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Supplement

STRATIGRAPHIC GUIDE TO THE ROGALAND GROUP, NORWEGIAN NORTH SEA

Harald Brunstad, Felix Gradstein, Jan Erik Lie, Øyvind Hammer, Dirk Munsterman, Gabi Ogg and Michelle Hollerbach

- Balder Formation
  - Odin Member
  - Radøy Member
- Sele Formation
  - Forties Member
  - Hermod Member
  - Fiskebank Member
  - Sula Member
- Sele/Lista Formations
  - Vidar Member
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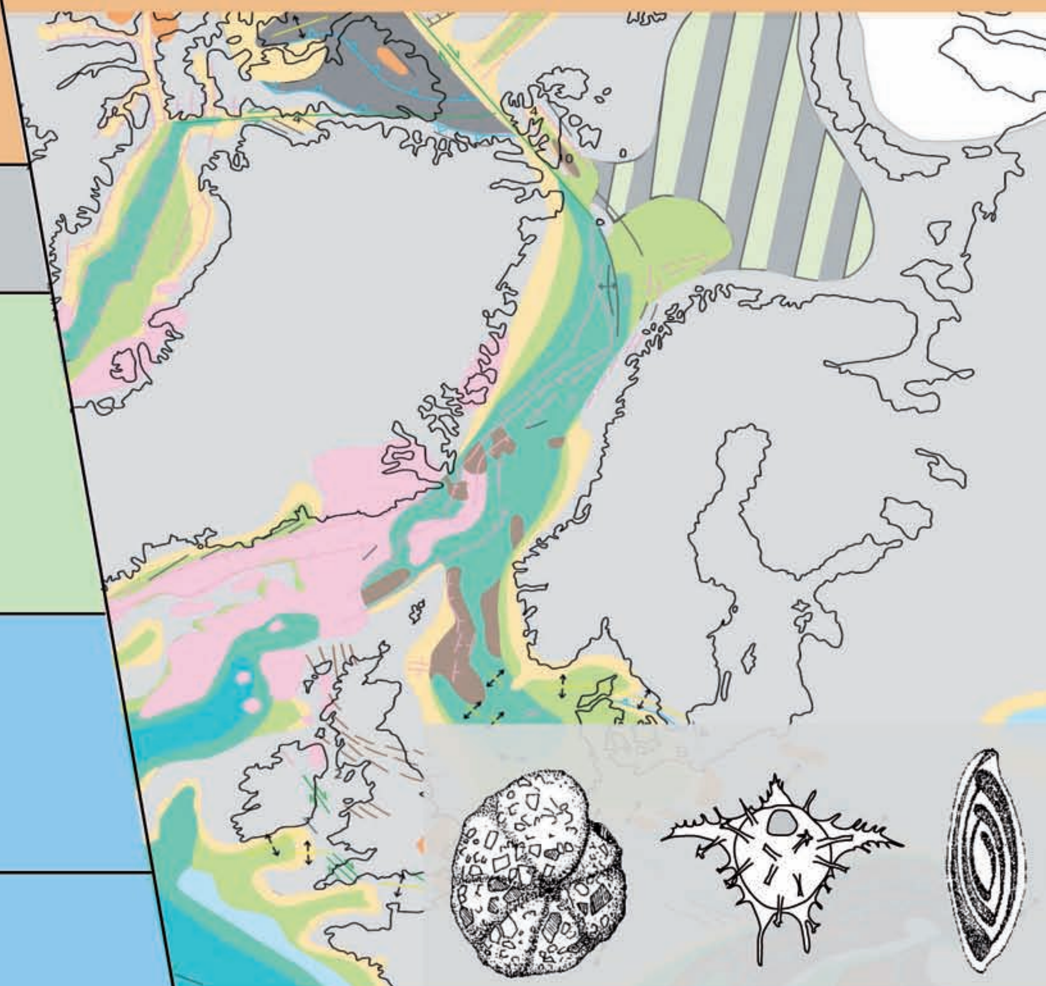
  - Mey Member
  - Heimdal Member
  - Sotra Member
  - Siri Member
- Våle Formation
  - Borr Member
  - Ty Member
  - Maureen Member
- Våle/Tang Formation
  - Egga Member



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Stratigraphic Guide to the Rogaland Group, Norwegian North Sea

Harald Brunstad[1], Felix Gradstein[2], Jan Erik Lie[1], Øyvind Hammer[2], Dirk Munsterman[3], Gabi Ogg[4], and Michelle Hollerbach[5]

With 152 figures and 3 tables

Abstract. This guide provides a major revision and update of the lithostratigraphy of the Rogaland Group for the Norwegian North Sea. An abundance of recent well and seismic data sheds new light on lithology, biostratigraphy, provenance, geographic distribution and terminology of all Rogaland rock units, used widely in the search for oil and gas.
While finer siliciclastic units largely remain as previously defined, previous sandstone/siltstone formations and one (reworked) chalky unit are now re-defined. These lithostratigraphic units are local sediment bodies of a lithology different from the surrounding and embracing formation. Hence, these lithostratigraphic units are members in the formal stratigraphical hierarchy. With the new definitions and re-definitions the Rogaland Group now consists of four formations and 15 members, which span the stratigraphic interval from lower Paleocene to lower Eocene.
The revisions concerning the sandstone bodies are of four different types:
– Re-definition from formations to members
– Re-definition of lithological criteria
– Introduction of members long used already offshore England and Denmark
– Definition of new members

For those practicing geologists not familiar with historic precedence, an important 'sine qua non' in (litho-) stratigraphy, it should be pointed out that 8 out of 15 members discussed here have been predefined in literature dealing with the UK and Danish sectors of the North Sea. The present study thus updates the Norwegian lithostratigraphic bulletins of the nineteen eighties for its offshore area. The internet site *www.nhm2.uio.no/norlex* provides an interactive digital version of this study, with links to well data, biozonations and core archives relevant to the Rogaland Group.

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Contents

Geological setting of the Rogaland Group, Norwegian North Sea

General setting

Paleocene to lowermost Eocene strata are extensively distributed throughout the whole of the North Sea Basin, and provide one of the most prolific hydrocarbons plays in the Norwegian North Sea. Hydrocarbons were first discovered in strata belonging to this age in 1967 at the Balder Field (Figure 1) in the Norwegian sector of the North Sea, while the first discovery in the UK, the Arbroath Field was in 1969. In the Danish sector, the Siri Field discovery was made in 1996 (Ahmadi et al. 2003).

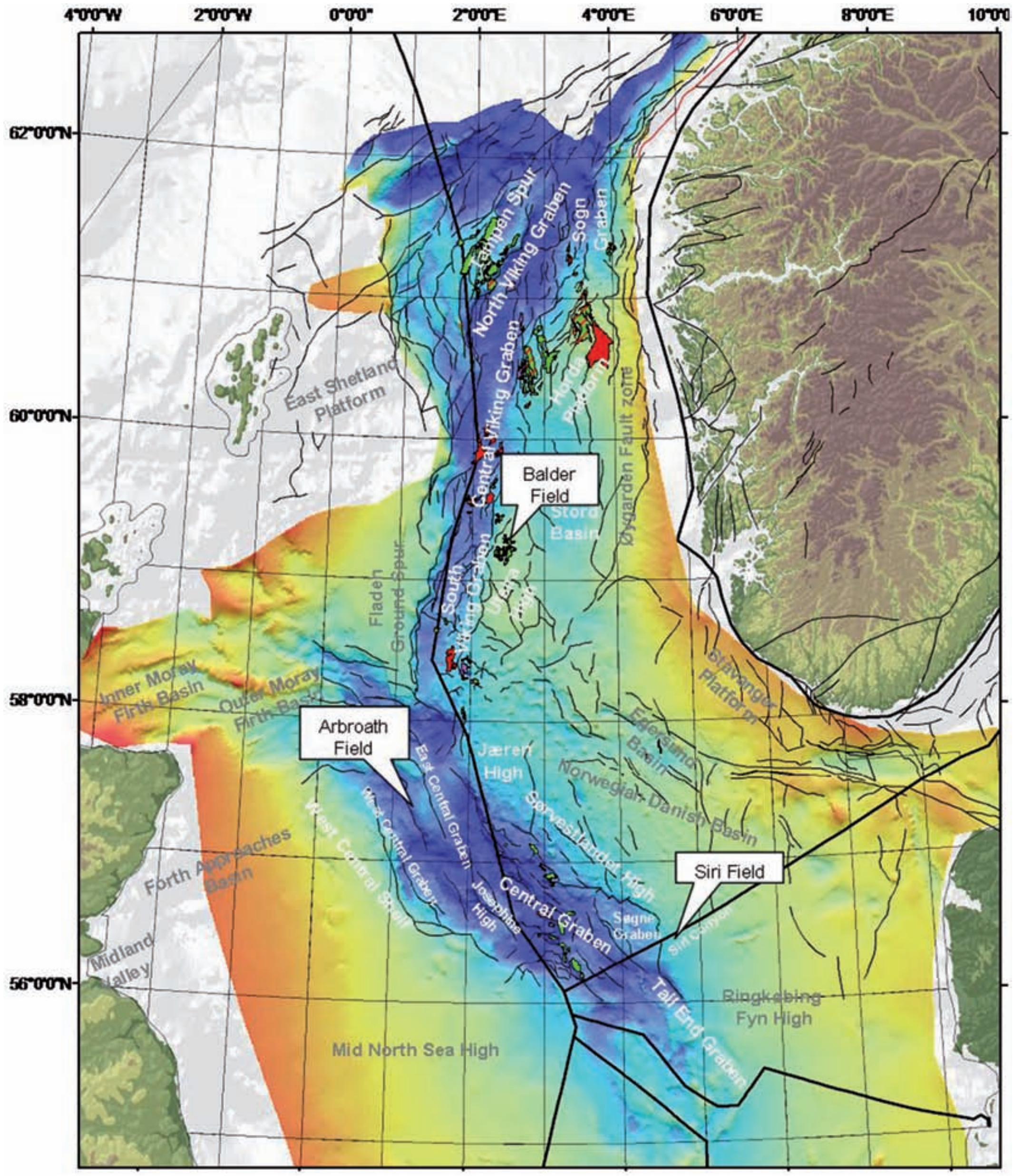


Fig. 1. Structural elements of the Norwegian North Sea at BCU level, with the first Paleogene hydrocarbon discoveries in Norway (Balder Field, 1967), UK (Arbroath Field, 1969) and Denmark (Siri Field, 1996) outlined.

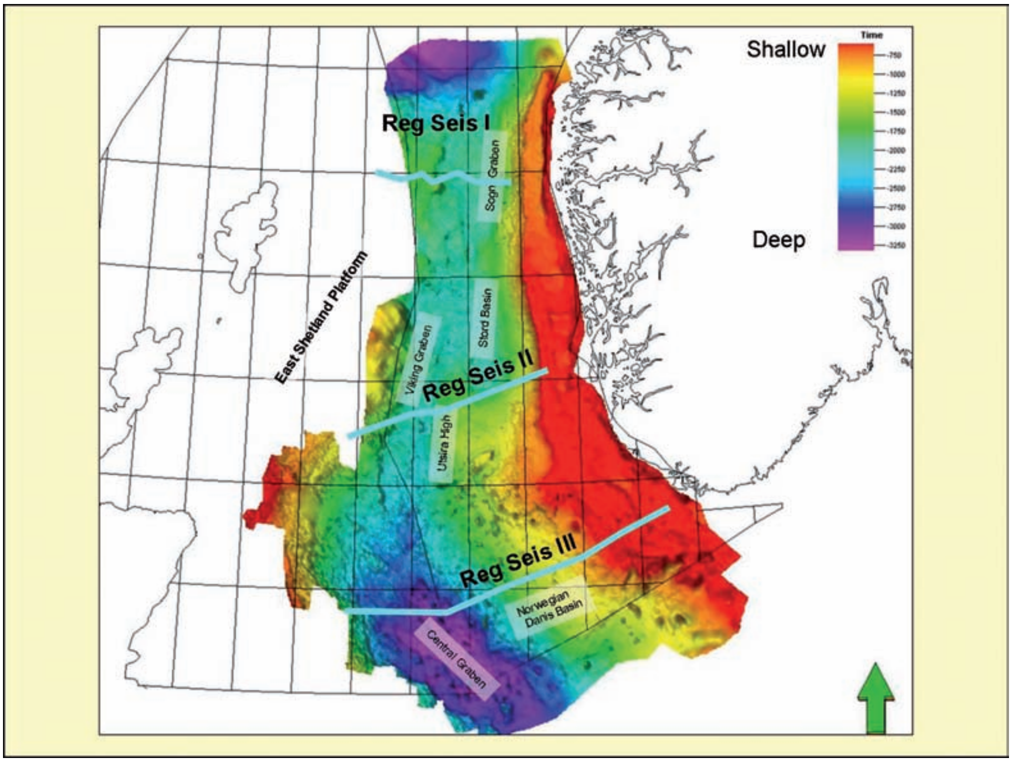


Fig. 2. Seismic time map of the Base Rogaland Group (Top Shetland Group) seismic horizon. Orientation of regional seismic lines I–III are shown as blue lines.

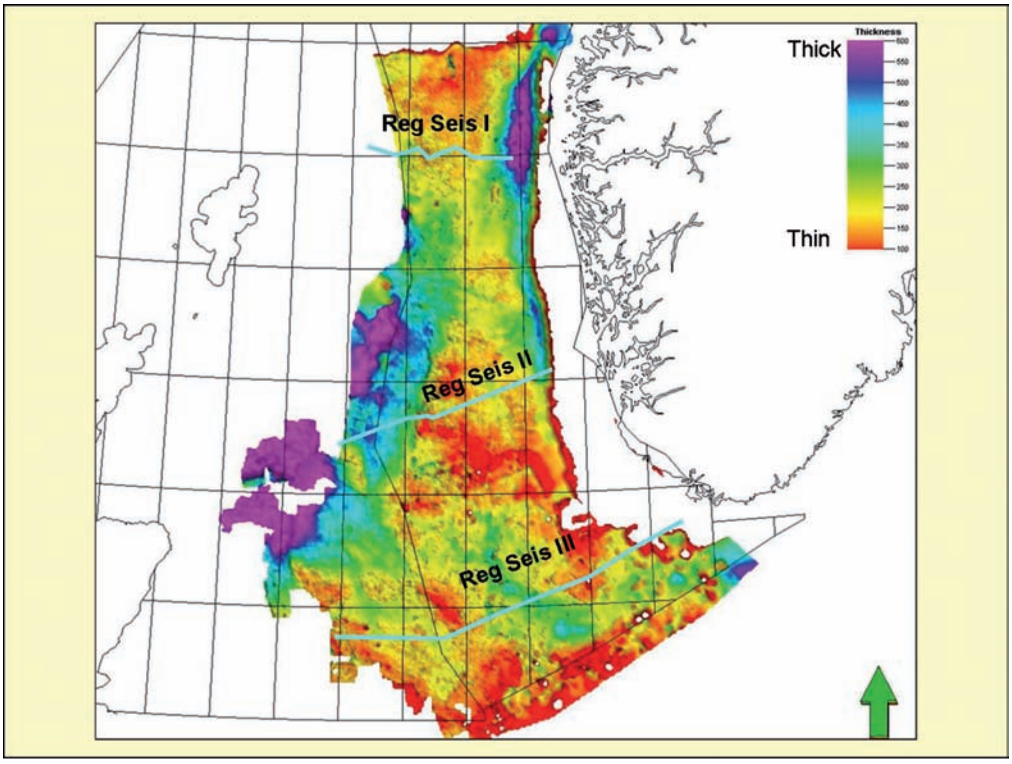


Fig. 3. Seismic time thickness map (TWT) of the Rogaland Group (Top Balder Formation to Top Shetland Group). Outlined regional seismic lines I–III are shown in Figures 16–18.

Paleocene to lowermost Eocene deposits in the central and northern North Sea occur from close below the sea bed to more than 3000 m deep, and reach a thickness of approximately 1000 m in the Outer Moray Firth. Figure 2 shows a time-depth map and areas of shallow and deep burial, whereas the time-thickness map in Figure 3 shows the thickness distribution of the Rogaland Group.

Improvements in seismic acquisition and processing quality, and the application of high resolution biostratigraphy, have caused a sustained economic interest in this stratigraphic interval. Although play models have existed for a long time, discoveries are still being made, exemplified by the 16/4-4 and the Storskrymten discoveries made in 2007.

The Rogaland Group comprises the most sand-prone interval of the Paleogene (Liu and Galloway 1997, Ahmadi et al. 2003). The preserved strata in the North Sea consist of siliciclastic deposits with volumetrically minor amounts of coal, tuff, volcanoclastic rocks, marls and reworked carbonate sediments. The Scotland–Shetland hinterland was the primary source for the great volume of siliciclastic deposits (Morton et al. 1993, Ahmadi et al. 2003), but Fennoscandia also acted as a provenance area.

During the Early Paleogene, basin architecture evolved from basin-centered to basin margin deposition as Atlantic and European tectonic events, oceanographic trends, eustasy, differential tilting and subsidence, climate and variable sediment supply all combined to influence the depositional systems (Milton et al. 1990, Ziegler 1990).

Lithofacies distribution within individual depositional systems was controlled by the combined effects of evolving basin physiography, underlying Mesozoic structures, syn-depositional tectonics and halokinesis (Ahmadi et al. 2003).

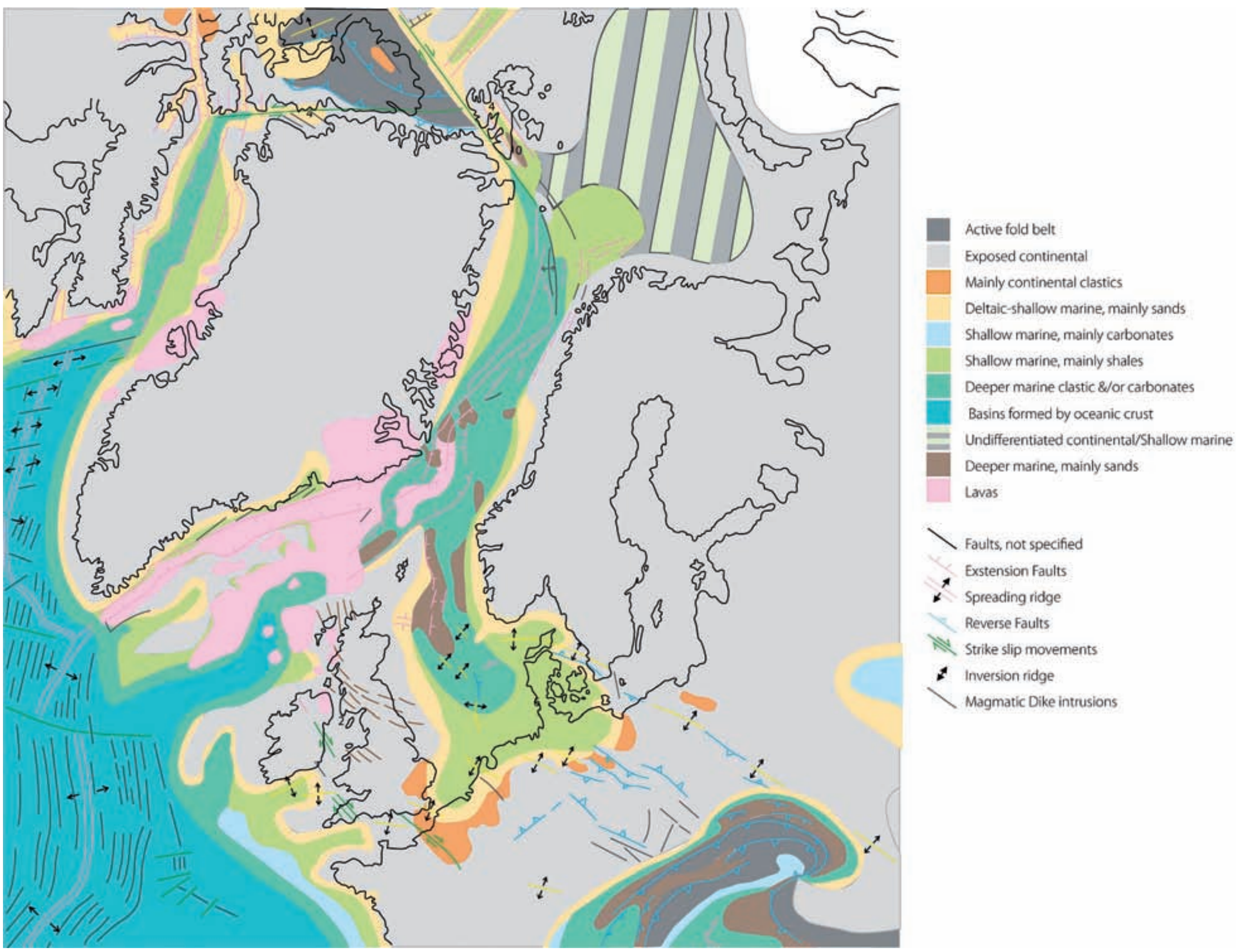


Fig. 4. Global reconstruction of North West Europe in late Thanetian, the period of maximum basin restriction of the Early Paleogene. Modified after Ziegler (1988), Torsvik et al. (2002) and Coward et al. (2003).

Tectonic activity at this time was related to the development of the Iceland Mantle Plume, which caused regional uplift and gradual enclosing and isolation of the North Sea basin from the Atlantic Ocean (Figure 4). Adjacent to the North Sea, the Scottish Highlands and the East Shetland Platform were uplifted, while Western Fennoscandia underwent less uplift. Further stresses along the line of the future Norwegian Sea led to major volcanic activity in that region, which is represented in the sedimentary stratigraphy as tuffs. The seismic time thickness map in Figure 3 clearly demonstrates the development of thick Paleocene–lowermost Eocene deposits.

Transformation of the North Sea and the Proto-Norwegian Sea from a semi-enclosed to enclosed basin system

Basin configuration and compartmentalization

From latest Thanetian to early Ypresian time a land bridge (the Thulean Land Bridge) connected Spitsbergen to Greenland, in the area between Scotland and Greenland. No sea-way connection existed here during that period (Figure 4). The Thulean Land Bridge in the area of the Wyville Thompson Ridge was generated by stacked basalt lavas along the volcanic active zone of the Paleocene transient rift that extended from Scotland to West Greenland through the Greenland–Faroe Ridge (Lundin and Doré 2005).

In the southern and central parts of the Norwegian North Sea the late Thanetian to early Ypresian part of the Rogaland Group is composed of dark laminated shales with high gamma-ray readings that were deposited under dysaerobic or anoxic bottom water conditions. In the northernmost North Sea the same stratigraphic interval is less laminated, has lower gamma ray readings, is more bioturbated, and seems to have been deposited under more oxic conditions. This change from restricted deep marine environments in central and southern areas to better oxygenated bottom waters in northern areas suggest that the North Sea Basin was compartmented into sub-basins of variable connectivity, separated by basinal highs.

Most prominent highs in the Norwegian North Sea were the Sørvestlandet High, the Utsira High and the Tampen Spur. From seismic time isopach maps of the Rogaland Group, NW-SE lineaments are observed crossing the Viking Graben and Sogn Graben. Many of these lineaments probably were controlled by syn-sedimentary fault activity, possibly influenced by long-reaching transform faults related to rifting and continental break-up in the Proto-Norwegian Sea region. Local highs seem to have developed along several of these lineaments, and could have acted as local barriers in the basin.

From several publications (Tsikalas et al. 2005, Brekke et al. 2001) it can be inferred also that the rather narrow Proto-Norwegian Sea was compartmented into sub basins separated by basinal highs. Tsikalas et al. (2005) illustrate the presence of several basinal highs and ridges; such highs were present along the uplifted basinal rift axis, transform-related elements as the Jan Mayen Bivrost Zones and transfer systems, as well as the Jan Mayen micro continent and other smaller rift-related horst features. Hence the Proto-Norwegian Sea had a variable basin physiography and a variable interconnectivity between the individual sub-basins that existed through Late Paleocene to Early Eocene time. Some of these sub basins may also have undergone basin restriction during this interval. Several studies indicate that large westerly trending ridge systems existed west of Lofoten (Utrøst High to Vøring Marginal High) (e.g., Larsen et al. 1999, Brekke et al. 2001, Kjennerud and Vergara 2005). As a consequence, the Proto-Norwegian Sea was separated into a southern and a northern basin. It is uncertain whether this ridge system or any of the other basinal high systems developed into land bridges in a manner comparable to the Thulean Land Bridge at the Wyville Thompson Ridge.

The chain of basins from the North Sea into the Proto-Norwegian Sea ended south of Spitsbergen and west of the Loppa High. This isolation to the north was caused by the transpressional orogeny in the area between North East Greenland and Spitsbergen and by a wide general uplift of the Central and South Western Barents Sea. This would imply that a land bridge existed between Eurasia and Greenland via a Barents Sea connection.

Hence, during Thanetian–Early Ypresian, the oceanic connection of the Norwegian Sea and the North Sea became fully controlled by the London–Brabant passage to the Atlantic Ocean. However, since the London–Brabant area was uplifted due to inversion tectonic and thereby at least periodically an area of terrestrial deposition, the North Sea Basin may at least periodically have been fully isolated from the Atlantic Ocean.

Carboniferous through Cenozoic segment of Geologic Time Scale 2012

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma	GSSP
Phanerozoic	Cenozoic	Quaternary	Holocene		0.0118	GSSP
Phanerozoic	Cenozoic	Quaternary	Pleistocene	Upper	0.126	
Phanerozoic	Cenozoic	Quaternary	Pleistocene	"Ionian"	0.781	
Phanerozoic	Cenozoic	Quaternary	Pleistocene	Calabrian	1.806	GSSP
Phanerozoic	Cenozoic	Quaternary	Pleistocene	Gelasian	2.588	GSSP
Phanerozoic	Cenozoic	Neogene	Pliocene	Piacenzian	3.600	GSSP
Phanerozoic	Cenozoic	Neogene	Pliocene	Zanclean	5.333	GSSP
Phanerozoic	Cenozoic	Neogene	Miocene	Messinian	7.246	GSSP
Phanerozoic	Cenozoic	Neogene	Miocene	Tortonian	11.63	GSSP
Phanerozoic	Cenozoic	Neogene	Miocene	Serravallian	13.82	GSSP
Phanerozoic	Cenozoic	Neogene	Miocene	Langhian	15.97	
Phanerozoic	Cenozoic	Neogene	Miocene	Burdigalian	20.44	
Phanerozoic	Cenozoic	Neogene	Miocene	Aquitanian	23.03	GSSP
Phanerozoic	Cenozoic	Paleogene	Oligocene	Chattian	28.1	
Phanerozoic	Cenozoic	Paleogene	Oligocene	Rupelian	33.9	GSSP
Phanerozoic	Cenozoic	Paleogene	Eocene	Priabonian	37.8 ±0.5	
Phanerozoic	Cenozoic	Paleogene	Eocene	Bartonian	41.2 ±0.5	
Phanerozoic	Cenozoic	Paleogene	Eocene	Lutetian	47.8 ±0.2	GSSP
Phanerozoic	Cenozoic	Paleogene	Eocene	Ypresian	56.0	GSSP
Phanerozoic	Cenozoic	Paleogene	Paleocene	Thanetian	59.2	GSSP
Phanerozoic	Cenozoic	Paleogene	Paleocene	Selandian	61.6	GSSP
Phanerozoic	Cenozoic	Paleogene	Paleocene	Danian	66.0 ±0.05	GSSP
Phanerozoic	Mesozoic	Cretaceous	Upper	Maastrichtian	72.1 ±0.2	GSSP
Phanerozoic	Mesozoic	Cretaceous	Upper	Campanian	83.6 ±0.2	
Phanerozoic	Mesozoic	Cretaceous	Upper	Santonian	86.3 ±0.5	
Phanerozoic	Mesozoic	Cretaceous	Upper	Coniacian	89.8±0.3	
Phanerozoic	Mesozoic	Cretaceous	Upper	Turonian	93.9 ±0.2	GSSP
Phanerozoic	Mesozoic	Cretaceous	Upper	Cenomanian	100.5 ±0.4	GSSP
Phanerozoic	Mesozoic	Cretaceous	Lower	Albian	113.0 ±0.4	
Phanerozoic	Mesozoic	Cretaceous	Lower	Aptian	126.3 ±0.4	
Phanerozoic	Mesozoic	Cretaceous	Lower	Barremian	130.8 ±0.5	
Phanerozoic	Mesozoic	Cretaceous	Lower	Hauterivian	133.9±0.6	
Phanerozoic	Mesozoic	Cretaceous	Lower	Valanginian	139.4 ±0.7	
Phanerozoic	Mesozoic	Cretaceous	Lower	Berriasian	145.0 ±0.8	

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma	GSSP
					145.0 ±0.8	
Phanerozoic	Mesozoic	Jurassic	Upper	Tithonian	152.1 ±0.9	
Phanerozoic	Mesozoic	Jurassic	Upper	Kimmeridgian	157.3±1.0	
Phanerozoic	Mesozoic	Jurassic	Upper	Oxfordian	163.5 ±1.1	
Phanerozoic	Mesozoic	Jurassic	Middle	Callovian	166.1 ±1.2	
Phanerozoic	Mesozoic	Jurassic	Middle	Bathonian	168.3 ±1.3	GSSP
Phanerozoic	Mesozoic	Jurassic	Middle	Bajocian	170.3 ±1.4	GSSP
Phanerozoic	Mesozoic	Jurassic	Middle	Aalenian	174.1 ±1.0	GSSP
Phanerozoic	Mesozoic	Jurassic	Lower	Toarcian	182.7 ±0.7	
Phanerozoic	Mesozoic	Jurassic	Lower	Pliensbachian	190.8 ±1.0	GSSP
Phanerozoic	Mesozoic	Jurassic	Lower	Sinemurian	199.3 ±0.3	GSSP
Phanerozoic	Mesozoic	Jurassic	Lower	Hettangian	201.3 ±0.2	GSSP
Phanerozoic	Mesozoic	Triassic	Upper	Rhaetian	~ 209.5	
Phanerozoic	Mesozoic	Triassic	Upper	Norian	~ 228.4	
Phanerozoic	Mesozoic	Triassic	Upper	Carnian	237.0±1.0	GSSP
Phanerozoic	Mesozoic	Triassic	Middle	Ladinian	241.5 ±1.0	GSSP
Phanerozoic	Mesozoic	Triassic	Middle	Anisian	247.1±0.2	
Phanerozoic	Mesozoic	Triassic	Lower	Olenekian	250.0±0.5	
Phanerozoic	Mesozoic	Triassic	Lower	Induan	252.2 ±0.5	GSSP
Phanerozoic	Paleozoic	Permian	Lopingian	Changhsingian	254.2 ±0.3	GSSP
Phanerozoic	Paleozoic	Permian	Lopingian	Wuchiapingian	259.8 ±0.4	GSSP
Phanerozoic	Paleozoic	Permian	Guadalupian	Capitanian	265.1 ±0.4	GSSP
Phanerozoic	Paleozoic	Permian	Guadalupian	Wordian	268.8 ±0.5	GSSP
Phanerozoic	Paleozoic	Permian	Guadalupian	Roadian	272.3 ±0.5	GSSP
Phanerozoic	Paleozoic	Permian	Cisuralian	Kungurian	279.3 ±0.6	
Phanerozoic	Paleozoic	Permian	Cisuralian	Artinskian	290.1 ±0.2	
Phanerozoic	Paleozoic	Permian	Cisuralian	Sakmarian	295.5 ±0.4	
Phanerozoic	Paleozoic	Permian	Cisuralian	Asselian	298.9 ±0.2	GSSP
Phanerozoic	Paleozoic	Carboniferous – Pennsylvanian	Upper	Gzhelian	303.7 ±0.1	
Phanerozoic	Paleozoic	Carboniferous – Pennsylvanian	Upper	Kasimovian	307.0 ±0.2	
Phanerozoic	Paleozoic	Carboniferous – Pennsylvanian	Middle	Moscovian	315.2 ±0.2	
Phanerozoic	Paleozoic	Carboniferous – Pennsylvanian	Lower	Bashkirian	323.2 ±0.4	GSSP
Phanerozoic	Paleozoic	Carboniferous – Mississippian	Upper	Serpukhovian	330.9 ±0.3	
Phanerozoic	Paleozoic	Carboniferous – Mississippian	Middle	Visean	346.7 ±0.4	GSSP
Phanerozoic	Paleozoic	Carboniferous – Mississippian	Lower	Tournaisian	358.9 ±0.4	GSSP

Fig. 5. Geologic Time Scale 2012 (Gradstein et al. 2012) showing stages with Global Stratotype Selection Points (GSSP). A GSSP is a location specific bedding plane where the base of each stage is defined. This definition is tied to an event in the rock record useful for correlation. As can be seen, three GSSP's have been defined within the time period when the Rogaland Group was deposited, base Selandian, base Thanetian and base Ypresian. The Thanetian/Ypresian transition at 56 Ma is within the Sele Formation, and close to the boundary between upper and lower Sele.

Basin development in the North Sea

A short summary of the basin evolution is given below, and in Figure 6. For reference to the following text we include the Carboniferous through Neogene segment of the International Geologic Time Scale published in 2012 (Figure 5, Gradstein et al. 2012).

Early Danian

The subtropical and well oxygenated marine environment that existed in the North Sea during the Late Cretaceous continued into the Danian. Southern and central parts of the North Sea were depositional sites remote from siliciclastic input, and sediments were dominated by calcareous, coccolithic mudstones. In the northern North Sea however, the shorter distance to terrestrial sediment source areas caused more siliciclastic sedimentation in that area than further south.

Late Danian–Early Selandian, increased siliciclastic input (Våle Fm)

The first pulse of the Alpine orogeny (Cretaceous to Early Paleogene, e.g., Ebner 2002), affected the southern and central parts of the North Sea with inversion tectonics and local movements along some of the deeper fault lineaments inherited from Pre-Cretaceous times. This caused tectonic uplift and sea level drop with exposure of more terrestrial areas closer to the North Sea Basin. There was also a change to a more temperate and more humid environment. With increased siliciclastic input and less favorable temperature the coccolithic carbonate systems of the Chalk group was gradually switched off, and deposition of the Rogaland Group started.

Late Selandian–Early Thanetian decreased connection to the Atlantic Ocean (Lista Fm)

In this interval the calcareous input from micro-organisms, and reworking from exposed chalk of the Shetland Group had practically come to an end, and the fines deposited in the basin were dominated by siliciclastic minerals. In general, the trace fossils became smaller in size and the sediments became darker, reflecting a lesser oxygenation of the basin in this interval. Coarser sediments were reworked and redeposited during three major episodes of sea level drops in this interval.

Global warming, sea level drop and basin isolation in the Late Thanetian (Sele Fm)

Tectonics and lava extrusions caused establishment of threshold barriers between the North Sea to Atlantic Ocean with resulting basin restriction. The thresholds were established by inversion tectonics in the London–Brabant Platform area in the southwest, rise of the Wyville Thompson Ridge west of Shetland, and early plate collisions in the south and east, isolating the North Sea from the Tethys Ocean and the Arctic Ocean. As a consequence the North Sea Basin became dysoxic to anoxic for a period that lasted for 3 million years, and thus well into the Early Ypresian. Coarser sediments were introduced into the basin during two major episodes of relative sea level drop. By the end of the Thanetian (57–56 my) large amounts of lava intruded organic-rich sediments, resulting in release of huge quantities of greenhouse-type gases, that were vented through thousands of hydrothermal vents along the Norwegian Margin (Svensen et al. 2004, Svensen 2009).

Early Ypresian (Balder Fm)

The basin isolation and restriction during the late Thanetian continued into the Early Ypresian. The rift volcanism continued with greater magnitude, and during this interval the basin became strongly influenced by tuffaceous ash falls related to extrusive activity. Sandy sediments were then introduced into the North Sea Basin during a phase of sea level drop.

Mid to Late Ypresian

In the mid to late Ypresian the North Sea Basin and the connection to the Atlantic and possibly the Tethys oceans were temporarily re-established, and the basin became better circulated and oxygenated. Benthic fauna fossils re-appeared, and also temperate planktonic foraminifera invaded, including an acme of *Subbotina patagonica* (Todd and Kniker). Light green grey to red colored heavily burrowed mudstones were deposited with the lowermost part of the Hordaland Group.

Some stratigraphic markers of regional importance

Intra-Danian unconformity (Top Shetland/ Base Rogaland Group Seismic marker)

The boundary between the Shetland Group and the Rogaland Group is regionally the most important unconformity affecting the Rogaland Group. It is extensively developed and is usually a prominent lithostratigraphical marker, making the distinction between the Rogaland and Shetland Groups easy in most cases

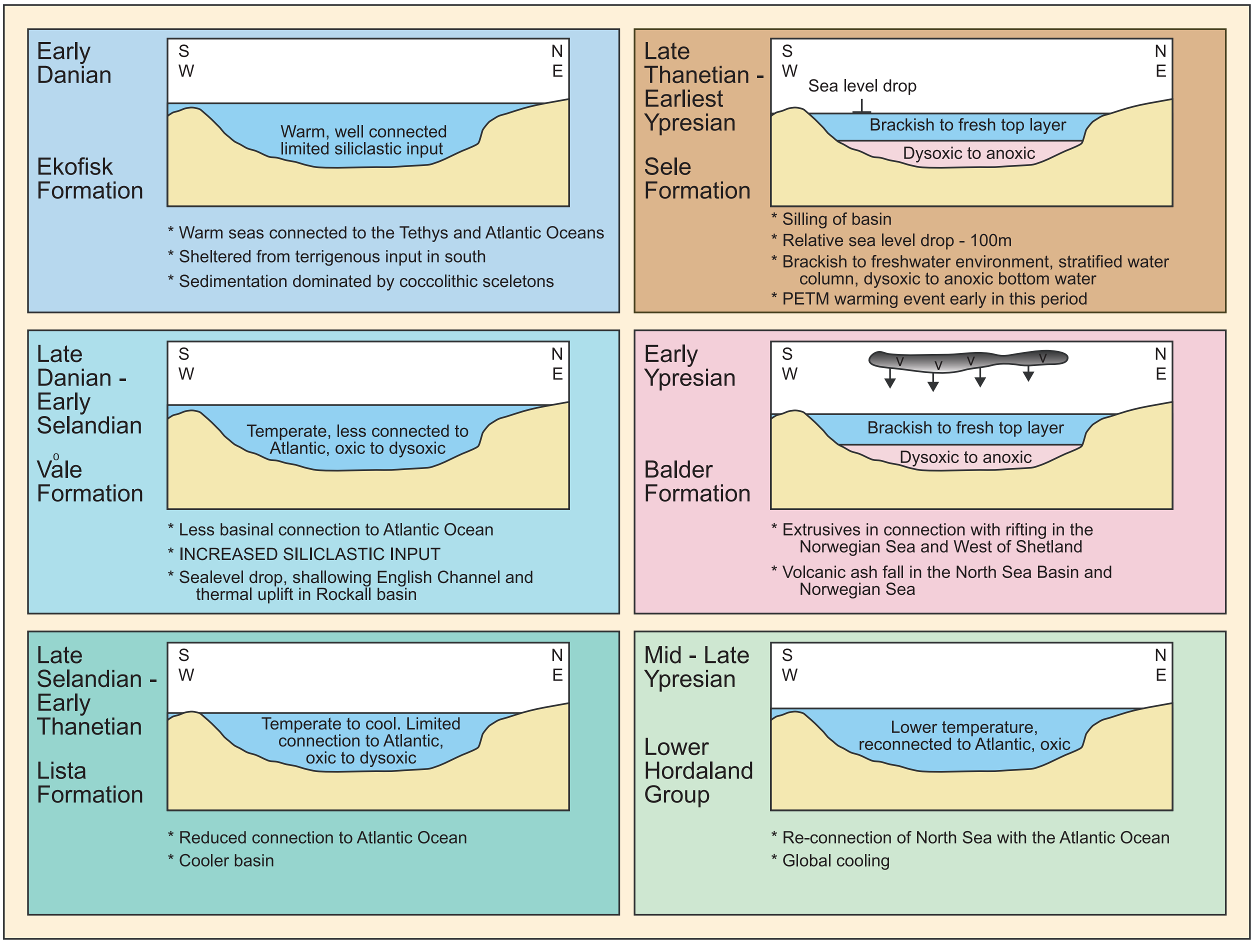


Fig. 6. Simplified basin development in the North Sea Basin trough the Early Paleogene.

(Figure 7). However, the unconformity is diachronous in many areas, and can hence not be used as a high resolution chronostratigraphic marker.

Late Thanetian unconformity–correlative conformity (Base Sele/Top Lista Formation regional seismic marker)

Within the stratigraphic interval spanning the Sele Formation there are two important unconformities in the Southern North Sea and the English Channel–London Basin area (Figure 8). Of these two the most important and easiest to recognize is the one represented by the Lista–Sele facies transition (latest Thanetian) which reflects a dramatic sea level fall as seen on the UK shelf and onshore, and a simultaneous basin restriction with anoxia in central and deeper parts of the North Sea Basin.

The overall fall in sea level for Southern England is inferred as being at least 100 m. This is not necessary a global eustatic signal. In Bradwell (Knox et al. 1994), the results of this sea level drop can be seen as an interval of fine-grained marine mudstones of the deeper marine foraminifera *Rhabdammina* biofacies (Thanet Formation, Lista equivalent), overlain by the pedogenically altered continental to lagoonal Reading Formation, Sele Fm equivalent. On the Isle of Wight, offshore South England (Figure 9), the pedogenically influenced strata of the Reading Formation are seen to lie unconformable between marine deposits of the Shetland Group and the London Clay Formation (time-equivalent to the Balder Formation). Knox (1996) and Neal (1996) argue that a sea level fall of a magnitude and rapidity to have caused this effect must be related to tectonic uplift. Ziegler (1988) and Ahmadi et al. (2003) infer that inversion tectonics has influenced the southern and central parts of the North Sea Basin, whereas e.g., Nilsen et al. (2005) also demonstrated substantial inversion along the Tornquist line and in the Norwegian–Danish Basin during the Paleocene. From France and

Fig. 7. Showing the unconformity at the base of the Rogaland Group, with the Våle Formation resting on the Chalk of the Shetland Group. Example is taken from well 25/11-17 at 1,742–1,747 m, drilled by Norsk Hydro. Photo taken from *http://www.npd.no*.

Belgium there is documented inversion of the Brabant Massif and the Artois Axis (Vandenberghe et al. 1998).

According to Simmons et al. (2007) the Sele–Lista Formation boundary is present as an unconformity as far as the southern part of the Central North Sea (Figure 8). Dreyer et al. (2004) report shallow marine indicators within the overall deep marine sandstones of the latest Thanetian Forties Member in the Pierce and the Josephine High areas. These shallow marine indicators could be a result of local tectonics/salt tectonics, but could also as well be explained as a result of more regional causes, reflecting the large-scale inversion-related sea level drop as mentioned above.

In the strata across this interval from the Central and Northern North Sea an abrupt transition from bioturbated to practically undisturbed dark shales may be seen. This transition is due to the above mentioned anoxia, lasting through deposition of the entire Sele and Balder Formations, and ending with deposition of the green and red colored bioturbated shales of the Hordaland Group. Both top and base boundaries of this anoxic shale zone are sharp and considered to be a very good litho- and chrono-stratigraphic marker. In the Central to Northern North Sea the basal parts of this interval represent the correlative conformity to the sub-regional unconformity seen at the base of the Reading Formation in the London Basin and at the Isle of Wight, and in the south to central North Sea.

The Sele–Lista Formation boundary thus appears to represent an unconformity in the southern North Sea and along the eastern and western margins of the basin further north, and a correlative conformity in the basinal areas from Central North Sea and northwards. This boundary is one of the best regional stratigraphic

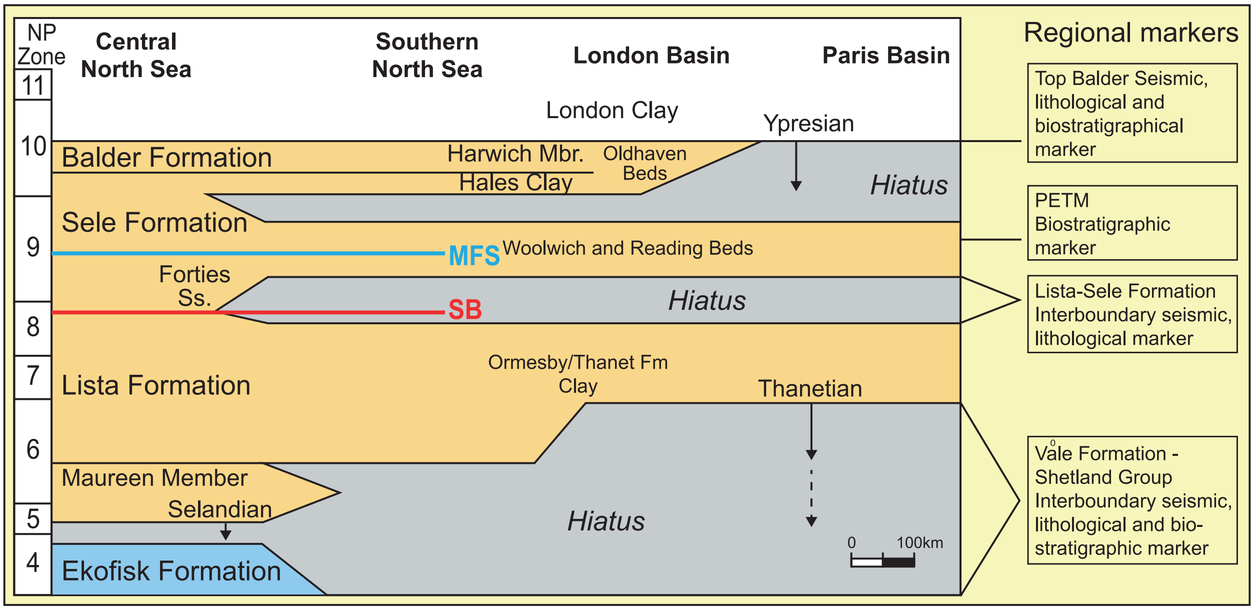


Fig. 8. Chronostratigraphic chart, modified after Knox et al. (1994) for the Paleogene of the North Sea-Paris Basin region showing that the type areas of the Paris Basin, the Ypresian and Thanetian stages are bounded by unconformities. To capture the missing time represented by these unconformities, the stages should incorporate the basinal sediments of the Central and Northern North Sea Basin, where there is continuous deposition. Modified after Simmons et al. (2007).

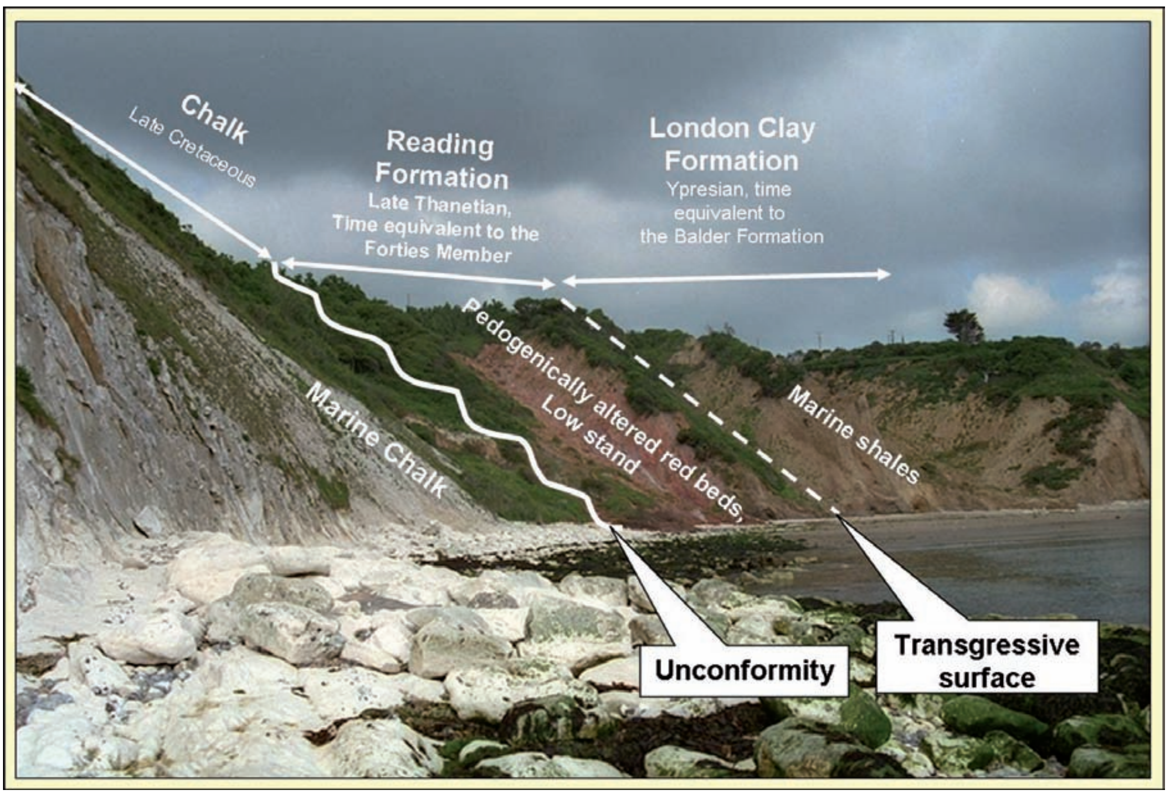


Fig. 9. Exposure of the Reading Formation at Whitecliff Bay, Isle of Wight. As can be seen, the terrestrial sediments of the Reading Formation lie unconformably between marine sediments, and represent a dramatic sea level drop relative to the adjacent sediments. Photo by H. Brunstad.

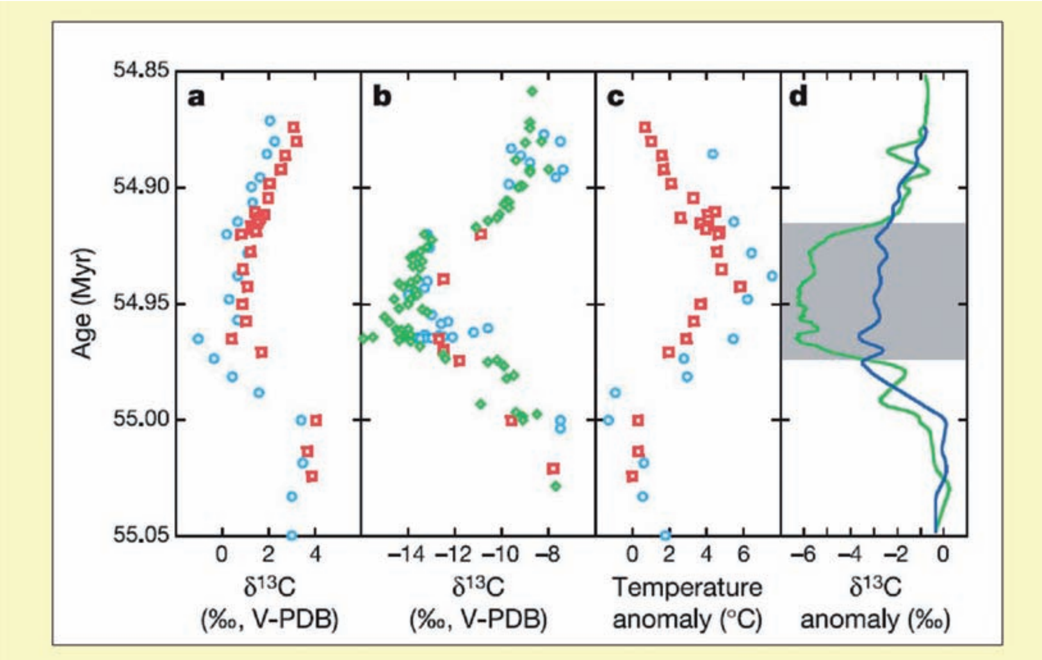


Fig. 10. Marine and Terrestrial records of the PETM, correlated to an age model for ODP site 690 (Antarctic Ocean). a) Marine $\delta^{13}C$ records derived from the surface dwelling genus *Acarinina* at ODP sites 690 (Antarctic, blue circles) and 1290 (subtropical Pacific Ocean, red squares); b) Paleosol carbonates $\delta^{13}C$ from northern Spain (blue circles), Hunan, Chona (red squares) and Wyoming, USA (green diamonds); c) Temperature anomalies for sites 690 and 1209 calculated from monospecific $\delta^{18}O$ and Mg/Ca records, respectively (symbols in a); d) normalized composite carbon isotope curves for paleosol carbonates (green) and planktonic foraminiferal carbonate (dark blue). Interval of terrestrial CIE amplification (PETM temperature increase) is shown in grey. After Bowen et al. 2004.

markers easily detectable from seismic, lithology and biostratigraphy.

Paleocene–Eocene Thermal Maximum, PETM, global biostratigraphy marker

Superimposed on the effects of basin isolation there was also a global warming pulse (Figure 10), the so-called Paleocene–Eocene Thermal Maximum (PETM), with global extinction of deep marine benthos (*Note: this type of benthos and their global extinction is not present in the North Sea Basin*). The warming pulse raised the global oceanic temperature by 6–7 °C for a period of ~ 60,000 years by the beginning of the Ypresian (Bowen et al. 2004). This short term effect is difficult to distinguish from other parts of the Sele Formation, since the North Sea Basin was already anoxic. Although the extreme PETM warming lasted only for a short period, global sea surface temperatures of the Paleocene–Early Eocene interval before and after this event were still much warmer than today. The Arctic and Antarctic seas were rather warm, and ice-free (Bowen et al. 2004, Moran et al. 2006).

With its short time duration, the PETM is almost a perfect chronostratigraphic marker. However, the definition of this stratigraphic event is not possible macroscopically, and must rely on high-resolution biostratigraphic analysis with dense sampling.

Volcanic extrusive regional seismic marker

The igneous activity in the North Atlantic (Figure 4) shows a wide age range, but peaks between 55 and 50 Ma (Torsi et al. 2002), spanning seen-rift and a continental break-up phase. During the late rift phase and especially during deposition of the Balder Formation large amounts of tuffaceous ash material were introduced into the atmosphere, and distributed over vast areas of North Europe. The lower and upper boundary of the tuff- rich zone (Figure 11) is a significant litho- and chronostratigraphic marker that makes recognition of the base of the Balder Formation easy in most cases. Some minor tuff stringers are also locally seen in the Lista and Sele formations, but are not easy to use for correlation.

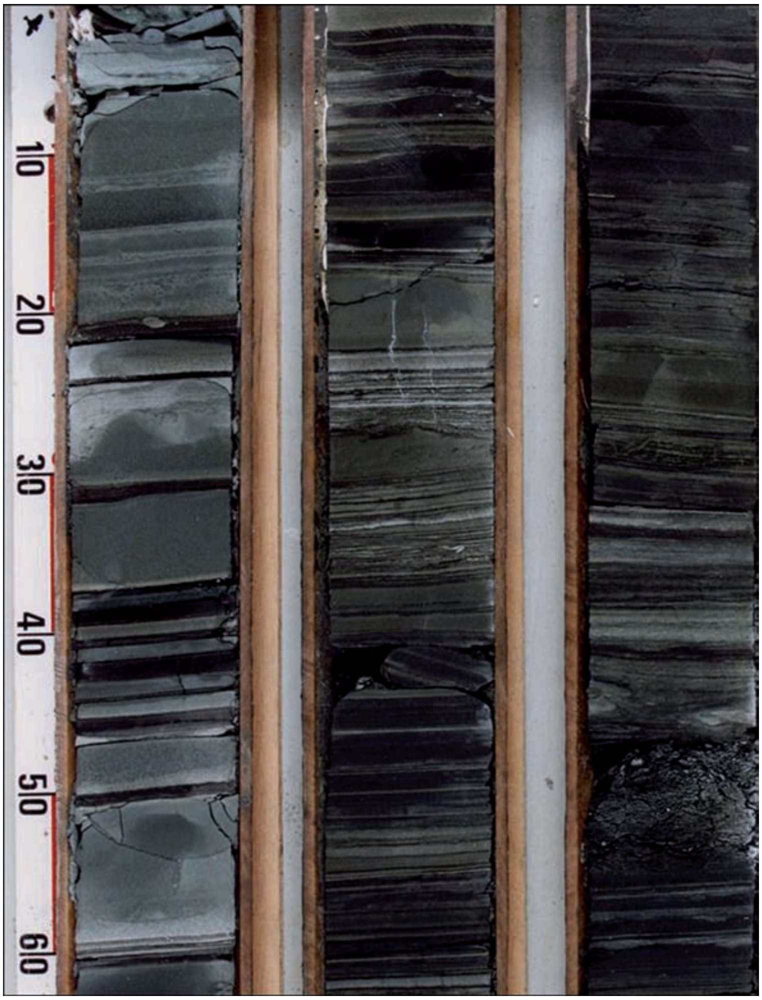


Fig. 11. Series of bright to medium dark greenish grey tuff layers of variable thickness, interlaminated with black anoxic shales. Example is taken from the Balder Formation in well 25/11-20 at 1,661–1,666 m, drilled by Norsk Hydro. Picture from *http://www.npd.no*.

Lithostratigraphic Nomenclature

General

This study deals with a revision and update of the lithostratigraphic nomenclature and classification of the Rogaland Group of Paleogene age in the Norwegian sector of the North Sea, south of 62° N. In broad terms, the Rogaland Group of this study corresponds with the formal definition by Hardt et al. in Isaksen and Tonstad (1989), where these authors joined Deegan and Scull's (1977) Montrose and Moray groups into the single Rogaland Group.

In this study, the finer siliciclastic formation units remain as previously defined, but some sandstone formations of Hardt et al. (1989) are changed into members. This procedure follows much of the same principle as in Mudge and Copestake (1992) and Knox and Holloway (1992) for the UK sector of the North Sea.

Since Hardt et al.'s (1989) work on the Norwegian sector, an abundance of new stratigraphic information from wells and 3D seismic has become available. The data has shown a complex situation concerning sand provenance and sand distribution. Hence, the new data have refined the geographic distribution of the sand units, and the stratigraphic resolution using microfossils has also become more detailed.

As a result, several new member names have been introduced in the period after Hardt et al.'s (1989) revision (Knox and Holloway 1992, Ahmadi et al. 2003, Schiøler et al. 2007), and are also used here. In addition, new members are proposed in our study, and several type and reference wells, originally defined by Hardt et al. (1989), have been amended. Additional type wells are also added when new stratigraphic units are established. This study also provides comprehensive figures of the geology of the new members.

Note on Formations and Members, according to the International Stratigraphic Guide (Salvador 1994)

The formation is the primary formal unit of lithostratigraphic classification used to map, describe and interpret the geology of a (subsurface) region. It is identified by its lithological character and stratigraphic position. Formations are the only formal lithostratigraphic units into which the stratigraphic column everywhere should be divided completely on the basis of lithology. The degree of change in lithology to justify the establishment of distinct formations (or other lithostratigraphic units) is not amenable to strict and uniform rules. It may vary with the geologic complexity of the region and the detail needed to portray its rock framework satisfactorily, and to work out its geological history. Where a unit changes laterally, either gradually or abruptly with a markedly different kind of rock, a new unit should be proposed for the different rock type.

A member is the formal lithostratigraphic unit next in rank below a formation, and is always part of a formation. It is recognized as a named entity within a formation because it possesses lithological properties distinguishing it from adjacent parts of the formation. No fixed standard is required for the extent or thickness of a member. Formations may or may not be partly or completely divided in members. A member may extend from one formation to another.

The assignment of new members to an existing formation, or changing an existing formation to a member follows the same procedures as for proposing a new unit. Change in rank of a stratigraphic unit does not require redefinition of the unit or of its boundaries, or alteration of the geographic part of its name. Thus, a formation may be raised to a group or reduced to a member without changing its name. Redefinition may be justified to make a unit more useful or easier to recognize, map, and extend throughout the area of its occurrence.

The type section of a layered unit serves as the standard of reference for the definition and charaterisation of the unit. In subsurface work, because of caving in wells drilled, it is generally best to define such arbitrary boundaries at the highest occurrence of a particular rock type rather than at the lowest.

The terms 'lower', 'middle' and 'upper' should not be used for formal subdivision of lithostratigraphic units. The use of both the lithological term and the unit-term (e.g., Kimmeridge Clay Formation) is discouraged, although lithological qualifiers may help the reader.

In the current revision of the Rogaland Group, it is intended to use existing naming as far as practical for the sandstone members. However, some major additions have been made in the northeastern North Sea and in the Siri Canyon of the southern parts of the Norwegian–Danish Basin, since the former official nomenclature (Hardt et al. 1989) did not describe any sandstone units there. Since the 1990s several wells have given more information about sandstones in these areas, and they are correspondingly included and defined here.

The fifteen sandstone members of the Rogaland Group have been defined according to their provenance area, sedimentary distribution and structural boundaries. This practice has also been used by Hardt et al. (1989) to separate their easterly derived 'Fiskebank Formation' from the westerly sourced 'Forties Formation'; by Schiøler et al. (2007) to separate easterly sourced sandstones of Siri Canyon and Tail End Graben/Søgne Graben from westerly sourced sandstones of the Central Graben; and by Hardt et al. (1989) and Knox and Holloway (1992), to distinguish northwestern from southwestern sandstones in the Central Graben and the Viking Graben.

Mudge and Copestake (1992) reduced the Forties Formation to the Forties Member within the Sele Formation. The Borr Member was originally defined by Schiøler et al. (2007). The Egga Member was meant by Gjelberg et al. (1999) to be an upper unit in the Våle Formation. The Mey Member is age-equivalent to the Andrew Member and to the Balmoral Member of Neal (1996). Knox and Holloway (1992) redefined the Heimdal Formation as the Heimdal Member. The Siri Member stems from the assignments by Schiøler et al. (2007), and Ahmadi et al. (2003) in the Millenium Atlas. The Fiskebank Member was redefined from Fiskebank Formation by Schiøler et al. (2007). The Odin Member was originally proposed by Mudge and Copestake (1992).

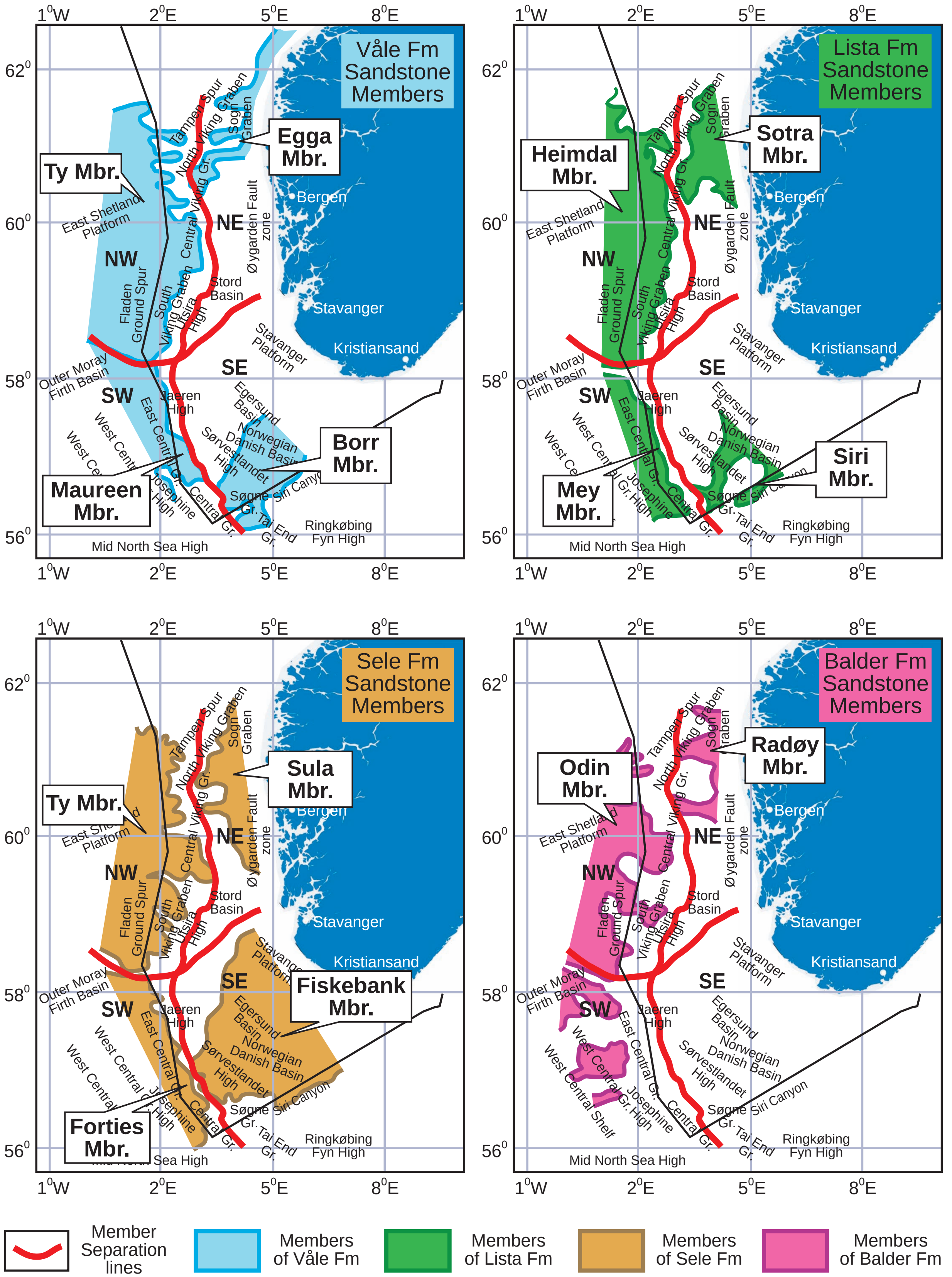


Fig. 12. Sketch showing rough distribution of the sandstone members belonging to the four shale formations of the Rogaland Group, relative to the Member Separation Lines.

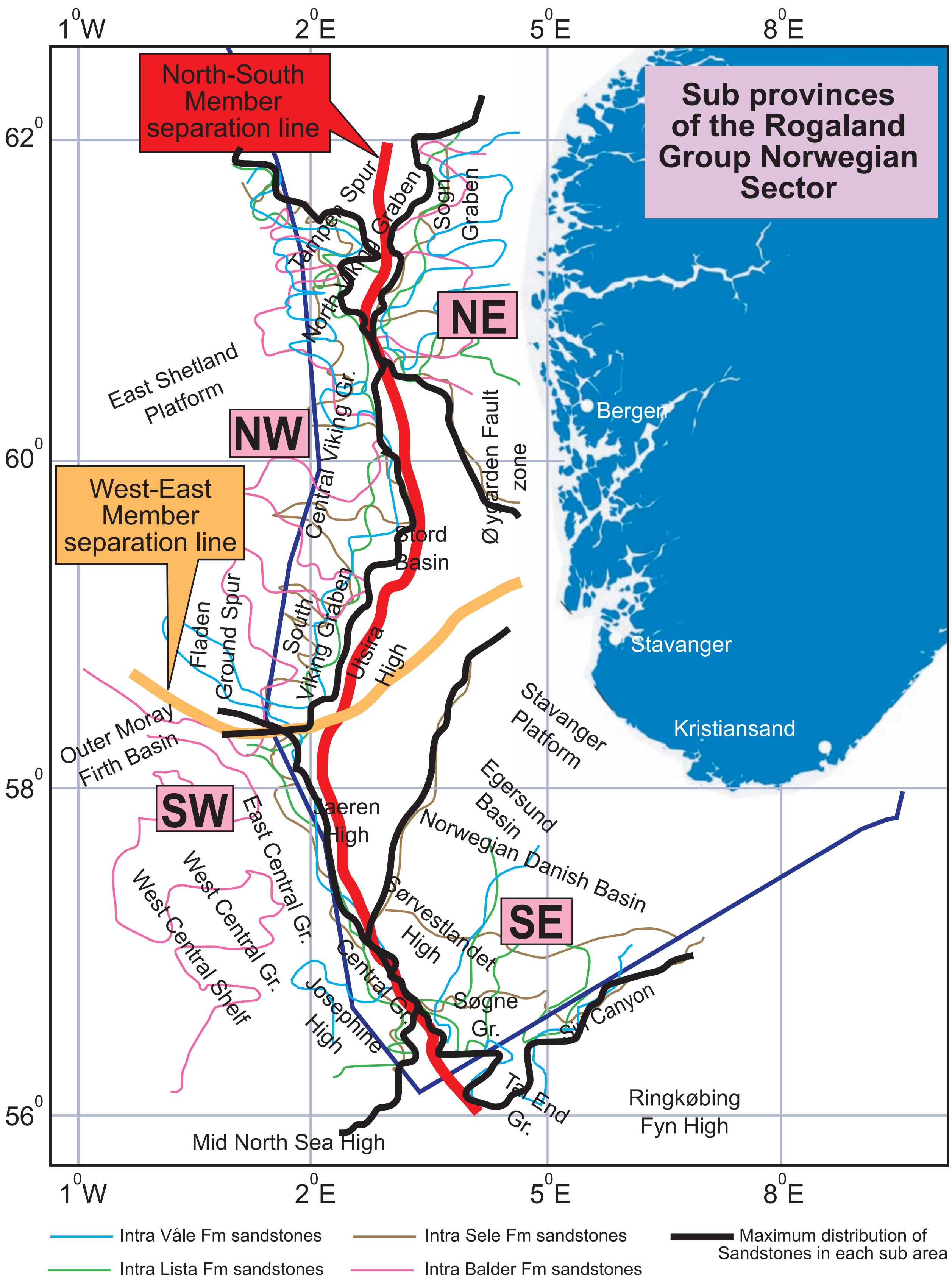


Fig. 13. Sketch demonstrating subareas and separation lines used to limit the various sandstone members.

Roughly, sandstone members within each shale formation are bounded by the two crossing member separation lines shown in Figures 12 and 13, which give four subareas each with their separate sandstone member:
1) North–South separation line.
2) West–East separation line.

Subjects covered in lithostratigraphic nomenclature

In this revision, each of the four formations and the fifteen members is described in the same successive steps, as follows:

- Unit definition
- Name
- Derivatio nominis
- Type well
- Reference wells
- Composition
- Wire-line log characterization
- Thickness
- Seismic characterization
- Age
- Biostratigraphy
- Correlation and subdivision
- Geographic distribution
- Depositional environment

The amount of text dedicated to each formation or member is dependent on the data coverage and importance.

Many composite well diagrams have been designed, and are shown under the respective stratigraphic units. The lithological codes used are shown in Figure 14a.

The sequence stratigraphic notations adopted in the regional study of the Rogaland Group are shown in Figure 14b. Depositional cycles or sequences have been recognized by several authors, who have interpreted these as global sea level changes. The number of sequences defined may vary between the workers: Armentrout et al. (1993) recognized 5 cycles, whereas Robertson (1996) shows 11 cycles. Time span for the individual cycle/sequence is in the order of less than 0.5 to more than 1 myr. Whereas Robertson (1996) subdivided their cycles by their basal unconformities and correlative conformities (depositional sequences), Mudge (1998) used correlatable high gamma peaks (genetic sequences) from logs assumed to represent condensed sections deposited during sediment starved conditions at maximum sea level. This is the approach used in the present study to subdivide the formations into sub-units, the reason being that these peaks are

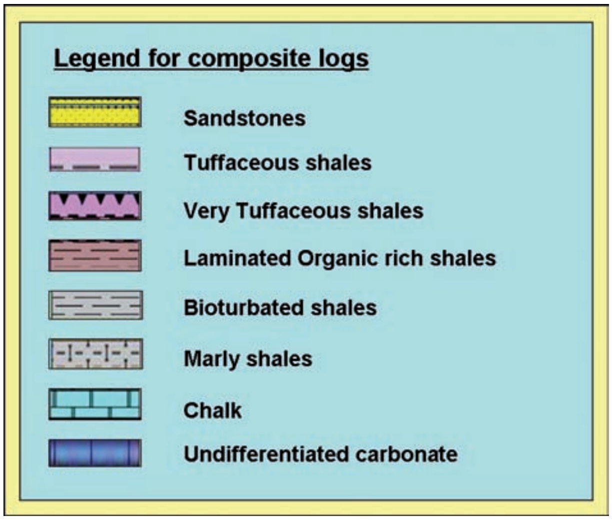


Fig. 14. (see also the following pages 18–19).
a. Lithological codes used in well composites for the Rogaland Group.
b. (pages 18, 19) Sequence stratigraphy and correlation cycles in the North Sea Basin. Depositional cycles or sequences have been recognized by several authors, claiming that they represent global sea level changes. The number of sequences defined may vary between the workers: Armentrout et al. (1993) recognizes 5 cycles, whereas Robertson (1996) shows 11 cycles. Time span for the individual cycle/sequence is in the order of less than 0.5 to more than 1 my. Whereas Robertson (1996) subdivide their cycles by their basal unconformities and correlative conformities (depositional sequences), Mudge (1998) uses correlative high gamma peaks (genetic sequences) from logs assumed to represent condensed sections deposited during starving condition at maximum sea level. This is the approach used in the present study to subdivide the formations into sub units, the reason being that these peaks are considered as good chronological markers that are recognized over much of the North Sea Basin. It could, however be discussed whether some of these high gamma peaks rather represent some other conditions than flooding. This could be the case for the Sele and the Balder Formations that were deposited in epicontinental oceans of the North Sea during restriction and isolation by a structural sill in the London-Brabant area. Moreover, the clastic wedges between the bounding high gamma shales at top and base may be explained to be a response to tectonic activity and climatic variations. Although the exact origin for the high gamma events may be disputable, the authors consider them well suitable and practical for basin wide log correlations in the North Sea (chart modified from Ahmadi et al. 2003, in The Millennium Atlas).

