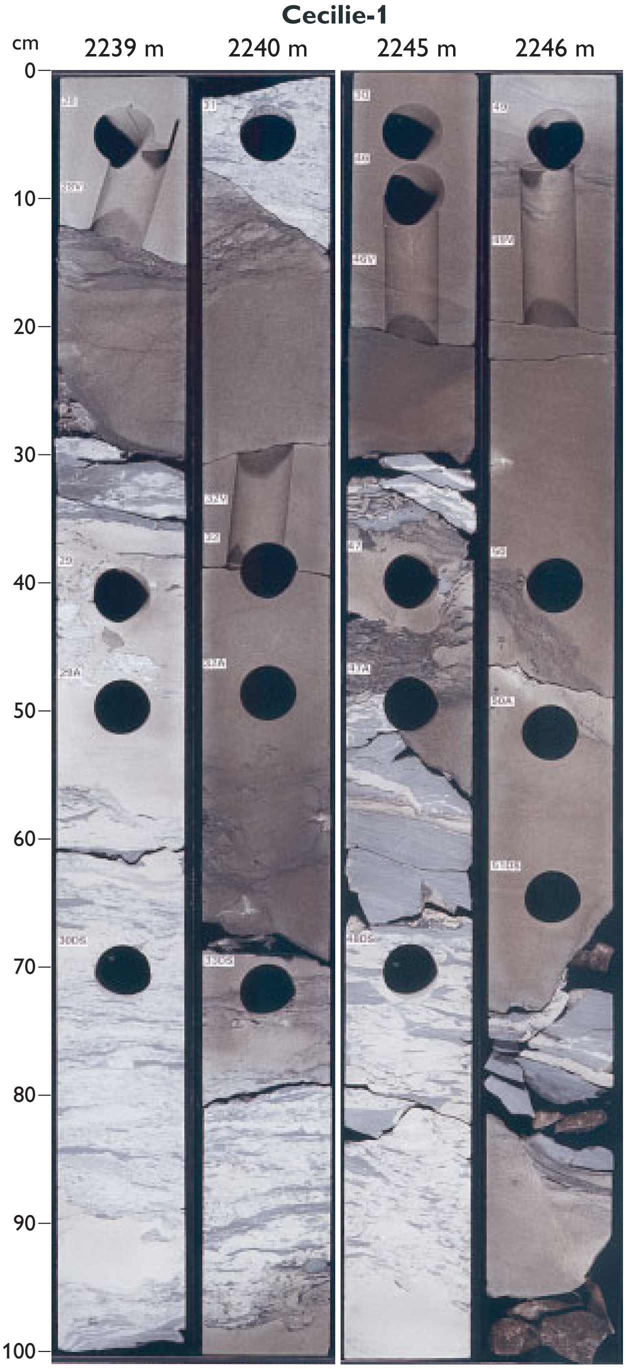


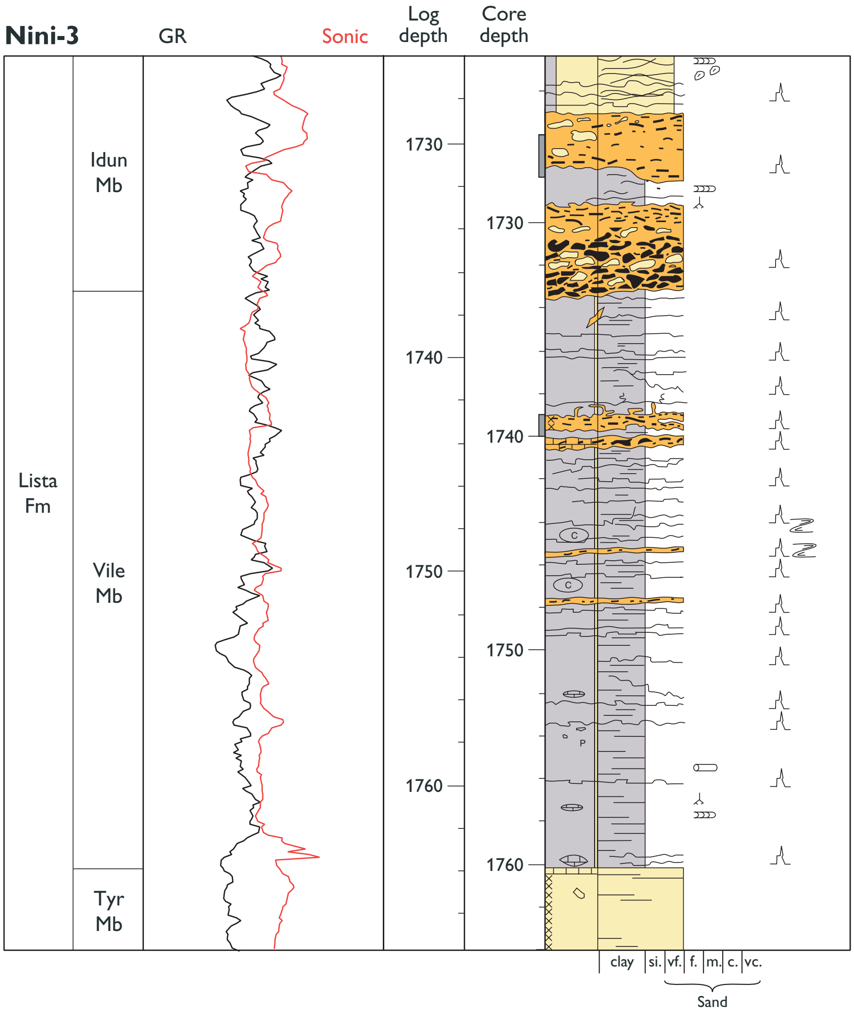
Fig. 10. Core photographs showing dark grey, largely structureless, discordant, intrusive sandstones within the lighter grey mudstones of the upper Tyr Member in the Cecilie-1 well. Depths are core depths. Stratigraphic positions of the figured intervals are shown on Fig. 8.

Rogaland Group

The Rogaland Group was established by Deegan & Scull (1977) and comprises the Paleocene to Lower Eocene marlstone and mudstone succession between the top of the Ekofisk Formation of the Chalk Group (Deegan & Scull 1977) and the glaucony-rich mudstones of the Hordaland Group (now Stronsay and Westray Groups) in the central North Sea. In most of the Danish sector, the Rogaland Group has a relatively uniform thickness and comprises the Våle, Lista, Sele and Balder Formations (Fig. 7). The Fur Formation is a part of the Rogaland Group and is present in a limited area in the north-eastern part of the Danish sector of the North Sea stretching into the Norwegian sector. Hardt *et al.* (1989) added three new sandstone units to the Rogaland Group in the southern Viking Graben (Norwegian sector): Ty Formation, Heimdal Formation and Hermod Formation (Fig. 4). Although these sandstone units are broadly comparable to coeval sandstone units encountered in the Siri Canyon System (Figs 1, 4) in the Danish sector, the Norwegian units and the Siri Canyon sandstones have different provenances and are not contiguous with each other. Therefore, the sandstone units in the Danish sector are described herein as new members.

In the Siri Canyon (Fig. 1), the mudstones of the Rogaland Group contain concordant or discordant postdepositional sandstone intrusions (Hamberg *et al.* 2005). In some wells (e.g. Cecilie-1 and Nini-3) sandstone intrusions are very common (Figs 8–11). The sands have intruded most levels in the Rogaland Group, but the Ve Member (new member of the Lista Formation, see below) in the middle part of the group is particularly rich in intrusions. Most of the intrusive sandstones are only a few millimetres thick, but they may reach a thickness of 5 m. In some wells they constitute up to 30% of the total sandstone thickness. The intrusions are usually massive, but faint lamination is locally present, especially at the top of the beds. Most of the intrusive sandstone bodies are separated by *in situ* mudstones, but they may also occur in intervals showing multiple intrusions. The boundaries with the host rock are slightly to very irregular or wavy, and in places discordant. Minor intrusive offshoots (apophyses) into the host rock are common. The petrography of the intrusive sandstones is similar to that of the *in situ* sandstones and they are therefore most likely sourced from the

Fig. 11. Core log showing intrusive sandstones in the Vile and Idun Members in the Nini-3 well. For legend, see Fig. 9. The two intervals marked by grey bars in the core depth column are shown as core photographs in Fig. 12.



latter. The intrusion of sand was mainly subhorizontal, parallel to the bedding, and most of the intrusions can thus be classified as sills. The sandstone intrusions are either unconsolidated or cemented by calcite or other carbonate minerals. In some wells the intrusive sandstones are chlorite-cemented.

In the Nini-3 cores, the Vile and Ve Members of the Lista Formation (new members, see below) are particularly rich in intrusive sandstones (Figs 11, 12); the intrusions increase in number and thickness upward through the Vile Member to terminate in a large intrusion complex in the Ve Member. Commonly, mudstone clasts are abundant in the sandstones and in the intrusion complex in the Nini-3 well. Where present, they constitute from a few percent up to 90% of the volume of the host sandstones. They are most abundant in the upper parts of the beds. The clasts range in size from a few millimetres to wider than the core diameter. Most of the clasts are angular, often with delicate protrusions, and aligned parallel to the bounding planes of the intrusive sandstone body. In thick intrusions, flow banding and dewatering structures are occasionally present. Top-bed rip-down mudstone clasts (Stow & Johansson 2000) are common (Fig. 12). Fossil wood fragments are present, but rare.

As the distribution of intrusive sandstones is the result of postdepositional rather than synsedimentary processes, they may cross lithostratigraphic boundaries. When an injected sandstone body occurs in direct contact with an *in situ* sandstone unit (e.g. as seen in the higher parts of the new Tyr Member in Fig. 8), it is impossible to distinguish between the two genetically different units on the basis of petrophysical logs and cuttings samples alone; only a sedimentological study of core material may reveal the different nature of the two sandstones.

Våle Formation

History. The Våle Formation was established by Hardt *et al.* (1989) for the marls with interbedded claystones, limestones and silt- and sandstone stringers that overlie the Chalk Group in the central and northern North Sea. The

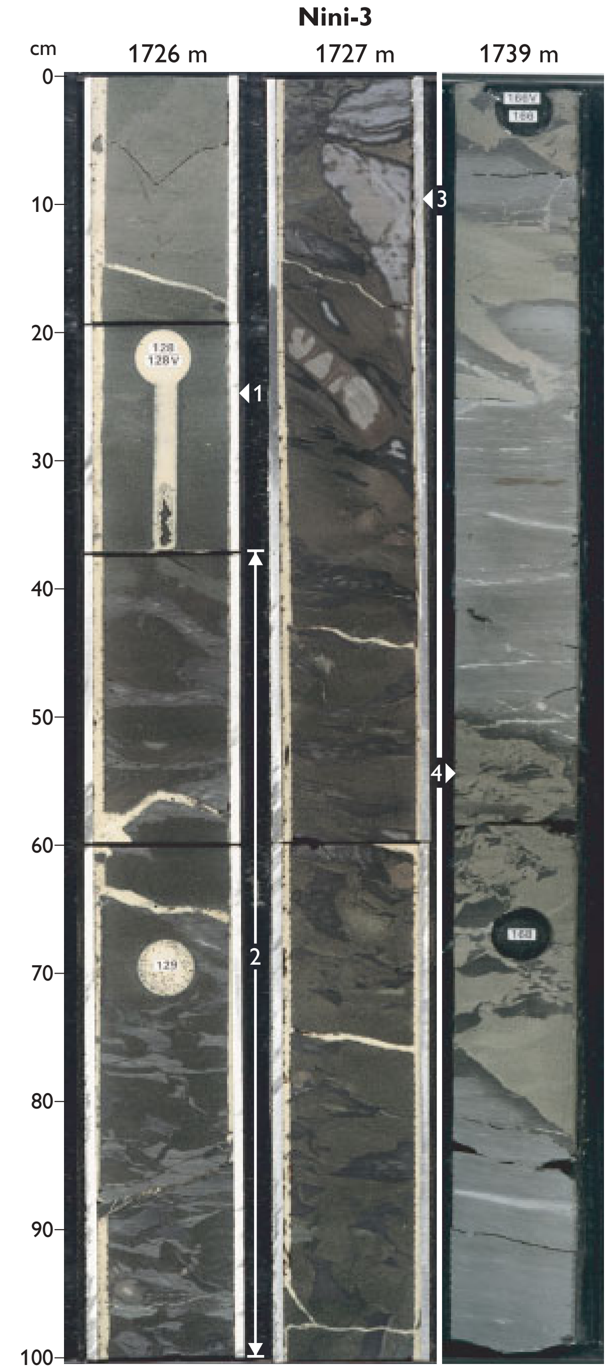


Fig. 12. Core photographs of the Vile and Idun Members in the Nini-3 well showing sandstone intrusions, weak flow banding (**1**), injection breccia with abundant irregular and angular clasts (**2**), mudstone clasts in injected sand (**3**) and top bed rip-down clasts (**4**). Depths are core depths. Stratigraphic positions of the figured intervals are shown on Fig. 11.

