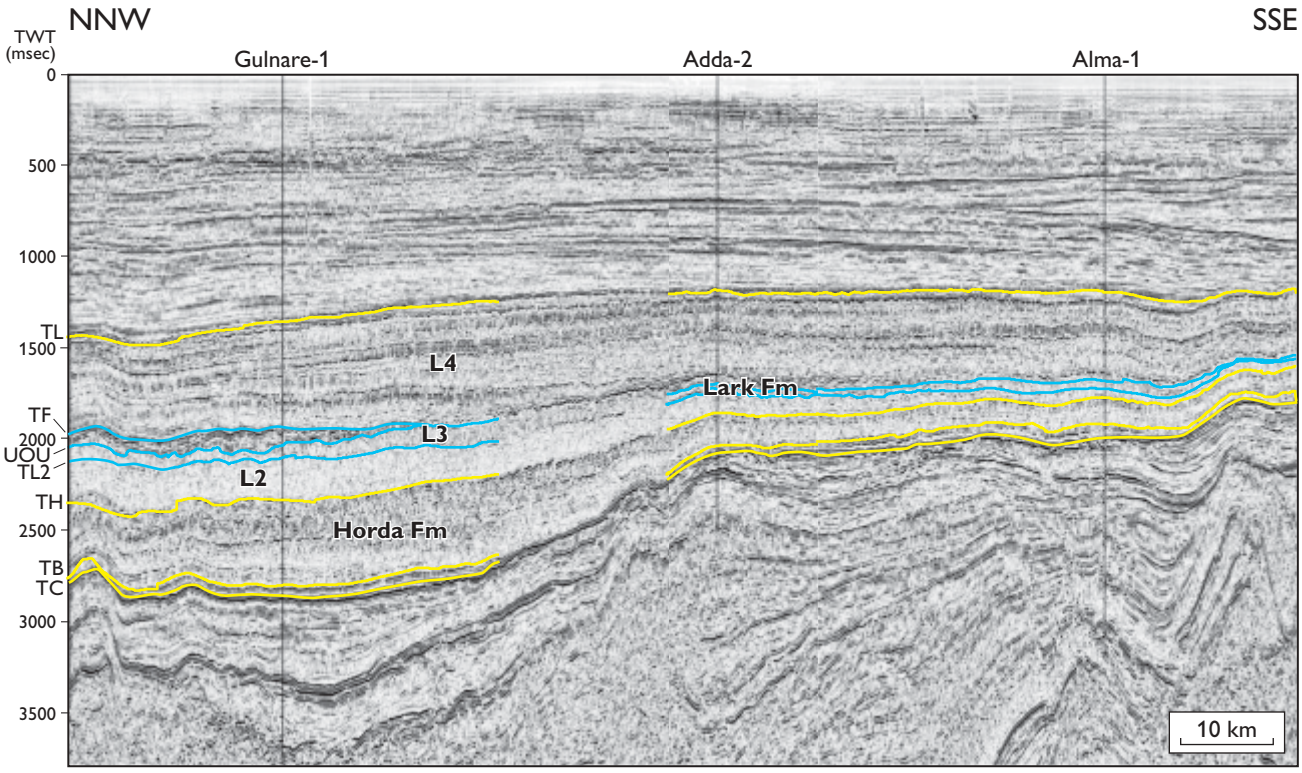


Fig. 49. NNW–SSE-trending seismic section (RTD81-RE94-17A) in the Central Graben showing south- and eastward thinning of the Horda Formation. The location of the seismic section is shown in Fig. 1. The **L2**, **L3** and **L4** subunits of the Lark Formation are indicated, as well as the mudstone-equivalent of the Freja Member. **TL**, Top Lark; **TF**, Top Freja; **UOU**, Upper Oligocene Unconformity; **TL2**, Top L2; **TH**, Top Horda; **TB**, Top Balder; **TC**, Top Chalk.