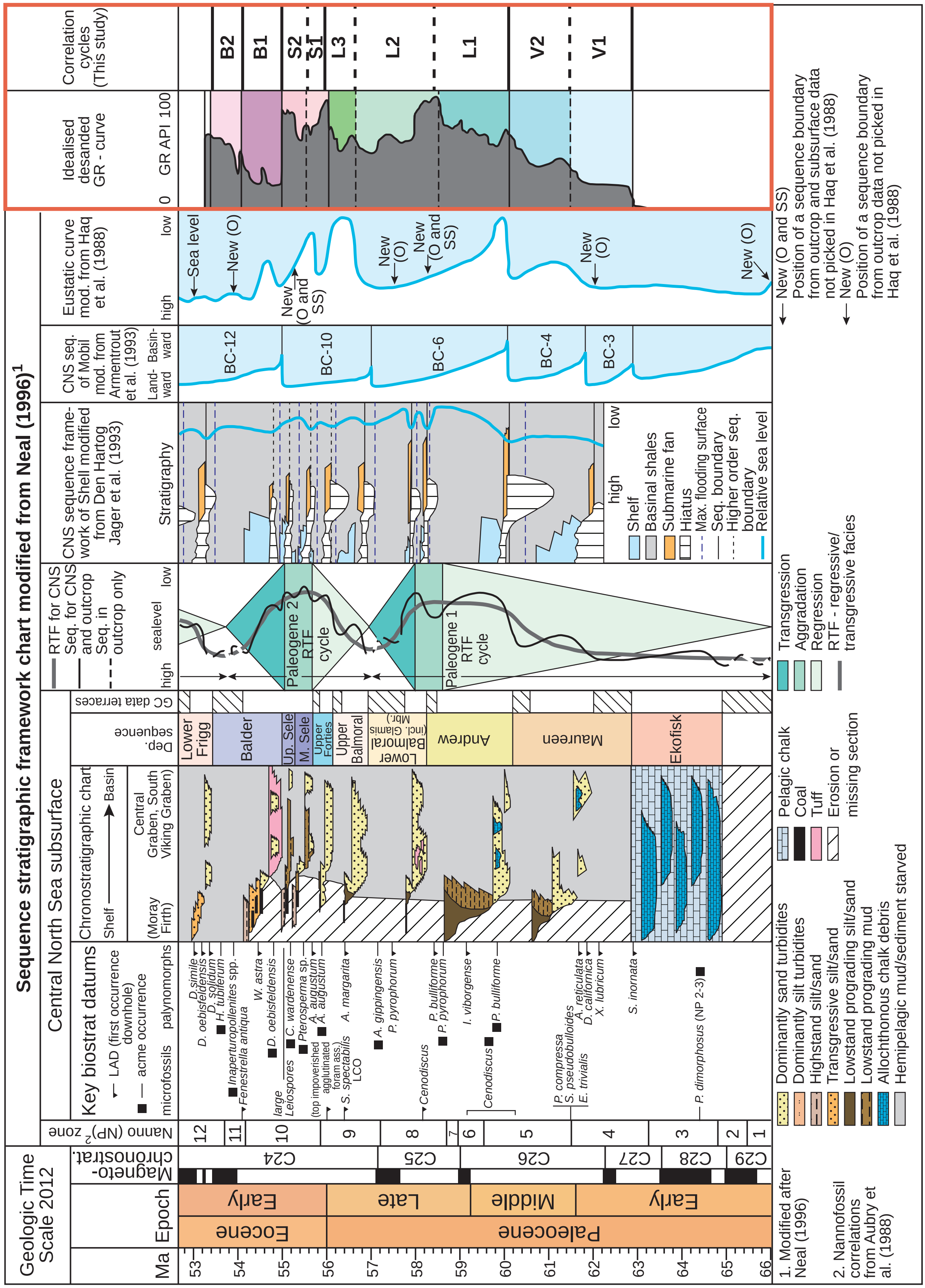

Sequence stratigraphic framework chart modified from Neal (1996)[1]
Central North Sea subsurface
Geologic Time Scale 2012
Ma
Epoch
Eocene
Paleocene
Early
Late
Middle
Early
Magneto-chronostrat.
C24
C25
C26
C27
C28
C29
Nanno (NP)[2] zone
Key biostrat datums
LAD (first occurrence downhole)
acme occurrence
microfossils
palynomorphs
Chronostratigraphic chart
Shelf
Basin
(Moray Firth)
Central Graben, South Viking Graben)
Dep. sequence
Lower Frigg
Balder
Up. Sele
M. Sele
Upper Forties
Upper Balmoral
Lower Balmoral (incl. Glamis Mbr.)
Andrew
Maureen
Ekofisk
GC data terraces
RTF for CNS
Seq. for CNS and outcrop
Seq. in outcrop only
high
sealevel
low
Paleogene 2 RTF cycle
Paleogene 1 RTF cycle
CNS sequence framework of Shell modified from Den Hartog Jager et al. (1993)
Stratigraphy
CNS seq. of Mobil mod. from Armentrout et al. (1993)
Landward
Basinward
BC-12
BC-10
BC-6
BC-4
BC-3
Eustatic curve mod. from Haq et al. (1988)
Sea level
New (O)
New (O and SS)
Idealised desanded GR - curve
0 GR API 100
Correlation cycles (This study)
B2
B1
S2
S1
L3
L2
L1
V2
V1
Dominantly sand turbidites
Dominantly silt turbidites
Highstand silt/sand
Transgressive silt/sand
Lowstand prograding silt/sand
Lowstand prograding mud
Allochthonous chalk debris
Hemipelagic mud/sediment starved
Pelagic chalk
Coal
Tuff
Erosion or missing section
Transgression
Aggradation
Regression
RTF - regressive/transgressive facies
Shelf
Basinal shales
Submarine fan
Hiatus
Max. flooding surface
Seq. boundary
Higher order seq. boundary
Relative sea level
New (O and SS) Position of a sequence boundary from outcrop and subsurface data not picked in Haq et al. (1988)
New (O) Position of a sequence boundary from outcrop data not picked in Haq et al. (1988)
1. Modified after Neal (1996)
2. Nannofossil correlations from Aubry et al. (1988)

Fig. 14b

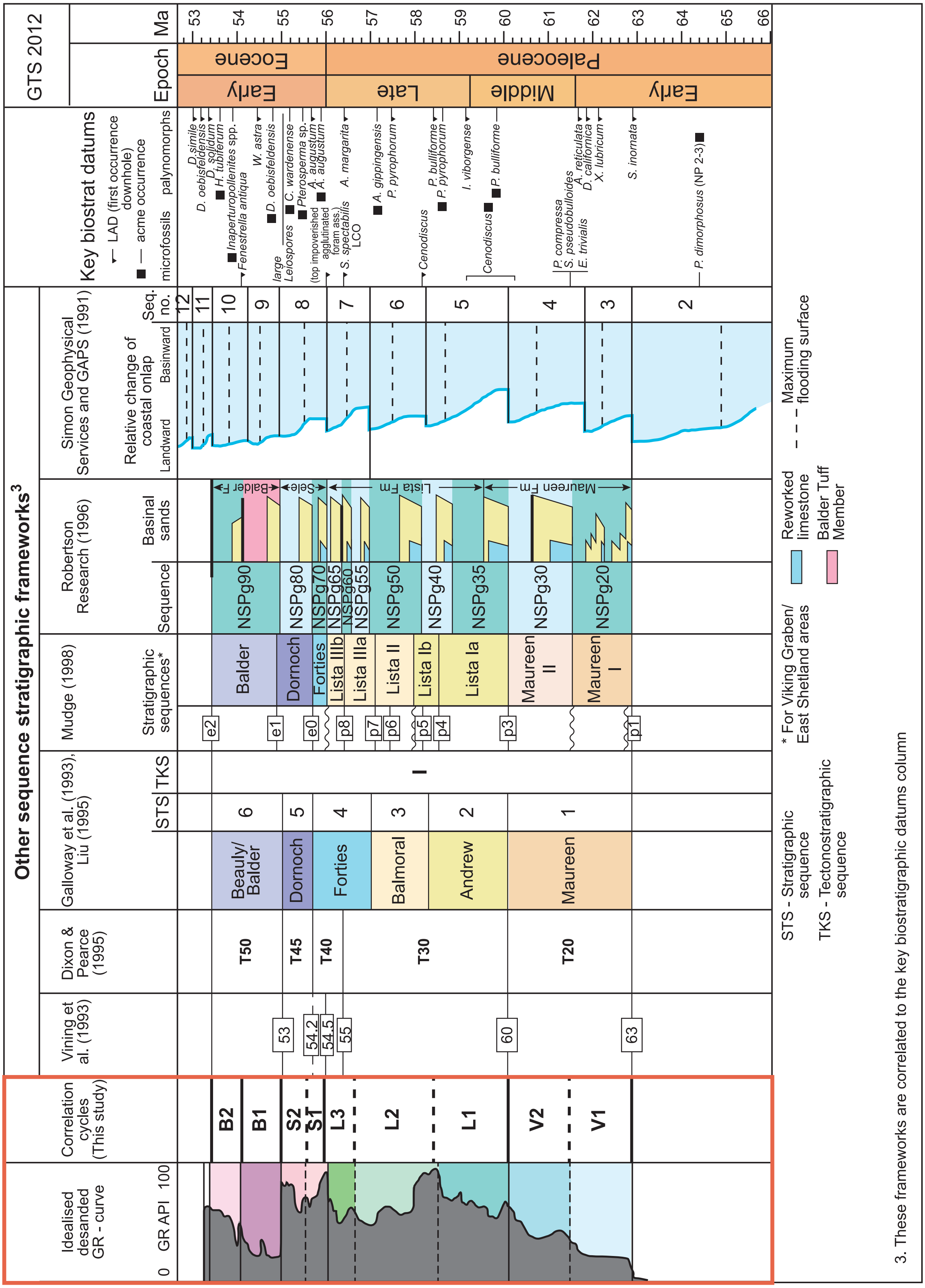

GTS 2012
Epoch
Ma
Eocene
Paleocene
Early
Late
Middle
Early
Key biostrat datums
LAD (first occurrence downhole)
acme occurrence
microfossils
palynomorphs
Other sequence stratigraphic frameworks³
Simon Geophysical Services and GAPS (1991)
Relative change of coastal onlap
Landward
Basinward
Seq. no.
Robertson Research (1996)
Sequence
Basinal sands
Mudge (1998)
Stratigraphic sequences*
Galloway et al. (1993), Liu (1995)
STS
TKS
Dixon & Pearce (1995)
Vining et al. (1993)
Correlation cycles (This study)
Idealised desanded GR - curve
0 GR API 100
Balder
Dornoch
Forties
Lista IIIb
Lista IIIa
Lista II
Lista Ib
Lista Ia
Maureen II
Maureen I
Beauly/ Balder
Balmoral
Andrew
Maureen
T50
T45
T40
T30
T20
B2
B1
S2
S1
L3
L2
L1
V2
V1
NSPg90
NSPg80
NSPg70
NSPg65
NSPg60
NSPg55
NSPg50
NSPg40
NSPg35
NSPg30
NSPg20
Balder F
Sele
Lista Fm
Maureen Fm
STS - Stratigraphic sequence
TKS - Tectonostratigraphic sequence
* For Viking Graben/ East Shetland areas
Reworked limestone
Balder Tuff Member
Maximum flooding surface
3. These frameworks are correlated to the key biostratigraphic datums column

Fig. 14b

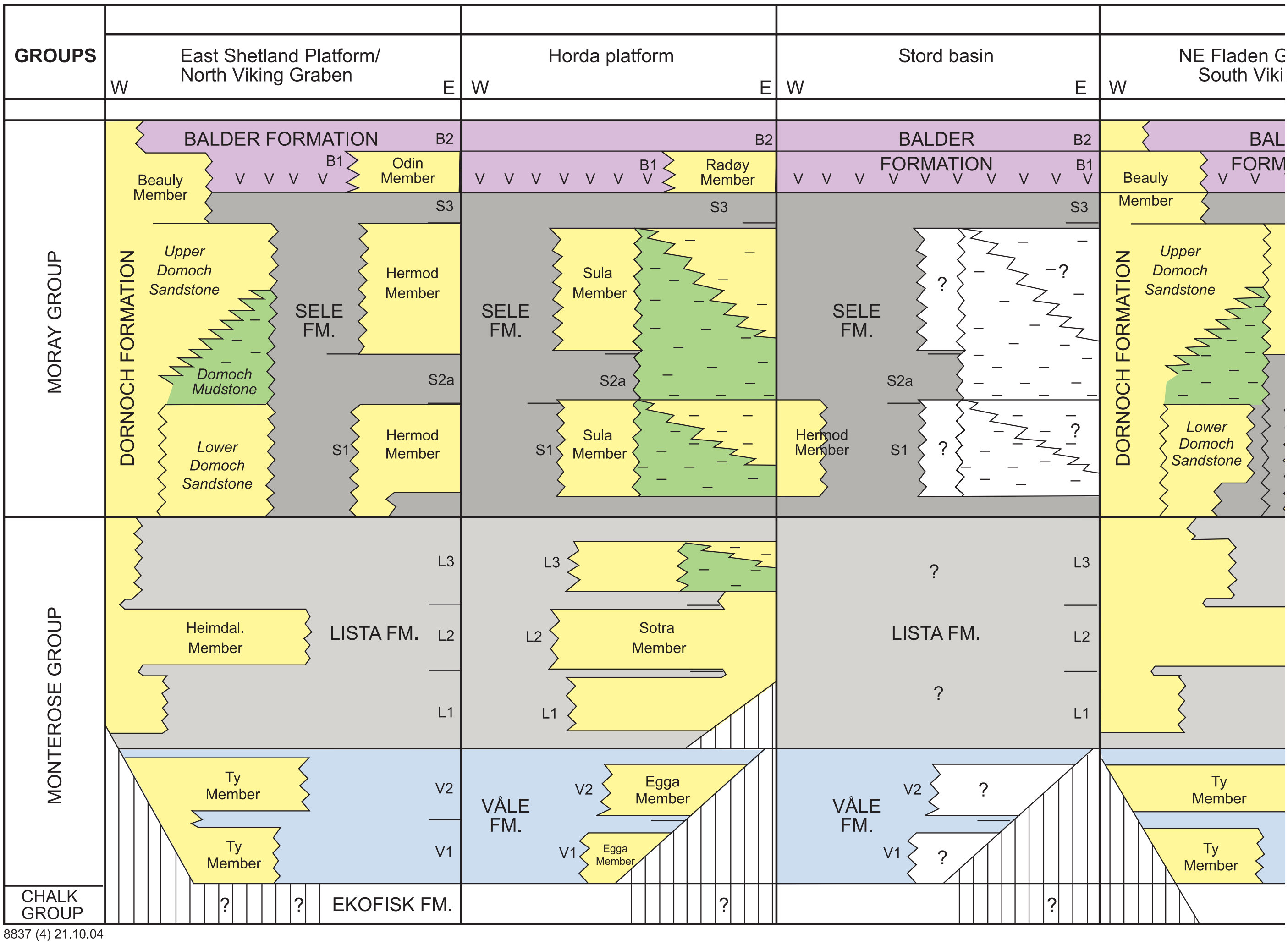
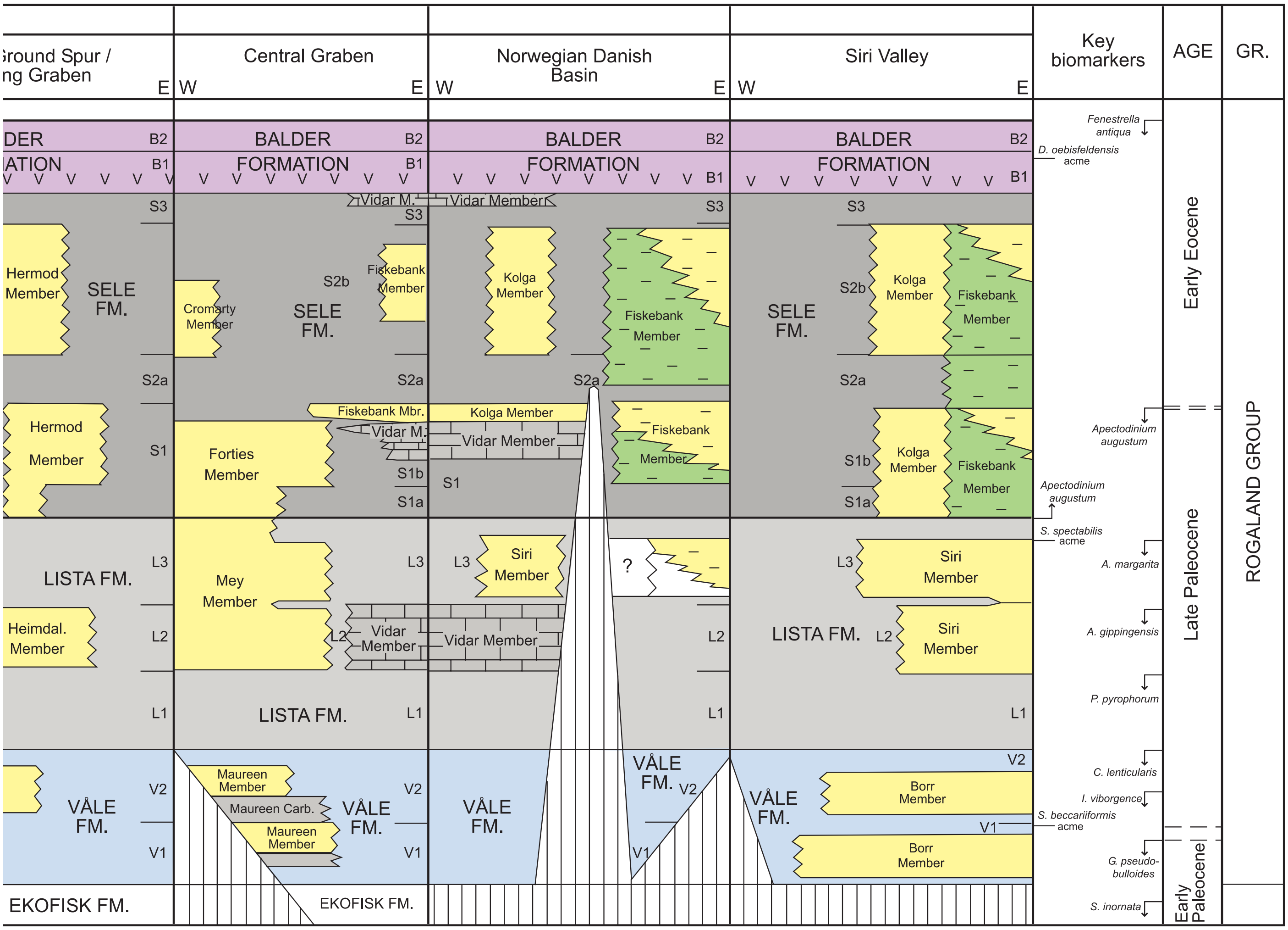


Fig. 15. Lithostratigraphic summary chart of the Rogaland Group, Northern and Central North Sea.

considered suitable chronological markers that are recognized over much of the North Sea Basin. It could, however be discussed whether some of these high gamma peaks rather represent some other conditions than flooding. This could be the case for the Sele and the Balder formations that were deposited in epicontinental oceans of the North Sea during restriction and isolation by a structural sill in the London–Brabant area. Moreover, the clastic wedges between the bounding high gamma shales at top and base could, alternatively to global sea levels, be explained to be a response to tectonic activity and climatic variations. Although the exact origin for the high gamma events may be disputable, the authors consider them well suitable and practical for basin-wide log correlations in the North Sea (Figure 14b chart was modified after Ahmadi et al. (2003), in The Millennium Atlas).

This is the first time that detailed stratigraphic information is presented on the Vidar Member, which, due to its olistolith character, has no fixed stratigraphic position, but in general was generated in megaslides after deposition of the Våle Formation and prior to deposition of the Balder Formation. The unit is covered at the end of this study.



The Rogaland Group

Unit Definition of the Rogaland Group

The Rogaland Group of the Norwegian sector of the North Sea corresponds to the combined Montrose and Moray groups of the UK sector (Knox and Holloway 1992). It is divided into four shale/mudstone formations. From old to young these are the Våle, Lista, Sele, and Balder formations, each containing their respective sandstone members (Table 1 and Figure 15).

The formations in this lithostratigraphic revision are defined geographically to include the main shale units of the Paleocene and lower Eocene of the North Sea as far as 62° N. An overview of the Rogaland Group, with its four shale formations and its many sandstone members is in Figure 15.

Name

The Rogaland Group was named by Deegan and Scull (1977) for Paleocene to Lower Eocene (dated Late Danian–Early Ypresian) siliciclastic strata of the central and northern North Sea.

Derivatio Nominis

The name Rogaland is after the county of Rogaland in southwest Norway.

Table 1 Overview of the Formations and Members of the Rogaland Group, Paleocene–Lower Eocene, North Sea, Norway.

Group	Formation	Member
Rogaland Group	Balder Formation	
		Odin Member
		Radøy Member
	Sele Formation	
		Forties Member
		Hermod Member
		Fiskebank Member
		Sula Member
	Olistolith unit with varying stratigraphic position	Vidar Member
	Lista Formation	
		Mey Member
		Heimdal Member
		Sotra Member
		Siri Member
	Våle Formation	
		Borr Member
		Ty Member
		Maureen Member
	Våle/Tang Formation	
		Egga Member

Upper boundary
The top of the Rogaland Group is taken at the transition between the dark grey, laminated and partly tuffaceous shales of the Balder Formation into the commonly pale green-grey to red colored basal parts of the overlying Hordaland Group.

Lower boundary
In the central North Sea, the Norwegian–Danish Basin and the southern Viking Graben the base of the Rogaland Group is taken at the change from marly mudstones with local sandstones and thin interbeds of limestone of the lower parts of the Våle Formation into the chalks and marls of the Shetland Group. In the northern North Sea the basal boundary is not as clearly defined as further south, since there is less distinct lithological difference between the Våle Formation and a less calcareous underlying Shetland Group in that area compared to further south.

General lithological characterization

The Rogaland Group is characterised by a siliciclastic succession of strata following the more carbonate-rich Cretaceous Shetland Group. The deposits are composed of basin-wide mudstones and shales, with intercalations of sandstones at several levels that vary widely in geographical distribution.

Wireline log characterization

From wire-line logs (Table 2) the Rogaland Group is defined by a significant upwards increase in gamma readings and a decrease in acoustic velocity when compared to the chalky or calcareous mudstones of the Shetland Group. The top of the Rogaland Group is often taken at or close to the top of the bell shape seen on wire-line logs for the Balder Formation.

Thickness

The thickness of the Rogaland Group varies significantly within the North Sea Basin. In the Norwegian sector a thickness of 918 m was found in well 24/9-3, 714 m in well 25/4-3, and 647 m in well 35/9-2. Minor thicknesses of the Rogaland Group are seen on top of salt diapirs in the Central Trough (e.g., 26 m in well 1/6-5), and on the Utsira High (88 m in well 16/6-1), and in the easternmost parts of the Norwegian–Danish Basin (55 m in well 9/2-2).

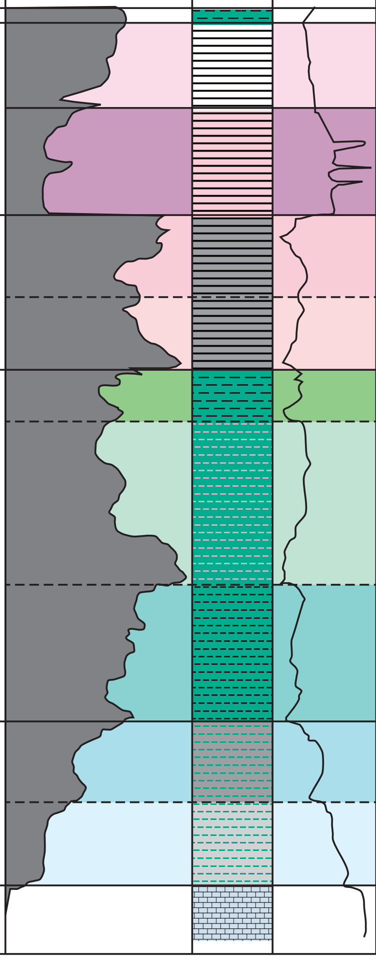
Seismic characterization

A tectonic map of the central and northern North Sea with the main structural elements is shown in Figure 1 and regional seismic maps from the Rogaland Group in Figures 2 and 3. These show an axial deep close to the UK/Norwegian border, with its deeper parts in the south. The greatest thickness is seen in the southern Viking Graben area and along the eastern margin of the Sogn Graben.

The top of the Rogaland Group is often distinguishable as the top Balder seismic reflector. However, in some areas the top of the Balder tuffaceous zone or the base of the Balder Formation are better defined than the formation top itself, and is often easier to map regionally.

Regional Cross-Sections
From regional seismic cross-sections (Figures 16 through 18) prominent progradational wedges with clinoforms can be seen west of the main depositional troughs of the Central and Viking Grabens. Along the

Table 2 High resolution shale stratigraphy of an idealized desanded log of the Rogaland Group in the Viking Graben.



Fm	GR	Color & Lam.	DT	Zone	Chrono-Strat. Surface	GR Log shape	Bioturbation	Morphology	Mineralogy	Basin Circulation
BALDER				B2	B2	Upper part of bell shape. Lower velocities	Rarely seen, mostly absent	Well laminated Alternating tuffaceous and black fissile shale. Shale dominated.	Common pyrite, Siderite nodules, calcite cement in tuff beds	Anoxic, cool
BALDER				B1	B1	Lower part of bell shape. Higher velocities	Rarely seen, mostly absent	Well laminated Alternating tuffaceous and black fissile shale. Tuff dominated.	Common pyrite, Siderite nodules, calcite cement in tuff beds	Anoxic, cool
SELE				S2	S2	High Gamma, readings, peaks at base and top	Rarely seen, mostly absent	Black laminated fissile shale.	Common pyrite, Siderite nodules.	Anoxic, cool
SELE				S1	S1	High Gamma, readings, peaks at base and top	Rarely seen, mostly absent	Black laminated fissile shale.	Common pyrite, Siderite nodules.	Anoxic, warmer
LISTA				L3	L3	Intermediate Gamma, readings, some spikes	Heavy to little disturbed. Small to medium trace fossils. *Thalassanoides, Zoophycus, Planolites.*	Generally faintly laminated	Siderite nodules, pyrite.	Dysoxic, cool
LISTA				L2	L2	Intermediate Gamma readings in upper parts. Often thick zone of higher readings in lower parts.	Heavily mottled *Thalassanoides, Zoophycus, Planolites.* Small to medium sized borrows.	Generally faintly laminated	Siderite nodules	Oxic to dysoxic, cool
LISTA				L1	L1	Intermediate Gamma readings, some spikes	Heavy to little disturbed. Small to medium sized trace fossils. *Thalassanoides, Zoophycus, Planolites.* Small to medium sized borrows.	Generally faintly laminated	Siderite nodules	Oxic, cool
VÅLE				V2	V2	Generally very low Gamma readings	Heavily mottled *Thalassanoides, Zoophycus, Planolites.* Medium to large borrows.	Disturbed, Non- to faintly laminated	Calcareous mudstone, Carbonate content decreasing upwards.	Oxic, intermediate
VÅLE				V1	V1	Generally very low Gamma readings increasing upward.	Heavily mottled *Thalassanoides, Zoophycus, Planolites.* Medium to large borrows.	Disturbed, mostly Non-laminated	?Marl, calcareous mudstone, and carbonate cemented Claystone	Oxic, intermediate to warm
						Generally very low Gamma readings			Chalky limestone with variable chert and clay	

eastern margin of the Stord Basin and the Sogn Graben similar wedges can be seen to dip from the east. The general impression is that clinoforms along the western flank have a steeper dip than those from the east. This may be interpreted as the result of a different sand to mud ratio in the deposits, and to a more active tectonic regime of the Shetland Platform than in southern Fennoscandia. During the Paleocene there were periods of active rifting along the western margin of the Shetland Platform which uplifted the platform and generated a more immature topography exposing erodable sediments, whereas southern Fennoscandia to the east remained a tectonically stable platform with a generally mature topographic profile in a landscape dominated by basement rocks.

Seismic character on a local scale

Sandstones are present in all of the fine-clastic Rogaland Group formations. Top and base of sand packages are often mappable due to contrast between blocky sandstones and adjacent shales. In other cases, tops of the sandstones have a more gradual transition to the shales above and there is not a good seismic contrast. In these cases the presence of sand is often seen to correspond to a mounded seismic character with discontinuous internal reflectors. An example of the seismic character of sandy facies is shown in Figure 19. Mounds are often interpreted as containing submarine channels/channel complexes or elongated submarine fan systems. In many instances seismic attribute analysis can delineate the aerial extension of these systems.

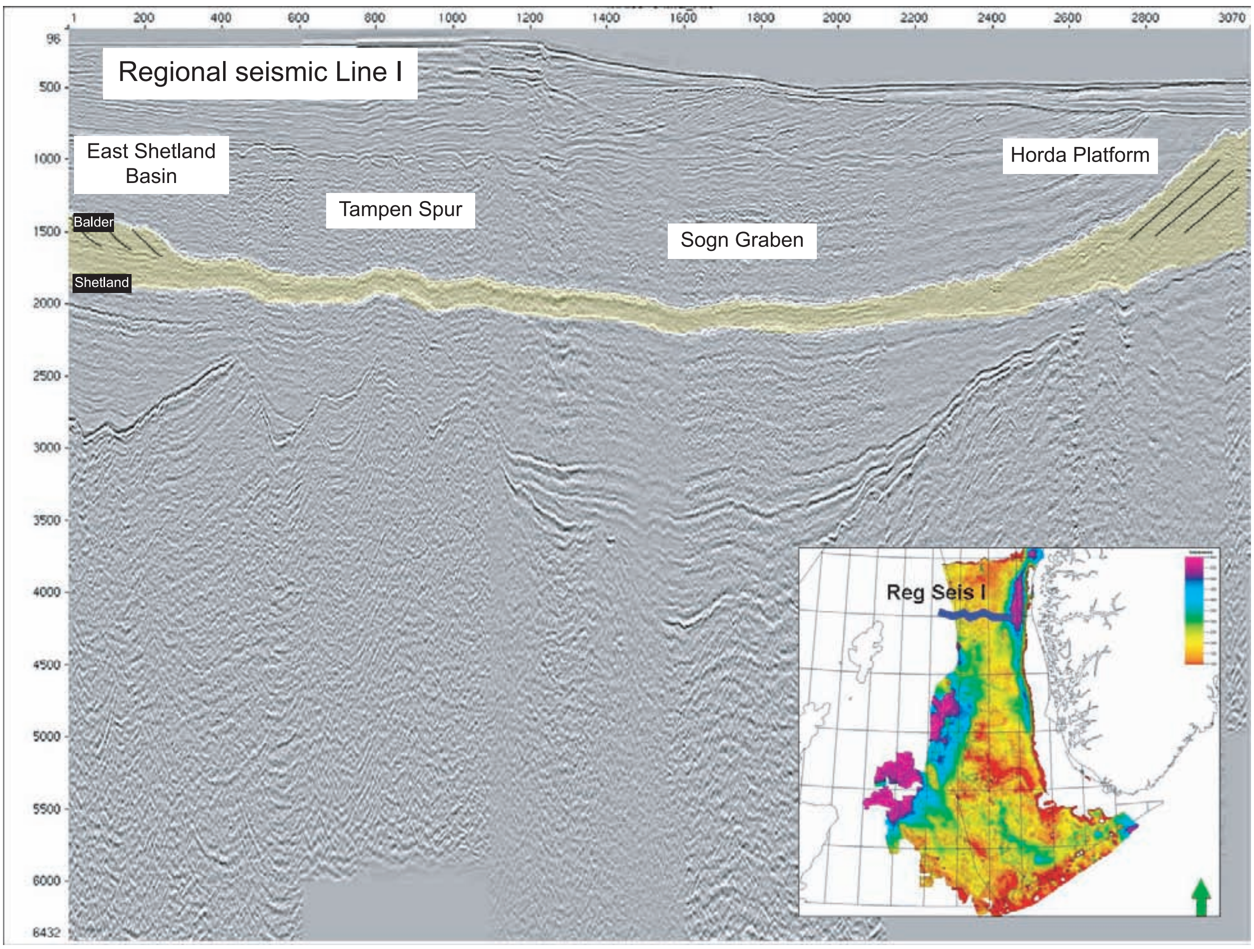


Fig. 16. Regional seismic line I, Northern North Sea. Note signs of dipping reflections/shelf buildout in the East Shetland basin, and dipping reflections representing slope wedges in the Horda Platform area. In the basinal area between the wedges there are thin deposits, reflecting a relatively sparse input of gravity flow material in that area compared to the South Viking Graben and the Central Graben.

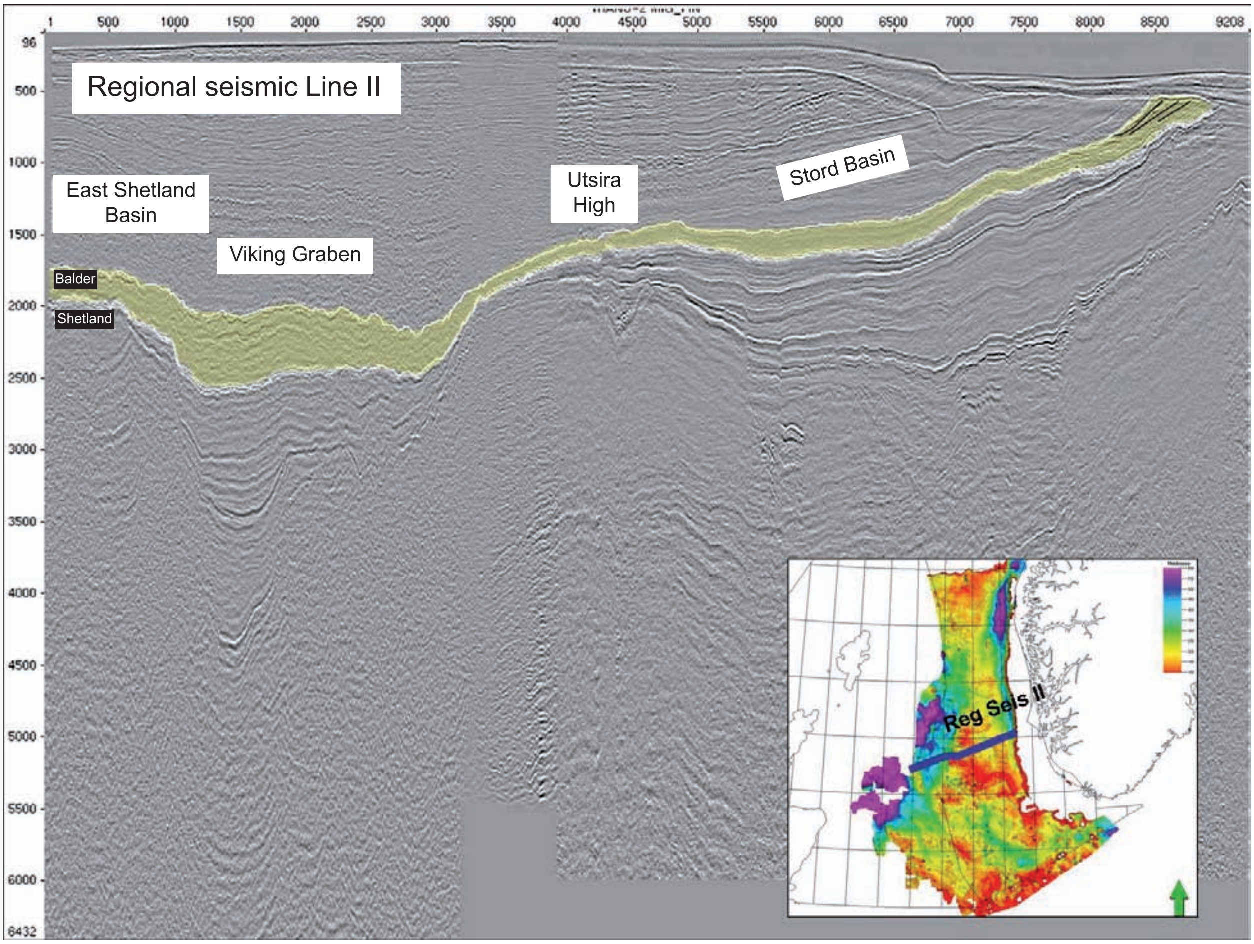


Fig. 17. Regional seismic line II, from the Shetland Platform to the Stord Basin, North Sea. Dipping reflections east of the Stord Basin are attributed to slope progradation from the East. The Viking Graben formed a deep basin filled with a mixture of gravity flow sediments sourced from the East Shetland Platform and background hemipelagic siliciclastics. Utsira High is characterized by a thinning of the sequence, and is believed to have formed a submarine basinal high during deposition.

Sediment composition and processes

Sandstone facies

In the Norwegian North Sea the Rogaland Group contains a wide variety of sandstone facies, ranging from deep marine and gravity flow to shallow marine and deltaic sandstones. Deep marine sandstones are dominating, but shallow marine deposits have also been recorded. In general, shallow marine facies are found in the easternmost parts of the Norwegian North Sea, but locally also in parts of the southern Central Graben succession (Dreyer et al. 2004).

The most pronounced deep marine sandstones are found along the trends of the Central Trough–Viking Graben and the Sogn Graben. On the East Shetland platform (UK), sandstones intercalated with shales and well developed coals or lignite beds witness deltaic/coastal plain setting. Distinct coal beds are not found in wells penetrating the Rogaland Group of the Norwegian North Sea.

Most wells in the Norwegian sector have been drilled in a paleo-slope to basin floor setting and sandstones here are in general interpreted as gravity flow/turbidites of submarine fans (e.g., Hardt et al. 1989, Knox and Holloway 1992). Possible exceptions include some occurrences of the intra Sele Formation sandstones of the Forties (Dreyer et al. 2004) and Fiskebank Members. This is discussed in more detail in the subchapters on these members. A seismic scale example of submarine fan deposits is shown in the seismic amplitude map of Figure 20. Examples of turbidites in cores from the Rogaland Group are shown in Figures 21 through 24.

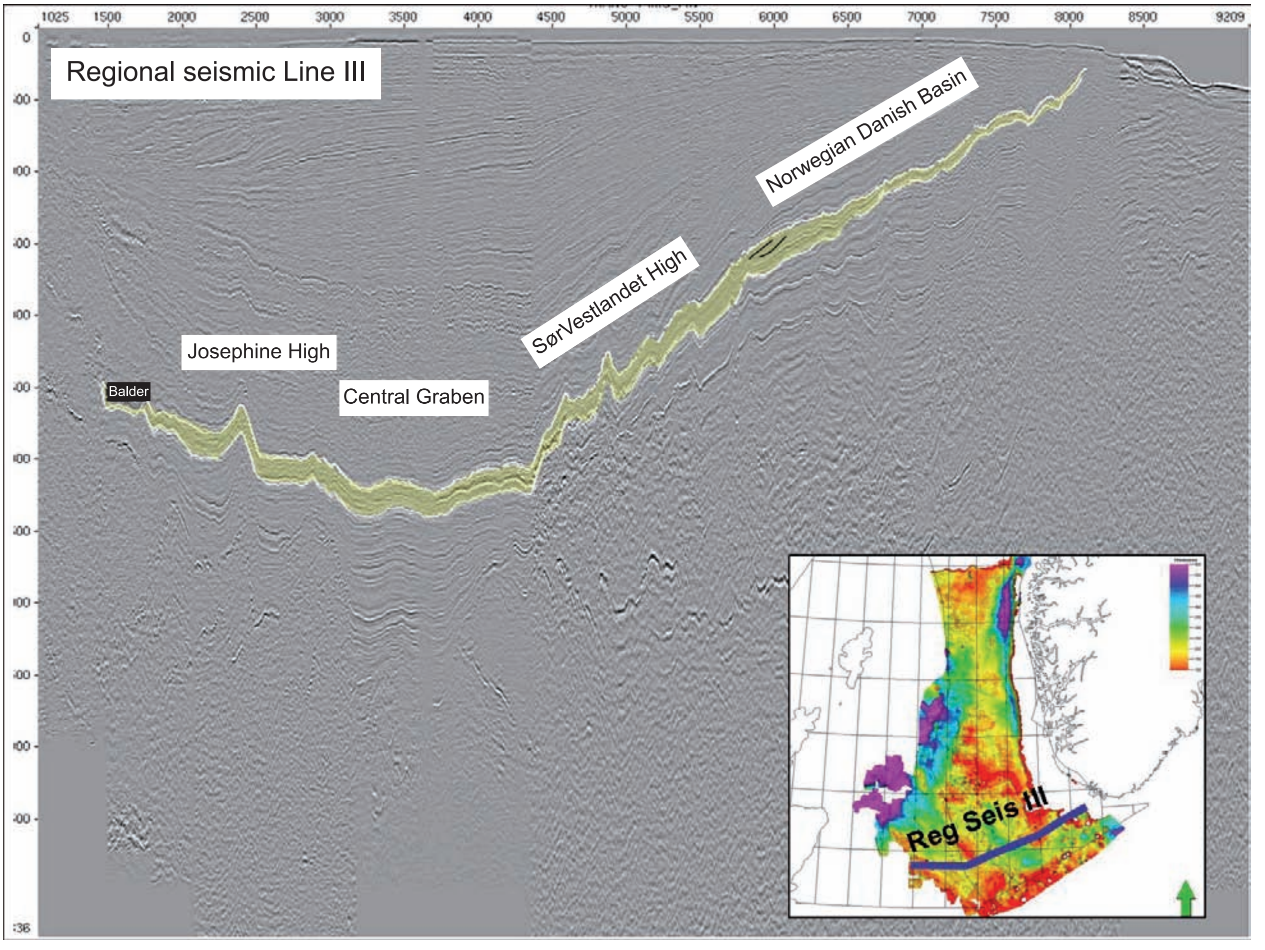


Fig. 18. Regional seismic line III, Through the Central Graben and the Norwegian Danish Basin, North Sea. Thickening in the Central Graben is mainly attributed to input of siliciclastics from the East Shetland Platform and the Moray Firth area in the North, but input from Southern Fennoscandia in the East and possibly the Midland Valley area may also have contributed. The Central Graben area is commonly interpreted as a deep marine environment, whereas the Norwegian Danish Basin is considered as a shallow to deep marine transition.

There is considerable variability in the composition of the gravity flows. Some consist of thick beds of massive sandstones with frequent fluid escape structures and only very sparse primary structures (Figures 21 and 22); others consist of interbedded shales and sandstone layers with primary structures as horizontal lamination and ripple cross bedding (Figures 23 and 24).

In general, the sandstones have fine to medium sized grains and are moderately to well sorted. Mineralogy is dominated by quartz and feldspar, although in some cases the sandstones may contain a large proportion of glauconitic or mica grains. Rip-up clast material of clay and drifted wood fragments may be common in the sandstones in some areas, especially in the lower parts of sandstone intervals.

Sandy debris flow deposits may also make up an important part of the primary deposited sandstones in some areas, consisting of massive, generally structureless sandstones, with a variable content of fine grained clayey matrix and larger angular mudstone clasts. In the sandstones of the Maureen and Mey members of the Central Trough, and the Ty Member of the Viking Graben, chalk clasts and occasional chert clasts are also common within the sands. An example of sandy debris flow deposits is shown in Figure 25.

Sand intrusions (injectites) and extrusions

One of the most prominent post-depositional features of sandstones in the Rogaland Group is the frequently occurrence of sand injection structures (e.g., Huuse et al. 2004, De Boer et al. 2007).

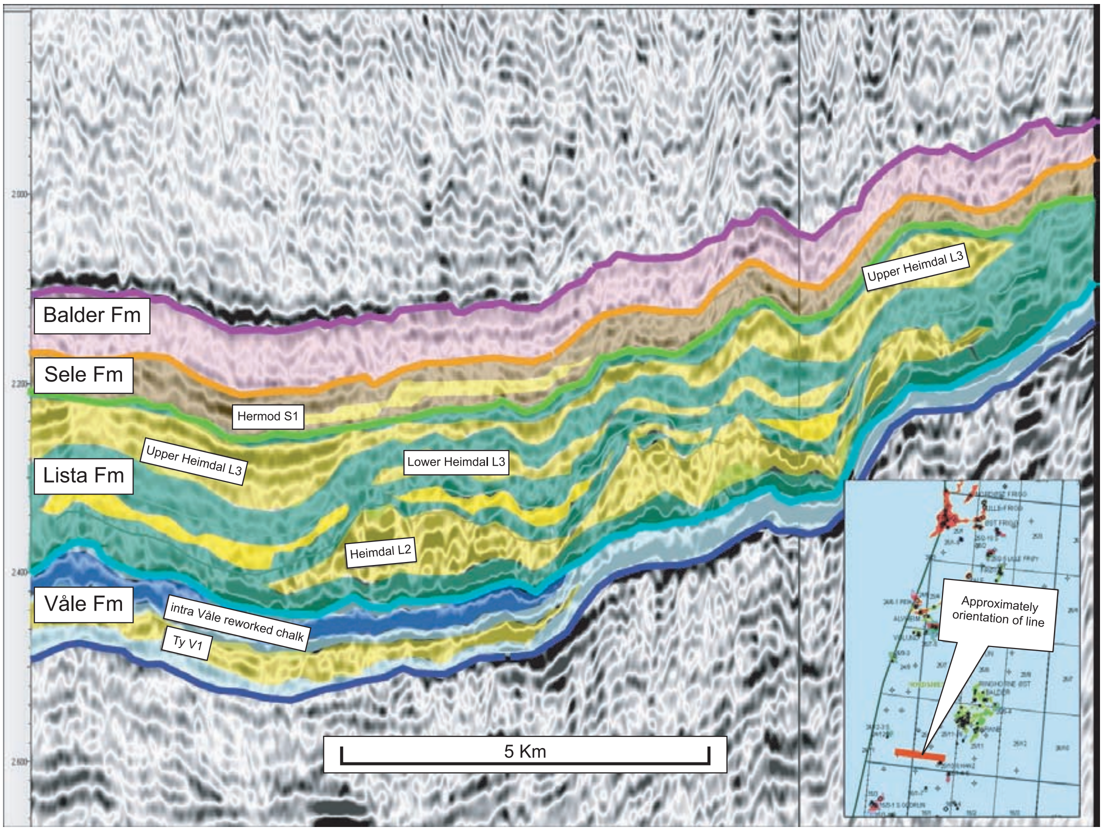


Fig. 19. Example of seismic character of sandy facies of the Rogaland Group, seen from a WE section through southern parts of block 25/10.

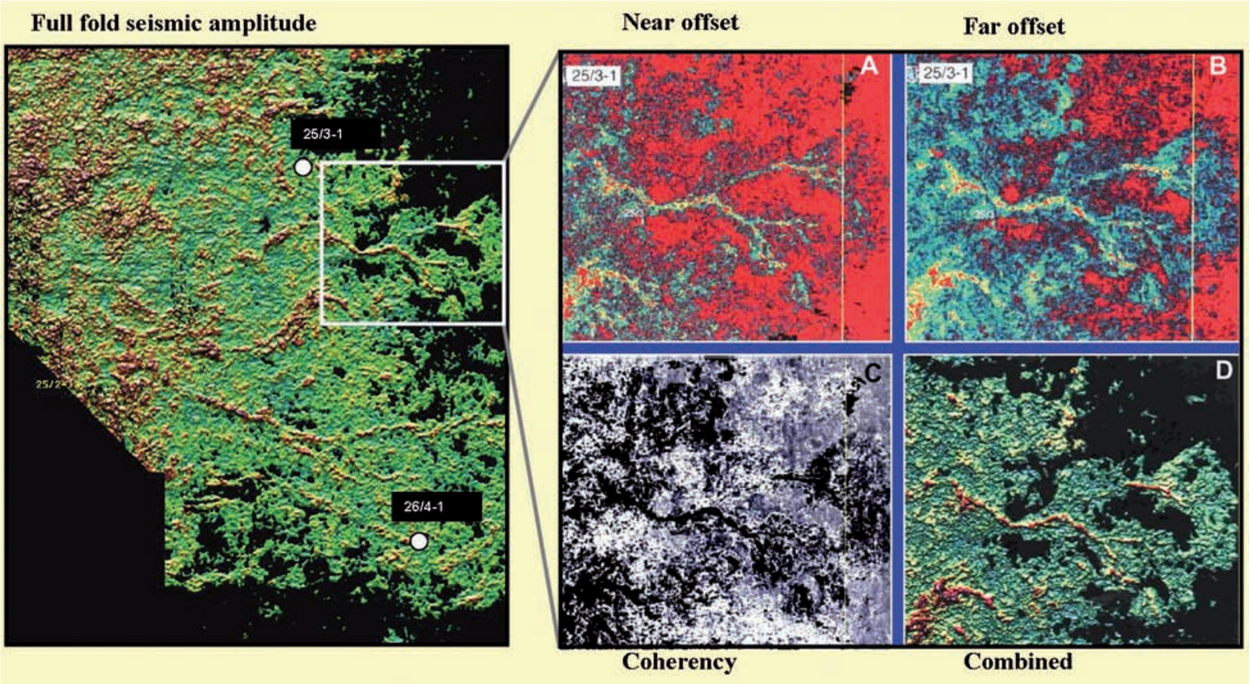


Fig. 20. Seismic amplitude maps of an intra Sele Formation seismic marker, displaying submarine fan deposits of the Hermod Member in North Eastern parts of Q25.

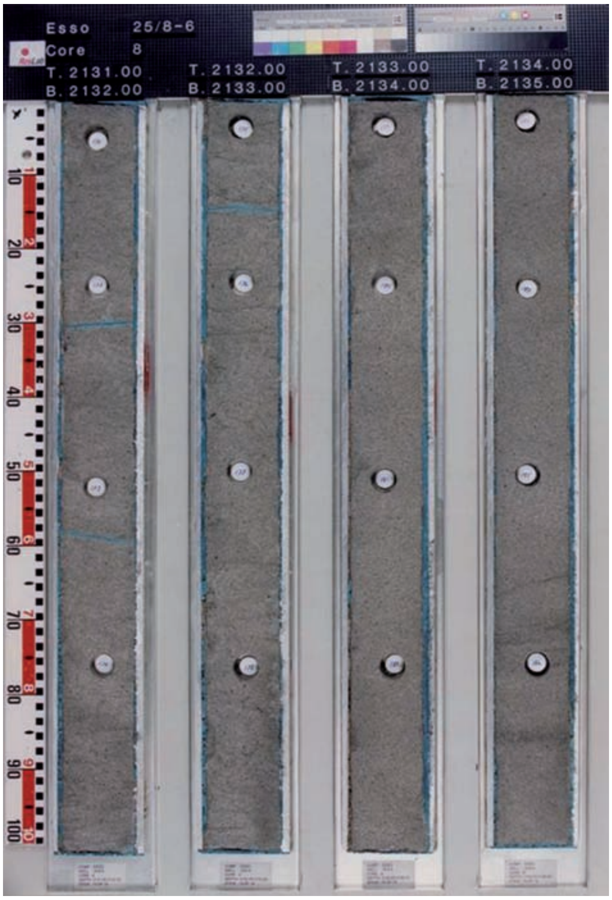


Fig. 21. Turbidite Example 1. Clean, massive sandstones in Heimdal Member well 25/8-6, at 2,131–2,135 m, interpreted as high density turbidites. Picture from NPD fact pages at http://www.npd.no.

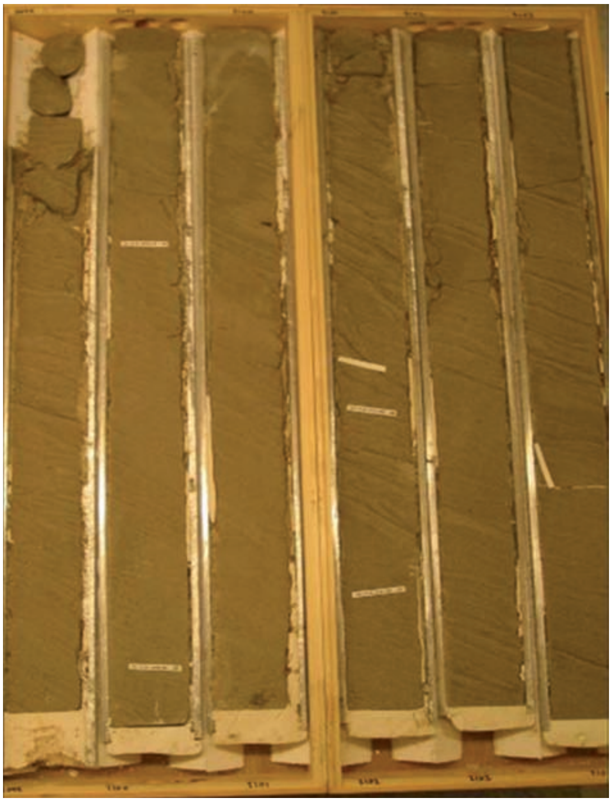


Fig. 22. Turbidite Example 2. Dish structured massive sandstone in Heimdal Member well 25/10-7, interpreted as high density turbidites influenced by water escape after deposition. Photograph by H. Brunstad.

Fig. 23. Turbidite Example 3. Normal graded beds, with sharp base and massive structure-less sandstone in lower parts of beds, and faintly cross laminated sandstones in the upper parts. Example from Heimdal Member, well 16/1-1. Deposits are interpreted as low-density turbidite deposited in a distal fan or overbank position. Photograph by H. Brunstad.

Fig. 24. Turbidite Example 4. Beds of clean, massive, structure-less sandstone at top, and thin-bedded, ripple cross laminated, heterolithic sandstones below. Massive sandstone is interpreted as high density turbidite deposited in a proximal/axial fan position, whereas heterolithics are interpreted as low density turbidites deposited in a fan fringe position. Example from Heimdal member, well 25/8-6 at 2,104–2,108 m. Photograph from *http://www.npd.no*.

Fig. 25. Example of sandy/gravelly debris flow deposits from the intra Lista Formation Mey Member. Cores are from well UK 30/14-1, Flyndre discovery, close to the UK/NOR border. The clast material consists of reworked chalk, mudstone, chert and sandstone. The sediments are matrix supported to grain supported. Photograph by H. Brunstad.

In the Rogaland Group such features are observed on several scales from seismic (Figure 26) to well core (Figures 28 and 29). In the cores the injectites are often seen to be of different generations with networks crosscutting and connecting each other. This indicates that the sand injection process occurred at repeated stages through burial.

A sketch showing various types of sand extrusives and intrusives is shown in Figure 27. Sand injectites are fluidized and mobilized sands that were injected into sediments generating dike and sill systems (Figures 27, 28 and 29), whereas sand extrusions were fluidized sands that extruded to the sea bottom as sand volcanoes, locally developing into turbidites.

Sand intrusion and extrusion is a result of pressure release and pressure reduction from over-pressured sands through water escape and escape of fluidized sands from higher pressured areas to lower pressured areas. Most commonly this involved stratigraphical upward movements of sands, but downward and lateral movements also seem to have occurred. Simultaneously with sand injection there was severe sand deformation of parent and receiver sand bodies with clay clasts being ripped up from sand/mud boundaries, both within the mother and the offspring sand bodies as well in the sill/dike systems themselves.

Genesis of overpressure

Sand mobilization and injection is believed to have occurred before lithification, which in most cases is believed to have happened before several hundreds of meters of burial. The system may have lived through several phases of over-pressuring with several different sources of over-pressuring. The most relevant sources of over-pressuring are considered to be:

1. Under compaction of clay formations containing the sands.
2. Stabilization of the sand grain framework with tighter grain packaging and fluid escape after burial.
3. Overpressuring release/fracturing from deeper strata.

The most powerful and volumetrically most important source is believed to be that of item 3) causing escape of highly pressured materials from deeper basin levels created by hydrocarbon generation and silica diagenesis.

Polygonal fault patterns

Polygonal fault patterns are commonly associated with the Rogaland Group. Such patterns are especially well developed and frequently occurring in the Balder Formation, but they are also common at other levels. An example of this phenomenon is shown in Figure 30.

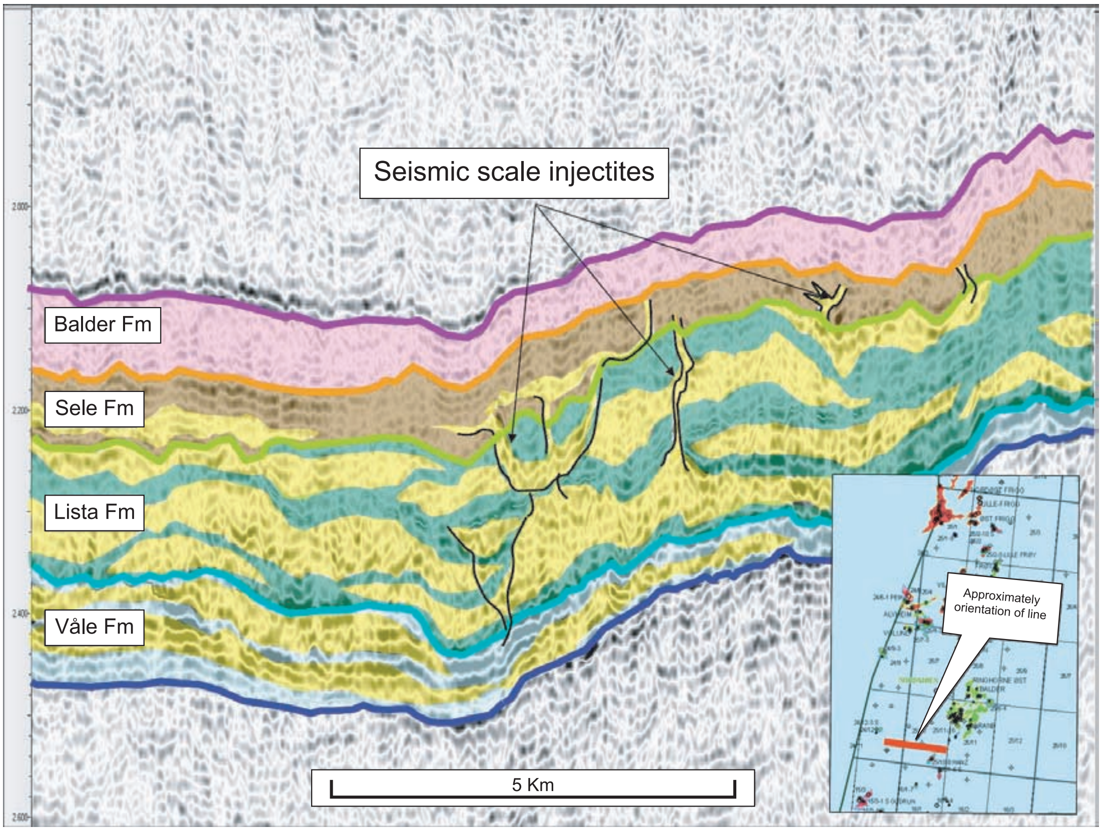


Fig. 26. Example of seismic scale injectite systems in the southern parts of block 25/10.

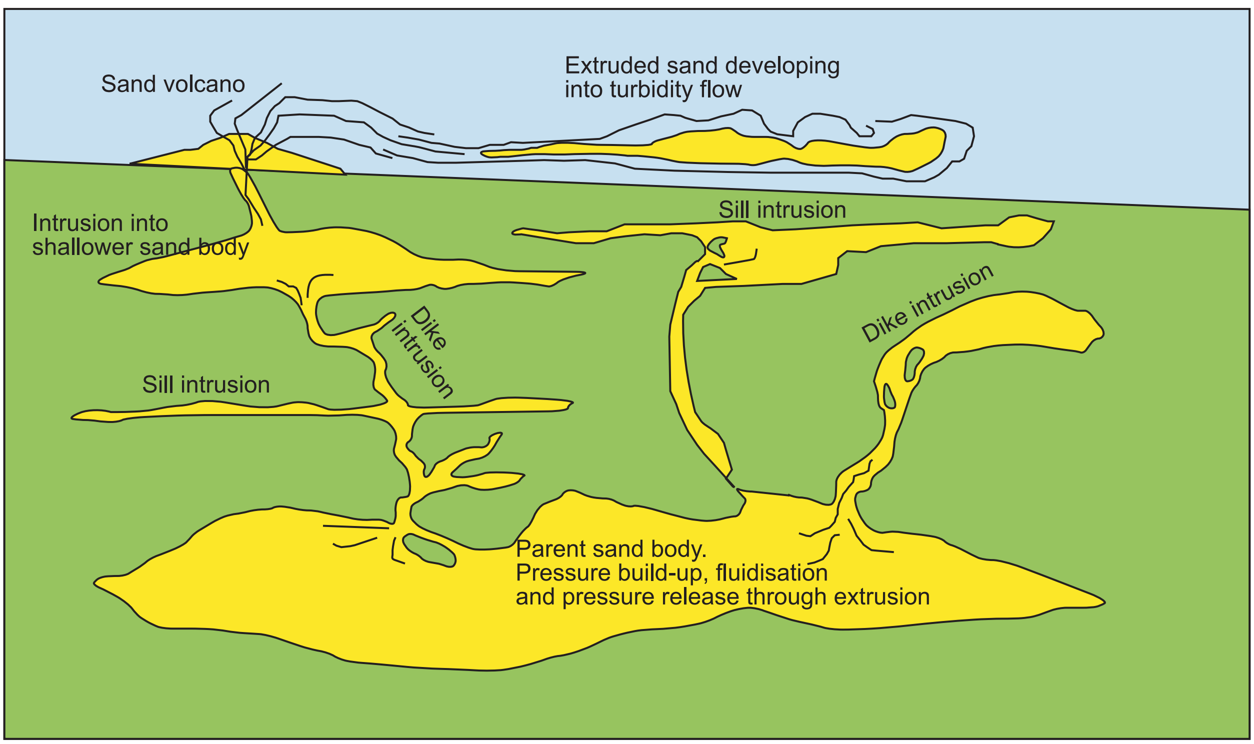


Fig. 27. Sketch showing different types of sand intrusion and sand extrusion.

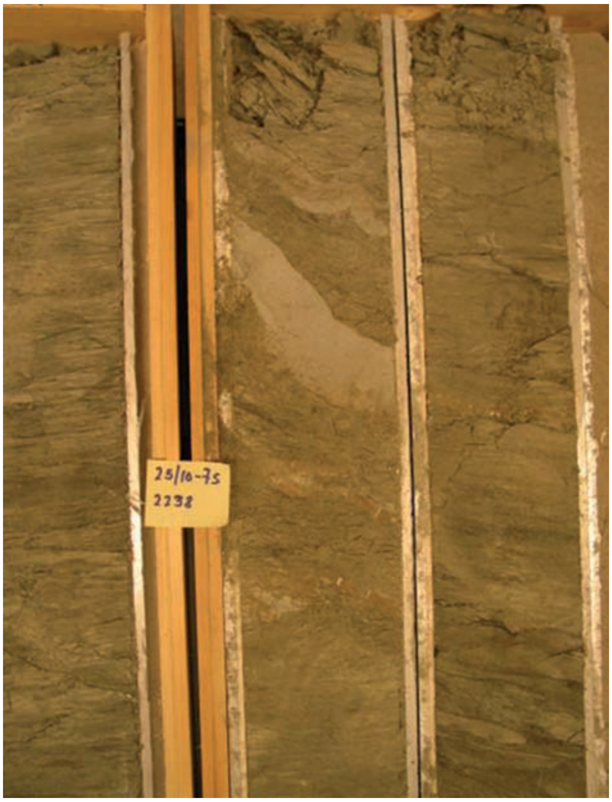


Fig. 28. Sandy dike injectites. Core example from the upper parts of the Lista Formation in well 25/10-7s at 2,238 m. Photograph from *http://www.npd.no*.

Fig. 29. Sandy sill injectite. Example from the Balder Formation well 25/11-23 at 1,762–1,766 m. Photo from NPD Factpages on http://www.npd.no.

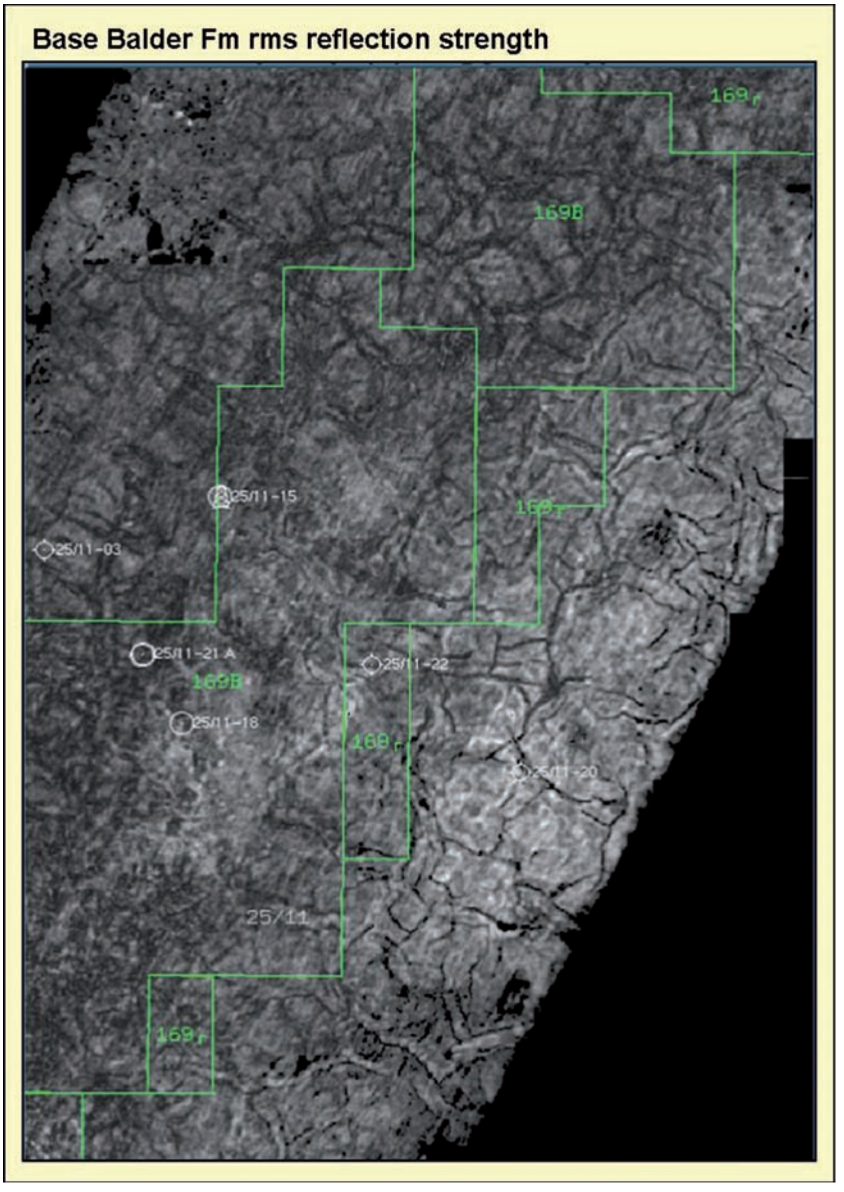


Fig. 30. Polygonal fault patterns seen from seismic amplitude map of the base Balder Formation seismic surface in the Grane area.

According to Dewhurst et al. (1999) the structure and geometry of the fault system are controlled by the colloidal nature of the sediments, and the volumetric contraction measured on seismic scale can be accounted for by syneresis of colloidal smectitic gels during early compaction.

Syneresis results from the spontaneous contraction of a sedimentary gel without evaporation of the constituent pore fluid. This process occurs due to the domination of interparticle attractive forces in marine clays, dependent on environment, and is governed by the change of gel permeability and viscosity with progressive compaction. The process of syneresis can account for a number of structural features observed within the fault systems, such as tiers of faults, the location of maximum fault throw and growth components at upper fault tips (Dewhurst et al. 1999).

Slides and slumps

In some areas chaotic folds associated with sub-horizontal shear planes through the sediments are seen from drill cores, and are evidence of slumping and sliding of sediments (Figure 31). Slumping is seen to be developed in association with movements on slopes, but also in connection with slide movements away from growing salt diapirs.

Fig. 31. Example of slump folded sediments. Example is taken from the Lista Formation in well UK30/14-1, Flyndre Discovery, close to the UK/NOR border. Photograph by H. Brunstad.

Wireline log correlations

For this study, a series of lithostratigraphic wireline log correlations have been made at four steps from north to south in the Norwegian North Sea (Figures 32 through 37).

Biostratigraphy, and age

The top of the Rogaland Group (top of the Balder Formation) is characterized by impoverished shelly microfossil assemblages, dominated by pyritized diatoms containing *Fenestrella antiqua* of Early Ypresian age (Knox and Holloway 1992, Mudge and Bujak 1996, Gradstein and Bäckström 1996).

The base of the Rogaland Group coincides closely with the last occurrence of *Senoniasphaera inornata* (Mudge and Bujak 1996). It is marked by a reduction in diversity of benthic assemblages towards the underlying Shetland Group (Knox and Holloway 1992). The age of the basal Rogaland Group is Late Danian. Table 3 shows diagnostic biostratigraphy events based on microfossils.

Correlation and subdivision

Segmentation of the Paleocene–lowermost Eocene into stratigraphic sequences was initiated by Stewart (1987), and has been continuously refined to date. Since the study of Knox and Holloway (1992) lithostratigraphic subdivision of this stratigraphic interval follows sequence stratigraphic boundaries. This is also the case for this study. The Paleocene succession in the North Sea contains two types of stratigraphic surfaces (e.g., Mudge and Bujak 1996, Mudge and Jones 2004):

1. High gamma value mudstones representing sediment condensation associated with maximum flooding surfaces (mfs.) and maximum marine transgression.

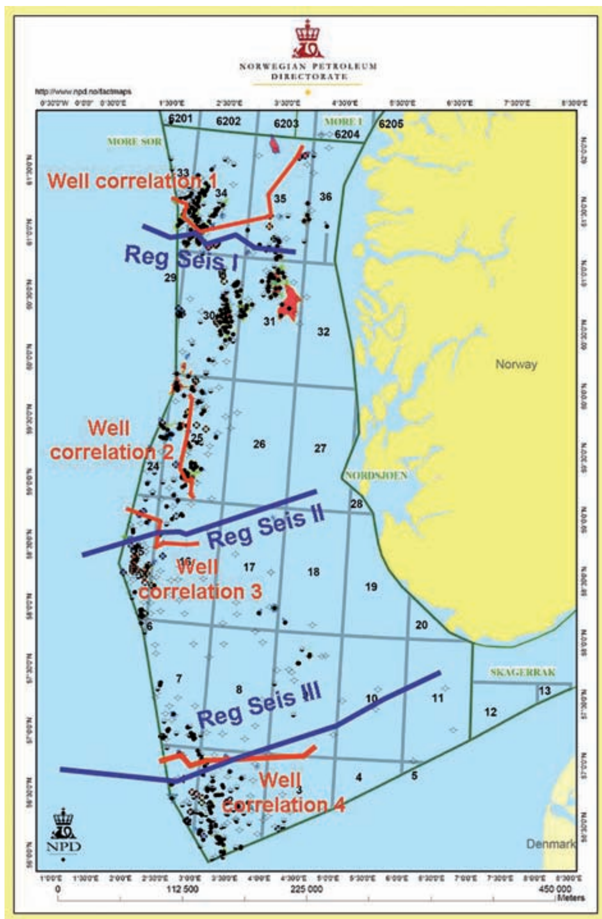


Fig. 32. Overview map showing orientation of regional seismic lines I–III and well correlation lines 1–4.

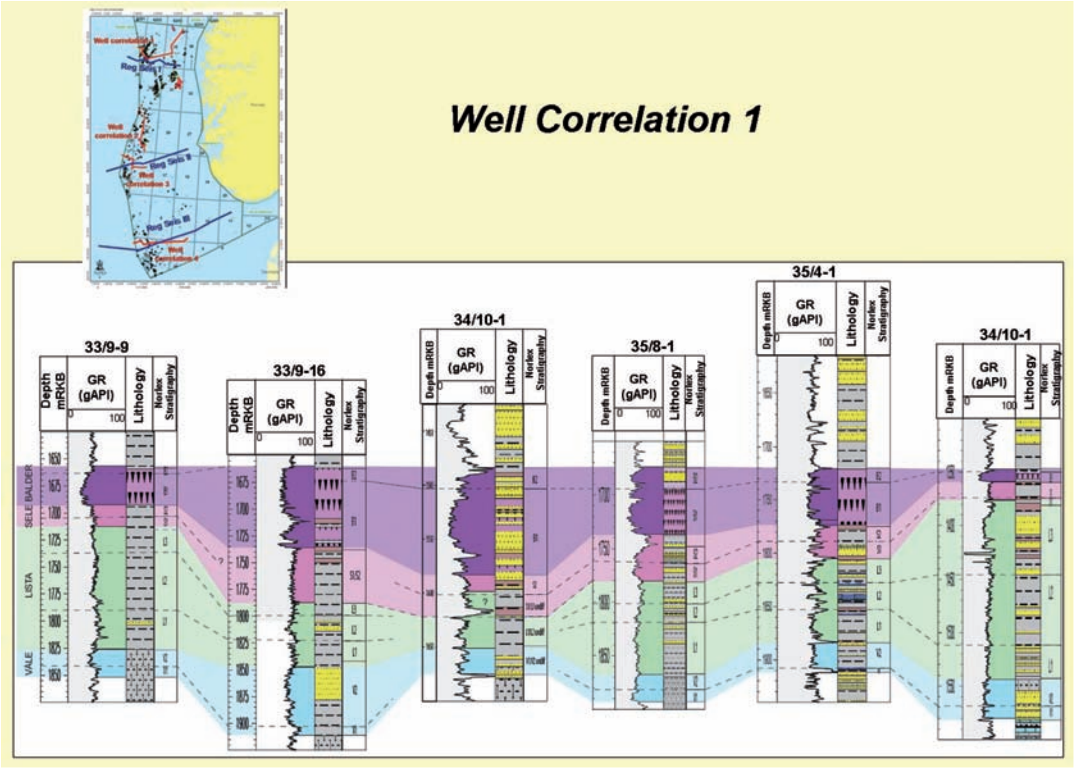


Fig. 33. Regional well correlation 1, northern North Sea.

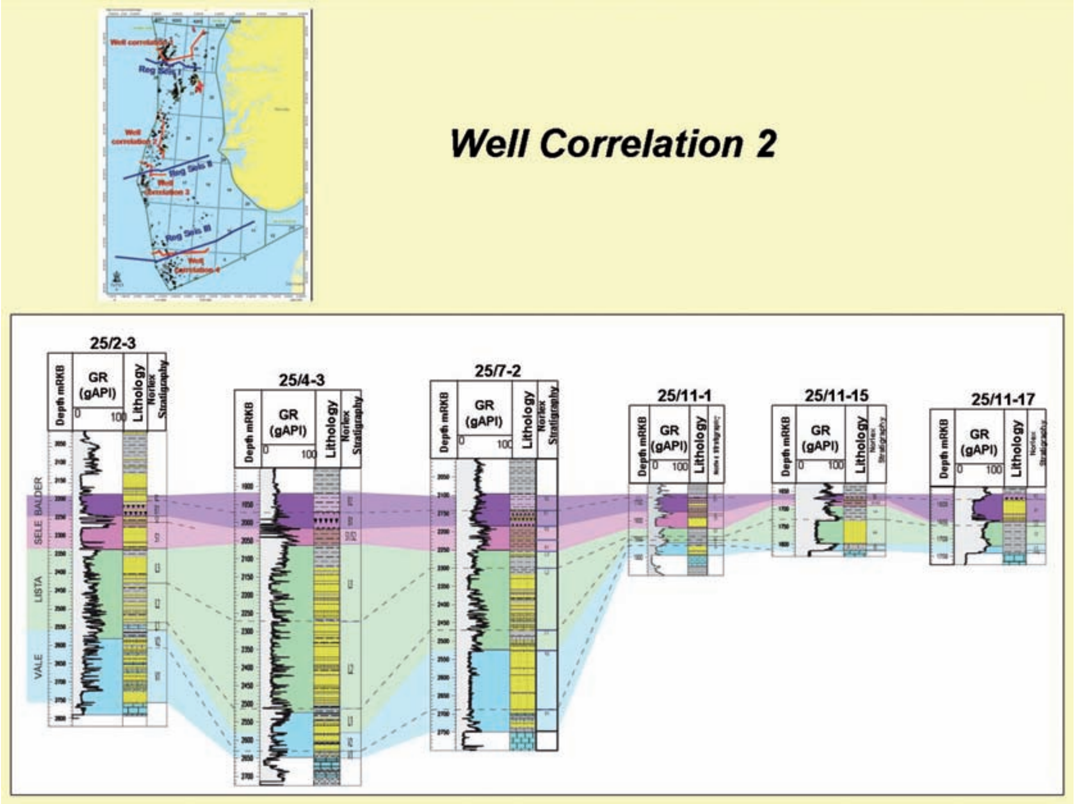


Fig. 34. Regional well correlation 2.

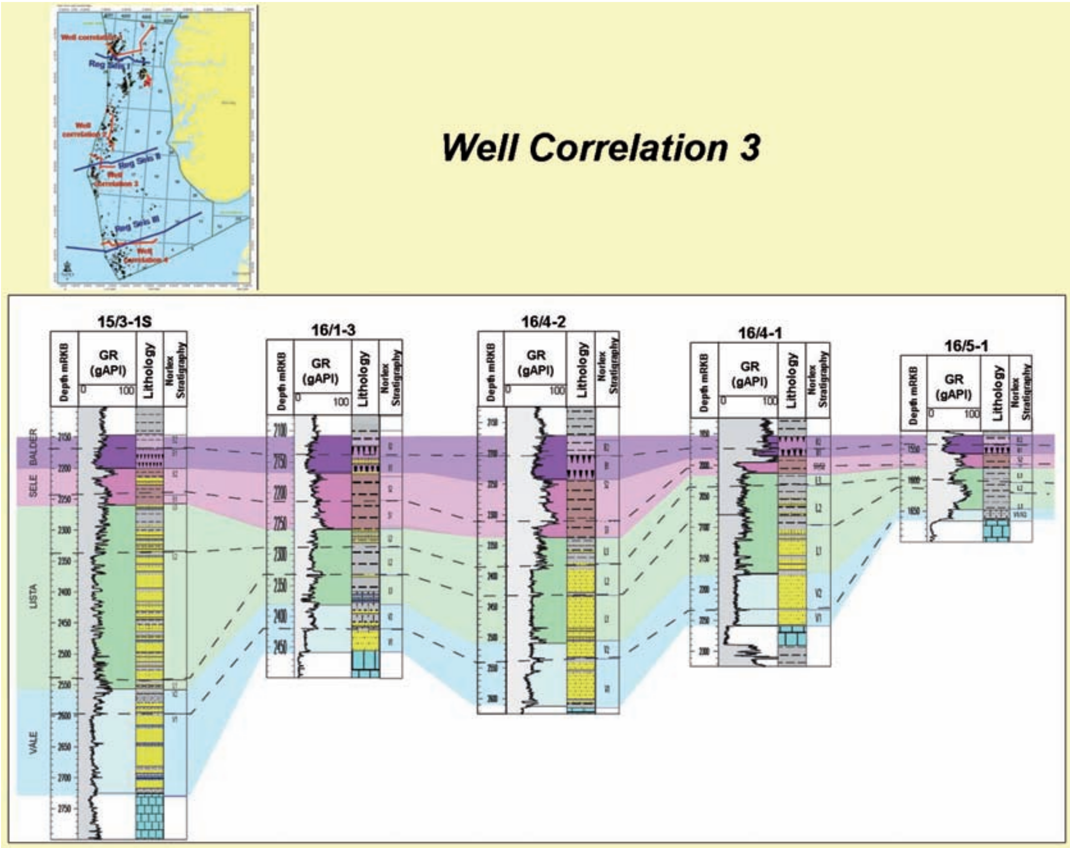


Fig. 35. Regional well correlation 3.

2. Unconformity surfaces overlain by sandstones and reworked chalk or tuff and representing submarine or subaerial erosion and missing section.

A refined sequence stratigraphic framework was established by Mudge and Bujak (1996), who used high-gamma value mudstones in combination with biostratigraphy to subdivide the Paleocene–lowermost Eocene succession (Rogaland Group plus the Ekofisk Formation of the Chalk Group) into stratigraphic sequences, high gamma mudstones being interpreted as maximum flooding surfaces. The stratigraphic position of these high-gamma mudstones shows a consistent relationship with microfossil bioevents and biostratigraphic levels (Mudge and Bujak 1996). These high-gamma mudstones have been used as background for the sequence stratigraphic subdivision of the shale formations in this study.

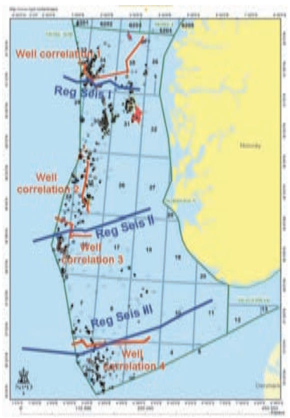
According to Mudge and Jones (2004) biostratigraphic dating allows the unconformity surfaces to be correlated throughout the North Sea Basin, as far south as the mid North Sea High. These authors found a series of short duration (0.1–0.3 my) unconformity–mfs couplets that may be recognized within the Danian (including the Ekofisk Formation) to lowest Ypresian interval. These uplift–subsidence cycles may have been caused by episodic plume related magmatic injection near the Moho and associated fluctuations in dynamic support, related to the initiation of the Iceland Plume. Alternatively, these cycles may reflect eustatic change (Mudge and Jones 2004).

Geographic distribution

The Rogaland Group is continuously present in the sedimentary fill of the Central Graben, Viking Graben and Sogn Graben. It is also present in the Måløy Terrace, in the Stord Basin and in the Norwegian–Danish Basin, but subcrops against younger strata of various ages in the eastern parts of these areas. Paleogeographic maps for the Rogaland Group are shown in Figure 38.

Depositional environments

The Rogaland Group was deposited in a bathyal to neritic environment. The majority of the wells in the



Well correlation 4, Alternative a

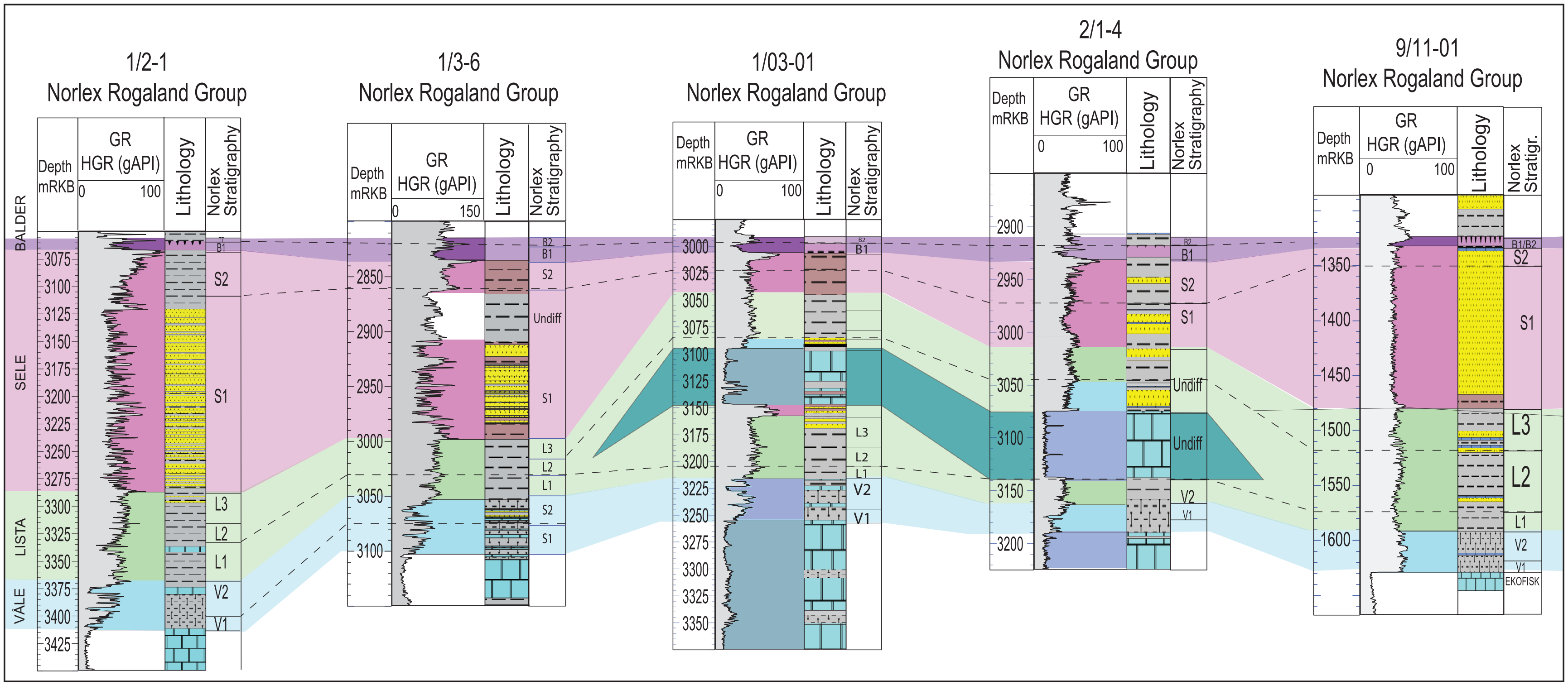


Fig. 36. Regional well correlation alternative 4a. Vidar Member deposited **before** Forties Member.