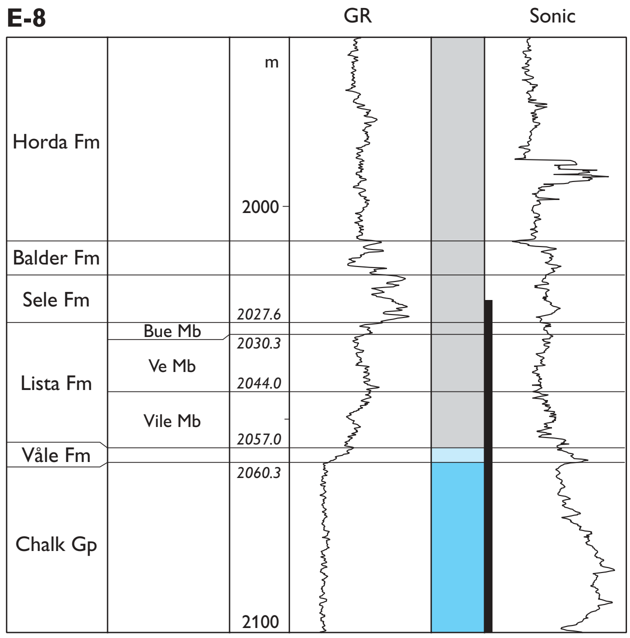


Fig. 13. E-8, Danish reference well for the Våle and Lista Formations, and reference well for the Vile, Ve and Bue Members. Black bar shows cored section.

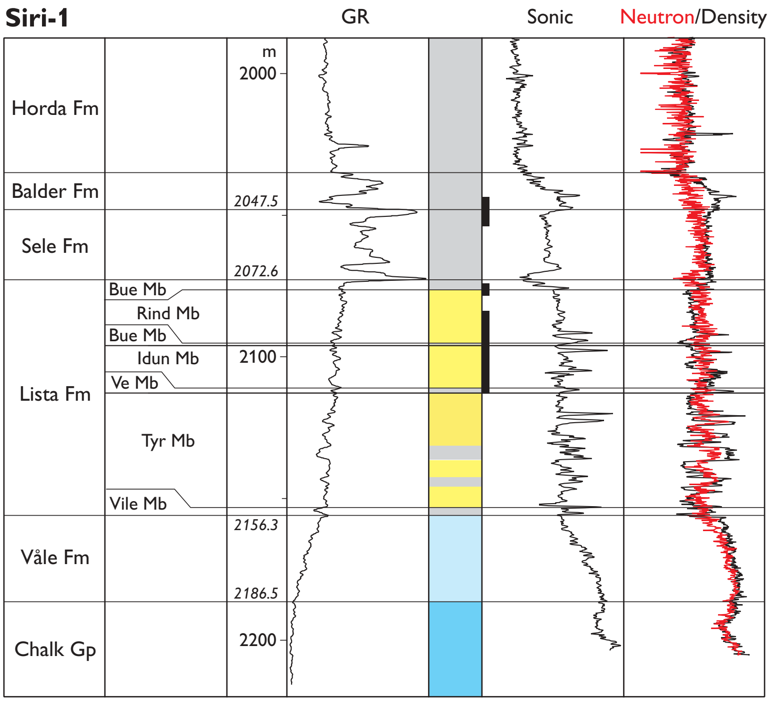
presence of a marly succession on top of the Chalk Group was previously noted by Deegan & Scull (1977) and treated informally as an equivalent to the more coarse-grained Maureen Formation in the UK sector of the North Sea. Kristoffersen & Bang (1982) established the North Sea Marl for an exclusively marly and calcareous unit corresponding to the Maureen Formation-equivalent unit of Deegan & Scull (1977). Although the description of the North Sea Marl fulfils the requirements for a formal description of a lithostratigraphic unit (with the exception of lacking indication of the rank of the unit), they specifically stated that their unit was only informally established. The name North Sea Marl has only rarely been used outside the Danish sector of the North Sea; the sediments are instead referred to the Våle Formation, which covers most national sectors of the North Sea Basin. As doubt may be raised about the formal status of the North Sea Marl unit, and in order to promote communication between North Sea stratigraphers, it is considered by the present authors that the Våle Formation of Hardt *et al.* (1989) serves as the better name for the marlstone unit.

Type well. Norwegian sector well 1/3-1, 3258–3209 m MDKB.

Danish reference wells. E-8, 2060.3–2057.0 m MDKB (Fig. 13); Siri-1, 2186.5–2156.3 m MDKB (Fig. 14; Plates 1, 4).

Distribution and thickness. The Våle Formation and its equivalents are present throughout the North Sea Basin, except in a few areas where their absence is due to non-deposition or erosion. The Våle Formation is absent on

Fig. 14. Siri-1, Danish reference well for the Våle and Sele Formations. Black bars show cored sections.



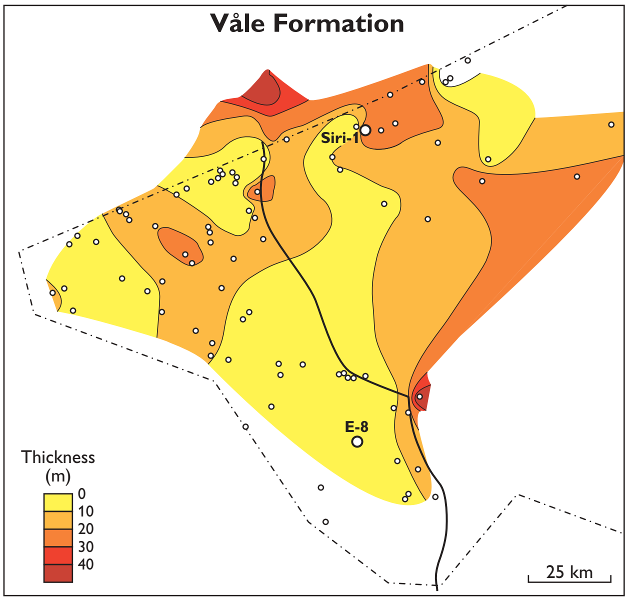


Fig. 15. Isochore map of the Våle Formation in the study area. The positions of the two Danish reference wells, E-8 and Siri-1, are indicated on the figure.

intrabasinal highs (Hardt *et al.* 1989) and in parts of the Siri Canyon where the Rogaland Group overlies the Chalk Group with an erosional unconformity. Its thickness varies from 0 to 48 m in the Danish sector of the North Sea (Fig. 15).

Lithology. Light grey to greenish grey, heavily bioturbated pyrite-bearing marlstones dominate the formation (Fig. 16). Thin sandstone intrusions are present locally. In the Siri Canyon, the marls are interbedded with turbidite sandstones; where sandstone-dominated, the succession is referred to a new member (Bor Member, defined below).

Log characteristics. From its base to its top, the Våle 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 with higher gamma-ray values and lower sonic readings interrupt this general trend (Fig. 17).

Boundaries. In most wells in the Danish sector, the change from the chalks of the Chalk Group to the marlstones of the Våle Formation is gradational and the boundary can be difficult to position (Fig. 16). In the Siri Canyon, however, most wells show an erosional contact between the Chalk Group and the Våle Formation and the formation boundary is sharp. On the petrophysical logs, the boundary is placed where the stable, low gamma-ray response characteristic of the Ekofisk Formation starts to increase upwards and the high sonic readings (also characteristic of the latter formation) start to decrease upwards. The change in the log pattern may be stepwise with each step represented by a small increase in gamma-ray values and an accompanying decrease in sonic readings. The Våle Formation is overlain by the Lista Formation.

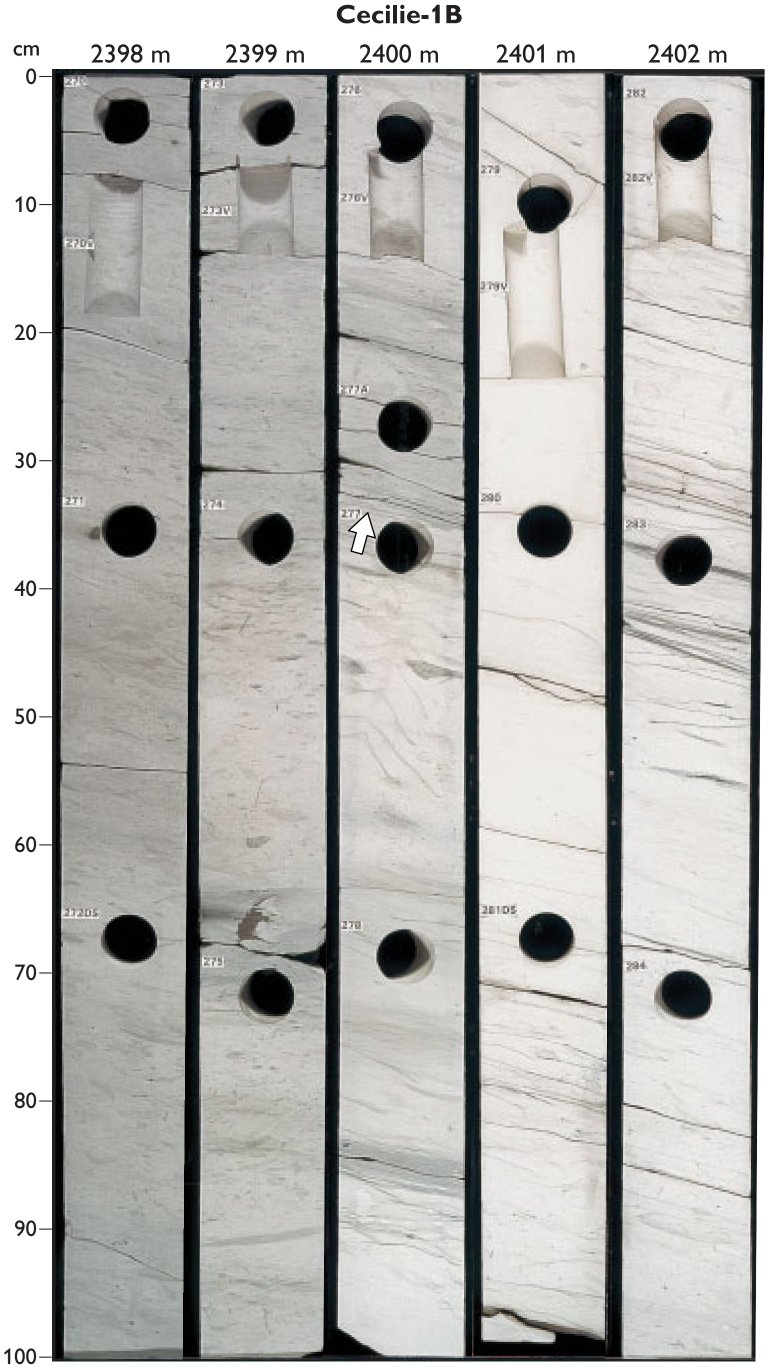


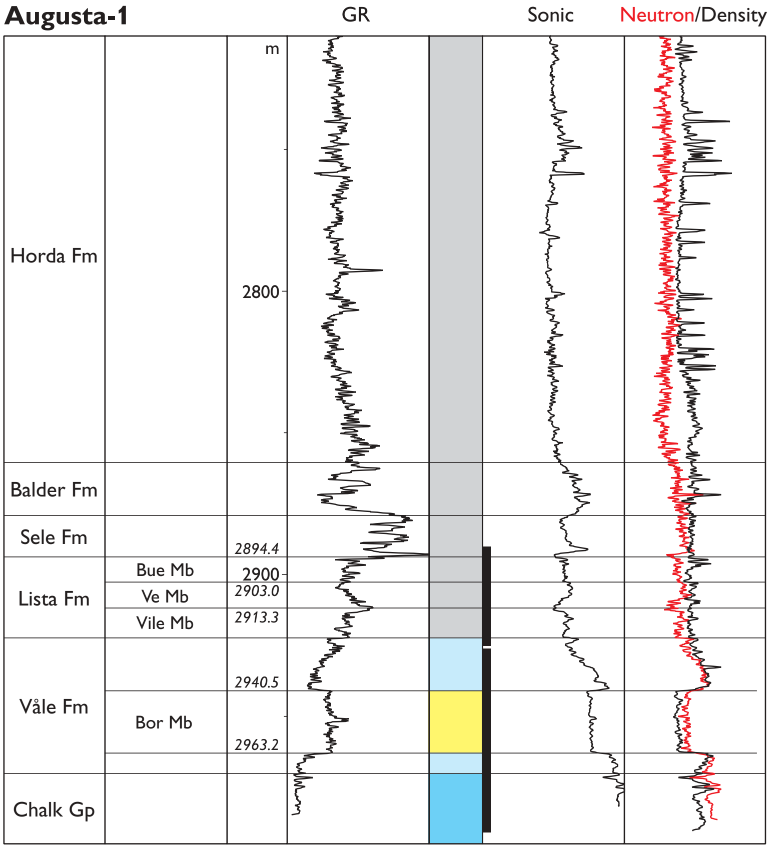
Fig. 16. Core photographs of the Ekofisk–Våle formation boundary in the Cecilie-1B well. The shift from chalk to marlstones is gradational and placing the boundary can be difficult; it is positioned in the middle part of the core interval 2400.00–2401 m, at 2400.35 m (arrow), where light grey marls become dominant. Depths are core depths.