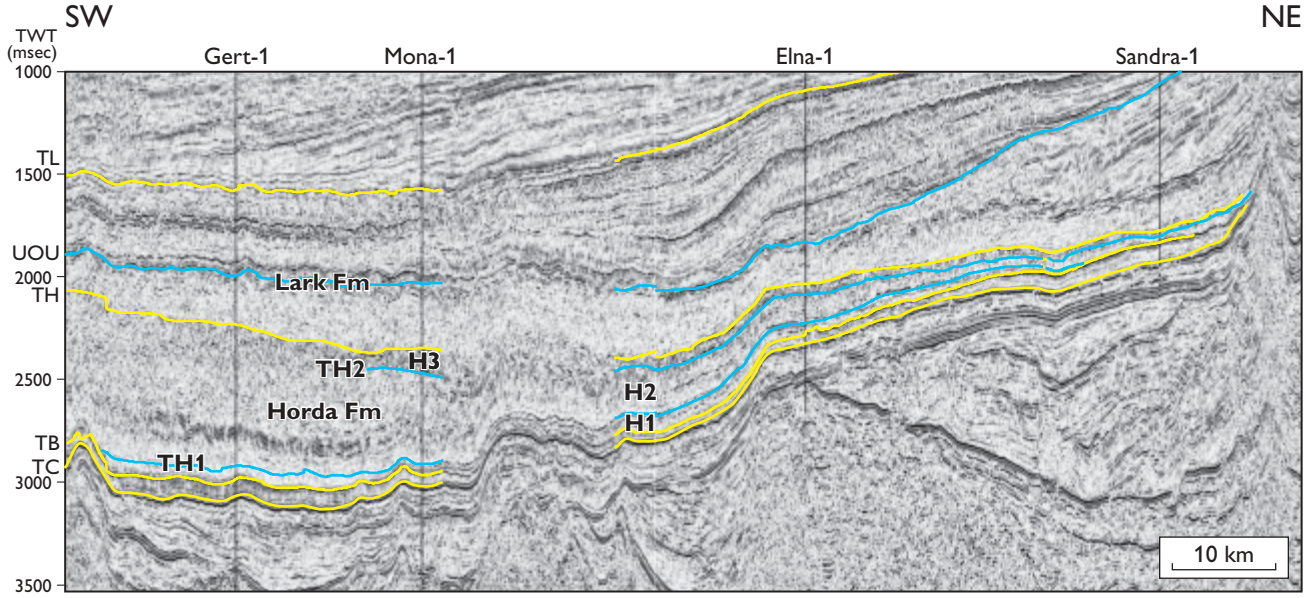


Fig. 50. SW–NE-trending seismic section (RTD81-RTD94-19A) showing the tripartite subdivision (**H1–3**) of the Horda Formation in the eastern part of the Danish Central Graben (Gert-1 and Mona-1) and pronounced thinning of the Horda Formation east of the Central Graben (Elna-1 and Sandra-1). The location of the seismic section is shown in Fig. 1. **TH1**, Top H1 marker; **TH2**, Top H2 marker; other abbreviations as in Fig. 49.

all wells in the Danish sector of the North Sea. However, the lower part of the Horda Formation (Fig. 4; equivalent to Sequence 2 of Michelsen *et al.* 1998) is lacking in the eastern wells R-1 and S-1 and in the eastern part of the Ringkøbing–Fyn High. The upper part of the Horda Formation (Fig. 4; equivalent to Sequence 3 of Michelsen *et al.* 1998) is thin or absent in the same area (Michelsen *et al.* 1998). The Horda Formation reaches a thickness of 906 m in the Central Graben well Tordenskjold-1, but thins towards the east and south-east to less than 100 m, with minimum recorded thicknesses of 9 m in the Ida-1 well and 4 m in the S-1 well. An isochore map of the Horda Formation is shown in Fig. 48. The overall thinning of the Horda Formation towards the south-east, east and north-east is also shown on the seismic sections in Figs 49 and 50 and on the log panel in Fig. 51.

Lithology. The Horda Formation is characterised by greenish grey to greyish green fissile mudstone. Subordinate limestone benches and thin layers of black mudstones 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 mudstones (Fig. 52). This lithology is apparently lacking in the eastern wells of the Danish sector.