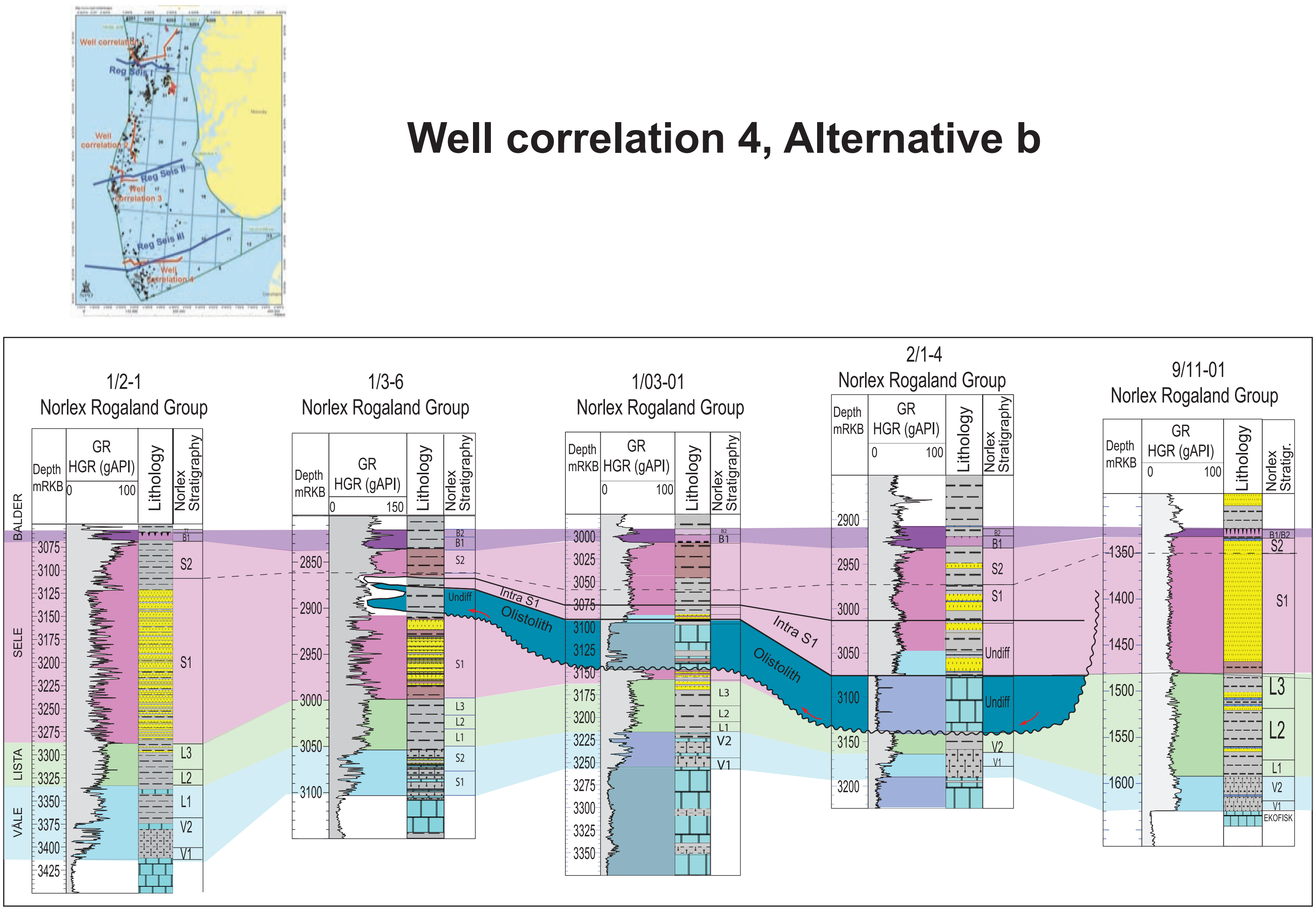


Fig. 37. Regional well correlation alternative 4b. Vidar Member deposited **after** the Forties Member.

Table 3 Some important biostratigraphic events of the Rogaland Group.

Formation	Shale Description	Dinocysts and Pollen Events	Microfaunal Events
Balder Formation Age: Early Ypresian	Dark grey to black, laminated shales with frequent tuff interbeds.	Top of unit slighly below top of *Deflandrea oebisfeldensis* top frequent *Deflandrea oebisfeldensis* Base of unit top acme of *Cenodinium wardenense*	Top of unit top *Fenestrella antiqua*
Sele Formation Age: Late Thanetian - Ypresian	Dark grey to black, laminated shales.	Top of unit top acme of *Cenodinium wardenense* Body of unit top *Apectodinium augustum* top *Cenodinium dartmoorium* top frequent *Inaperturopollenites* spp. and *Taxodiaceae* spp. Base of unit base *Apectodinium augustum*	The Sele Formation reflects and corresponds to closure of passages to and from the North Sea, resulting in a freshening of surface water mass and dysaerobia in deeper water mass, hence microfauna is rare and limited to few agglutinated taxa, including isolated *Trochamminoides* spp., plus pyritized diatoms of mostly *Fenestrella antiqua.*
Lista Formation Age: Late Selandian - Thanetian	Mostly green-grey bioturbated mud-stones sometimes with reddish interbeds. Parts may be more dark grey or grey brown in color.	Top of unit Last down-hole occurrence of an assemblage dominated by *Apectodinium* spp. Body of unit in order from young to old top *Alisocysta margarita* top *Areoligera gippingensis* top *Palaeocystodinium* cf. *australinum* top consistent *Palaeoperidinium pyrophorum* top acme *Palaeoperidinium pyrophorum* Base of unit Just below top acme *Palaeoperidinium pyrophorum* and top *Isabelidinium ?viborgense.*	Top of unit Low diversity agglutinated foraminiferal assemblage Body of unit contains in most likely stratigraphic order top *Reticulophragmium paupera* top *R. garcilassoi* (rare) top *Rzehakina minima* top *Saccamina placenta* last common occurrence *Spiroplectammina spectabilis* top *Ammoanita ruthvenmurrayi* top *Hormosina excelsa* top *Labrospira pacifica* (rare) top *Cystammina sveni* top *Ammoanita ingerlisae* (rare) Base of unit *Cenosphaera lenticularis*
Våle Formation Age: Late Danian - Early Selandian The Våle Formation belongs in the upper half of the foraminiferal zone NSR1 (Gradstein & Bäckström, 1996)	Light to dark grey bioturbated calcareous mudstones	Top of unit Just below top acme *Palaeoperidinium pyrophorum* and top *Isabelidinium ?viborgense.* Body of unit in order from young to old base *Alisocysta margarita* top *Thalassiphora* cf. *delicata* top *Damassadinium californicum* top *Spiniferites magnifica* top *Alisocysta reticulata* base *Palaeocystodinium bulliforme* Base of unit top *Senoniashaera inornata*	Top of unit *Cenosphaera lenticularis* Body of unit contains in most likely stratigraphic order top *Gavelinella beccariiformis* top *Remesella varians* top *Morozovella pseudobulloides* top *Globanomalina* cf. *compressa* top *Subbotina triloculinoides* top *"Globigerina" trivialis* Base of unit slighly above top of *Globoconusa daubjergensis* and *"Globigerina" simplicissima*

Norwegian North Sea have been drilled into deep-water deposits, with few penetrating shallow-water deposits. Since exploration has been focused in areas of basin that contain deep-water deposits, the under-standing of these is better than that of the shallow-water time-equivalent deposits.

It was Parker (1975) who first interpreted Paleocene sandstones of the North Sea to be submarine-fan sediments. It is now widely accepted that the dominant process for sand transport from the shelfal areas into the various basins and subbasins was confined and unconfined gravity flows derived from either point or line source areas (Reading and Richards 1994, Ahmadi et al. 2003). Depositional features of confined systems involve depositional channels, locally erosional channels, overbank and levee deposits and channelised lobes. Features of the unconfined systems include single terminal lobes, amalgamated and compensating lobes and submarine aprons (Ahmadi et al. 2003). In both confined and unconfined systems, sand deposition and preservation has been controlled by sea-floor topography. The sedimentation process included high and low-density sediment gravity flows, slurries, slumps and debris flows.

Low-density gravity flow deposits are commonly observed in overbank deposits of levee and crevasse splays, in distal terminal lobes and distal submarine aprons. They may also be a result of flow stripping from high-density gravity flows. Slumps are common features in the overbank deposits (Ahmadi et al. 2003). High-density gravity-flow deposits often occur in confined channels, proximal terminal lobes and sub-

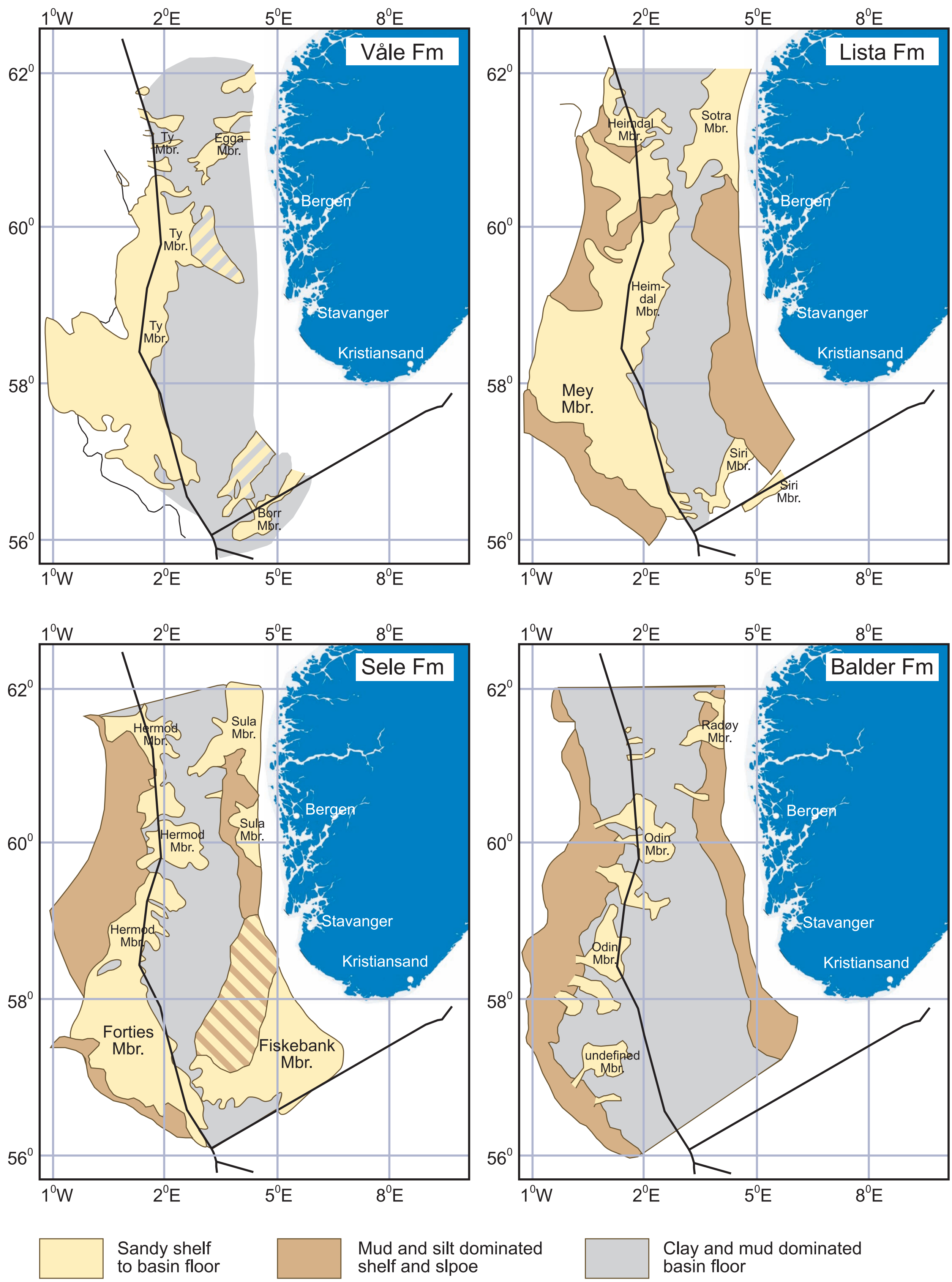


Fig. 38. Regional distribution of the formations and members of the Rogaland Group.

marine aprons, where they exhibit massive, unstructured sandstones, massive sandstones with load and dish structures and planar-laminated sandstones. High sedimentation rates and dipping morphological gradient frequently led to post-depositional mobilization and redeposition of sediments seen as debris flow deposits, sandy injectites and slumps.

Volcanic activity and deposition of tuffs

The volcanic tuffs have already been mentioned above. In the North Sea, tuffs were mostly deposited in the Balder formation, but minor tuff stringers are also sometimes seen in the Lista and Sele Formations. These tuffs are deposits from air-borne volcanic ash material settling on the seafloor. Commonly a bright grey color is observed in the tuffite layers/stringers, but may change into pale greenish grey.

Classification of sand type and prediction of sand presence from Sand/Gross ratio (S/G) cross plotting

By Sand/Gross ratio is meant the relative proportions (cumulative sand thickness) of sand in a gross stratigraphic interval, read as a fraction. Cross-plotting of S/G from wells is a technique that has been much used to predict sand/reservoir presence in Paleocene exploration targets. By cross-plotting S/G data from wells drilled in a certain area, a prediction of background shale, shale cut-off, sand thickness and S/G ratio of a prospect can be made. The technique is most reliable in basinal positions, and must be limited to subbasins and subsystems since there is much variability between individual subbasins.

As a working hypothesis the following values are commonly adopted (after Reading and Richards 1994): Sand-rich deep marine systems have S/G ratio 1.0–0.6, mixed sand–mud systems 0.6–0.3, and mud-rich systems < 0.3. Some S/G-plots are shown in Figures 39 through 41. It must be stressed that this technique works best in basinal position with aggradation, and does normally not give a good correlation in prograding slope settings.

Importance of provenance areas

The major source areas for sands being shed into the North Sea Basin are the East Shetland platform and southwestern Fennoscandia. Sandstones vary in composition from almost pure quartzite to arenaceous sandstone to highly micaceous or glauconitic sandstone. This is a result of such factors as:

- Maternal rock composition,
  - Generation from igneous/metamorphous (first order sand) or
  - Generation from sedimentary rocks (second order sand grains).
- Weathering processes and alteration of feldspar to clay and mica.
- Grain sorting processes.
- Shelf width.
- Sub-aqueous mineral precipitation and aggregation of glaucony and glauconite/chamosite grains.

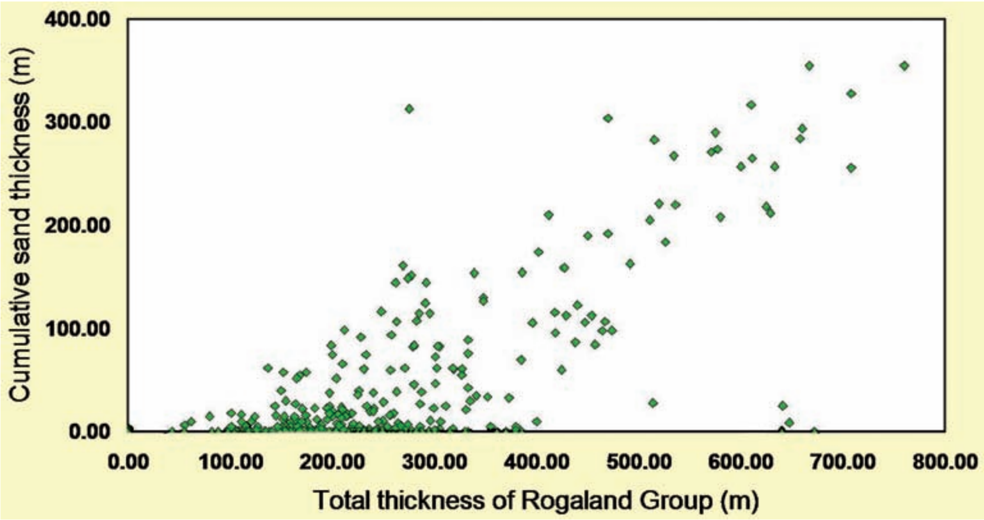


Fig. 39. Sand/gross ratio for the Rogaland Group from ~300 wells in the Norwegian North Sea; from Brunstad (2002).

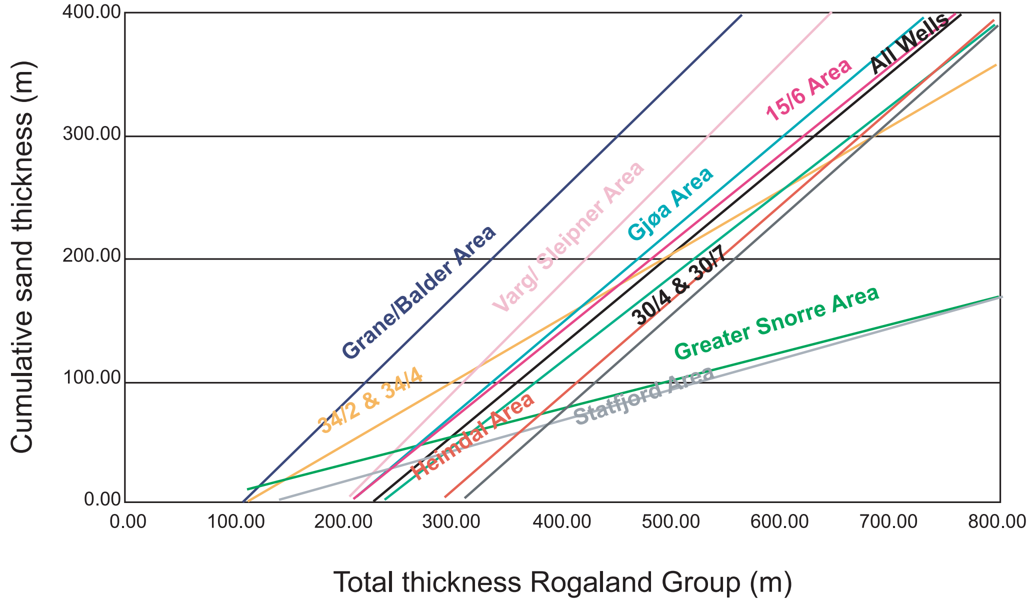


Fig. 40. Sand/gross trends for the Rogaland Group. Trend lines are based on cross plots of wells in various Sub Areas of the North Sea; from Brunstad (2002).

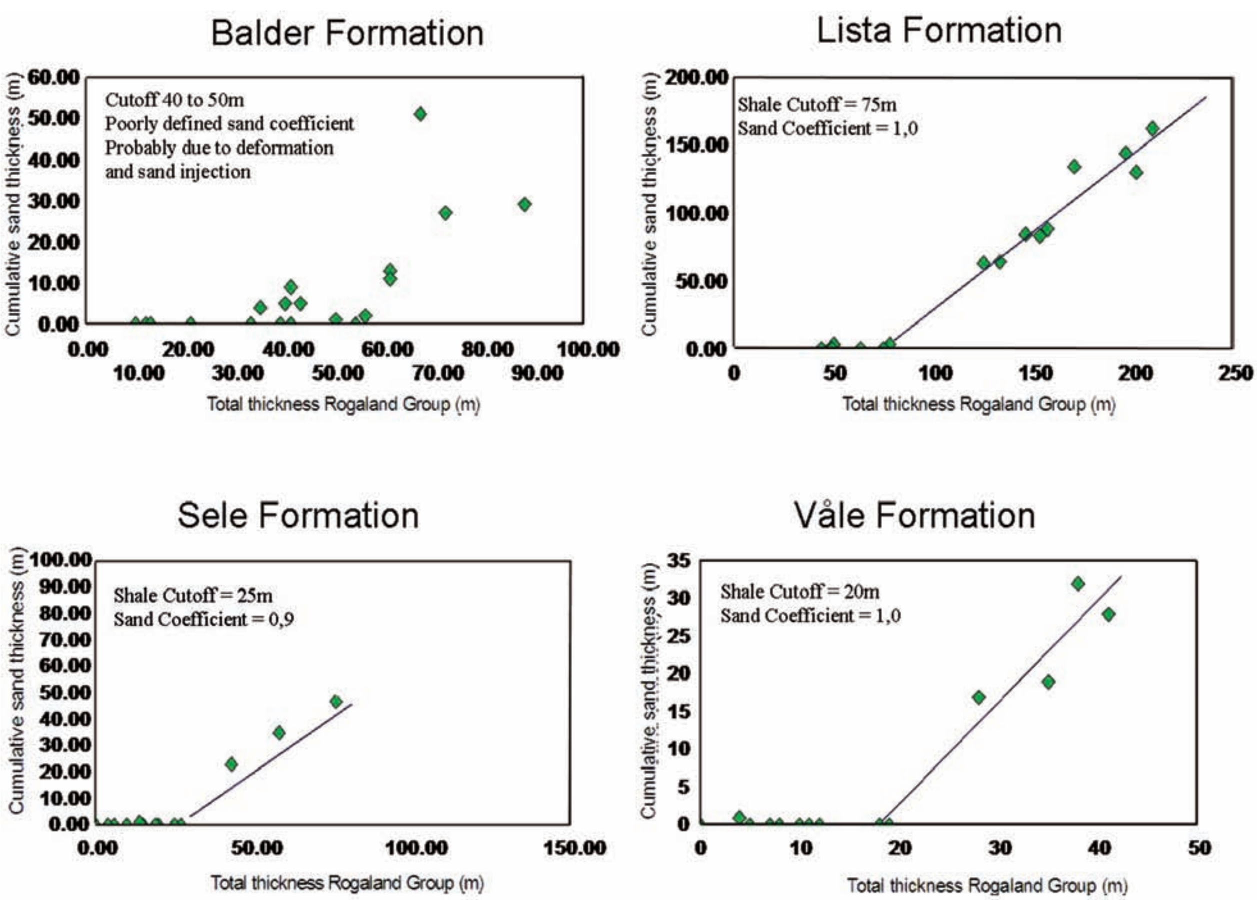


Fig. 41. Sand/gross from cross plotting of each of the formations of the Rogaland Group in Southern parts of Quadrant 25; from Brunstad (2002). Crossing point with the horizontal axis gives the threshold thickness for sand, whereas slope of line indicates N/G that can be expected for sandstone bodies in each of the formations.

Våle Formation with Members

Våle Formation

Below, a lithostratigraphic overview is given of the Våle Formation and its sandstone members (Figure 42).

Unit definition

Våle Formation is attributed to the lowermost, marly shales of the Rogaland Group.

Name

The Våle Formation was named by Hardt et al. (in Isaksen and Tonstad 1989), and is equivalent to the Maureen Formation in the UK.

Derivatio nominis

The Formation was named after the son of the Norse god Odin and his wife Rind.

Type well

Norwegian well 1/3-1 (Figure 43). Depth: 3,258–3,209 m (defined by Hardt et al. 1989). Coordinates: N 56° 51′ 21.00″, E 02° 51′ 05.00″. No cores.

Reference wells

Norwegian well 15/9-5 (Figure 44). Depth: 2,774–2,736 m. Coordinates: N 58° 24′ 12.47″, E 01° 42′ 29.20″. No cores. Well defined by Hardt et al. (1989).

Norwegian well 2/7-1 (Figure 45). Depth: 2,934–2,918 m. Coordinates: N 56° 25′ 44.68″, E 03° 12′ 14.21″. No cores. Well defined by Hardt et al. (1989).

Composition

The Våle Formation reflects a transition from pure chalks of the Shetland Group to the low carbonate content shales and mudstones of the Lista Formation. The formation is dominated by marls and/or mudstones with occurrences of sandstone and carbonate layers. Layers of reworked and redeposited Danian and Cretaceous chalk are common in the Central Graben and the southern Viking Graben. In the Central Graben the formation is developed as light grey marl, with chalk and limestone interbeds often eroded from actively rising diapirs. In the southern Viking Graben area chalk and limestone interbeds are sparser (Hardt et al. 1989). From cores, bioturbation in the Våle Formation is seen to vary between major and minor occurrences of variably sized trace fossils. Marly intervals are commonly intensively bioturbated, with rather large burrows. A core photo example of the Våle Formation is shown in Figure 46.

Wire line log characterization

Lower boundary
In the central North Sea, the Norwegian–Danish Basin and the southern Viking Graben pure chalks and marls of the Shetland Group stratigraphically upwards usually change abruptly to marly mudstones with local sandstones and thin interbeds of limestone of the Våle formation. Gamma ray logs show an abrupt change from pure chalk with a constant baseline of low gamma-ray response to the overall, but irregularly, increasing gamma values through the overlying Våle Formation.

In the northern North Sea the basal boundary is not as evident as further south because the Upper Cretaceous is significantly less calcareous, and from lithology alone the Våle Formation is sometimes difficult to distinguish from the underlying Shetland Group.

Upper boundary
The upper boundary of the Våle Formation is marked by a change from dark grey, silty and variously calcareous mudstones to the bioturbated, green and locally red-tinted, commonly waxy shales of the overlying Lista Formation. From wire line logs, the top of the Våle Formation is picked where the overall increase in gamma-ray and decrease in sonic velocity bends again to a baseline of more constantly high gamma readings and relatively low sonic velocity of the Lista Formation. The boundary is commonly associated with a high gamma peak and may be established with support from the first downhole occurrence of *Cenosphaera lenticularis*.

Thickness

The thickness of the Våle Formation varies greatly. Including its sandstone members, it reaches a maximum thickness of 290 m in well 25/3-1, and in well 25/2-1 a thickness of 268 m is recorded. At other places, like in 16/1-4 on the Utsira High it is very thin (17 m), or absent, as in well 3/5-2 on the Sørvestlandet High.

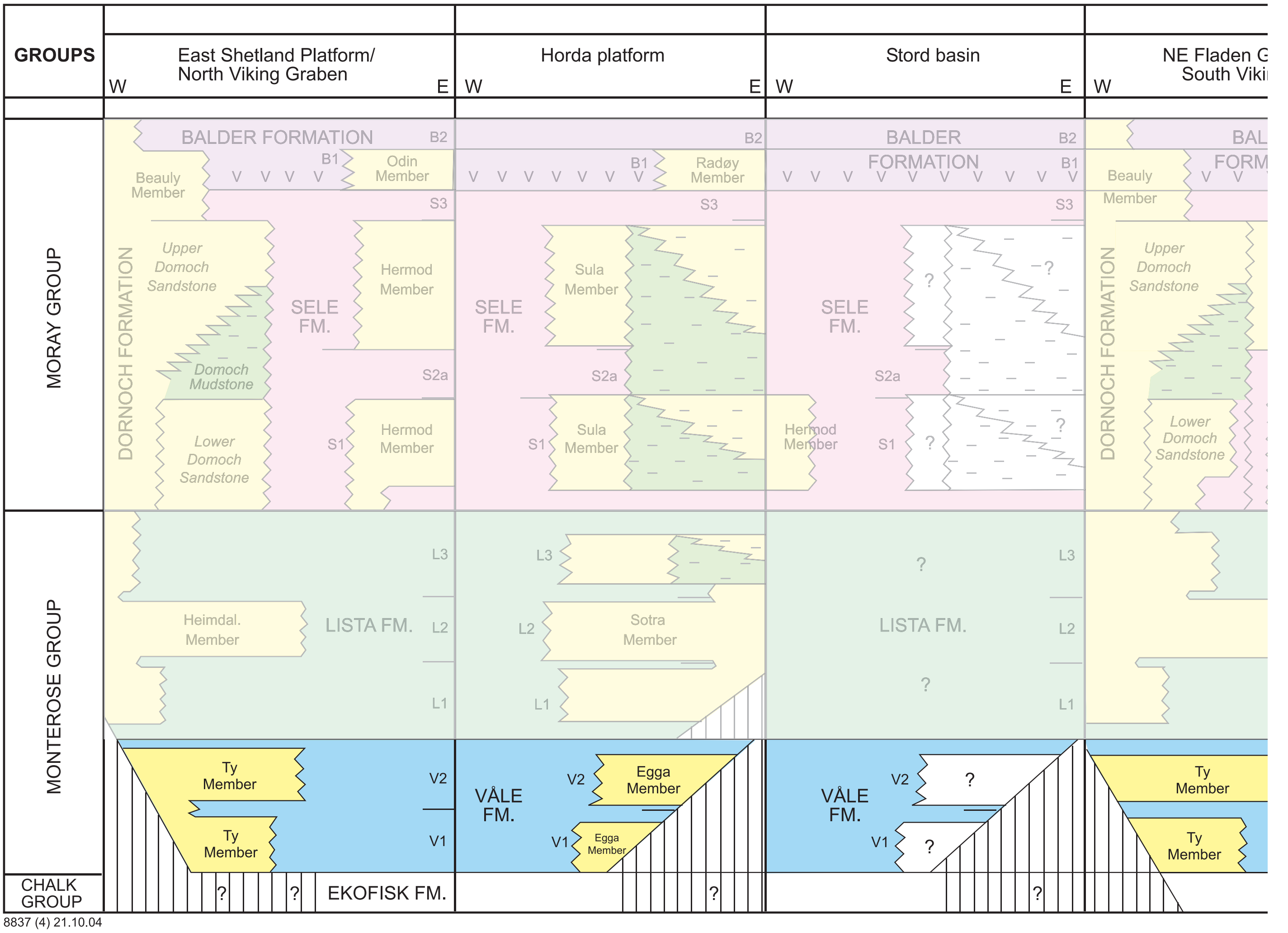


Fig. 42. Lithostratigraphic summary chart of the Våle Formation (color) with members.

Seismic characterization

The top of the Våle Formation can often be picked at a seismic reflector defining a downward shift from lower velocity and density in the shales of the Lista Formation to higher velocity and density in the Våle Formation, giving positive acoustic impedance. This is locally disturbed by the presence of sandstone members close to the boundary between the two formations.

Internal seismic character is highly variable, spanning from parallel to chaotic, with continuous to discontinuous internal reflections of highly variable amplitude.

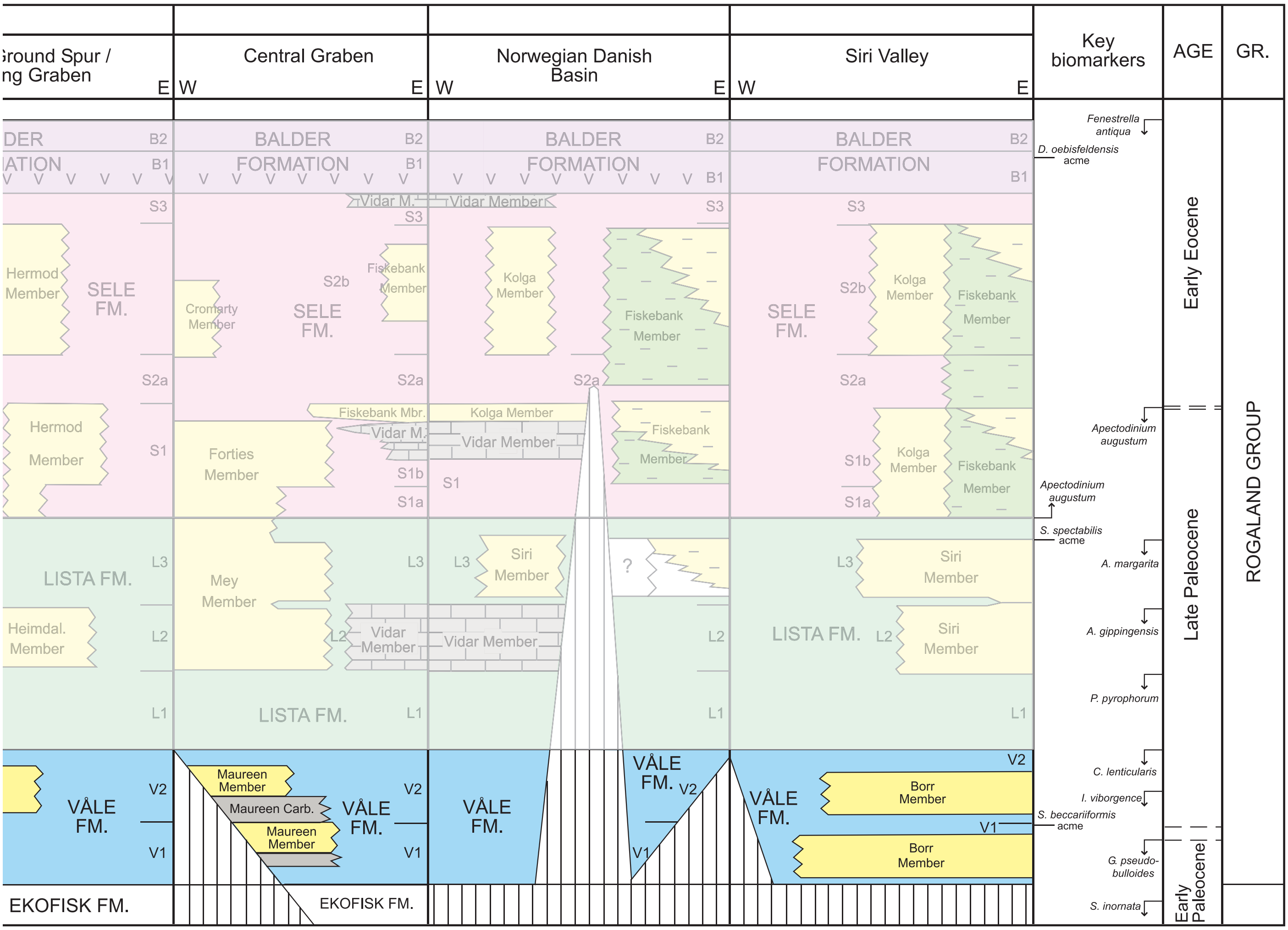
The most pronounced seismic reflector associated with the Våle Formation is the top Shetland/Base Våle interboundary. This boundary is usually seen as a marked high amplitude event highlighting the boundary between the hard and high velocity chalk sediment and the lower velocity marly shales of the Våle Formation. However, locally interfingering and reworked chalk beds in the lower parts of the Våle Formation make the boundary difficult to establish.

Age

The Våle Formation is of Early to Late Paleocene (Danian to earliest Thanetian) age, and spans about 2 myr (cf. Mudge and Bujak 1996).

Biostratigraphy

The top of the Våle Formation is picked below the top of *I. ? viborgense* (Iv) and above the top of *T.* cf. *delicata* (Td), and falls within the *Cenodiscus* zone.



Correlation and sub division

Based on the sequence stratigraphic zonation established by Mudge and Bujak (1996) with maximum flooding surfaces or condensation surfaces associated with specific chronostratigraphic bioevents, the Våle Formation can be subdivided into a lower (V1) and an upper (V2) part.

The base of the V1 is picked at the intra-Danian unconformity. This surface is associated with a major influx of sand and reworked chalk in the North Sea Basin. The V1 subzone is assigned to the planktonic interval of the Våle Formation (Mudge and Jones 2004), which contains an assemblage of *Parasubbotina pseudobulloides*, *Planorotalites compressus* and other planktonic foraminifera and the dinocyst taxa *Spiniferites magnificus* and *Alisocysta reticulata* (Figure 47). Because of the transition from a calcareous to a siliciclastic environment, there is no well developed high gamma shale associated with the flooding surface at top of the V1 zone. However, the "Near top Danian Unconformity", close to base of the V2 zone is often well expressed, and can be taken as an upper restrictive event. Biostratigraphically, the top of the V1 zone can be picked at the top of the *Spiniferites magnificus* dinocyst Zone and slightly below the top of the *Parasubbotina pseudobulloides* microfaunal Zone. The top of the V2 zone is picked at the high gamma shale that occurs between the *I. ? viborgense* and *T.* cf. *delicata* dinocyst zones and close to the top of *Cenosphaera lenticularis* microfaunal Zone.

The V2 is in general less marly and less carbonate-rich than the V1. The Våle Formation corresponds to the Maureen Formation of the UK sector, except for the sandstones. Internally within the Våle Formation there are several sandstone members (Figures 12, 13 and 42). The Borr and the Egga members have an east-

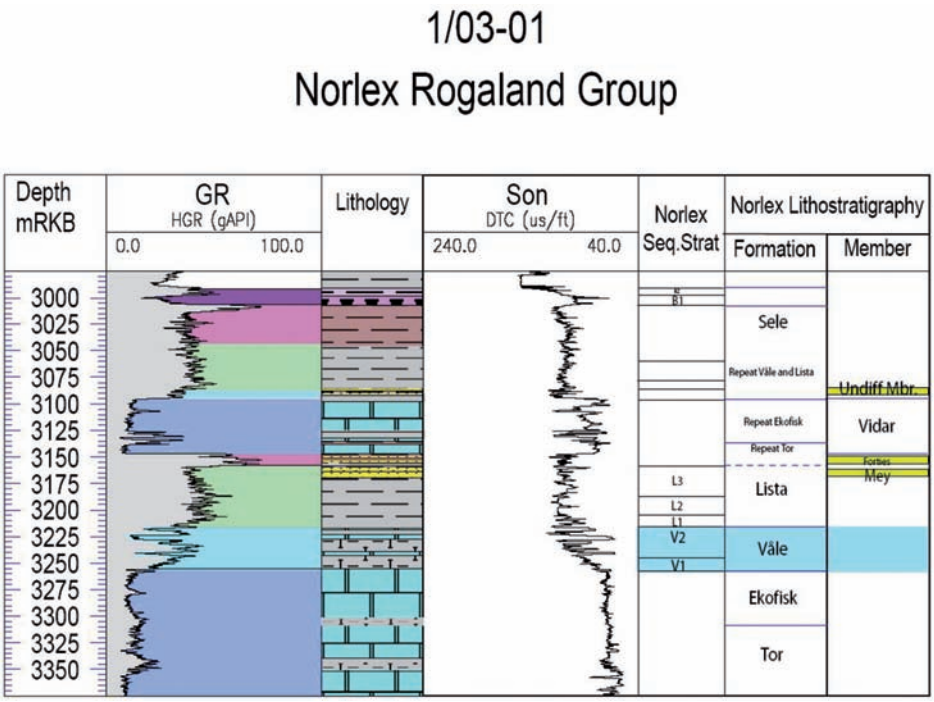


Fig. 43. Well 1/3-1 composite log Rogaland Group. Stratigraphic position of the Våle Formation is outlined in the stratigraphic column to the right.

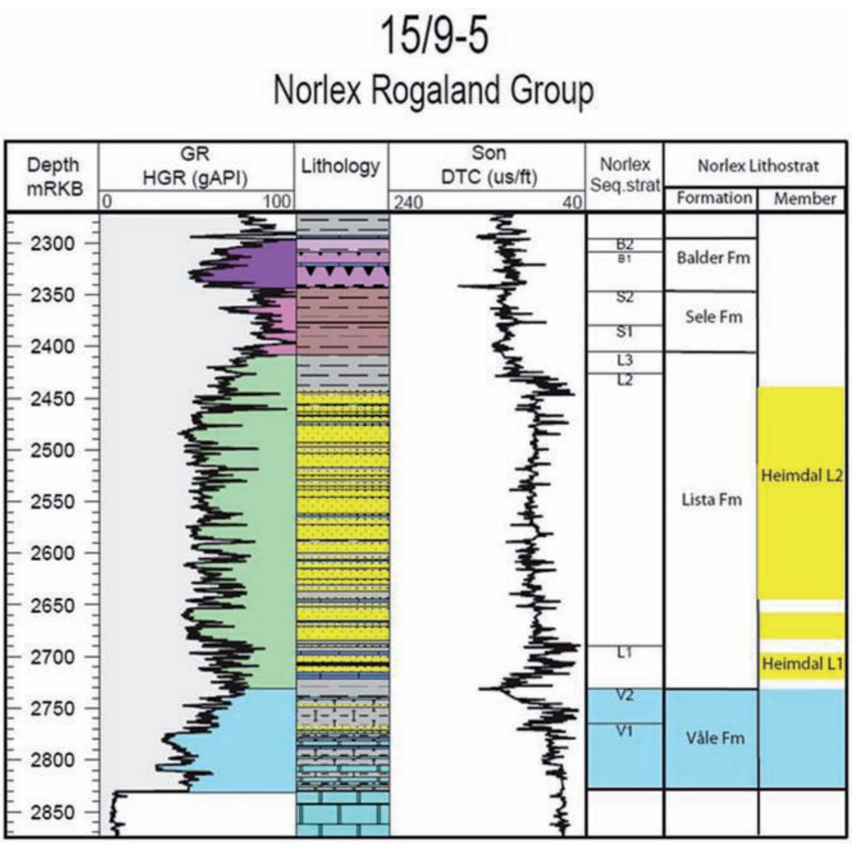


Fig. 44. Well 15/9-1 composite log Rogaland Group. Stratigraphic position of the Våle Formation is outlined in stratigraphic column to the right.

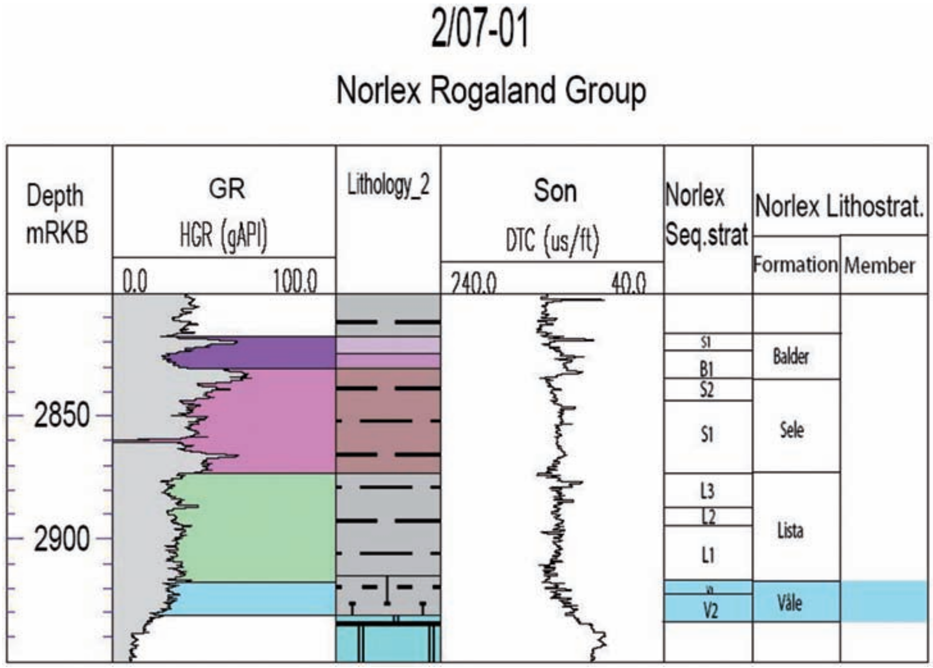


Fig. 45. Well 2/7-1 composite log Rogaland Group. Stratigraphic position of the Våle Formation is outlined in stratigraphic column to the right.

ern provenance (Fennoscandia), whereas the Ty and the Maureen member have a western provenance (East Shetland Platform).

In some areas a dark-colored, non-calcareous zone is found in the upper part of the Våle Formation. In the Danish sector of the Siri Canyon area this zone is named as a distinct member, the Vile Member. The same type of development can locally be seen also further north, e.g., in well 25/11-17, but we prefer not to give this part of the Våle Formation a separate member status in the Norwegian sector of the North Sea.

Geographic distribution

The Våle Formation (and intra-Maureen mudstones) is present along the topographic basin lows inherited from major Jurassic graben axes of the Central Graben, Viking Graben, Stord Basin and Måløy Terrace and in the Norwegian–Danish Basin. The formation is locally absent due to non-deposition or erosion at the Shetland Platform and along the eastern margins of the Måløy Terrace, the Horda Platform, the Stord Basin and the Norwegian–Danish Basin. On several basinal highs, such as the Utsira and the Jæren highs, the whole formation or parts of it are found to be absent due to local erosion or non-deposition. Figure 48 shows the distribution of the Våle Formation with sandstone members.

Depositional environment

The combined effect of a sea level drop in the Late Danian, with increased siliciclastic input from larger exposed terrestrial surfaces and overall climatic cooling gradually switched off the coccolithic carbonate systems of the Chalk Group.

The marly clay and siltstones that were deposited early in this interval were succeeded by less calcareous fines by the end of the Danian. The sea level drop at the beginning of this stage led to reworking and redeposition of chalky material. Subsequently, erosion decreased and the North Sea basin and its flanks were transgressed. In general, circulation in the basin was well established, especially in the beginning of this interval, reflected by the occurrence of large trace fossils. Transition to somewhat less oxygenated conditions towards the end of the interval is inferred from the presence of generally smaller trace fossils upwards in the Våle Formation.

Maureen Member, Våle Formation

Unit definition

Intra-Våle Formation sandstones in sub-area SW in Figures 12 and 13 are assigned to the Maureen Member, and stratigraphically belong to the oldest sandstones of the Rogaland Group in this area.

Fig. 46. Core example from the Våle Formation well 25/11-17 at 1,737–1,742 m, showing light to medium grey marly shales and calcite cemented fractures. Well drilled by Norsk Hydro. Photograph from *http://www.npd.no*.

Name

The Maureen Formation in the UK was defined by Deegan and Scull (1977) and attributed to a mixed lithology of Danian to Early Selandian age, i.e. time-equivalent to the Våle Formation. The same definition was used by Hardt et al. (1989) for the correlative lithologies stretching from the UK into the Norwegian part of the Central Graben, onlapping basin margins to the east.

Derivatio nominis

In this study we make a lithostratigraphic subdivision of the interval regarding the Norwegian part of the Central Graben. We attribute the name Maureen Member to sandstones internally in the Våle Formation of the Norwegian Central Graben, corresponding to the sandstone part of the Maureen Formation on the UK side.

Type well (new, this study)

We define Norwegian well 7/11-1 as the type well for the Maureen Member (earlier reference well). The stratigraphy of this well is redefined from the reference well for the Maureen Formation to the type well for the Maureen Member in the Norwegian sector:

Well 7/11-1 (Figure 49). Depth: 3,173–3,069 m. Coordinates: N 57° 04′ 15.60″, E 02° 26′ 24.40″. No cores.

Reference wells (new, this study)

Norwegian well 15/12-1 (Figure 50). Depth: 2,616–2,644 m. Coordinates: N 58° 10′ 32.60″, E 01° 44′ 23.10″. Core example 8642–9698′.

Composition

The Maureen Member shows much the same characteristics as the Ty sandstones, but displays more frequent interbeds of reworked chalk. The sandstones are generally fine grained. Thick units of clean, poorly sorted sandstones are present locally, but more commonly the sandstones occur as several packages of thinner units, often with a chalky matrix. Thin beds of muddy, matrix-supported sandstone with mudstone and limestone fragments are locally present in the upper part of the formation (Knox and Holloway 1992).

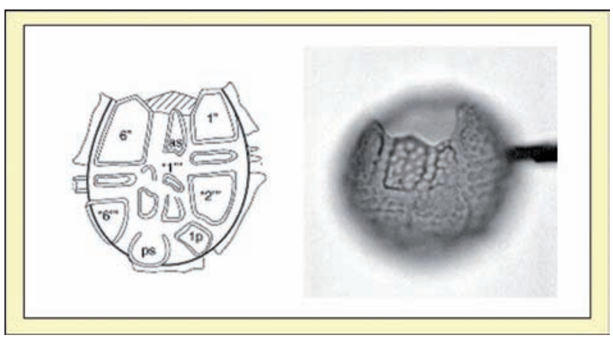


Fig. 47. Example of one of the diagnostic microfossils in the Våle Formation, *Alisocysta reticulata*, ventral view, with size: length = 55 µm, width = 51 µm. From the ODP Drilling Program at *http://www-odp.edu*.

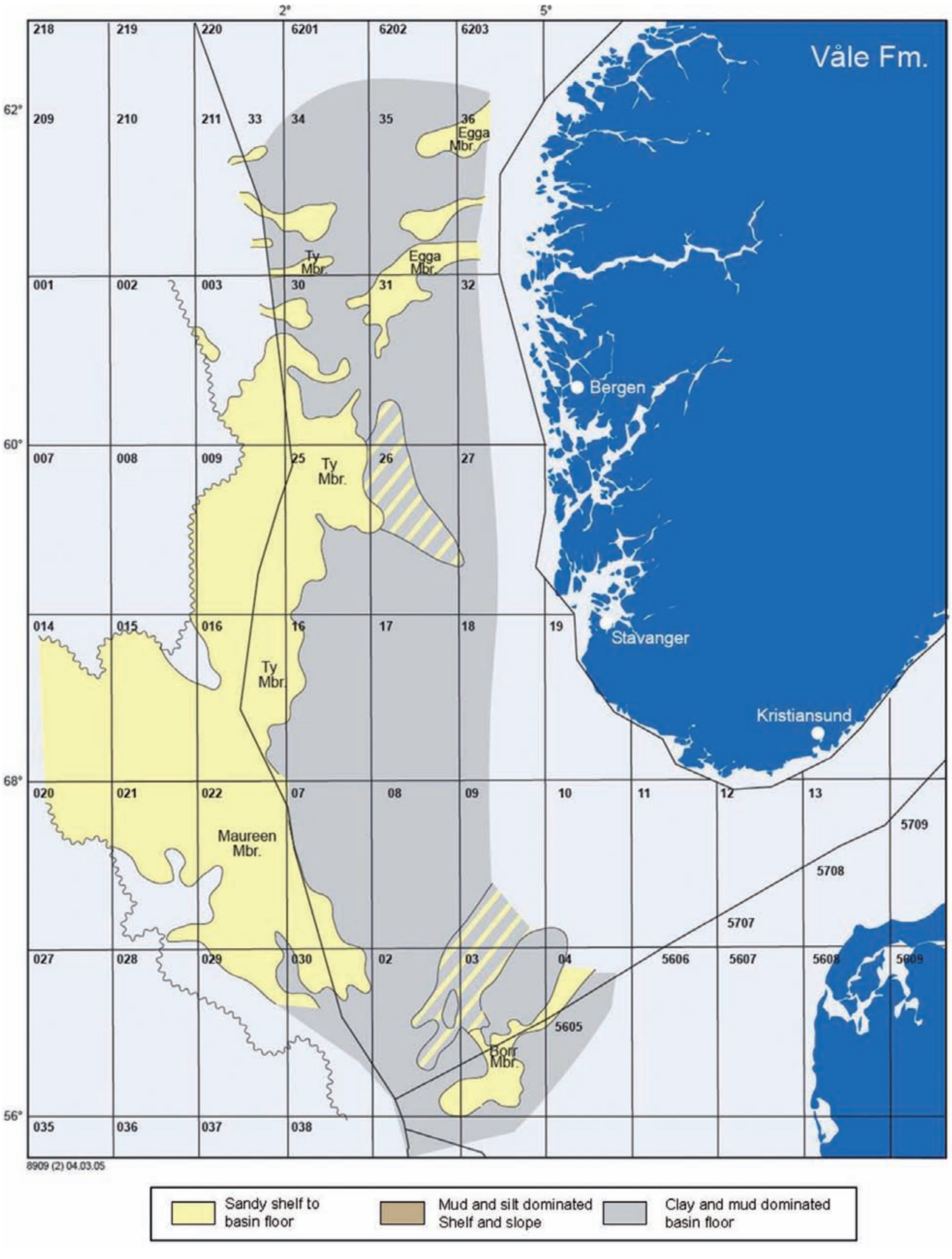


Fig. 48. Distribution of the Våle Formation and its sandstone members.

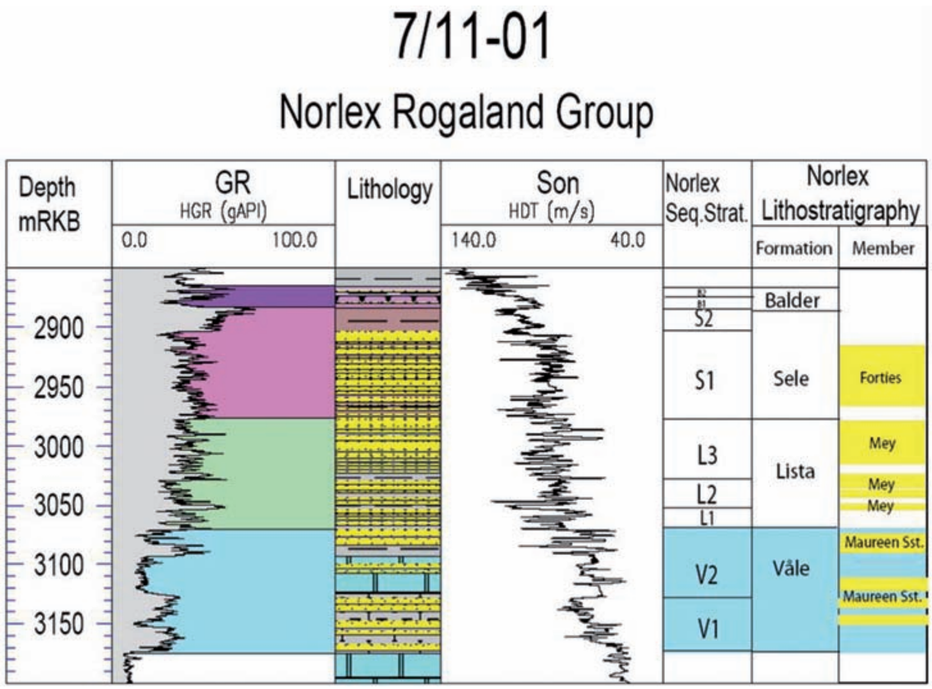


Fig. 49. Well 7/11-1 composite log Rogaland Group. Stratigraphic position of the Maureen Member is outlined in stratigraphic column to the right.

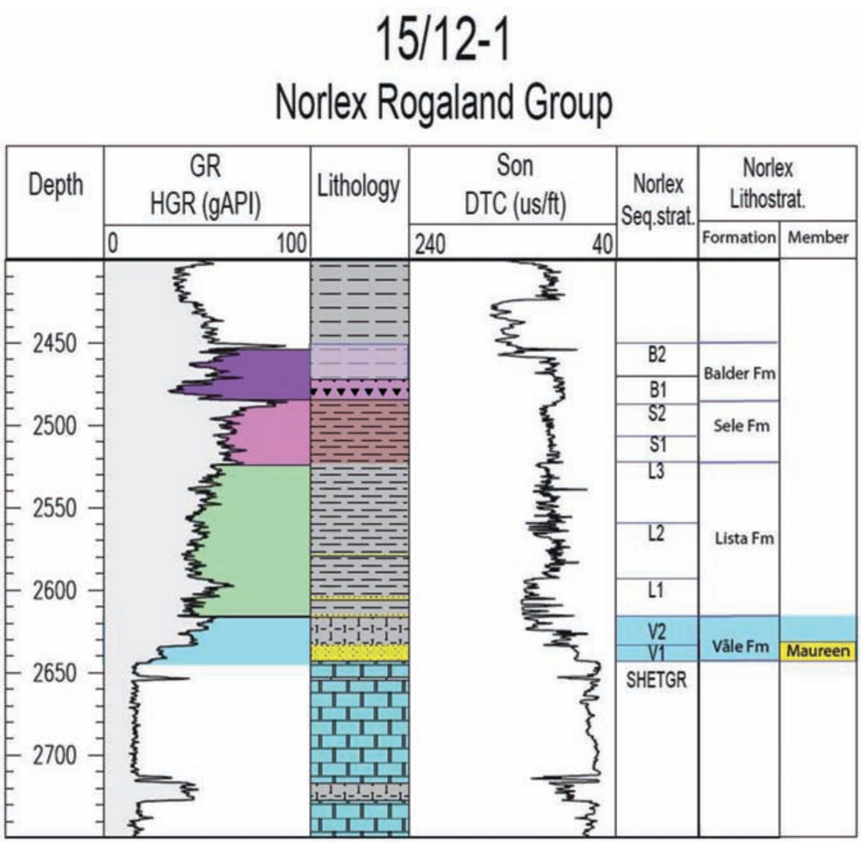


Fig. 50. Well 15/12-1 composite log Rogaland Group. Stratigraphic position of the Maureen Member is outlined in stratigraphic column to the right.

Wireline log characterization

From wire line logs sandstones of the Maureen Member are seen to have a blocky to serrated appearance. Carbonate interbeds are characterised by low gamma-ray readings and high velocity beds. The thickness of sandstones in the Maureen V2 Member (upper member, see text below) generally is larger and chalk interbeds are less frequent than in the Maureen V1 Member. Sonic logs indicate that the upper sandstones in general are less cemented than the lower Maureen V1 Member.

Upper boundary

The upper boundary is characterised by a downwards transition from higher gamma-ray readings and lower velocity in the Våle or Lista Formation to lower gamma-ray readings and higher velocity in the Maureen Member.

Lower boundary

The Maureen Member rests on Våle Formation strata, or directly on the Shetland Group. There is a distinct upwards change from low gamma-ray readings and high velocities in the calcareous sediments of the Shetland Group or the Våle Formation to higher and more irregular gamma-ray readings and decreasing velocities in the Maureen Member.

Thickness

In the Norwegian Central Graben area, the Maureen Member usually is of m-scale to a few tens of meters in thickness. In the type well 7/11-1 the thickness is 104 m, and in reference well 15/12-1 it is 28 m. The thickness of corresponding sandstone beds on UK side of the Graben may be substantially larger, with up to 400 m of mainly sandstones in the Witch Ground Graben (Hardt et al. 1989).

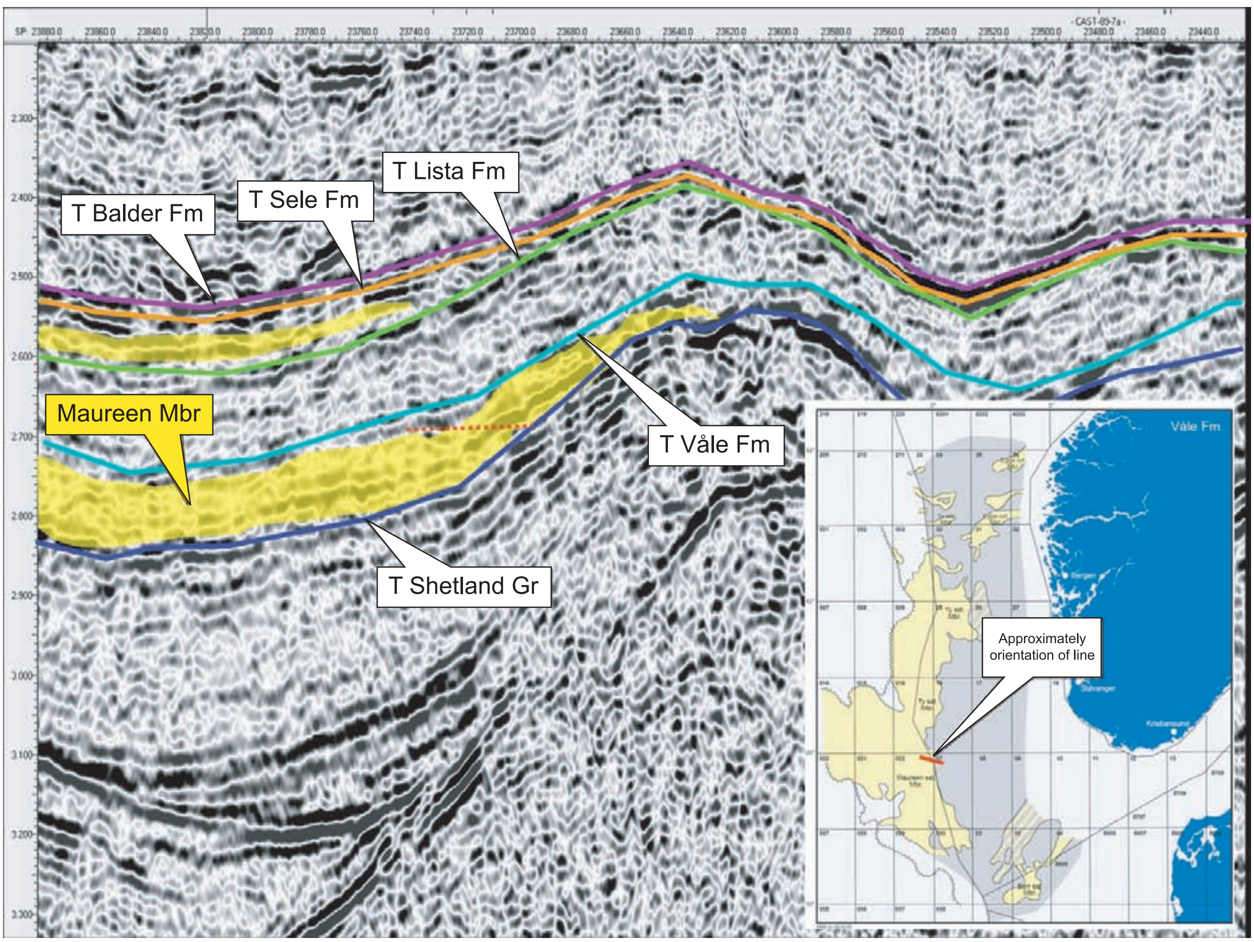


Fig. 51. Seismic section through the northern Central Graben with sandstones of the Maureen Member pinching out in the Everest Field (Armada Complex).

Seismic characterization

The Maureen Member generally consists of laterally stacked seismic bodies of lenticular to mounded character (Figure 51). They are interbedded with and interrupted by interlayers of reworked chalk. This gives variable continuity and character. Because amplitudes of internal seismic reflectors also vary substantially, the Maureen Member can be difficult to map seismically.

Age

The age of the Maureen Member is Danian to Early Selandian (Morton et al. 1993, Neal 1996, Mudge and Bujak 1996).

Biostratigraphy

The top occurrence of *S. magnificus* is characteristic for the Maureen Member in the lower part of the Våle Formation, whereas the dinocyst *I. ? viborgense* (bio-event Iv.) is typical of the upper parts. Top Iv. normally occurs near the top of the Våle Formation, or slightly into the Lista Formation (Mudge and Bujak 1996).

Correlation and sub division

It is possible to subdivide the Member into two units: MaureenV1 and MaureenV2 Sub-members. The MaureenV1 Sub-member is found in the lower Våle interval, the MaureenV2 Sub-member in the upper. The two can be distinguished biostratigraphically by the *S. beccariformis* acme, which separates Upper and Lower Våle Formation.

Geographic distribution

The Maureen Member is an extensive sandstone interval in the Våle Formation in the Norwegian Central Graben. The member is limited south eastwards by the Jæren High, and to the north by the member separation line from Fladen Ground Spur to the southern end of

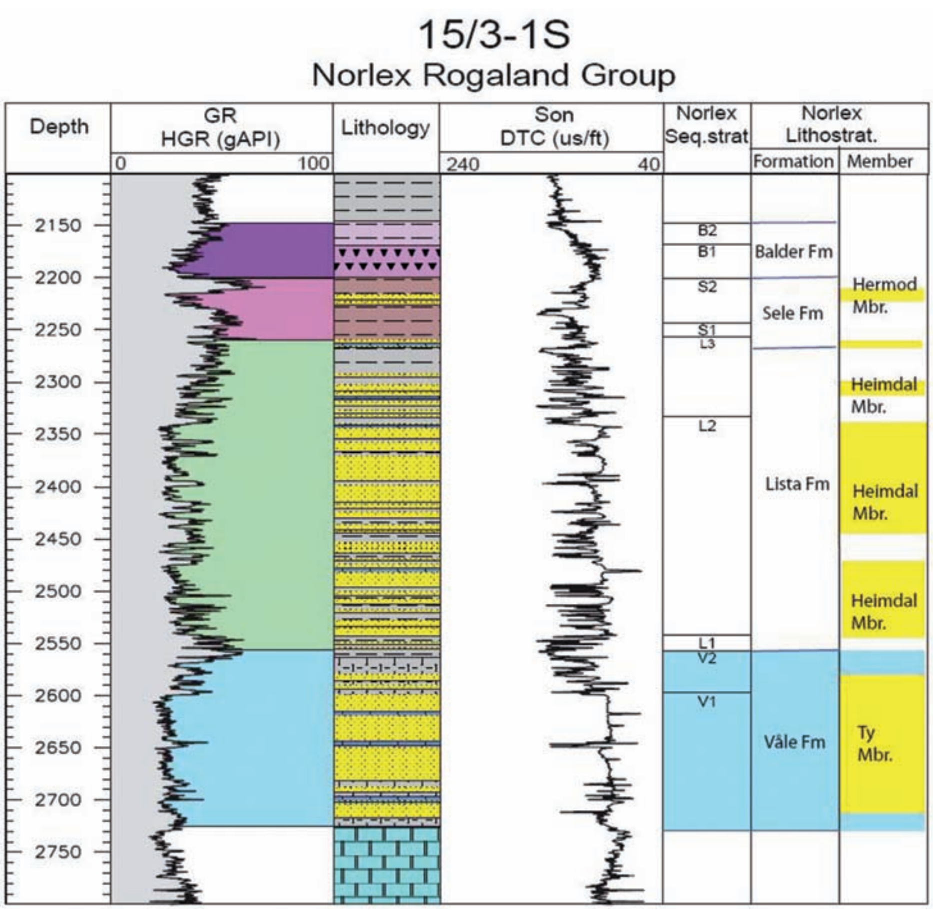


Fig. 52. Well 15/3-1S composite log Rogaland Group. Stratigraphic position of the Ty Member is outlined in stratigraphic column to the right.

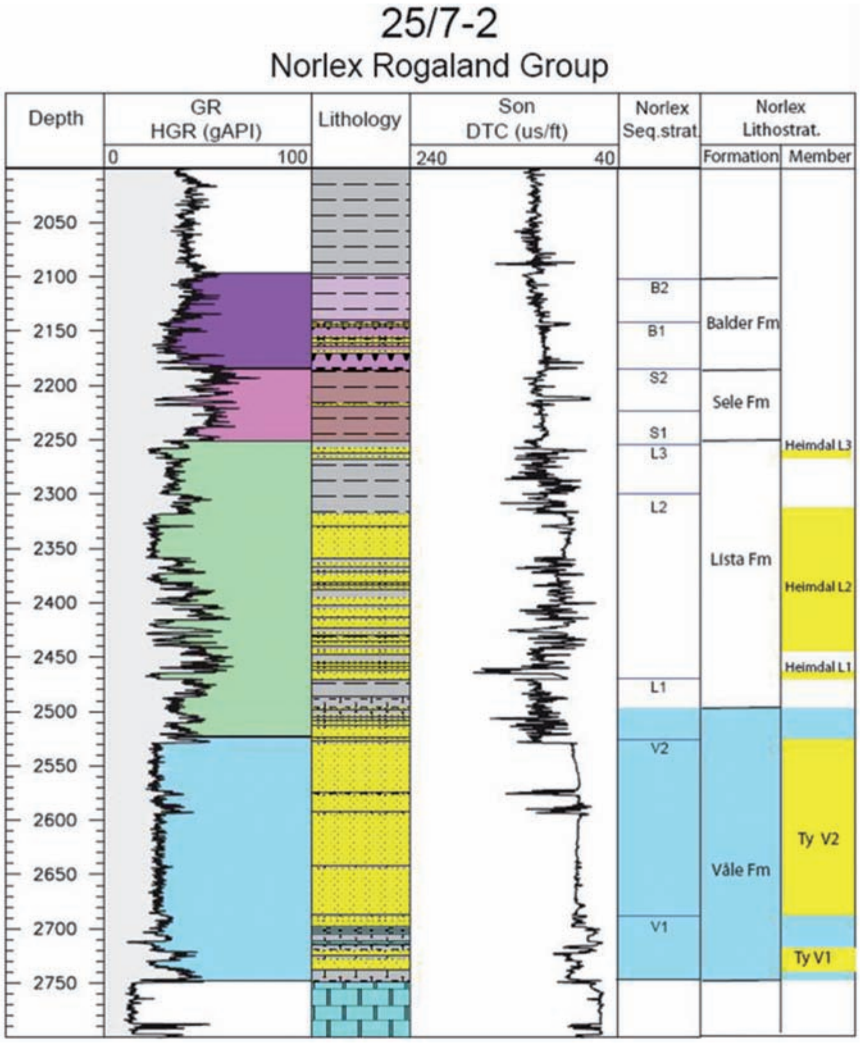


Fig. 53. Well 25/7-2 composite log Rogaland Group. Stratigraphic position of the Ty Member is outlined in stratigraphic column to the right.

the Utsira High (Figures 12 and 13). These westerly sourced sandstones have their eastern extension in the western part of the Norwegian sector (Central Trough). The member extends into the southeastern part of the Breiflabb Basin, and the westernmost part of Quadrant 7 and northwestern part of quadrant 1 (Figure 48).

Depositional environment

In the Norwegian sector the Maureen Member was deposited in the same way as the Ty Member, i.e. from gravity flows along the terminal edge of a deep marine slope to basin fan system. The sandstones have the East Shetland Platform and the mid North Sea High as their provenance. More frequently occurring interbeds of reworked chalk in the Maureen Member relative to the Ty Member can be explained by a more extensively exposed provenance area of chalky lithologies in the Moray Firth area than on the East Shetland Platform. Post-depositional cementing of sandstones may be explained by carbonate leaching from reworked chalk and Våle marls, with subsequent precipitation in the Maureen sandstones.

Ty Member, Våle Formation

Unit definition

The Ty Member is attributed to the intra-Våle Formation sandstones in sub area NW in Figures 12, 13 and 42.

Name

The Ty Member is named after Ty, a son of the Norse god Odin, and one of the twelve principal gods in Norse Mythology

Derivatio nominis

The Ty Formation (now Ty Member) was defined by Hardt et al. (in Isaksen and Tonstad 1989).

Type well

UK well 10/1-1A. Depth: 2,767–2,421 m. Coordinates: N 59° 50′ 10.50″, E 02° 00′ 33.60″. No cores. Defined by Hardt et al. (1989).

Reference well

Norwegian well 15/3-1S (Figure 52). Depth: 2,715–2,556 m. Coordinates: N 58° 50′ 57.00″, E 01° 43′ 13.25″. No cores. Defined by Hardt et al. (1989).

Norwegian Well 25/7-2 (new, Figure 53). Depth: 2,529–2,698 m. Coordinates: N 59° 16′ 28.59″, E 02° 12′ 26.09″. No cores.

Composition

The Ty Member generally consists of massive, clean sandstones of varying grain size. Although the Ty sandstones are mostly quartzitic, they can contain glauconite. The sandstone of the Ty Member, especially Ty V1 is often interbedded with zones of reworked chalk material and flint clasts. The V1 sandstones are often carbonate-cemented, especially when sand layer thickness is limited. The color is clear to light grey in color (Hardt et al. 1989). Ty Member is well represented by cores in the Sleipner East and Balder/Grane areas and in well 26/4-1. Most of the sandstones are rather thick, clean, massive and structureless, but silty sandstones are also observed. Occasionally, ripple cross-lamination may be found.

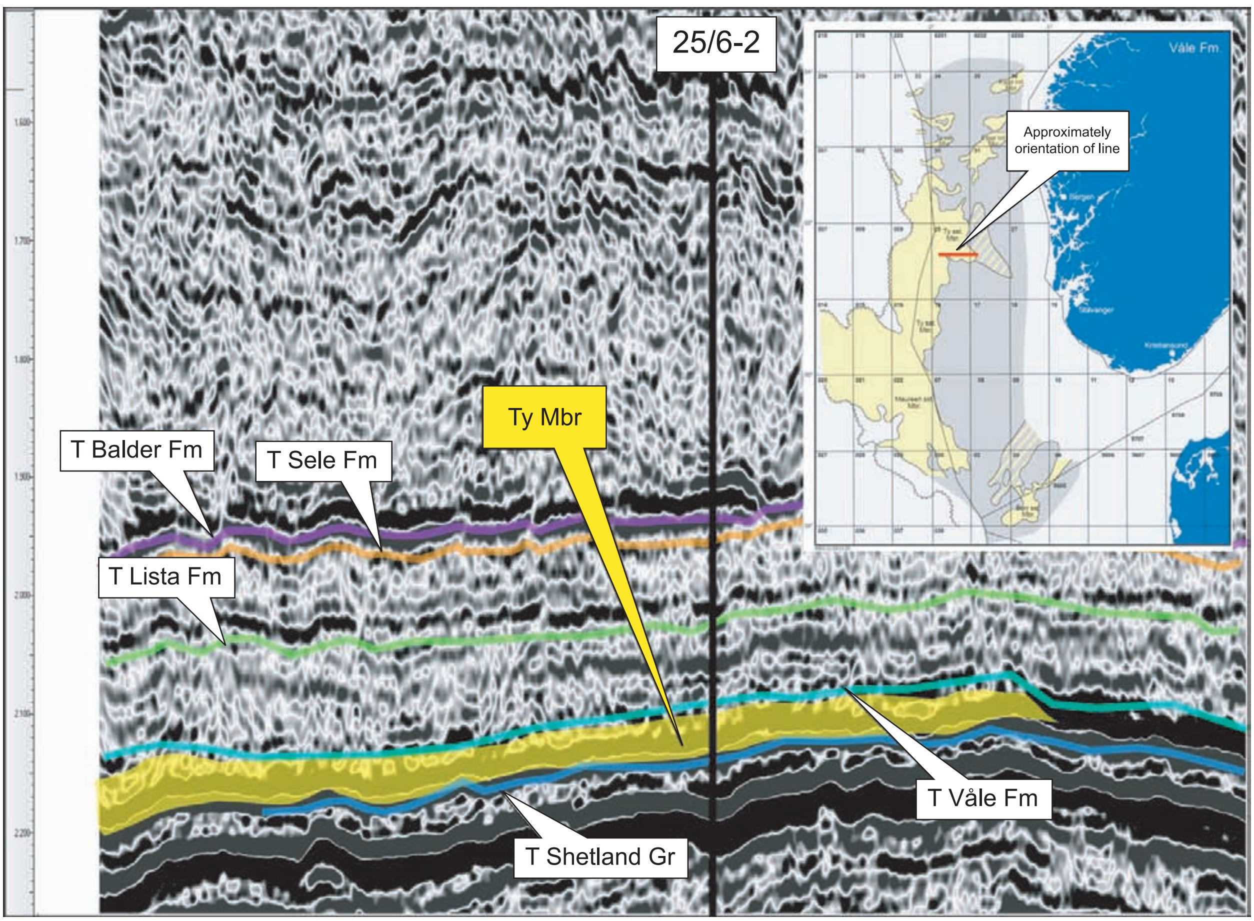


Fig. 54. Seismic WE section through well 25/6-2, highlighting the interval with Ty Member present.

Wireline log characterization

On wire line logs, sandstones of the Ty Member generally have a blocky appearance. Sandstones in the Ty V2 (upper Ty Member) generally are thicker than in the lower Ty V1 Member, and sonic logs suggest that they are generally less cemented.

Upper boundary
The upper boundary is characterised by a downwards transition from higher gamma-ray readings and lower velocity in the Våle or Lista Formation to lower gamma-ray readings and higher velocity in the Ty Member.

Lower boundary
The Ty Member rests on Våle Formation strata, or directly on the Shetland Group. There is a distinct upwards change from low gamma-ray readings and high velocities in the calcareous deposits of the Shetland Group or the Våle Formation to higher gamma-ray readings and lower velocities in the Ty Member.

Thickness

The thickness of the Ty Member is 346 m in type well 10/1-1A. In reference well 15/3-1 it is 159 m, and in type well 25/7-2 it is close to 200 m. A thickness of 170 m is attained in the in well 25/5-1 and 250 m in well 25/3-1.

Seismic characterization

The Ty Member mostly consists of laterally stacked seismic bodies of lenticular to mounded character. Continuity and character and amplitude of internal seismic reflectors vary considerably, and are generally only mappable in local areas. Figure 54 shows an example of seismic character associated with Ty sandstones in the south eastern parts of block 25/6.

Biostratigraphy

Being contained in the Våle Formation, the age of the Ty Member is constrained by biostratigraphic age assignments for the Våle Formation. See description of the Våle Formation in this study.

Age

Early to Mid Paleocene (Danian–Early Selandian).

Correlation and sub division

The Ty Member is divided into Ty V1 Sub-member (Lower Ty Member) and Ty V2 Sub-member (Upper Ty Member).

Geographic distribution

The Ty Member is represented by an interval of aerially extensive sandstones in the Våle Formation interval of the Viking Graben. The Ty Member has its eastern limit against the Utsira High. The southern limit is the east-west member separation line from Fladen Ground Spur to the southern tip of the Utsira High (Figures 12 and 13). In the north, the Ty sandstones reach their limit before 62° N (Figure 48).

Depositional environment

In the Norwegian sector the Ty Member was deposited from gravity flows in a deep marine slope to basinal setting. The sandstones have the East Shetland Platform as their provenance and probably have multiple sources. The sandstones appear to have been deposited from gravity flows in the form of turbidity currents and possibly grain flows, and may in general be classified as sand-rich systems.

Hydrocarbon discoveries in the Ty Member

- Sleipner East
- Norwegian 16/7-2 gas and condensate discovery

Borr Member, Våle Formation

Unit definition

The Borr Member consists of intra-Våle Formation sandstones in the sub-area of the Norwegian–Danish Basin to the Søgne Graben and the southeastern most part of the Central Trough (Figures 12, 13 and 48).

Name

Since the mid 1990s, the name Borr Member has been informally attributed to sandstones discovered in the lower part of the Våle Formation in the Siri Valley, Danish North Sea. The sands are time-equivalent to the lower Ty sands in the Viking Graben and the Maureen Member of the Central Trough. For the Norwegian North Sea we extend the definition to account for all easterly derived sandstones in the Central Trough, Siri Valley and the Norwegian–Danish Basin that are enclosed in the Våle Formation.