Subdivision. The Våle Formation includes a sandstone unit (Bor Member, new) in the Danish North Sea sector.

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

Microfossils and palynomorphs. The uppermost part of the underlying Ekofisk Formation is characterised by the HO of the dinoflagellate *Senoniasphaera inornata* followed uphole by the HO of the planktonic foraminifer *Globoconusa daubjergensis*. There is a hiatus at the contact between the Ekofisk and Våle Formation in many sections and wells (Clemmensen & Thomsen 2005). The basal part of the Våle Formation, just above the top of the Ekofisk Formation, is marked by the downhole increase in calcareous foraminifer diversity and the HO of the planktonic foraminifers *Globanomalina* cf. *compressa* and *Subbotina*

Fig. 17. Augusta-1, type well for the Bor, Ve and Bue Members. Black bars show cored sections.



trivialis. Thus, the boundary between the two formations may in practice be located by reference to these three events (Fig. 5a). The HO of the dinoflagellate *Alisocysta reticulata* marks a level in the lower part of the Våle Formation. Calcareous microfossil events near the top of the Våle Formation in the Danish sector include the provisional HO of planktonic foraminifers.

Depositional environment. Over most of the Danish sector, the marlstones of the Våle Formation comprise hemipelagic deposits and deposits from dilute turbidity currents. The marlstones are probably largely of turbiditic origin. The foraminifer fauna of the Våle Formation is characterised by common calcareous taxa. Taxa belonging to the neritic 'Midway-type' fauna (Berggren & Aubert 1975) are especially common. The plankton/benthos ratio varies from approximately 1:1 in some areas to a total dominance of calcareous benthic foraminifers in other areas. The microfaunal composition indicates that the Våle Formation was deposited in an open marine, outer neritic environment that periodically reached upper bathyal depths. The bottom conditions were predominantly oxic with periods of dysoxia. The indications from the microfauna are 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 common in the Våle Formation, gravity flows played a major role during the deposition of the formation.

Age. Selandian.

Correlation. The Våle Formation is equivalent to the Lellinge Greensand and the Kerteminde Marl onshore Denmark and lithologically most closely resembles the latter. The oldest part of the Kerteminde Marl and the Lellinge Greensand are coeval, but the latter has a more restricted distribution (Sjælland and Storebælt regions only, Fig. 1; Thomsen 1994; Clemmensen & Thomsen 2005). *Alisocysta reticulata* is consistently present in the lowest part of the Kerteminde Marl (Clemmensen & Thomsen 2005). The HO of *A. reticulata* is therefore an important intra-Våle as well as intra-Kerteminde Marl marker that may be used to correlate the two formations. The Våle Formation correlates with the marly facies of the Maureen Formation in the UK and Norwegian sectors of the Central and Viking Grabens (Knox & Holloway 1992).

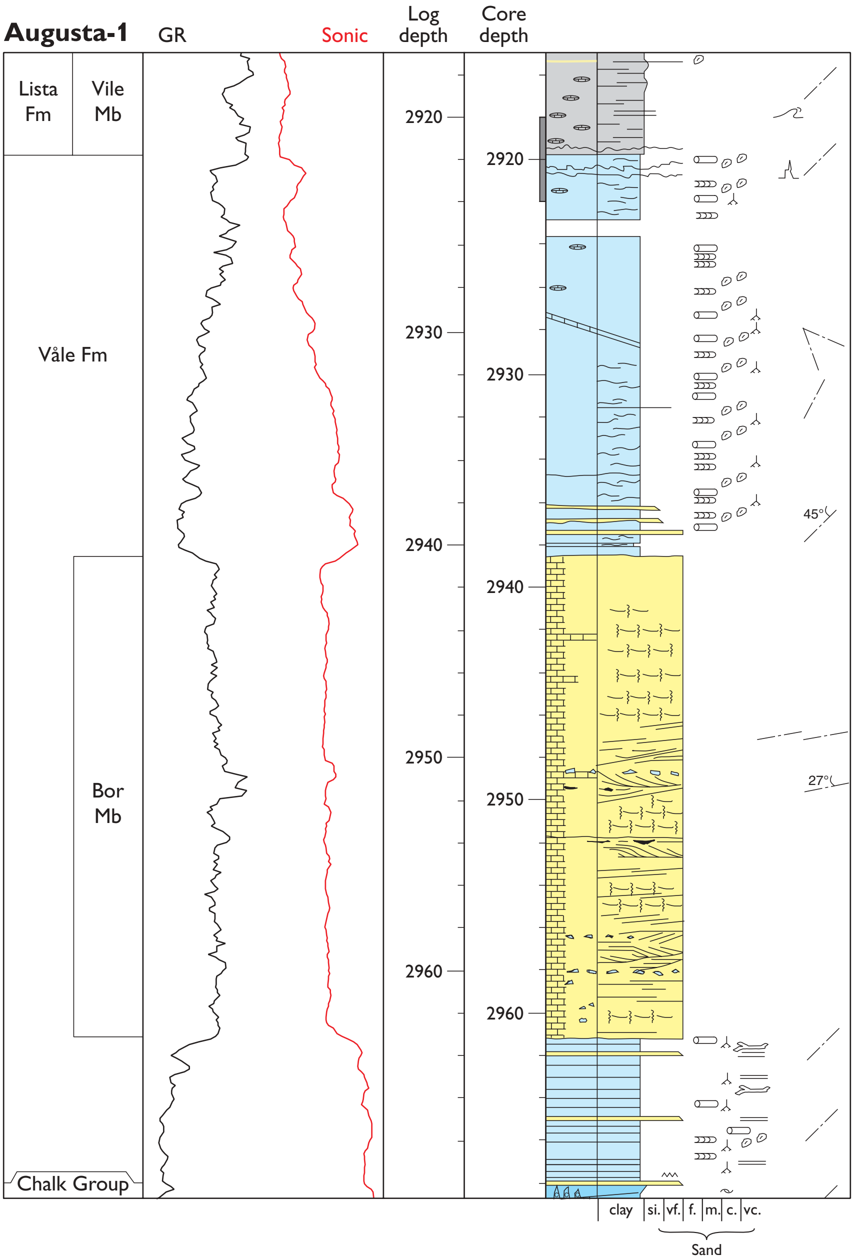


Fig. 18. Core log of Bor Member sandstones in the Augusta-1 well. Legend in Fig. 9. The interval around the Våle–Lista formation boundary marked by a grey bar in the core depth column is shown as core photographs in Fig. 23.

Bor Member

new member

History. The Bor Member encompasses sandstone bodies enveloped in the marlstones of the Våle Formation in the Danish North Sea sector. Hardt *et al.* (1989) recognised a pure sandstone unit, the Ty Formation, located between the Ekofisk and Lista Formations in the southern Viking Graben. The Ty Formation replaces the Våle Formation in its occurrence area and may be contemporaneous with the Bor Member, but it is not contiguous with it and it has a different source area. The presence of sandstone bodies in the Våle Formation in the Danish sector was recognised by a stratigraphic working group at Statoil Norway in the mid-1990s and the sandstones were informally named the 'Borr Member'.

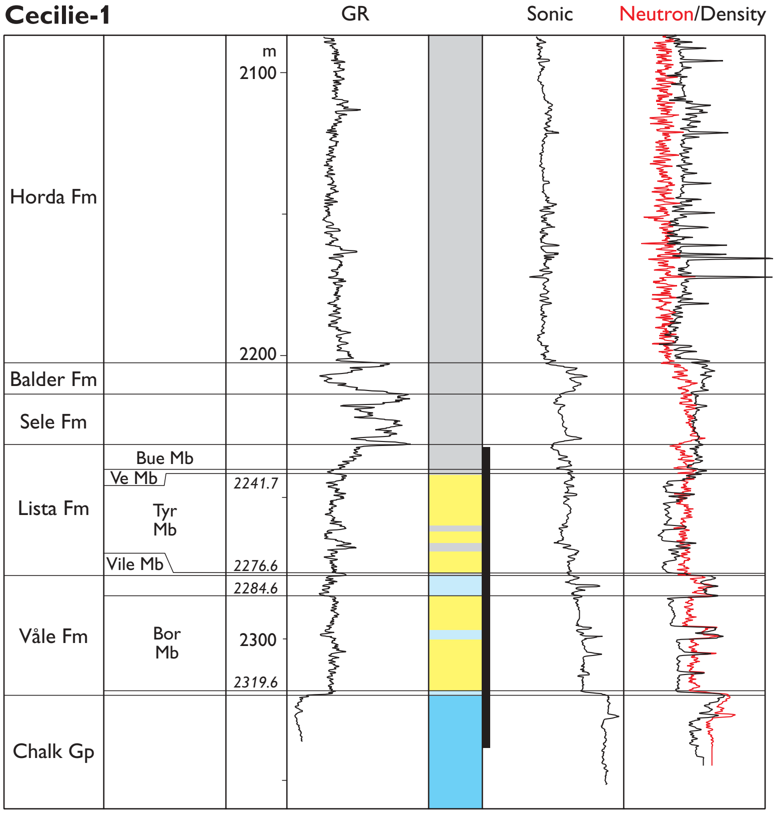
Derivation of name. After Bor (Danish spelling), the father of Odin.

Type well. Danish sector well Augusta-1, 2963.2–2940.5 m MDRT (Figs 17, 18).

Reference well. Danish sector well Cecilie-1, 2319.6–2284.6 m MDRT (Fig. 19).

Distribution and thickness. The Bor Member has been encountered at the mouth of the Siri Canyon as well as in

Fig. 19. Cecilie-1, reference well for the Bor and Tyr Members. Black bar shows cored section.



the nearby wells Tabita-1, Augusta-1 and Cleo-1 (Fig. 20a; Plate 1). It reaches a thickness of up to 23 m.

Lithology. The Bor Member consists of olive-green, partly calcite-cemented sandstones. The sandstones are very fine grained to fine grained and well sorted (Fig. 18). Rounded and translucent quartz grains dominate, but the content of glaucony grains is high (20–25%). Mica and pyrite concretions are present in small amounts. Angular chalk and claystone clasts occur locally. Although composed exclusively of sandstone in the type well (Fig. 18), the member may also include subordinate interbedded marlstones (e.g. Cecilie-1, Fig. 19).

Log characteristics. The Bor Member sandstones are best identified on the density log where they produce a blocky pattern with density values significantly lower than those of the marlstones beneath and above. The sandstones may also be identified from a combination of the density and neutron logs, as the presence of pure sandstone results in a 'cross-over' of the two log curves (Figs 17, 19). On the gamma-ray log, the Bor Member is characterised by a blocky log signature with only small-scale increasing or decreasing trends and with values clearly higher than those of the subjacent, suprajacent and locally interbedded marlstones.

Boundaries. The boundaries with the marlstones of the Våle Formation, the chalks of the Ekofisk Formation and the mudstones of the Lista Formation are sharp and characterised by prominent shifts on the gamma-ray, sonic and density logs (Figs 17–19, 21).

Depositional environment. The sandstones of the Bor Member were deposited from highly concentrated gravity flows at bathyal depths.

Age. Selandian.

Correlation. The Bor Member is contemporaneous with parts of the Kerteminde Marl onshore Denmark. The Lellinge Greensand, which appears between the top chalk surface and the Kerteminde Marl in some areas in eastern Denmark, may also be broadly contemporaneous with the Bor Member, but differs from it lithologically in being predominantly a glaucony-rich calcilutite, rich in bryozoan fragments. The Bor Member may be compared with the Ty Formation (Hardt *et al.* 1989) and with sandstones in the Maureen Formation (Deegan & Scull 1977) in the Norwegian and UK sectors of the southern Viking Graben and the Central Graben. However, it is not contiguous with these units and it has a different source area.