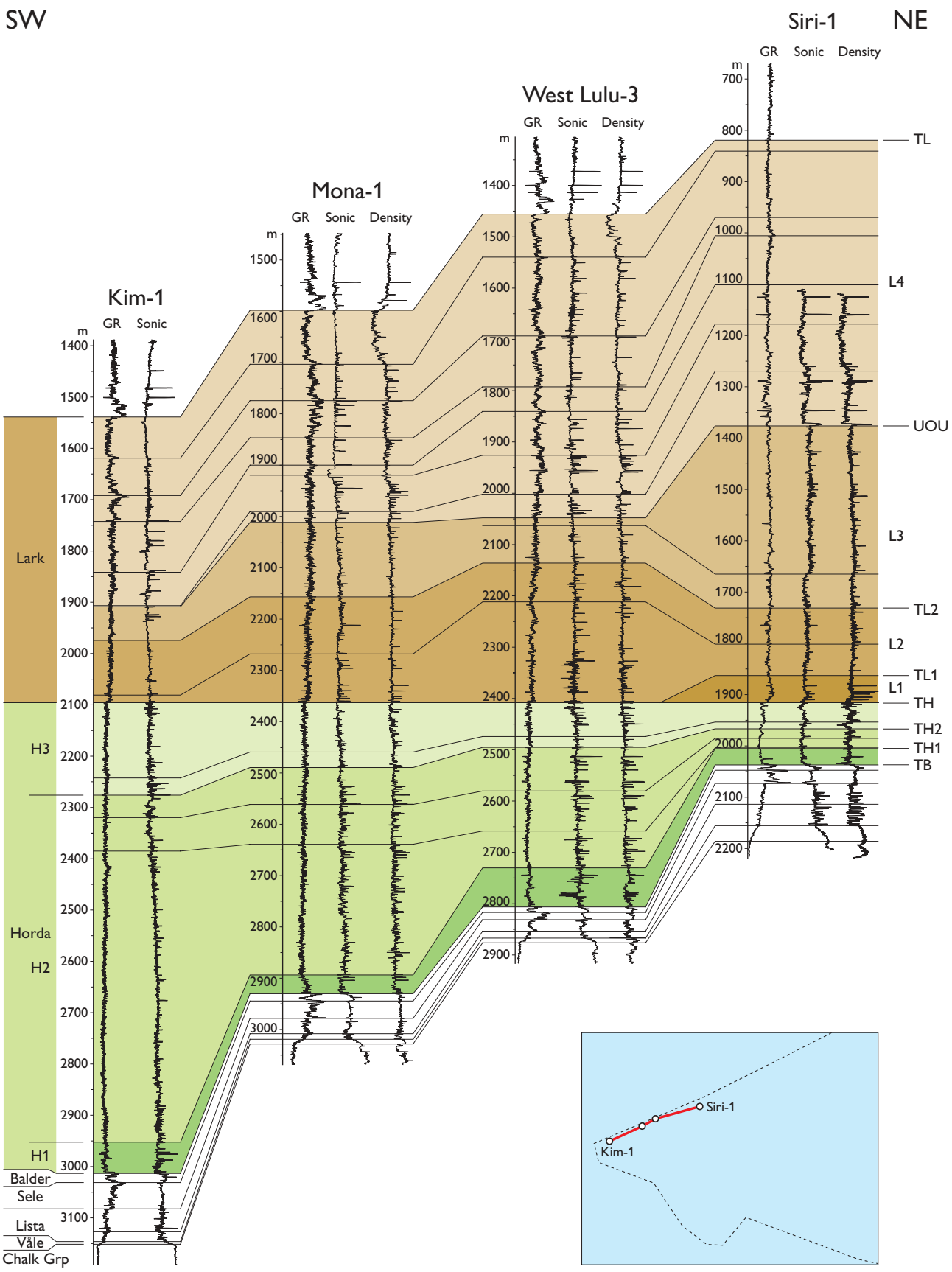
Log characteristics. The Horda Formation is characterised by an overall stable gamma-ray and sonic log motif with a lower gamma-ray response than that displayed by the underlying Balder Formation and the overlying Lark Formation. In a few wells, the base of the Horda Formation shows relatively high gamma-ray values, which decrease to lower and more stable values over a short interval. The sonic readings decrease slightly upwards from the base to the top of the Horda Formation.

