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.

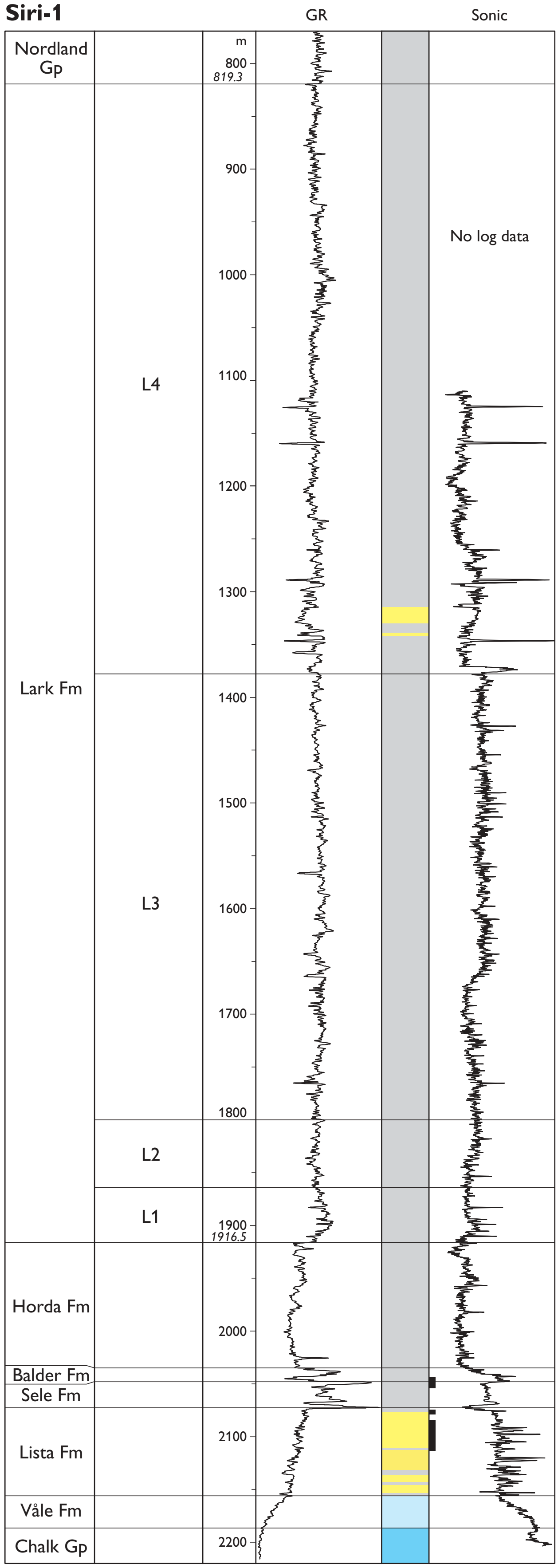
Lark Formation

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).



Lithology. The lower Lark Formation (L1–3, see below) is dominated by dark, greenish grey, non-fissile mudstones in most wells; in some wells subordinate intervals of brownish grey mudstones are also present. Thin layers of white or reddish brown carbonate are also recorded in the upper levels of the lower Lark Formation.

The upper Lark Formation (L4, see below) is dominated by pale to dark brownish grey mudstones with subordinate intervals of greenish grey mudstones in its lower levels. The uppermost 50–100 m of the formation consist of yellowish grey to light brown mudstones. In eastern and northern parts of the Danish sector, discrete sandstone interbeds and thin sandstone stringers occur throughout the formation.

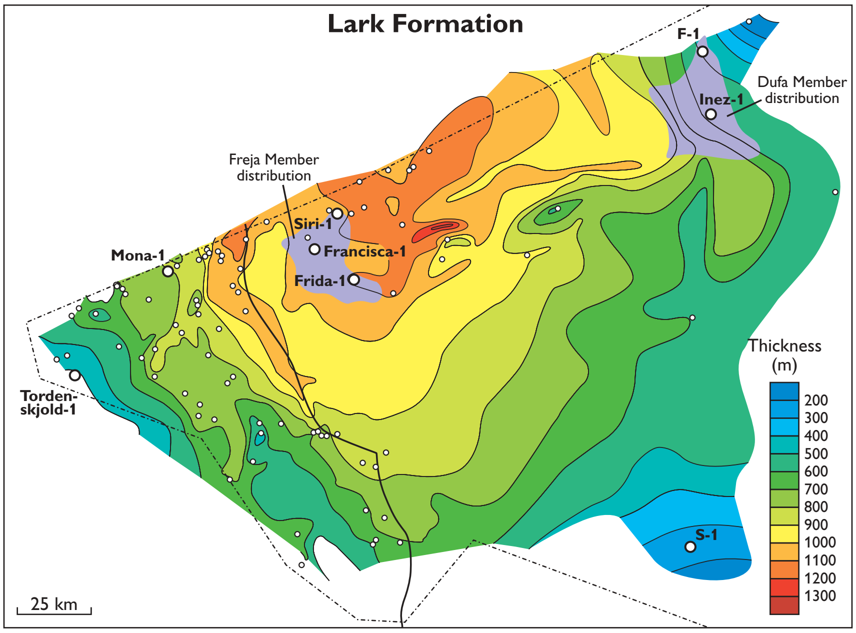
Log characteristics. The lower part of the Lark Formation is characterised by an overall stable gamma-ray log signature, whereas the upper part of the formation has a more unstable signature (Figs 46, 54). This change in gamma-ray log signature coincides approximately with the change from lithologies dominated by greenish grey mudstones to lithologies dominated by dark to light brownish grey mudstones at the base of unit L4 (see below).

Boundaries. The base of the Lark Formation is marked by a change from fissile, greenish grey mudstones of the Horda Formation to non-fissile, greenish grey mudstones of the Lark Formation. This change in lithology coincides with an abrupt increase in gamma-ray values to a consistently higher level than that displayed by the Horda Formation (Figs 46, 51, 54). Wells in the eastern part of the Danish Central Graben and on the Ringkøbing–Fyn High show a conspicuous log break on the gamma-ray log at the formation boundary, whereas the log break is less pronounced in wells from the central and western parts of the Danish Central Graben (Fig. 51). Although the actual increase in gamma-ray response may be limited in the latter wells, the offset is usually sharp and well defined. On the sonic log, the boundary between the Horda Formation and the Lark Formation is characterised by a transition from a stable sonic signature to one characterised by numerous fluctuations.