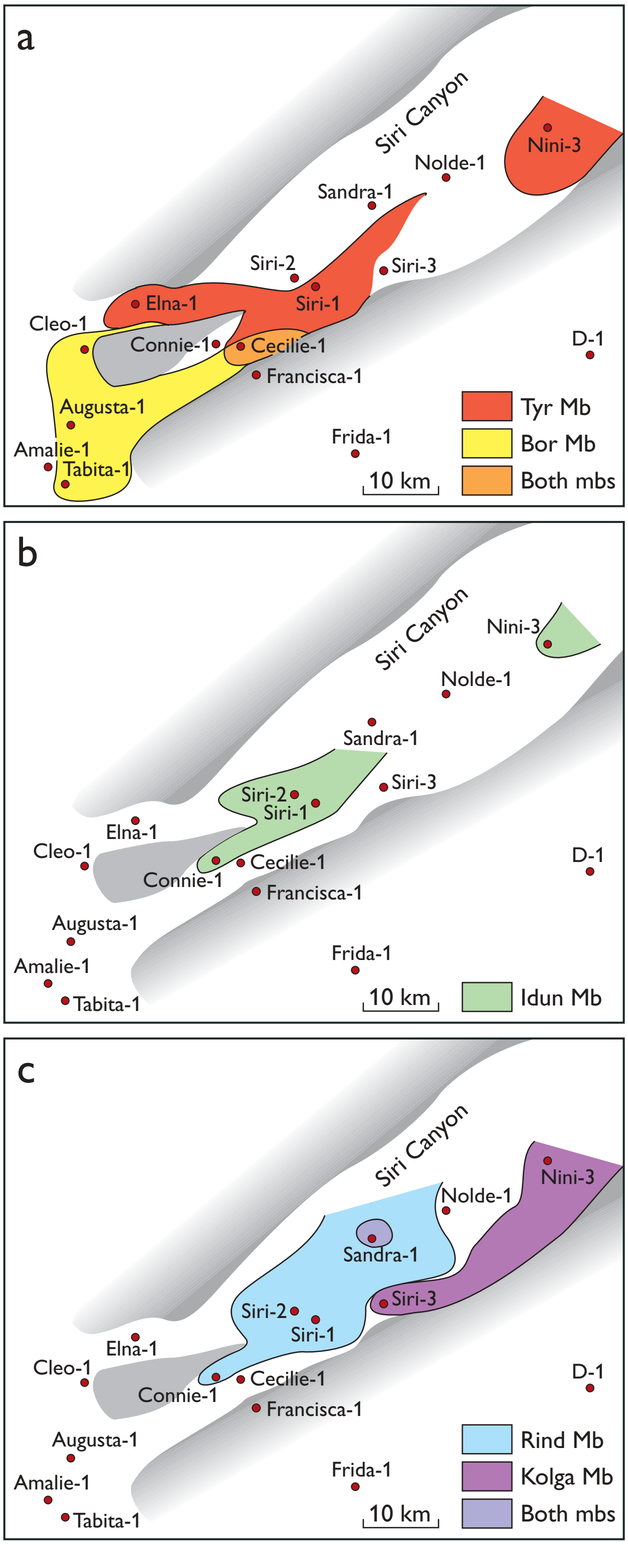


Fig. 20. Location map showing the distribution of the Rogaland Group sandstones in the Siri Canyon (the outline of the canyon is indicated by grey shading, the grey shading inside the canyon indicates an area of positive relief within the canyon). **a**: Bor and Tyr Members. **b**: Idun Member. **c**: Rind and Kolga Members.

Lista Formation

History. Deegan & Scull (1977) established the Lista Formation for the widespread, non-laminated mudstones that overlie the marls of the unit equivalent to the Maureen Formation (Våle Formation). Kristoffersen & Bang (1982) established the non-calcareous clay and shale unit CEN-1 between the top of their North Sea Marl (Våle Formation) and the base of the beds with volcanic tuff. They noted that the CEN-1 unit corresponds to the Lista Formation. For reasons of seniority and the informal nature of the CEN units, we maintain the name Lista Formation for this stratigraphic unit.

Type well. Norwegian sector well 2/7–1, 2917.5–2872.5 m MDKB.

Danish reference wells. E-8, 2057.0–2027.6 m MDKB (Fig. 13); Cleo-1, 2812.0–2765.5 m MDKB (Fig. 21; Plate 1).

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 (Fig. 22).

Lithology. The formation is characterised by dark coloured, predominantly greyish, greenish or brownish, non-laminated to faintly laminated, non-calcareous mudstones. The Lista Formation is predominantly non-tuffaceous but becomes tuffaceous towards its top. In the Siri Canyon, glaucony-rich, massive sandstone layers and injected sandstone bodies occur in the Lista Formation.

Log characteristics. Although fluctuating, both the gamma-ray and sonic log readings in the Lista Formation have higher mean values than those of the underlying Våle Formation and lower mean values than those of the overlying Sele Formation. In wells where mudstone facies dominate in the Lista Formation, the gamma-ray and sonic log patterns can be subdivided into three. The tripartite log pattern reflects the succession of three different mudstone units, established as new members herein (see below).

Boundaries. In most wells where the transition has been cored, the boundary is sharp between the light-coloured marlstones of the Våle Formation and the dark-coloured, non-calcareous mudstones of the lower Lista Formation (Vile Member, see below; Fig. 23). On the gamma-ray log, the boundary is picked at an abrupt upward shift to higher values than in the underlying Våle Formation. This level can typically be identified on the sonic log at a velocity

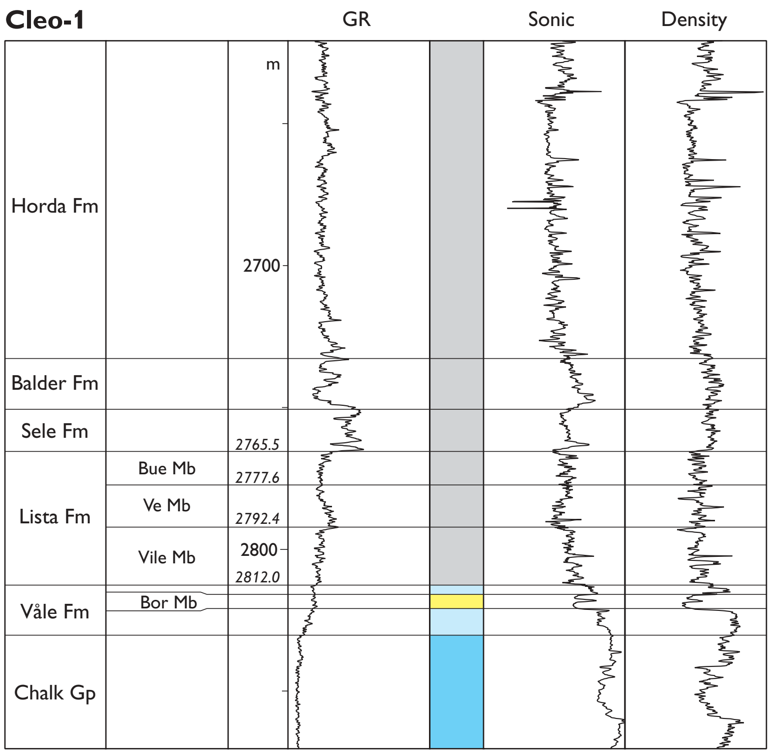


Fig. 21. Cleo-1, Danish reference well for the Lista Formation and the Vile, Ve and Bue Members.

minimum. Above this minimum, the sonic readings increase slightly upwards.

The Lista Formation is overlain by the Sele Formation. The base of the Sele Formation was defined by Deegan & Scull (1977 p. 34) at the contact between "non-laminated, non-tuffaceous shales" (Lista Formation) and "laminated tuffaceous shales" (Sele Formation). This boundary definition was followed by Mudge & Copestake (1992a, b). On the other hand, Knox & Holloway (1992 p. 46) followed O'Connor & Walker (1993) and placed the boundary somewhat lower, at the contact between "grey-green and green-grey, blocky, bioturbated claystones" of the Lista Formation and "dark grey fissile mudstones" of the Sele Formation. The boundary concept of Knox & Holloway implies that the "non-laminated, non-tuffaceous shales" of Deegan & Scull are incorporated in the Sele Formation where these, together with overlying laminated indisputable Sele mudstones, constitute the basal Sele unit S1a (Knox & Holloway 1992). In the present paper, the boundary concept of Deegan & Scull (1977) is followed, and the lower part of the unit of "non-laminated, non-tuffaceous shales" (the "dark grey, fissile mudstones" of Knox & Holloway) that overlies the grey-green mudstones is retained in the Lista Formation as its topmost unit. This unit is formalised as a new member of Lista Formation herein (Bue Member, see below).

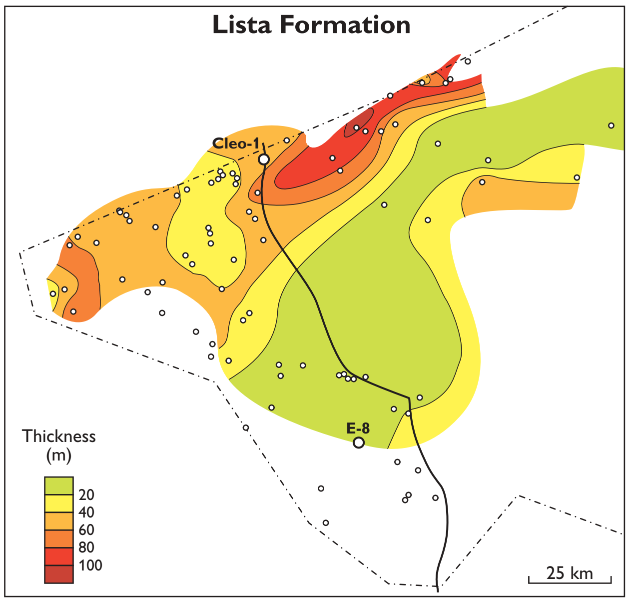


Fig. 22. Isochore map of the Lista Formation in the study area. The positions of the two Danish reference wells, Cleo-1 and E-8, are indicated.

Subdivision. The Lista Formation is subdivided into six new members. Three of these, the Vile, Ve and Bue Members, are mudstone units that have widespread distribution in the North Sea Basin and can be correlated with Danish onshore units. In the Siri Canyon, fine-grained

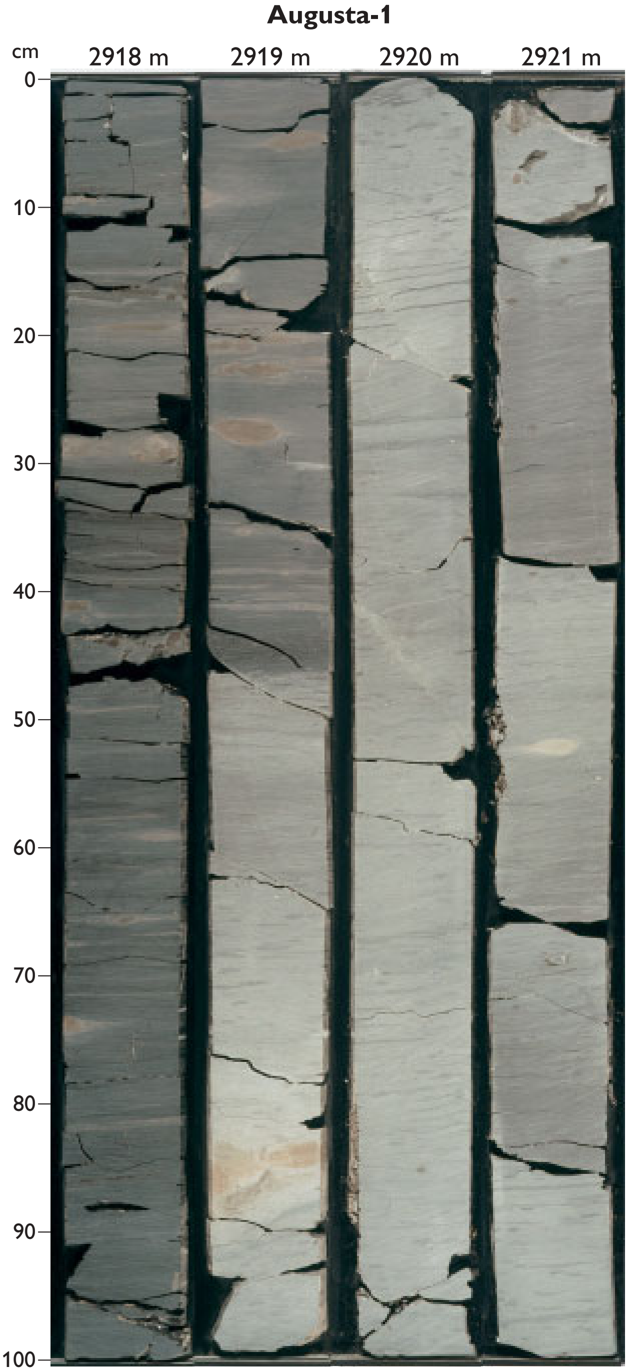


Fig. 23. Core photographs of the Våle–Lista formation boundary interval in the Augusta-1 well. The boundary is at 2919.46 m where dark grey non-calcareous mudstones of the Vile Member overlie greenish grey marls of the Våle Formation. In most cores the boundary is sharp, as illustrated here. Depths are core depths. Stratigraphic position of the figured interval is shown in Fig. 18.

sandstone bodies occur within each of the three mudstone units. These sandstone-dominated units are proposed here as three new members: the Tyr Member for the sandstones in the Vile Member, the Idun Member for the sandstones in the Ve Member, and the Rind Member for the sandstones in the Bue Member.