Boundaries. The base of the Horda Formation is placed at the change from the laminated, predominantly grey mudstones with interbedded sandy tuffs of the Balder Formation to the predominantly non-laminated, fissile, greenish grey or red-brown massive mudstones that form the basal part of the Horda Formation. The Balder–Horda boundary may be conformable or marked by a hiatus. The boundary is often difficult to pick on petrophysical logs. In basinal settings, Knox & Holloway (1992) advocated placing the lower boundary of the Horda Formation at the base of a marked gamma-ray peak believed to represent a glaucony-rich condensed layer in the basal part of the Horda Formation. However, in many sections in the Danish sector there are two or more gamma-ray peaks in the Balder–Horda boundary interval. As the glaucony-rich layer has not been identified with certainty in the few cores taken across the boundary in the Danish sector, it is not possible to identify the key gamma-ray peak unambiguously. Therefore, it is suggested that the lower boundary of the Horda Formation is placed on the basis of the sonic log where a gradual decrease in values in the upper part of the Balder Formation is succeeded by relatively stable, but somewhat lower readings in the Horda Formation (Figs 46, 47). The upper boundary is at the base of the Lark Formation.

Subdivision. Knox & Holloway (1992) suggested a threefold subdivision of the Horda Formation (H1–3), based on lithology and biostratigraphy. A threefold subdivision can also be seen on seismic sections in the Danish sector of the North Sea (Fig. 50). In some Central Graben wells, the subdivision may also be recognised on shifts in log patterns on both gamma-ray and sonic logs (Fig. 51). In these wells, subtle peaks separate the three units on the gamma-ray log and coincide with the top H1 and top H2 seismic markers. Based on analysis of cuttings samples, the subdivision apparently lacks lithological expression in the Danish sector. Knox & Holloway (1992) noticed that the top of unit H1 is close to the HO of the dinoflagellate *Eatonicysta ursulae*, and that the top of unit H2 is close to the HO of the foraminifer *Spiroplectammina spectabilis*. This observation is supported by biostratigraphical data from the present study. A sandstone body within the Horda Formation has been encountered in the well Floki-1 on the Ringkøbing–Fyn High) in the Danish sector of the North Sea. This sandstone is defined herein as the new Hefring Member (see below).

Macro- and ichnofossils. The Horda Formation is moderately to intensely bioturbated. Ichnofossils comprise *Chondrites* ispp., *Phycosiphon* ispp. and *Planolites* ispp.

Microfossils and palynomorphs. In wells where the Horda Formation rests conformably on the Balder Formation, the dinoflagellate events HO *Deflandrea oebisfeldensis* and HO *Dracodinium condylos* occur in the lowermost part of the Horda Formation. Characteristic microfossil datums from the lowermost part of the Horda Formation are the HO of the planktonic foraminifer *Subbotina* ex gr. *linaperta*, which occurs abundantly, followed upwards by the almost coeval HOs of the benthic foraminifers *Uvigerina batjesi, Turrilina brevispira* and *Gaudryina hiltermanni*. A hiatus between the Horda and Balder Formations is indicated in wells in the northern and eastern part of the Danish sector by the absence of *D. oebisfeldensis* and *D. condylos* from the lower part of the Horda Formation. Central


SW
NE
Kim-1
GR Sonic
Mona-1
GR Sonic Density
West Lulu-3
GR Sonic Density
Siri-1
GR Sonic Density
m
Lark
H3
Horda
H2
H1
Balder
Sele
Lista
Våle
Chalk Grp
TL
L4
UOU
L3
TL2
L2
TL1
L1
TH
TH2
TH1
TB
Siri-1
Kim-1

Graben wells contain the downhole succession of the dinoflagellate cyst events HO *Areosphaeridium diktyoplokum,* HO *Areosphaeridium michoudii,* HO *Heteraulacacysta porosa* and HO *Cerebrocysta bartonensis* from the top of the Horda Formation, indicating an age as young as earliest Rupelian (Fig. 5b). In wells to the north and east, the top of the Horda Formation seems to be slightly older since *A. michoudii* is recorded from the top of the formation, indicating a mid-Priabonian age (Fig. 5b). Significant dinoflagellate events from the middle to upper part of the Horda Formation are the succession of the HOs of *Eatonicysta ursulae*, *Diphyes ficosoides* and *Phthanoperidinium clithridium* in the middle part of the formation, and the HOs of *Diphyes colligerum* and *C. bartonensis* in the upper part of the formation. In Central Graben wells, significant microfossil events in the lower part of the Horda Formation include the HO of abundant radiolaria of the genus *Cenosphaera* and the HO of the planktonic foraminifer *Cyclammina amplectens*. Key events in the middle and upper parts of the formation are the HOs of *Pseudohastigerina* spp. (planktonic foraminifers), *Lenticulina gutticostata*, *Spiroplectammina amplectens* and *Planulina costata* (benthic foraminifers). The top of the Horda Formation contains the HOs of *Cibicidoides truncanus* and *Vaginulinopsis decorata*.