The Lark Formation is overlain by the undifferentiated Nordland Group of Deegan & Scull (1977). Over most of the area, the boundary seems conformable and is represented by a change from yellowish grey and light brown mudstones to medium to dark grey mudstones characte-

Fig. 54. Siri-1, Danish reference well for the Lark Formation. The units **L1–4** are all present in this well. Black bars show cored sections.

Fig. 55. Isochore map of the Lark Formation in the study area. The positions of the two Danish reference wells, Mona-1 and Siri-1, are indicated in the figure. The map also shows the distribution of the sandstones of the Dufa and Freja Members and the location of their type and reference wells, Inez-1 and F-1, and Francisca-1 and Frida-1, respectively.



rised by intervals with shell-hash and coarse-grained sands. This boundary is marked by a conspicuous gamma-ray peak at the base of a 20–40 m thick interval with elevated gamma-ray values in the lowermost Nordland Group (Figs 46, 51). This interval is further characterised by a marked double peak on the gamma-ray log.

In the north-eastern parts of the Danish sector (Nini-1, Vanessa-1, Cecilie-1 and Siri-1; Figs 1, 51, 54), sediments of the Nordland Group rest unconformably on the Lark Formation. In this area the uppermost Lark Formation and the lowermost Nordland Group are missing, probably due to erosion and/or non-deposition. The distinct gamma-ray peak that marks the top of the Lark Formation as well as the double gamma-ray peak in the lowermost Nordland Group are lacking in these wells, and therefore the top of the Lark Formation is more difficult to identify on petrophysical logs.

Subdivision. The Lark Formation can be subdivided into four major mudstone packages, L1–L4, based on seismic and log evidence (Figs 46, 49, 51, 54, 56; Plates 1–5). These units are described below; isochore maps of the units are shown in Fig. 57a–d.

L1 (Figs 51, 56a, b, 57a; Plates 1, 4, 5)
This unit has been recognised in the north-eastern part of the Danish sector only (Fig. 57a). It is bounded beneath by the TH marker and above by the TL1 marker (Fig. 56a, b). It is characterised by downlapping reflectors and represents a south-westwards prograding mudstone succession. On the gamma-ray log, the L1 unit is characterised by a relatively high and relatively stable response. In most wells, it shows a weakly concave pattern, going from a relatively high gamma-ray response at its base, over a gamma-ray low halfway through the unit to a level close to starting level at the top of the unit (e.g. Ida-1, Inez-1, K-1, F-1 and Sandra-1; Plates 1, 4, 5). In the Siri-1 and Siri-3 wells, near the south-western limit of the L1 unit, the gamma-ray log motif instead appears slightly convex (Figs 51, 54; Plates 1, 4). The L1 unit consists predominantly of greenish grey mudstones but also includes yellowish brown and dark grey mudstones.

L2 (Figs 46, 51, 56a, b, 57b; Plates 1–5)
The unit is recognised over the entire study area. On the gamma-ray and sonic logs the unit is characterised by a stable log signature. The gamma-ray log shows two to three slightly concave patterns with signatures similar to that of the L1 unit (Fig. 51; Plates 1, 4). The lithology is characterised by dark beige-grey to greenish grey mudstones, greenish colours becoming dominant towards the top of the unit.

L3 (Figs 46, 51, 56a, b, 57c; Plates 1–5)
This unit is encountered in the northern and eastern parts of the Danish sector, east of the Central Graben (Fig. 57c) but is not recognised on logs or seismic sections in the Central Graben area. It is characterised by stable gamma-ray and sonic log signatures (Figs 46, 51; Plates 1–4). The unit consists almost invariably of dark, greenish grey mudstones.

L4 (Figs 46, 51, 56a, b, 57d; Plates 1–5)
The unit is recognised over the entire study area (Fig. 57d). The interval is characterised by a slightly more unstable gam-