Knox & Holloway (1992) recognised a threefold subdivision of the Lista Formation exclusively based on biostratigraphy. Their L1 and L2 units are separated by the HO of the dinoflagellate *Palaeoperidinium pyrophorum*, and the L2 and L3 units are separated by the HO of *Areoligera gippingense*. It is noticeable that these two bioevents occur close to the boundaries between the three mudstone members of the Lista Formation proposed herein on the basis of lithology.

Macro- and ichnofossils. Macrofossils have not been reported from the Lista Formation; the formation is moderately to heavily bioturbated (for ichnotaxa, see individual members below).

Microfossils and palynomorphs. The Lista Formation differs from the underlying Våle Formation by lacking common planktonic foraminifers and from the overlying Sele Formation by having an impoverished agglutinated benthic foraminifer assemblage. The Lista Formation contains a characteristic sequence of palynomorph datums that can aid separation of its members. These datums are treated under the individual Lista members below.

Depositional environment. The Lista Formation consists predominantly of hemipelagic mudstones and was probably deposited from very dilute turbidity currents and from suspension.

The composition of the microfaunal assemblage indicates a relatively open marine depositional setting in upper to possibly middle bathyal depths with oxic to dysoxic bottom conditions. This is based on the presence of an impoverished agglutinated foraminifer assemblage 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 is higher in wells in the Siri Canyon than in wells outside the canyon. This probably indicates slightly deeper water within the canyon area during deposition of the Lista Formation.

Age. Selandian–Thanetian (Upper Paleocene). The Selandian–Thanetian boundary may be placed in the middle part of the Lista Formation (in the lower part of the Ve Member, see below), at the HO of the dinoflagellate *Palaeoperidinium pyrophorum*.

Correlation. The Lista Formation corresponds to the following succession of upper Paleocene units from onshore

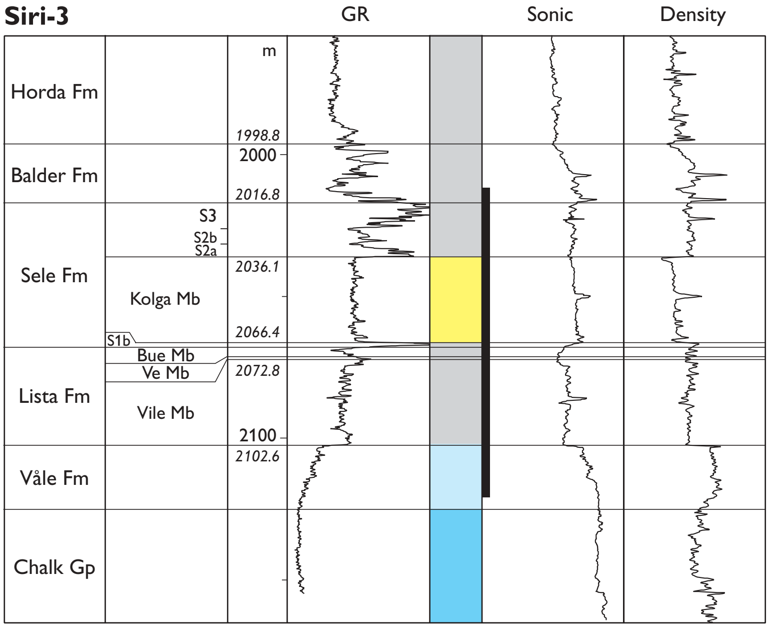


Fig. 24. Siri-3, type well for the Vile and Kolga Members, and Danish reference well for the Balder Formation. The figure also shows the subdivision of the Sele Formation used by Knox & Holloway (1992); in this well, the Bue Member is equivalent to the S1a subunit of these authors. Black bar shows cored section.

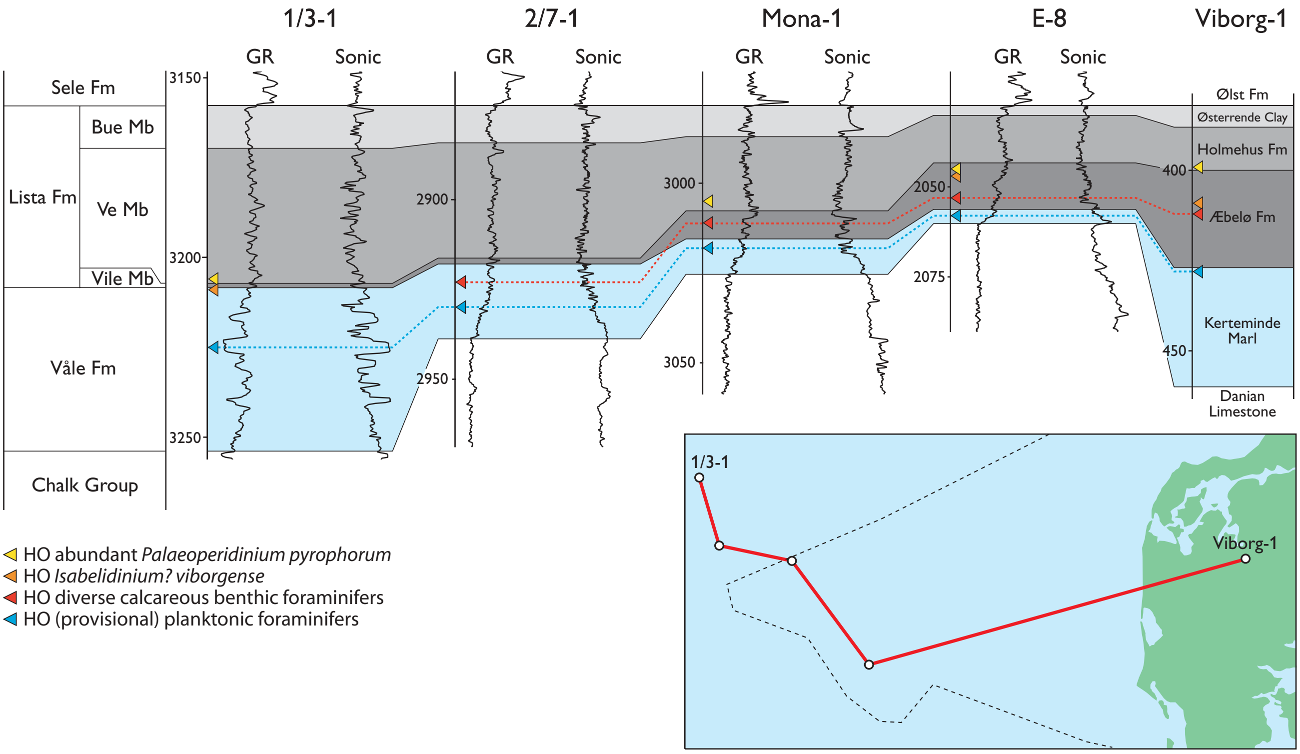


Fig. 25. Correlation diagram showing possible diachronism of the Våle–Vile boundary in an east–west transect extending into the Norwegian sector of the North Sea (1/3-1 and 2/7-1 are Norwegian sector wells). The distribution of biostratigraphic events shows that the Våle–Vile boundary youngs in a westerly direction (**HO**, highest occurrence). Alternatively, the event distribution could be explained as a result of reworking of older strata into the Lista Formation in the Danish sector. The figure also shows an example of a well (2/7-1) with a relatively large separation between the base of the Sele Formation and the lowest and most conspicuous gamma-ray peak in the formation (see text for further explanation).

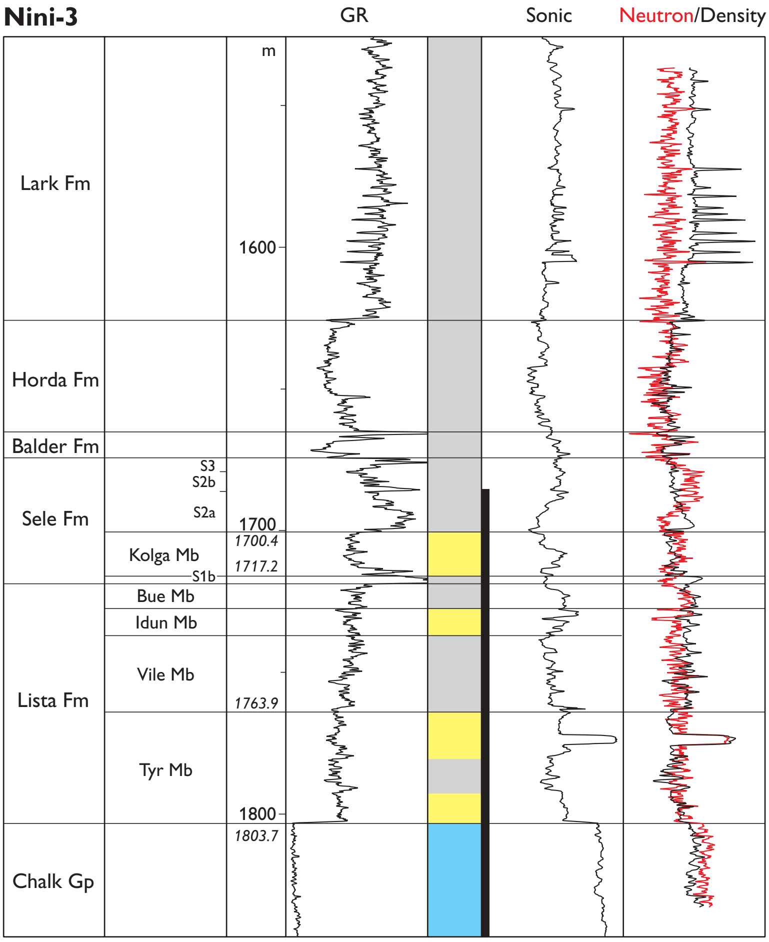


Fig. 26. Nini-3, type well for the Tyr Member and reference well for the Kolga Member. The figure shows the subdivision of the Sele Formation used by Knox & Holloway (1992); in this well, the Bue Member is equivalent to the S1a subunit of these authors. Black bar shows cored section.

Denmark: Æbelø Formation (informal mudstone unit described by Bøggild 1918 and Heilmann-Clausen 1995), Holmehus Formation (Heilmann-Clausen *et al.* 1985) and Østerrende Clay (informal mudstone unit described by Nielsen *et al.* 1986 and Heilmann-Clausen 1995).

Vile Member

new member

History. The Vile Member comprises the widespread, dark olive-grey to dark grey, non-calcareous, fissile mudstones that constitute the lower part of the Lista Formation. The unit was recognised by a stratigraphic working group at Statoil Norway in the mid-1990s and informally named the 'Vile Formation'.

Derivation of name. After Vile, the brother of Odin.

Type well. Danish sector well Siri-3, 2102.6–2072.8 m MBRT (Fig. 24; Plate 4).

Reference wells. Danish sector wells E-8, 2057.0–2044.0 m MDKB (Fig. 13); Cleo-1, 2812.0–2792.4 m MDKB (Fig. 21; Plate 1).

Distribution and thickness. The Vile Member has been recognised in a large number of North Sea wells, and the unit probably has a basinwide distribution. However, it is apparently lacking in the Siri Canyon wells Connie-1 and Siri-2 (Figs 29, 31), probably due to erosion. Its thickness varies between 0 and 30 m over most of the Danish sector. It greatest thickness is reached in the Siri Canyon.

Lithology. The member consists of dark olive-grey to dark grey, non-calcareous, swelling, smectitic, fissile mudstones (Fig. 23). Thin silicified layers occur in the member. Calcite is common and occurs as small nodules and larger concretions.