Derivatio Nominis

The Borr Member is named after Borr, a giant in the Norse myths of Voluspá and Gylfaginning.

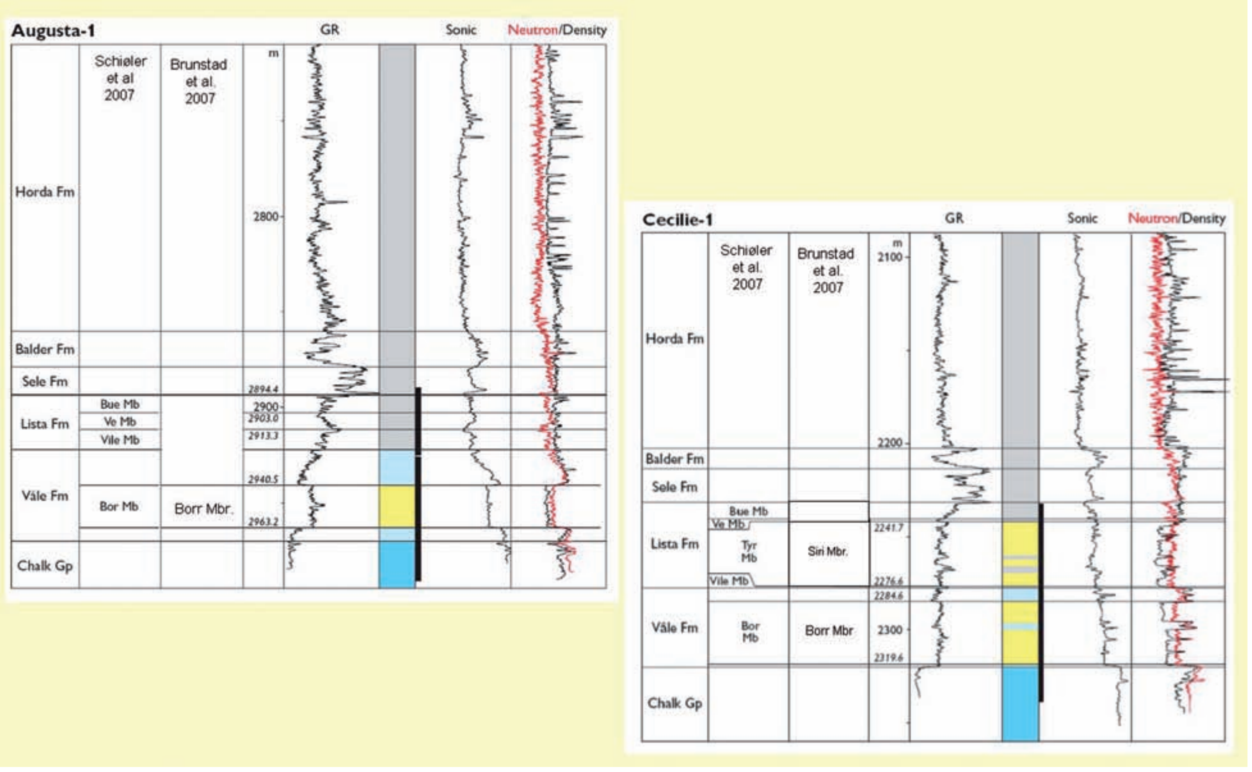


Fig. 55. DK Wells Augusta-1 (type well) and Cecilie-1 (reference well) composites log, Rogaland Group. Position of Borr Member is seen in 2nd column from left. Modified from Schiøler et al. (2007) to fit nomenclature for Norwegian North Sea (this study).

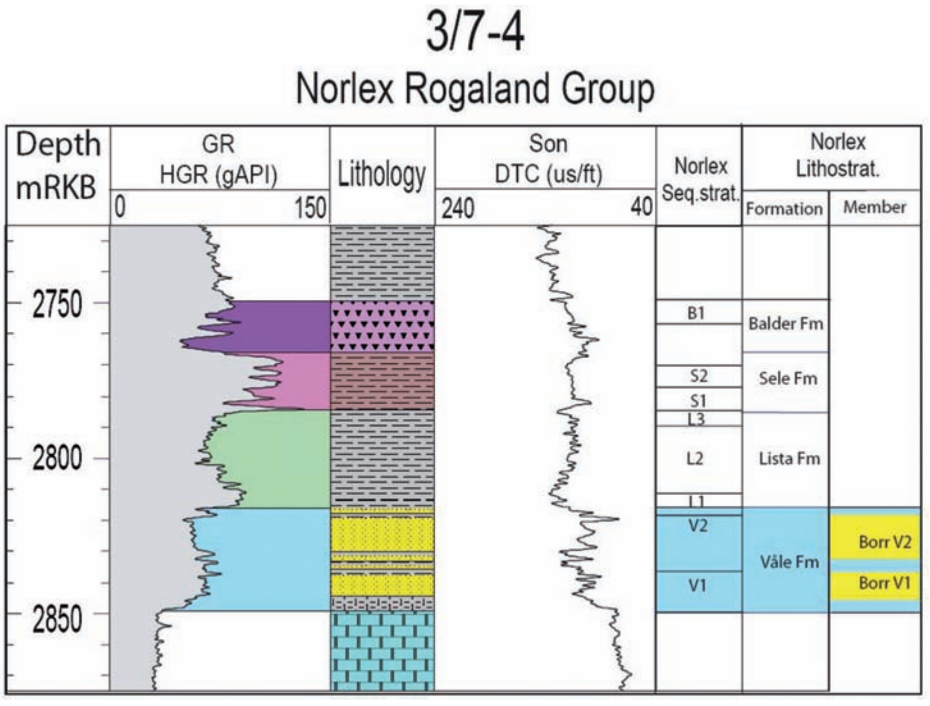


Fig. 56. Well 3/7-4 composite log Rogaland Group. Stratigraphic position of the Borr Member is outlined in stratigraphic column to the right.

Type wells

For Danish sector Schiøler et al. (2007) has defined the DK well Augusta-1 as the type well for the Borr Member (Figure 55). Depth: 2,963.2–2,940.5 mRKB. Coordinates: N 56° 17′ 57.40″, E 04° 24′ 04.64″. Cores: Core 1, 2,923.5–2,889 mRKB.

Reference wells

Norwegian well 3/7-4 (new), (Figure 56). Depth: 2,815–2,845 mRKB. Coordinates: N 56° 24′ 15.60″, E 04° 14′ 22.24″. In this study we select 3/7-4 as a reference wells for the Borr Member, Norwegian North Sea. There are no cores from the Borr Member in any Norwegian wells.

Reference well for Danish sector: Cecilie-1 (Figure 55). Depth: 2,319.6–2,284.6 mRKB. Coordinates: N 56° 24′ 23.73″, E 04° 45′ 42.00″. Cores: 2,230–2,336.4 mRKB.

A suitable reference section for the Borr Member is Norwegian well 3/6-1 (Figure 57). Depth: 2,051–2,092 m. Coordinates: N 56° 35′ 00.14″, E 04° 53′ 30.35″. No cores from the Borr Member.

Composition

The Borr Member consists of massive, olive-green, clean sandstones with a grain size that varies from very fine to fine-grained. The sandstones are quartzitic and glauconitic (up to 25 %), and often calcite-cemented, especially when sand layer thickness is limited. Mica and pyrite are also present in small amounts.

Wire line log characterization

Wire line log appearance of the sandstones of the Borr Member relative to the Våle Formation above and below is variable. The response may be blocky, easily distinguishable with low gamma-ray readings, to more subtle fine-grained sands with a gradual transition from clay and silt into very fine sand. From sonic and density logs thin-bedded sandstones are often carbonate-cemented.

Upper boundary
The upper boundary is usually characterised by a downwards transition from somewhat higher gamma-ray readings and lower velocity in the Våle or Lista Formation to lower gamma-ray readings and higher velocity in the Borr Member.

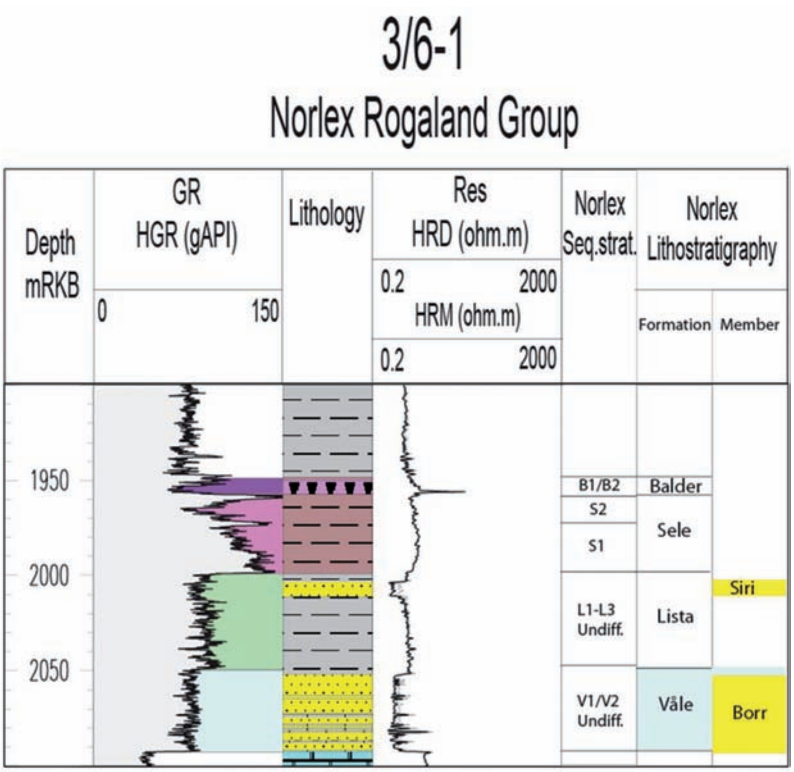


Fig. 57. Well 3/6-1 composite log Rogaland Group. Stratigraphic position of the Borr Member is outlined in stratigraphic column to the right.

Lower boundary

The Borr Member rests on marly shales of the Våle Formation, or directly on the Shetland Group chalks. Where the sandstones rest on the Shetland Group or very calcareous Våle Formation there is an upwards change from low gamma-ray readings and high velocities in the calcareous strata to higher gamma-ray readings and lower velocities in the Borr Member. The lower boundary of the Borr Member can often be difficult to pick where the Våle Formation is calcareous because the gamma-ray values in the two stratigraphic units can locally be very similar.

Where the Borr Member rests on less calcareous Våle Formation the wire line response depends on the calcareous content. There is an upwards change from intermediate to low gamma-ray readings and high velocities in the calcareous strata to higher gamma-ray readings and lower velocities in the Borr Member.

Thickness

In the Norwegian North Sea the Borr Member is generally rather thin; a maximum thickness of 29 m is found in Norwegian well 3/7-3. In the Danish sector in the Siri Valley sand fairway, the Borr Member reaches 24 m in Cecilie-1.

Seismic characterization

The top of the Borr Member is in places seismically well defined, and can be mapped sub-regionally in detail. Seismic character varies between one cycle sub-parallel to mounded facies. Locally, thicker infills of depressions or canyons in the substratum can be seen. Seismic 3D amplitude maps of near top or base Våle Formation may display channel- or fan-shaped geometries, that represents submarine channels or fan systems. A seismic cross-section example from the

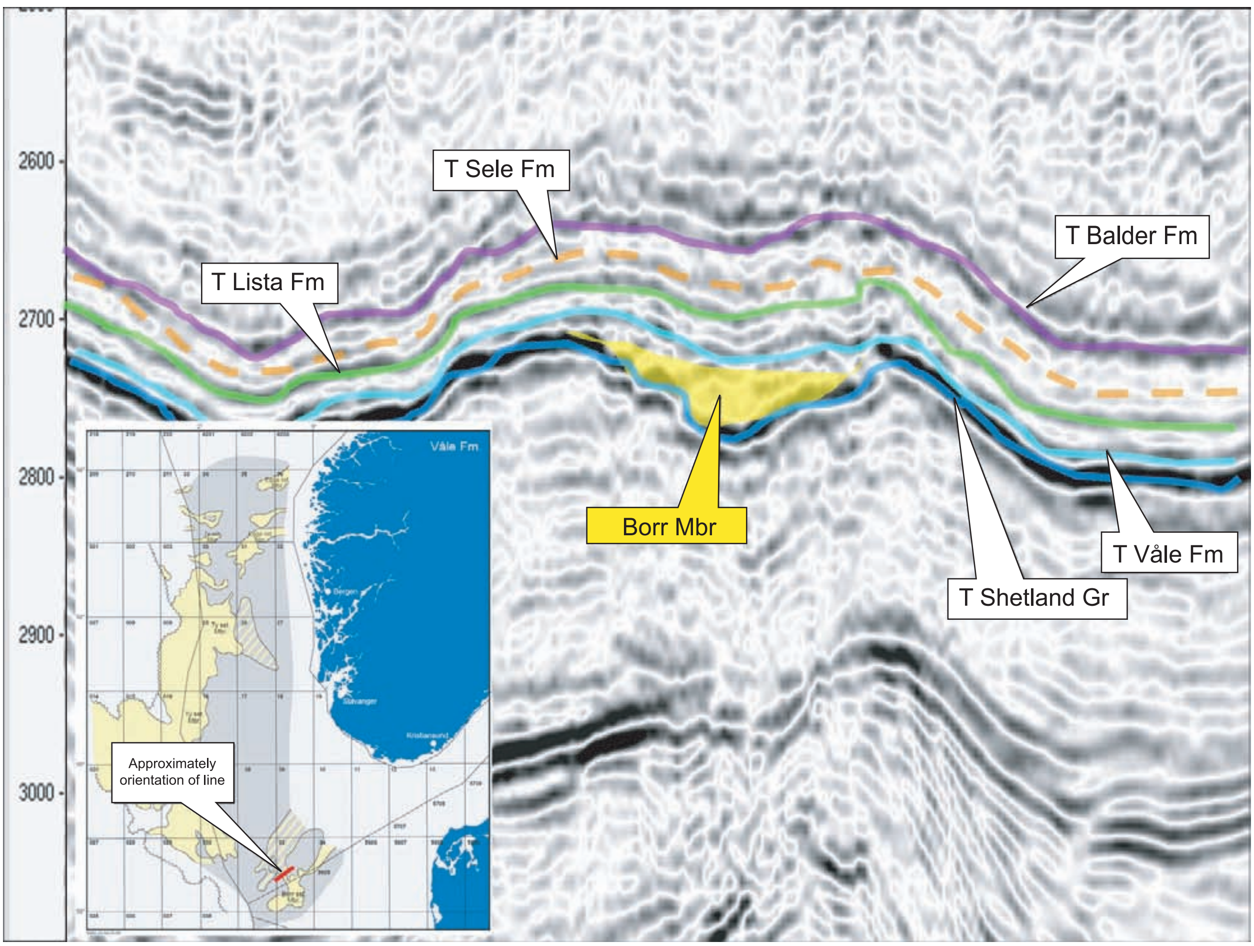


Fig. 58. Seismic SW/NE section through the Trym salt collapse structure, showing sandy interval of the Borr Member filling in a collapse feature.

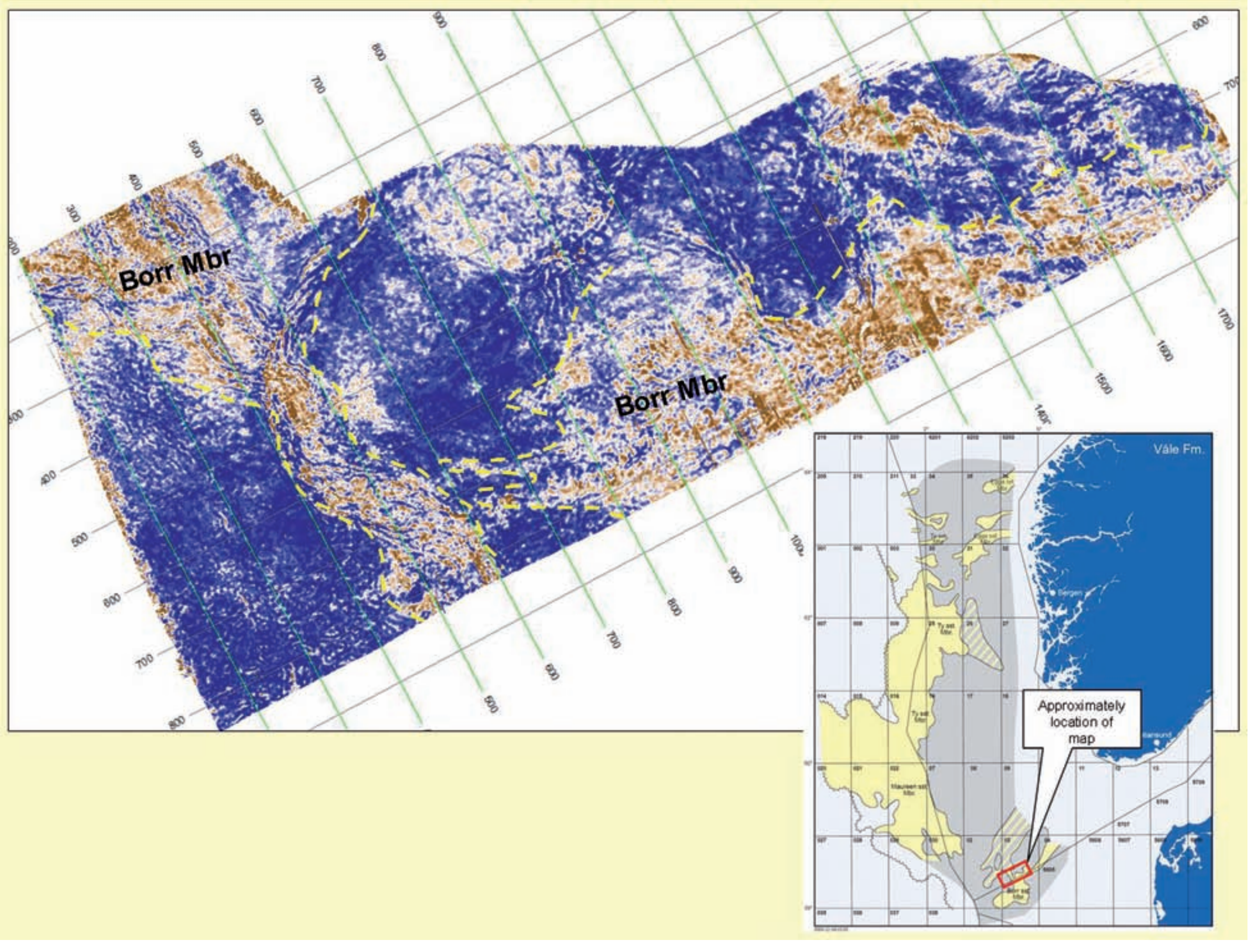


Fig. 59. Seismic map from blocks 3/7 and 3/8, showing amplitude at Top Våle Level. Red color shows high amplitude, and inferred presence of Borr sandstone (demonstrated with geological evidence in wells in these blocks).

southwestern part of the Søgne Graben is shown in Figure 58, and a seismic attribute map in Figure 59.

Age

Early to Mid Paleocene (Danian–Early Selandian).

Biostratigraphy

Being contained in the Våle Formation, the age of the Borr Member is bounded by biostratigraphic age assignments for the Våle Formation; see description for the Våle Formation.

Correlation and sub division

The Borr Member is divided into the Borr V1 Submember (Lower Borr Member) and Borr V2 Submember (Upper Borr Member), following the subdivision of the Våle Formation.

Geographic distribution

The Borr Member is deposited in the Norwegian–Danish Basin and the Siri Valley fairway, and appears to have offshoots westwards into the Søgne Graben and the Central Graben (Figure 48), where it is found in Norwegian wells 3/7-2, -3 and -4. It is uncertain how far north the Borr sandstones are distributed, but in seismic data, mounded characters are seen far north in the Egersund Basin, which indicates that the Borr Member possibly is also present in that area.

Depositional environment

The Borr Member is generally believed to have been deposited in a slope to deep marine setting, mainly as highly concentrated gravity flow deposits. In eastern areas of the Norwegian–Danish Basin, parts of the Borr Member may have been deposited in a neritic, shallow marine environment.

Egga Member

Unit definition

The Egga Member comprises sandstones of the intra-Våle Formation and the lower Tang Formation, found along the northeasternmost parts of the North Sea Basin and along the mid Norwegian Shelf.

South of 62° N the Egga Member is included in the Våle Formation, and north of 62° N it is included in the fine grained siliciclastic deposits of the Tang Formation (no carbonate content, hence not Våle Formation).

Name

The name Egga has been informally used since 1990, when hydrocarbon reservoir sands penetrated in Norwegian well 6205/3-1 were assigned this name. The name Egga first appeared in the literature in an extended abstract published by Gjelberg et al. (1999). The name is commonly attached to the Ormen Lange gas field in the Møre Basin where the Egga sandstones form the main reservoir (Gjelberg et al. 2001, 2005, Möller et al. 2004). The unit was assigned by Gjelberg et al. (1999) to be an upper member of the Våle Formation (see below). At that time the Egga unit had not been formally defined lithostratigraphically.

Derivatio nominis

In the 6205/3-1 well completion report (unpublished) the unit is named after the 'Eggakant' shelf break to the east of the Møre Basin.

Type well

Norwegian well 6305/5-1 (Figures 60a, b). Depth: 2,718–2,770.4 m, 52.4 m thick. Coordinates: N 63° 32′ 27.50″, E 05° 20′ 14.90″; UTM coordinates: 7048160.15 N, 616189.14 E.

Although Gjelberg et al. (1999, 2001) did not select a type well it is evident that this well is best suited as type section for the Egga Member. Information about the lithology, mineralogy, cores, biostratigraphy, sedi-

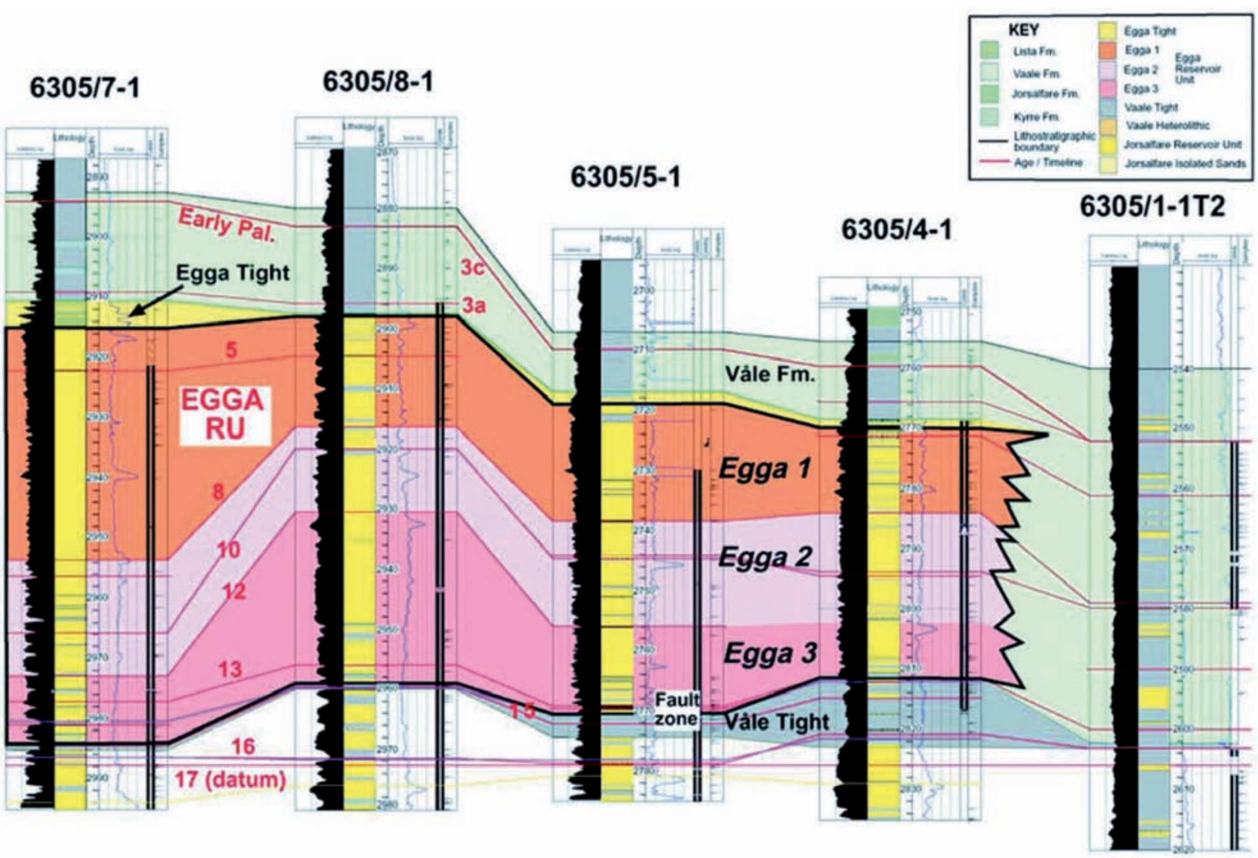


Fig. 60. **a** Well correlation for the Egga Member Møre Basin area. Modified from Møller et al. (2004). **b** Well 6305/5-1, Type section Egga Member (new). Depth interval: 2,718–2,770.4 m, 52.4 m thick. Coordinates: N 63° 32′ 27.50″, E 5° 20′ 14.90″; UTM coordinates: 7048160.15 N–616189.14 E.

mentology, wireline logs and depositional setting is provided by Gjelberg et al. (1999, 2001) and Möller et al. (2004).

Cores 1–3 are available at the NPD, as well as cuttings for the interval 2,718–2,770.4 m.

Reference wells

Well 6205/3-1. Depth: 1,317–1,482 m, 165 m thick. Coordinates: N 62° 57′ 08.62″, E 05° 56′ 38.11″; UTM coordinates: 6983872.90 N, 649328.84 E.

We select this well as the primary reference section, since with 165 m of the Egga Member it exhibits the best development of the unit drilled to date. The well is drilled in the Slørebotn Sub-basin of the Møre Basin.

Well 6305/8-1 (Figure 60a), Depth: 2,898–2,959 m, 61 m. Coordinates: N 63° 28′ 34.70″, E 05° 24′ 14.40″; UTM coordinates 704080.68 N, 619765.5 E.

This second reference well provides complete core coverage of the Egga Member and illustrates lithostratigraphic details of its upper boundary within the Tang Formation.

Composition

According to Gjelberg et al. (1999, 2001) and Möller et al. (2004) the unit is sandstone-dominated with some greenish color and strongly bioturbated texture. The sandstones are texturally mature, medium to coarse grained, and alternate with thin, fining upwards sandy mudstones.

A core photograph example for well 6305/5-1 is shown in Figure 62. Core photographs for 6305/8-1 are available from the NPDs website (http://www.npd.no/engelsk/cwi/pbl/en/well/all/4109.htm) for the interval 2,895–2,988 m; this includes the underlying Jorsalfare Formation.

Wireline log characterization

Lower boundary

From the core descriptions of the type well 6305/5-1 the lower boundary is a sharp contact between shales referred to as a "lower mudstone unit" and the overlying sandstones of the Egga Member. Across the boundary, hemipelagic black, virtually non-bioturbated mudstones change to greenish, strongly bioturbated sands

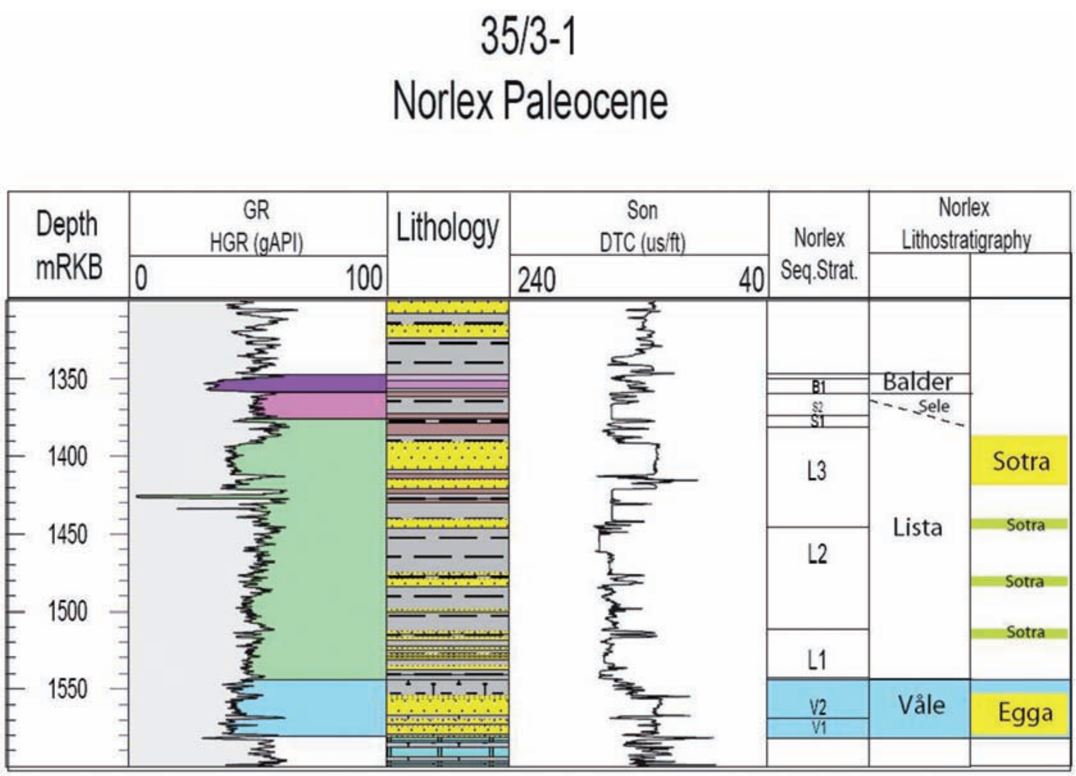


Fig. 61. Well 35/3-1 composite log Rogaland Group. Stratigraphic position of the Egga Member is outlined in stratigraphic column to the right. This well has been chosen to represent the Egga Member south of 62° N. No cores have been taken from this well.

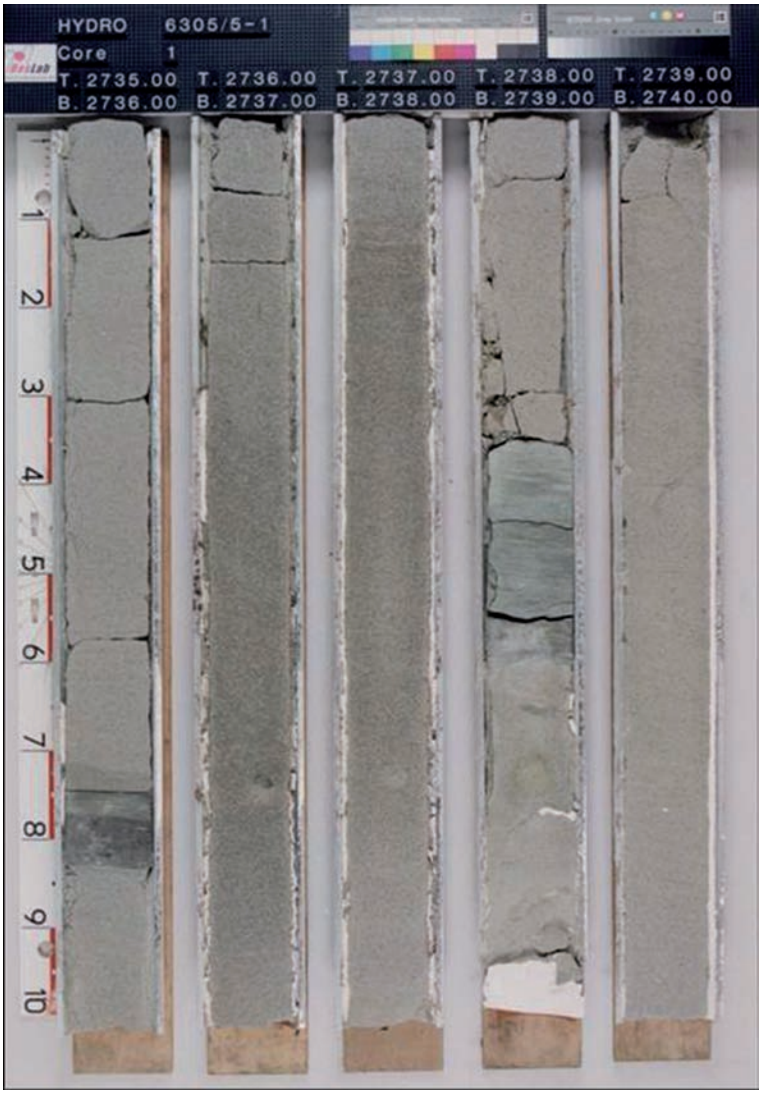


Fig. 62. Core photo from the Egga Member well 6305/5-1 at 2,735–2,740 m. Well drilled by Norsk Hydro. From NPD Fact Pages at http://www.npd.no.

that become dominant in the Egga Member (Gjelberg et al. 2001). The lower mudstone unit is assigned to the Våle Formation by Gjelberg et al. (2001), but we note that the Våle Formation commonly has carbonate content, whereas the Egga enveloping mudstone is purely siliciclastic, and is better referred to as the Tang Formation. In the 6205/3-1 and 6305/8-1 reference sections the contacts on wireline logs appear to be less sharp and more gradational.

Upper boundary
The upper boundary is drawn at 2,718 m in the type well (Gjelberg et al. 2001). This level corresponds to the top of the sandstone section overlain by shales of the Tang Formation in which the Egga Member is confined.

Thickness

In well 6305/5-1, the Egga Member is 52.4 m thick; in well 6205/3-1 it attains a thickness of up to 165 m. Values close to 100–150 m appear to be typical along the eastern margin of the Møre Basin (wells 6305/12-1 and 6306/10-1). In the Ormen Lange gas field area itself, the unit varies in thickness from 41.5–69 m.

Seismic characterization

South of 62° N, the Egga Member is seen to have a mounded to lenticular shape on seismic sections. The sandstones often have little seismic contrast to the locally calcareous claystones and mudstones of the Våle/Tang formations above and below it. This may make it difficult to map the exact top and base of the sandstones. Thus interpretation of the presence of Egga sandstones is often related to thickening of the stratigraphic interval between mappable shale events, such as maximum flooding surfaces or sequence boundaries. A seismic cross-section through blocks 35/2 and 35/3 is shown in Figure 63.

Age

The Egga Member sandstones are of Danian to Early Selandian age (Vergara et al. 2001).

Biostratigraphy

The deep marine shale encompassing the reservoir interval of the type well 6305/5-1 of the Egga Member is rich in shelly and organic-walled microfossils.

Shelly microfossils
In the type well the following shelly microfossils are found:

2,620–2,744.65 m (Early Selandian–Danian): *Cenodiscus lenticularis* LO, rare *C. hyphalus*, rare *Parasubbotina pseudobulloides*, *Planorotalites compressus*, *Gavelinella beccariiformis*.
2,779.15–2,810.40 m (Late Maastrichtian): *Arenobulimina* spp., *Globigerinelloides asper*, *Heterohelix striata*, *Abathomphalus mayaroensis*, *Racemiguembelina fructicosa*, *Contusotruncana contusa*, and *Rugoglobigerina rugosa*, *Pseudotextularia elegans*, *Bolivinoides incrassata*, *Globotruncanella havanensis*.
2,805.10–2,810.40 m (Early Maastrichtian): Coarse agglutinated benthic foraminifers LCO, *Bolivinoides incrassata incrassata*, *Reussella szajnochae*.

Twenty-seven palynological slides from this well covering the Egga Member interval are available from the Norwegian Petroleum Directorate (NPD). No thin sections are reported.

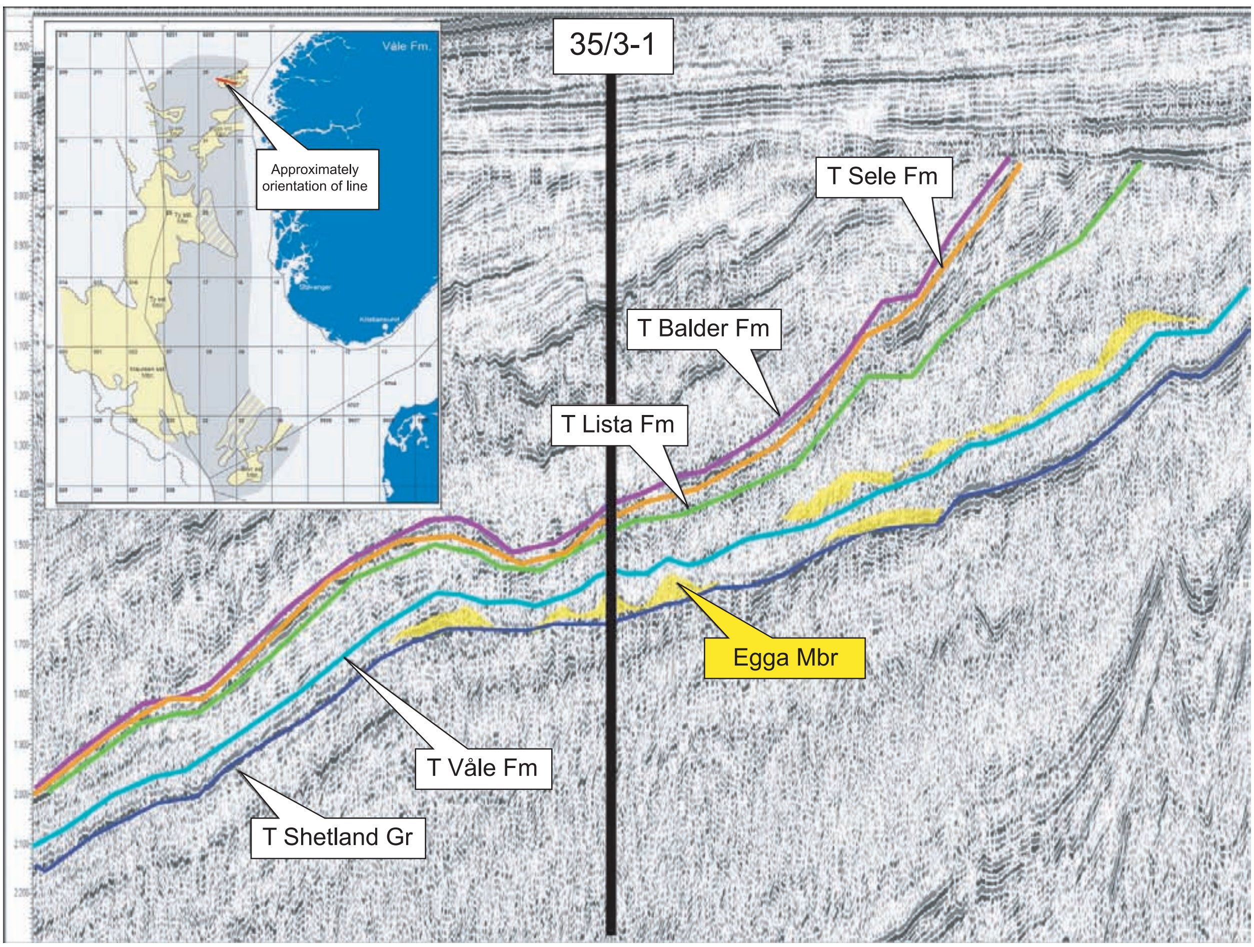


Fig. 63. Seismic WE Cross Section through well 35/3-1, showing inferred presence of Egga Member.

Organic walled microfossils
In the type well the following organic-walled microfossils are found:
2,650.00–2,700.00 m (Early Selandian): *P. pyrophorum* LAO, *I. ? viborgense* LO, *C. diebeli* LO.
2,720.00–2,779.15 m (Danian): *A. reticulata*, *S. magnifica*, *S. delitiense*, *S. inornata*, *T. fragile*.
2,779.40–2,806.15 m (Late Maastrichtian): *P. grallator*.
2,810.40–1,816.15 m (Early Maastrichtian): *T. utinensis*, *A. acutulum*.

Based on the combined microfossil content from 2,718–2,770 m, the Egga Member is of Early Paleocene (Danian) age, overlying mudstones of Late Maastrichtian age.

Correlation and subdivision

Correlation of the Egga Member south of 62° N follows the same stratigraphic subdivision as with the Ty Member, and relates to its position relative to the Våle subzone where it occurs, e. g., the Egga V1 Sub-member for occurrence in lower parts and the Egga V2 Sub-member for an occurrence in upper parts of the Våle Formation.

Geographical distribution

The Egga Member type area is the east Møre Margin, including the Ormen Lange dome and the Slørebotn Sub-basin, where it is a proven gas reservoir, and an ongoing exploration target. It extends southwards into the northern North Sea (Figure 64), Måløy and Uer Terraces (Quadrant 35), although the distribution in that area is patchy. An age equivalent sandstone unit is developed in the Vestfjorden and Træna Basins, along the northwestern part of the Norwegian continental margin. There are no well penetrations of the unit in the Vøring Basin, and the unit is absent in the Halten and Dønna Terraces, and in the Trøndelag Platform.

Depositional setting

The Egga Member sands are interpreted to infill shallow, intra-slope basins or depressions in the Slørebotn Sub-basin, or to have laterally bypassed and deposited into the deeper parts of the Møre Basin, where they accumulated as thick amalgamated turbidites in a basin floor setting in the Ormen Lange area (Gjelberg et al. 2001, Möller et al. 2004).

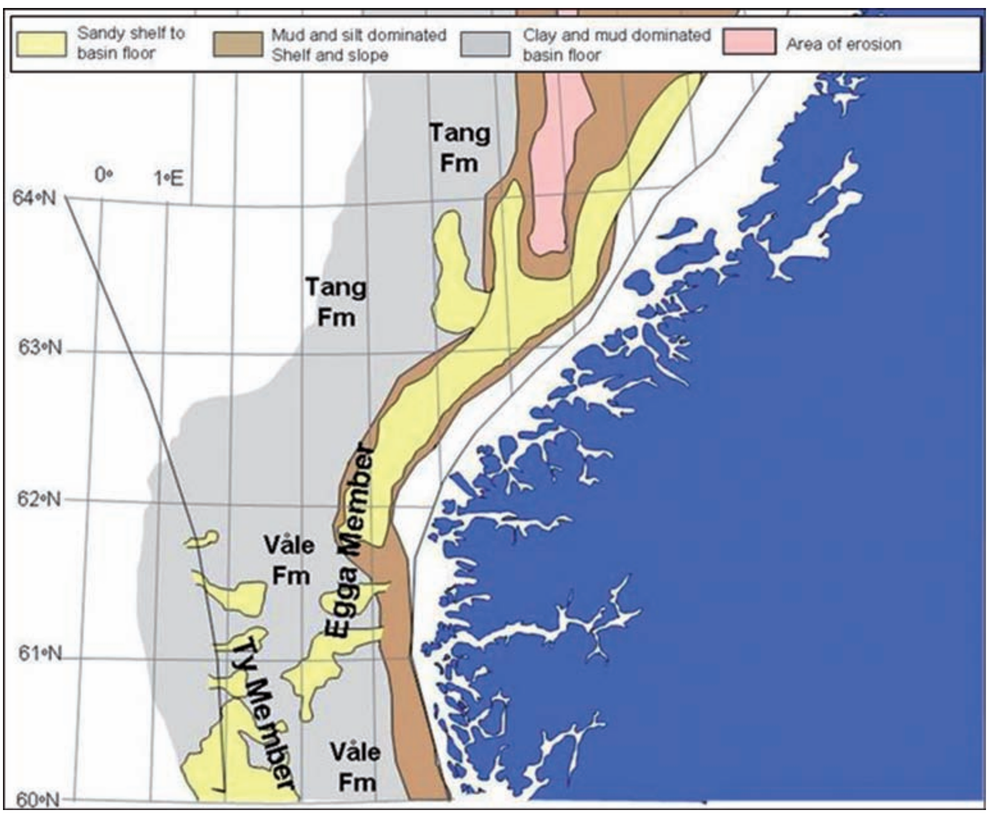


Fig. 64. Map of the Egga north and south of 62° N.

Lista Formation with Members

Lista Formation

Unit definition

Non-marly, bioturbated and poorly laminated greenish grey claystones and mudstones, stratigraphically located between the underlying Våle and overlying Sele formations are assigned to the Lista Formation (Figure 65).

Name

The Lista Formation was named by Deegan and Scull (1977).

Derivatio nominis

The formation is named after the Lista district, onshore Norway, and the Lista Spur structure (Lista Fault Block Complex) in the Norwegian–Danish Basin.

Type wells

Norwegian well 2/7-1 (Figure 66). Depth: 2,918–2,873 mRKB. Coordinates: N 56° 25′ 44.68″, E 03° 12′ 14.21″. No cores. Defined by Hardt et al. (1989).

Reference wells

Norwegian well 15/9-11 (Figure 67). Depth: 2,386–2,308 m. Coordinates: N 58° 24′ 02.53″, E 01° 53′ 41.79″. Ten meters with cores from the lowest part of the formation. Defined by Hardt et al. (1989).

Norwegian well 16/8-1 (Figure 68). Depth: 1,749–1,708 m. Coordinates: N 58° 27′ 24.80″, E 02° 25′ 56.80″. No cores. Defined by Hardt et al. (1989).

Norwegian well 9/11-1 (new, Figure 69). Depth: 1,483–1,592 mRKB. Coordinates: N 57° 00′ 41.40″, E 04° 31′ 40.60″. No cores.

Composition

The Lista Formation consists of pale green-grey to grey-green shales, with subordinate pale yellow-grey, red-grey, red-brown and dark grey zones.

The shales are generally non-tuffaceous, non-calcareous, non-carbonaceous, blocky, bioturbated and poorly laminated. The degree of fissility is directly related to the intensity of bioturbation (Knox and Holloway 1992), with the mudstones in middle and upper parts being totally homogenized. *Zoophycos* burrows are common.

Occasionally, the Lista Formation contains stringers of limestone, dolomite and pyrite. Thin argillaceous, primary air-fall tuff layers are present in the lower parts of the formation (Knox and Holloway 1992).

Representative core photo examples of mudstones of the Lista Formation are shown in Figure 70. The photo examples show mudstones of dominantly green-grey color, and with purple red patches. As can be seen the mudstones have a mottled and poorly laminated appearance, which can be explained by intense bioturbation. *Zoophycos*, (Figure 70), *Chondrites* and *Planolites* are common trace fossils in the Lista Formation.

Wireline log characterization

The shales of the Lista Formation are generally characterized by intermediate wire line log readings, but there is considerable variability, and several internal zones with high gamma-ray readings occur, representing flooding or condensation surfaces. Velocity logs display spikes of high acoustic velocity that can be related to thin beds or nodules of carbonate.

Upper boundary
The upper boundary of the Lista Formation is usually well defined where the upper parts of this formation or the lower parts of the overlying Sele Formation are not sandy. Typically, the boundary can be seen as an abrupt upwards increase in the gamma-ray response from the Lista Formation, often with a well defined peak in the lowest part of the Sele Formation. Lithologically, the boundary can be seen as an abrupt transition from green-grey, bioturbated mudstones of the Lista Formation into dark grey to black laminated shales, with only occasional bioturbation.

Lower boundary
The lower boundary of the Lista Formation is synonymous with top of the Våle Formation. The boundary is picked at the top of a trend of overall increase in gamma-ray response and general reduction in velocity. Lithologically the boundary is picked at the top of an upwards decrease of carbonate content in the mudstones.

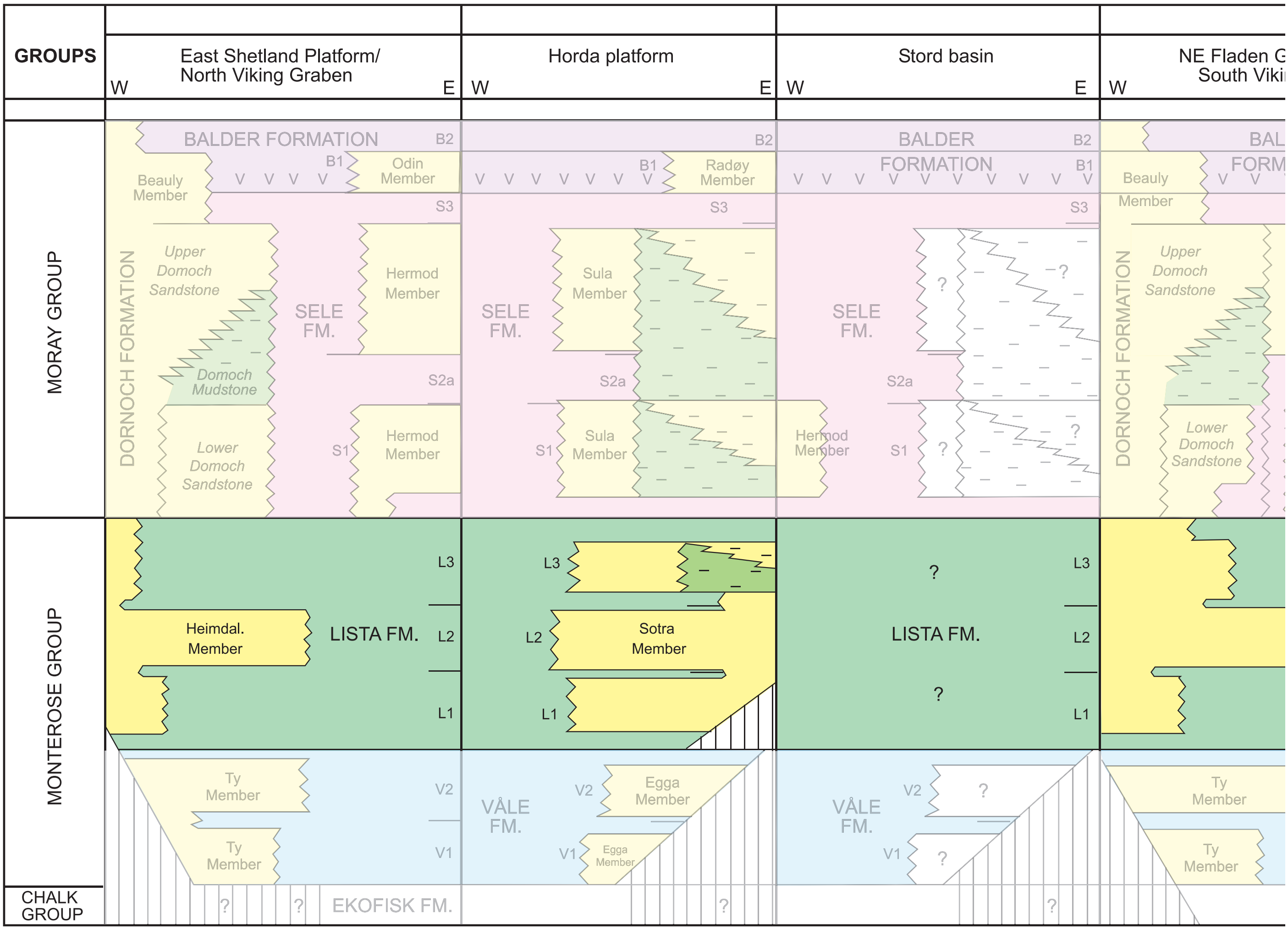


Fig. 65. Lithostratigraphic summary chart of the Lista Formation (color) with members.

Thickness

The Lista Formation, including sandstone members, reaches a thickness of more than 500 m (523 m Norwegian well 25/4-1). In the Viking Graben, shale thickness of the Lista Formation varies between 100 and 200 m. The formation generally thins towards the strutural highs, where thicknesses are less than 50 m. Where the Lista Formation is thin it usually contains no sandstones.

Seismic characterization

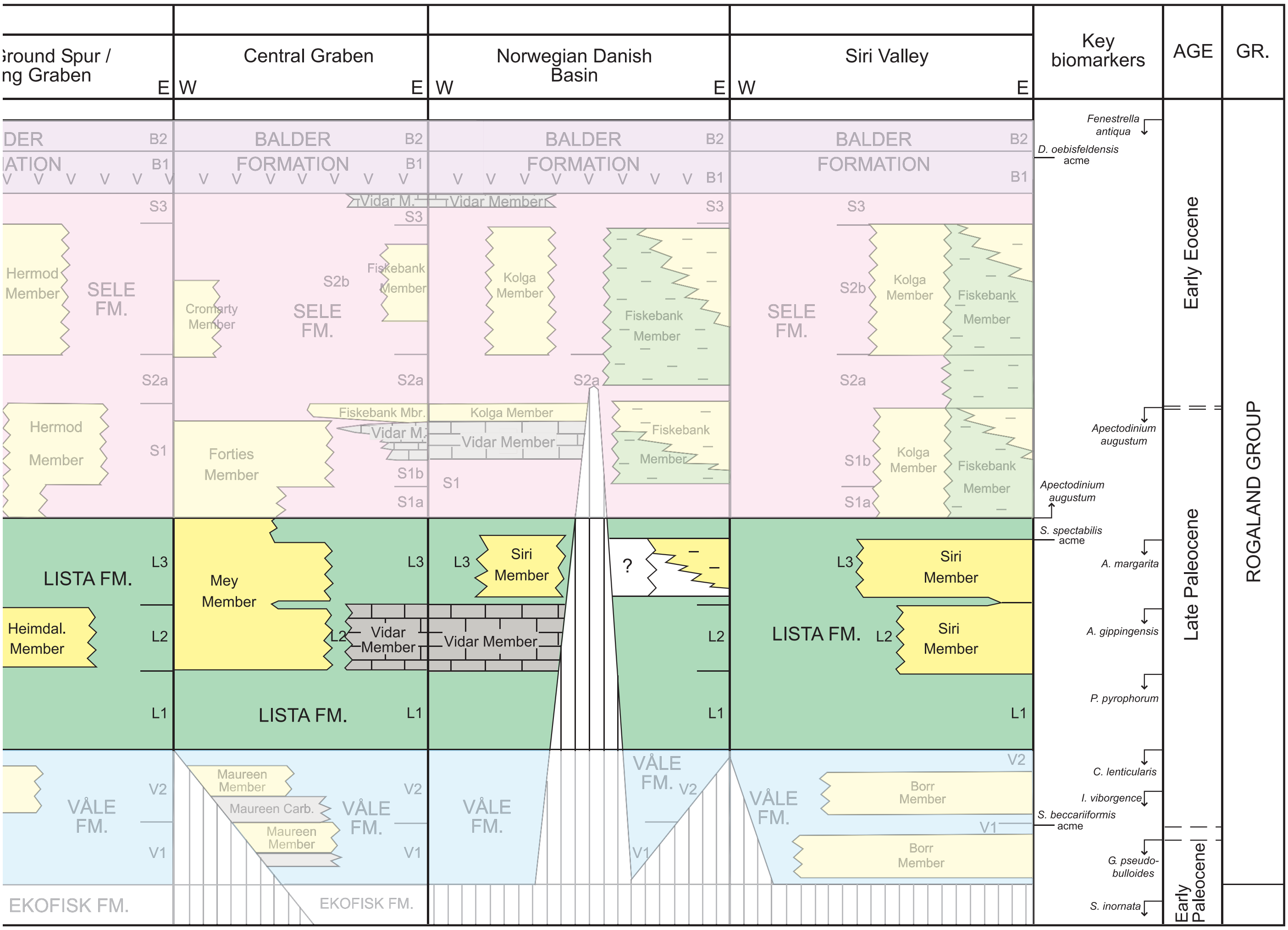
The base of the Lista Formation is associated with the change from higher density and higher acoustic velocity of the Våle Formation into the lower velocity and lower density Lista Formation, giving a positive acoustic impedence contrast.

The top of the Lista Formation is commonly associated with a well expressed, extensive seismic event. Where the higher velocity Lista Formation underlies a low velocity zone in the lowermost part of the Sele Formation, it gives positive acoustic impedance contrast.

Where sandstones are present in the Lista Formation this is often associated with thickening as well as with semi-continuous, undulating internal reflectors and lens shapes, mounds and trough infills.

Age

Late Mid to Late Paleocene (Late Selandian–Early Thanetian).



Biostratigraphy and age

The top of the Lista Formation coincides with the last occurrence (stratigraphic top) of a dinocyst assemblage dominated by *Apectodinium* spp. The body of the formation contains in downhole order from young to old:

- Top *Alisocysta margarita*
- Top *Areoligera gippingensis*
- Top *Palaeocystodinium* cf. *australinum*
- Top consistent *Palaeoperidinium pyrophorum*, and
- Top acme *Palaeoperidinium pyrophorum*.

The base of the Lista Formation is slightly below the top acme *Palaeoperidinium pyrophorum* and top *Isabelidinium ? viborgense*.

In terms of shelly microfossils the top of the formation contains a low-diversity agglutinated foraminiferal assemblage, greatly increasing in diversity stratigraphically downwards.

The body of the Lista Formation contains the last occurrences (tops) of the following agglutinated taxa, in most likely stratigraphic order:

- *Rzehakina minima*
- *Saccamina placenta*
- *Reticulophragmium paupera*
- *R. garcilassoi* (rare)
- Top diversified and abundant agglutinated foraminifera
- Last common occurrence of *Spiroplectammina spectabilis*
- *Ammoanita ruthvenmurrayi*
- *Hormosina excelsa*
- *Labrospira pacifica* (rare)
- *Cystammina sveni*
- *Conotrochammina voeringensis* (rare)
- *Ammoanita ingerlisae* (rare)

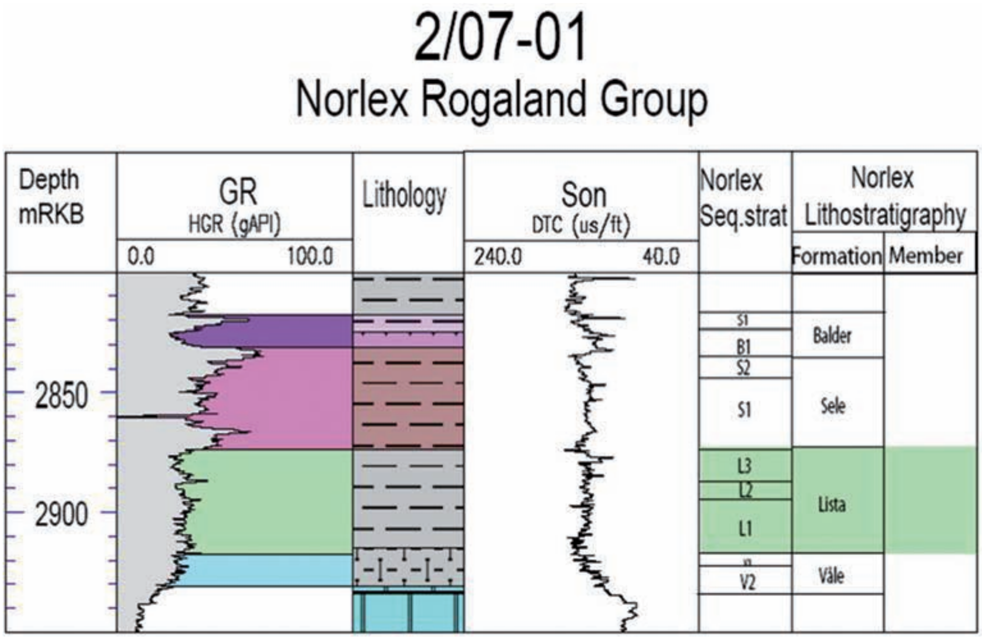


Fig. 66. Well 2/7-1 composite log, Rogaland Group. Stratigraphic position of the Lista Formation is outlined in the stratigraphic column to the right.

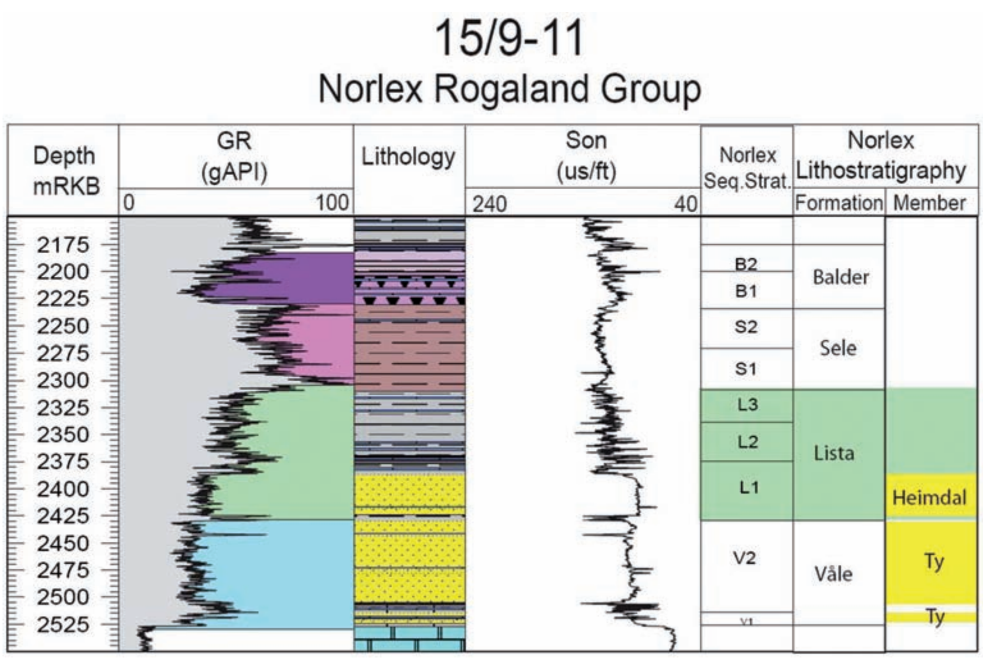


Fig. 67. Well 15/9-11 composite log, Rogaland Group. Stratigraphic position of the Lista Formation is outlined in stratigraphic column to the right.

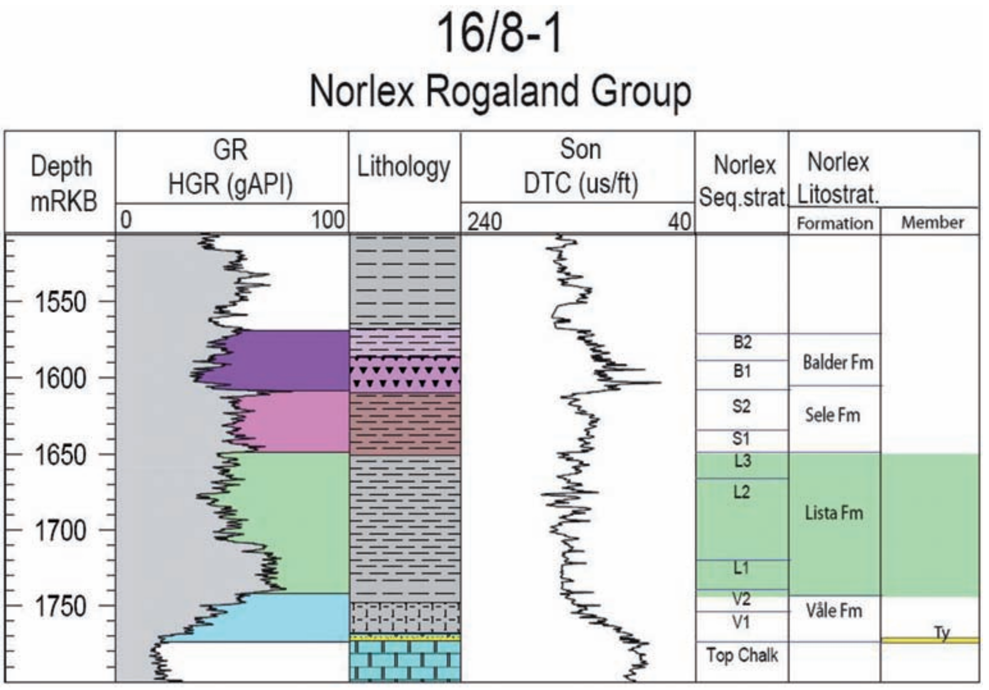


Fig. 68. Well 16/8-1 composite log of the Rogaland Group. Stratigraphic position of the Lista Formation is outlined in stratigraphic column to the right.

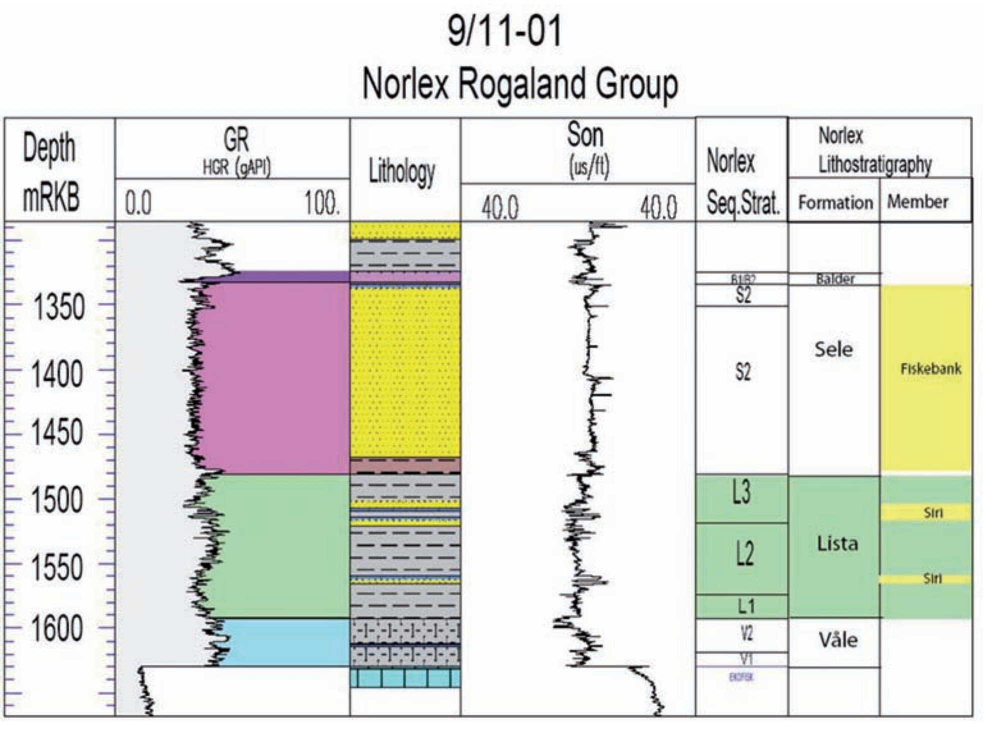


Fig. 69. Well 9/11-1 composite log Rogaland Group. Stratigraphic position of the Lista Formation is outlined in stratigraphic column to the right.

Fig. 70. Core photographies of Lista Formation well 35/10-2. Left: Sediments are composed of bioturbated green claystone with common purple red patches. Right: Nice example of *Zoophycos* burrows in sediments. Photographs by L. Vergara and H. Brunstad.

Fig. 71. Some diagnostic organic walled microfossils of the Lista Formation. *Palaeoperidinium pyrophorum*; dorsal view of dorsal surface; 450 ×. *Areoligera gippingensis*; ventral view; Range of type material: overall length = 32–42 µm, overall width = 45–59 µm, process length = 15–33 µm. *Alisocysta margarita*; ventral view; holotype dimensions: length = 44 µm, width = 40 µm. From the ODP Drilling Program at *http://www-odp.edu*.

The base of the Lista Formation agrees with the youngest occurrence of *Cenosphaera lenticularis*. The Lista Formation belongs in the foraminiferal Zone NSR2A–2B, *A. ruthvenmurray–R. pauperum* (Gradstein and Bäckström 1996), and the dinocyst Zones D3b–D4 in Luterbacher et al. (2004). The age is Late Selandian through Thanetian, late Mid through Late Paleocene. Some diagnostic microfossils of the Lista Formation are shown in Figure 71.

Correlation and sub division

The Lista Formation can be subdivided into a lower (L1), a middle (L2) and an upper (L3) part which are separated by condensation surfaces associated with specific bioevents (Knox and Holloway 1992). These condensations are associated by high gamma shales and seem to have a regional importance, and may be related to relative sea level changes (e.g., Mudge and Bujak 1996).

The base of the L1 zone is picked at the high gamma shale that occurs between the *I. ? viborgense* and *T.* cf. *delicata* dinocyst zones and close to the top of the *Cenosphaera lenticularis* microfaunal zone. The boundary between the L1 and L2 is taken at the high gamma shales associated with the *P. pyrophorum* acme, and the boundary between L2 and L3 is taken at a high gamma zone associated with the *A. gippingensis* acme. The top of the L3 zone is taken at the high gamma peak near the base of the Sele Formation, which is associated with the top of an impoverished agglutinated assemblage.

Internally in the Lista Formation several sandstone members are found (Figures 12 and 13). The Siri Member and Sotra Member are thought to have an eastern provenance (Scandinavia), whereas the Mey Member and the Heimdal Member have a western provenance (Shetland Platform).

Geographic distribution

The Lista Formation, for all practical purposes, has a distribution related to the presence of the Rogaland Group in the Norwegian North Sea. The Sotra Member is found in the area of Måløy Platform and Sogn Graben, and may stretch into the Stord Basin (Figure 72).

Depositional environment

Going from the Våle Formation and into the Lista Formation, the climate became temperate/cooler and the connection with the warmer Atlantic and Tethys oceans became more limited. This had an impact on the paleo-water temperature in the North Sea Basin, which became lower, and may have had lower salinity. As a response, calcareous microplankton disappeared in the North Sea.

The Lista Formation was deposited in a marine environment where the earlier calcareous input from micro-organisms, and reworking from exposed chalk of the Shetland Group had come to an end. Accordingly, the fines deposited in the basin were dominated by siliciclastic minerals. The trace fossils in the deposits in general are smaller and the deposits darker, reflecting a less well oxygenated basin.

In the basinal areas of the Viking Graben, Stord Basin and the Central Graben paleo-water depth was mostly deep marine, bathyal. To the east, paleo-water depth was shallower, extending on to an upper continental shelf slope or shelf setting. Changes between faint dark purple red and medium grey to dark green bioturbated mudstones probably reflects changes in the balance between water circulation and sedimentation rate. The change between diverse and abundant bioturbation in the mudstones reflects a change from generally oxygen rich and well circulated bottom waters to dysoxic or locally anoxic conditions. The silty fraction increases towards the slope wedges flanking the basin to the east and west (UK).

Mey Member, Lista Formation

Unit definition

The Mey Member is attributed to the intra-Lista Formation sandstones in sub-area SW in Figures 12, 13 and 72.

Name

In the Central Graben of the North Sea this unit was formerly called the Andrew Formation. The Mey Member was introduced by Knox and Holloway (1992), and attributed to all major sandstone units and associated tuffaceous deposits within the Lista Formation of the Outer Moray Firth and the Central Graben. The Mey Member includes the Andrew Member (Lower Mey) and the Balmoral Member (Middle and Upper Mey) of Neal (1996) on the UK side of the North Sea (see also Kilhams et al. 2012).

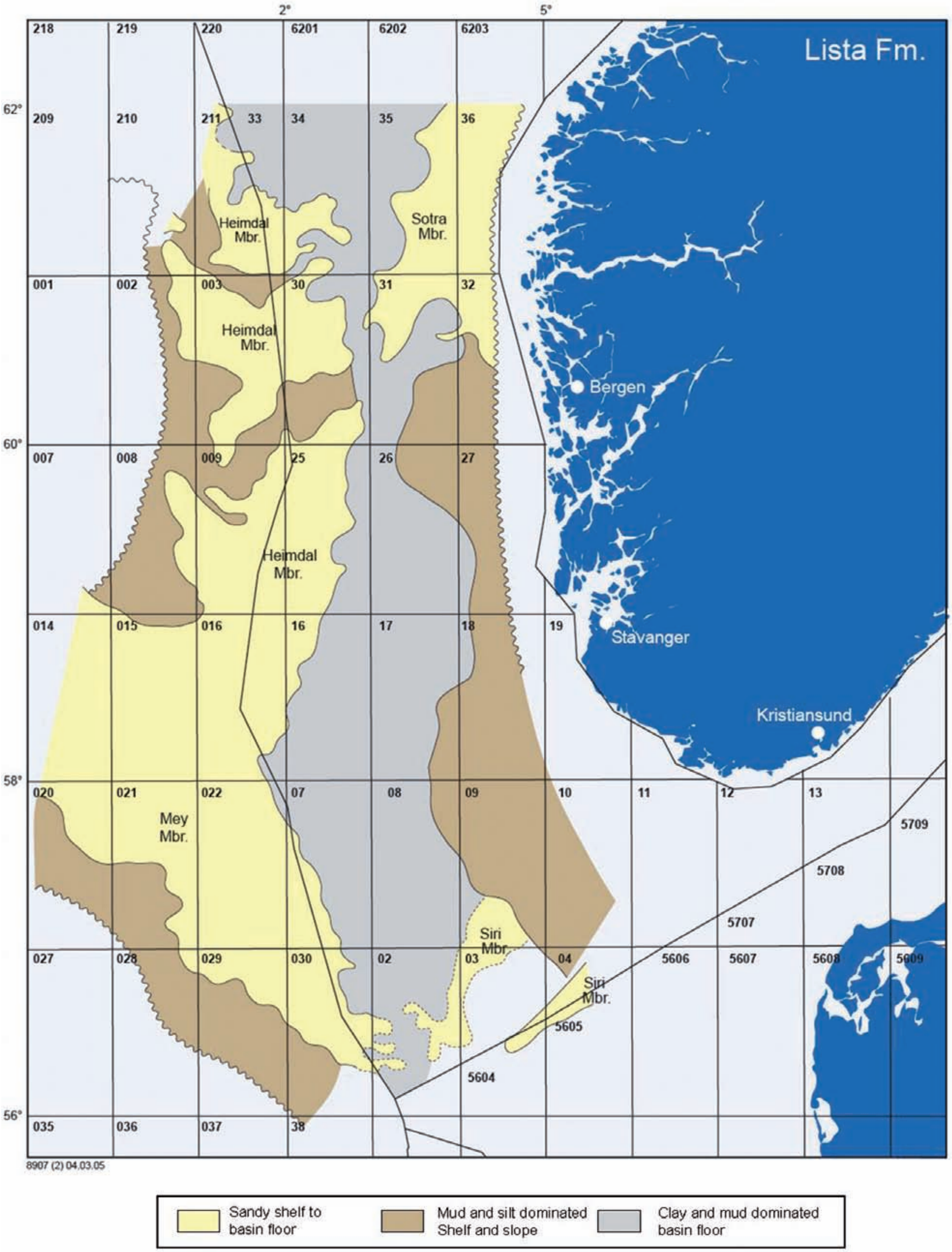


Fig. 72. Distribution of the Lista Formation and its sandstone Members.

Derivatio Nominis

The Mey Member is named after the Castle Mey, Caithness, Scotland.

Type wells

UK well 21/2-1: Depth: 2,002.5–2,356.5 mRKB. Coordinates: N 57° 55′ 14.490″, E 00° 15′ 46.930″. Defined by Knox and Holloway (1992).

Reference wells

NOR 7/11-2 (Figure 73). Depth: 3,027–3,107 mRKB. Coordinates: N 57° 4′ 15.20″, E 02° 24′ 26.50″. Cores: 3,030.6–3,046.2 mRKB.

Norwegian well 7/11-1 (new, Figure 74). Depth: 2,975–3,070 mRKB. Coordinates: N 57° 04′ 15.60″, E 02° 26′ 24.40″. No cores.

Norwegian well 1/5-2 (new, Figure 75). Depth: 3,137–3,190 mRKB. Coordinates: N 56° 34′ 41.59″, E 02° 38′ 30.53″. No cores.

Composition

The Mey Member typically consists of stacked units of fine- to medium-grained, or occasionally coarse-grained, sandstones with common mudstone and chalk clasts (Figures 76–78).

The non-tuffaceous sandstones of the Mey Member mostly range from fine to medium, occasionally coarse, sand grade, and commonly include angular clasts of mudstone or limestone. Rounded and glauconite-stained pebbles of chalk and flint are encountered in some beds. The sandstones consist of a succession of superimposed sandstone units, commonly with sharp, erosional bases, interbedded with typical variegated, bioturbated Lista mudstones. Primary structures are scarce, with most sandstones being structureless or displaying water-escape structures (Knox and Holloway 1992). The sandstones include sporadic zones of calcite cementation, with pervasive cementation in the lowermost sandstone unit (Mey L1 Sub-member, see below), reflected as consistently higher sonic velocities. Sandstone intrusions are fre-

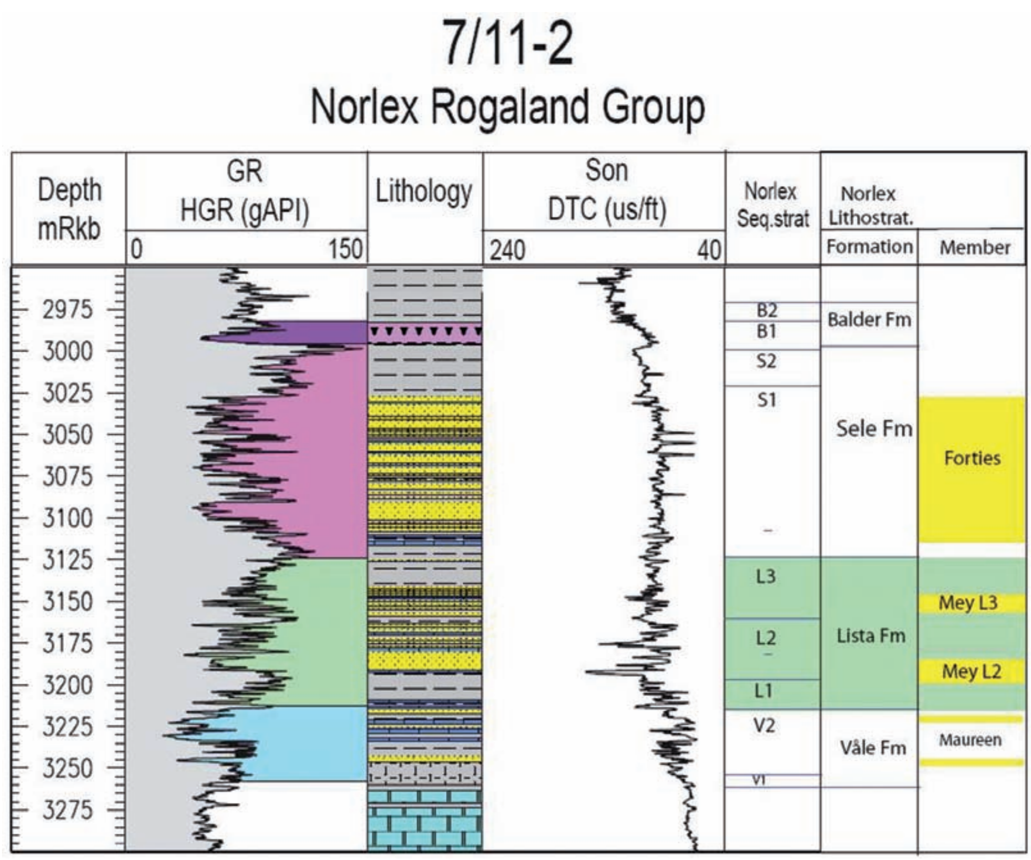


Fig. 73. Well 7/11-2 composite log, Rogaland Group. Stratigraphic position of the Mey Member is outlined in stratigraphic column to the right.