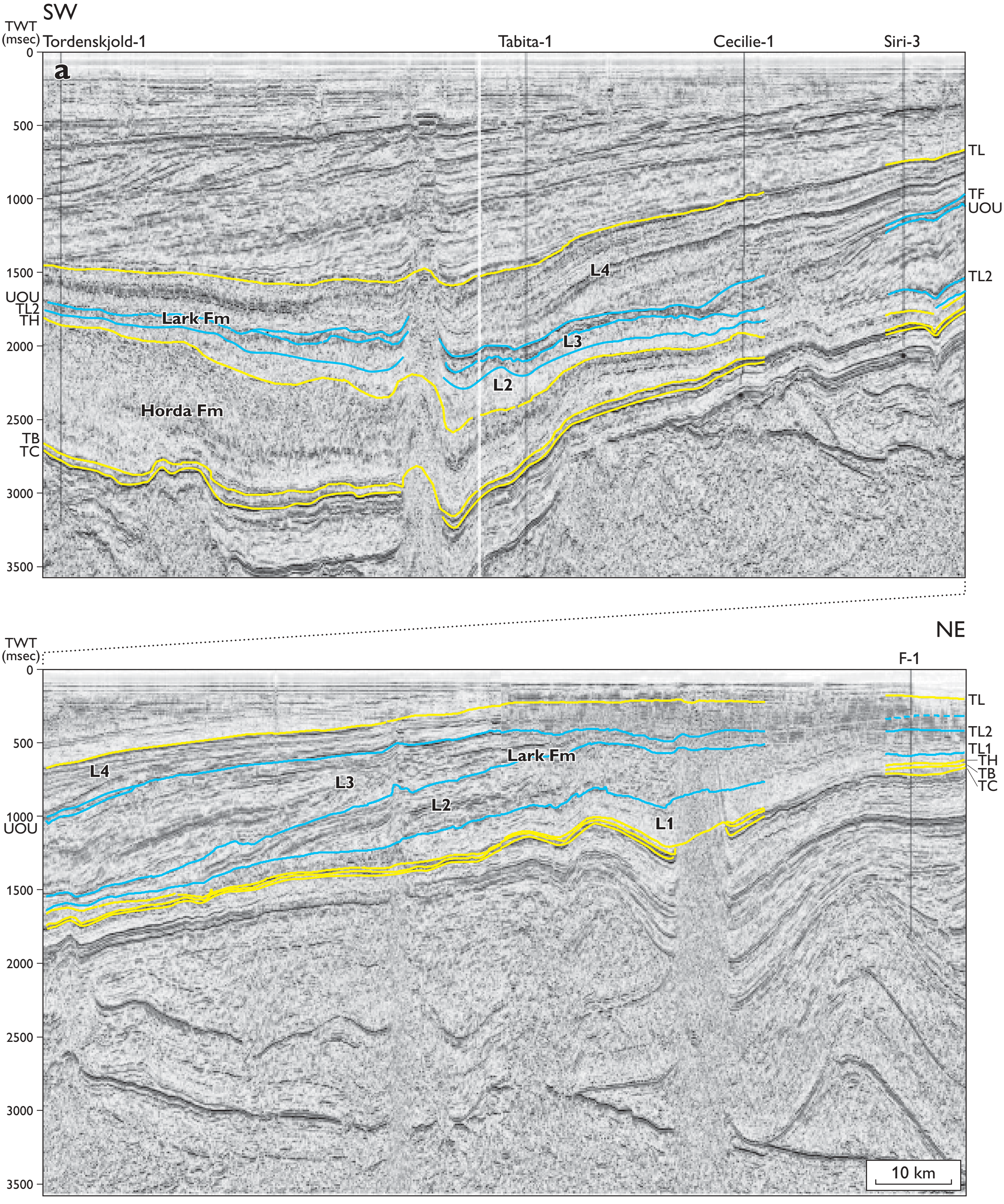


Fig. 56. **a**: SW–NE-trending seismic section (RTD81-RE94-22A) showing the complex architecture of the Lark Formation and its subdivision into **L1–4** units. The vertical white line indicates change in section direction. The locations of the two seismic sections are shown on Fig. 1; abbreviations as in Figs 49 and 51.

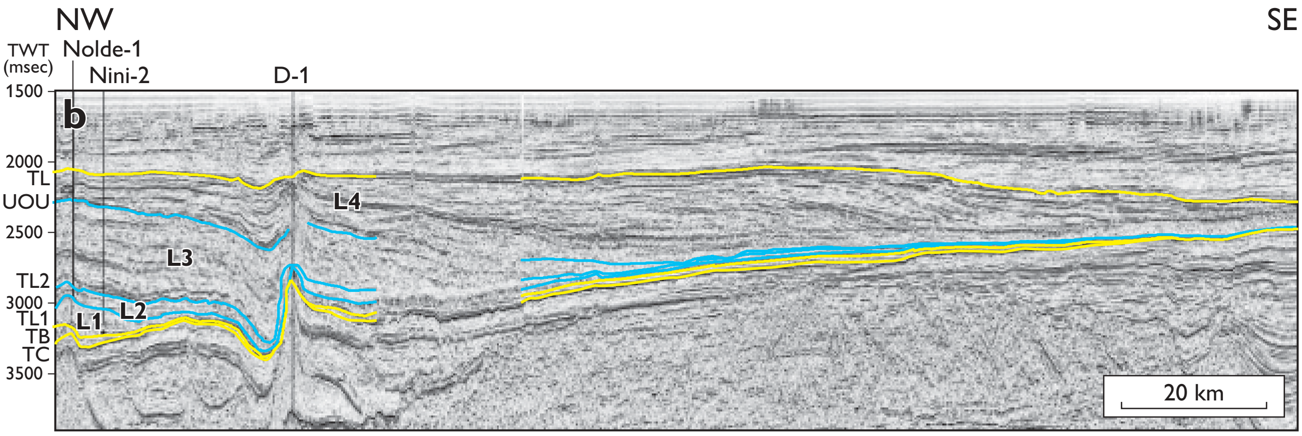


Fig. 56. **b**: NW–SE-trending seismic section (RTD81-RE94-14A) showing subdivision of the Lark Formation and marked thinning of this formation towards the south-east. The locations of the two seismic sections are shown on Fig. 1; abbreviations as in Figs 49 and 51.