Depositional environment. The lower part of the Horda Formation contains a microfauna that is significantly different from that of the underlying Balder Formation. The basal 5–40 m of the Horda Formation are characterised by a diverse fauna of both benthic and planktonic calcareous foraminifers together with agglutinated foraminifers. 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 foraminifer fauna. Calcareous foraminifers are very sparse or absent in this interval. The assemblage of *Rhabdammina discreta*, *Haplophragmoides* spp., *Recurvoides* spp. and *Usbekistania charoides* indicate that the upper part of the Horda Formation was deposited at upper bathyal depths 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 recorded throughout the upper part of the formation suggest that deeper marine conditions prevailed periodically.

The palynofacies of the Horda Formation is characterised by a rich and dominant dinoflagellate assemblage with dispersed terrestrial matter (phytoclasts, spores and pol-

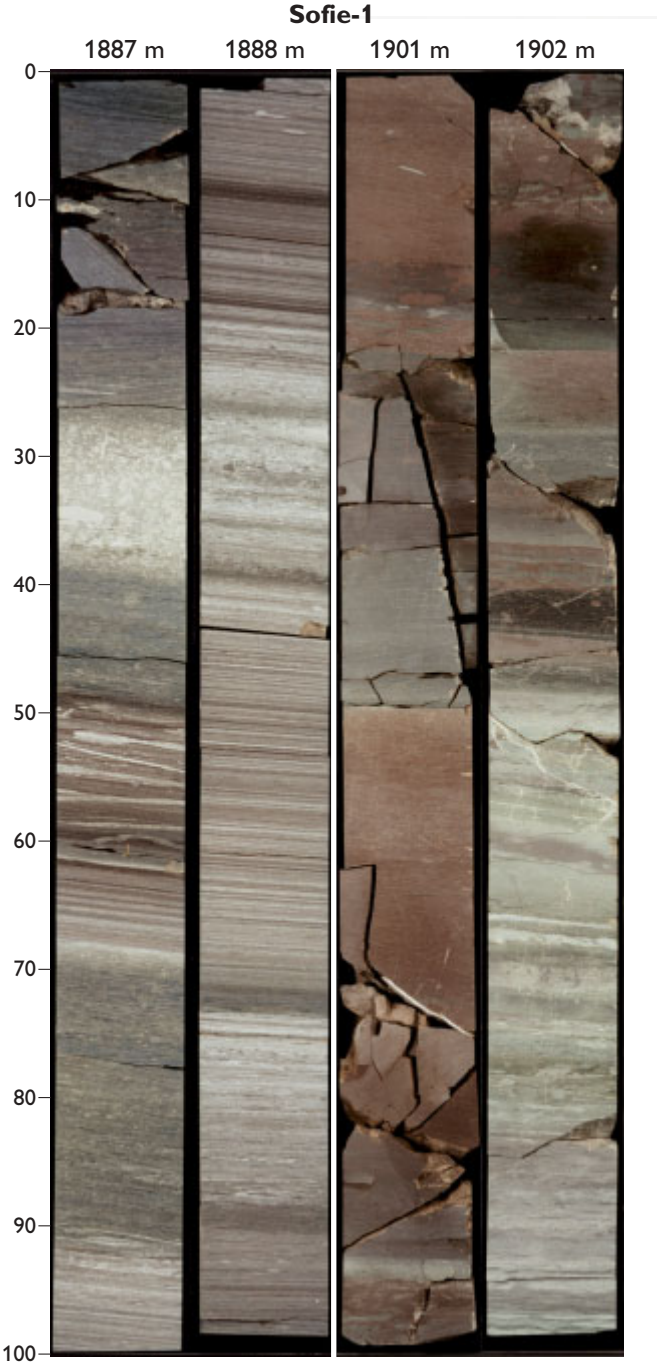


Fig. 52. Core photographs showing red to reddish grey mudstones of the lowermost part of the Horda Formation in the Sofie-1 well. Depths are core depths.