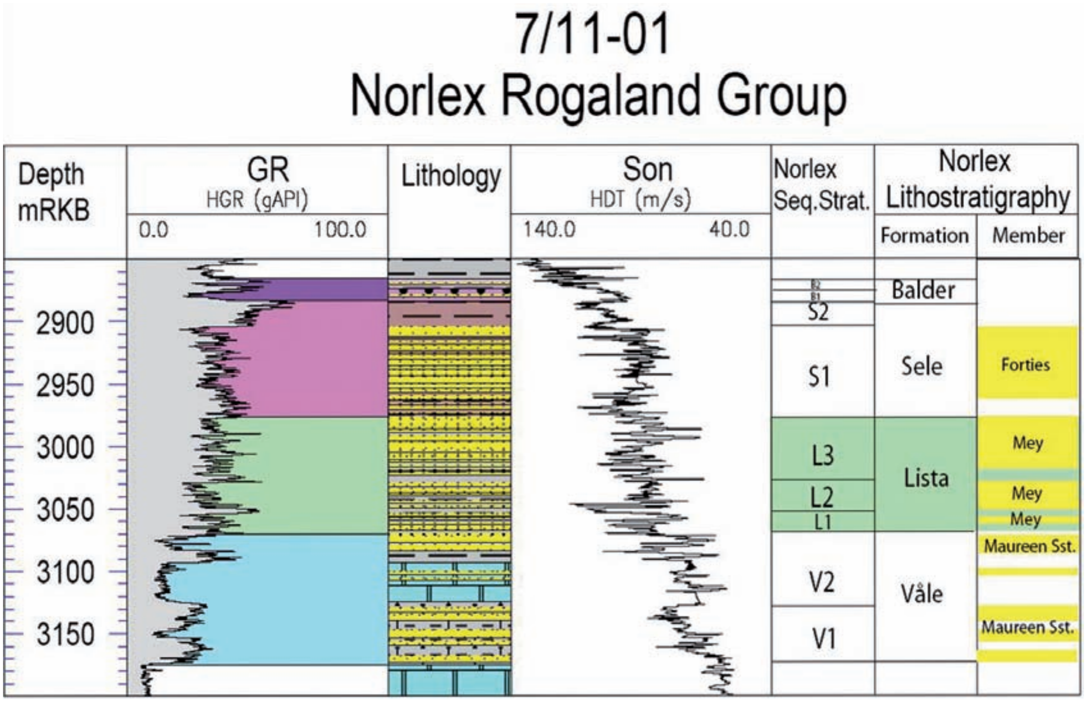


Fig. 74. Well 7/11-1 composite log, Rogaland Group. Stratigraphic position of the Mey Member is outlined in stratigraphic column to the right.

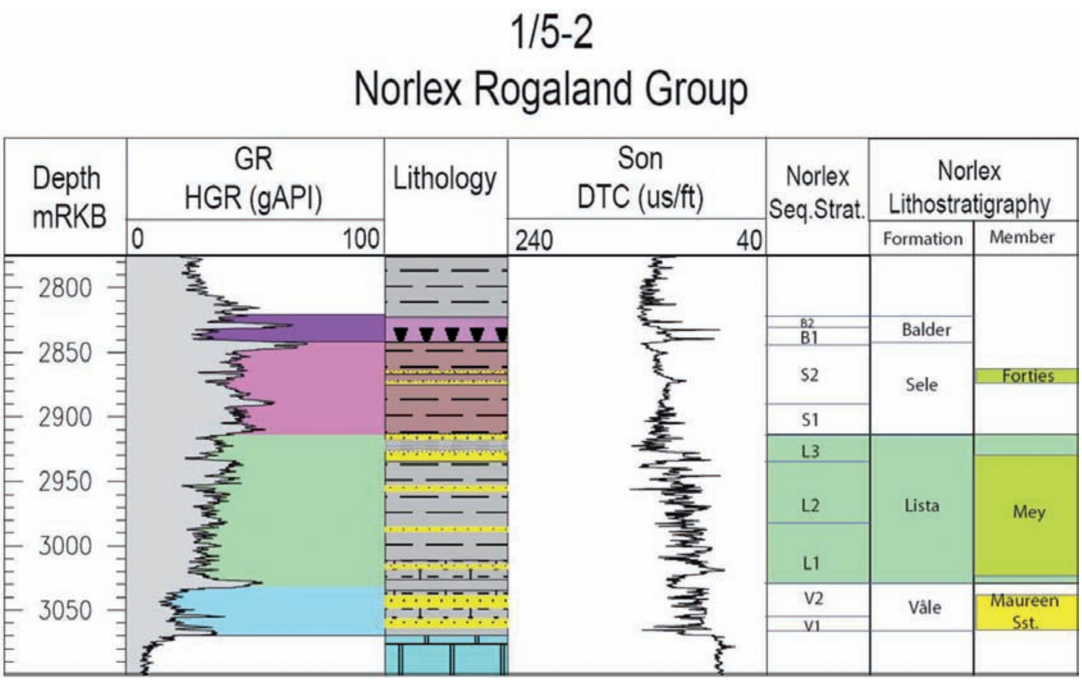


Fig. 75. Well 1/5-2 composite log, Rogaland Group. Stratigraphic position of the Mey Member is outlined in stratigraphic column to the right.

quently found associated with the upper boundary of sandstone bodies commonly with an abundance of angular and tabular mudstone clasts.

Wireline log characterization

Upper boundary

The Lista Formation shales may envelope or overlie the Mey Member, and the boundary is characterised by higher gamma-ray readings and lower velocity upwards into the Lista Formation. Where the Forties Member directly overlies the Mey Member, the boundary may be more difficult to define, but the Forties Member generally has a lower velocity than the Mey Member. This boundary can be difficult to determine in the Norwegian sector of the North Sea.

Fig. 76. Core photograph Mey Member well UK30/14-1. Well sorted sandstones with mud flakes. The well is drilled at the Flyndre Discovery at the Norwegian/UK Boundary. Photograph by H. Brunstad.

Fig. 77. Core photograph of the Mey Member in well 7/7-1 at 2,796–2,801 m. Photograph by H. Brunstad.

Lower boundary

The Mey Member usually overlies shales of the Lista and in places the Våle Formation. The boundary is characterised by lower gamma readings and increased velocity upwards from the Lista or Våle Formation below.

Thickness

The Mey Member reaches thicknesses of more than 500 m in the Moray Firth area, but crossing the Norwegian boundary in the Central Graben, the Mey Member thickness usually does not exceed more than some tens of meters.

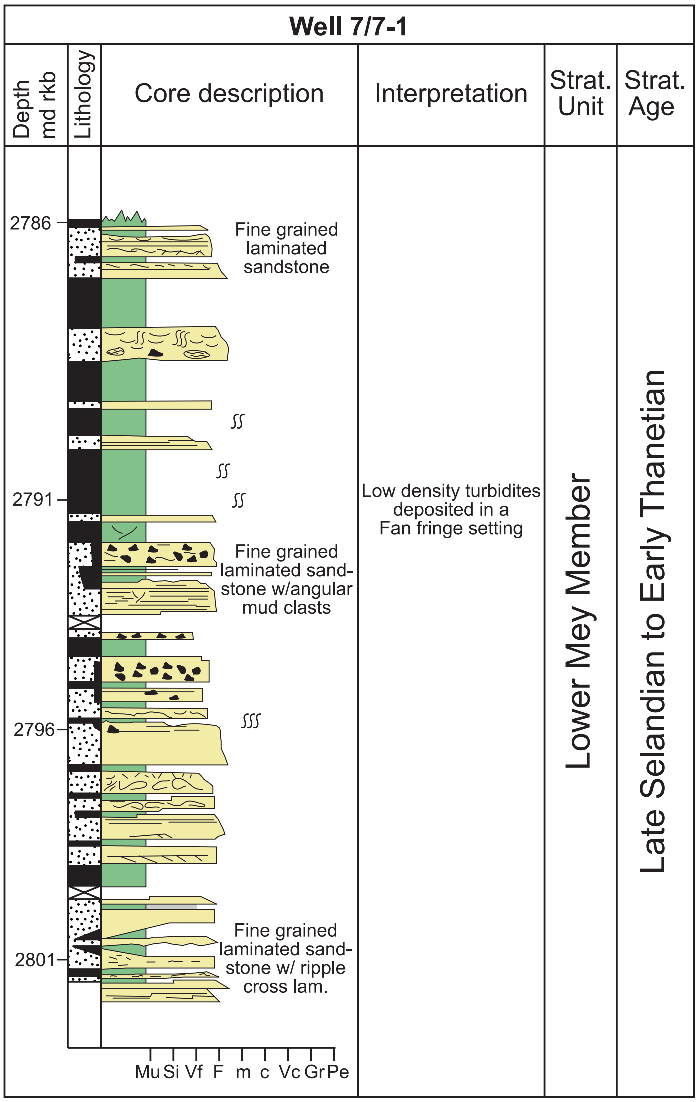


Fig. 78. Well 7/7-1 core description log.

Seismic characterization

Seismic expression is highly variable due to the variable composition of the Mey sandstones. In some areas the tops and bases of the sandstones can be picked confidently (Figure 79) whereas in other cases the sandstones are mapped out based on seismic isopach thickenings between mappable events as MFS or sequence boundaries.

By applying the technique of S/G cross-plotting explained earlier in this study, the minimum threshold thickness for the presence of Mey sandstones can be assessed.

Age

Late Mid to Late Paleocene (Late Selandian–Early Thanetian).

Biostratigraphy

The biostratigraphic subdivision of the Mey Member is directly comparable to that of the Lista Formation, with the *A. gippingensis* acme biomarker and the *P. pyrophorum* biomarker allowing further subdivision (Knox and Holloway 1992).

Correlation and subdivision

The Mey Member is more or less time-equivalent with the Heimdal Member of the northern North Sea. To some extent the two fan systems seem to intermix across the Fladen Ground Spur (Figures 12 and 13), but they are separated there by a line of supposed minimum sandstone thickness (Knox and Holloway 1992).

The Mey Member is divided into the Mey L1, L2 and L3 Sub-members. Mey L1 Sub-member corre-

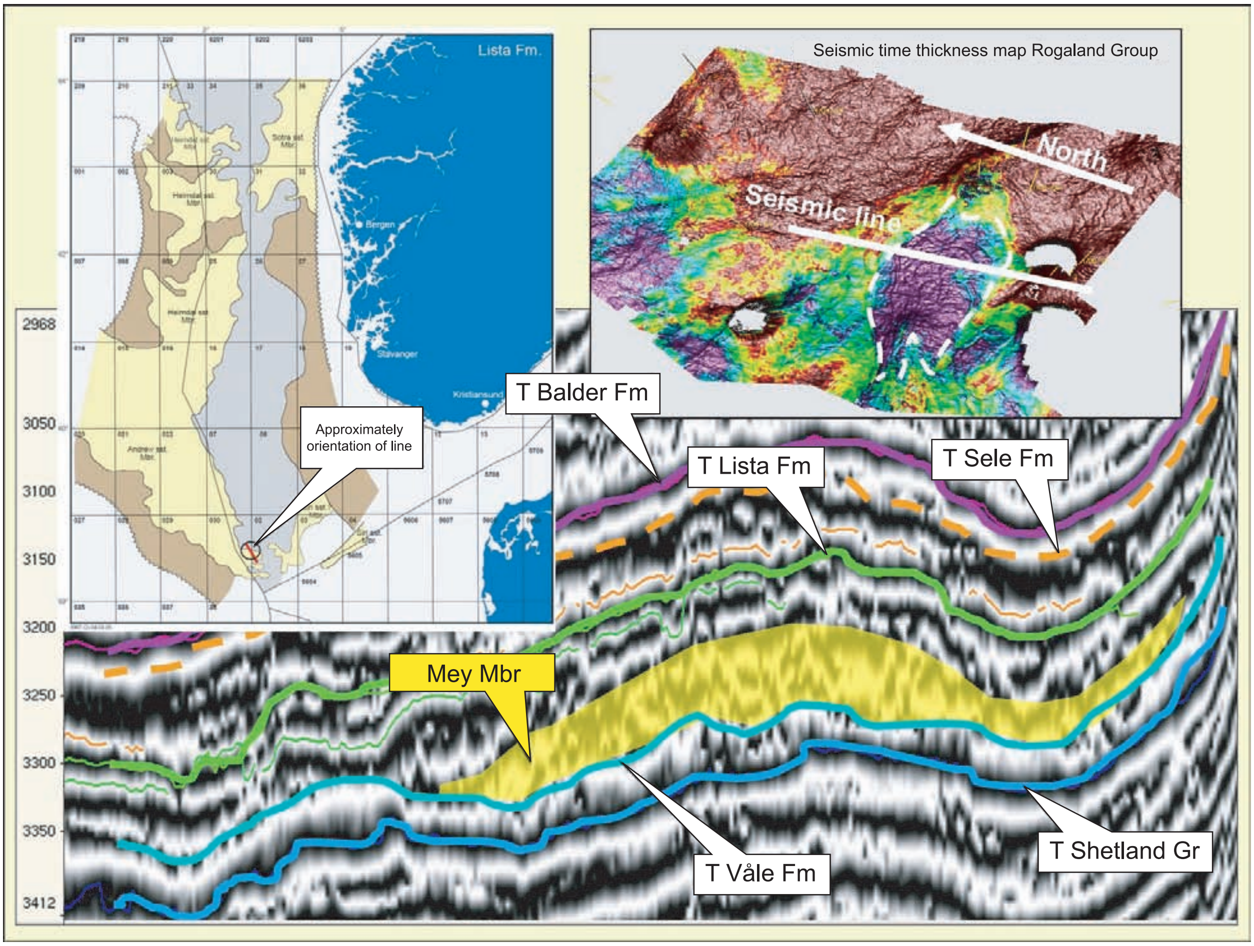


Fig. 79. Seismic section through a lobe shaped thickness anomaly of the Mey Member. Example is from the blocks 1/5–1/6 area, between Flyndre and Albuskjell discoveries.

sponds to the Andrew Member, Mey L2 Sub member to Balmoral, and the Mey L3 Sub member to the Glamis Member of Mudge and Copestake (1992).

Geographic distribution

The Mey Member is distributed in the Outer Moray Firth area and extends into the Central Graben, lapping onto the eastern margins of the basin in the Central Graben (Figure 72).

Depositional environment

In general, the Mey sandstones were laid down in outer shelf, slope and basin environments, with the shelf sands being redistributed to form a slope apron made up of superimposed, laterally coalescing fans (Parker 1975, Stewart 1987, Kilhams et al. 2012). Shelfal areas were in general located west of the Central Graben, whereas in the Central Graben the sandstones were deposited by gravity flows in submarine slope to distal basin floor settings.

Heimdal Member, Lista Formation

Unit definition

The Heimdal Member is attributed to the intra-Lista Formation sandstones in sub-area NW in Figures 12, 13 and 72.

Name

The name Heimdal Formation was introduced by Deegan and Scull (1977) for sandstones age-equivalent to the mudstones of the Lista Formation. Knox and Holloway (1992) redefined the sandstones of the Heimdal Formation as the Heimdal Member. This redefinition is maintained in this study.

Derivatio nominis

The Heimdal Formation (now Heimdal Member) is named after the Norse god Heimdal, one of Odin's sons.

Type well

Norwegian well 25/4-1 (Figure 80). Depth: 2,067–2,423 mRKB. Coordinates: N 59° 34′ 27.30″, E 02° 13′ 22.60″. Defined by Hardt et al. (1989).

Reference wells

Norwegian well 15/9-11 (New, Figure 81). Depth: 2,385–2,423 mRKB. Coordinates: N 58° 24′ 02.53″, E 01° 53′ 41.79″. Cores: Core 3–4.

Norwegian well 15/9-5 (Figure 82). Depth: 2,448–2,716 mRKB (revised). Coordinates: N 58° 24′ 12.47″, E 01° 42′ 29.20″. No cores. Defined by Hardt et al. (1989).

Composition

According to Knox and Holloway (1992), the Heimdal Member consists of thick sandstone units alternating with thinly bedded sandstones and mudstones. A core photo example is shown in Figure 83, and a core description example in Figure 84. The sandstones are friable to lightly cemented, moderately sorted and of very fine to coarse sand grade. They include minor and variable amounts of glauconite and are occasionally associated with thin beds of chalk. The interbedded mudstones are light to medium grey grading to olive-green and green-grey. They are poorly bedded, and variably silty and generally non-calcareous. Sandstone intrusions are frequently found associated with the upper boundaries of sandstone bodies commonly with an abundance of angular and tabular mudstone clasts.

Wireline log characterization

Upper boundary
The Lista Formation usually overlies the Heimdal Member, and the boundary is characterised by higher gamma-ray readings and lower velocity upwards into the Lista Formation. Where the Hermod Member directly overlies the Heimdal Member, the boundary may be more difficult to define.

Lower boundary
The Heimdal Member overlies the Lista and in places the Våle Formation, and the boundary is characterised by lower gamma readings and increased velocity upwards from the Lista or Våle Formation below.

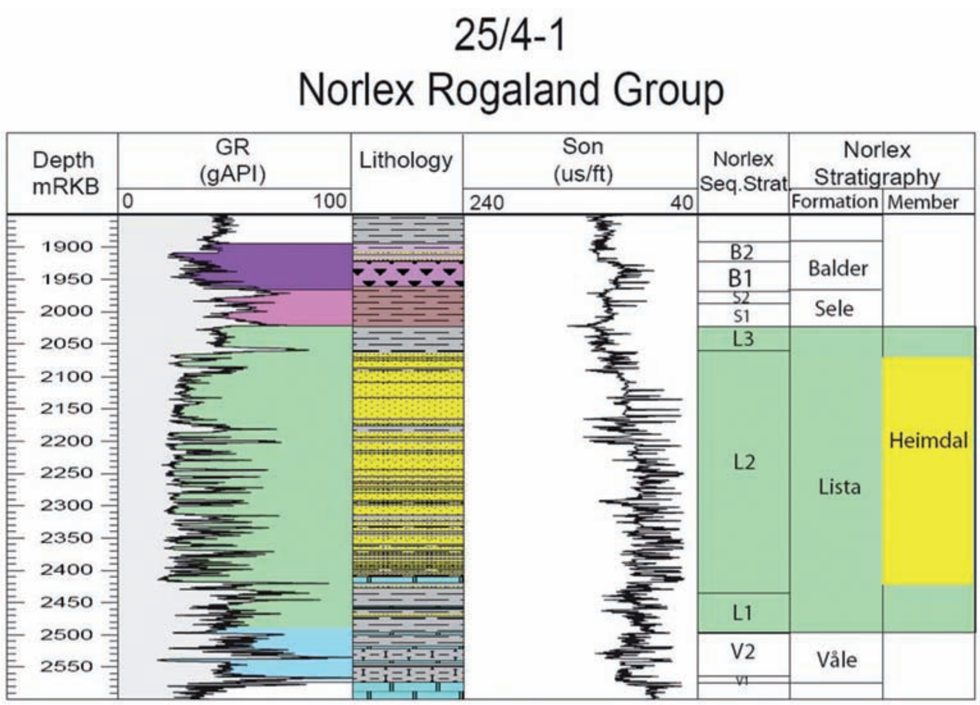


Fig. 80. Well 25/4-1 composite log, Rogaland Group. Stratigraphic position of the Heimdal Member is outlined.

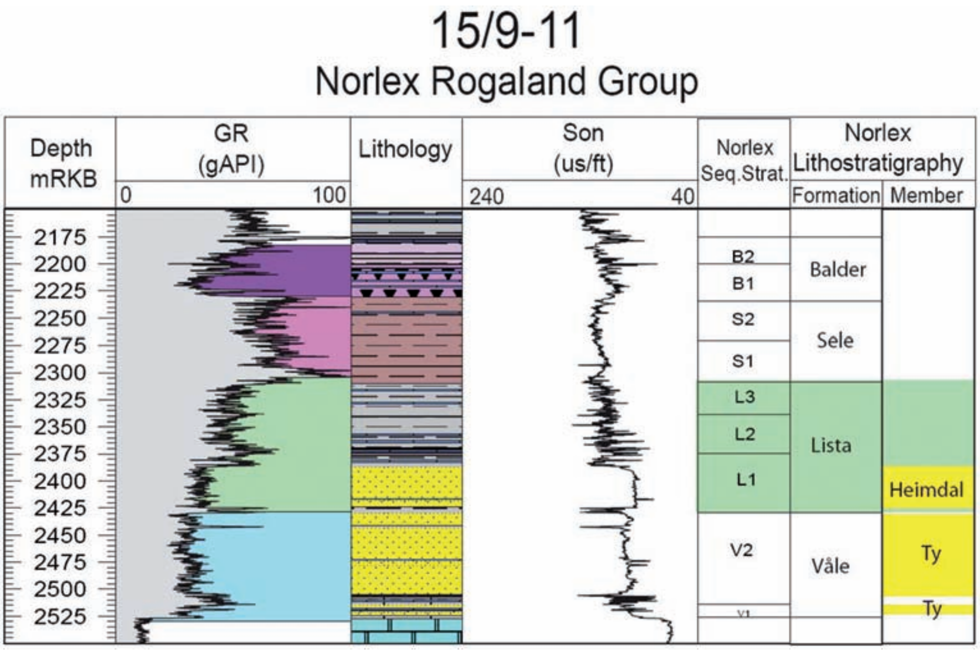


Fig. 81. Well 15/9-11 composite log Rogaland Group. Stratigraphic position of the Heimdal Member is outlined.

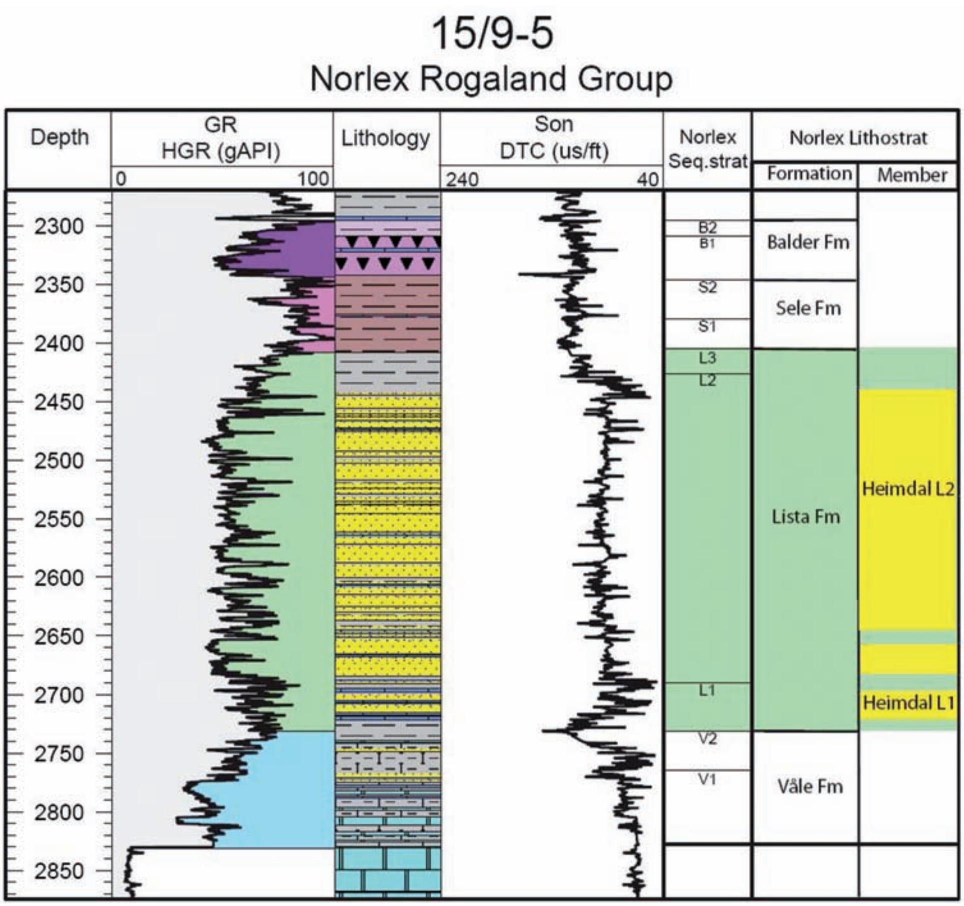


Fig. 82. Well 15/9-5 composite log, Rogaland Group. Stratigraphic position of the Heimdal Member is outlined.

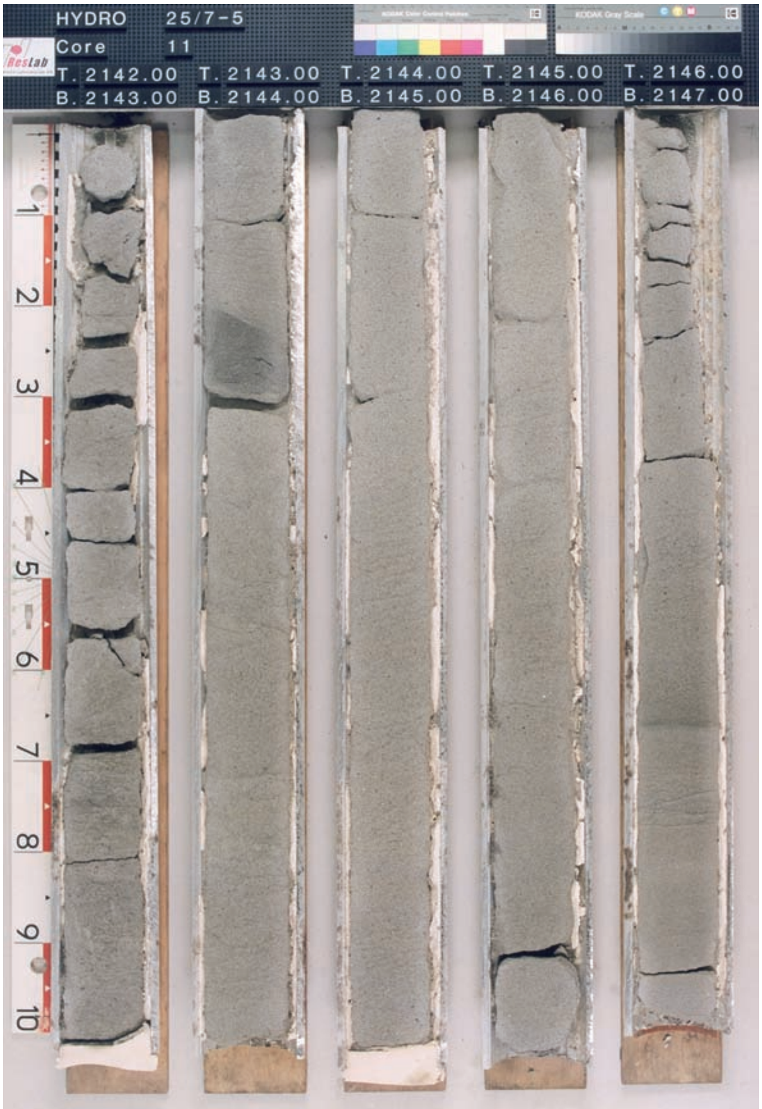


Fig. 83. Core photograph in well 25/7-5 at 2,142–2,147 m of massive, faintly dish structured sandstones of the Heimdal Member. Well drilled by Norsk Hydro. Photograph from *http://www.npd.no*.

Thickness

The Heimdal Member occurs over much of the Viking Graben, and can attain a thickness of more than 400 m in this area (436 m in well 24/6-2).

Seismic characterization

The seismic pick of the top Heimdal Member is variable and varies from well defined positive acoustic impedance to poorly defined or even negative acoustic impedance. The identification of the Heimdal Member is often characterized by a mounded internal character within an envelope of mapped flooding surfaces or sequence boundaries. Figure 85 shows a seismic cross-section through two major bodies of the Heimdal Member, representing sand-rich submarine fan deposits. Figure 86 shows a seismic amplitude map of the uppermost Heimdal sand body in block 15/5, displaying a fan-shaped high amplitude feature. This feature represents the sand-rich submarine fan system that is reservoir rock in the Glitne Field.

Age

Late Mid to Late Paleocene (Late Selandian–Early Ypresian).

Biostratigraphy and age

The Heimdal Member contains the acme occurrences of *A. gippingensis* and *P. pyrophorum*. The member is contained within the Lista Formation, thus correspon-

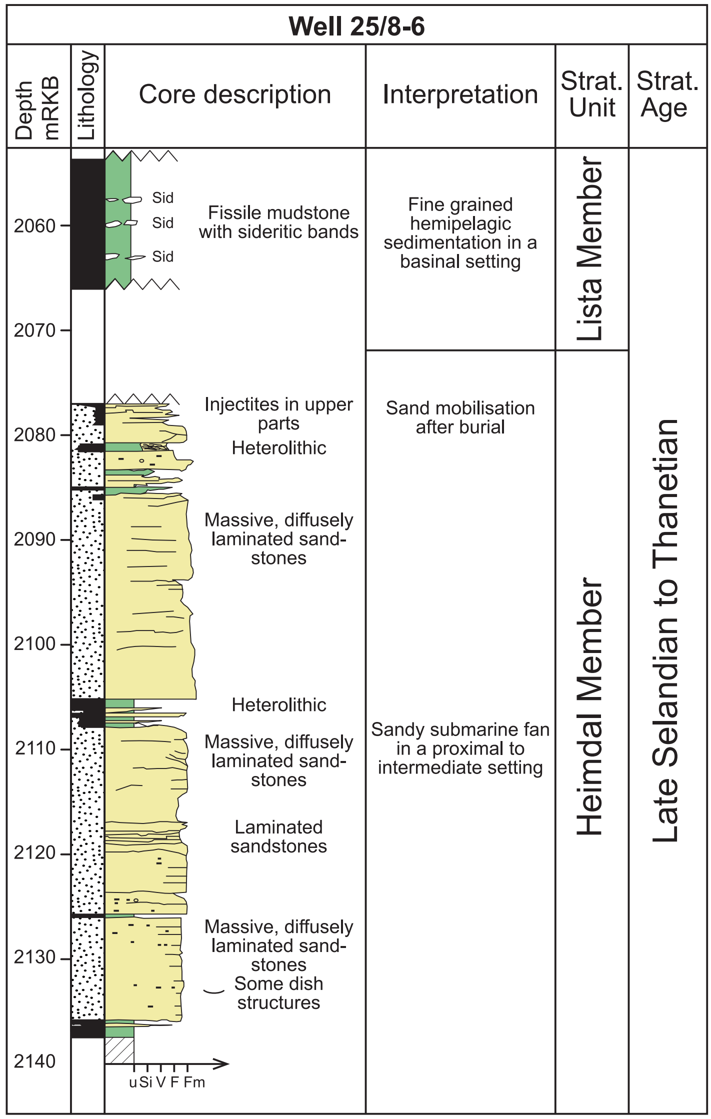


Fig. 84. Core description log from upper part of the Heimdal Member in well 25/8-6.

ding in age to that of the Lista Formation, Late Selandian and Thanetian.

Correlation and sub division

The acme occurrences of *A. gippingensis* and *P. pyrophorum* allow further subdivision of the Heimdal Member, related to the three-division of Lista, with distinction of Heimdal L1 Sub-members, Heimdal L2 Sub-members and Heimdal L3 Sub-member sandstones.

Geographic distribution

The Heimdal Member is more or less time-equivalent to the Mey Member of the Outer Moray Firth and Central Graben. Limited interfingering of the two sand fan systems appears to have taken place over the Fladen Ground Spur (Figures 12 and 13), and they are here separated along a line of supposed minimum sandstone thickness between the depocentres of the South Viking Graben and the Fisher Bank Basin (Knox and Holloway 1992). The geographical distribution is mainly in the Viking Graben to Shetland Platform, with thin sands reaching the Viking Graben across the Tampen Spur (Figure 72).

Depositional environment

The sand-rich Heimdal Member was deposited in coalescing sand fan systems. The sands were mainly transported with high-density turbidity flows, depositing thick bodies of amalgamated sand beds. Minor heterolithic sandstone bodies were deposited in inter-

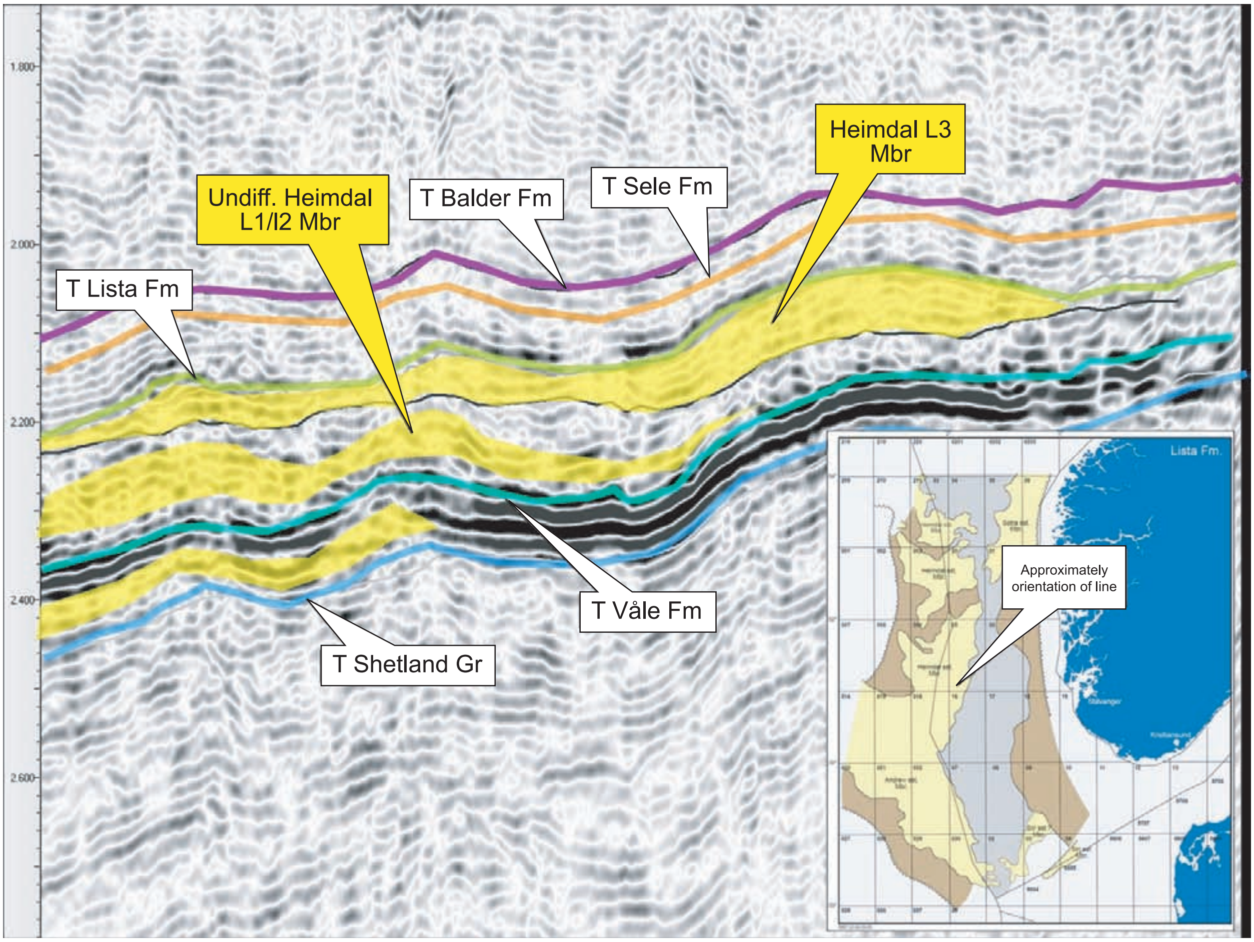


Fig. 85. Seismic WE Line through southern parts of Block 25/10. The line shows partly mounded thicks. The two uppermost represent sub-members of the Heimdal Member.

channel and terminal edges of depositional lobes. Water depths may have reached several hundreds of meters in central parts of the basin.

Hydrocarbon discoveries with Heimdal Member reservoirs

- Balder Field
- Grane Field
- Jotun Field
- Heimdal Field
- Alvheim Field
- Glitne Field
- Sleipner East Field (part of reservoir)
- Well 24/12-3 oil discovery
- Well 16/1-6 gas discovery
- Well 16/4-4 gas and condensate discovery

Siri Member, Lista Formation

Unit definition

The Siri Member is attributed to the intra-Lista Formation sandstones in sub-area SE in Figures 12 and 13. While some authors split the intra-Lista Formation sandstones of the Siri Canyon area, and the southern parts of the Norwegian–Danish Basin into three separate members (Schiøler et al. 2007), we choose to give all these intra-Lista Formation sandstones a common name: the Siri Member, a practice that has been followed also in other studies, e.g., by Ahmadi et al. (2003) in The Millennium Atlas.

Name

It is not clear who defined the member name first, but it was used by Ahmadi et al. (2003) in The Millennium Atlas.

Derivatio nominis

The Siri Member is named after the Paleocene Siri oil and gas field, which contains intra-Lista reservoir sandstones.

Type well

Danish well, DK Siri-2. Depth: 2,205.5–2,127 mRKB and 2,124–2,100 mRKB. Coordinates: N 56° 29′ 40.53″, E 04° 52′ 13.26″ (Figure 87). Cores: 2,092–2,200.3 mRKB.

Reference wells (this study)

Connie-1 (Figure 87): Depth: 2,368.3–2,292.2 mRKB. Coordinates: N 56° 24′ 28.34″, E 04° 42′ 30.36″. Cores: 2,273–2,389.6 mRKB.

Norwegian well 3/6-1 (New). Depth: 2,004–2,011 mRKB. Coordinates: N 56° 35′ 00.14″, E 04° 53′ 30.35″. Cores taken (Figure 88).

Norwegian well 9/11-1 (New, Figure 89). Depth: 1,499–1,515 and 1,559–1,567 mRKB. Coordinates: N 57° 0′ 41.40″, E 04° 31′ 40.60″. No cores.

Composition

The Siri Member is characterized by thick beds of olive-green to greenish grey sand. The sandstones of the main sand bodies are in general very fine to fine-grained, very well sorted and remarkably clean (< 0.1 % detrial clay). Sand grains are quartz dominated with a high percentage of glauconite grains (15–20 %), giving a greenish grey color.

Glauconite grains are found as rounded pellets of the same grain size as the quartz grains. Angular chalk and claystone clasts occur locally in the sandstones. The sandstones are partly calcite-cemented. Intrusive sandstones are common, in particular towards the top of the member where they may be several meters thick (Hamberg et al. 2005, Schiøler et al. 2007).

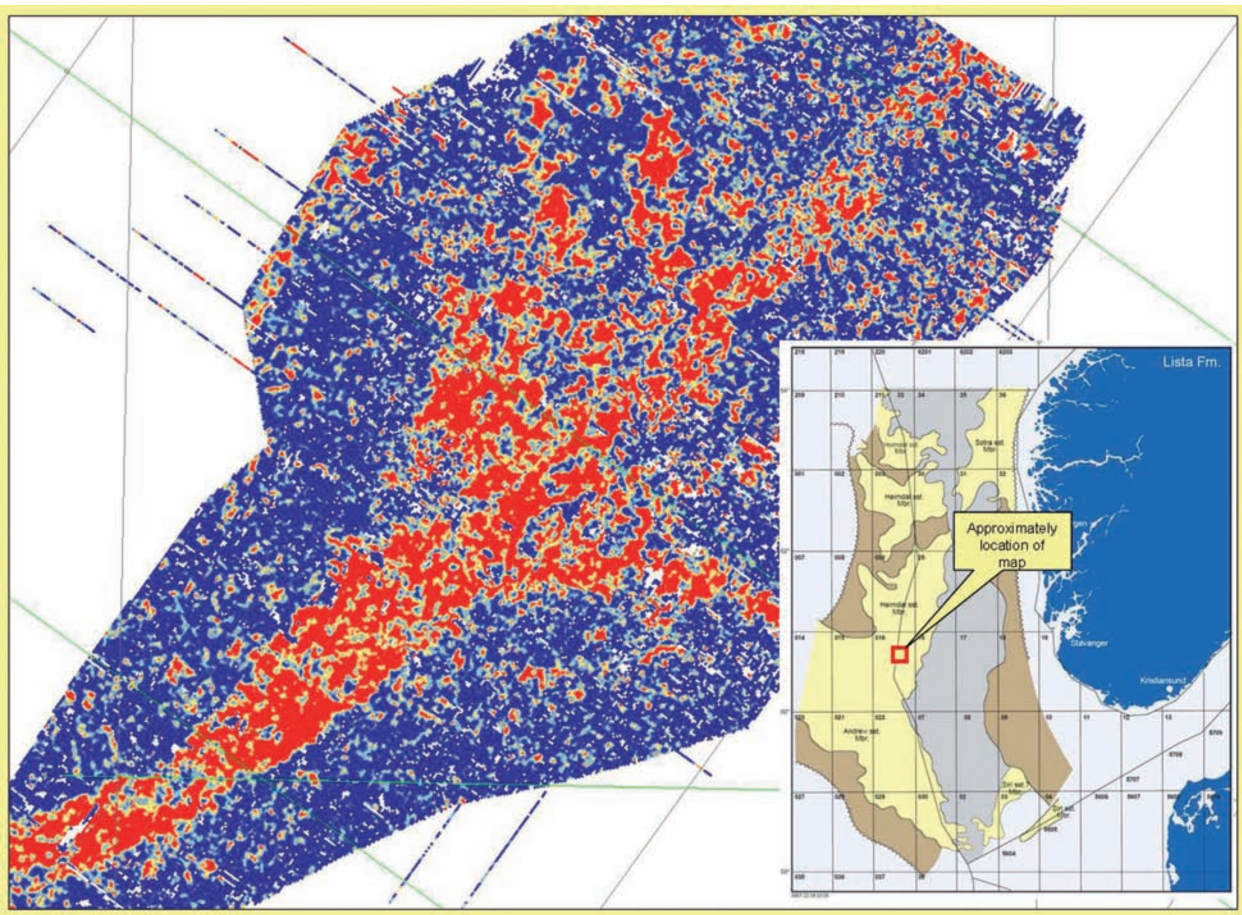


Fig. 86. Seismic amplitude map from an internal event in the Upper part of the Lista Fm in Block 15/5. Fan shaped anomaly forms the reservoir in the Glitne hydrocarbon discovery, and is attributed to presence of Heimdal L3 sub-member.

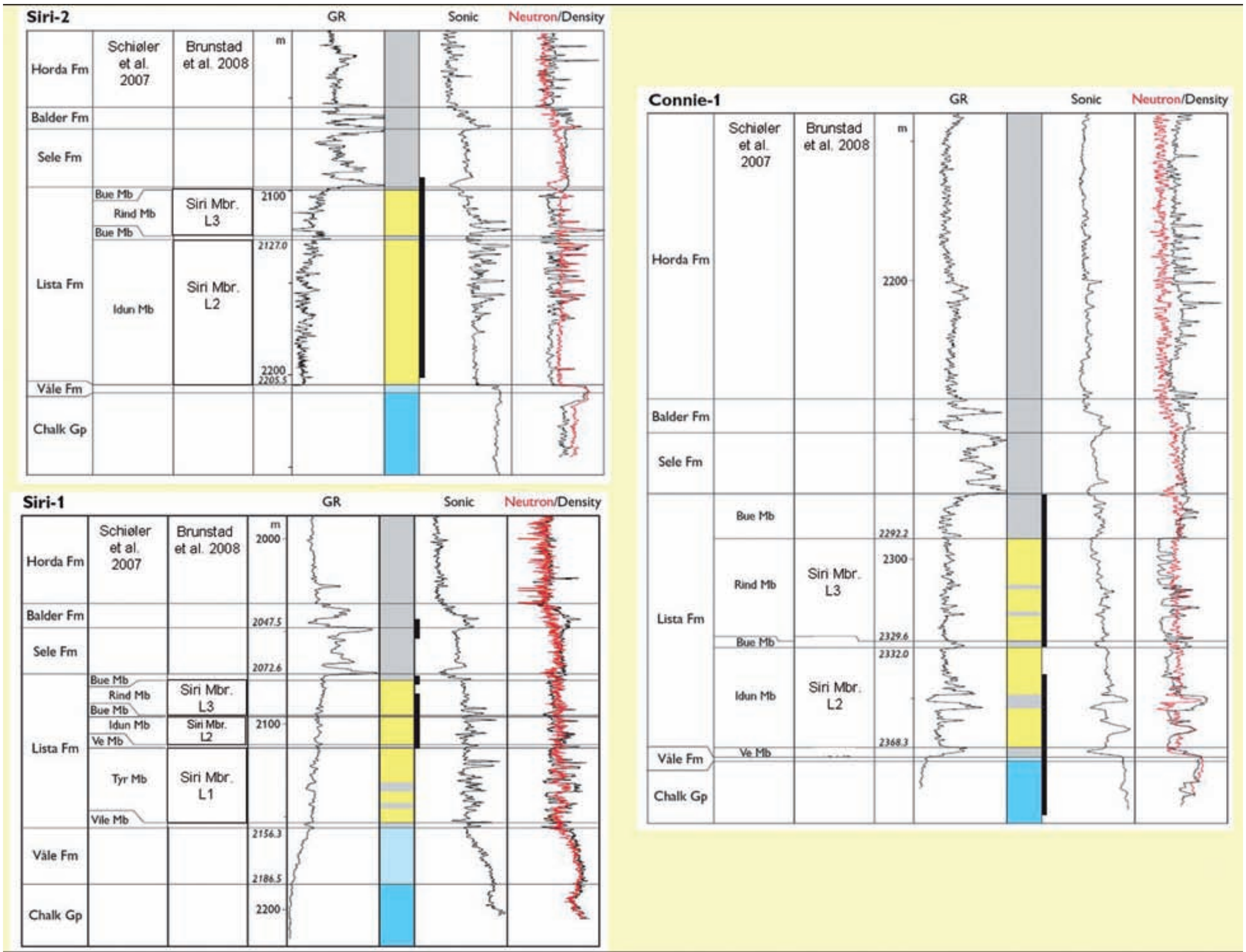


Fig. 87. Well composite logs in wells DK Siri-2 and Connie-1. Position of the Siri Member is outlined. Modified from Schiøler et al. (2007) to concur with the nomenclature for the Norwegian North Sea (this study).

In cores, sandstones of the Siri Member are often observed as generally massive, homogenous and with few structures. Faint deformed lamination and dish and pillar structures are rather common, and witness post-sedimentary water movement through the sediments. There are few signs of primary sedimentary structures in the sandstones, although a few examples of faint cross-bedding seem to occur.

Sandstone intrusions are frequently found associated with the upper boundaries of sandstones bodies, commonly with an abundance of angular and tabular mudstone clasts (Hamberg et al. 2005).

Norwegian sector wells have penetrated only thin layers of the Siri Member. The sand layers are very fine grained, micaceous and glauconitic compared to the better developed sands described from cores in the Danish wells of the Siri Canyon.

Wireline log characterization

The sandstones have a high content of glauconite that increases their natural radioactivity. This sometimes makes it difficult to distinguish Siri Member sandstones from the mudstones of the Lista Formation based on gamma logs, and their identification must rely on other logs such as density, neutron and resistivity logs.

Upper boundary
Where the Lista Formation shales overlie the Siri Member, the boundary is usually characterised by higher gamma-ray readings and lower velocity upwards into the Lista Formation.

Lower boundary
Where the Siri Member overlies the Lista and in places the Våle Formation, the boundary is characterised by

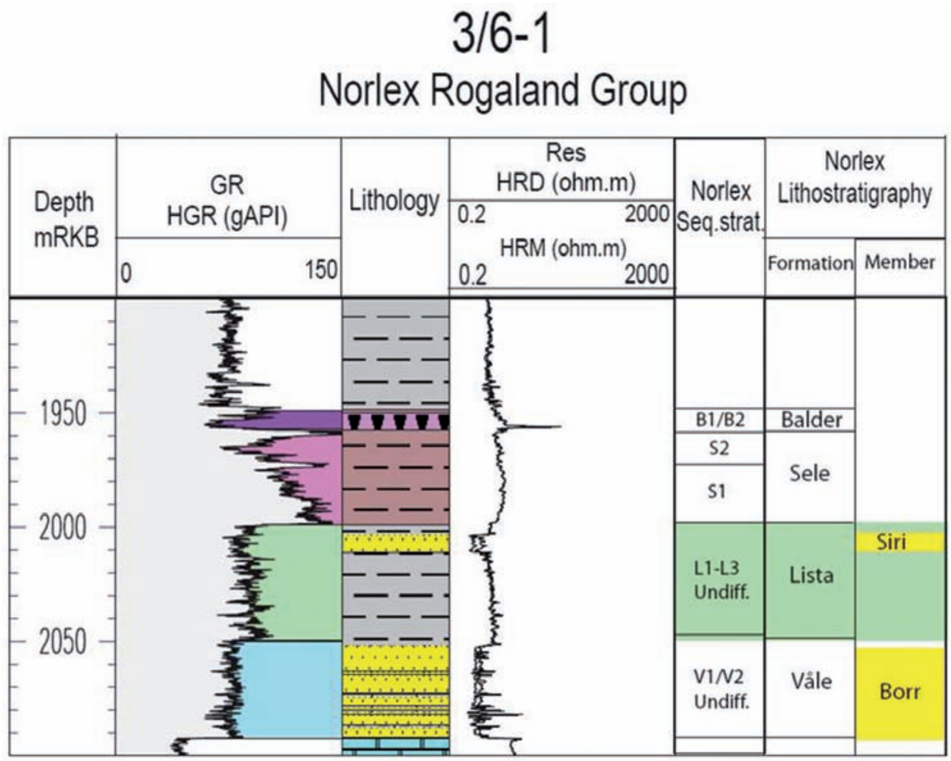


Fig. 88. Well 3/6-1 composite log Rogaland Group. Stratigraphic position of the Siri Member is outlined.

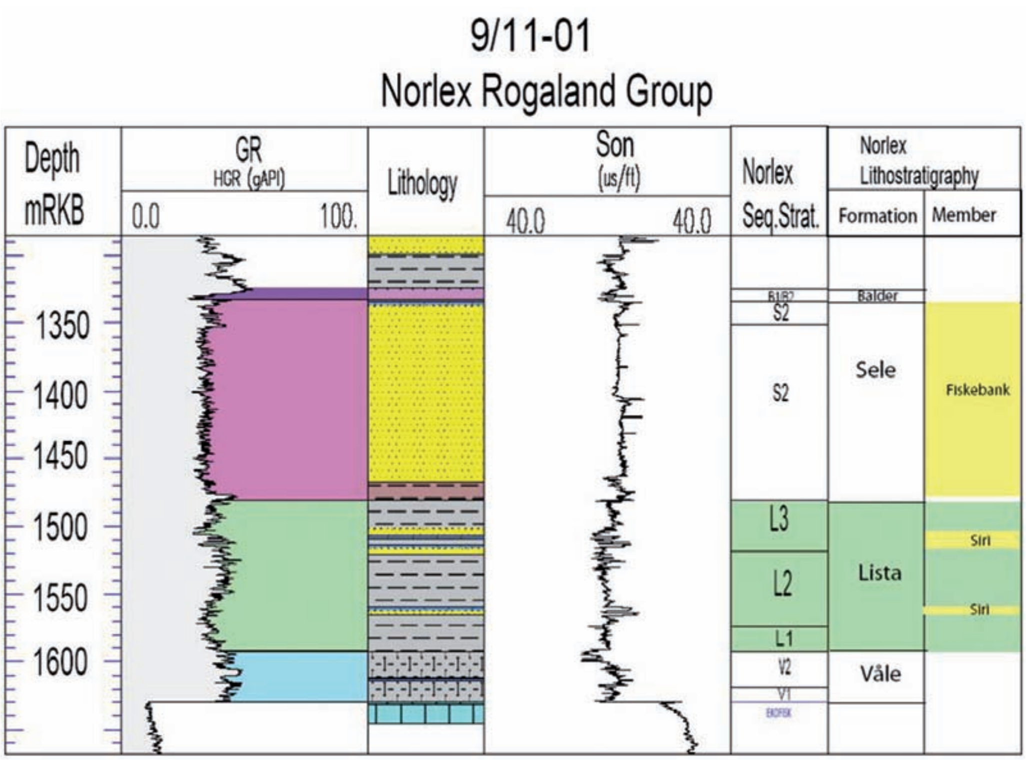


Fig. 89. Well 9/11-1 composite log Rogaland Group. Stratigraphic position of the Siri Member is outlined.

lower gamma readings and increased velocity upwards from the Lista and Våle Formation below.

Thickness

The Siri Member is 78 m in DK well Siri-2, and 72 m in DK well Connie-1 (Figure 87).

Seismic characterization

Figure 90 shows a seismic line example of Siri Member through well Siri-2. From seismic mapping of the Lista Formation, thickness anomalies can be observed that have an elongated shape, and a lenticular to mounded shape in seismic cross-sections. This thickening usually coincides with the presence of thick sand bodies of the Siri Member in the area along the Norwegian–Danish border and the Siri Canyon.

Age

Late Mid to Late Paleocene (Late Selandian–Early Thanetian).

Biostratigraphy

The Siri Member is embedded in the Lista Formation and is limited by the biostratigraphic boundary of the Lista Formation. For biostratigraphic details see Lista Formation.

Correlation and sub division

The Siri Member is further subdivided into Siri L1, Siri L2 and Siri L3 sub-members, corresponding to the three Lista L1, L2 and L3 sub-members, equivalents to Tyr (L1), Idun (L2) and Rind (L3) members of Schiøler et al. (2007).

Geographic distribution

The Siri Member is deposited across most of the central parts of the Siri Canyon, but seems to stop before it reaches the southern parts of the Søgne Graben. However, some minor tongues of the Siri Member seem to reach into the northern parts of the Søgne Graben, and into the Gyda Area farther northwest (Figure 72).

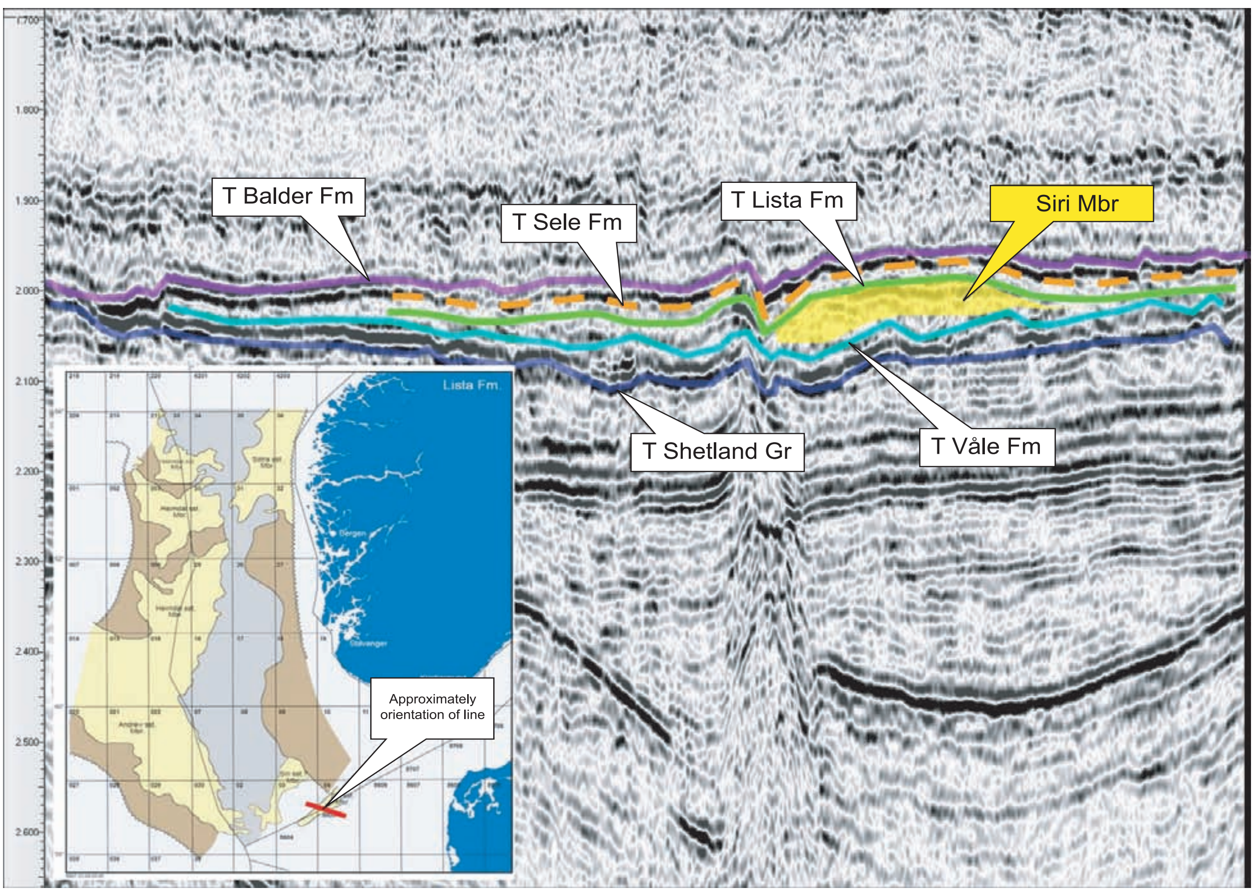


Fig. 90. Seismic section crossing the Siri Canyon and the Siri discovery. Interval with presence of Siri Member is outlined.

Depositional environment

The Siri Member was deposited by gravity flows in sand-rich basin-floor to toe-of-slope fan systems. These deposits lie in front of the shallow marine and shelf slope progradation of the Fiskebank Member. The gravity-flow mechanism was probably a combination of high-density sandy turbidity currents and sandy debris flows. The high glauconitic content suggests that there was a significant contribution of shelf sands.

Sotra Member, Lista Formation (New)

Unit definition

The Sotra Member is attributed to the intra-Lista Formation sandstones in sub-area NW in Figures 12 and 13.

Name

The Sotra Member is defined for the first time in this study. This member status is attributed to sandstones of intra-Lista Formation with an eastern provenance in the Sogn Graben and the Stord Basin.

Derivatio nominis

The Sotra Member is named after one of the largest islands in Hordaland.

Type well

Norwegian well 35/8-3 (new, see Figure 91). Depth: 1,665–1,709 mRKB. Coordinates: N 61° 21′ 05.35″, E 03° 32′ 02.63″. No cores.

Reference wells

Norwegian well 35/3-1 (new, see Figure 92). Depth: 1,392–1,422 mRKB, major body of Member. Several thinner sandstone beds in interval 1,422–1,540 mRKB. Coordinates: N 61° 50′ 41.89″, E 03° 43′ 41.36″.

Norwegian well 35/11-3S. Depth: 1,905–1,997 mRKB. Coordinates: N 61° 10′ 59.27″, E 03° 20′ 18.47″. Cores: Core 1.

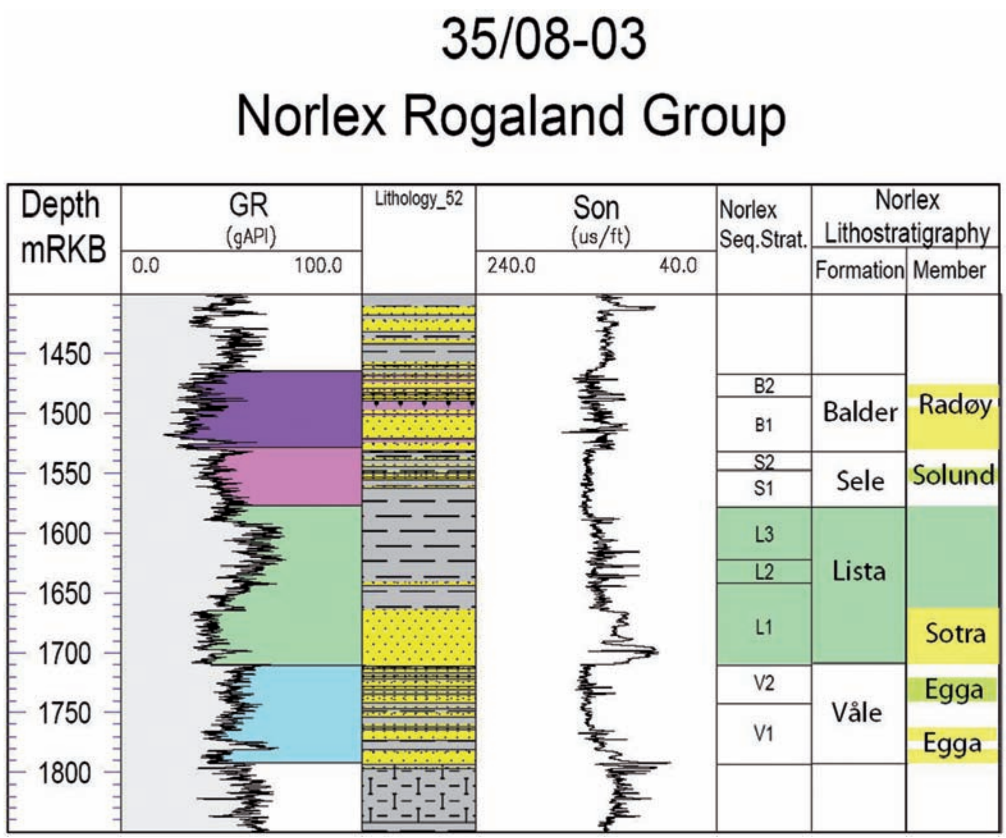


Fig. 91. Well 35/8-3 composite log Rogaland Group. Stratigraphic position of the Sotra Member is outlined in stratigraphic column to the right.

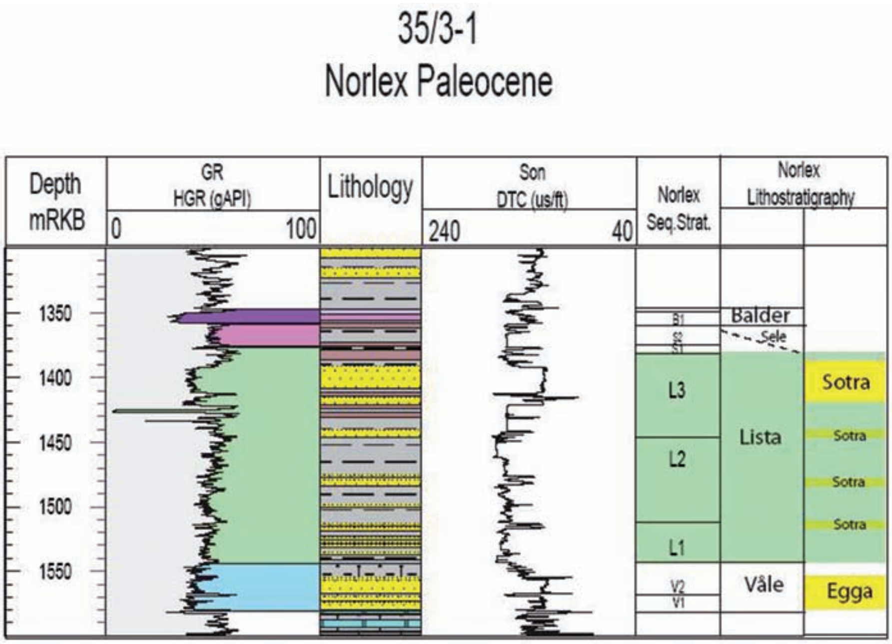


Fig. 92. Well 35/3-1 composite log Rogaland Group. Stratigraphic position of the Sotra Member is outlined in stratigraphic column to the right.

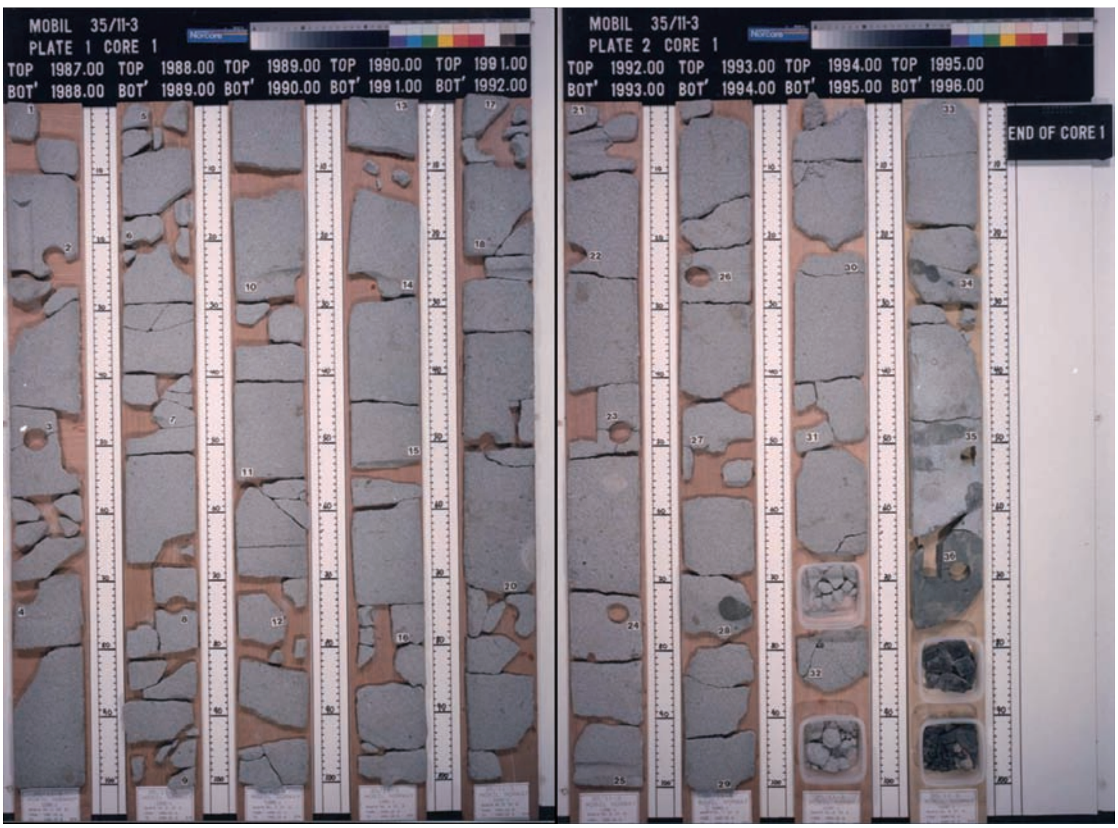


Fig. 93. **a** Example of massive, clean, structureless sandstones of the Sotra Member in well 35/11-3s at 1,987–1,992 m. Photo from *http://www.npd.no*. **b** Example of massive, clean, structureless sandstones of the Sotra Member in well 35/11-3s at 1,992–1,996 m. Photo from *http://www.npd.no*.

Composition

The Sotra Member consists of clear to white, in places grey quartzitic sandstones. Grain size is fine to very coarse, but predominantly medium and sorting poor to moderate, with angular to surrounded grains. The sandstones have traces of pyrite, glauconite and mica, and are occasionally calcite-cemented.

There are few cores taken from the Sotra Member, and thus there is limited information about variability in facies. Cores photo examples from Norwegian well 35/11-3s are shown in Figures 93a and b.

Wireline log characterization

Wire-line log response of the Sotra Member is blocky to serrated, representing thick clean sandstones and a succession of thinner sandstone layers in alternation with mudstones. Locally, zones of high velocity sonic readings and high values on density logs are seen, which seem to correspond to zones of calcite cementation in the sandstones.

In some cases the content of glauconite in the sands increases their natural radioactivity and thereby makes it difficult to assess the sand amount and the distinction between the Sotra Member and the the Lista Formation from gamma logs. In these cases their identification must rely on density, neutron and resistivity logs.

Upper boundary
The Lista Formation usually overlies the Sotra Member, and the boundary is usually characterised by higher gamma-ray readings and lower velocity upwards into the Lista formation.

Lower boundary
The Sotra Member locally overlies the Lista and/or Våle formations, and the boundary is characterised by

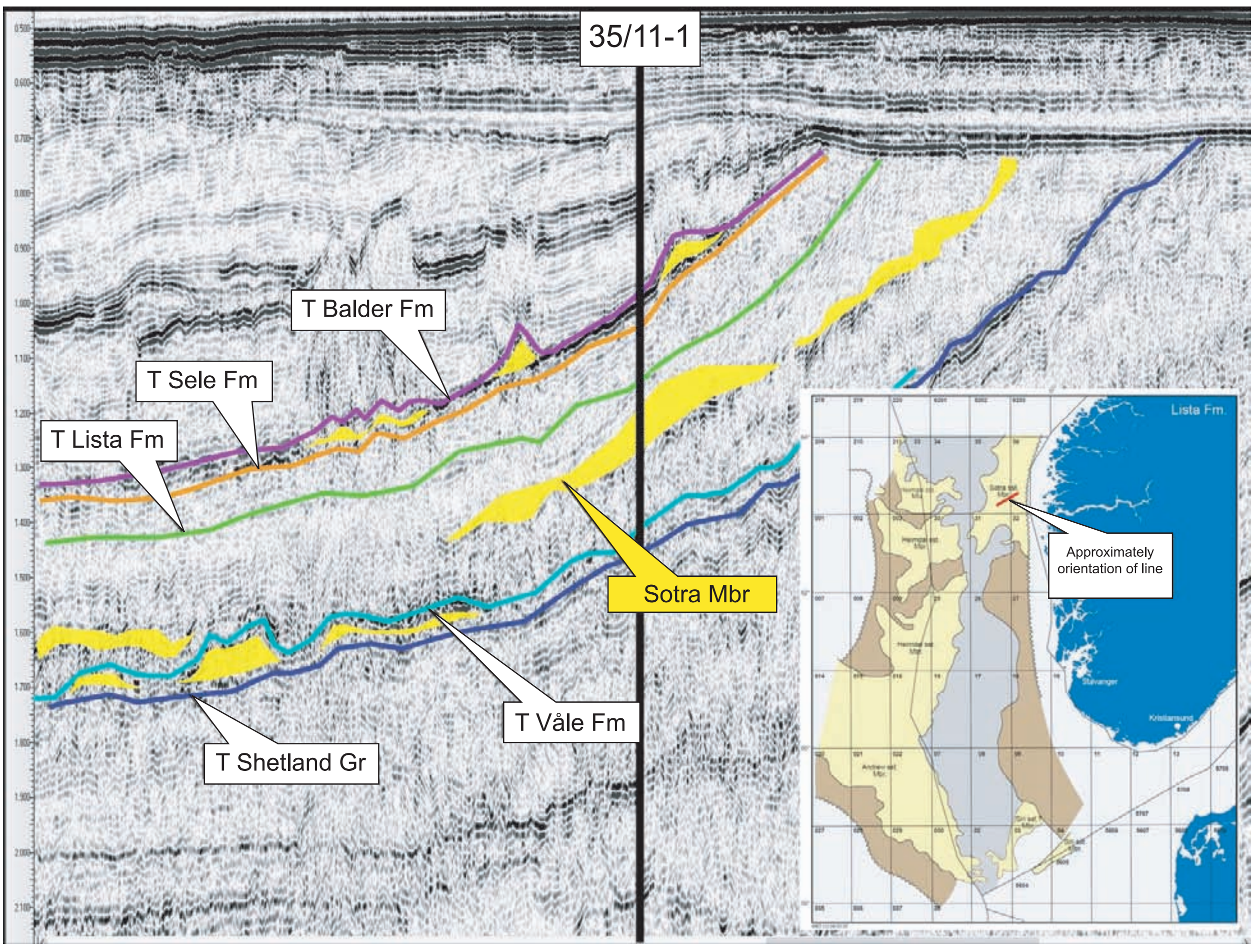


Fig. 94. Seismic Cross section through southern parts of Quadrant 35 and well 35/11-1. Inferred presence of Sotra Member is outlined.

lower gamma readings and increased velocity upwards from the Lista and Våle formations below.

Thickness

The Sotra Member is often seen as scattered stringers of meter scale, and up to some tens of meters. Thickness of the Sotra Member is 44 m in type well 35/8-3, 92 m of blocky sand in reference well 35/11-1, and 132 m of blocky sand in 31/2-19s.

Seismic characterization

To the east in the distribution area the sandstones belonging to the Sotra Member typically occur in westwards-dipping layers, and in westwards-thinning wedges (prograding slope) of the Rogaland Group on the Måløy Terrace and the Horda Platform, partly stretching into the Sogn Graben. In some cases a blocky log response corresponds to mounded geometries, especially in the lower part of the wedge.

West of the wedge, in what is believed to represent a basin floor setting, channels and lobe-like geometries in places stand out as thickness increase of the Lista Formation, and can be interpreted as the presence of sands belonging to the Sotra Member. Figure 94 shows a seismic section through Norwegian well 35/11-1, with the Sotra Member shown.

Age

Late Mid to Late Paleocene (Late Selandian–Early Thanetian).

Biostratigraphy and age

Being contained in the Lista Formation, the age of the Sotra Member is bounded by that of the Lista Formation. The Lista Formation belongs in the foraminiferal Zone NSR2A–2B, *A. ruthvenmurray–R. pauperum* (Gradstein and Bäckström 1996), and the dinocyst Zones D3b–D4 in Luterbacher et al. (2004). The age is Late Selandian through Thanetian, late Mid through Late Paleocene. See also description for the Lista Formation.

Correlation and sub division

The Sotra Member is divided in three units: Sotra L1, Sotra L2 and Sotra L3, corresponding to Lista L1, L2 and L3 (see Lista Formation).

Geographic distribution

The Sotra Member is present south of 62° N, stretching south to the Horda Platform, and westwards into the Sogn Graben (Figures 12, 13 and 72). It is not known whether the Sotra Member stretches further southwards into the Sogn Graben; this is due to a lack of wells in that area.

Depositional environment

In eastern areas the Sotra Member was deposited as gravity flow sands in a prograding slope setting locally in submarine slope fans. Further west in the Sogn Graben the member was deposited in a basin floor setting (Figure 72).

Sele Formation with Members

Sele Formation

Unit definition

The Sele Formation is attributed to the laminated, non-tuffaceous shales located stratigraphically between the Lista and Balder formations (Figure 95).

Name

The Sele Formation was given its name by Deegan and Scull (1977).

Derivatio nominis

The Formation is named after the Sele High off the coast of southwest Norway.

Type well

UK well 21/10-1. Depth: 2,131–2,100 mRKB. Coordinates: N 57° 43′ 50.37″, E 00° 58′ 29.19″. No cores.

Reference wells

Norwegian well 31/2-6 (Figure 96). Depth: 1,225–1,167 mRKB. Coordinates: N 60° 54′ 13.57″, E 03° 38′ 49.43″. No cores.

Norwegian well 16/5-1 (Figure 97). Depth: 1,557–1,580 mRKB. Coordinates: N 58° 38′ 53.66″, E 02° 29′ 39.69″. No cores.

Norwegian well 7/11-2 (Figure 98). Depth: 2,996–3,124 mRKB. Coordinates: N 57° 04′ 15.20″, E 02° 24′ 26.50″. One core.

Composition

The formation consists of montmorillinite-rich shales and siltstones which are medium to dark grey or greenish-grey. The deposits are finely laminated and carbonaceous, with minor interbeds of laminated sandstones which are frequently glauconitic. Scattered tuffaceous beds are also observed.

Core photos from Norwegian well 25/7-5, and a core description of Upper Sele Formation Norwegian well 7/11-A5, Central Trough are shown in Figures 99 and 100.

Wireline log characterization

The shales of the Sele Formation are generally characterized by intermediate to high gamma readings. Sonic log spikes with high acoustic velocity can be related to thin beds or nodules of carbonate.

Upper boundary
The upper boundary of the formation is taken at an abrupt decrease in gamma-ray response and an increase in velocity when going upwards into the Balder Formation. Lithologically an abrupt increase in the number of tuffaceous beds in the transition to the Balder Formation can be seen.

Lower boundary
The lower boundary of the Sele Formation is usually well defined where the lower parts of this formation or the upper parts of the underlying Lista Formation are not sandy. Typically the boundary can be seen as an abrupt upwards increase in the gamma-ray response from the Lista Formation, often with a well defined peak in the lowest part of the Sele Formation. Lithologically, the boundary can be seen as an abrupt transition from green-grey, bioturbated mudstones of the Lista Formation into dark grey to black laminated shales with only occasional bioturbation.

Where the transition is sandy, an overall increase in gamma readings is seen when going from the Lista into the Sele Formation.

Thickness

The thickness of the Sele Formation is variable. It is 31 m thick in the type well UK 21/10-1, and 58 m thick in the reference well 31/2-6. Including sandstone members, the Sele Formation has a thickness of 220 m in well 7/11-3, and 243 m in well 25/1-4.

Seismic characterization

The Top Sele/Base Balder reflector
The top of the Sele Formation (near top S2) is often characterized by a marked acoustic impedance drop, when going from the high velocity tuffaceous shales in B1 (Lower Balder Formation) into the lower velocity shales of the Sele Formation. However the top Sele Formation can sometimes be difficult to pick and may be masked by the effect of top Balder Formation tuff (B1 zone).

Base Sele/Top Lista reflector
The base of the Sele Formation is generally the seismic surface that is easiest to pick. It can be related to the chronostratigraphic surface that marks the boundary between the organic-rich shales of the Sele Formation and the bioturbated shales of the Lista Formation. The seismic marker seems associated with a low-velocity spike (corresponding with high gamma spike) in the lowermost part of the Sele Formation, seen as a negative amplitude event. However, the character and amplitude of this event changes laterally.

Age

Latest Paleocene to earliest Eocene (Late Thanetian–earliest Ypresian).