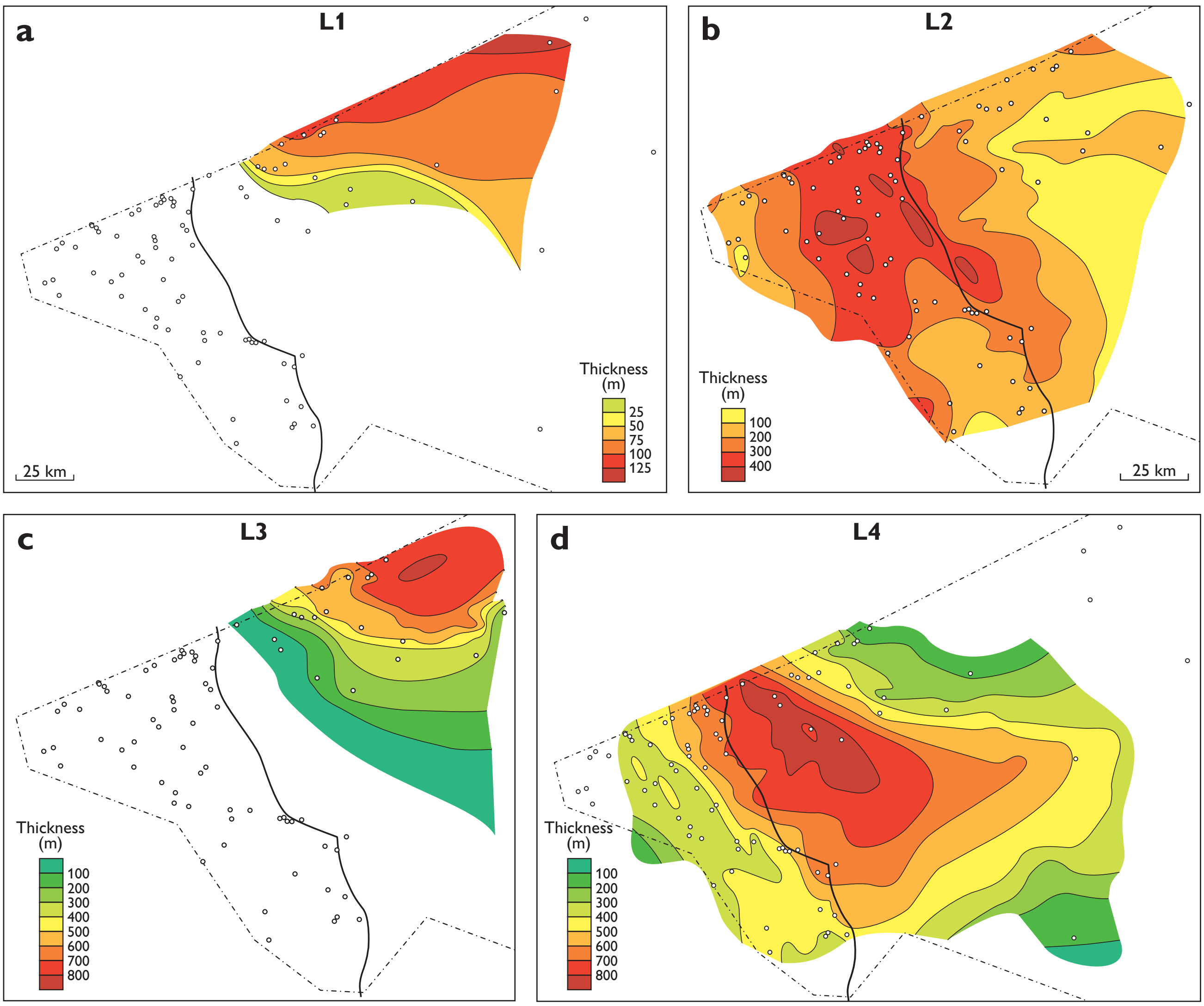


Fig. 57. Isochore maps of Lark Formation subunits. **a**: L1. **b**: L2. **c**: L3. **d**: L4. **a** and **d** are at the same scale, **b** and **c** are at the same scale.

ma-ray and sonic log signature than that of the underlying units (Figs 46, 51; Plates 1–5). It is dominated by brown to yellowish brown mudstones, but in some wells an interval of greenish grey mudstones occurs in its lower part. In wells to the east and north, thin sandstones are interbedded with the mudstones and become more frequent towards the top of the unit.

Two thick sandstone units occur in the Lark Formation on the Ringkøbing–Fyn High and are described here as two new members (Dufa and Freja Members).

Macro- and ichnofossils. Only observed in cores taken in the Freja Member (see below).

Microfossils and palynomorphs. Farthest to the north and east the basal part of the formation includes the downhole succession of HO *Areosphaeridium diktyoplokum* and HO *A. michoudii* indicating a late Priabonian (Late Eocene) age for the base of the formation in this area. In the Central Graben area, the base of the Lark Formation is significantly younger. Here it contains an event succession characteristic of the middle and lower Rupelian (Lower Oligocene) Stage (HOs of *Phthanoperidinium amoenum*, *Achilleodinium biformoides* and *Phthanoperidinium comatum*).

The top of the Lark Formation is bracketed by a number of conspicuous biostratigraphic events: the uppermost part contains the HOs of the benthic foraminifers *Asterigerina staeschei* and *Elphidium inflatum* followed downhole by the HO of *Uvigerina tenuipustulata*. Dinoflagellate events near the top of the Lark Formation include the HOs of *Apteodinium spiridoides* and *Cousteaudinium aubryae*. The lowermost part of the overlying Nordland Group contains the HOs of the calcareous microfossils *Bolboforma clodiusi*, *Bolboforma spiralis* and *Bolboforma metzmacheri*, the HO of the benthic foraminifer *Bulimina elongate,* and the HO of the dinoflagellate cyst *Cannosphaeropsis passio*. A large number of HOs characterise the Lark Formation; key events are listed in Fig. 5c.

Depositional environment. The L1 unit is characterised by abundant agglutinated foraminifers dominated by *Rhabdammina discreta* and similar tubular taxa, together with *Haplophragmoides* spp. and *Recurvoides* spp. The microfaunal assemblage indicates that the unit was predominantly deposited in an open marine, dysoxic palaeoenvironment at upper bathyal depths.

The L2 unit and most of the L3 unit are characterised by an increasing abundance and diversity of calcareous benthic and planktonic foraminifers. The relative proportions of agglutinated, calcareous planktonic and benthic foraminifers vary considerably from well to well, indicating pronounced lateral changes in the depositional environment. The calcareous plankton/benthos ratio is usually low, indicating a neritic setting for most of the succession, but in a few restricted intervals it may reach 1:2 or even 1:1 indicating an outer neritic setting. Thus, the foraminifer assemblage indicates an open marine, neritic to outer neritic setting with well-oxygenated bottom conditions for the lower to middle part of the Lark Formation.

The microfossil assemblage in the uppermost part of the L3 unit as well as the L4 unit is dominated by calcareous benthic foraminifers, and agglutinated foraminifers are generally rare. Epifaunal and shallow infaunal foraminifers are more common than deep infaunal taxa, indicating oxic bottom conditions during this interval. In general, the microfaunal assemblage in this part of the Lark Formation suggests that it was deposited in a neritic, probably middle neritic, palaeoenvironment over most of the study area.

The palynofacies assemblage in the Lark Formation is characterised by a rich dinoflagellate assemblage and abundant dispersed terrestrial matter (phytoclasts, spores and pollen), indicating an open marine environment with considerable influx from nearby land areas. Stratigraphic variations in the relative abundance of terrestrial palynomorphs in the Lark Formation suggest successive pulses of progradation and backstepping of the palaeocoastline.