In the Siri Canyon, small pyrite concretions and less than 1 cm thick, silty, very fine-grained glaucony-rich sand- or siltstone laminae are locally present in the Vile Member. The laminae are parallel to the bedding of the mudstones; they have sharp bases and are normally grad-

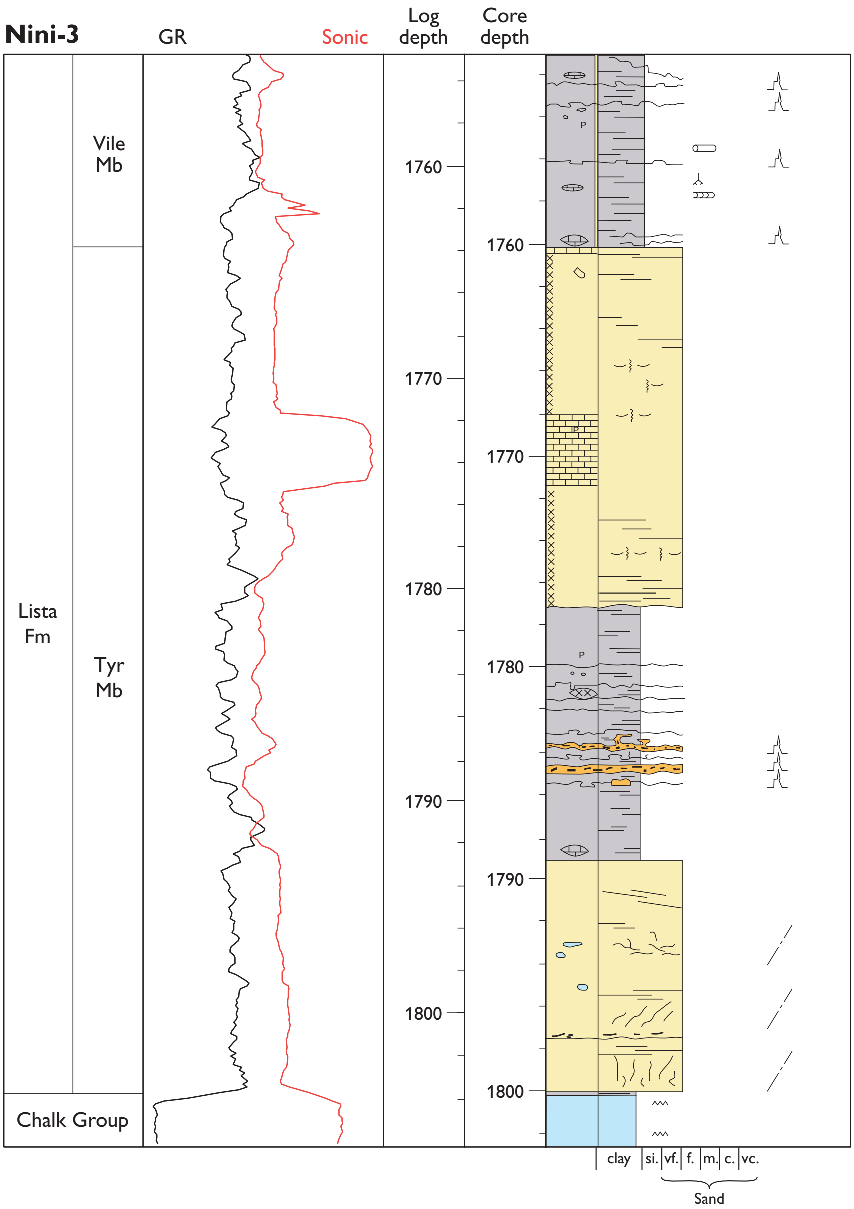


Fig. 27. Core log of the Tyr Member in the Nini-3 well. For legend, see Fig. 9.

ed. Thin concordant or discordant, postdepositional sandstone intrusions are locally present. In the lower part of the Vile Member, the intrusions are only a few millimetres thick, but they often increase in number and thickness towards the top of the member (Fig. 11).

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

Boundaries. The lower boundary of the Vile Member is that of the Lista Formation. The upper boundary is defined by the base of the Ve Member; boundaries with the sandstone-dominated Tyr Member are described under that member.

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

Microfossils and palynomorphs. The Vile Member is characterised by a general decrease in the diversity of benthic foraminifers and radiolaria from its base to its top. In the Danish sector, the transition from the underlying Våle Formation to the Vile Member is marked by the provisional HO of planktonic foraminifers. A conspicuous drop in diversity of benthic foraminifers takes place in the middle of the Vile Member. The HO of the dinoflagellate *Isabelidinium*? *viborgense* is an important intra-Vile marker located in the upper part of the member. Above it, a sudden decrease in the abundance of radiolaria further char-

Fig. 28. Core photographs of mudstones of the Vile and Ve Members in the Augusta-1 well. Depths are core depths. The boundary between the two members is placed where greenish and reddish grey mudstones become dominant, at 2910.4 m (arrow). This depth corresponds to log depth 2913.3 m on Fig. 17.

acterises a level within the uppermost part of the Vile Member. The transition from the Vile Member to the overlying Ve Member is marked by a conspicuous drop in the abundance of the dinoflagellate *Palaeoperidinium pyrophorum* (which has its HO at a slightly higher stratigraphic level, within the lower part of the Ve Member, see below).

Depositional environment. The mudstones of the Vile Member are hemipelagic deposits, whereas the thin sandstone and siltstone laminae are interpreted as the deposits of low-density turbidity currents. The presence of *Zoophycos* ispp. suggests depositional water depths of at least 200 m (Bottjer & Droser 1992).

Age. Selandian.

Correlation. The Vile Member corresponds to the Æbelø Formation, onshore Denmark (informal mudstone unit described by Bøggild 1918 and Heilmann-Clausen 1995). It corresponds to the Lista L1 subunit of Knox & Holloway (1992).

Biostratigraphic correlation with well sections in the Norwegian North Sea sector may indicate that the lower boundary of the Vile Member is diachronous (Fig. 25). In the type well for the Lista Formation (Norwegian well 2/7-1; Fig. 25), its base (i.e. its contact with the marlstones of the underlying Våle Formation) is above the HO of a diverse calcareous benthic foraminifer assemblage. In wells in the Danish sector, this event occurs within the Vile Member. Similarly, the provisional HO of planktonic foraminifers, an event that is close to the boundary between the Våle and Lista Formations in Denmark, is found well within the Våle Formation in well 2/7-1. In the type well for the Våle Formation (Norwegian well 1/3-1; Fig. 25), the HO of *I.*? *viborgense* coincides with the Våle–Lista boundary (I. Prince, unpublished biostratigraphic data). This event occurs above the Våle Formation in the Danish sector, in the middle to upper part of the Vile Member. In the Danish onshore well Viborg-1, the latter event and the HO of the diverse calcareous benthic foraminifer assemblage occur above the Kerteminde Marl in the upper part of the Æbelø Formation, a correlative of the Vile Member (Fig. 25; Heilmann-Clausen 1985). The distribution pattern of the biostratigraphic events indicates that sedimentation of marls continued in the Norwegian sector some time after marl sedimentation was replaced by sedimentation of non-calcareous mudstones in the Danish sector. Alternatively, calcareous foraminifer assemblages and associated lithologies have been reworked into higher levels of the Våle Formation or even into the Lista Formation in the Danish sector.

Tyr Member

new member

History. The Tyr Member consists of glaucony-rich, sandstone-dominated deposits that are laterally equivalent to, and commonly underlain and overlain by, mudstones of the Vile Member. These sandstones were previously recognised by a stratigraphic working group at Statoil Norway in the mid-1990s and informally referred to the Ty Formation of Hardt *et al.* (1989).

Derivation of name. After Tyr, the son of Odin.

Type well. Danish sector well Nini-3, 1803.7–1763.9 m MDRT (Figs 26, 27; Plate 4).

Reference well. Danish sector well Cecilie-1, 2276.6–2241.7 m MDRT (Figs 8, 19).

Distribution and thickness. The Tyr Member has only been encountered in the Siri Canyon and it may be restricted to that area. It reaches a thickness of up to 40 m (Fig. 20a).

Lithology. The Tyr Member is characterised by thick beds of olive-green to greenish grey, very fine-grained to fine-grained and well-sorted sandstone (Fig. 27). Rounded and translucent quartz grains dominate, but the content of glaucony grains is high (15–20%), hence the greenish colour of the sandstones. Mica and small pyrite concretions are present in small amounts throughout the member. Angular chalk and claystone clasts occur locally in the sandstones. The sandstones are partly calcite-cemented. Intrusive sandstones are common, particularly towards the top of the member where they may be several metres thick (Fig. 8). Subordinate interbedded dark grey non-calcareous mudstones resemble those of the laterally equivalent Vile Member.

Log characteristics. The Tyr Member is best identified on the density log where the sandstones are characterised by a conspicuously lower density than the associated mudstones. The sandstones may also be identified from a combination of the density and neutron logs, as the presence of pure sandstone results in a 'cross-over' of the two log curves (Figs 19, 26). The gamma-ray response resembles that of the underlying Våle Formation, but is slightly lower than the response of the Vile Member (Figs 8, 26). This log pattern makes it feasible to differentiate even minor sand units from mudstone beds in the Tyr Member. Thicker sand units may show decreasing- or increasing-upwards gamma-ray values. These trends do not seem to be related to grain-size variations, judging from core studies.

Boundaries. The boundaries to the mudstones of the Vile Member, the marlstones of the Våle Formation and the chalks of the Ekofisk Formation are sharp and characterised by prominent shifts in gamma, sonic and density log readings (Figs 19, 26, 27). In some wells, the Tyr Member overlies the Våle Formation or the Ekofisk Formation with an erosional contact (e.g. Nini-3; Figs 26, 27).

Depositional environment. Although the sandstones of the Tyr Member were deposited from highly concentrated gravity flows, their present appearance is dominated by the effects of postdepositional liquefaction and fluidisation.

Age. Selandian.

Correlation. The Tyr Member is contemporaneous with parts of the lithologically dissimilar Æbelø Formation in onshore Denmark and with the lower part of the Heimdal Formation of Deegan & Scull (1977) as well as the Andrew Sandstone and the Mey Sandstone Member of Knox & Holloway (1992) in the Norwegian and UK sectors of the southern Viking Graben. However, it is not contiguous with the latter three sandstone units and has a different source area.

Ve Member

new member

History. The Ve Member consists of variegated mudstones that have previously been recognised from North Sea wells as the Holmehus Formation by Heilmann-Clausen *et al.* (1985), who gave no further details, and by Danielsen & Thomsen (1997), who indicated its presence in several wells. The unit was also recognised by a stratigraphic working group at Statoil Norway in the mid-1990s and informally named the 'Ve Formation'.

Derivation of name. After Ve, the brother of Odin.

Type well. Danish sector well Augusta-1, 2913.3–2903.0 m MDRT (Fig. 17).

Reference wells. Danish sector wells E-8, 2044.0–2030.3 m MDKB (Fig. 13); Cleo-1, 2792.4–2777.6 m MDKB (Fig. 21; Plate 1).

Distribution and thickness. The sediments of the Ve Member have been recognised from a large number of North Sea wells, and the unit probably has an almost basinwide distribution. Its thickness varies from 0 to 21 m in the Danish sector.

Lithology. The Ve Member consists of mottled green, bluish green, reddish brown and brown mudstones (Fig. 28). 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 throughout the member. A weak biogenic lamination is sometimes observed in cores. Only very little organic material is present in the member. In the Siri Canyon, thin intrusive sandstones are common in the Ve Member.

Log characteristics. In general, the gamma-ray log shows a decreasing-upwards trend through the Ve Member, as opposed to the increasing trend through the underlying Vile Member. In the uppermost part of the Ve Member, the gamma-ray response increases over a short interval before reaching the base of the overlying Bue Member. The sonic log pattern throughout the Ve Member is smooth and relatively stable compared with the sonic pattern of the Vile Member. It also differs from the latter in having an increasing-upwards trend. The log pattern of the Ve Member differs from that of the overlying Bue Member in having a lower gamma-ray response level.