Biostratigraphy

Organic-walled microfossils: The top of the Sele Formation agrees with the top acme *Cenodinium wardenense*. The body of the Sele Formation contains the top of *Apectodinium augustum* (Figure 101), top of *Cenodinium dartmoorium*, and top frequent *Inaperturopollenites* spp. and *Taxodiaceae* spp. The base of the Sele Formation agrees with the base of *Apectodinium augustum*. Hence, the Sele Formation is assigned to the

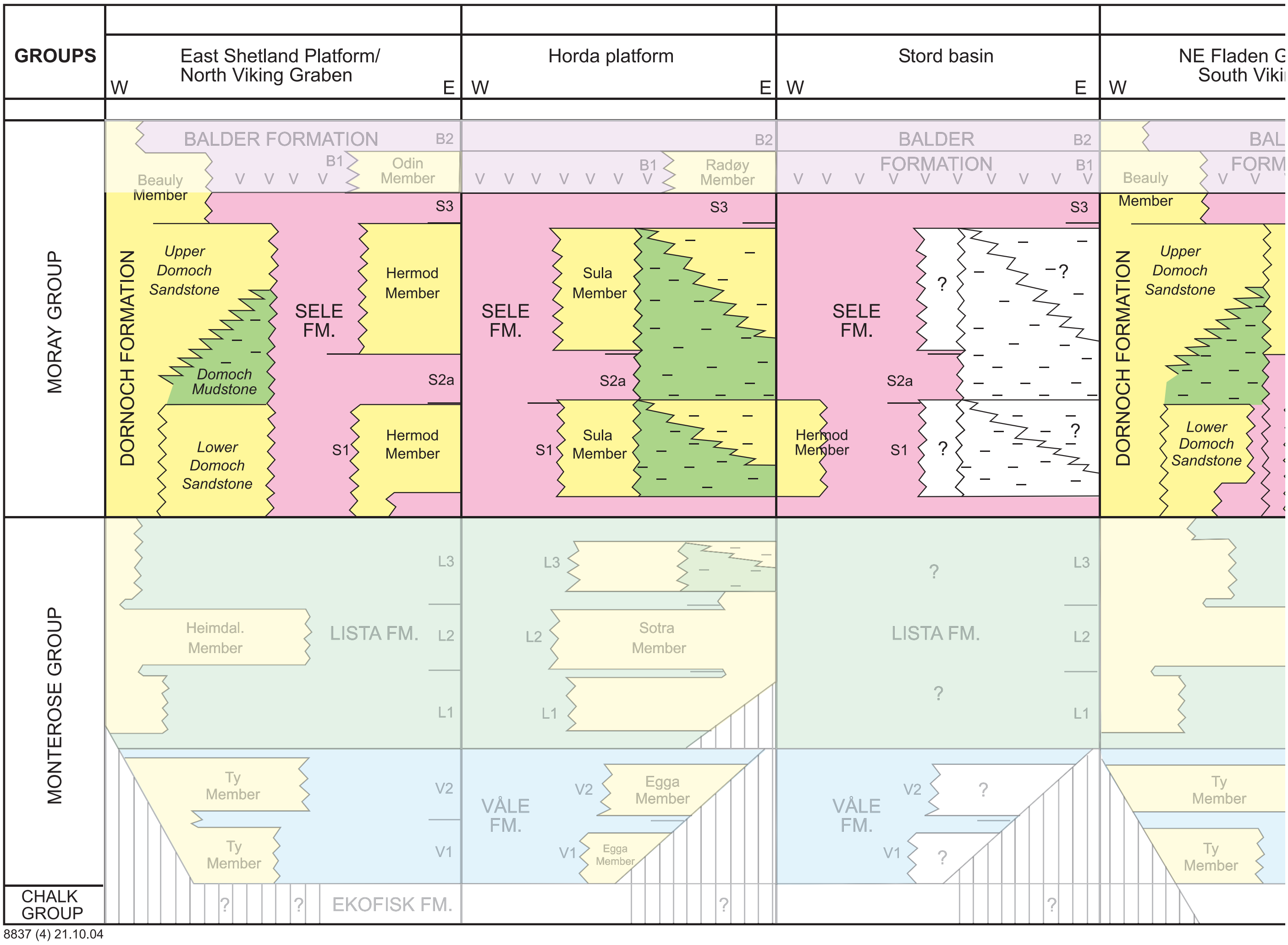


Fig. 95. Lithostratigraphic summary chart of the Våle Formation (color) with members.

A. augustum Zone plus the lower *D. oebisfeldensis* Zone, using dinoflagellates.

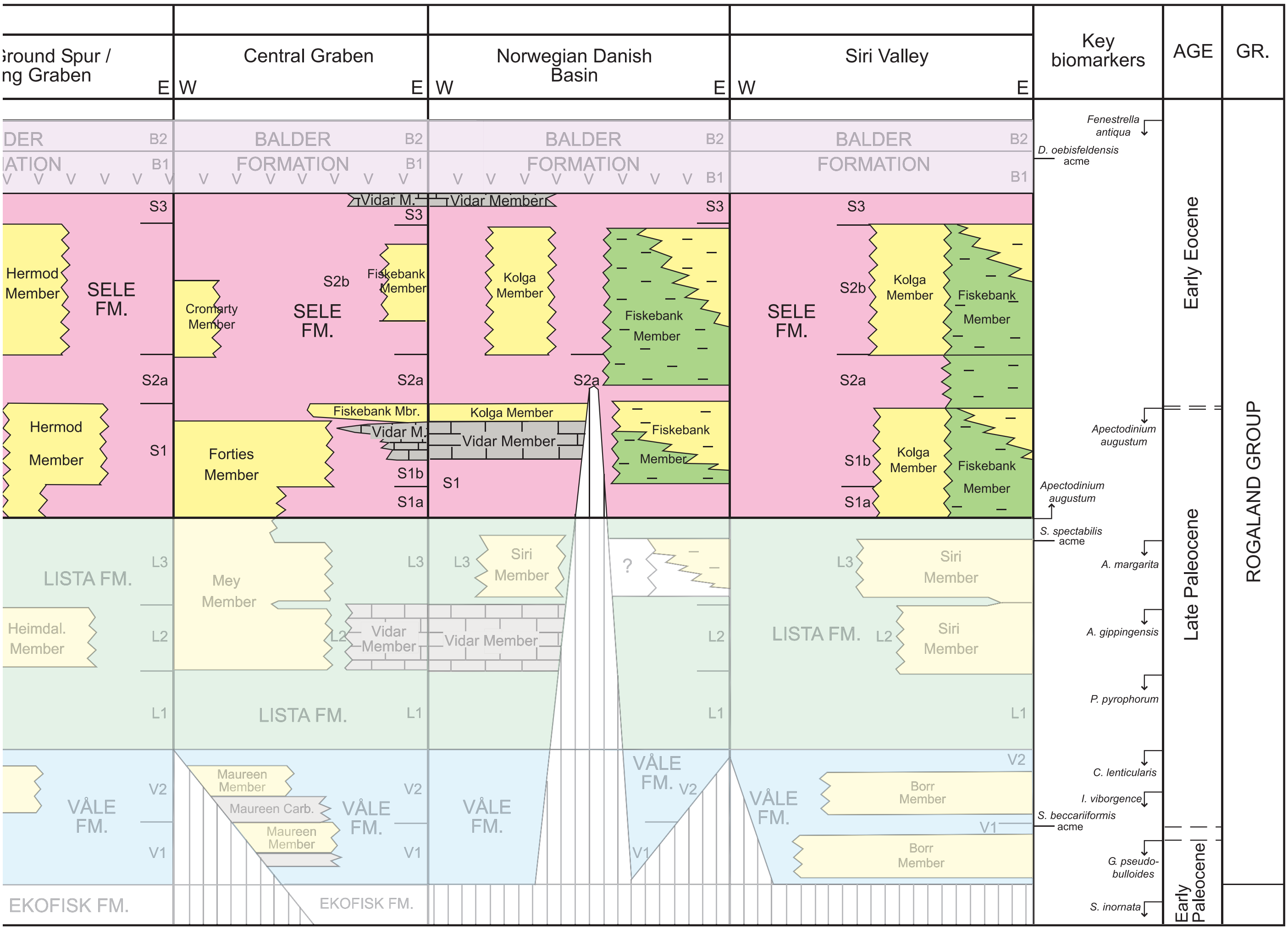
Shelly microfossils: The Sele Formation reflects and corresponds to closure of passages to and from the North Sea, resulting in a freshening of surface water mass and dysaerobia in the deeper water mass. Hence, bottom dwellers are rare and limited to a few agglutinated foraminiferal taxa, including isolated *Trochamminoides* spp. Diatoms are well adapted to freshening surface watermass, and pyritized diatoms of mostly *Fenestrella antiqua* are common.

The Sele Formation is assigned to the upper part of Zone NSR2B–*Reticulophragmium pauperum* and the lower part of the *Fenestrella antiqua* Zone of Gradstein and Bäckström (1996), using shelly microfossils.

The above biostratigraphy shows that the age of the Sele Formation is Late Thanetian through Early Ypresian, straddling the Paleocene–Eocene boundary. The disappearance of *Apectodinium augustum* in the North Sea Basin coincides with the standard Paleocene–Eocene boundary, as defined by the onset of a pronounced negative carbon isotope excursion (CIE), which allows global correlation of a wide variety of marine and terrestrial strata. Note that this formal, international definition of the Paleocene–Eocene boundary places the Lower Sele Formation in the uppermost Paleocene and the Upper Sele Formation in the lowermost Eocene.

Correlation and sub division

The Sele Formation is well expressed and easy to recognize from wire-line logs in most of the Norwegian North Sea. In northern parts of the Sogn Graben and



Måløy Terrace, the Sele Formation is more difficult to distinguish from the Lista Formation, and in the northeasternmost parts the two formations appear to interfinger. This interfingering could be a result of less anoxic conditions during deposition of the Sele Formation in this area. Based on the sequence stratigraphic zonation established by Mudge and Bujak (1996) with high gamma shales associated with specific chronostratigraphic bioevents, the Sele Formation can be subdivided into a lower (S1) and an upper (S2) part. The base of the S1 zone is taken at the high gamma peak near the base of the Sele Formation, which is associated with the top of the *impoverished agglutinated* assemblage. The boundary between the two zones is picked at the *Apectodinum* spp. acme, and is often associated with a marked high gamma peak internally in the Sele Formation. The top of the S2 zone is taken at the common *Ceratopsis wardenense*.

The Sele Formation contains four sandy members (Figures 12 and 13). The Fiskebank Member occurs in the Norwegian–Danish Basin, in the Siri Valley and southeastern flank of the Central Trough fairway. The Sula Member is found along the eastern flank of the Måløy Terrace and Sogn Graben. Both members are considered to have an eastern provenance. The Forties Member in the Central Trough and the Hermod Member in the Viking Graben have a western provenance. These sandy members are coded according to whether they are found in Sele zone S1 or S2; Hermod S1 and Hermod S2; and Forties S1 and Forties S2, etc.

Geographic distribution

The Sele Formation is present in most of the areas where Paleocene strata are present in the central and

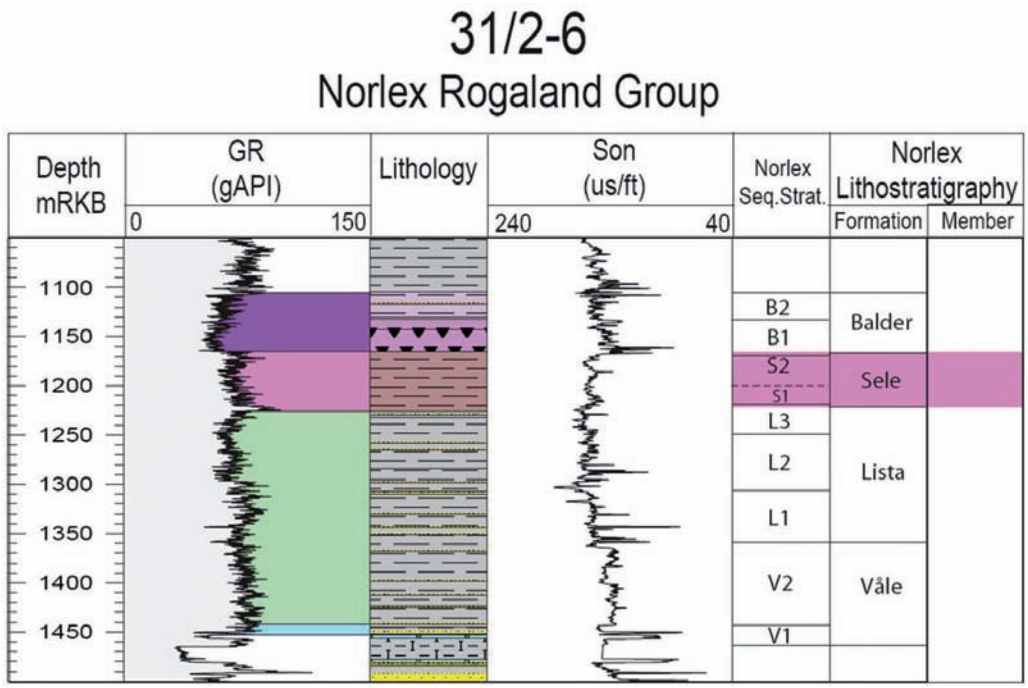


Fig. 96. Well 31/2-6 composite log, Rogaland Group. Stratigraphic position of the Sele Formation is outlined.

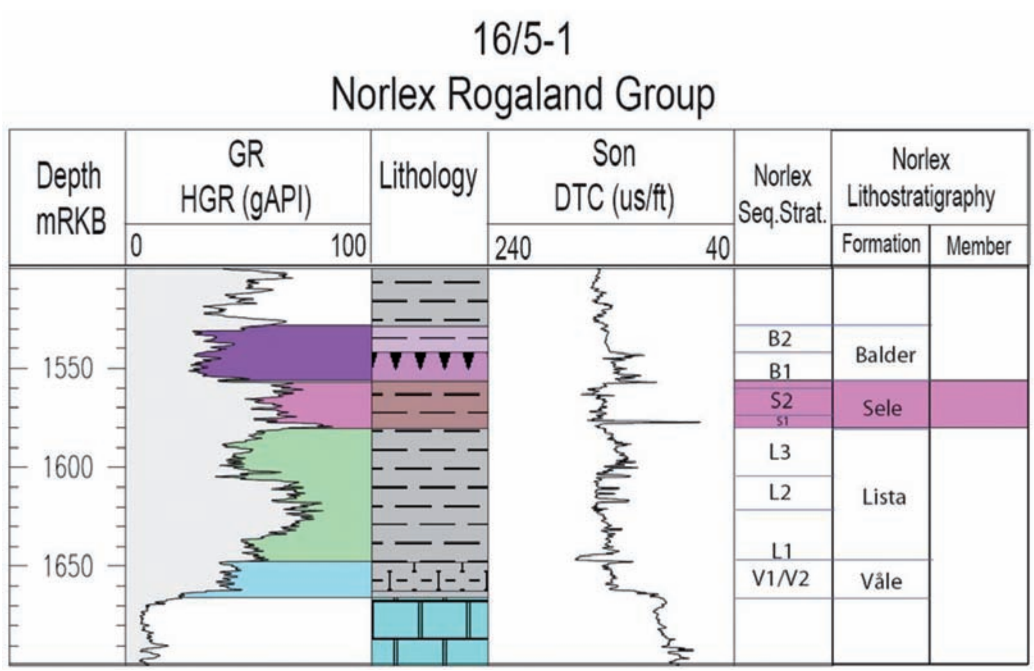


Fig. 97. Well 16/5-1 composite log, Rogaland Group. Stratigraphic position of the Sele Formation is outlined.

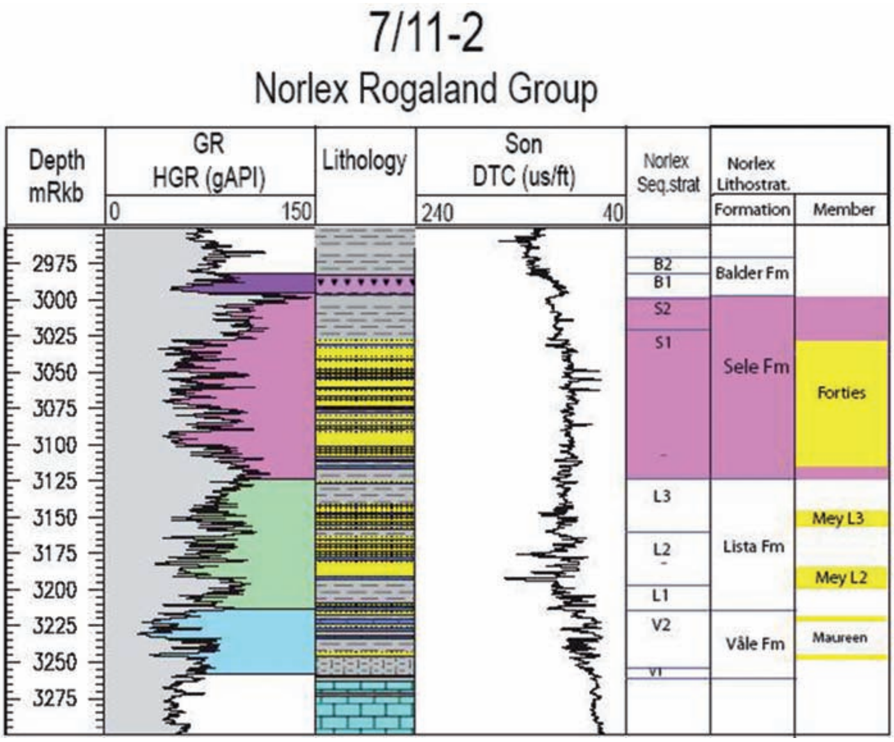


Fig. 98. Well 7/11-2 composite log, Rogaland Group. Stratigraphic position of the Sele Formation is outlined.

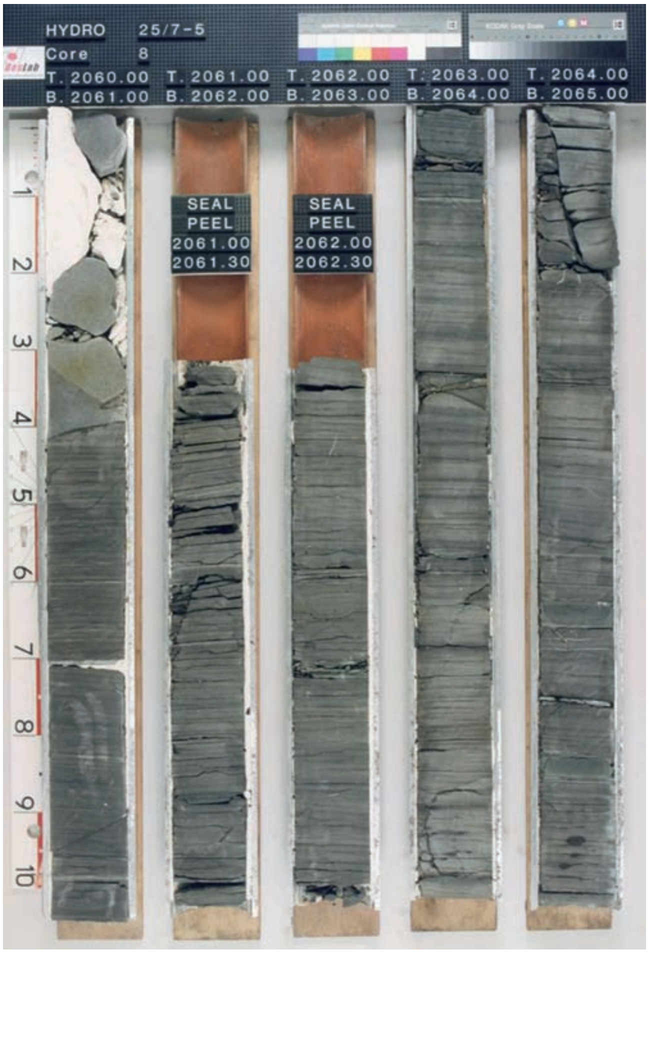


Fig. 99. Core photo displaying dark grey non-bioturbated shales of the Sele Formation in well 25/7-5 at 2,060–2,065 m. Photo from *http://www.npd.no*.

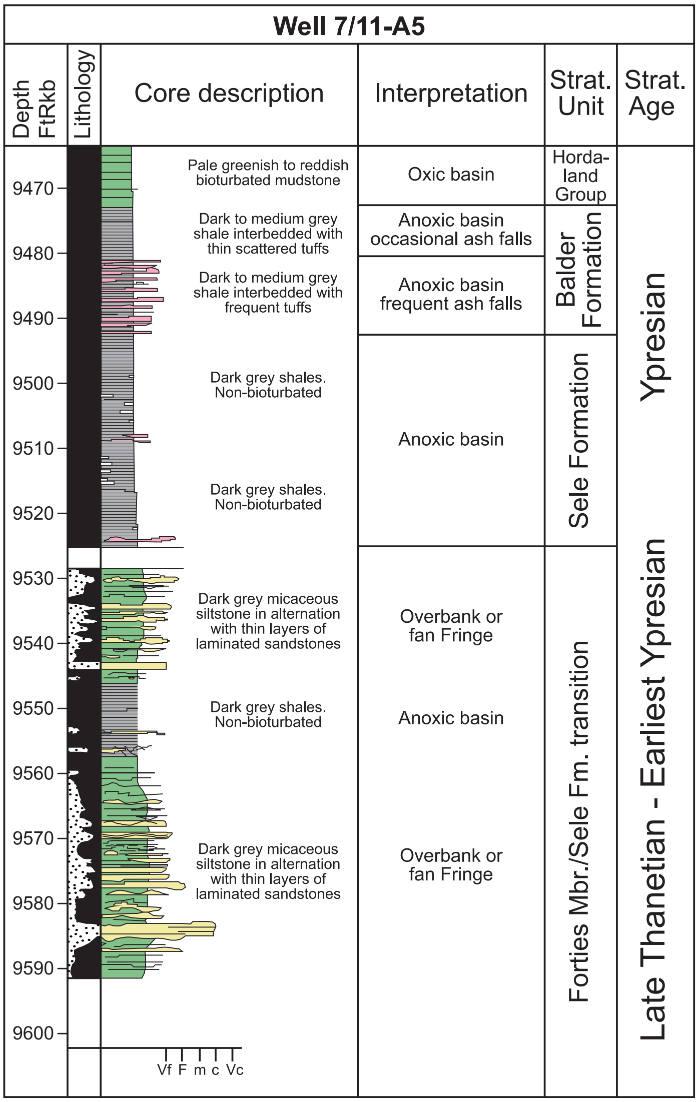


Fig. 100. Core description log from the Sele Formation in the Rogaland Group in well 7/11-A5.

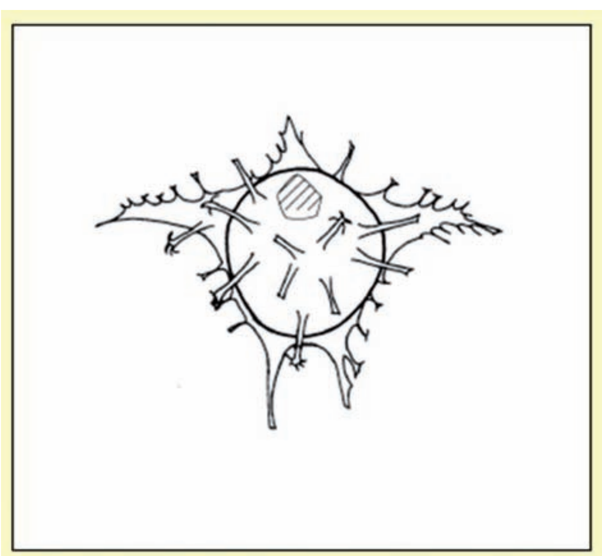


Fig. 101. Example of diagnostic microfossil in the Sele Formation: *Apectodinium augustum*. Dorsal view. Holotype dimensions: pericyst length (excluding horns) = 63.75 µm, pericyst width (excluding horns) = 66.25 µm. From the ODP Drilling Program at *http://www-odp.edu*.

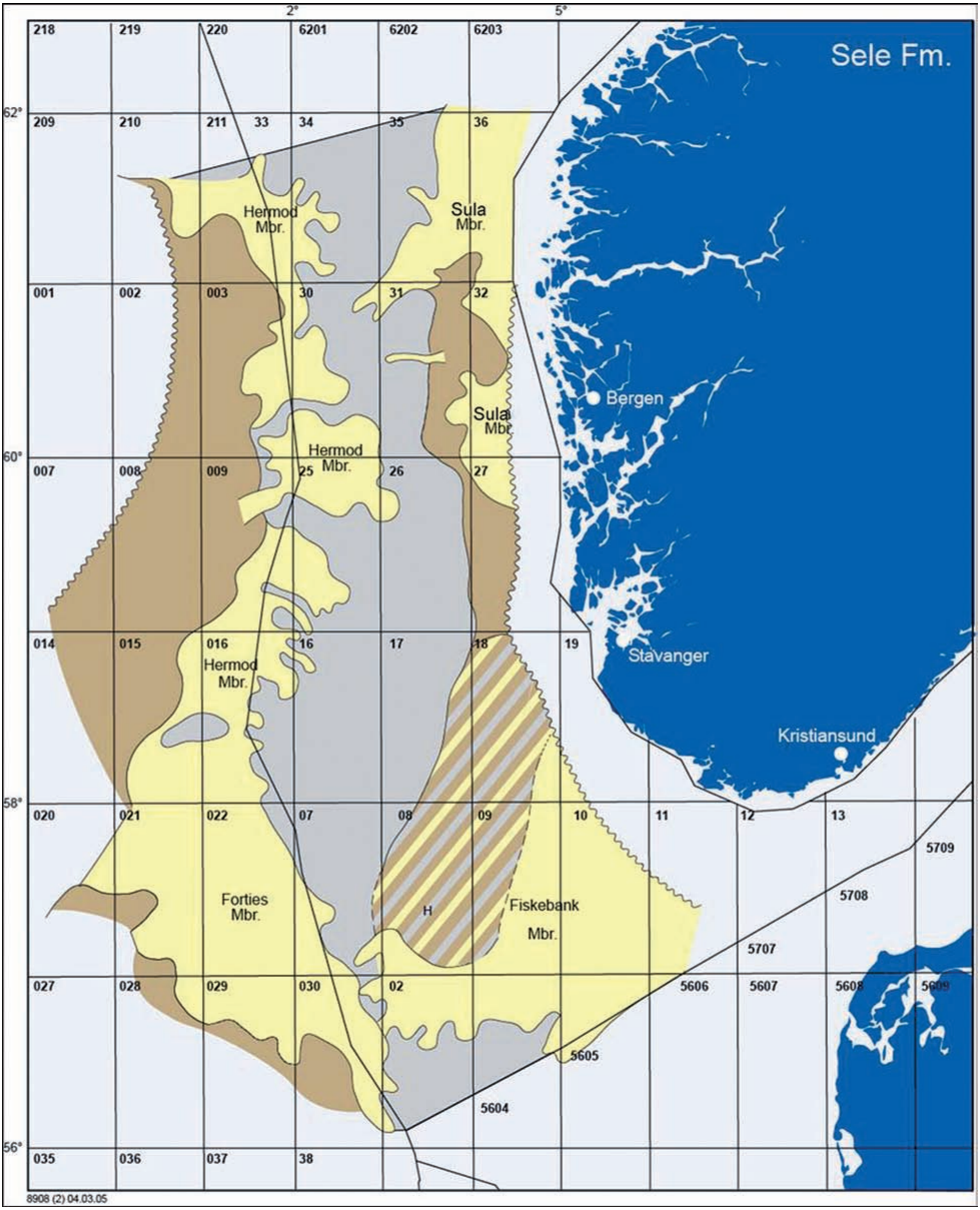


Fig. 102. Distribution of the Sele Formation and its sandstone members.

northern North Sea (Figure 102). Only along the eastern flanks where Paleocene deposits are partly truncated, the Sele Formation is partly or completely eroded. The distribution of the Sele Formation with its respective members is shown below.

Depositional environment

As earlier mentioned, the Sele Formation was deposited in an anoxic basin, restricted by sills established as a response to regional uplift (Wyville Thompson Ridge, Inversion ridge in the London–Brabant area, and closing of the earlier seaway passage to Tethys in the Polish Trough). Accordingly, the Sele Formation was deposited during a period of general basin restriction in the North Sea Basin, with freshening of surface water (brackish) and dysoxic to anoxic bottom water. This had led to disappearance of benthic organisms, and hence sediments remained undisturbed after deposition, giving laminated, non-bioturbated deposits upon burial.

Hermod Member, Sele Formation

Unit definition

The Hermod Member is attributed to those intra-Sele Formation sandstones encountered in sub-area NW in Figures 12 and 13, mainly in the Viking Graben and the East Shetland Basin.

Name

The Hermod Member is renamed from the Hermod Formation defined by Hardt et al. (in Isaksen and Tonstad 1989). The Hermod Member is age-equivalent to the marginal to slope marine sandstones of the Dornoch Member of the UK sector.

Derivatio nominis

The Hermod Member is named after the Norse god Hermod, a son of Odin (Hardt et al. 1989).

Type well

Well 25/2-6 (Figure 112). Depth: 2,221–2,361 m. Coordinates: N 59° 45′ 33.55″, E 02° 33′ 05.96″. No cores. Defined by Hardt et al. (1989).

Reference wells

UK well 10/1-1A. Depth: 2,126–2,212 mRKB. Coordinates: N 59° 50′ 10.51″, E 02° 00′ 33.60″. No cores. Defined by Hardt et al. (1989).

Norwegian well 25/11-1 (new, Figure 113). Depth: 1,790–1,818 mRKB. Coordinates: N 59° 10′ 53.00″, E 02° 24′ 49.00″. No cores.

Norwegian well 30/7-2 (new, Figure 114). Depths: 2,039–2,095 m and 2,123–2,147 m. Coordinates: N 60° 29′ 26.06″, E 02° 01′ 40.85″. No cores.

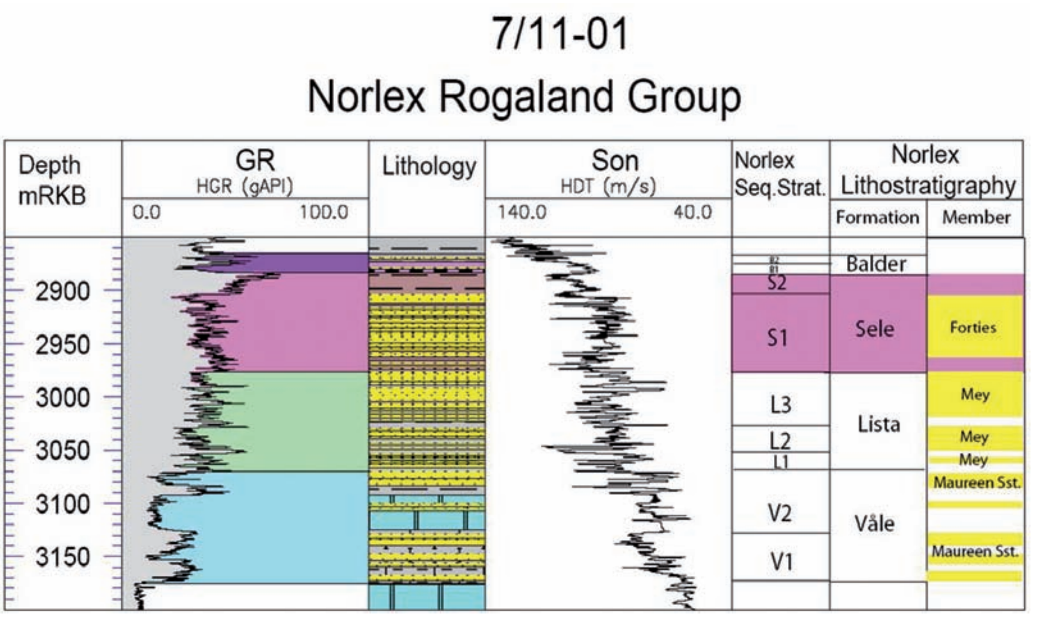


Fig. 103. Composite log in well 7/11-1, Rogaland Group. Stratigraphic position of the Forties Member is outlined.

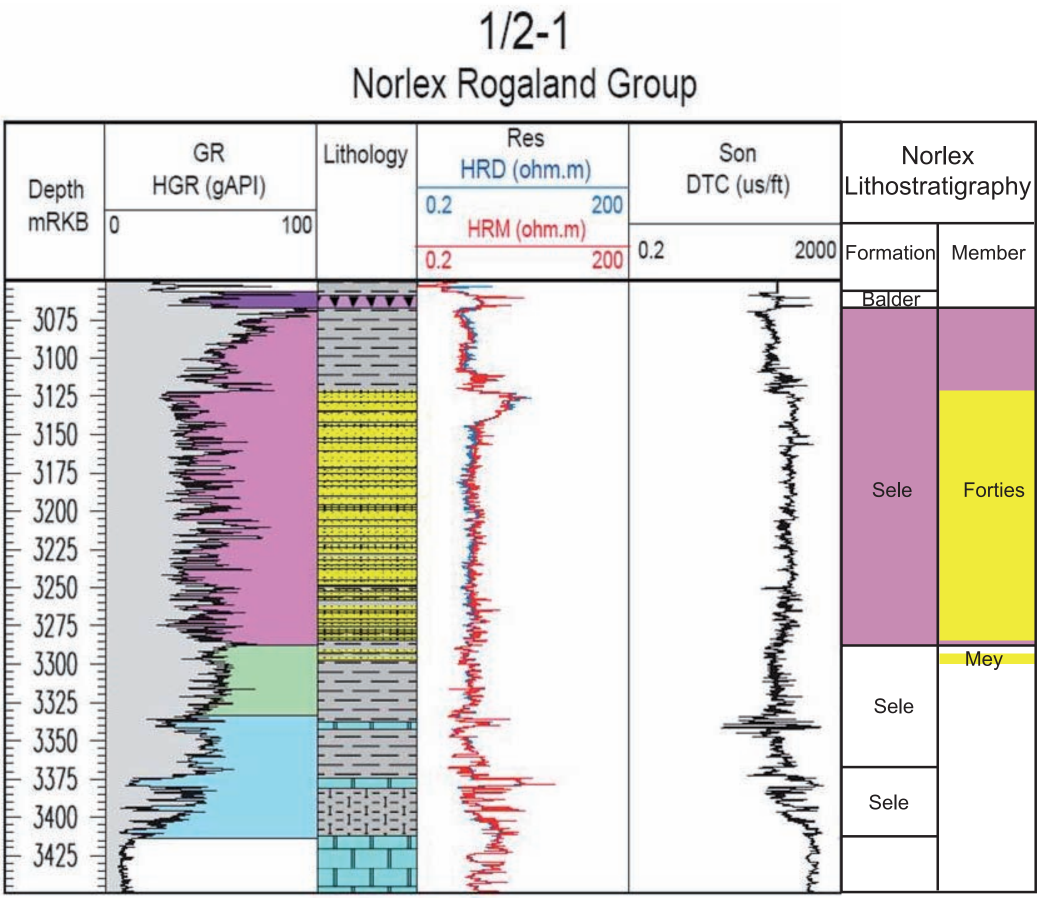


Fig. 104. Composite log in well 1/2-1, Rogaland Group. Stratigraphic position of the Forties Member is outlined.

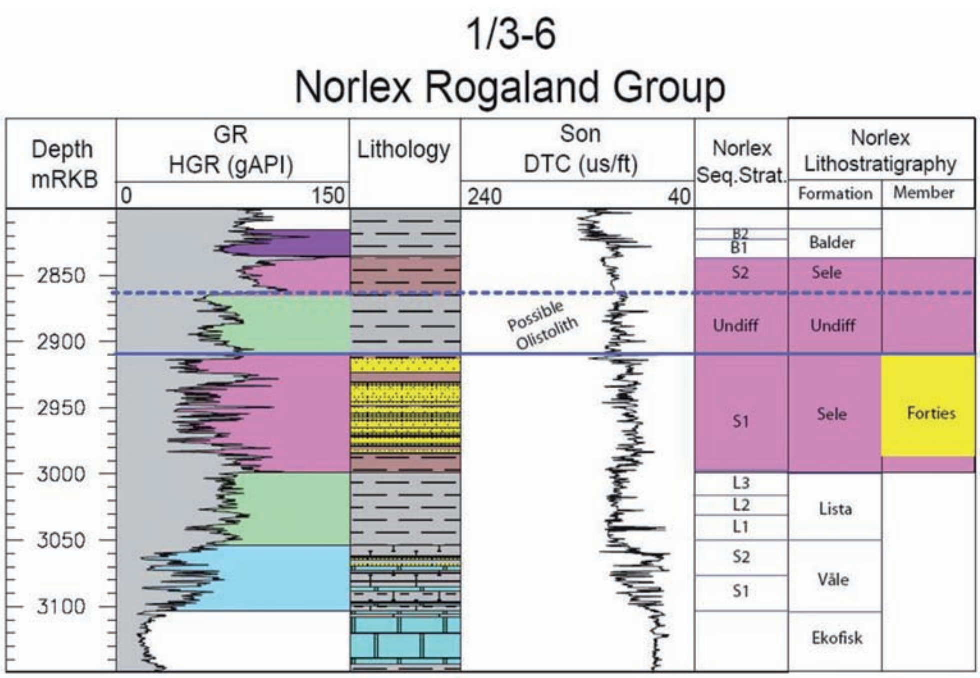


Fig. 105. Composite log in well 1/3-6, Rogaland Group. Stratigraphic position of the Forties Member is outlined.

Fig. 106. Core photo from well 1/2-1 at 10,383–10,395 ft. Graded beds of turbiditic origin, displaying horizontal lamination, and convolute lamination. Photograph from *http://www.npd.no*.

Composition

The Hermod Member consists of well-sorted, very fine- to medium-grained sandstones, interbedded with claystones. Internally the sandstones locally have thin interbeds of fissile mudstone. The top and base of the Hermod Member is restricted to the diagnostic Sele Formation mudstones above and below.

Sandstone intrusions are frequently found associated with the upper boundaries of sandstone bodies, often with an abundance of angular and tabular mudstone clasts.

A core example from Norwegian well 15/3-6 is shown in Figure 115, displaying clean, massive beds of sandstone with interbeds of heterolithic deposits, probably representing a series of stacked high-density turbidite beds.

Thickness

The Hermod Member can be more than 100 m thick (101 m in well 25/1-1 and 172 m in well 25/2-1), but is mostly in the order of a few meters to a few tens of meters.

Wireline log characterization

The sandstones of the Hermod Member often display massive blocky zones of low gamma-ray readings with distinct and abrupt transitions against the higher gamma-ray and low velocity of the enclosing shales.

Upper boundary

The Hermod Member is overlain by the Sele Formation, and the boundary is an abrupt change from sandstones to dark shales. The gamma-ray response changes upwards from low readings in the sandstones to significantly higher readings in the Sele Formation above. The sonic log changes from high to low readings.

Lower boundary

The lower boundary of the Hermod Member is identified by an upwards transition from the shales of the Sele or the Lista Formation below. The log response is characterised by a sharp upwards change from high gamma-ray readings and low velocity in the shales to low gamma-ray readings and high velocity in the Hermod sandstone.

Seismic characterization

The Hermod Member commonly exhibits a high acoustic contrast when low-velocity Sele Formation shales are found above and below. In such cases a high amplitude response is often seen.

The external geometry of the Hemod Member can be mounded, lenticular or trough-like channel fills, locally associated with seismic scale injectites.

A seismic example from block 25/10, is shown in Figure 116, displaying Hermod Member as the uppermost sandstone unit.

Age

Latest Paleocene to earliest Eocene (Late Thanetian–earliest Ypresian).

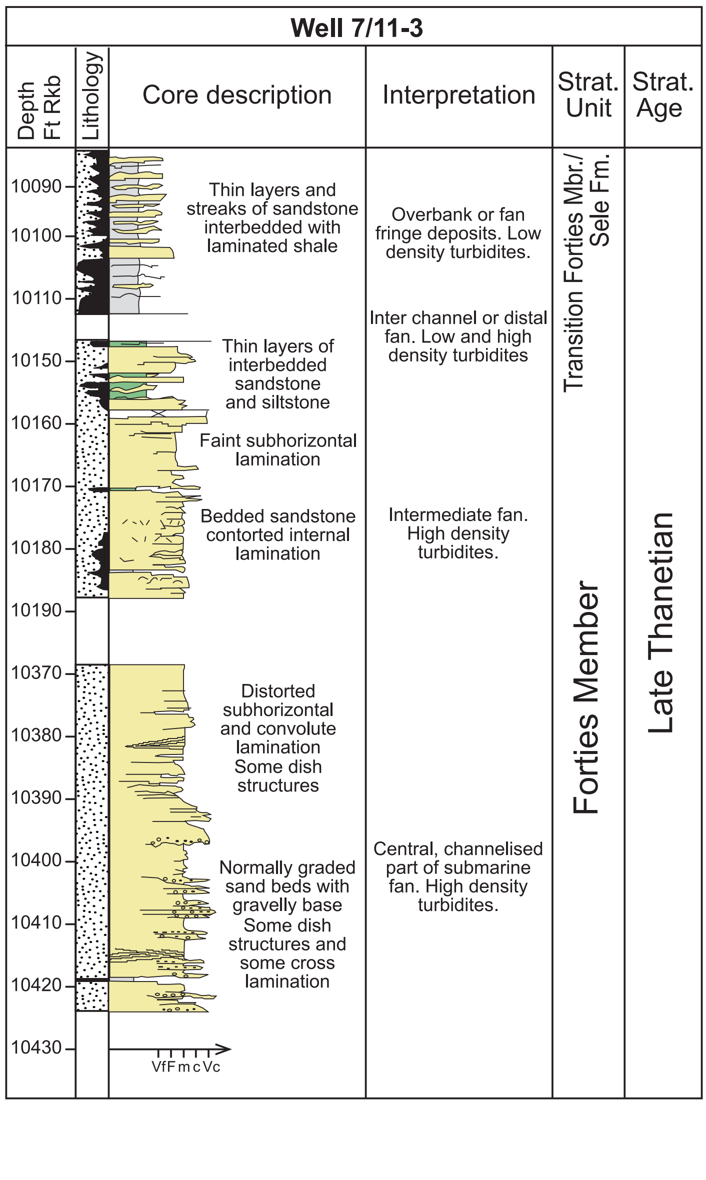
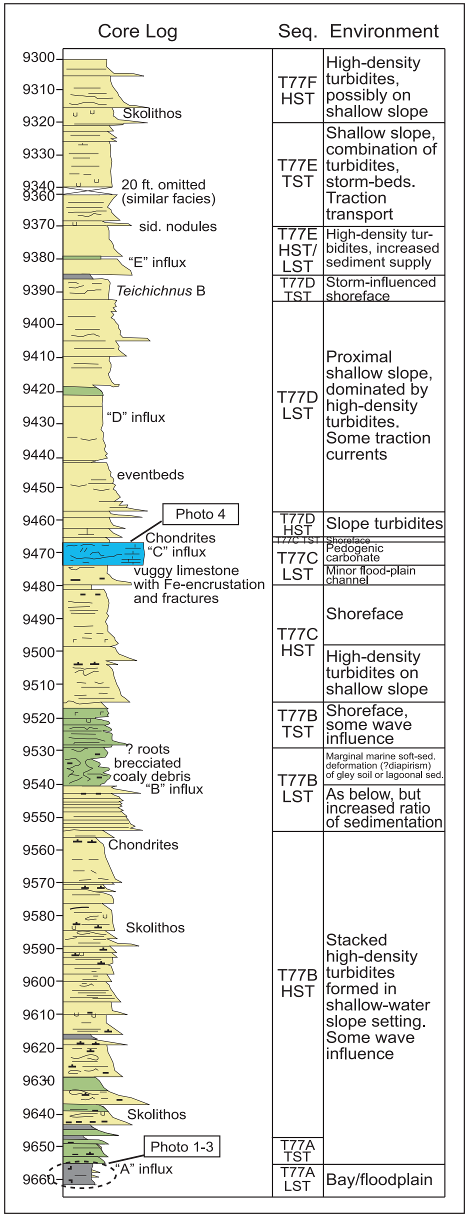
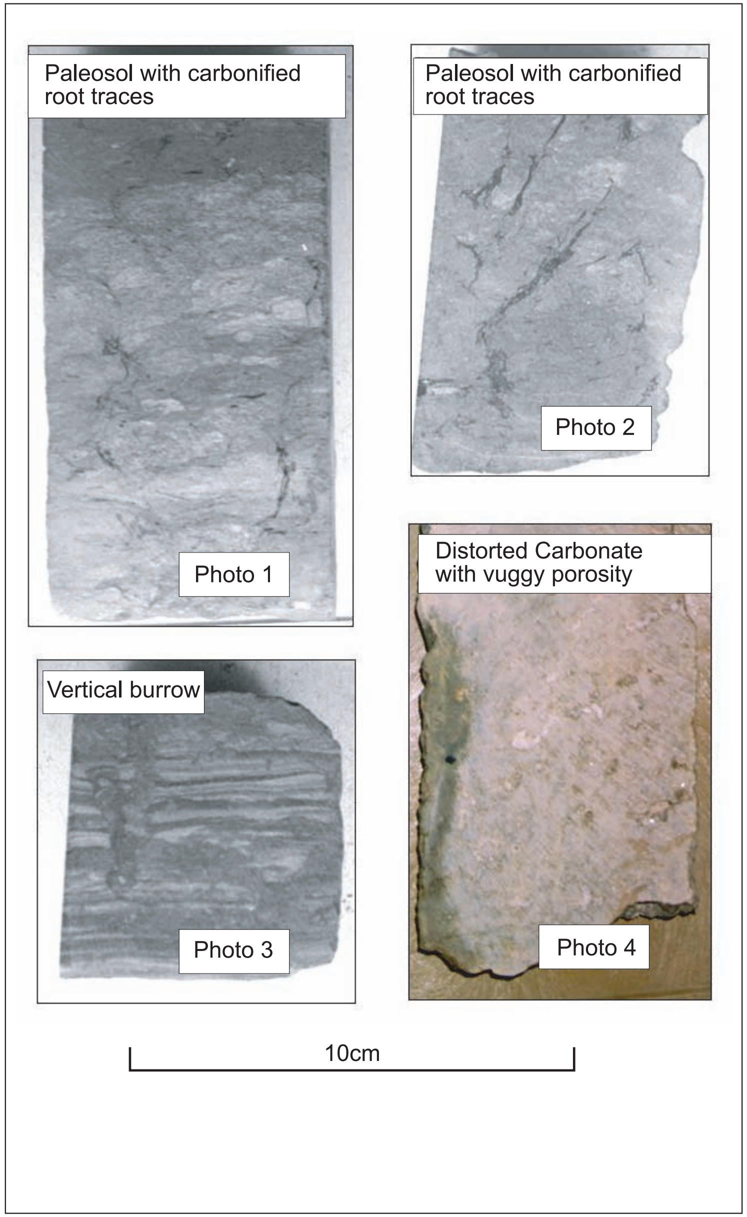


Fig. 107. Core description example from the upper parts of the Forties Member in well 7/11-3.





Core description and core photos from Well UK23/27-1

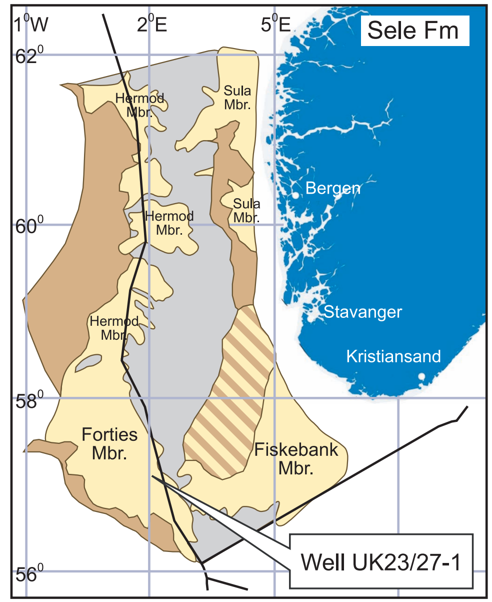


Fig. 108. Possible shallow marine indicators from Forties Member, well UK23/27-1 Pierce Field, close to the Norwegian-UK border. Core photographs show inferred paleosols, vertical burrows of *Diplocraterion* type and pedogenically altered/freshwater influences carbonates. Wireline log to the left show position of shallow marine indicators relative to sandstone beds of partly turbiditic origin.

Biostratigraphy

Being contained in the Sele Formation, the age of the Hermod Member is constrained by biostratigraphic and age assignments for the Sele Formation. See description for the Sele Formation.

Correlation and subdivision

Based on the diagnostic *Apectodinium* spp. acme biomarker internally in the Sele Formation, the Hermod Member is subdivided into Hermod S1, which lies below the biomarker, and correlates to the Skadan and the Teal members in the UK Viking Graben, and the Hermod S2, which lies above the biomarker, and correlates to what is called the Hermod Member in the UK sector.

Geographic distribution

The Hermod Member is mainly restricted to the Viking Graben, and pinches out distally to the east. Locally it stretches onto the western flank of the Utsira High (Figure 102).

Depositional environment

The Hermod sandstones are related to submarine-fan systems where the most distal parts are interpreted as lobe deposits. The sands were shed eastwards from the shelf areas of the East Shetland Platform (Conort 1986). The feeder systems are in places discrete channels, that lead into radiate fans. In other cases, the Hermod sand system consists of channel/lobe complexes of more amalgamated lobes and channels.

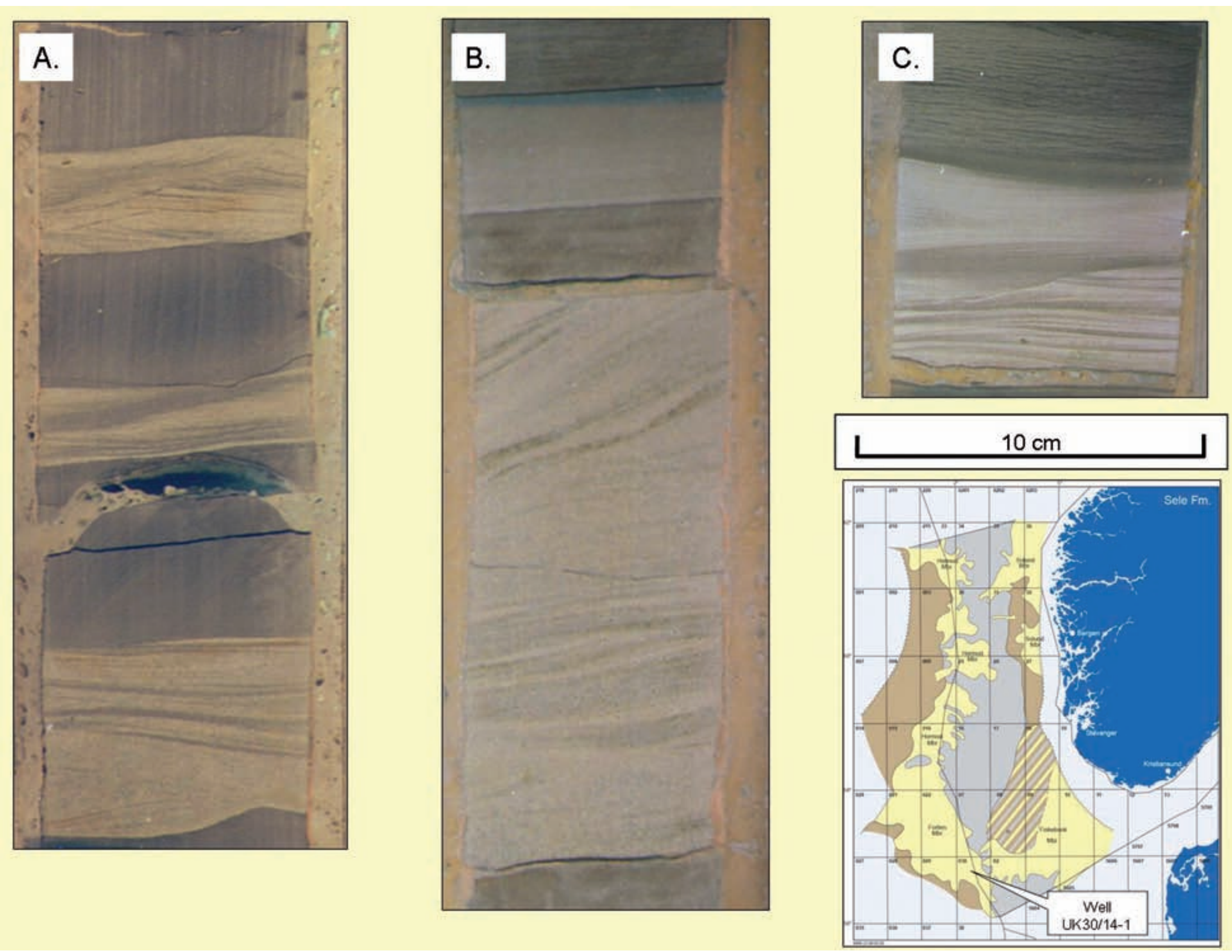


Fig. 109. Sedimentary structures showing deposition under fluctuating flow regime. It seems possible that their undulating appearance with cut and fill of offshooting pinch and swell laminas can be explained by influence of oscillatory currents generated by wave activity.

Discoveries in Norway with the Hermod Member as hydrocarbon reservoirs are:
– Balder Field, part of the reservoir. Oil discovery.
– Enoch Field. Oil discovery (UK/Norway cross border Field)
– Alvheim Field, part of the reservoir. Oil discovery.
– Ringhorne Field, part of the reservoir. Oil discovery.

Forties Member, Sele Formation

Unit Definition

Forties Member is attributed to the intra-Sele Formation sandstones in sub-area SW in Figures 12 and 13.

Name

The name "Forties Formation" was introduced by Deegan and Scull (1977). Mudge and Copestake (1992) reduced the unit to member status within the Sele Formation.

Derivatio nominis

The name is from the Forties Field, UK Block 21/10 (Deegan and Scull 1977).

Type well

UK 21/10-1. Depth: 2,131.5–2,314 mRKB. Coordinates: N 57° 43′ 50.370″, E 00° 58′ 29.190″. Cores.

Reference wells

Norwegian well 7/11-1 (revised by Dreyer et al. 2004). (Figure 103). Depth: 2,904–3,069 mRKB. Coordinates: N 57° 04′ 15.60″, E 02° 26′ 24.40″. No cores.

Norwegian well 1/2-1 (Figure 104). Depth: 3,121–3,287 mRKB. Coordinates: N 56° 53′ 15.07″, E 02° 28′ 35.70″. Cores: Cores 1–8.

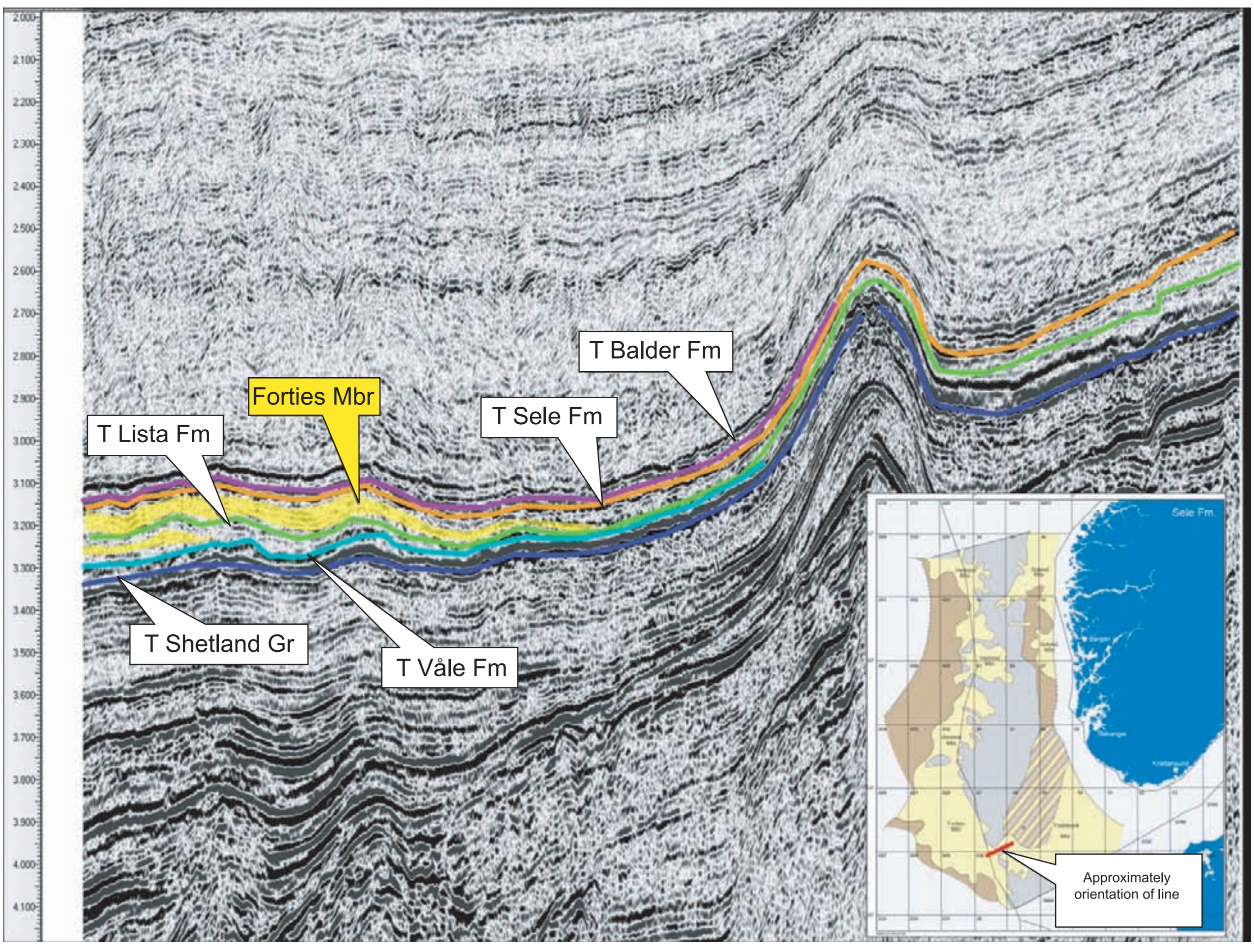


Fig. 110. Seismic section through the Breiflabb Basin and the Ula structure. Interval with inferred presence of Forties Member is outlined.

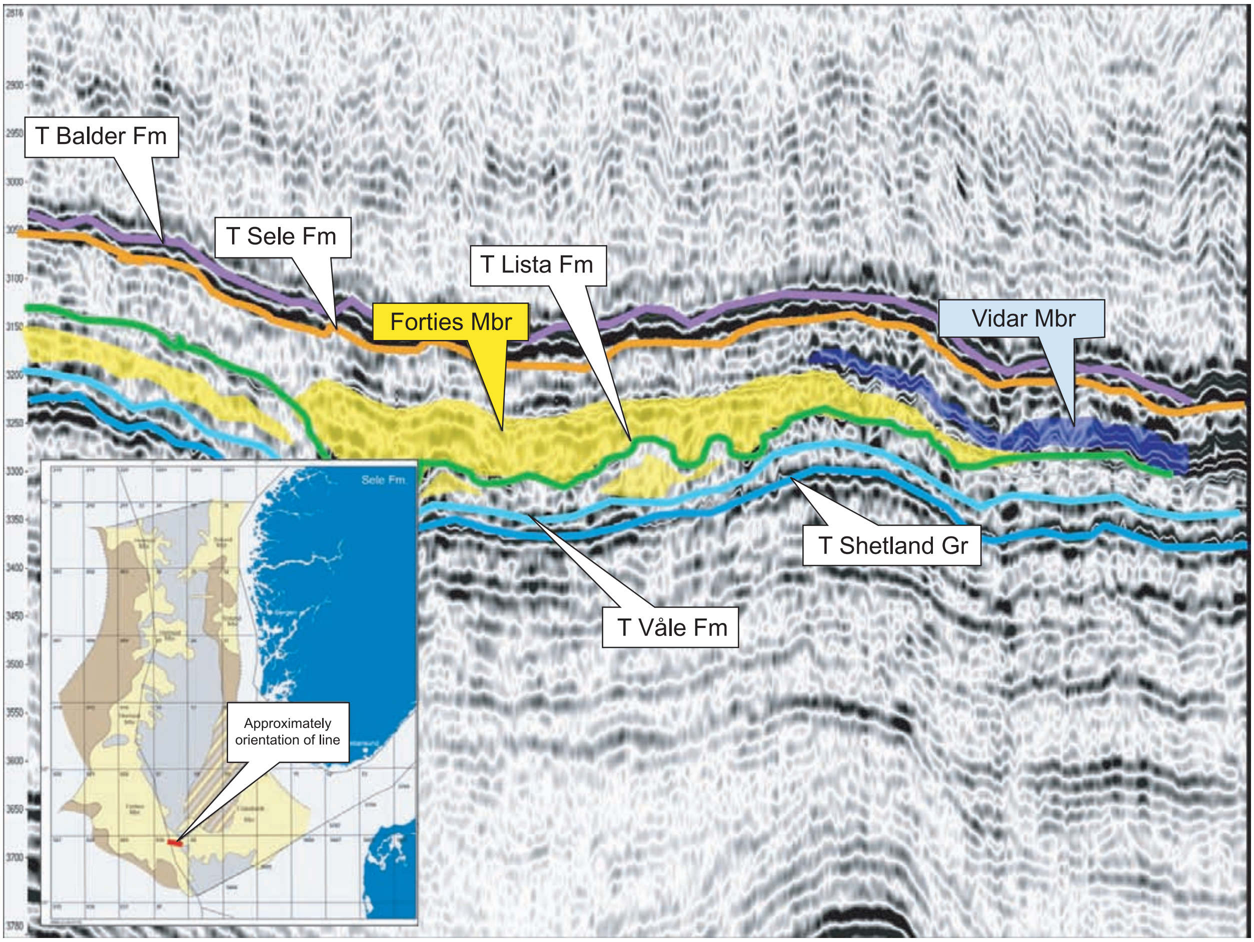


Fig. 111. Seismic cross section along the axis of channelised Forties Member in blocks 1/5 and 1/6.

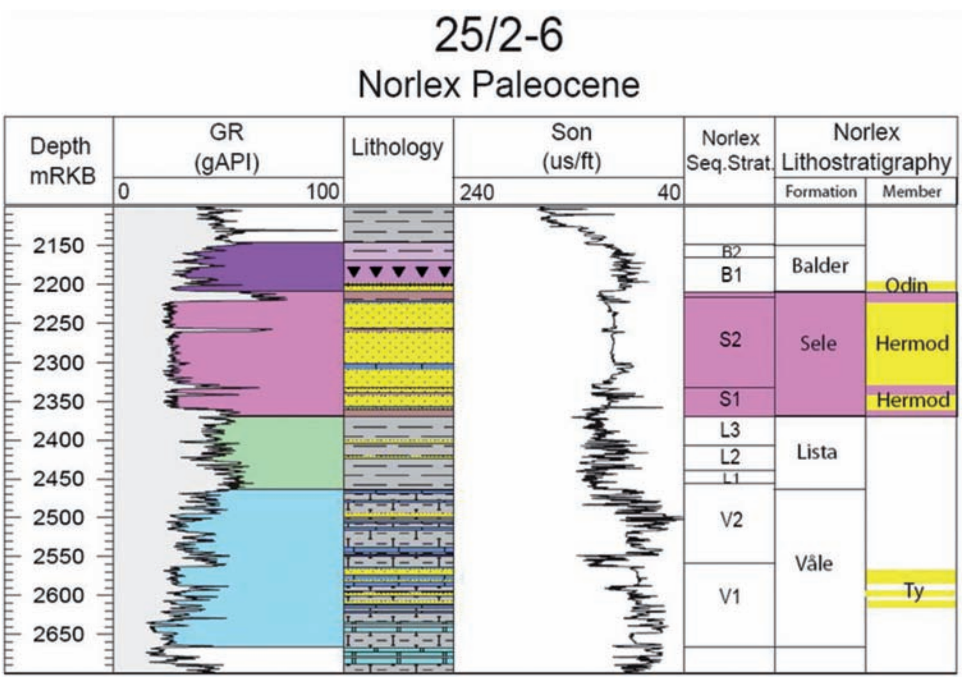


Fig. 112. Composite log in well 25/2-6, Rogaland Group. Stratigraphic position of the Hermod Member is outlined.

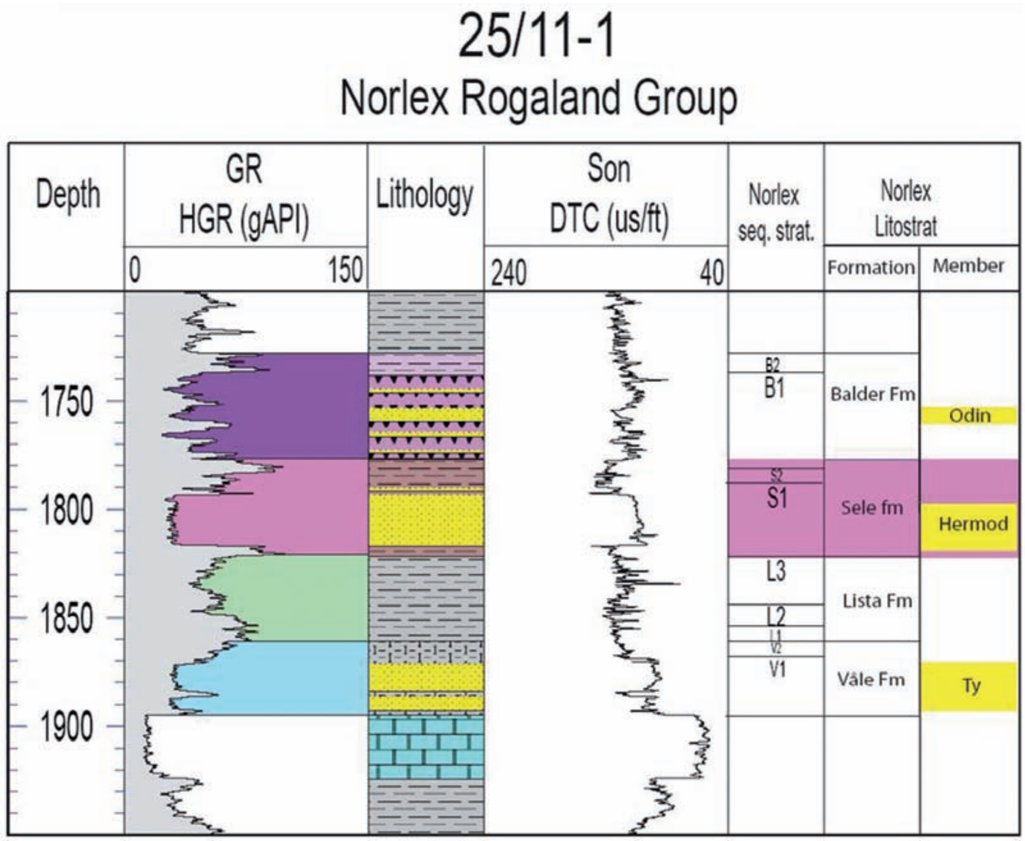


Fig. 113. Composite log in well 25/11-1, Rogaland Group. Stratigraphic position of the Hermod Member is outlined.

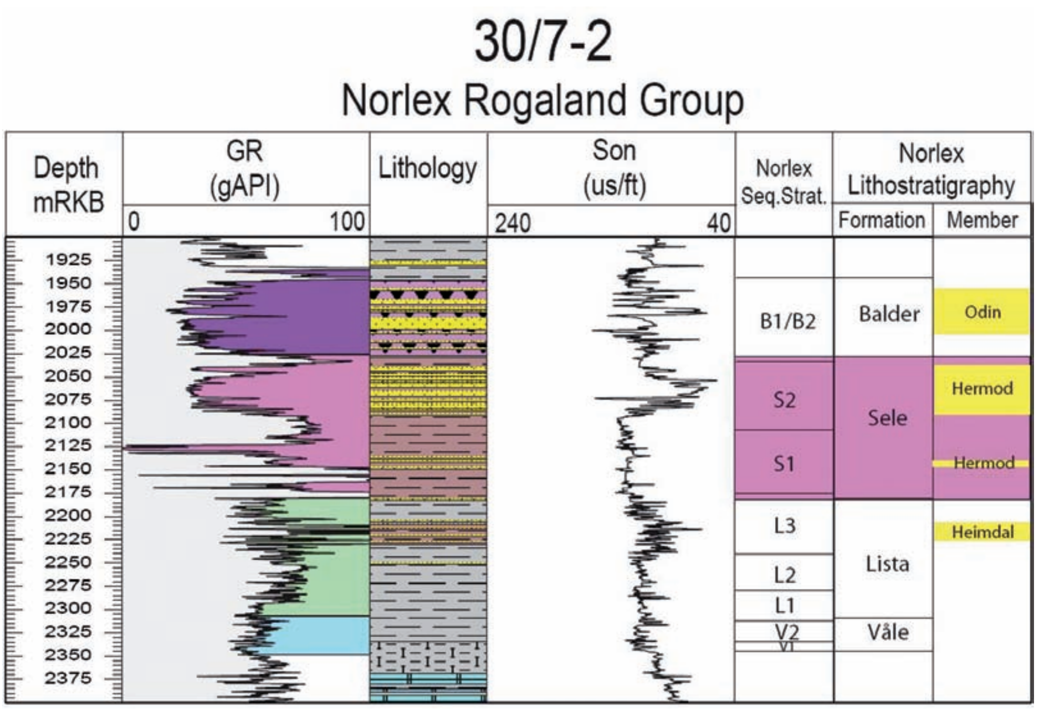


Fig. 114. Composite log in well 30/7-2, Rogaland Group. Stratigraphic position of the Hermod Member is outlined.

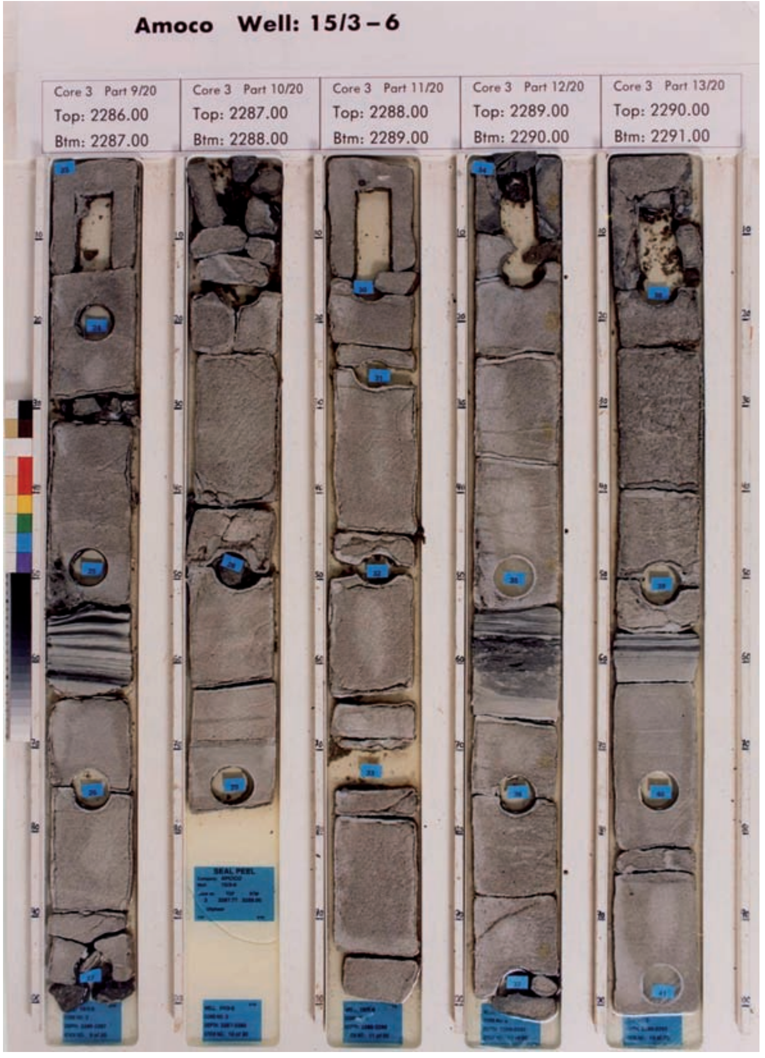


Fig. 115. Core photo example from the Hermod Member. Sediments consist of clean, massive sandstones with water escape structures and heterolithic interbeds. Well 15/3-6 at 2,286–2,291 m, drilled by Amoco. Photo from *http://www.npd.no*.

Norwegian well 1/3-6 (Figure 105). Depth: 2,914–2,984 mRKB. Coordinates: N 56° 56′ 14.92″, E 02° 42′ 20.81″. Cores: Core 1.

Composition

The Forties Member consists of fine- to coarse-grained, moderately to poorly sorted, locally pebbly sandstones that are commonly massively bedded and homogenous, or display dewatering structures. Beds of muddy, extremely poorly sorted, pebbly sandstone are also encountered, with reworked Sele and Lista Formation mudstone clasts.

Primary structures include planar lamination and sporadic small scale cross-lamination. Bed thickness is highly variable. Distal facies display repetitive successive units that rarely exceed two meters in thickness, whereas proximal facies often include units of 20 m or more. The interbedded mudstones and siltstones are generally carbonaceous, micaceous, poorly sorted and crudely laminated (Knox and Holloway 1992).

A core photo example from well 1/2-1 is shown in Figure 106 and a core description log from well 7/11-3 in Figure 107.

In the southern part of UK Quad 23 and northern part of Q30 Dreyer et al. (2004) have recognized several shallow marine to non-marine indicators (Figures 108 and 109), including:

- Fresh/brackish water indicative microfossils assemblages,
- possible root trace and
- possible small scale HCS.
- A limestone unit characterized by vuggy karst-like fabric and
- meniscate, vertical burrows.

These observations are incompatible with the accepted idea that deep water anoxia dominated in the entire basinal area throughout deposition of the Sele Formation, and gives strong indications that local areas in the southern Norwegian North Sea Basin were shallow and oxic at least for a short time during the Late Thanetian–Early Ypresian interval.

Wireline log characterization

On a larger scale the Forties Member displays a coarsening upwards trend with decreasing gamma-ray values and increasing velocity, reflecting a progradational system.

Upper boundary
The upper boundary is defined as the break between the Forties sandstones and the shales of the Sele Formation above. The log response changes upwards from low gamma-ray readings and high velocity to high gamma-ray readings and low velocities in the Sele Formation.

Lower boundary
Where the Forties Member rests on the Mey Member its lower boundary is defined by a decrease in velocity into the sandstones of the Forties Member. Where the Forties Member rests on the Sele or Lista Formation the boundary is characterised by an upwards increase in gamma-ray readings and decrease in velocity.

Thickness

The Forties Member is variable in thickness: 70 m in well 1/3-6, 73 m in reference well 7/11-1, 165 m in example well 1/2-1 and 182.5 m in type well UK 21/10-1. In the Central Graben it reaches a thickness of more than 200 m, as in reference well UK 21/10-2, where it reaches 262 m.

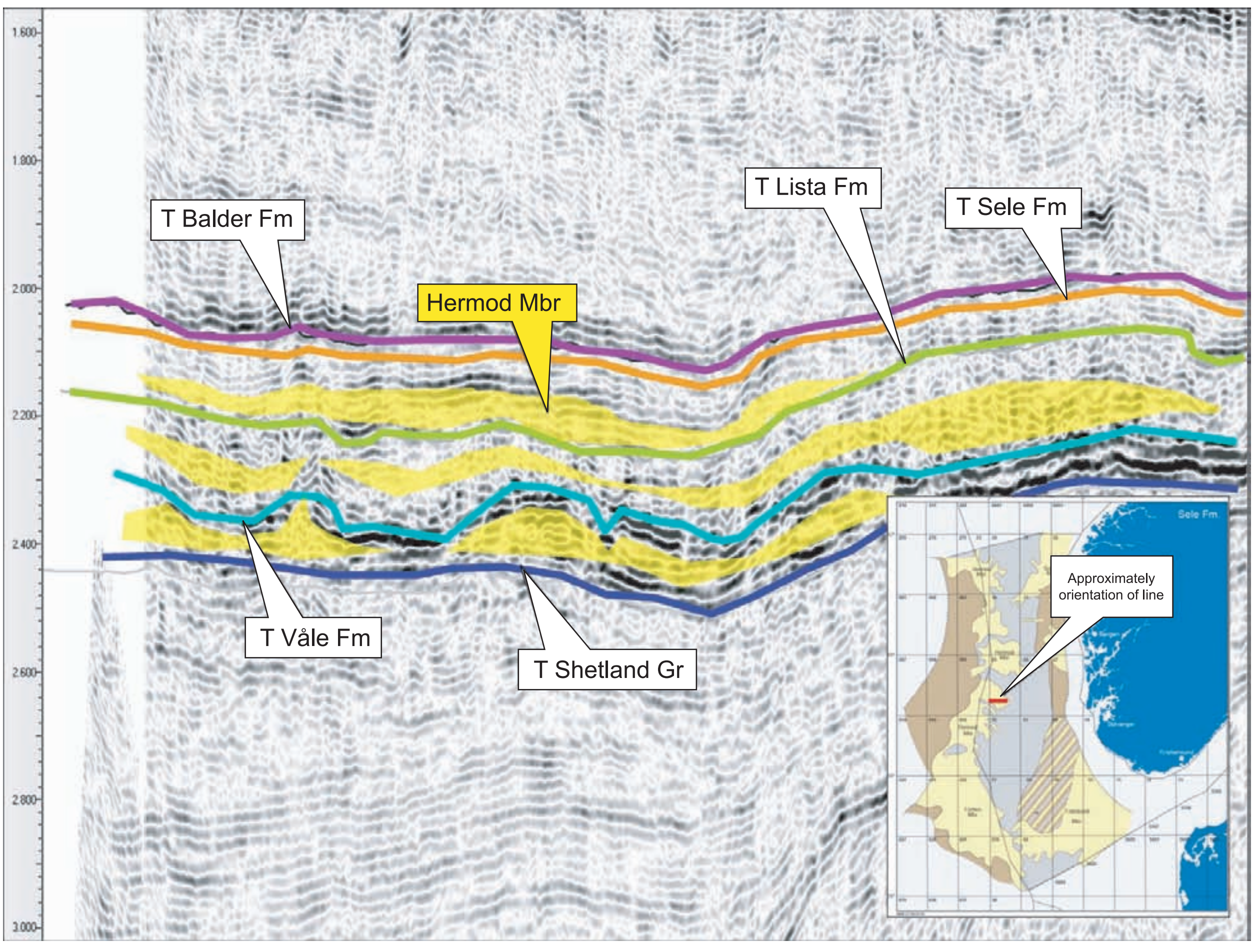


Fig. 116. Seismic cross section through southern parts of block 25/10. Inferred presence of Hermod sandstones are outlined.

Seismic characterization

Top of the Forties Member
The top of the Forties Member is often associated with a strong to moderate positive amplitude event that can be correlated locally to sub-regionally. Locally it interferes with the base Balder Formation reflector making it more difficult to pick.

Base of the Forties member
The base of the Forties Member is commonly visible as a moderate to weak variably negative to positive acoustic amplitude event, and can be correlated sub-regionally.

The Forties Member is usually identified by the presence of seismic thicks. Its thickest development follows axial parts of the Central Graben. To the east a wedge-shaped geometry may be seen in cross section, believed to represent distal thinning of submarine fan systems.

In the area around the Cod Field a seismic convex-up geometry can be seen at top and the bottom reflector is generally flat. Internally there may be seen dipping reflectors (Dreyer et al. 2004). This may represent a mixture of submarine fan systems and prograding slope and shallow marine systems. A seismic line from south of the Cod Field to the Ula Field is shown in Figure 110, and an example from east of Flyndre is shown in Figure 111.