Age. The Lark Formation is of Priabonian to Serravallian (Late Eocene to Middle Miocene) age with Eocene sediments being present in the L1 unit only. The L1 unit is Priabonian to early Rupelian (Early Oligocene) in age, the base of the unit being oldest farthest to the north and east and younging towards the south and west. The age of the L2 unit is Rupelian; the L3 unit is Rupelian in age in its lower part and Chattian (Late Oligocene) in its upper part. The Rupelian–Chattian boundary is located in the lower part of the unit. The Chattian–Aquitanian (Oligocene–Miocene) boundary is located just above the top of the L3 unit. In some wells, a hiatus is indicated at this level by the clustering of HOs. The Chattian–Aquitanian, Aquitanian–Burdigalian, Burdigalian–Langhian and Langhian–Serravallian stage boundaries are all located in the L4 unit. The uppermost part of the Lark Formation is of mid-Serravallian age.

Correlation. Based on biostratigraphic correlation, the lowermost L1 unit is probably largely coeval with the Viborg Formation onshore Denmark, and with Sequence 4.1 of Michelsen *et al.* (1998). The L2 unit may be corre-

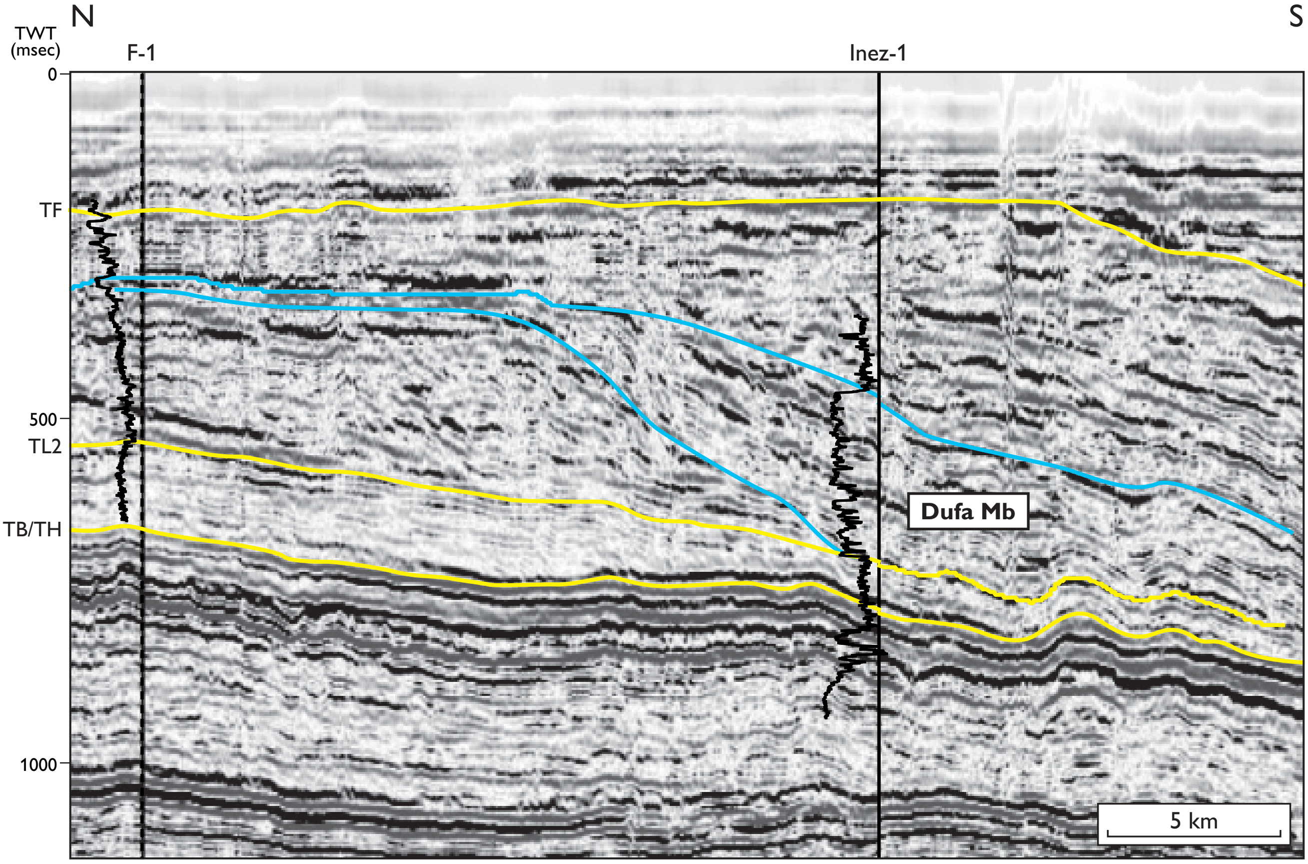


Fig. 58. N–S-trending composite seismic section (RTD81-RE94-45/RTD81-RE94-09). Blue-coloured lines indicate the outline of the Dufa Member. The gamma-ray logs from the Inez-1 and F-1 wells are inserted (see Figs 55 and 59 for depth-converted gamma-ray logs for the two wells). The Horda Formation is thin in this area and the Top Horda reflector (**TH**) is therefore indistinguishable from the Top Balder reflector (**TB**). The location of the seismic section is shown in Fig. 1; abbreviations as in Fig. 49.

lated with the Linde Clay onshore Denmark (informal mudstone unit described by Heilmann-Clausen 1995). Intervals in the L3 unit may be correlated with the Branden Clay (Ravn 1906) onshore Denmark, based on lithological similarities and biostratigraphy. Intervals in the Lark Formation around the L3–L4 boundary (around the Chattian–Aquitanian boundary) may be correlated with the two lowermost, clay-rich units of the onshore Vejle Fjord Formation (the Brejning Clay and Vejle Fjord Clay of Larsen & Dinesen 1959). The uppermost part of the Lark Formation possibly correlates with the onshore Arnum Formation (Sorgenfrei 1958) and the Hodde Formation onshore Denmark (Rasmussen 1961), based on biostratigraphy.

Dufa Member

new member

History. The Dufa Member comprises a thick sandstone-dominated unit that occurs within unit L3 of the Lark Formation in the northern and eastern part of the Danish sector of the North Sea. The unit has not been previously described.

Derivation of name. After the goddess Dufa.

Type well. Danish sector well Inez-1, 697.1–485.5 m MDKB (Figs 41, 58; Plates 1, 5).

Reference well. Danish sector well F-1, 337.5–324.3 m MDKB (Figs 58, 59; Plate 5).