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Fig. 51. SW–NE-trending log panel showing eastward thinning of the Horda Formation. The figure also shows the variation in architecture and distribution of the Horda units **H1–H3** and Lark units **L1–4** between the Central Graben (Kim-1, Mona-1 and West Lulu-3) and the Ringkøbing–Fyn High (Siri-1). Seismic ties: **TL1**, Top L1; **TH2**, Top H2; **TH1**, Top H1; other abbreviations as in Fig. 49.

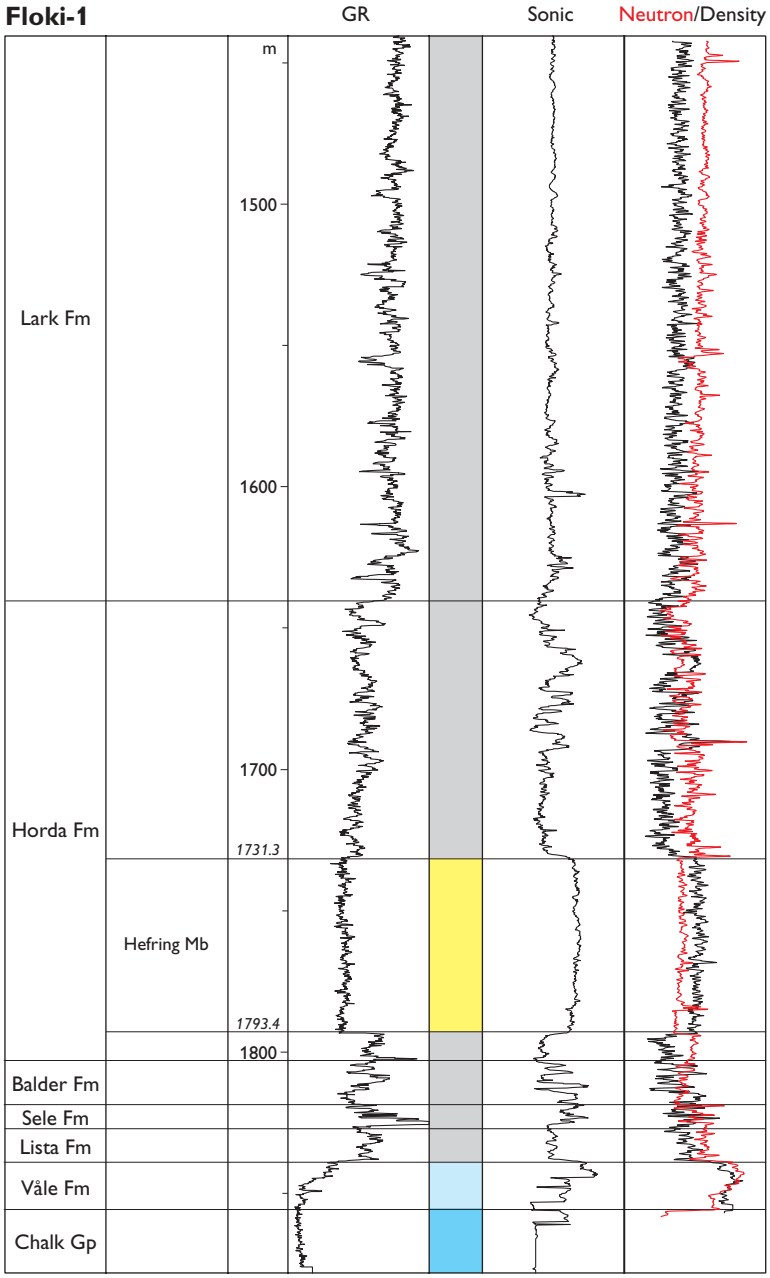

Fig. 53. Floki-1, type well for the Hefring Member.

len) as a minor component, indicating an open marine environment with only limited influx from surrounding terrestrial areas.