Age

Latest Paleocene to earliest Eocene (Late Thanetian–earliest Ypresian).

Biostratigraphy

Being contained in the Sele Formation, the age of the Forties Member is constrained by biostratigraphic age assignments for the Sele Formation. See description for the Sele Formation.

Correlation and subdivision

The Forties Member is grossly considered as being deposited in one pulse, reflecting the S1 (Lower Sele Formation), and is roughly time-equivalent to the Hermod S1 of the Viking Graben. Sandstones of S2 (Upper Sele Formation), the so-called Cromarty sandstones in the UK, do not seem to be deposited in the Norwegian part of the Central Graben.

Geographic distribution

The Forties Member is distributed in the area from the Outer Moray Firth and into the northern part of the Central Graben, where it appears to reach into the area northwest of the Ekofisk field (Figures 12, 13 and 102).

Depositional environment

According to Knox and Holloway (1992), the sands were shed southeastwards off the shelf areas of the East Shetland Platform and the Inner Moray Firth, and deposited within a submarine sand fan system, probably of slope-apron or ramp type (Stewart 1987). The association with grey, commonly laminated mudstone indicates that the bottom waters were dysaerobic to anoxic. The presence of green and red mudstones is ascribed to reworking from local highs.

According to Dreyer et al. (2004) the palynofacies of the Forties Member of the Central Graben in UK Q23 and 30 and Norwegian Q1 and Q7 varies between normal to low salinity, and anaerobic to aerobic. The depositional environments range from slope and basin plain environments to near-shore and possibly even non-marine environments.

Hydrocarbon discoveries with Forties Member as reservoir
- Flyndre discovery, part of the reservoir, oil.
- Oselvar discovery, gas and condensate.
- Blane discovery, oil.
- Cod Field, gas and condensate.

Fiskebank Member, Sele Formation (revised)

Unit definition

The Fiskebank Member is attributed to the intra-Sele Formation sandstones in sub-area SE in Figures 12 and 13, where it is found in the Norwegian–Danish Basin, the Siri Canyon Area and in the eastern parts of the Central Graben in the Gyda-Ula Area.

Name

The former Fiskebank Formation defined by Deegan and Scull (1977) is hereby downgraded to the Fiskebank Member. The Fiskebank Member has also been attributed to the intra-Sele Formation sandstones of the Siri Canyon (Ahmadi et al. 2003). Although Schiøler et al. (2007), have redefined the Fiskebank Member to the Kolga Member at the Danish side of the Siri

Canyon, we keep the name Fiskebank Member for the Norwegian side in this area.

Derivatio nominis

Named after the Fiskebank (Fisher bank), offshore southern Norway. Named by Deegan and Scull (1977).

Type well

Norwegian well 9/11-1. Depth: 1,483–1,335 m (New definition). Coordinates: N 57° 00′ 41.40″, E 04° 00′ 33.52″ (Figure 117). No cores.

Reference wells

Norwegian well 8/9-1 (Figure 118). Depth: 1,315–1,375 mRKB (new definition). Coordinates: N 57° 26′ 27.28″, E 03° 51′ 03.48″. No cores.

DK well Siri-3 (the Kolga Member is seen in seismic sections to be continuous with the Fiskebank Member in Norway) (Figure 119). Depth: 2,206.4–2,036.1 mRKB. Coordinates: N 56° 30′ 34.92″, E 05° 03′ 48.27″. Cores: Core 2, 2,065–2,120 mRKB.

DK Well: Nini-3. Depth: 1,717.2–1,700.4 mRKB. Coordinates: N 56° 41′ 31.96″, E 05° 24‘24′ 12.35″ (Figure 119). Cores: Core 1, 1,684–1,765 mRKB.

Composition

The Fiskebank Member consists of dark grey to grey brown very fine-grained sandstones, but varies from medium to silt-sized and is remarkably clean (< 0.1 % detrial clay). It has sub-rounded grains, is fairly uniform, well sorted, micaceous, partly micro-micaceous, friable, and with calcareous cement in places. There is a high content of 15–25 % black to dark glauconite pellets (Hamberg et al. 2005) that are found as rounded pellets of the same grain size as the quartz grains. Pyritic grains may also be present. Locally sandstones may be cemented by calcite or chlorite.

In Danish cores the sandstones of the Fiskebank Member (Kolga Member close to the Norwegian Border) are observed as generally massive, homogenous and with few structures. Faint deformed lamination and dish and pillar structures are moderately common, and witness post-sedimentary water movement through the sediments. There are few signs of primary sedimentary structures in the sandstones, although a few examples of possible faint cross-bedding occur.

Sandstone intrusions are frequently found associated with the upper boundaries of sandstone bodies, often with an abundance of angular and tabular mudstone clasts (Hamberg et al. 2005).

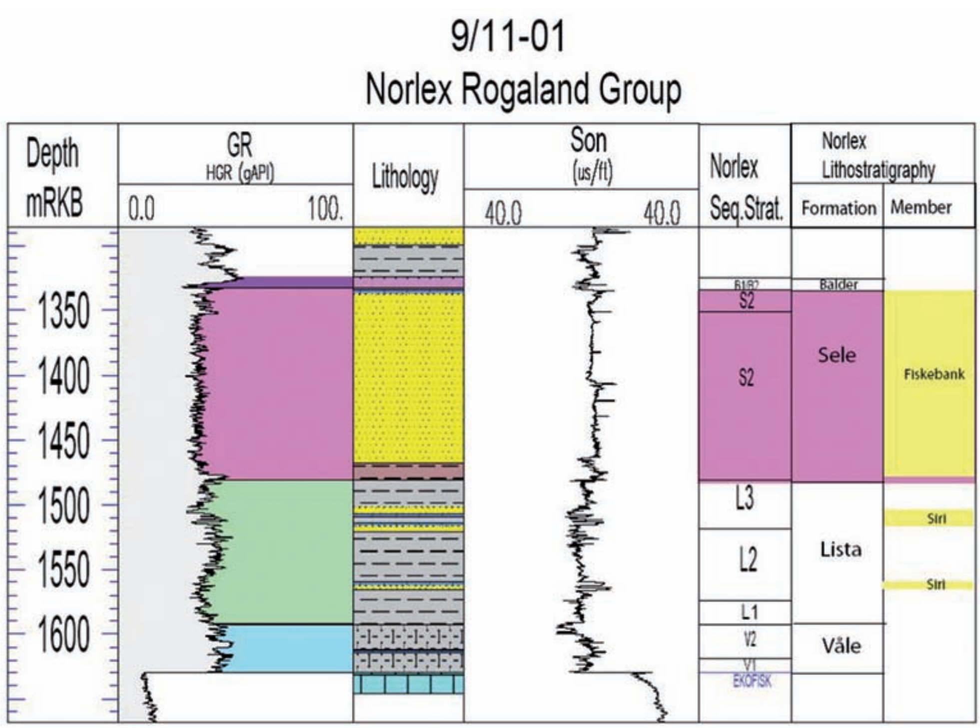


Fig. 117. Composite log in well 9/11-1, Rogaland Group. Stratigraphic position of the Fiskebank Member is outlined.

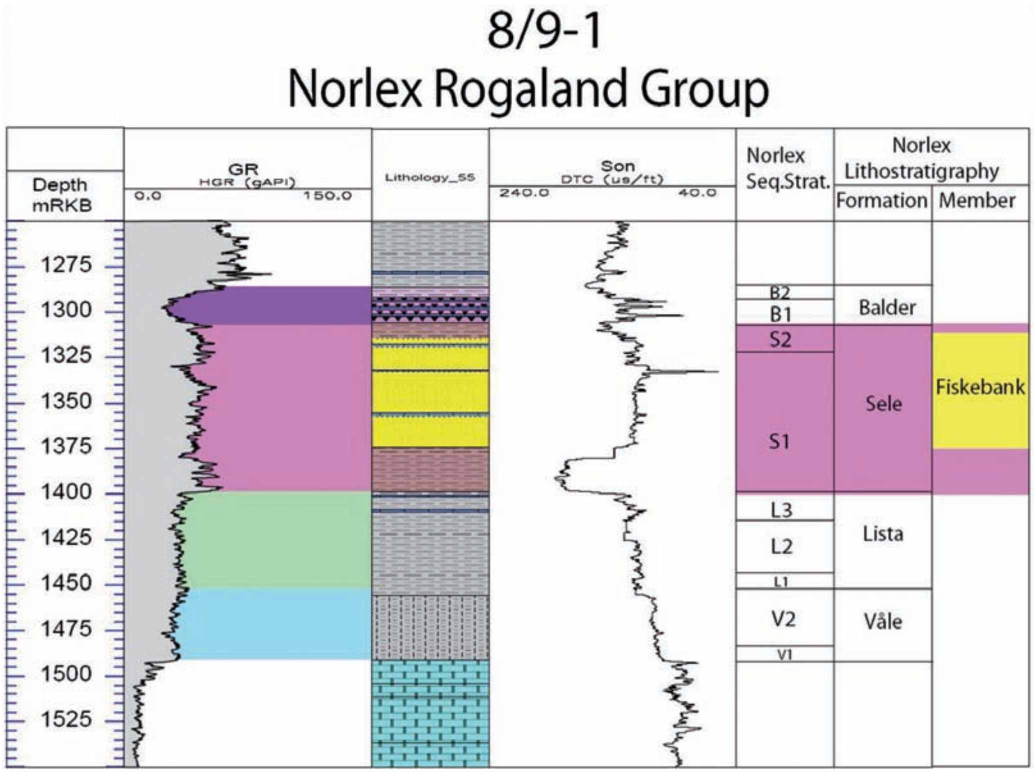


Fig. 118. Composite log in well 8/9-1, Rogaland Group. Stratigraphic position of the Fiskebank Member is outlined.

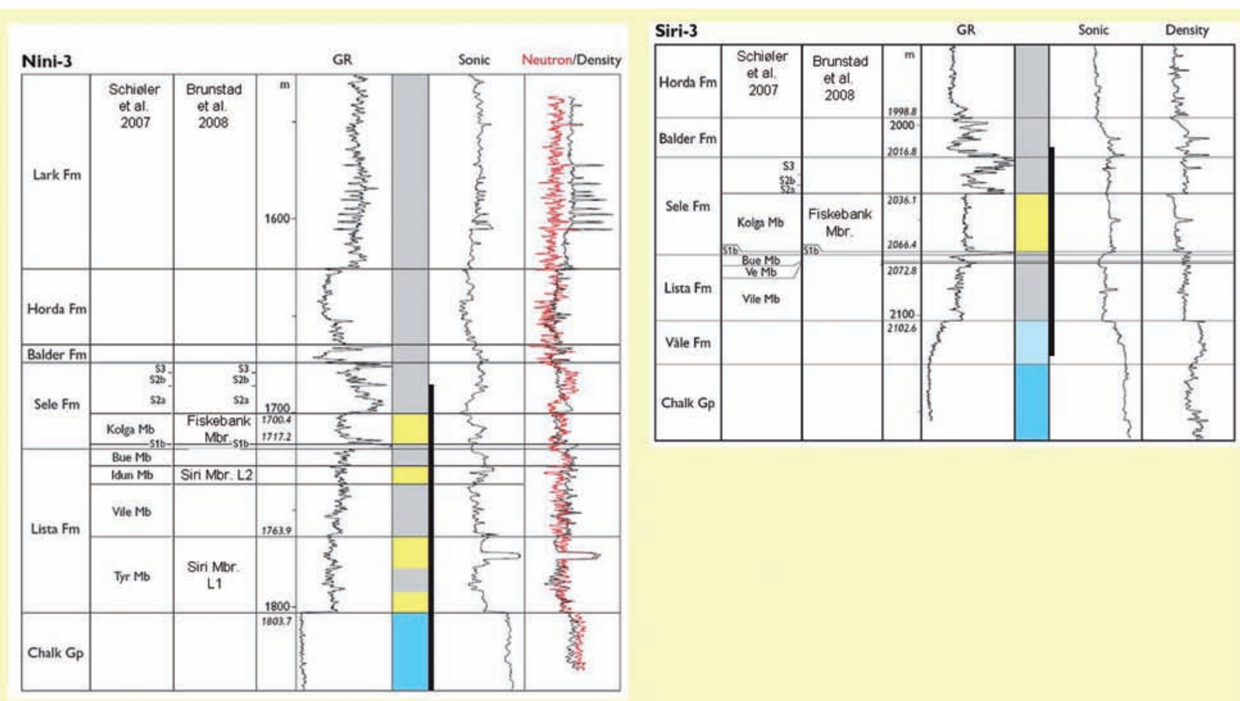


Fig. 119. Composite logs in wells DKNini-3 and Siri-3. Position of the Fiskebank Member is outlined. Modified from Schiøler et al. (2007) to fit the nomenclature for the Norwegian North Sea (this study).

Wireline log characterization

The Fiskebank Member is more often associated with lower gamma-ray response than the surrounding shales of the Sele Formation (and possibly the upper parts of the Lista Formation). However, it is locally difficult to distinguish from the shales by gamma logs because of the content of radioactive grains of mica and glauconite in the sandstones. Here other logs such as neutron, density and resistivity logs are more reliable for detecting the sands. Often a coarsening-upwards trend can be inferred from the logs.

Upper boundary
The Fiskebank Member is usually overlain by the Sele Formation, and the boundary often marks an abrupt change from sandstones to dark shales. In this case the boundary is generally seen as an upwards increase in gamma-ray response and a decrease in velocity.

In some cases the Balder Formation directly overlies the Fiskebank Member. In these cases the boundary may be seen as an upwards decrease in gamma-ray response and an increase in velocity readings.

Lower boundary (revised)
The lower boundary of the Fiskebank Member is identified by an upwards transition from the shales of the Sele or the Lista Formations below to the coarser deposits of the Fiskebank Member above.

In the Siri Canyon the log response is characterised by a sharp upwards change from high gamma-ray readings and low velocity in the shales to low gamma-ray readings and high velocity in the Fiskebank sandstone. In the north and east the boundary is often not well defined on the gamma-ray log, and must sometimes be picked by use of sonic log in combination with other logs as resistivity and caliper logs to pinpoint the shale–sandstone interboundary.

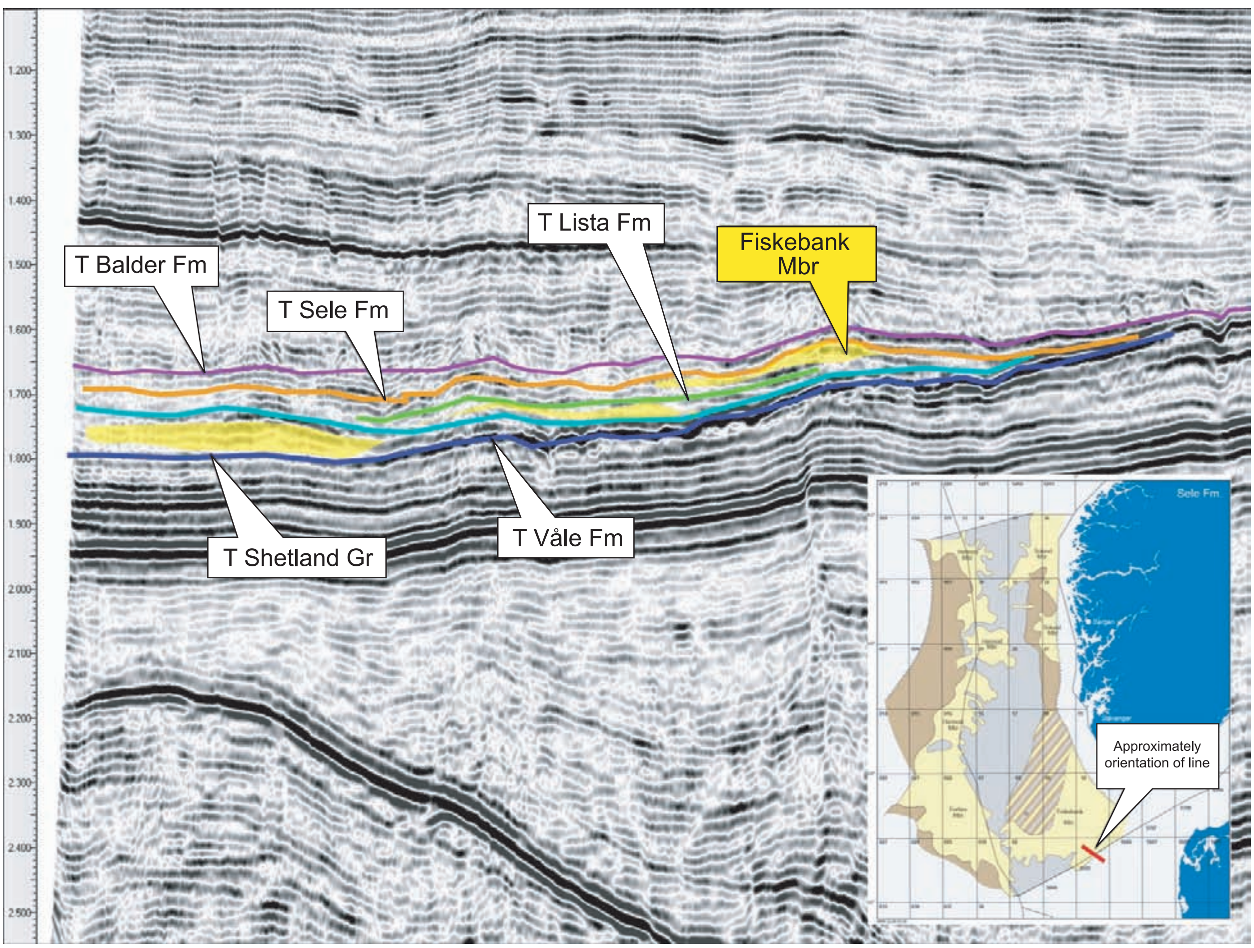


Fig. 120. Seismic line from Axis of Siri Canyon thorough the Nini discovery. Presence of the inferred Fiskebank Member is highlighted.

Thickness

The member is 82 m thick in the type well, 60 m in the reference well 8/9-1, 17 m in DK well Nini-3 and 30 m in well Siri-3.

Seismic characterization

In the Siri Canyon area, and in the western parts of the Fiskebank Member, there appears to be correlation on seismic data between thick development of the Sele Formation and the presence of sandstones. From seismic mapping of the Sele Formation interval, sandstones can be inferred by the observation of elongated thickness anomalies and from seismic cross-sections by the presence of a lenticular to mounded shape. A seismic line through the Siri Canyon and the Nini Discovery is shown in Figure 120.

In the Norwegian–Danish Basin the Fiskebank Member reflects progradation and there is not a good correlation between thickness and sandstone presence. Here other indicators may be used to detect presence of the sandstones, such as high- amplitude response and mounded seismic facies. A seismic WE line example from Sør-Vestlandet High to the Norwegian–Danish Basin through well 8/9-1 is shown in Figure 121. Dipping strata can be observed, which may indicate progradation.

Age

Latest Paleocene to earliest Eocene (Late Thanetian–earliest Ypresian).

Biostratigraphy

Being contained in the Sele Formation, the age of the Fiskebank Member is constrained by biostratigraphic age assignments for the Sele Formation. See description for the Sele Formation.

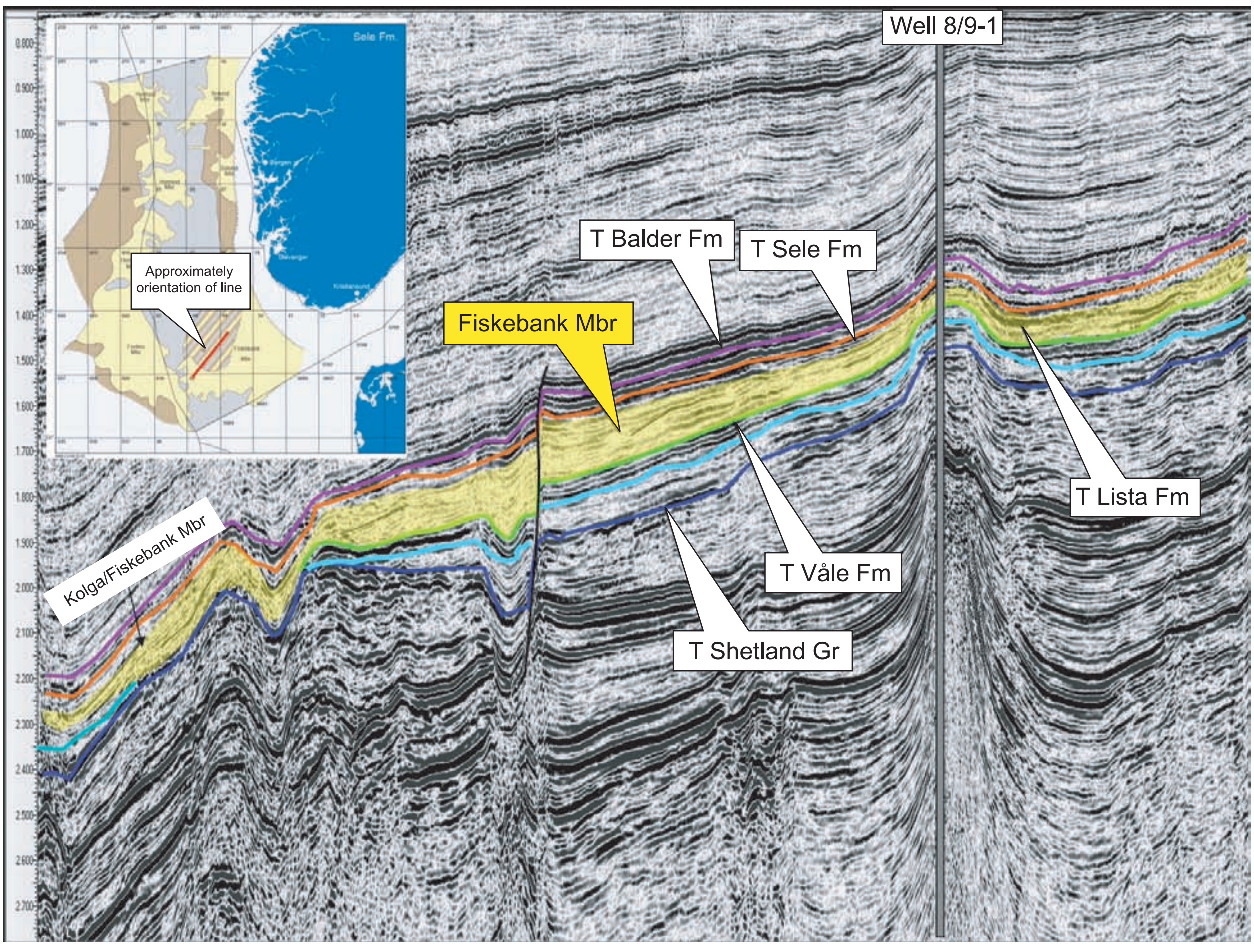


Fig. 121. Seismic cross section through Norwegian Danish Basin and well 8/9-1. Presence of inferred Fiskebank Member is highlighted.

Correlation and subdivision

Deposits of the Fiskebank Member occur both above and below the intra-Sele Formation *Apectodinum* spp. acme biomarker. Hence, using this criterion the Fiskebank Member may be subdivided in a lower unit, Fiskebank S1 and an upper unit, Fiskebank S2.

Geographic distribution

The Fiskebank Member is encountered in the Norwegian–Danish Basin, the eastern parts of the Central Graben, possibly in the Søgne Graben and southeastward into the Siri Canyon (Figures 12, 13 and 102).

Depositional environment

The coarsening-upwards trend seen in the eastern parts of the Fiskebank Member probably represents shelf to basin margin deposits laid down by a mixture of shallow marine to turbiditic processes on a prograding slope.

The western and south western parts of the Fiskebank Member were deposited by gravity flows in sand-rich basin-floor to toe-of-slope fans systems. The gravity flows were probably a result of a combination of high density sandy turbidity currents and sandy debris flows. The high glauconitic content suggests that there was a significant contribution of shelf sands.

Discoveries with Fiskebank Member as reservoir

– Siri Field (DK). Part of the reservoir complex. Oil discovery.

Sula Member, Sele Formation (new)

Name

The Sula Member is defined for the first time in this study. The Sula Member is attributed to intra-Sele Formation sandstones in the northeastern parts of the North Sea Basin.

Derivatio nominis

The Sula Member is named after one of the largest islands in Hordaland.

Unit definition

Sula Member is attributed to the intra Sele Formation sandstones in Subarea NE in Figures 12 and 13.

Type well

Norwegian well 35/3-2 (new, Figure 122). Depth: 1,355–1,363 mRKB. Coordinates: N 61° 51′ 05.98″, E 03° 46′ 28.22″. No cores.

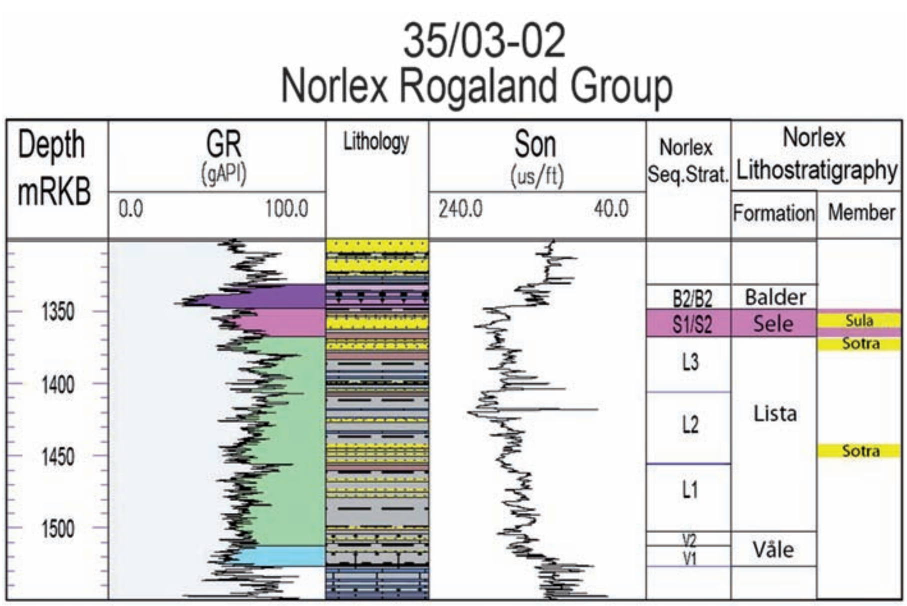


Fig. 122. Composite log in well 35/3-2, Rogaland Group. Stratigraphic position of the Sula Member is outlined.

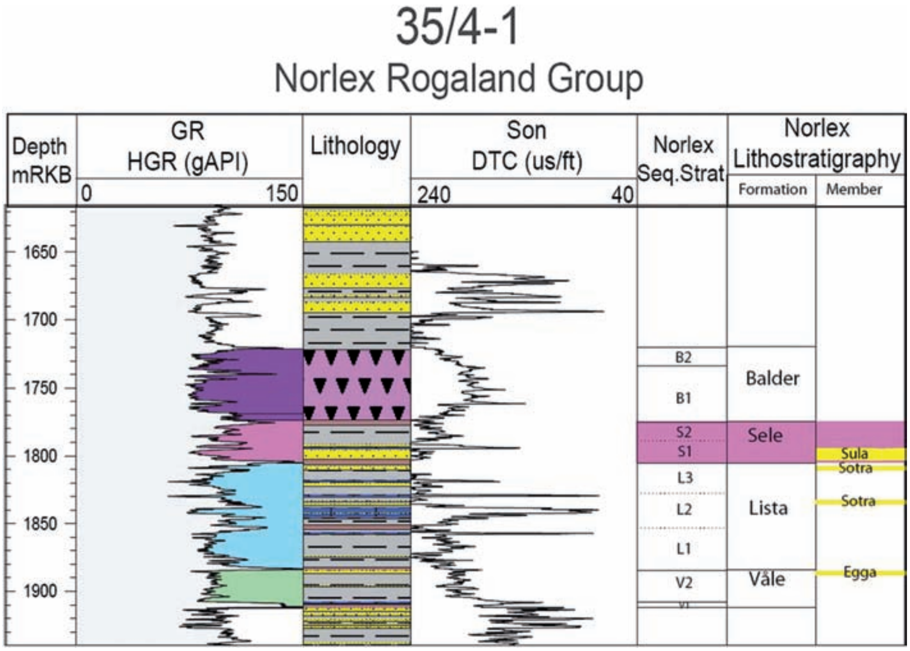


Fig. 123. Composite log in well 35/4-1, Rogaland Group. Stratigraphic position of the Sula Member is outlined.

Reference well

Norwegian well 35/4-1 (new, Figure 123). Depth: 1,795–1,803 mRKB. Coordinates: N 61° 32′ 00.55″, E 03° 18′ 00.26″. No cores.

Norwegian Well 35/10-3 (new). Depth: 1,948–1,985 mRKB. Coordinates: N 61° 02′ 47.96″, E 03° 07′ 40.70″. No cores.

Composition

The Sula Member consist of friable quartzitic sandstones, clear to white, yellow to green, fine to coarse grained, but mostly medium sized with sub rounded to sub-angular grains. The sandstones are mostly non calcareous with occasional interbeds of grey claystone, and slightly silty. Poorly to well sorted, sub rounded to sub angular, often well sorted. Traces of mica, glauconite and shell debris are common. No cores exist for the Sula Member, and limited information on facies variability is available.

Wireline log characterization

The wireline log response of the Sula Member is blocky to serrated, variably representing thick clean sandstones and series of thinner sandstone layers in alternation with mudstones. Sometimes high velocity and density values are seen, corresponding to zones of calcite cementation in the sandstones.

Upper boundary

The Sula Member is overlain by the shales of the Sele or Balder Formation. Where the Sele Formation lies on top, the boundary is generally seen as an upwards increase in gamma-ray response and a decrease in velocity.

Where the Balder Formation directly overlies the Sula Member, the boundary may be seen as an upwards decrease in gamma-ray response and an increase in velocity from the Sele and Lista formations.

Lower boundary

The basal contact of the Sula Member is seen as the boundary between shales of the Sele or Lista Formation below and the coarser deposits of the Sula Member above, but this boundary is often not well defined. The boundary is placed where there is an upwards transition from higher gamma-ray readings and higher velocity.

Thickness

In wells, the Sula sandstones are usually found as successions of thin, serrated sandstones with thicknesses of only a few meters. A 37 m thick blocky Sula sandstone is found in well 35/10-3. From seismic there is evidence of thicker development elsewhere.

Seismic characterization

The sandstones belonging to the Sula Member in places occur within westward dipping seismic reflectors inside the overall westwards thinning wedges (prograding slope) of the Rogaland Group from the Måløy Terrace/Horda Platform into the Sogn Graben.

In some cases the presence of blocky log response in wells corresponds to mounded geometries, or channel-like lenses, especially in the lower and distal parts of the prograding wedge.

Figure 124 shows a seismic line through well 35/10-2 where thin stringers of Sula Member sandstones are found and well 35/10-3, where a blocky Sula Member sandstone of 37 m thickness is present.

Age

Latest Paleocene to earliest Eocene (Late Thanetian–earliest Ypresian).

Biostratigraphy

The Sula Member is stratigraphically contained within the Sele Formation, and its biostratigraphic age is thus limited by the same biostratigraphic events that bound the Sele Formation.

Correlation and subdivision

The Sula Member is stratigraphically divided in Sula S1 and Sula S2 corresponding to Sele 1 and Sele 2 and a high gamma peak. However, the recognition of the boundary between the two sub-units is often difficult in this area because there is generally a less diagnostic development of the high gamma-ray peaks within the Sele formation in this area compared to further south.

Geographic distribution

The Sula Member is present from the area south of Selje High, stretching south to the Horda Platform, and westwards into the Sogn Graben (Figures 12, 13 and 102). It is not known whether the Sula Member stretches southwards into the Stord Basin Graben due to lack of well control in that area.

Depositional environment

The sandstones of the Sula Member were deposited from sand transported by submarine gravity flow systems. In the eastern areas the Sula Member was largely deposited as proximal turbidites in proximal parts of submarine slope fans on a prograding slope. Further west in the Sogn Graben, the sands were deposited in a basin floor fan setting.

Discoveries

No commercial discovery has been made in the Sula Member.

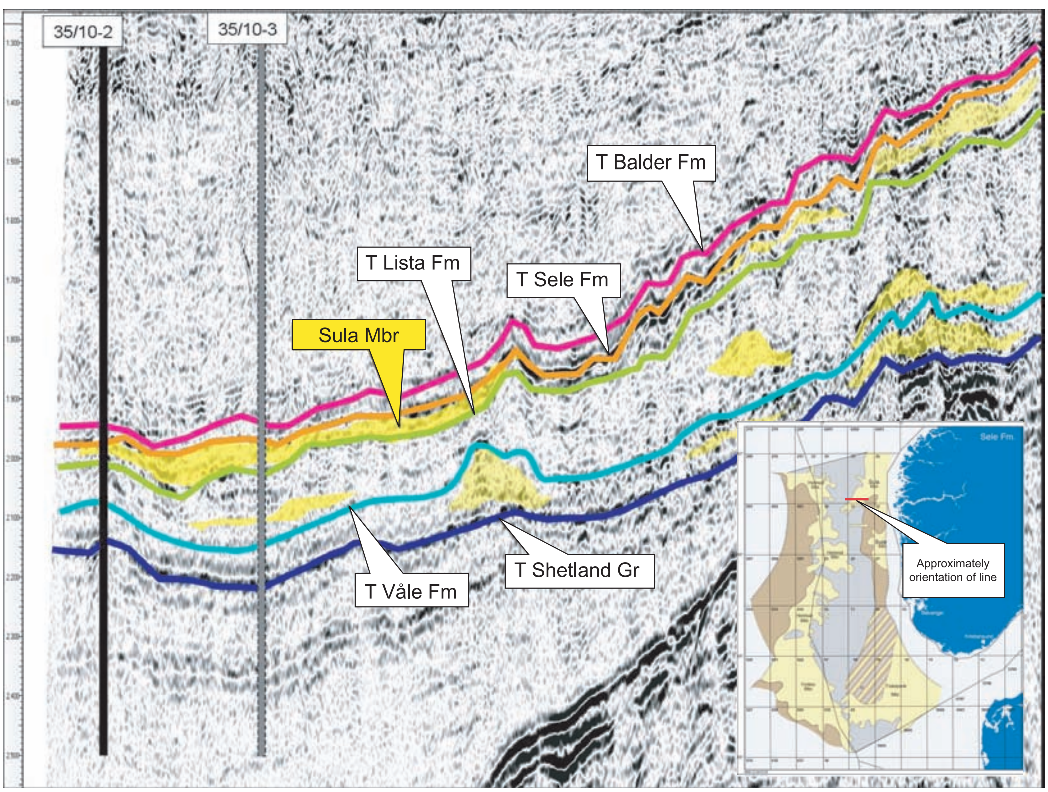


Fig. 124. Seismic section from Sogn Graben to Horda Platform running through well 35/10-2 and close to 35/10-3. Inferred presence of Sula Member is highlighted.

Balder Formation with Members

Balder Formation

Balder Formation is the uppermost formation of the Rogaland Group (Figure 125).

Name

The Balder Formation name was given by Deegan and Scull (1977) to the tuffaceous shales above the Sele Formation in the North Sea.

Derivatio nominis

The formation was named after the Balder Field in Norwegian blocks 25/10 and 25/11. Balder was a son of Odin, and one of the most famous gods in Norse mythology.

Unit definition

Balder Formation is the uppermost of the formations in the Rogaland Group.

Type well

Norwegian well 25/11-1 (Figure 126). Depth: 1,780–1,705 m (Deegan and Scull 1977). Coordinates: N 59° 10′ 57.39″, E 02° 24′ 28.18″. Cores.

Reference wells

Norwegian well 30/2-1 (Figure 127). Depth: 1,993–1,917 mRKB. Coordinates: N 60° 52′ 05.42″, E 02° 38′ 49.16″. Cores: Core 1 and 2.

Norwegian well 15/9-17 (Figure 128). Depth: 2,253–2,204 m. Coordinates: N 58° 26′ 44.19″, E 01° 56′ 53.58″. No cores.

Composition

The Balder Formation is composed of laminated light to dark grey, fissile shales with interbedded grey, green and buff, volcanic tuffs (Figure 129). The formation has occasional stringers of limestone, dolomite and siderite and is often pyritic. The tuffs are in places sandy. In the lower part of the formation, the mudstone is well laminated with light to medium grey indurated siliceous mudstone alternating with medium to dark grey soft, fissile mudstone. In the upper part of the formation, the mudstone is soft and poorly laminated. The tuffs mostly occur as thin strata, up to a few centimeters in thickness, with sharp bases, commonly normal graded, and are interpreted as undisturbed ash falls. In cores from Viking Graben wells, structureless units, tens of centimeters thick, displaying dewatering structures are observed. These beds are interpreted as resulting from gravity flow re-sedimentation of primary air-fall tuff (Malm et al. 1984, Knox and Holloway 1992).

Sandstone units named the Odin Member and Radøy Member are locally present in the Balder Formation (Figures 12, 13 and 132). These are described below. A core description log example is shown in Figure 130.

Wireline log characterization

The shales of the Balder Formation are generally characterized by low gamma readings and high sonic readings. Spikes with high acoustic velocities are frequently seen, and can be related to thin beds or nodules of carbonate or cemented tuffs.

Upper boundary
The top of the Balder Formation is taken at the top of a prominent bell shape, commonly expressed as base of a high gamma peak and a low acoustic trough. The lower tuff-rich parts of the Lower Balder Formation can often be distinguished as a zone or a “belly” of higher acoustic velocities.

Lower boundary
From wire-line logs the Balder Formation is characterised by a bell-shaped log response. At the base a shift from high gamma readings and low acoustic velocities in the Sele Formation to lower gamma readings and higher acoustic velocities in the Balder Formation is seen. Lithologically an abrupt increase in tuffaceous interbeds from Sele upwards into the Balder Formation can be seen.

Thickness

The Balder Formation is 75 m thick in the type well. Generally its thickness varies from less than 20 m to more than 100 m. Normally, it is between 40 and 60 m. Sandstone units belonging to Balder of over 200 m occur in the central and northern parts of the Viking Graben; maximum thickness is 285 m, including the Odin Member.

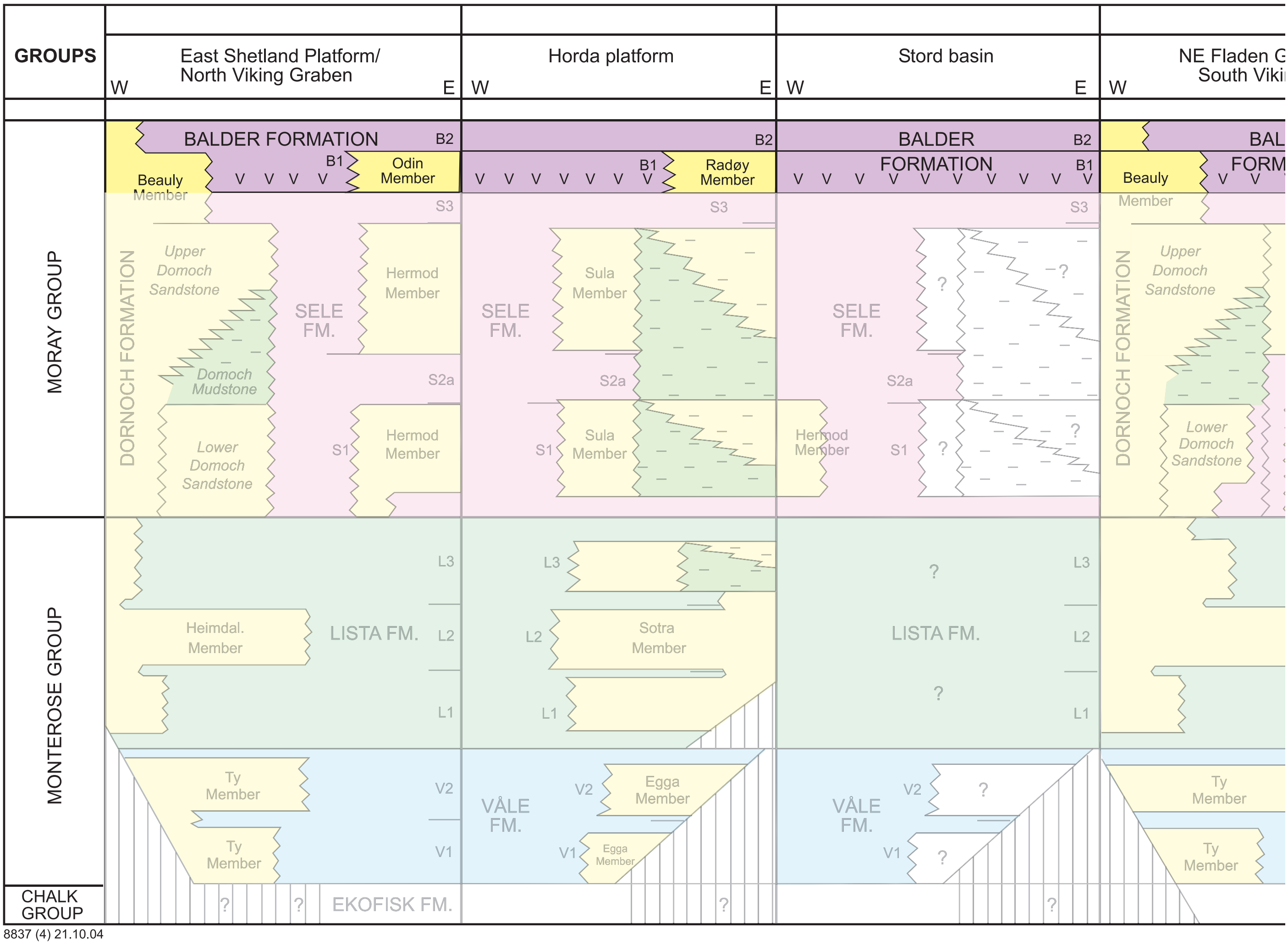


Fig. 125. Lithostratigraphic summary chart of the Balder Formation (color) with members.

Seismic characterization

Top Balder reflector
The top of the Balder Formation (Top B2) is often defined at a positive acoustic impedance contrast that varies in strength. It is often weak and difficult to pick.

Base Balder/Top Sele reflector
The base of the Balder Formation (Near Top S2/ Base B1) is often characterised by a marked negative acoustic impedance.

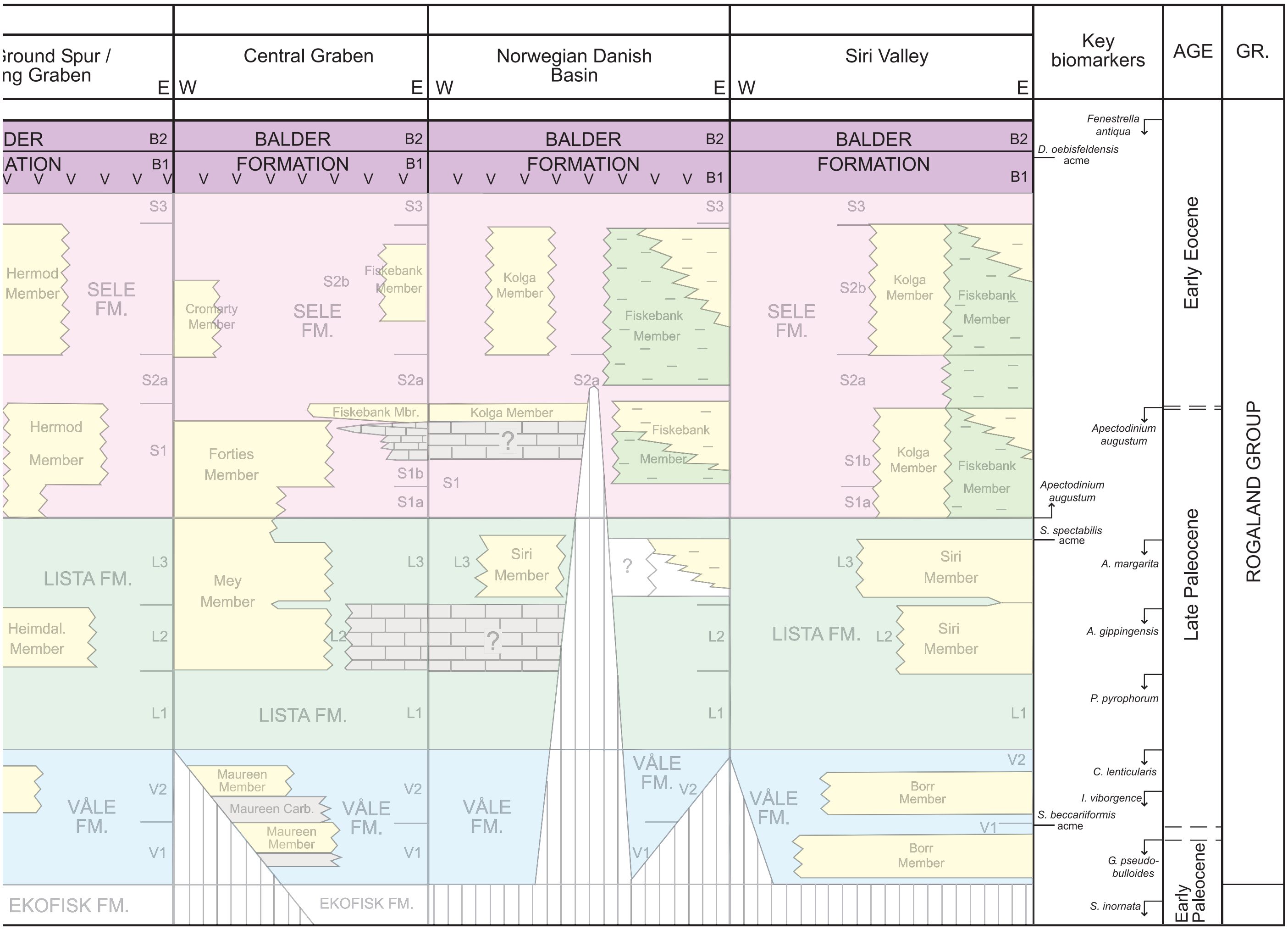
Top Tuff zone – The Tuff Marker (Top B1)
The top of the Balder tuff-rich zone (Top of zone B1) is a pronounced seismic surface that can be regionally identified. It is characterised by a positive amplitude event and the velocities increase downwards in Zone B1 related to a downward increase in silica cementation (Knox and Holloway 1992). This seismic event is often more distinct and easier to pick than the Top Balder Formation, and is sometimes mistaken for the true top Balder Formation.

Age

Lower Eocene (Early Ypresian).

Biostratigraphy

The upper boundary of the Balder Formation is slightly below the top of dinocyst *Deflandrea oebisfeldensis*, at the upper level of frequent *Deflandrea oebisfeldensis*. The base of the Balder Formation is at the top of the acme of *Cenodinium wardenense*. Characteristic shelly



microfossils are pyritized pillbox-shaped diatoms belonging to *Fenestrella antiqua*. The taxon ranges throughout the Balder unit, and does not occur stratigraphically higher. The Balder Formation is assigned to Zone NSR3–*Fenestrella antiqua* of Gradstein and Bäckström (1996), and to dinocysts zones D5b–D7a in Luterbacher et al. (2004), of Early Ypresian, earliest Eocene age. Some diagnostic microfossils of the Balder Formation are shown in Figure 131.

Correlation and subdivision

The Balder Formation can be subdivided into a lower (B1) and an upper (B2) unit (Knox and Holloway 1992). The base of the B1 zone is taken at the common *Ceratopsis wardenense*. B1 is the lower and older zone, and is generally more tuffaceous than the B2 zone. Due to sparse internal biostratigraphic diagnostic criteria, the subdivision into the two zones is based on wire-line log pattern recognition. The B1 zone has higher velocity and lower gamma readings than the upper parts of B2, and commonly there is a pronounced transition into lower gamma values and sonic log values going into the B2 zone. The top of the B2 zone is picked near the top of the bell shape defining the Balder Formation from wire-line logs, coinciding with the common *Deflandrea oebisfeldensis* and common *Hystrichospheridium tubiferum* events. Internally in the Balder Formation two sandstones are found, the Odin Member sandstones have a distribution in western areas of the Norwegian North Sea and the Radøy Member has a distribution in north-eastern areas of the North Sea. See below for a description of the Odin and Radøy members.

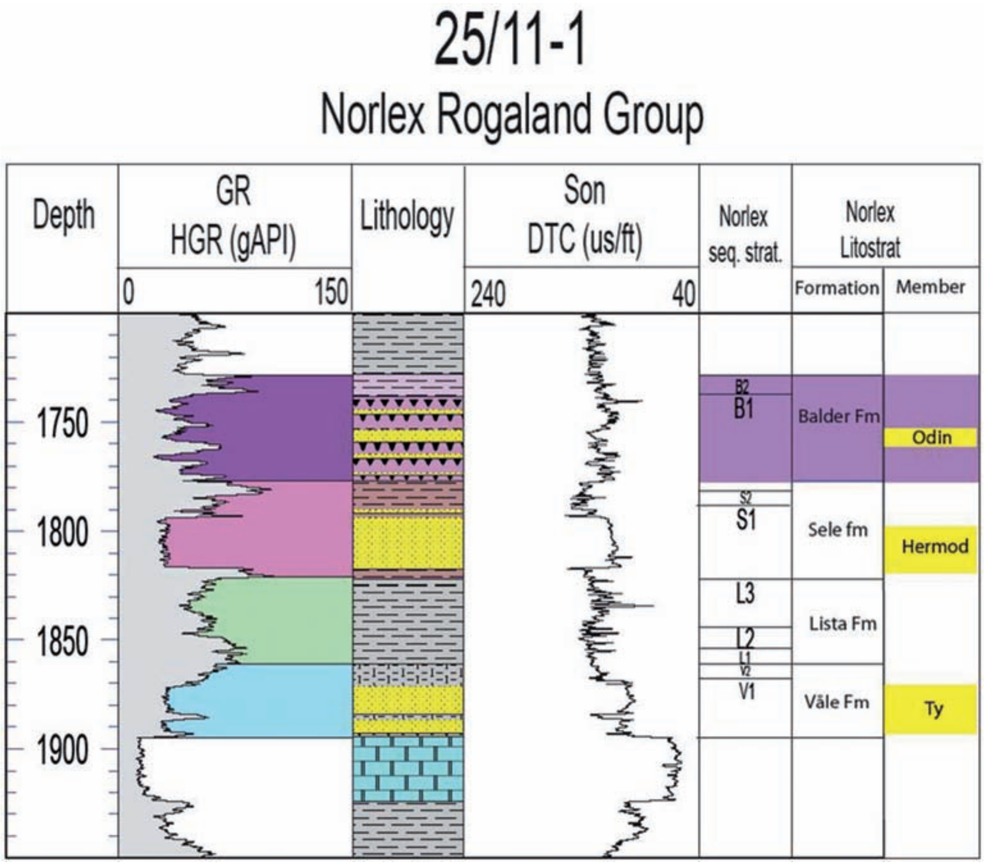


Fig. 126. Composite log in well 25/11-1, Rogaland Group. Stratigraphic position of the Balder Formation is outlined.

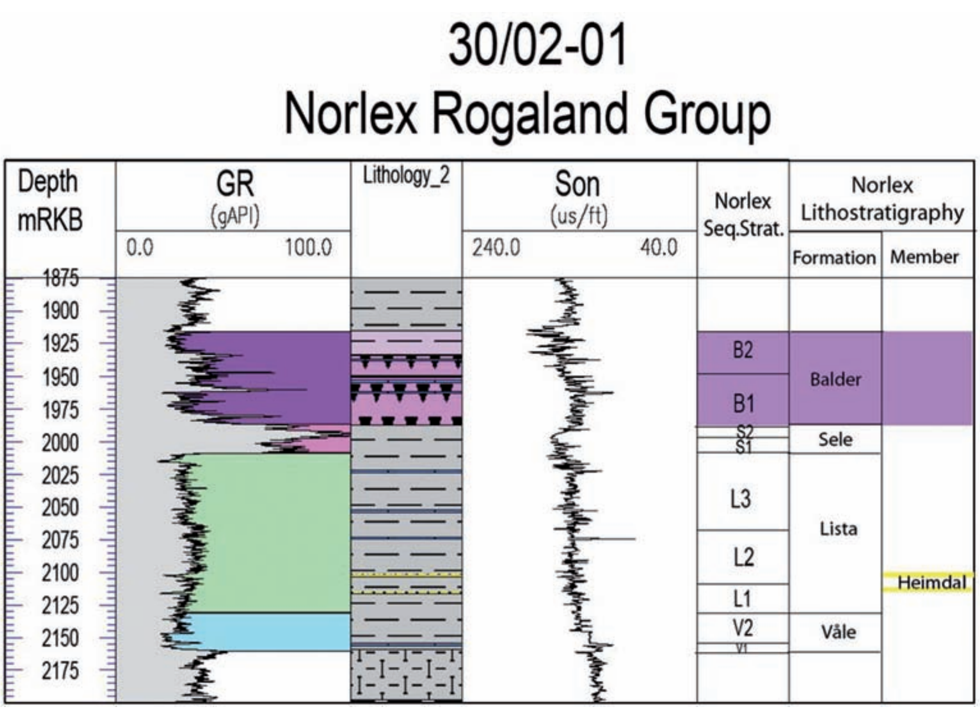


Fig. 127. Composite log in well 30/2-1, Rogaland Group. Stratigraphic position of the Balder Formation is outlined.

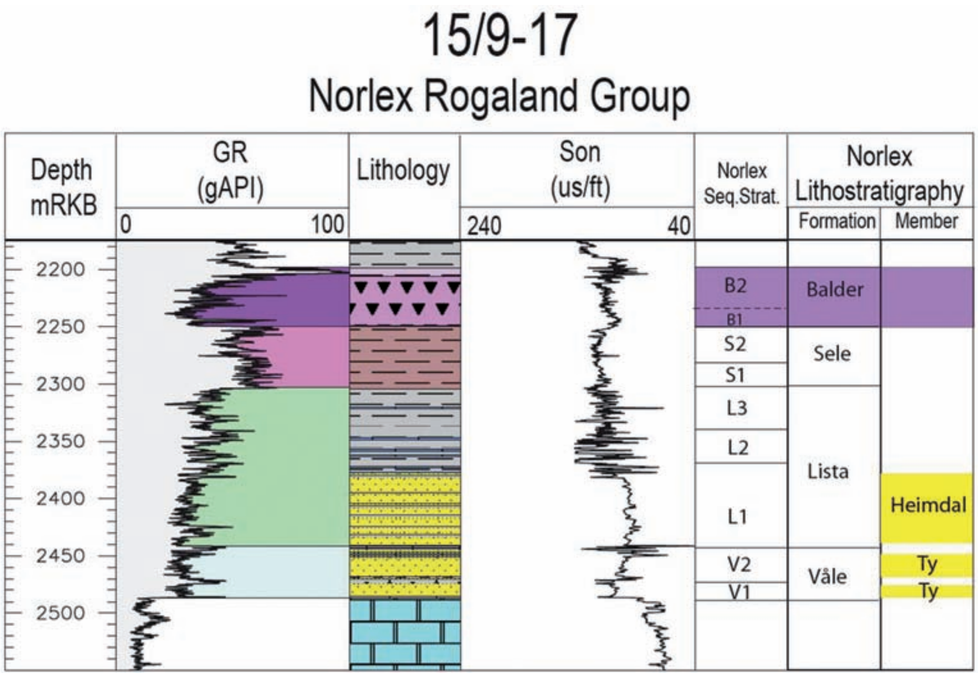


Fig. 128. Composite log in well 15/9-17, Rogaland Group. Stratigraphic position of the Balder Formation is outlined.

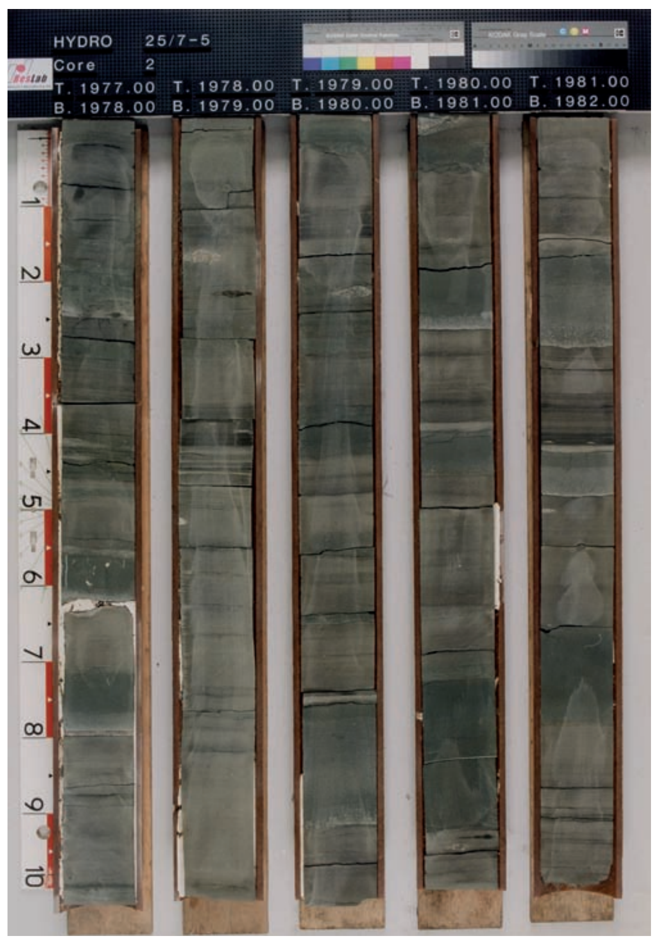


Fig. 129. Core photo from Balder Formation in well 25/7-5 at 1,977–1,982 m, drilled by Norsk Hydro. Photo from *http://npd.no*.

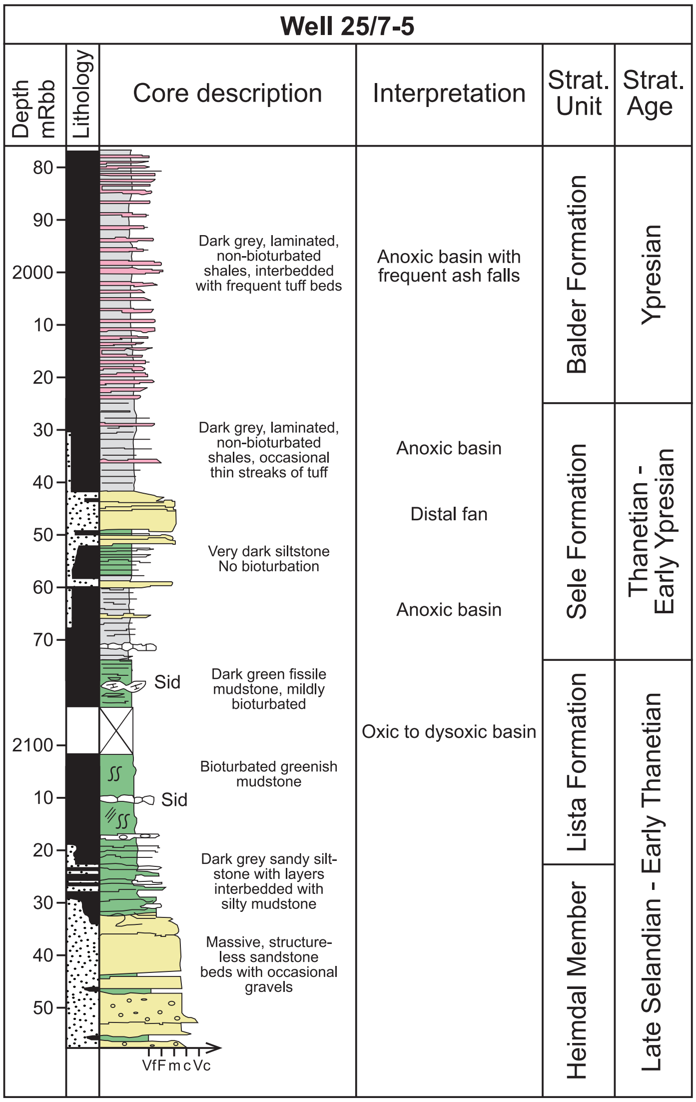


Fig. 130. Core description log from well 25/7-5. Section covers Upper parts of the Lista Formation with upper parts of the Heimdal Member, the Sele Formation with sandstones belonging to Hermod Member, and most of the Balder Formation.

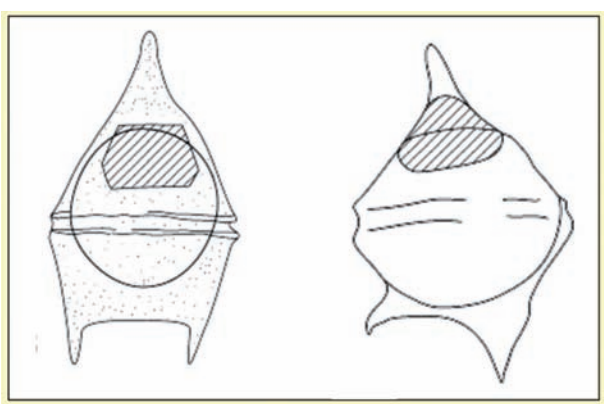


Fig. 131. Some diagnostic microfossils of the Balder Formation. Left: *Deflandrea oebisfeldensis* dorsal view; holotype dimensions: pericyst length = 150 µm, pericyst width = 88 µm., Right: *Cerodinium wardenense* dorsal view; holotype dimensions: pericyst length = 57 µm, pericyst width = 46 µm, endocyst length = 36 µm, endocyst width = 43 µm. From the ODP Drilling Program at *http://www-odp.edu*.

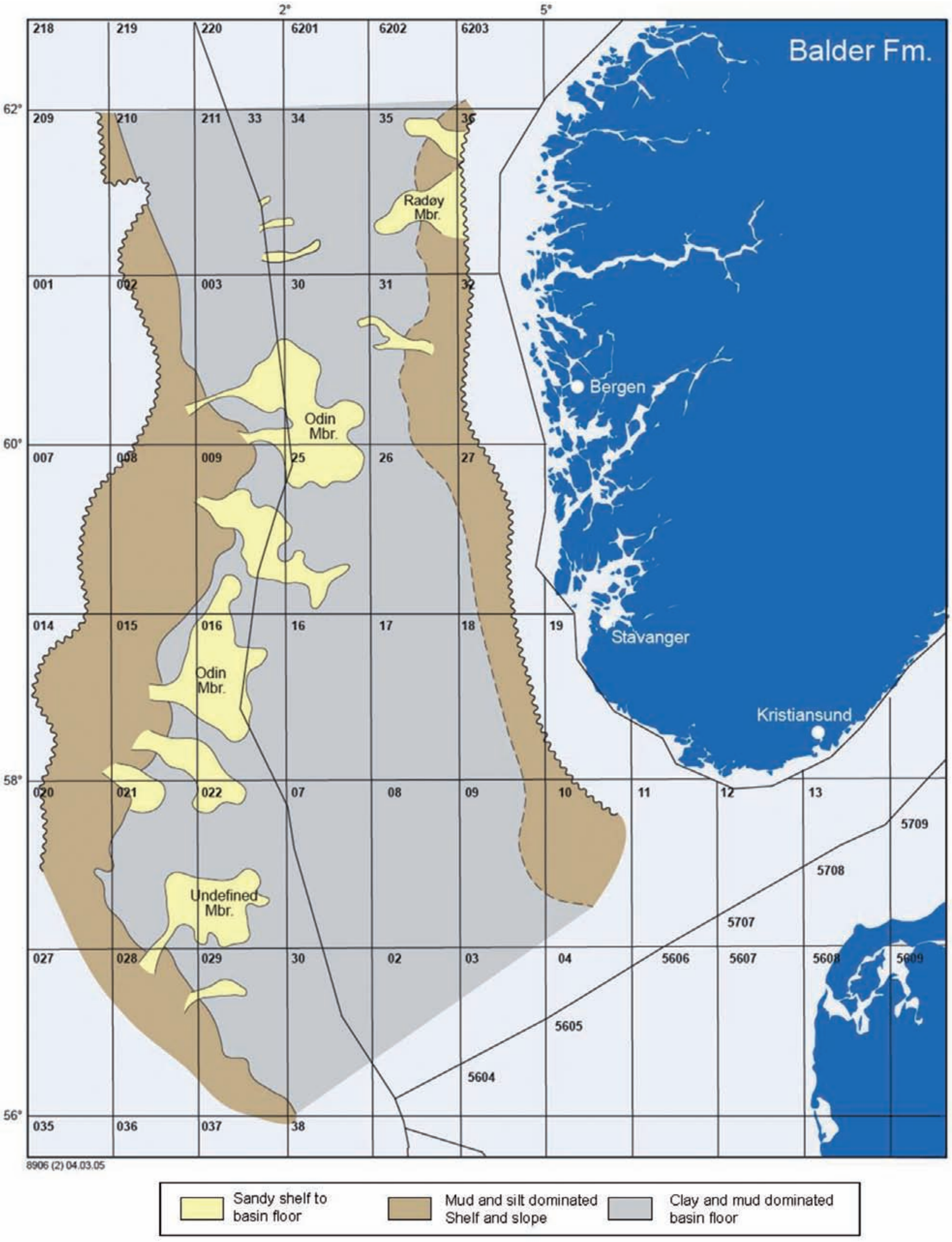


Fig. 132. Distribution of the Balder Formation and its sandstone members.

Geographic distribution

The Balder Formation is present in most of the areas where Paleocene strata are also present. Only along the eastern flanks where Paleocene strata are partly truncated, the Balder Formation is partly or completely eroded. The distribution of the Balder Formation, with its respective members, is shown in Figure 132.

Depositional environment, volcanic activity and deposition of tuffs

The North Sea Basin restriction that started with the deposition of the Sele Formation continued through the deposition of the Balder Formation. The Balder Formation was deposited in a generally deep marine, anoxic environment, mainly as hemipelagic sediments, with frequent influx of tuffaceous rain caused by ash falls from volcanic activity.

Igneous activity in the North Atlantic shows a wide age range (Torsvik et al. 2002), with peaks between 55 and 50 Ma, spanning Norwegian sea syn-rift and a continental break-up phase. At that time, large amounts of tuffaceous ash material were introduced into the atmosphere, and distributed over vast areas of North Europe, particularly during the late rift phase. The delicate lamination in the lower, tuff-rich Balder mudstones is probably related to varying proportions of diatoms, reflecting seasonal variations in productivity (Knox and Holloway 1992). The upwards change from tuff-rich to tuff-poor mudstone at the B1/B2 boundary is believed to reflect a rise in sea-level combined with a decrease in pyroclastic activity. The trend of upwards-increasing gamma values in the B2 mudstones is interpreted as reflecting continued deepening (Knox and Holloway 1992), and gradually decreased tuffaceous input.

Odin Member

Unit definition

The Odin Member is attributed to the intra-Balder Formation sandstones in sub-area NW in Figures 12 and 13.

Name

The name Odin Member was proposed for sandstones in the Balder Formation by Mudge and Copestake (1992). The Odin Member is the age and lateral equivalent to the shallow to slope marine sandstones of the Dornoch Member further west.

Derivatio nominis

The Member is named after the Norse God Odin.

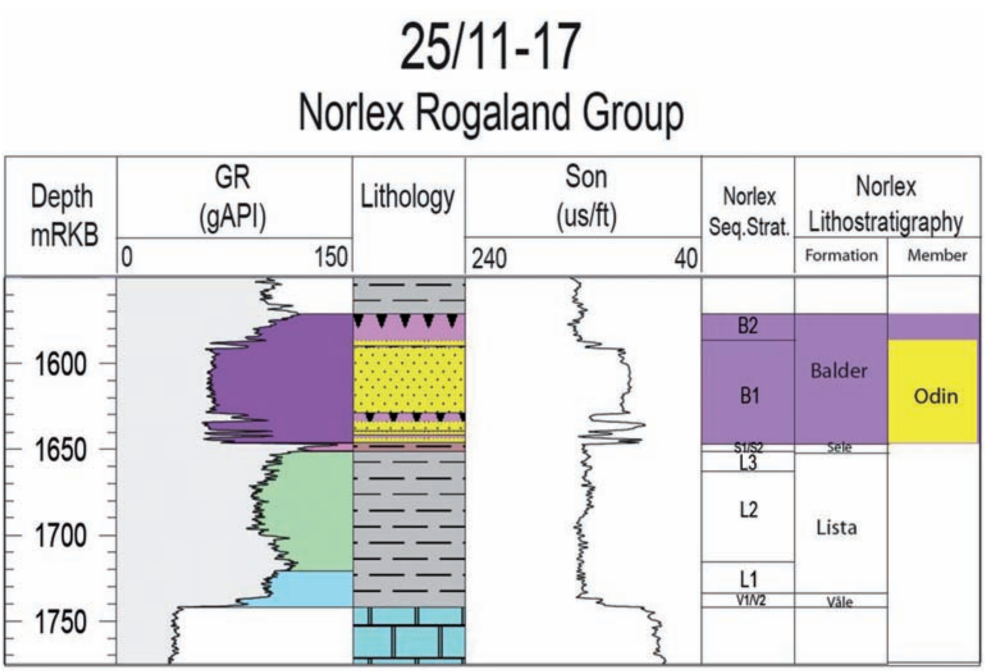


Fig. 133. Composite log in well 25/11-17, Rogaland Group. Stratigraphic position of the Odin Member is outlined.

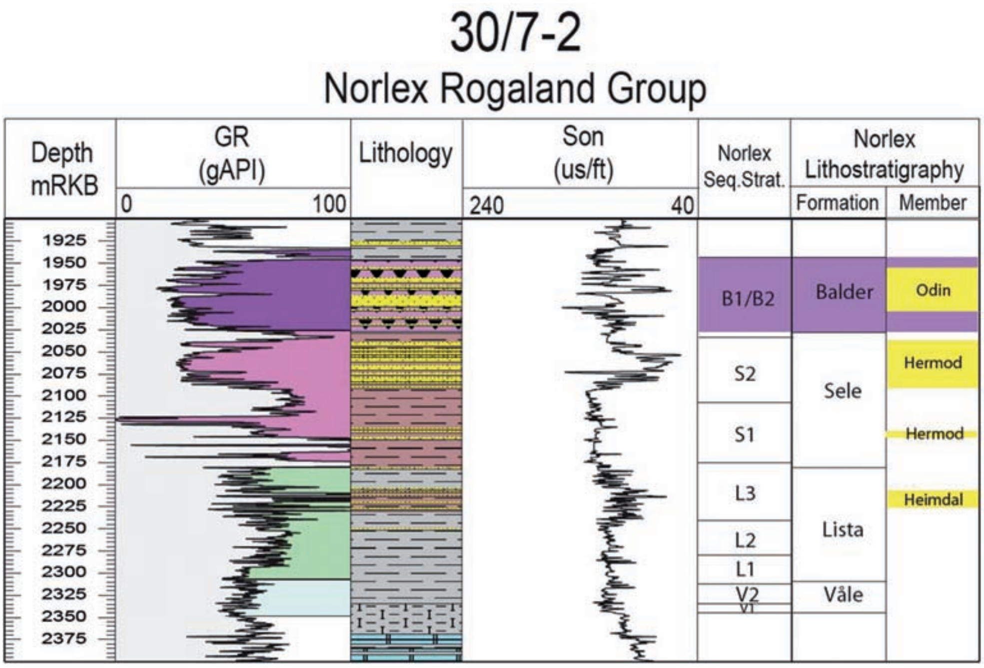


Fig. 134. Composite log in well 30/7-2, Rogaland Group. Stratigraphic position of the Odin Member is outlined.

Type well

UK well 9/18a-15. Depth 1,676–1,875 mRKB. Coordinates: N 59° 26′ 36.670″, E 01° 33′ 20.080″.

Reference wells

Norwegian well 25/7-17 (Figure 133). Depth: 1,587–1,647 mRKB. Coordinates: N 59° 03′ 26.66″, E 02° 29′ 06.59″. Cores: Core 1 and 2.

Norwegian well 30/7-2 (Figure 134). Depth: 1,955–2,004 mRKB. Coordinates: N 60° 29′ 26.06″, E 02° 01′ 40.85″. Cores: Cores 7 and 8.

Composition

The sandstones are well to moderately sorted, clean and poorly cemented, although tightly cemented sandstones occur locally. Grains are medium rounded to sub-angular. A core example from the Odin Member is shown in Figure 135. Sandstone intrusions are frequently found associated with the upper boundary of sandstone bodies commonly with an abundance of angular and tabular mudstone clasts

Wireline log characterization

The sandstones of the Odin Member often have a blocky appearance, but also a serrated log pattern or fining/coarsening upwards patterns can be seen in some wells. Sometimes the Odin Member can be difficult to distinguish from gamma-ray and sonic logs, since the surrounding tuffaceous Balder Formation has relatively low gamma-ray readings and high velocity. In such cases resistivity and porosity/density logs can be useful.

Upper boundary (revised)

The Odin Member is overlain by the Balder Formation with variable amounts of tuff. The transition from the Balder Formation is usually seen as a downwards decrease from low/intermediate gamma-ray readings to lower gamma-ray readings together with an increase in velocity readings.

Lower boundary (revised)

The basal contact of the Odin Member is seen as the boundary between shales of the Sele or Balder Formation and the lower parts of the Odin Member. The boundary is placed where there is an upwards transition from higher gamma-ray readings and higher velocity in the shales to lower gamma-ray readings and higher velocity in the sandstones.

Thickness

Sandstone units of up to 200 m thick, belonging to the Odin Member, occur in central and northern parts of the Viking Graben (Knox and Holloway 1992).

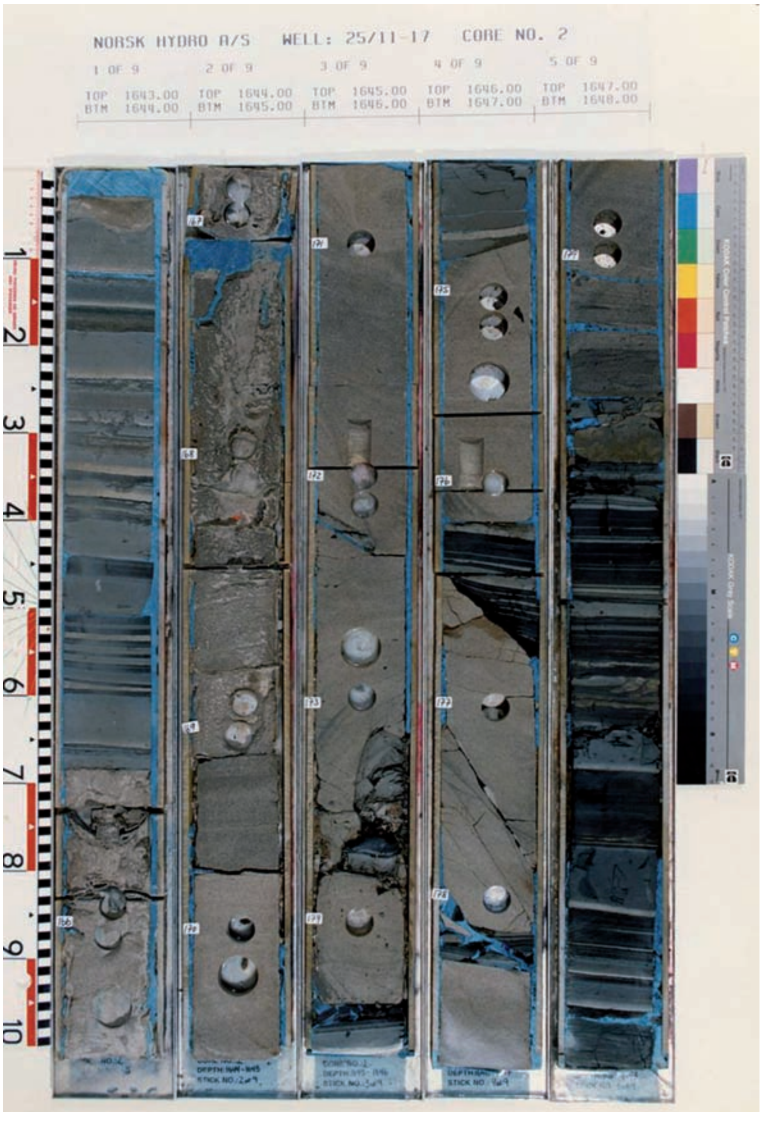


Fig. 135. Core photo from lower parts of the Odin Member in well 25/11-17 at 1,643–1,648 m. Sediments are interpreted as high density turbidites influenced by secondary water escape and sand mobilization. Note striped appearance of bedded shale. Darker lamina represent normal anoxic shales, whereas lighter lamina/thin beds represent tuffs. Well drilled by Norsk Hydro. Photo from *http://www.npd.no*.

Seismic characterization

The seismic character of the Odin Member varies from mounded to lenticular or trough-shaped channel infills. Locally the top of the sandstones of the Odin Member are associated with a marked change in acoustic impedance and an increased amplitude (Figure 130 rightmost parts). In other cases the top of the Odin Member is difficult to recognize, and its presence is inferred from a thickening of the Balder Formation interval (central left in Figure 136).

Age

Earliest Eocene (Early Ypresian).

Biostratigraphy

Being contained in the Balder Formation, the age of the Odin Member is constrained by biostratigraphic age assignments for the Balder Formation. See description for the Balder Formation.

Correlation and subdivision

The Balder Formation, which contains the Odin Member, is divided into a lower very tuffaceous unit (B1) and an upper less tuffaceous unit (B2). Sandstones of the Odin Member mostly belong to the B1 unit of the Balder Formation (Odin B1 sandstones), but sandstones are also found in the B2 unit (Odin B2 sandstones).

Geographic distribution

In the Norwegian sector, the Odin Member is mostly restricted to the Viking Graben, but it is also found locally at the Utsira High, as for example in the Balder Field (Figures 12, 13 and 132), and in well 25/11-17, east on the Utsira high.

Depositional environment

The Odin sandstones are mostly interpreted as representing mass flow transport and deposition in channels or fans sourced from shallow marine environments of the East Shetland Platform. Some sandstones are considered to have been emplaced by injection from lower levels.

Discoveries

– Balder Field. Part of reservoir complex. Oil discovery.

Radøy Member, Balder Formation (new)

Unit definition

The Radøy Member is attributed to the intra-Balder Formation sandstones in sub-rea NE (Figures 12 and 13).

Name

The Radøy Member is defined for the first time in this study.

Derivatio nominis

The Radøy Member is named after one of the large islands in northern Hordaland.