Distribution and thickness. The Dufa Member is present in the north-eastern part of the Danish sector of the North Sea (Fig. 55). In its type well, the Dufa Member is 210 m thick and consists of three major sandstone units with thicknesses 30–120 m (Fig. 41). The sandstone units are separated by mudstone intervals up to 20 m thick. Towards the north, in the F-1 well, the lower sandstone units are

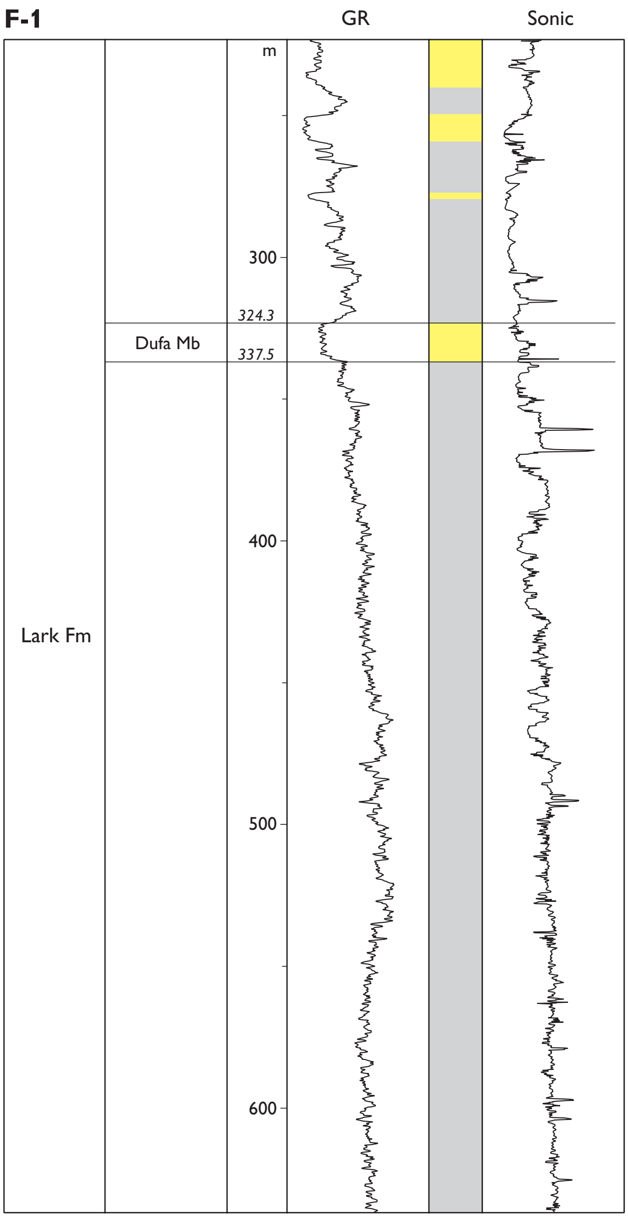


Fig. 59. F-1, reference well for the Dufa Member.

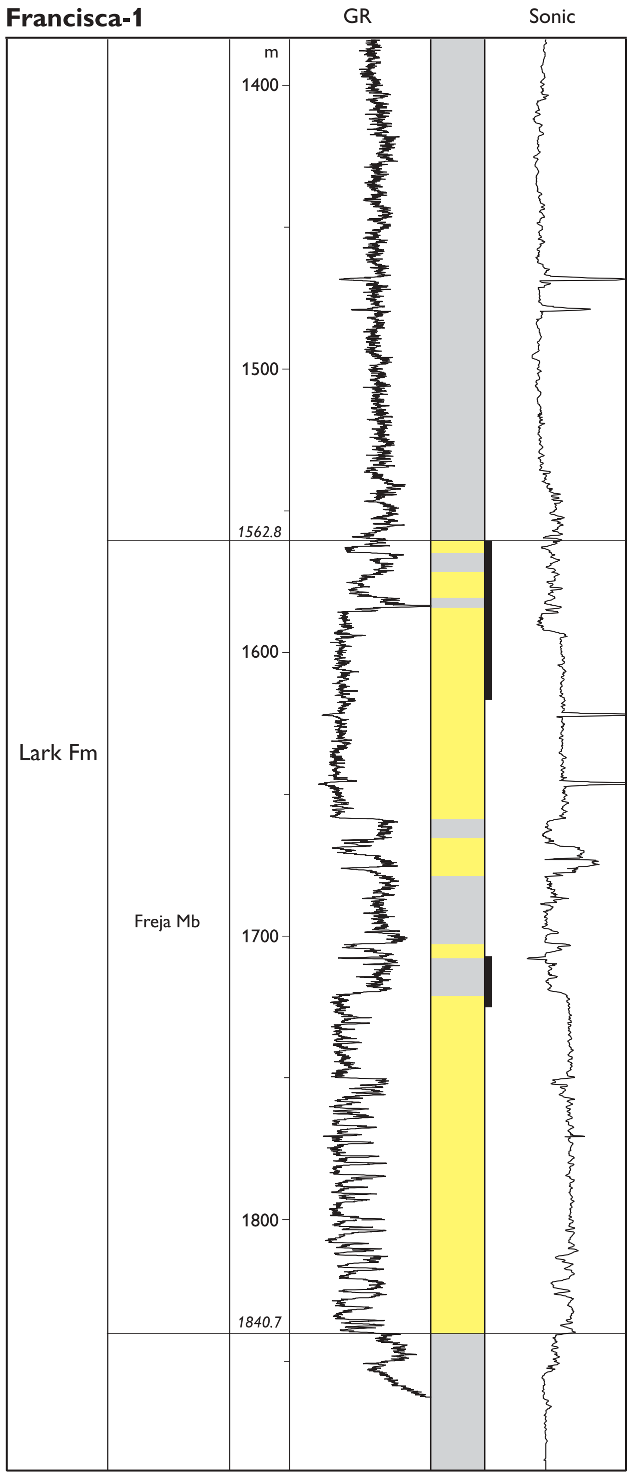


Fig. 60. Francisca-1, type well for the Freja Member. Black bars show cored sections.

missing (Figs 58, 59). The Dufa Member is absent in wells west of F-1.