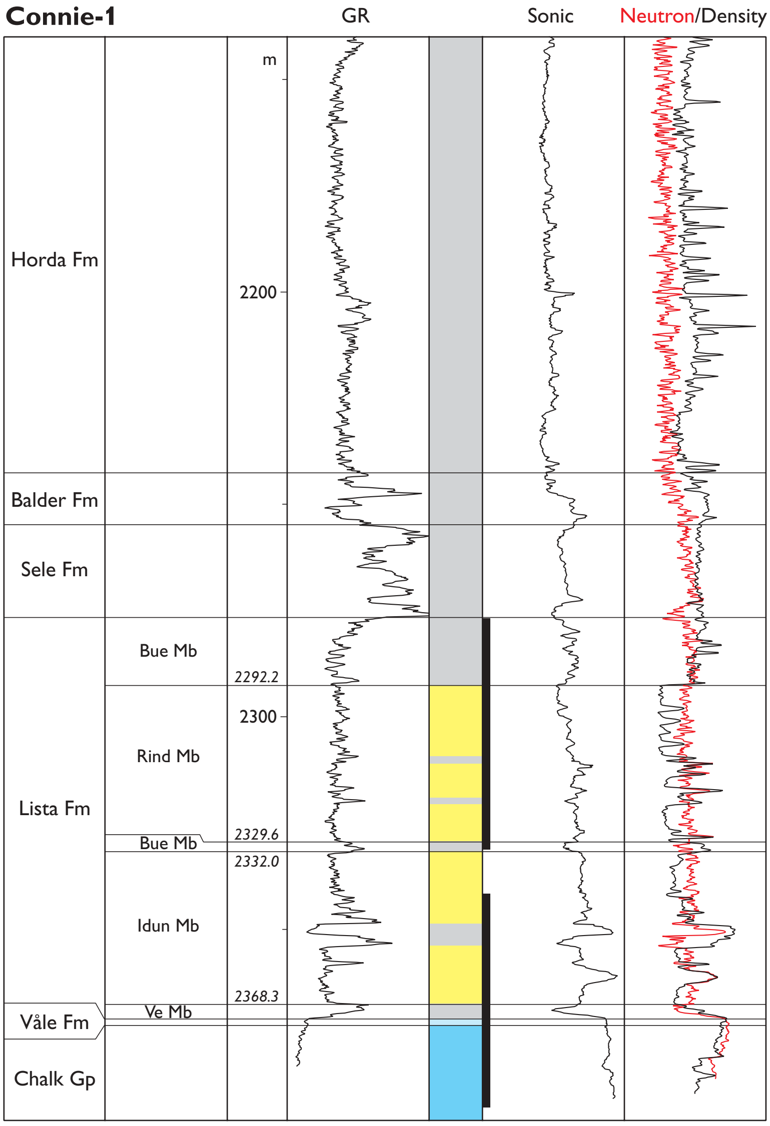
Boundaries. The lower boundary, with the Vile Member, is placed at the first appearance of greenish, bluish or reddish brown mudstones above the dark olive-grey to dark grey mudstones of the Vile Member. The colour change from Vile to Ve mudstones is often gradational and the boundary may be difficult to define precisely (Fig. 28), especially when only cuttings samples are available. However, in the colour transition interval, a gamma-ray spike separates an interval with an increasing-upwards gamma-ray trend below from an interval with a decreasing gamma-ray trend above (compare Figs 17 and 28). In the absence of a clear indication of the boundary level from sediment colour change, the gamma spike at the shift from increasing to decreasing gamma-ray values may be used as a marker for the boundary. The Vile Member is absent from the Connie-1 well, and in this well the lower contact of the Ve Member is with the marlstones of the Våle Formation (Fig. 31). The upper boundary is at the base of the Bue Member (see below). Boundaries with the Idun Member are described under that member.

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

Microfossils and palynomorphs. In the Danish sector of the North Sea, the HO of abundant *Palaeoperidinium pyrophorum* is located at or close to the Vile–Ve boundary. The HOs of *P. pyrophorum* and *Palaeocystodinium australinum* are in the lower part of the Ve Member. In general, the dinoflagellate assemblage from the upper part of the Ve Member is sparse and is characterised by specimens of *Areoligera gippingensis*. An acme of the latter species marks a level in the upper part of the Ve Member. The highest *in situ* occurrence of the dinoflagellate *Alisocysta margarita* is located close to the top of the Ve Member.

Depositional environment. Deposition of the mudstones of the Ve Member was controlled by hemipelagic sedimentation and sedimentation from dilute turbidites. The

Fig. 29. Connie-1, type well for the Idun and Rind Members. In this well, the Rind Member may be divided into three major sandstone intervals. The Idun Member consists of two thick sandstone intervals, separated by a thick mudstone unit. Black bars show cored sections.



occurrence of the trace fossil *Zoophycos* ispp. indicates a water depth of at least 200 m (Bottjer & Droser 1992). The overall high degree of bioturbation, the lack of organic material and the greenish, bluish and reddish brown colours together suggest oxygenated bottom conditions.

Age. Selandian–Thanetian. The Selandian–Thanetian boundary is placed at the HO of the dinoflagellate *Palaeoperidinium pyrophorum*, in the lower part of the Ve Member.

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

Idun Member

new member

History. The Idun Member consists of sandstone-dominated deposits that are laterally equivalent to, and commonly underlain by, mudstones of the Ve Member. This sandstone unit was previously recognised by a stratigraphic working group at Statoil Norway in the mid-1990s and was informally referred to the Heimdal Formation of Deegan & Scull (1977).

Derivation of name. After Idun, the goddess of youth.

Type well. Danish sector well Connie-1, 2368.3–2332.0 m MDRT (Figs 29, 30).

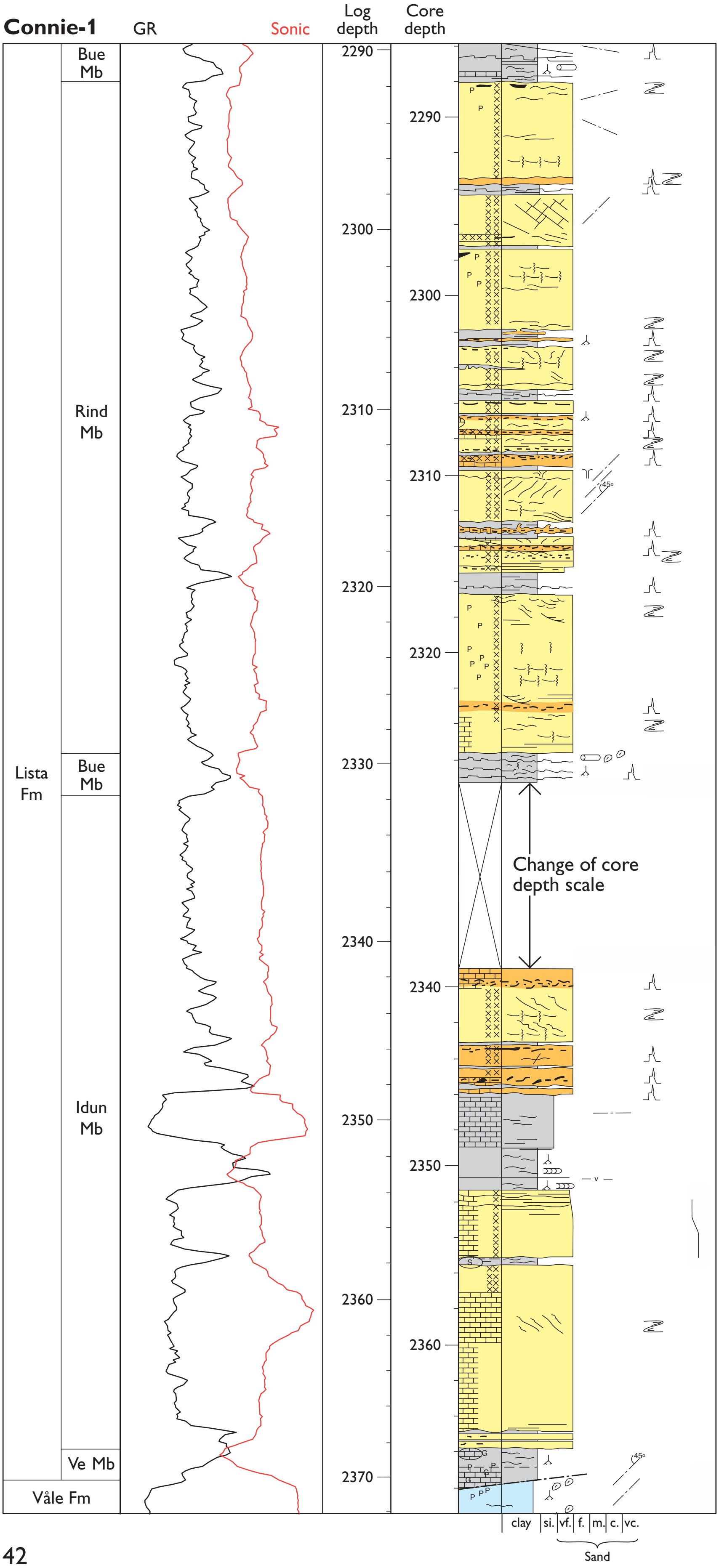
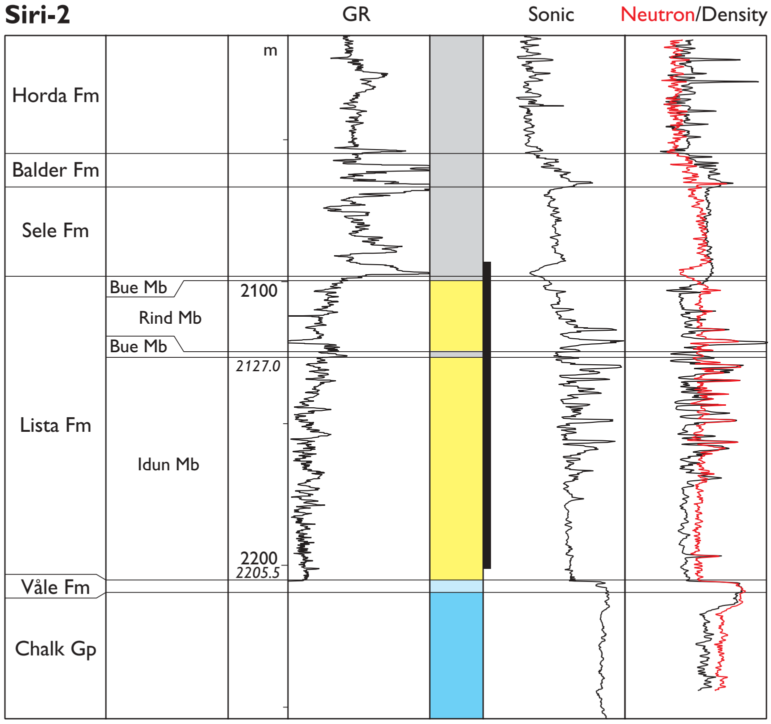


Fig. 30. Core log of the Idun and Rind Members in the Connie-1 well. For legend, see Fig. 9. Minor mudstone beds separate the three major sandstone intervals of the Rind Member. Minor mudstone layers are also intercalated with the Idun Member sandstone intervals. The core depth scale of the lower core is offset by *c.* 1.6 m relative to the scale of the upper core in the figure. For reasons of consistency with core data from this well, the original (albeit erroneous) core depths of the lower core are maintained in the figure. This does not affect the depths of the top and base of the Idun Member given in the text, as these are based on log depths.

Fig. 31. Siri-2, reference well for the Idun Member. Black bar shows cored section.



Reference well. Danish sector well Siri-2, 2205.5–2127.0 m MDRT (Fig. 31).

Distribution and thickness. The Idun Member is only known from the Siri Canyon, and it may be restricted to that area (Fig. 20b). It reaches a thickness of up to 179 m in the Siri-2 well.

Lithology. The Idun Member is dominated by very fine-grained to fine-grained, well-sorted sandstones (Fig. 30). Rounded and translucent quartz grains dominate, but the content of glaucony grains is high (15–25%). The sandstones are olive green to greenish grey due to the high content of glaucony. Mica and small pyrite concretions are present in small amounts. Angular chalk and claystone clasts occur locally. Intrusive sandstones are also represented (Figs 11, 12, 30). The sandstones and adjacent mudstones are partly calcite-cemented. In the Nini and Siri wells, the sandstones occur in thick amalgamated successions with only rare, thin mudstone interbeds; the latter are lithologically comparable to the laterally equivalent Ve Member mudstones (see above). In the Connie-1 well, however, the sand-rich succession is interrupted by a discrete 6 m thick mudstone unit (Fig. 30).

Log characteristics. The sandstone-dominated Idun Member is best identified on the density log where it is characterised by a conspicuously lower density than the underlying and overlying mudstones (Figs 29, 31). The sandstone component may also be identified 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 (Figs 29, 31). The Idun Member is characterised by a blocky, decreasing-upwards gamma-ray and density log pattern. Intervals with an overall constant gamma-ray pattern may be characterised by many small-scale increasing- or decreasing-upwards gamma-ray cycles.

Boundaries. In sections where the sandstones of the Idun Member are enveloped by mudstones of the Ve Member, the boundaries are sharp and characterised by prominent shifts on the gamma-ray, sonic and density logs (Figs 29, 30). Where the Ve Member is absent, comparable, sharp boundaries are observed with the mudstones of the Vile Member beneath and the Bue Member above (Figs 11, 26, 30). In the Siri-2 well, the lower Lista Formation is absent and an erosive unconformity separates the Idun Member sandstones from the marlstones of the Våle Formation (Fig. 31).