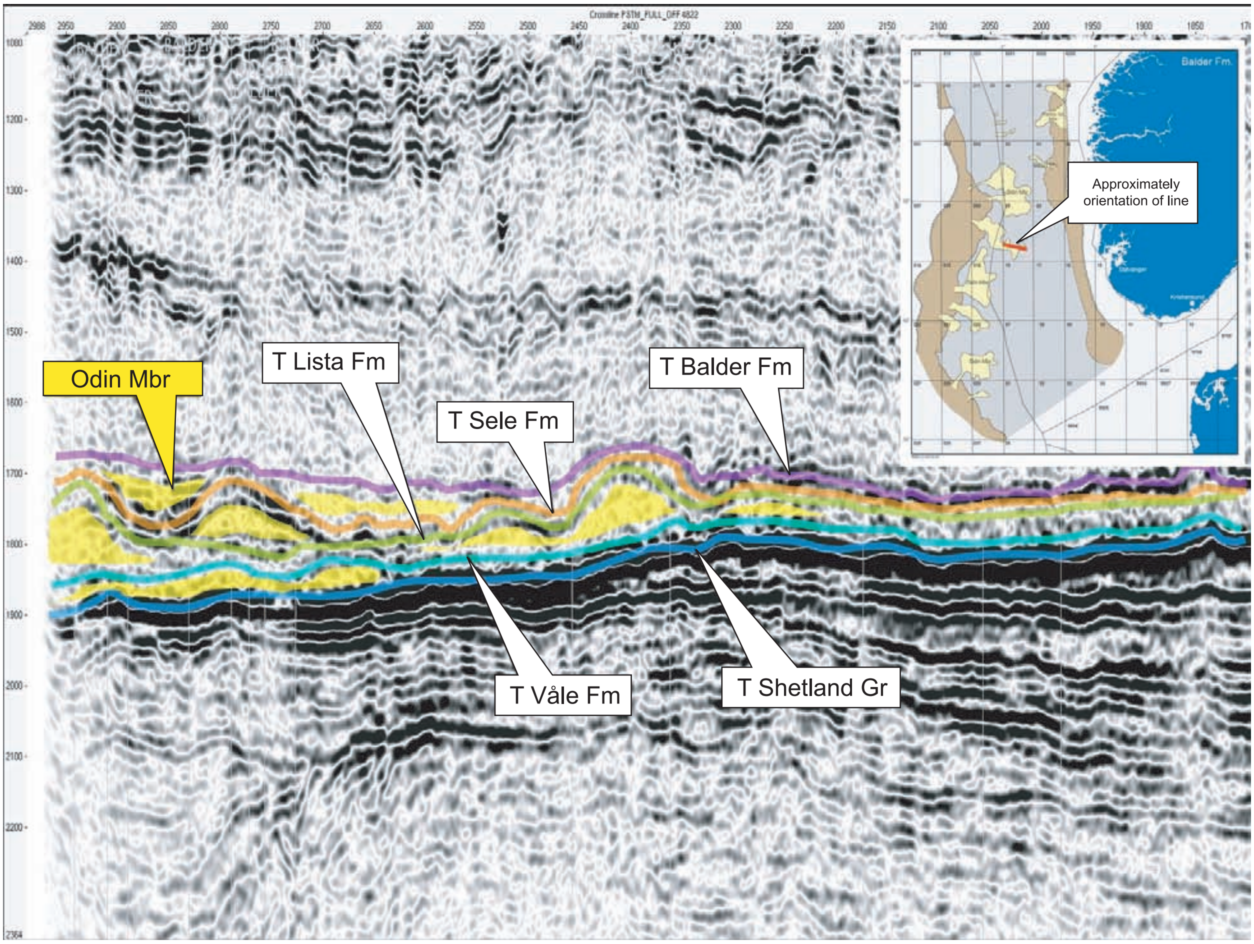


Fig. 136. WE seismic cross section through area between northern Balder and Grane discoveries, Blocks 25/10 and 25/11. Inferred presence of Odin Member is highlighted.

Type well

Norwegian well 35/8-3 (new, Figure 137). Streaks and thin beds of sandstone through depth interval 1,418–1,525 mRKB. Coordinates: N 61° 21′ 05.35″, E 03° 32′ 02.63″. No cores.

Reference wells

Norwegian well 35/8-1 (new, Figure 138). Thin beds and streaks of sandstone through depth interval 1,675–1,685 mRKB. Coordinates: N 61° 21′ 26.37″, E 03° 21′ 44.09″. No cores.

Norwegian well 35/8-4 (new). Depth: 1,536–1,558 mRKB. Coordinates: N 61° 21′ 33.03″, E 03° 30′ 20.45″. No cores.

Norwegian well 35/3-4 (new). Thin beds of sandstones through depth interval 1,164–1,176 mRKB. Coordinates: N 61° 51′ 54.54″, E 03° 52′ 26.99″. No cores.

Composition

The Radøy Member consists of moderately hard to friable clear-white, occasionally yellow or light green to grey quartzitic sandstones. Grain size is very fine to coarse, sorting is poor to moderate, and grains are subangular to well rounded. The sandstones are mostly non-calcareous and contain traces of mica and glauconite

There are no cores taken from the Radøy Member, and thus limited information about variability in facies and composition exists.

Wireline log characterization

The wire-line log response for the Radøy Member is blocky to serrated, representing thick clean sandstones and successions of thinner sandstone layers in alternation with mudstones. Sometimes zones of high velocity sonic readings and high values on density logs are seen, which seem to correspond to zones of calcite cementation in the sandstones.

Upper boundary (revised)
The Radøy Member is overlain by the Balder Formation with variable amounts of tuff. Since the sandstones often are serrated, and the Balder Formation often contains calcite-cemented stringers, the boundary

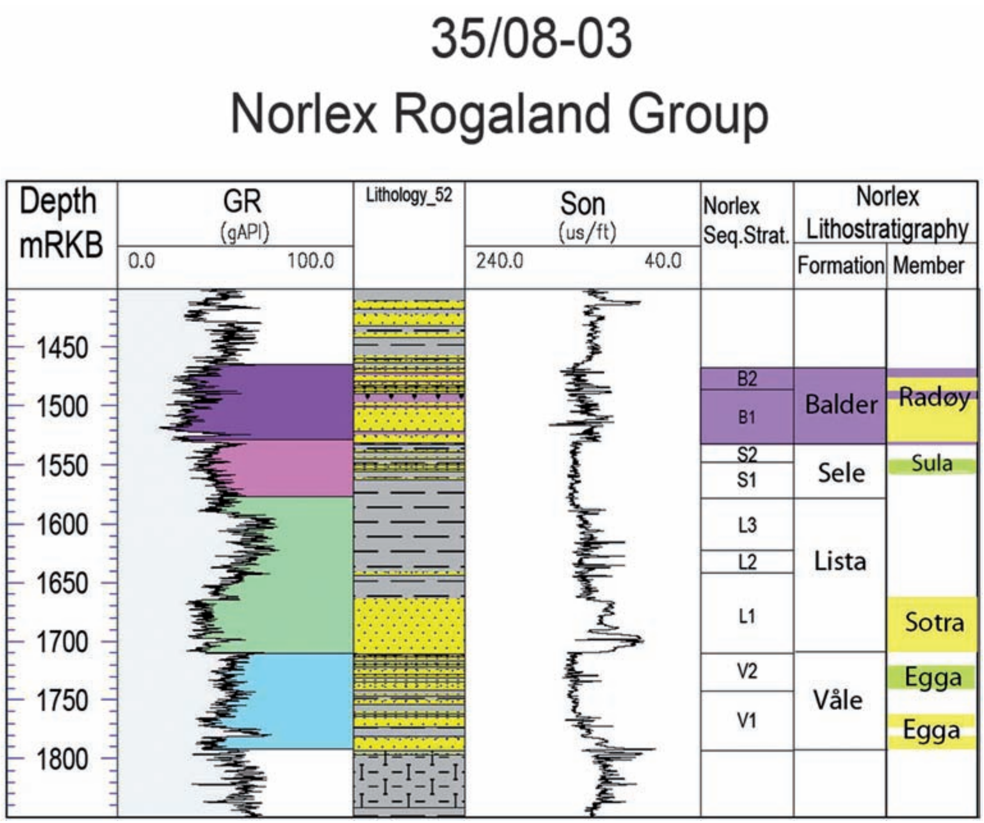


Fig. 137. Composite log in well 35/8-3, Rogaland Group. Stratigraphic position of the Radøy Member is outlined.

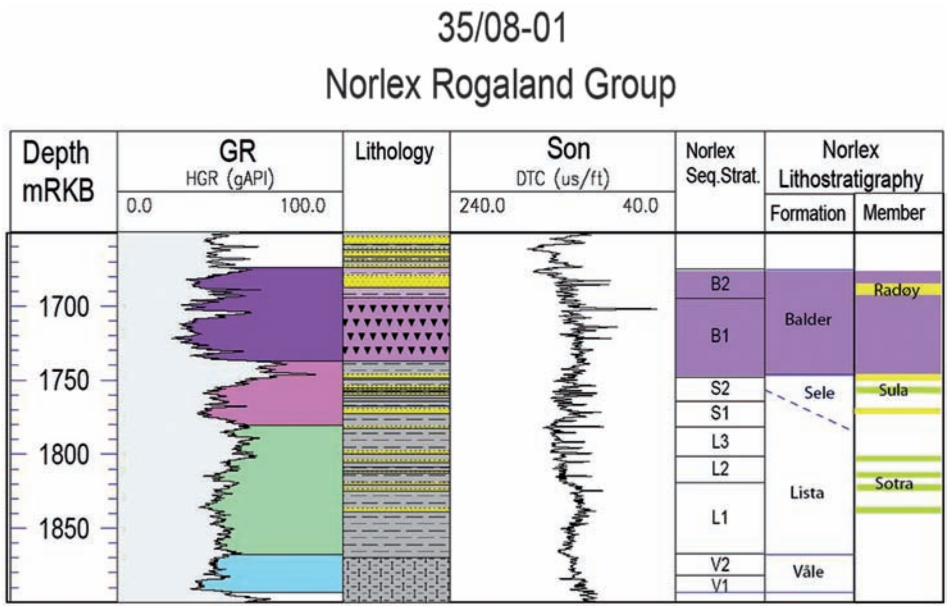


Fig. 138. Composite log in well 35/8-1, Rogaland Group. Stratigraphic position of the Radøy Member is outlined.

can often be difficult to pick. The transition from the Balder Formation is ideally seen as a downwards decrease from low/intermediate gamma-ray readings to lower gamma-ray readings and an increase in velocity.

Lower boundary (revised)
The basal contact of the Radøy Member is seen as the boundary between the sandstones of the Radøy Member and the shales of the Sele or Balder Formation. Due to the commonly thin-bedded appearance of the Radøy Member and intercalation with tuffaceous beds and calcite stringers, the boundary may be difficult to pick. Ideally the boundary is placed where there is an upwards transition from higher gamma-ray readings and lower velocity to lower gamma-ray readings and higher velocity.

Thickness

The thickness of the Radøy Member interval consisting of thin beds of sandstones interbedded with siltstones is 107 m in type well 35/8-3. In reference well 35/8-4 the Radøy Member is cleaner and 22 m thick, and in well 35/8-2 there are several sandstone bodies of 5–10 m thickness.

Although few wells have penetrated a thick, well developed Radøy Member, seismic from the Sogn Graben area indicate that better developed sandstones of several tens of meters exist (e.g., in well 35/8-4, Figure 139).

Seismic characterization

Sandstones belonging to the Radøy Member locally occur within westwards dipping layers in the westwards thinning wedges (prograding slope) of the Rogaland Group at the Måløy Terrace and the Horda Platform, partly stretching into the Sogn Graben. In other cases, the presence of blocky log response corresponds to mounded geometries, especially in lower parts of the wedge. West of the wedge, in what is believed to represent a basin floor setting, channels and lobe-like geometries in places stand out as Balder Formation thicks which may be interpreted as the potential presence of Radøy Member sandstones.

Locally the top of the Radøy Member is associated with a pronounced change in acoustic impedance and an increased amplitude (Figure 139, right of well). In other cases the top of the Radøy Member is difficult to recognize, and its presence is inferred from a marked thickening of the Balder Formation interval.

Age

Earliest Eocene (Early Ypresian).

Biostratigraphy

Being contained in the Balder Formation, the age of the Radøy Member is bounded by biostratigraphy and age assignments for the Balder Formation. See description for the Balder Formation.

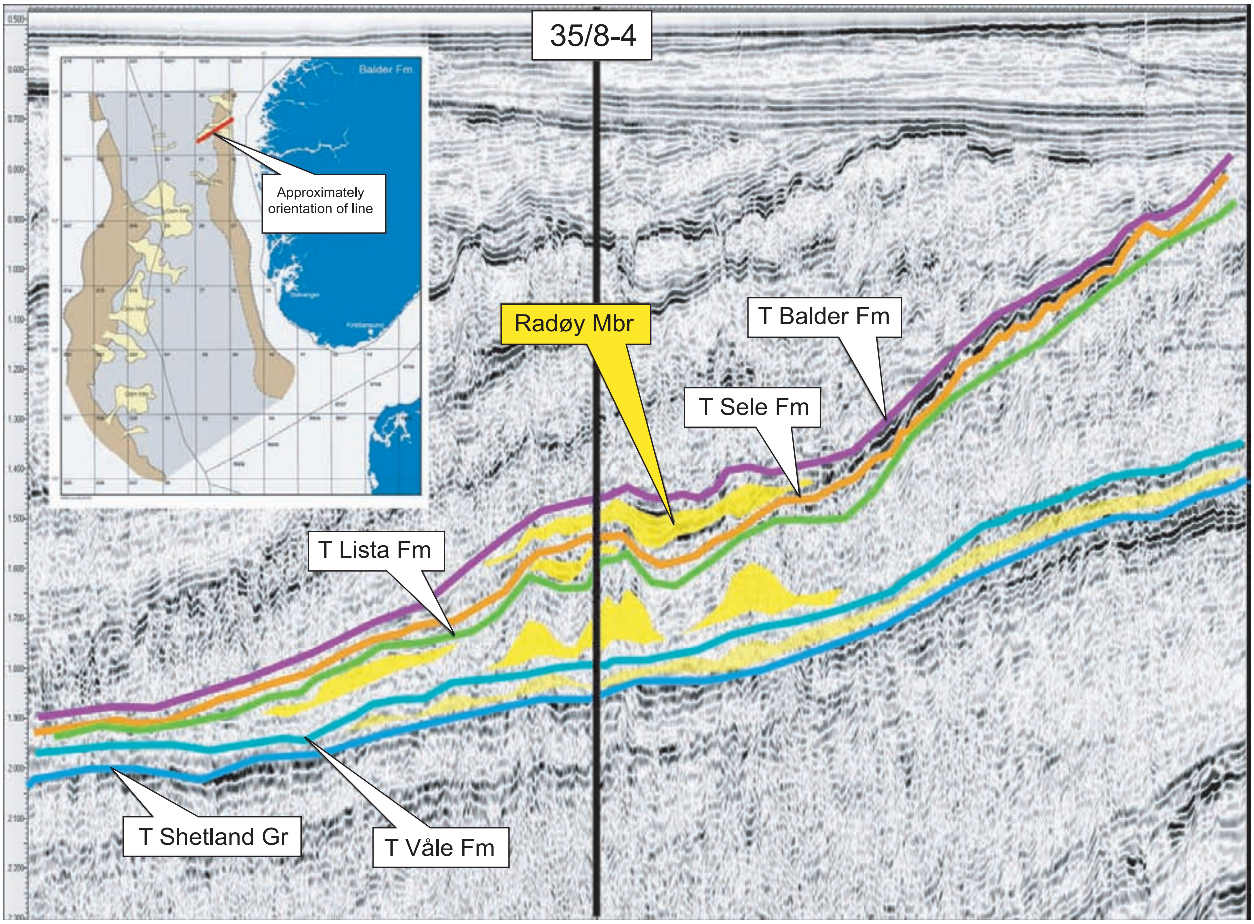


Fig. 139. Seismic line through from Sogn Graben to Måløy Terrace, running through well 35/8-4. Inferred presence of Radøy Member is outlined.

Correlation and subdivision

The Radøy Member is subdivided into Radøy B1 and Radøy B2, corresponding to Balder B1 and B2.

Geographic distribution

The Radøy Member is distributed along the western flank of Sogn Graben and the Måløy Platform, and is penetrated by several wells in the Quadrants 35 and 31. The sandstones had their provenance in catchments areas east of the Måløy Terrace and Horda Platform and possibly the Stord Basin (Figure 132).

Depositional environment

The Radøy Member was deposited in a distal shelf to prograding slope setting in eastern areas. Westwards it was deposited by various types of sandy gravity flow processes in local submarine channels and fans in a slope–basin floor setting.

Discoveries

No discoveries have been made in the Radøy Member.

Vidar Member (new), Rogaland Group

Unit definition

The Vidar Member consists of large, displaced limestone masses; its (final) stratigraphic position varies, and so does its age (Figure 140). This description incorporates new depositional and stratigraphic information.

The Vidar Member is mainly attributed to a seismically correlatable chalk body within the Rogaland Group; this lithology allows it to be mapped, although mappability is not a prerequisite for a member. It is present along the eastern margin of the Central Graben and eastwards onto the Sørvestlandet High and was deposited in an area covering parts of Quadrants 1, 2, 3, 7, 8 and 9. Stratigraphically it can be found in and on top of strata belonging to the Våle, Lista and Sele formations. The exact age span is variable.

The Vidar Member is part of an olistolith that consists of a slump sheet of Ekofisk chalk and sediments of the Våle, Lista and Sele formations that slumped along with it.

Name

The former Vidar Formation (now Vidar Member) was named by Hardt et al. (1989).

Derivatio nominis

The lithostratigraphic unit is named after one of Odin's sons Vidar.

Type well

Hardt et al. (1989) defined the interval 3,138–3,075 mRKB in well 2/1-4 (Figure 141) as the type section for the former Vidar Formation, here classified as Vidar Member. In this well the Vidar Member directly overlies the Lista Formation.

Reference well

Hardt et al. (1989) defined well 1/3-1, 3,147–3,095 mRKB as reference well and reference section for the Vidar Member (Figure 142). In this study we include well 1/3-5, 3,152–3,202 mRKB as second reference well (Figure 143). In both these well sections the Vidar Member directly overlies the Sele Formation.

Through biostratigraphical analysis in connection with Dreyer et al.'s (2004) study (Figure 144) it was demonstrated that the high gamma peak deposits seen from the well logs below the Vidar Member contains typical intra-Sele microfossils.

Seismic expression

From seismic the Vidar chalk is easily mappable as a generally continuous seismic hard event internally in the Rogaland Group (Figure 145). The basal part of the chalk can also often be mapped, and is a marked soft event.

In the west the chalk lithologies of the Vidar Member appear to onlap the Forties Member (Figure 146). In its central parts the Vidar chalk occurs in lower to middle parts of the Rogaland Group. Towards the east it dives downwards into the lower parts of the Rogaland Group before it seems to lap onto the top Shetland Group. Further east it is difficult to distinguish from the top Shetland Group, and is probably absent (Figure 147). East of this there is a marked cliff feature that cuts lithologies belonging to upper parts of the Shetland Group, as well as the Våle and Lista formations and possibly the lower parts of the Sele Formation.

Biostratigraphy and age

Exact dating of the Vidar Member is not straightforward, since the Vidar Member itself contains Maastrichtian to Danian chalk fossils, and the shales above and below vary much in age. In well 1/3-1 strata on top of the Vidar Member vary in age but are mostly Selandian to Thanetian.

Strata immediately below the Vidar Member vary in age from Danian (well 7/12-10) to early Ypresian (well 1/3-1). The variable age dating of lithologies above and below the Vidar Member is considered to be an expression of re-deposition of youngest Ekofisk and oldest Rogaland strata.

In order to provide more systematic biostratigraphic and chronostratigraphic information on deposits belonging to the Vidar Member and its 'envelope', core samples were obtained from well 1/3-7, and cuttings samples from wells 1/3-5 and 2/1-4. On these samples nannofossil and organic microfossil analysis were performed, respectively by J. Lees (London, UK) and D. Munsterman (Utrecht, The Netherlands). The results are summarized below.

The nannofossils taxonomy and zonation follow Burnett et al. (1998) and Varol (1989, 1998); the palynology zonation is that of D. Munsterman, using Gradstein et al. (2005) and unpublished information used by TNO for routine palynology of North Sea well samples.

Well 1/3-7

Three core samples were analyzed of well 1/3-7 at 3,164.1, 3,164.6 and 3,177.1 m to provide insight in the age of the youngest samples overlying the Vidar Member (cf. Dreyer et al. 2004) (see Figure 148).

The Sele shale sample at 3,177.1 m was barren of nannofossils. The Cretaceous component in the other two samples is UC20cBP (Upper Maastrichtian), based on the presence of *Arkhangelskiella maastrichtiensis*. There are very few Paleogene taxa in the two productive samples, and the age of mid-Danian/Early Selandian is tentative, based on the presence of *Octolithus multiplus* and a rare occurrence of a rela-

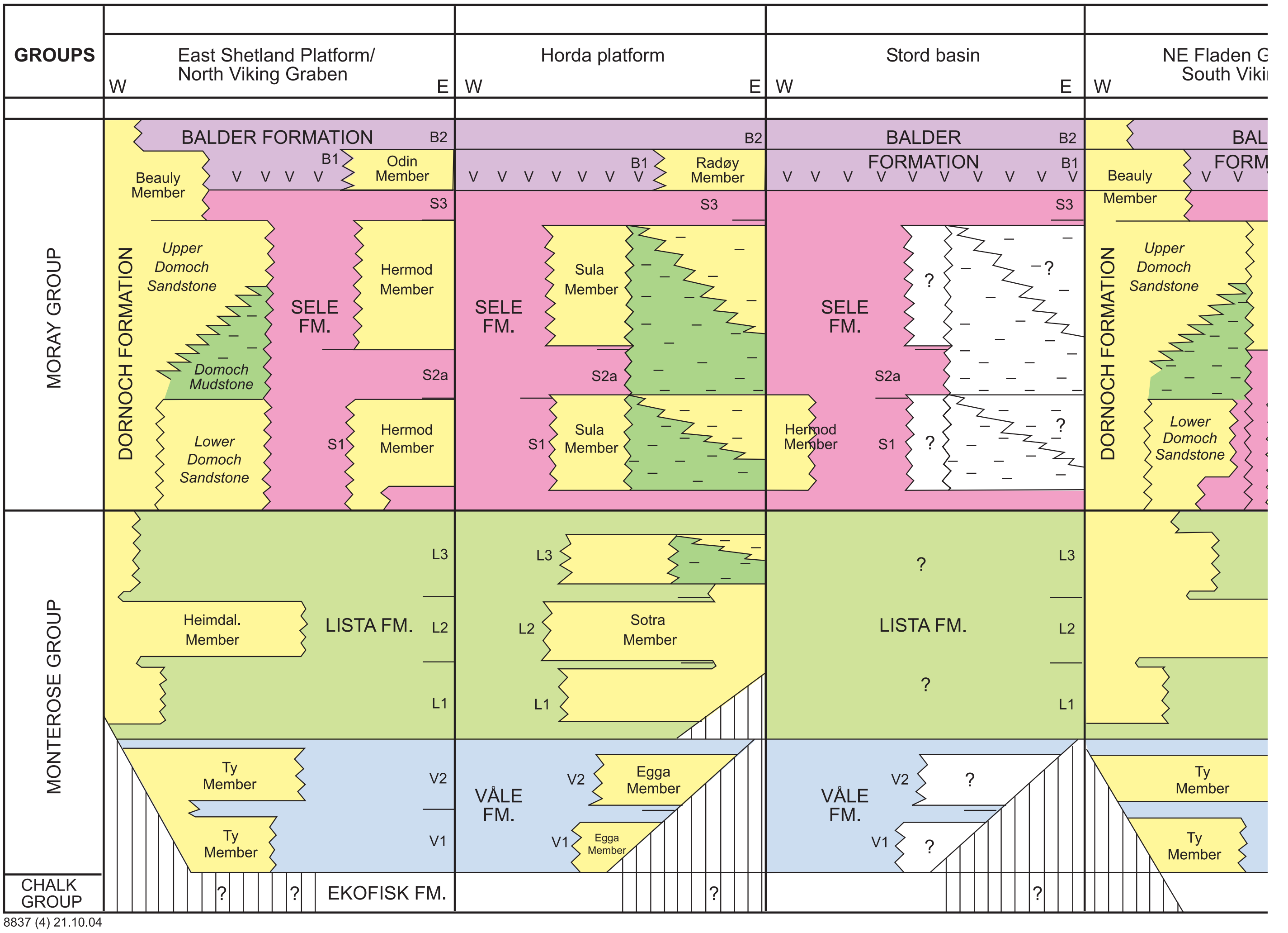
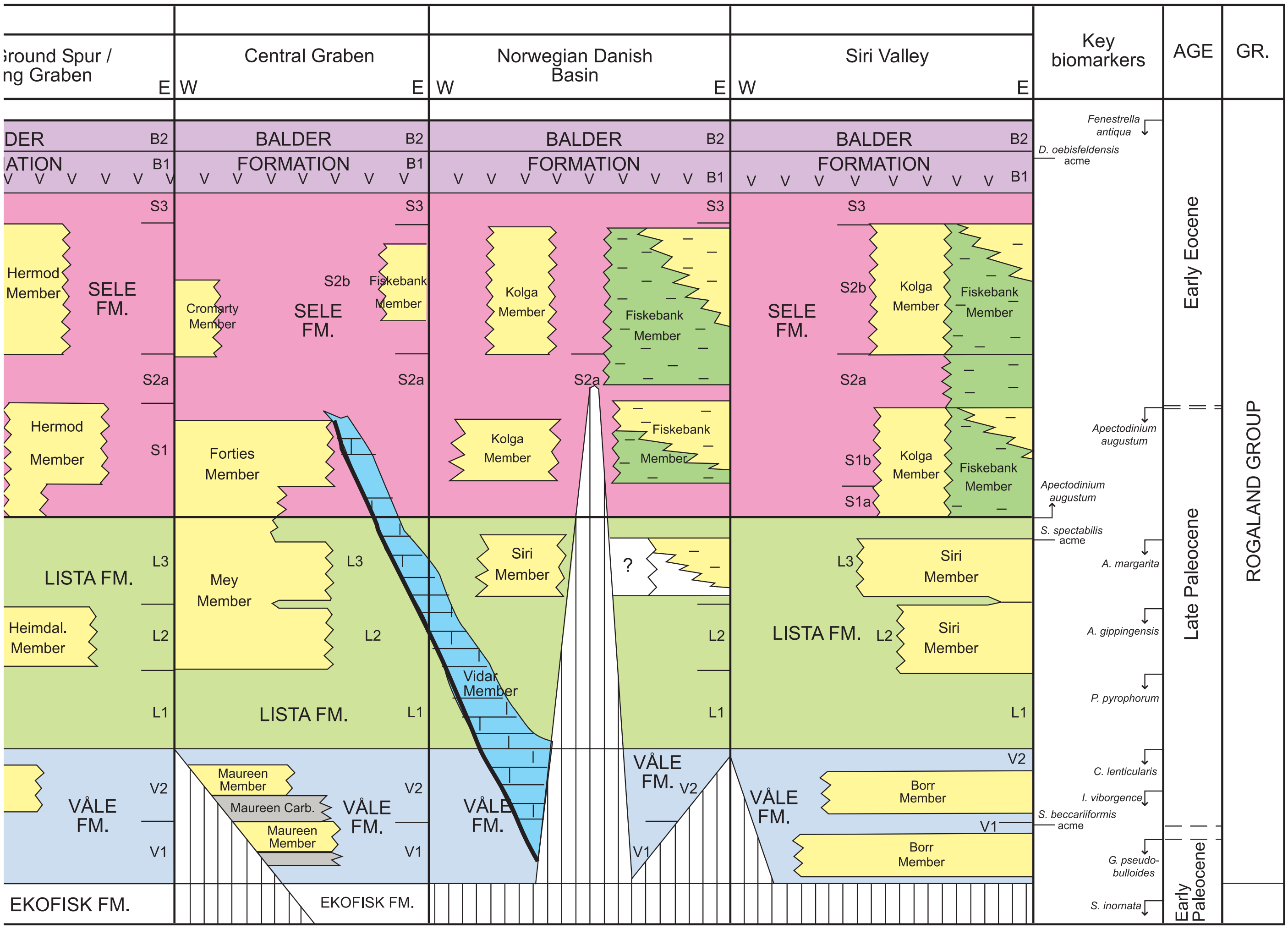


Fig. 140. Inferred stratigraphic development and position of the Vidar Member, as a part of an olistolith moving down slope from the Sørvestland High during the Thanetian-Ypresian transition.


Central Graben
Norwegian Danish Basin
Siri Valley
Key biomarkers
AGE
GR.
BALDER FORMATION
B2
B1
S3
S2b
S2a
S1
S1b
S1a
SELE FM.
Hermod Member
Cromarty Member
Fiskebank Member
Kolga Member
Forties Member
Mey Member
Siri Member
Vidar Member
Heimdal. Member
LISTA FM.
L3
L2
L1
VÅLE FM.
V2
V1
Maureen Member
Maureen Carb.
Borr Member
EKOFISK FM.
Fenestrella antiqua
D. oebisfeldensis acme
Apectodinium augustum
S. spectabilis acme
A. margarita
A. gippingensis
P. pyrophorum
C. lenticularis
I. viborgence
S. beccariiformis acme
G. pseudo-bulloides
S. inornata
Early Eocene
Late Paleocene
Early Paleocene
ROGALAND GROUP

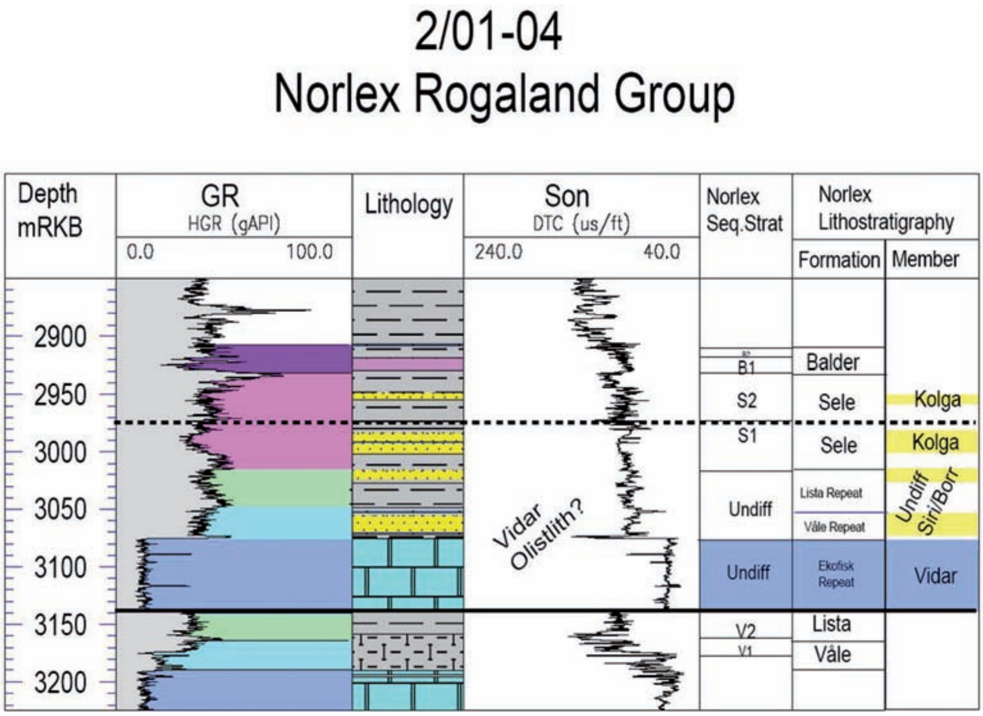


Fig. 141. Logs from well 2/1-4 (pdf) 2/1-4: 3,138–3,075 m; stratigraphic position of the Vidar Member outlined.

tively large *Prinsius martinii*. Palynological results in the cores indicate younger ages stratigraphically downwards and are summarized below:

Depth (m)	Type	Age	(Sub)Zone
3,164.1	CO	Danian	D1
3,164.6	CO	Selandian	D4a
3,177.1	CO	IETM	D5a

Core sample 3,164.1 m is assigned a Danian age (Zone D1) based on the dinoflagelate *Senoniasphaera inornata*, but specimens may have been reworked into Selandian strata if weight is given to the presence of *Palaeoperidinium pyrophorum*. Alternatively, the latter could have been reworked also.

Core sample 3,164.6 m is assigned a Selandian age (Zone D4a), based on the presence of *Alisocysta margarita* and *Palaeoperidinium pyrophorum*.

Core sample 3,177.1 m contains the acme of *Apectodinium* spp. and up to 15 % of *Apectodinium augustum* typical for the Initial Eocene Thermal Maximum (IETM) of Early Ypresian, earliest Eocene age. The relatively large numbers (24 % of the total sum dinocysts) of the genus *Palaeoperidinium* are considered to be reworked from Selandian or older successions.

The sporomorphs comprise ca. 50 % of the total sporomorph and dinocyst sum at sample depth 3,177.1 m. The genus *Apectodinium* constitutes of 45 % of the total sum of insitu dinocysts. The conditions are interpretated to reflect a coastal marine depositional setting.

The Paleocene/Eocene Thermal Maximum (or Initial Eocene Thermal Maximum or Eocene Thermal Maximum 1), ~55.5 Ma ago, was marked by a sudden global warming event and associated with changes in oceanic and atmospheric circulation. The event is linked to a negative excursion in the $\delta^{13}C$ isotope record. The global temperature rose ca. 6 °C over 20 ka, and is associated with a world-wide sea level rise (Sluijs et al. 2006).

The above analysis is in good agreement with the results of Dreyer et al. (2004) that the youngest deposits overlain by the Vidar Member are earliest Eocene in age.

Well 2/1-4

In well 2/1-4 two cuttings samples at 2,900 and 2,920 m were processed and analyzed for nannofossils, and five cuttings samples at 2,900, 2,920, 3,030, 3,100 and 3,190–3,200 m for palynology (see Figure 149 for results).

The Cretaceous nannofossil component is assigned to zones UC20cBP to UC20dBP (Upper Maastrichtian), based on the presence of *Arkhangelskiella maastrichtiensis* and *Cribrosphaerella daniae*, respectively. Sample 3,100 m contains a greater diversity of Cretaceous taxa than 3,200 m (33 species), including *Reinhardtites levis* (which has a last stratigraphic occurrence in the Lower Maastrichtian), and indicates a reworked Cretaceous component at 3,100 m. The Paleogene nannofossils are again characteristic of mid Danian to Early Selandian age strata (NP3–NP5), as observed also in the core samples of well 1/3-7. The palynological results are summarized below:

Depth (m)	Type	Age	(Sub)Zone
2,900	CU	Ypresian–Lutetian boundary	D9b
2,920	CU		
3,030	CU	Selandian	D4a
3,100	CU		D3a
3,190–3,200	CU	Early Selandian or older	D3a or older

Cuttings samples 2,900 m and 2,920 m are assigned to the D9b subzone across the Ypresian–Lutetian boundary, based on the presence of *Eatonicysta ursulae* in

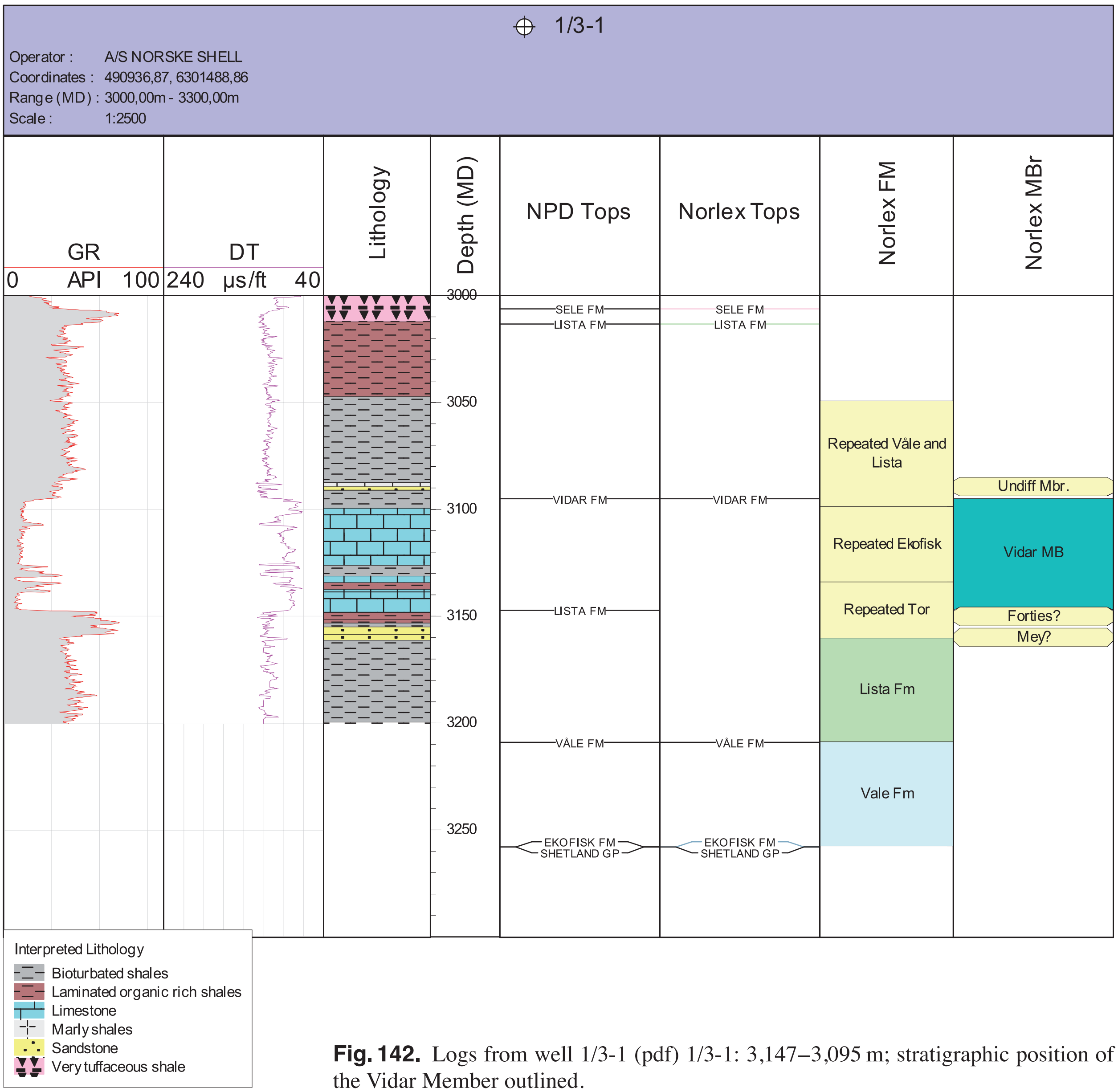


Fig. 142. Logs from well 1/3-1 (pdf) 1/3-1: 3,147–3,095 m; stratigraphic position of the Vidar Member outlined.

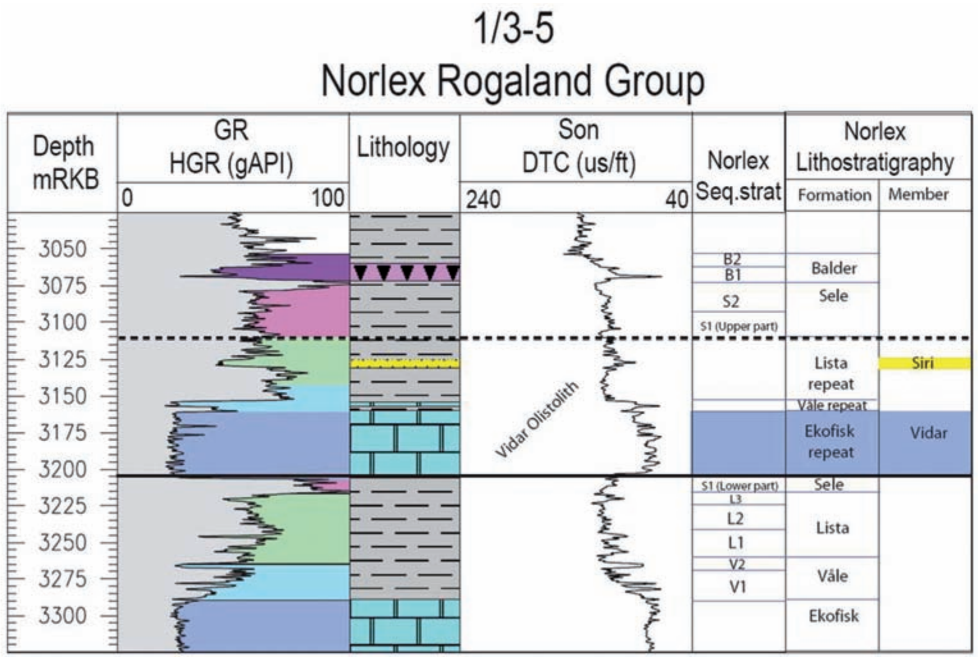


Fig. 143. Logs from well 1/3-5: stratigraphic position of the Vidar Member outlined.

the higher sample and *Membranilarnacia glabra* in the lower one. *Areoligera gippingensis* is interpreted as reworked from Thanetian strata, and carbonized sporomorphs such as *Classopollis* from the Mesozoic, and *Lycospora* from the Carboniferous.

Cuttings sample 3,030 m contains *Palaeoperidinium pyrophorum* and *Cerodinium diebelii* assigned to subzone D4a, Selandian. *Thalassiphora* cf. *delicata* was found in sample 3,100 m in the Vidar Member strata, and is assigned to subzone D3a, early Selandian.

Cuttings sample 3,190–3,200 m contains two distinct lithologies that were analyzed separately. The red-brown shale chips are dominated by *Areoligera gippingensis*. This association is considered caved from an Upper Selandian–Lower Thanetian level (D4b dinocyst subzone sensu Gradstein et al. 2005). The assemblages from the greyish chalk part of the cuttings, including *Palaeoperidinium pyrophorum* and *Spinidinium densispinatum*, confirm an age in the Selandian or older successions. Note that the taxon *Areoligera gippingensis* is absent in the greyish chalky part of the same sample. The presence of *Palaeocystodinium australinum* constrains the dating at sample depth 3,200 m.

The new biostratigraphy in well 2/1-4 indicates a Late Danian through Early Selandian resting place for Vidar strata, in itself containing Maastrichtian strata. The top Ekofisk Formation is assigned a Danian–Early Selandian age.

Well 1/3-5

Five cuttings samples were processed for nannofossils and palynology in well 1/3-5 (Figure 150).

The Cretaceous nannofossil component is from subzone UC20cBP (Upper Maastrichtian), based on the presence of *Arkhangelskiella maastrichtiensis*, or UC20dBP (Upper Maastrichtian), based on the presence of *Cribrosphaerella daniae*. No Paleogene-restricted taxa were found in Vidar unit sample 3,175 m, only above Cretaceous and K/T survivor taxa. The presence of common *Prinsius martinii* and *Neocrepidolithus fossus* indicates NP3–NP4 (mid Danian to Early Selandian) in the two samples below this. Palynological results are summarized below:

Depth (m)	Type	Age	(Sub)Zone
3,022	CU	Lutetian	D9e
3,052	CU	Ypresian–Lutetian boundary	D9b
3,175–3,256	CU	Selandian	D3b
3,268	CU	Early Selandian	D3a
3,289–3,301	CU	Early Selandian or older	D3a or older

Sample 3,022 m is assigned to subzone D9e, Lutetian, based on *Areosphaeridium ebdonii*, *Diphyes ficusoides*, *Hystrichosphaeridium tubiferum* and *Phthano-*

peridinium clithridium. Reworking of Jurassic–Lower Cretaceous origin, e.g., the genera *Callialasporites* and *Ischyosporites*, is recorded.

Sample 3,052 m is assigned to subzone D9b, Ypresian/Lutetian, based on the presence of *Eatonicysta ursulae*, and sample interval 3,175–3,256 m to subzone D3b based on *Spinidinium densispinatum*, Selandian. The latter interval is in the Vidar Member. The cuttings at depth 3,175 m include a morphotype with two specimens with affinity to *Chatangiella*; this genus indicates a Late Cretaceous age.

Samples 3,268 m and 3,289–3,301 m contain *Thalassiphora* cf. *delicata* of D3a subzone, Early Selandian; palynomorph reworking of Jurassic–Cretaceous origin is recorded. Note that based on palynology the samples could be older than early Selandian, but no Danian palynomorphs were observed. Nannofossils provide a mid Danian through Early Selandian age for this interval.

Correlation

The Vidar Member seems to extend within the LV1, LV2 and LV3, S1 and possibly S2? areas (Figures 151, 152).

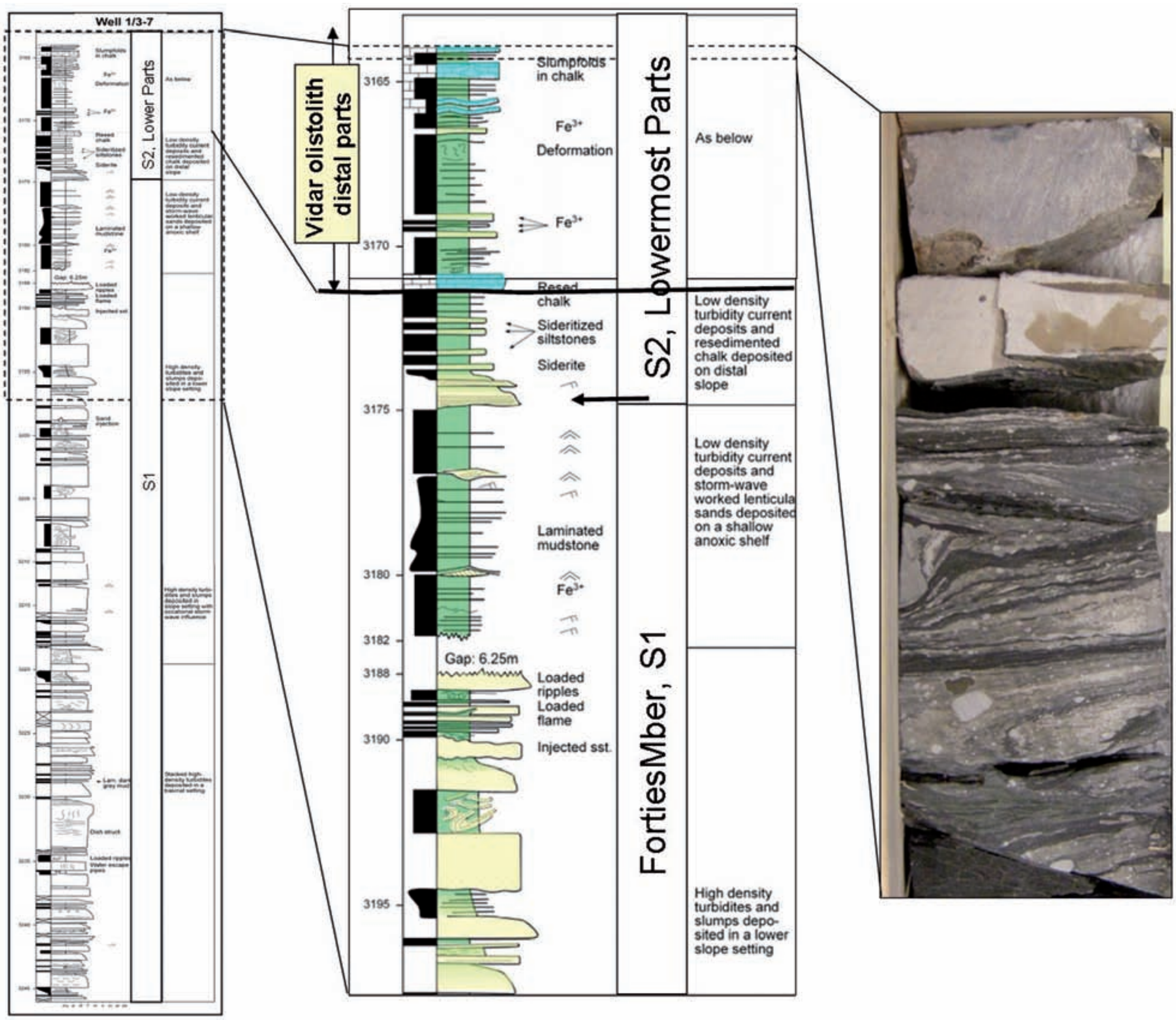
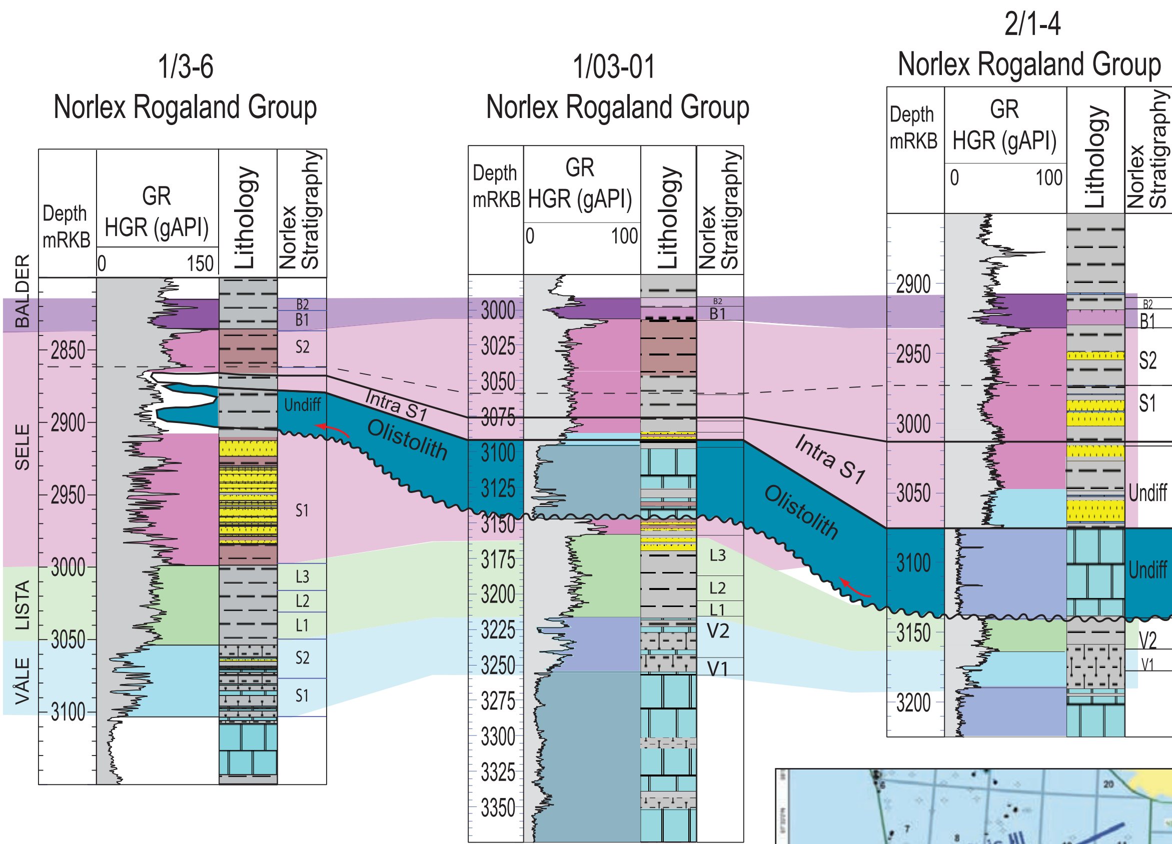


Fig. 144. Reworked marly mudstones with small rounded chalk clasts, belonging to the Vidar Member. The sediments are found in the section above Forties Formation in cores from well 1/3-7, and can be seismically correlated to top Vidar Member in wells in Quad 2, and 7, where the Vidar Member is seen to directly overlie Lista or the Våle Formation. The core description log is adapted from Dreyer et al. (2004).



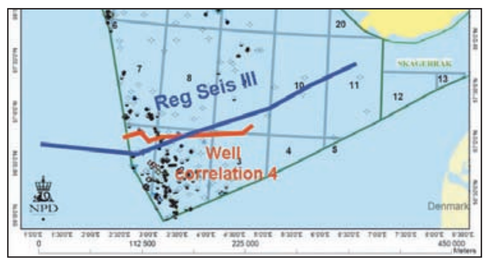


Fig. 145. Well correlation chart showing preferred depositional model for the Vidar Member olistolith (insert is part of location map in Fig. 32, correlation line 4).

Geographic distribution

The Vidar Member is present in the area west of what we here define as the Vidar escarpment, over an area of more than 500 km^2 in Quadrants 1, 2, 3 and 7, 8 and 9 (Figure 151).

Depositional model

The chalky and marly mudstones of the Vidar Member are interpreted to represent reworked chalk of the uppermost part of the Shetland Group and the Våle Formation. Exact timing and depositional process is not completely resolved, but this study narrows the options.

At present our preferred model is that the Vidar Member represents olistolithic slides that happened during short periods, perhaps as a series of mega slides. This involved movement of slide blocks consisting of a basal chalk body and the overlying siliciclastic lithologies of the Våle, Lista and lowermost Sele formations. The non-presence of Våle Formation, and possibly also the absence of the Lista Formation in well 2/2-2, is interpreted to represent rafting away of lithologies of Upper Shetland Group together with Våle, Lista and possibly lower parts of the Sele formations.

The provenance of the Vidar Member with its chalk and overlying lithologies seems to have been the Sørvestlandet High, and we believe that the steep cliff feature seen in seismic data east of the Vidar Member distribution area reflects the proximal collapse scar of the olistolith (Figure 152).

Mapping of the chalk lithologies in Vidar Member

In seismic data, the base of the Vidar is difficult to separate from the Shetland Group, in the areas close to the Vidar escarpment. We believed that this can be explained partly by translational movements and the

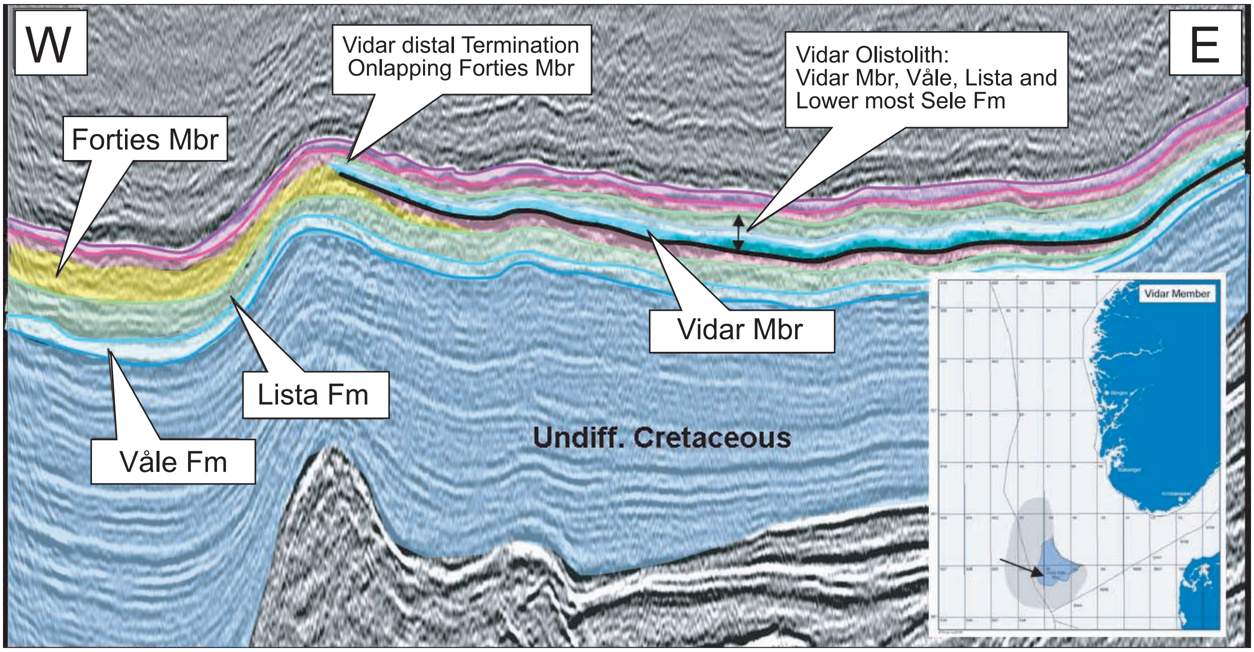


Fig. 146. Western parts of the Vidar Member, showing the climbing/crosscutting of stratigrapy and the ponding against top of the Forties Member.

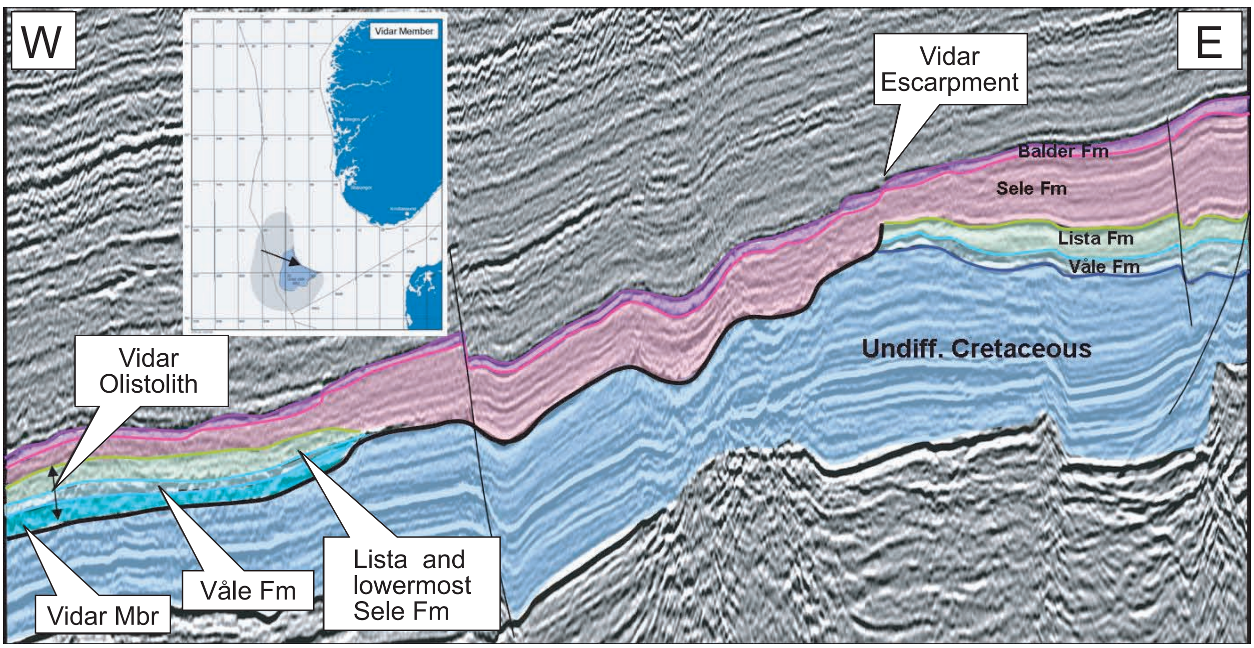


Fig. 147. Eastern slump scar, where the Vidar olistolith originated. To the East (right) is indicated which lithostratigraphic units slumped.

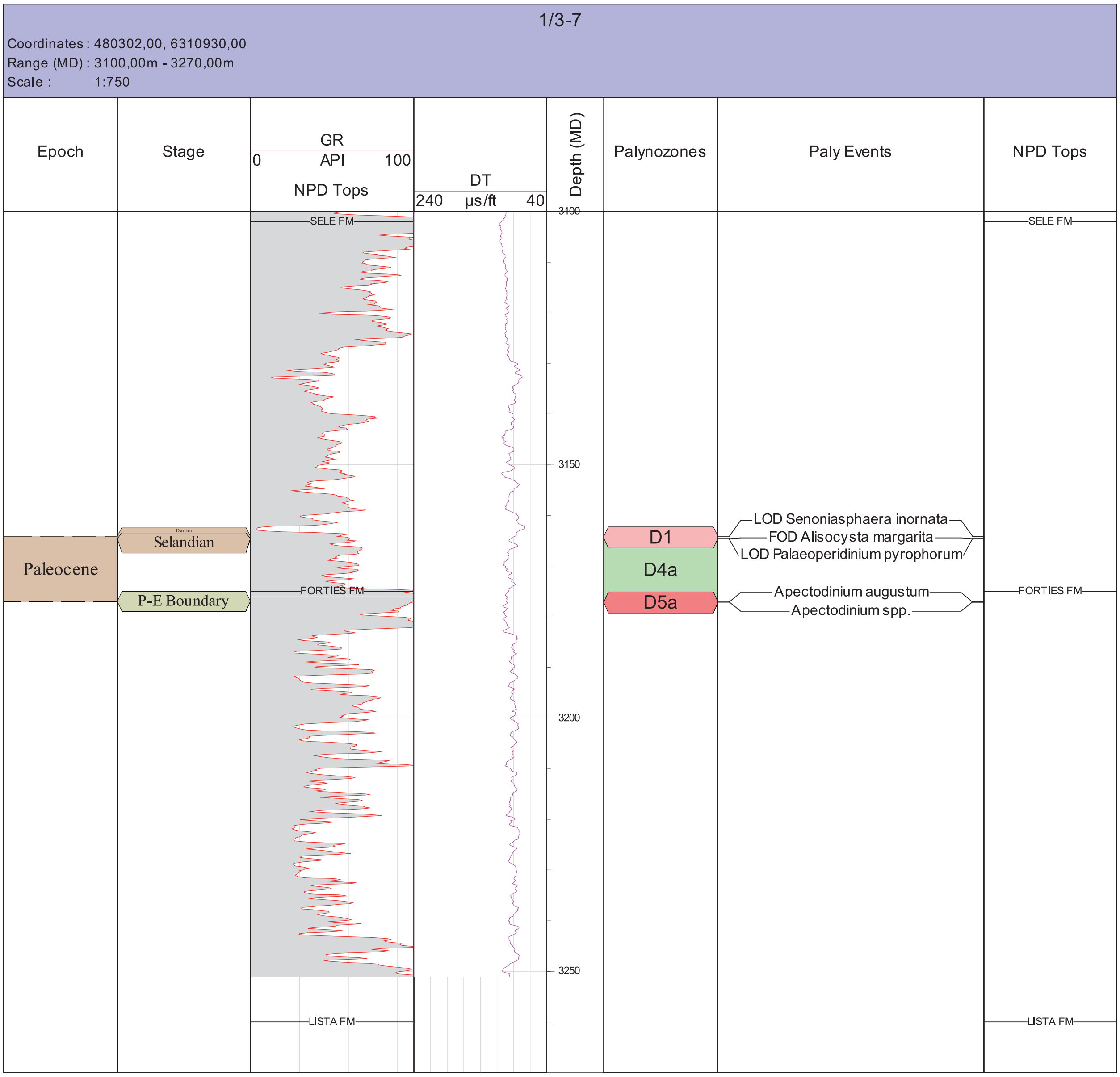


Fig. 148. Approximate paleogeographic distribution of the Vidar Member.

non-presence of the slide close to the escarpment, with younger sediments directly overlying the former basal shear plane.

In the proximal parts of the olistolith the shear plane is believed to have been along bedding planes within the chalk. Further west towards the Central Graben, the basal shear plane climbs in the stratigraphy, cutting the Våle, Lista and eventually the Sele Formations.

Timing of the Vidar Member

Mapping of the inferred olistolith, and age dating of Vidar and 'envelope'strata show that the youngest lithology overlain by the olistolith is Early Ypresian in age. This indicates that olistolithic failure and redeposition went on until this time. It may have started in (Late) Selandian time. The post-sedimentary process locally displaced on almost complete Paleocene succession down-flank from east to west.

Discoveries

No hydrocarbon discoveries have been made in the Vidar Member.

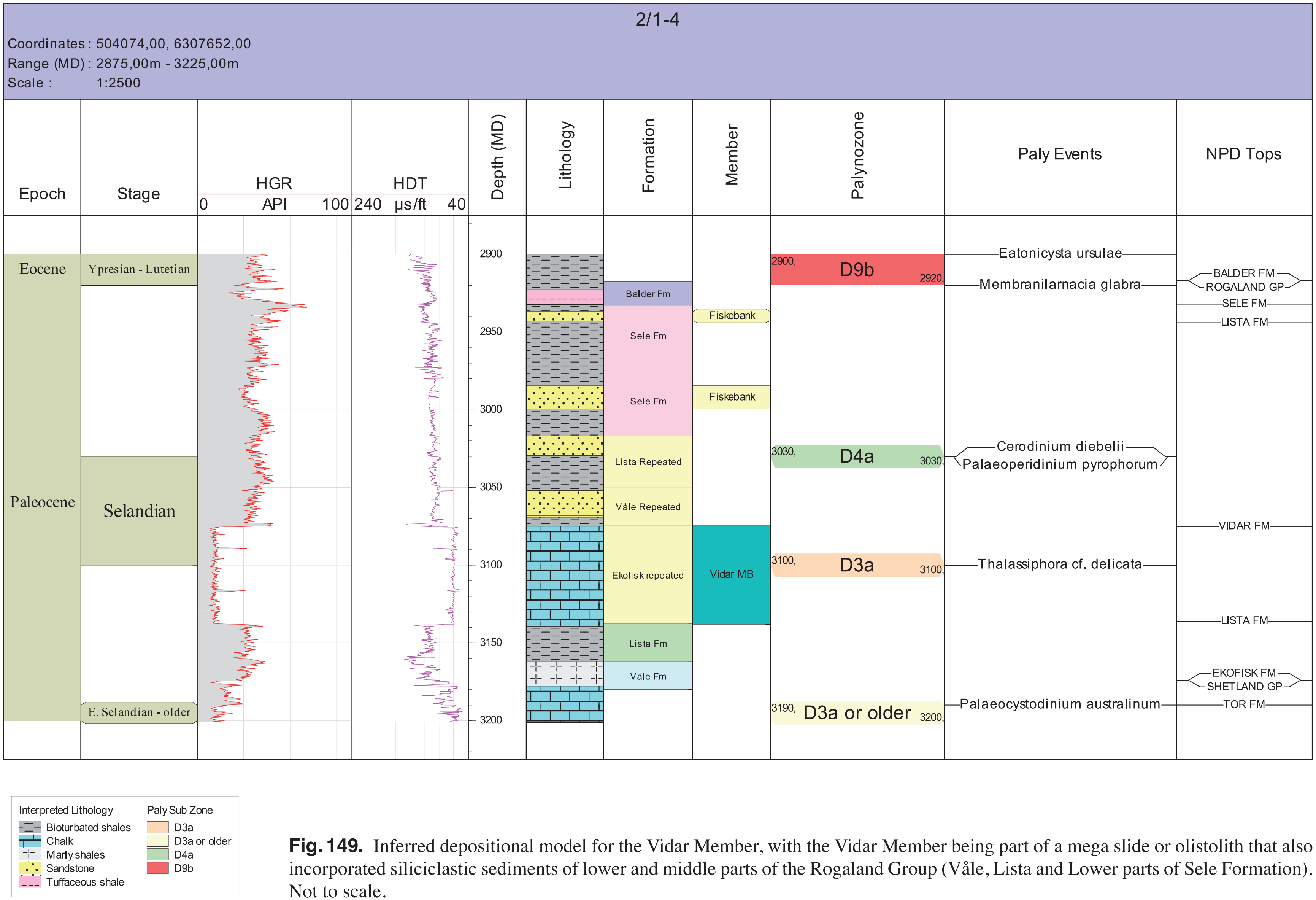


Fig. 149. Inferred depositional model for the Vidar Member, with the Vidar Member being part of a mega slide or olistolith that also incorporated siliciclastic sediments of lower and middle parts of the Rogaland Group (Våle, Lista and Lower parts of Sele Formation). Not to scale.

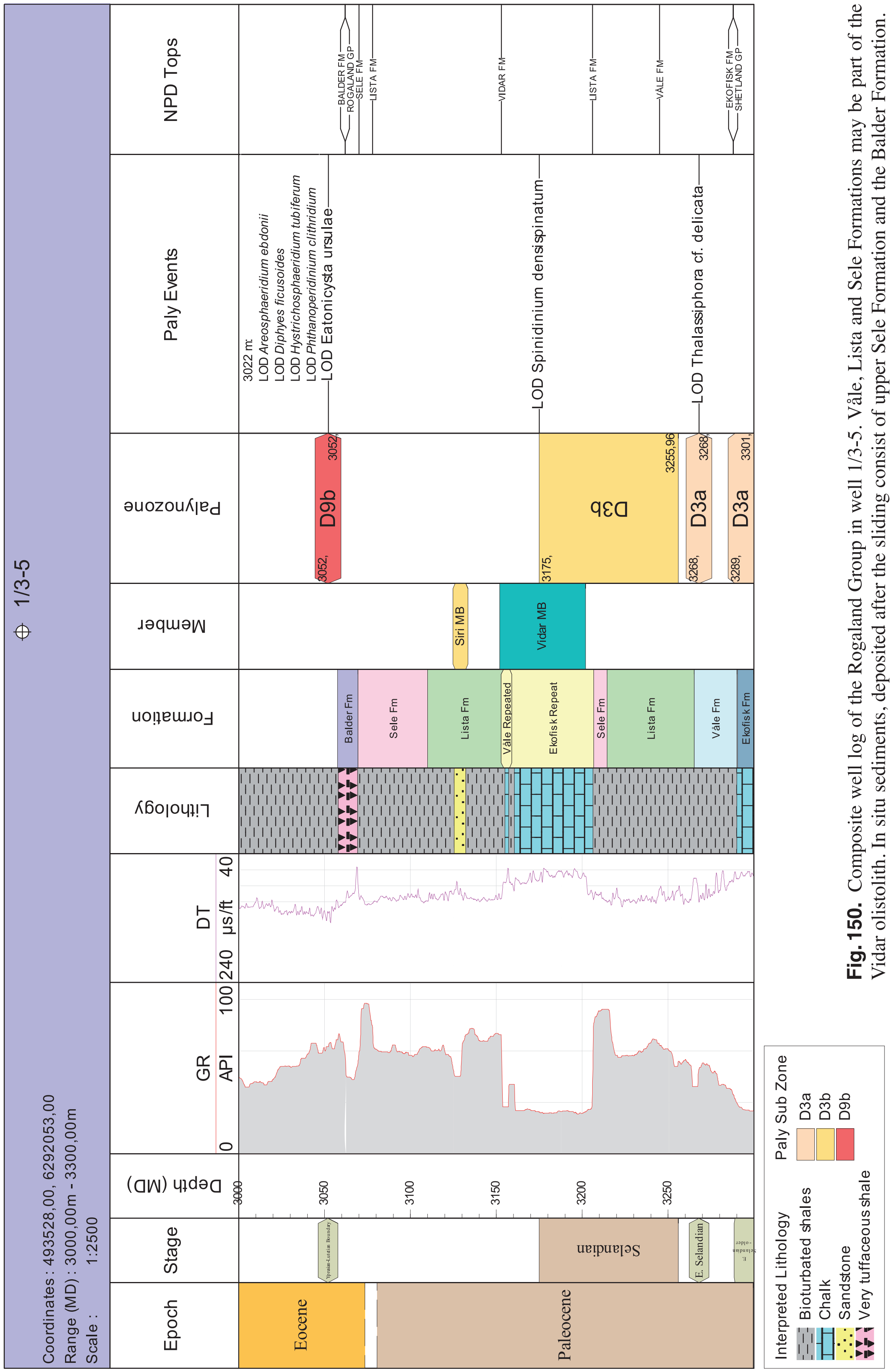


Fig. 150. Composite well log of the Rogaland Group in well 1/3-5. Våle, Lista and Sele Formations may be part of the Vidar olistolith. In situ sediments, deposited after the sliding consist of upper Sele Formation and the Balder Formation.

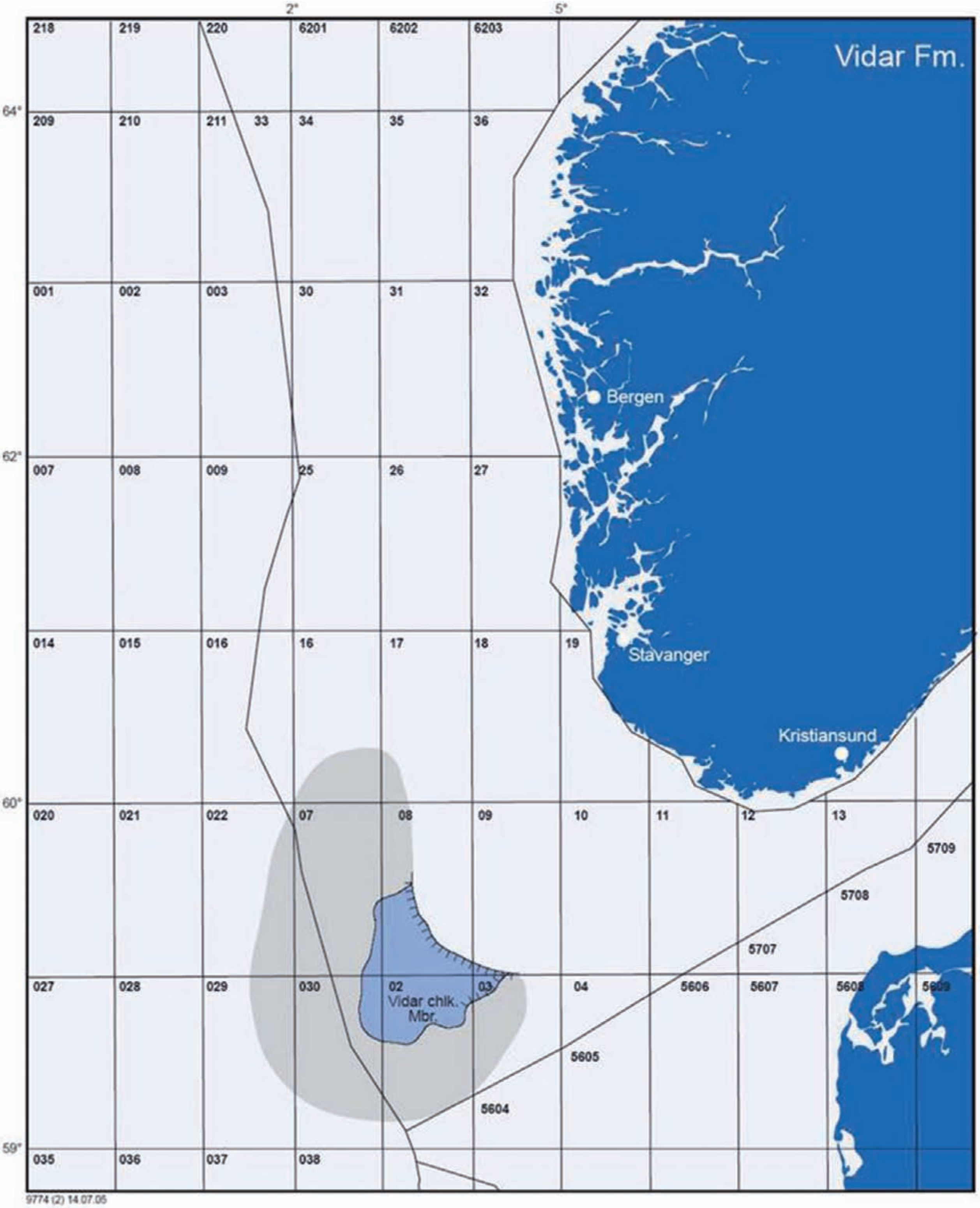


Fig. 151. The Vidar Member is present in the area west of what we here define as the Vidar escarpment, over an area of more than 500 km^2 in Quadrants 1, 2, 3, and 7, 8, 9.

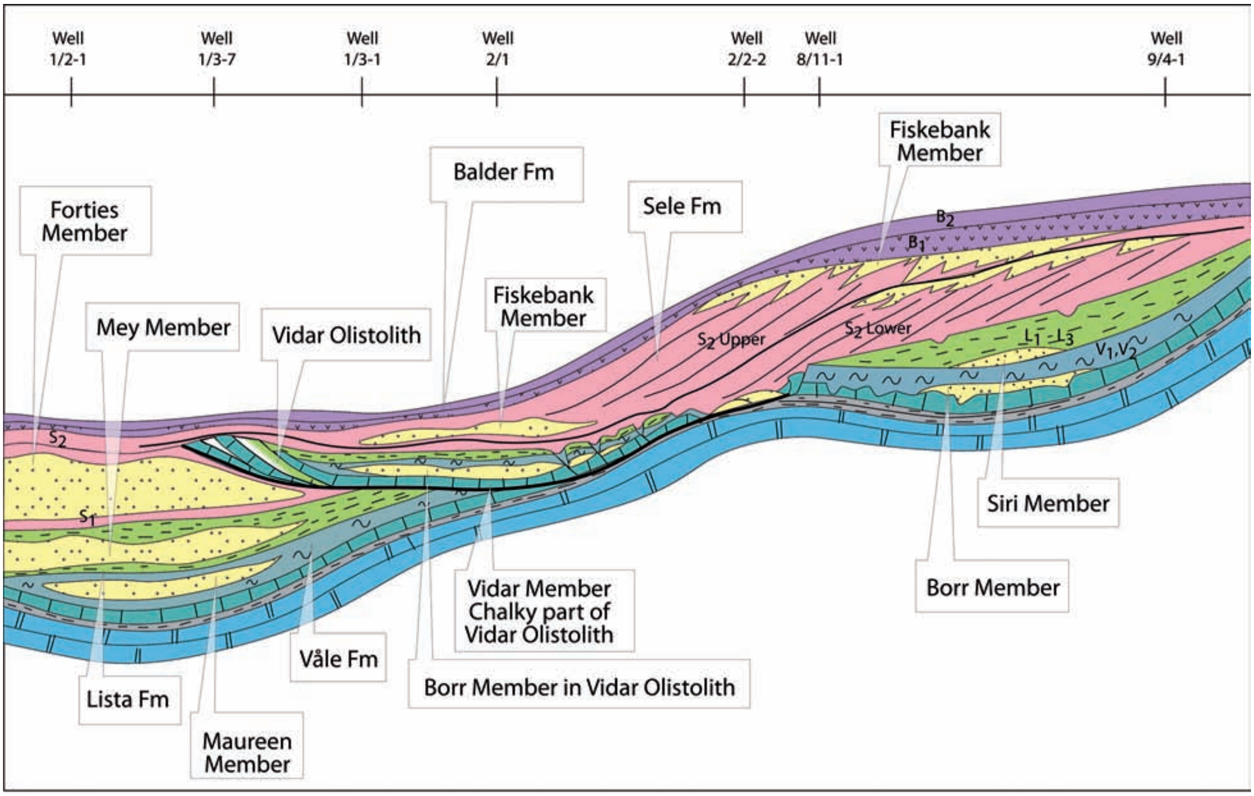


Fig. 152. Depositional model for the Vidar olistolith: the correlation sketch shows approximate position of relevant wells projected; not to scale.

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