Lithology. The lower sandstone units predominantly consist of coarsening-upwards successions of very fine-grained to fine-grained, greenish brown, muddy sandstones. The upper sandstone unit fines upwards and consists of medium- to coarse-grained, quartzitic, relatively pure sand with intervals rich in glaucony. Lignite has been observed in cuttings samples.

Log characteristics. The member is characterised by an overall blocky signature on the gamma-ray log. In the type well, the lower sandstone intervals of the Dufa Member show the presence of a number of 5–10 m thick sandstone packets showing blocky, decreasing-upwards gamma-ray log signatures suggesting coarsening-upwards sand bodies. These sandstones are separated by intervals of mudstones with higher gamma-ray response. The upper unit is characterised by an overall blocky signature with minor gamma-ray peaks and trends suggesting a number of fining-upwards intervals, 10–20 m thick, and a few coarsening-upwards intervals, 5–10 m thick (Fig. 41).

Boundaries. The upper and lower boundaries of the member with the mudstones of the Lark Formation are sharp and characterised by prominent shifts on the gamma-ray log (Figs 41, 59).

Depositional environment. Judging from seismic evidence, the Dufa Member is positioned partly on the offlap break, partly seaward of it (Fig. 58). Based on this palaeosetting and the presence of lignite in cuttings samples, the Dufa Member sandstones are interpreted to represent deltaic, shallow-marine sediments, probably deposited in pulses during an overall relative sea-level low.

Age. Rupelian, based on the age of the enveloping mudstones.

Correlation. There are no Danish onshore correlatives to the Dufa Member. The correlation with the Norwegian offshore successions is currently uncertain.

Freja Member

new member

History. The Freja Member is a conspicuous sandstone-dominated unit that occurs within the upper levels (L4) of the Lark Formation in the northern and central parts of the Danish sector of the North Sea. The unit has not previously been described.

Derivation of name. After the goddess Freja.

Type well. Danish sector well Francisca-1, 1840.7–1562.8 m MDRT (Figs 60, 61).

Reference well. Danish sector well Frida-1, 1623.5–1487.7 m MDRT (Fig. 62; Plate 4).

Distribution and thickness. The Freja Member is present in the northern and central parts of the Danish sector of the North Sea (Fig. 55). In its type well, the Freja Member spans a stratigraphic interval of *c.* 280 m and includes major sandstone units separated by subordinate intervals of mudstones (Fig. 60). In the Cecilie-1 well, the member is *c.* 150 m thick whereas in the Frida-1 well the member attains *c.* 130 m (Fig. 62).

Lithology. In its type well, the lower half of the Freja Member consists of very fine-grained to fine-grained quarzitic sandstones with many thin mudstone interbeds. The member becomes less muddy in the upper third of this interval. The upper third of the Freja Member consists largely of relatively pure quarzitic, very fine-grained sandstones with mudstone interbeds becoming frequent towards the top (Fig. 60). Between these two major sandstone units is a *c.* 60 m thick interval dominated by mudstones but with carbonate-cemented, sandstone-dominated packets in its upper part.

Log characteristics. The Freja Member has an overall blocky gamma-ray log signature. In the type well, its lowermost part (1840.7–1750 m) can be split into a number of smaller units with blocky or increasing-upwards gamma-ray log signatures separated by gamma-ray peaks. In comparison, the overlying sandstones (1750–1720 m) display a more stable, low gamma-ray log pattern with few gamma-ray log spikes (Fig. 60). The mudstone-dominated interval (1720–1660 m) separating the two sandstone-dominated units in the type well generally shows high gamma-ray values: Thin calcite-cemented sandstone packets are intercalated with the mudstones in this interval (e.g. 1680–1670 m) and show decreasing-upwards gamma-ray values.

Boundaries. The lower boundary of the Freja Member with the Lark Formation mudstones is sharp and characterised by prominent shifts on the gamma-ray and sonic logs. In the type well, where the upper levels of the Freja Member are characterised by interbedded mudstones and sandstones, the upper boundary of the member is less prominent. In this well, it is placed at the top of the uppermost discrete sandstone bed, at 1562.8 m (Fig. 60).

Macro- and ichnofossils. Intervals with shell debris have been observed in core sections of the Freja Member in the Francisca-1 well. Ichnofossil genera from the Freja Member comprise *Chondrites* ispp., *Phycosiphon* ispp., *Planolites* ispp., *Terebellina* ispp., *Thalassinoides* ispp. and *Zoophycos* ispp.

Depositional environment. The Freja Member represents stacked successions of thick- and thin-bedded turbidite sands deposited in submarine channels and proximal levee environments (Figs 60, 62). The upper parts of the turbidite successions show transitions from normally graded turbidites, deposited in slightly more distal levee environ-