Depositional environment. Although the sandstones of the Idun Member were deposited from highly concentrated gravity flows, their present appearance largely records post-depositional liquefaction and fluidisation processes.

Age. Selandian–Thanetian.

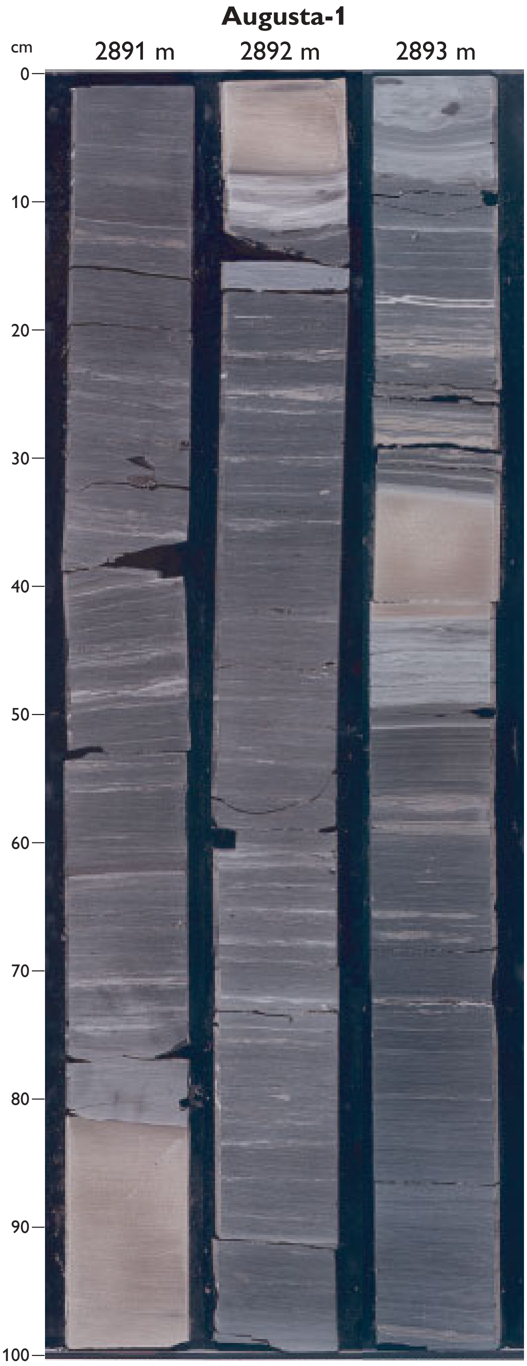


Fig. 32. Core photographs showing the Bue Member mudstones with numerous sandstone laminae in the Augusta-1 well. Depths are core depths.

Correlation. The Idun Member is contemporaneous with parts of the lithologically dissimilar Holmehus Formation onshore Denmark and with parts of the Heimdal Formation of Hardt *et al.* (1989) and the Lower Balmoral Sandstone and Tuffite of the Mey Sandstone Member of Knox & Holloway (1992). The Idun Member is not contiguous with these sandstone units, however, and has a different source area.

Bue Member

new member

History. The Bue Member encompasses the light to dark grey and greyish black mudstones that occur between the top of the Ve Member and the base of the Sele Formation. These mudstones have not previously been recognised as a separate unit in the Danish sector.

Derivation of name. After Bue, the son of Odin and Rind.

Type well. Danish sector well Augusta-1, 2903.0–2894.4 m MDRT (Fig. 17).

Reference wells. Danish sector wells E-8, 2030.3–2027.6 m below MDKB (Fig. 13); Cleo-1, 2777.6–2765.5 m MDKB (Fig. 21; Plate 1).

Distribution and thickness. The sediments of the Bue Member have been recognised from a large number of North Sea wells, and the unit probably has a basinwide 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. In the Siri Canyon, the upper part of the member sometimes contains laminae of very fine-grained to fine-grained sandstones or siltstones, mimicking the laminated mudstones of the overlying Sele Formation (Figs 32, 39). The laminae are less than 2 cm thick, have sharp bases, are normally graded and show parallel lamination. Concordant or discordant sandstone intrusions are locally present in the member (Fig. 8). Small calcite and siderite concretions are occasionally present. Moderately to intensely bioturbated intervals are interbedded with non-bioturbated intervals. Tuff layers may be present in the member.

Log characteristics. The gamma-ray response of the Bue Member is generally higher than that of the underlying Ve Member, but lower than that of the overlying Sele Formation. In some Siri Canyon wells, minor coarsening-upwards cycles are indicated by the gamma-ray log of the Bue Member.

Boundaries. The transition from typical lithologies of the Ve Member to those of the Bue Member is often gradational and the boundary may therefore be difficult to position precisely. It is placed where mottled green, bluish green, reddish brown and brown mudstones pass upwards into grey mudstones with sandstone and siltstone laminae. On the petrophysical logs, this transition is reflected by a shift from decreasing- to increasing-upwards gamma-ray values or at an abrupt increase in the gamma-ray response. The upper boundary of the Bue Member is at the base of the Sele Formation.

Macro- and ichnofossils. Trace fossils recognised in the Bue Member are *Phycosiphon* ispp., *Planolites* ispp., *Thalassinoides* ispp. and rare *Zoophycos* ispp.

Microfossils and palynomorphs. The Ve–Bue boundary is bracketed by the stratigraphic succession of the HO of *in situ Alisocysta margarita* (occurring in the upper Ve Member) followed by the HO of an impoverished assemblage of benthic agglutinated foraminifers (in the lower part of the Bue Member). The upper part of the Bue Member is characterised by common spores and pollen, in particular bisaccate pollen and *Inaperturopollenites* spp. The Bue–Sele boundary is marked by the base of an acme of the dinoflagellate genus *Apectodinium* and the LO of *Apectodinium augustum*.

Depositional environment. The normally graded sandstone to siltstone laminae in the upper part of the member indicate that deposition of the Bue Member took place from dilute, low-density, turbidity currents in a generally sediment-starved environment at this level. The minor coarsening-upwards cycles observed on petrophysical logs from some Siri Canyon wells probably indicate either small distal lobes of deep-water channel-sandstones or levee deposits.

Age. Thanetian.

Correlation. The Bue Member corresponds to the Østerrende Clay (informal mudstone unit described by Nielsen *et al.* 1986 and Heilmann-Clausen 1995) onshore Denmark. The level here defined as the boundary between the Ve and the Bue Members was correlated by Knox (1997 fig. 3; the Lista–Sele boundary of this worker) with the boundary between the Holmehus Formation and the Østerrende Clay (as 'Grey Clay') onshore Denmark. The Bue Member further correlates with the lower part of the S1a subunit of the Sele Formation established by Knox & Holloway (1992; see correlation section under the Lista Formation for further details).

Rind Member

new member

History. The Rind Member consists of sandstone-dominated deposits that are laterally equivalent to, and commonly underlain and overlain by, mudstones of the Bue Member. Sandstone bodies at this stratigraphic level were previously recognised by a stratigraphic working group at Statoil Norway in the mid-1990s and were informally referred to the Heimdal Formation of Deegan & Scull (1977).

Derivation of name. After the giantess Rind.

Type well. Danish sector well Connie-1, 2329.6–2292.2 m MDRT (Figs 29, 30).

Reference well. Danish sector well Sandra-1, 2066.3–2004.8 m MDRT (Fig. 33).

Distribution and thickness. The Rind Member has only been encountered in the Siri Canyon, and it may be restricted to that area where it reaches a thickness of 62 m (Fig. 20c).

Lithology. The Rind Member consists of very fine-grained, well-sorted sandstones interbedded with thin mudstone beds that typically form less than 15% of the member (Fig. 30). Rounded and translucent quartz grains dominate in the sandstones, but the content of glaucony grains in the very fine-grained to fine-grained size fraction is high (15–25%). The sandstones are olive green to greenish grey due to the high content of glaucony. Mica and small pyrite concretions are present in small amounts. Angular chalk and claystone clasts occur locally in the sandstones, which are partly calcite-cemented. The interbedded mudstones are lithologically comparable to the Bue Member mudstones (see above).

Log characteristics. The Rind Member is best recognised on the density log where it shows either a blocky or a serrate pattern created by the alternation of sandstone beds or amalgamated units (low density) with thin mudstone beds (high density; Figs 29, 33). The sandstones may also be identified from a combination of the density and neutron logs, since the presence of pure sandstones results in a 'cross-over' of the two log curves (Figs 29, 33). The gamma-ray log shows a low-amplitude serrate pattern. This pattern does not reflect alternating sand or mudstones, judging from core inspection.

Boundaries. The boundary between the sandstones of the Rind Member and the mudstones of the Bue Member is

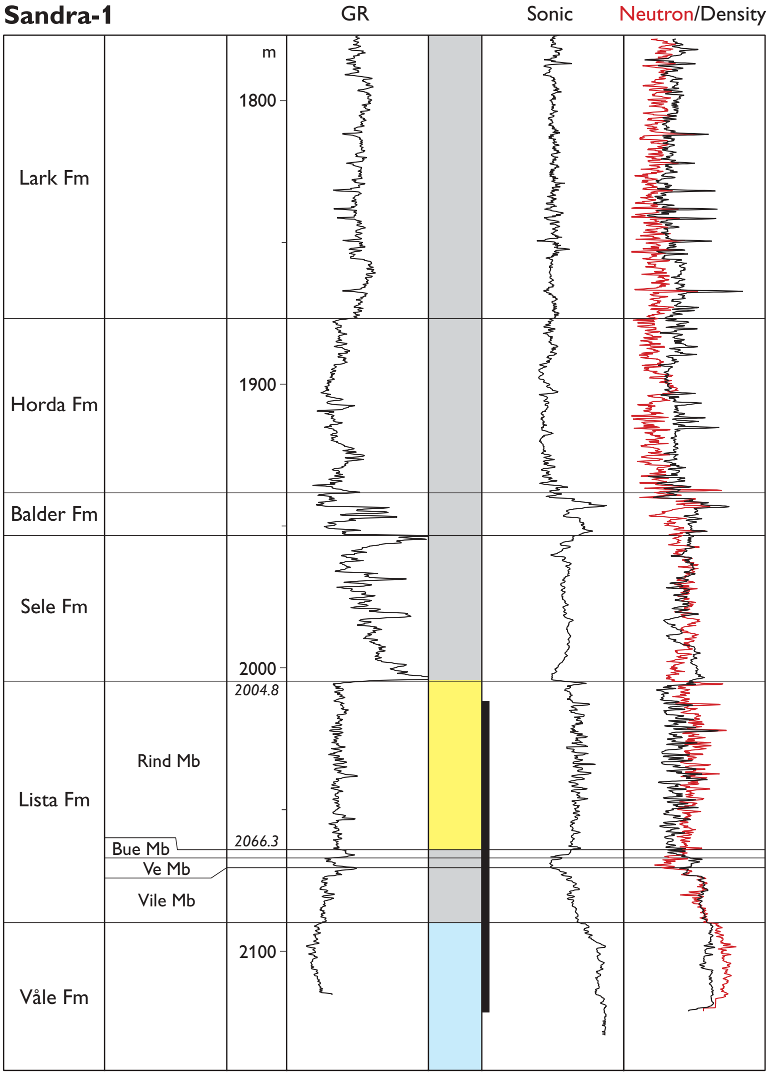


Fig. 33. Sandra-1, reference well for the Rind Member. Black bar shows cored section.

sharp and characterised by prominent shifts on both the sonic and density logs (Figs 29, 33). It is often difficult to identify the boundaries on the gamma-ray log alone.

Depositional environment. Although the sandstones of the Rind Member were deposited from highly concentrated gravity flows, their present appearance largely records post-depositional liquefaction and fluidisation processes.

Age. Thanetian.

Correlation. The Rind Member may be contemporaneous with parts of the lithologically dissimilar Østerrende Clay encountered in the Storebælt region (Fig. 1), with sandstones in the higher parts of the Heimdal Formation (Hardt *et al.* 1989) and with the Upper Balmoral Sandstone of the Mey Sandstone Member of Knox & Holloway (1992). However, the Rind Member is not contiguous with those sandstone units and has a different source area.

Sele Formation

History. The Sele Formation was established by Deegan & 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 definition 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 & Scull 1977; see Boundaries section under the Lista Formation for further details). Sandstones occur in the Sele Formation in the Danish sector; these are established as a new member, the Kolga Member.

Type well. British sector well 21/10-1, 2131–2100 m MDKB.