Age. In the Central Graben, where the Horda Formation is most complete, the formation spans from the middle Ypresian (Early Eocene) at its base to earliest Rupelian (earliest Oligocene) at its top. In wells to the east and north, the top is as old as middle Priabonian (see also biostratigraphic section above). This 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, or both.

Correlation. The Horda Formation can be correlated with the onshore Danish succession of the Røsnæs Clay Formation, the Lillebælt Clay Formation and the Søvind Marl Formation (Heilmann-Clausen *et al.* 1985), and the Viborg Formation (Christensen & Ulleberg 1973).

The red-brown mudstones near the base of the Horda Formation in the central North Sea can be correlated lithologically with the Røsnæs Clay Formation and the lower part of the Lillebælt Clay Formation.

The lower part of the overlying main body of greenish and greyish mudstones in the offshore succession can be correlated with the coeval and lithologically similar upper part of the Lillebælt Clay Formation. The upper part of the Horda Formation can be correlated with the Søvind Marl Formation, which consists of grey marls. The highest part of the Horda Formation, only observed in Central Graben wells, may be correlated with the Viborg Formation on biostratigraphic evidence.

Hefring Member

new member

History. The Hefring Member consists of sandstone deposits within the Horda Formation. These sandstones have not previously been recognised as a separate unit in the Danish sector.

Derivation of name. After the goddess Hefring.

Type well. Danish sector well Floki-1, 1793.4–1731.3 m MDRT (Fig. 53).

Distribution and thickness. The Hefring Member is only known from the Floki-1 well located in the northern part of the Danish sector. As the unit currently cannot be identified on seismic sections, its further distribution is unknown. In the Floki-1 well, the member is 62 m thick.

Lithology. The Hefring Member consists of greenish grey, fine-grained, immature sandstones with glaucony grains.

Log characteristics. The Hefring Member is characterised by a conspicuous blocky signature on the gamma-ray, sonic and density logs (Fig. 53). Gamma-ray responses are lower than those of the enveloping Horda Formation mudstones. The Hefring Member can also be recognised from a combination of the density and neutron logs as the presence of pure sandstones results in a 'cross-over' of the two log curves (Fig. 53).

Boundaries. The boundaries with the mudstones of the Horda Formation are sharp and characterised by prominent shifts on the gamma-ray and sonic logs (Fig. 53).

Depositional environment. No cores have been taken in the Hefring Member, but the sandstones were probably deposited from concentrated gravity flows, based on log similarity with the other fine-grained sandstone bodies in the nearby Siri Canyon.

Age. Lutetian (Middle Eocene) based on the age of the associated Horda Formation mudstones.

Correlation. Based on biostratigraphic data, the Hefring Member may be contemporaneous in part with the Lillebælt Clay Formation onshore Denmark, with the lower part of the Grid Sandstone Member (Knox & Holloway 1992) in the Viking Graben and with the upper part of the Tay Sandstone Member (Knox & Holloway 1992) in the northern part of the Central Graben.

Westray Group

The Westray Group is the upper of the two groups established by Knox & Holloway (1992) to replace the Hordaland Group of Deegan & Scull (1977; Fig. 3). In the central North Sea and in the Danish sector of the North Sea, the Westray Group is represented by the Lark Formation.

Lark Formation

History. The Lark Formation was established by Knox & Holloway (1992) for the brownish grey mudstone-dominated lithofacies of the Westray Group that overlies the more variable association of red and green-grey mudstones, silty mudstones and sandstones of the Horda Formation and underlies the grey, sandy and shelly mudstones, siltstones and sandstones of the Nordland Group of Deegan & Scull (1977; Fig. 3). The Lark Formation is also recognised in the Danish sector although its lithology is more variable than that given in the original description.

Type well. British sector well 21/10-4, 1867–1217 m MDKB.

Danish reference wells. Mona-1, 2363.5–1598.3 m MDKB (Fig. 46); Siri-1, 1916.5–819.3 m MDKB (Fig. 54).

Distribution and thickness. The Lark Formation extends over the central and northern North Sea and is probably present in the entire Danish sector of the North Sea. Its depocentre is in the central and northern 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 west to a thickness of 389 m in the Tordenskjold-1 well in the Central Graben, and east to a thickness of 240 m in the S-1 well on the Ringkøbing–Fyn High (Fig. 55).