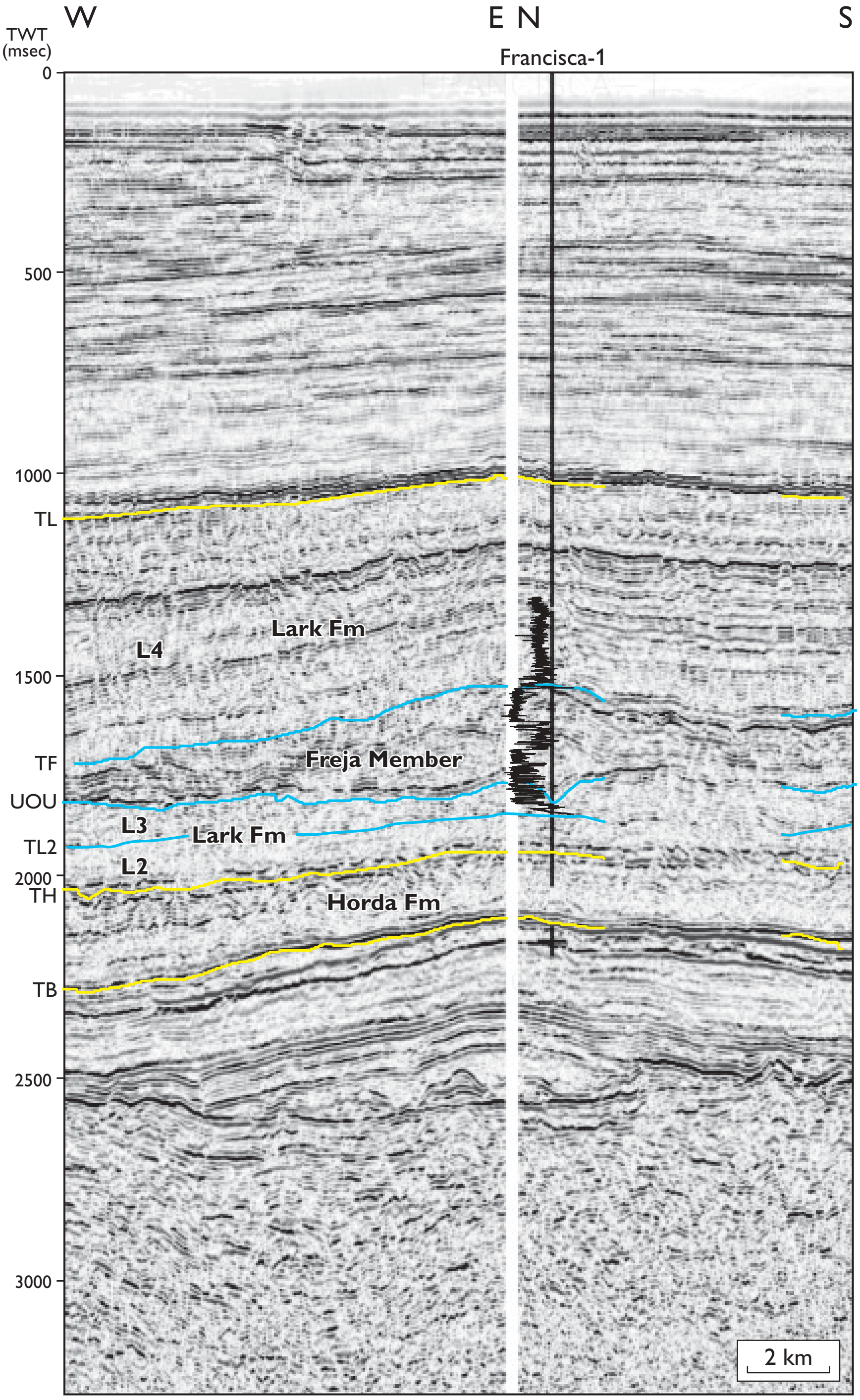


Fig. 61. Composite seismic section (DK1–5623A RE94/DK1–0448B RE94) with the Freja Member indicated between the reflectors **UOU** and **TF**. The gamma-ray log from the Francisca-1 well is indicated on the figure (see Fig. 60 for depth-converted gamma-ray log). The vertical white bar indicates where the section changes direction. The location of the seismic section is shown on Fig. 1; abbreviations as in Fig. 49.

ments and minor turbidite channels, to mainly silty turbidite deposits that represent distal levee and fan fringe environments and the transition to the open slope. The source of the sand was probably a marginal marine shelf environment, judging by the abundance of the marginal marine acritarch *Paralecaniella indentata.*

Age. In the type well, the Freja Member is Chattian to Aquitanian in age, based on the age of mudstones within and bounding the member. In the Frida-1 well, the Freja Member is entirely Chattian in age.

Correlation. The Freja Member is broadly contemporaneous with the Vejle Fjord Formation onshore Denmark, with the Vade Formation (Hardt *et al.* 1989) in the Norwegian Central Graben and with the Skade Formation (Hardt *et al.* 1989) in the Viking Graben. Thick, coarsening-upward sandstone bodies are present above the Dufa Mem-

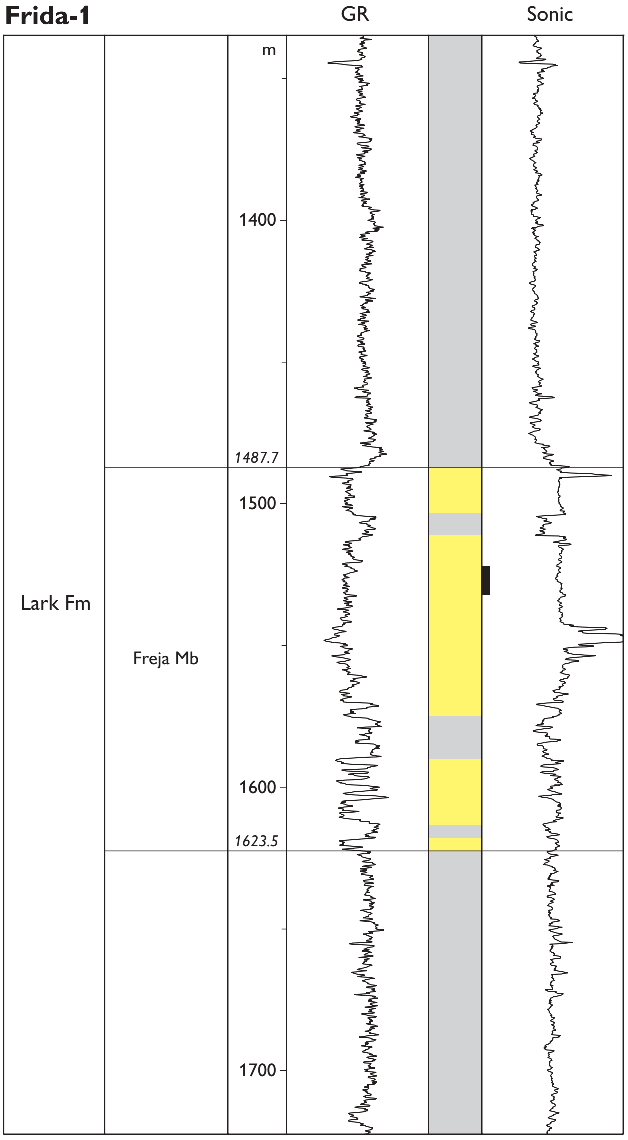


Fig. 62. Frida-1, reference well for the Freja Member. Black bar shows cored section.

ber in the Inez-1 well (shown as unnamed sandstones in Fig. 2); these sandstones may be contemporaneous or even contiguous with those of the Freja Member. However, confident correlation on the basis of log and seismic data is not possible at present.

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