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Shallow stratigraphic drilling applied in hydrocarbon exploration of the Nordkapp Basin, Barents Sea

Tom Bugge[a,1,*], Geir Elvebakk[a,1], Stein Fanavoll[b,1], Gunn Mangerud[c,1], Morten Smelror[d,1], Hermann M. Weiss[e], John Gjelberg[c], Stein Erik Kristensen[c], Kåre Nilsen[f]

[a]*Norsk Hydro ASA, N-9480 Harstad, Norway*
[b]*Ipres Norway AS, P.O. Box 1208, Pirsenteret, N-7462 Trondheim, Norway*
[c]*Norsk Hydro ASA, N-5020 Bergen, Norway*
[d]*Geological Survey of Norway, N-7491 Trondheim, Norway*
[e]*SINTEF Petroleum Research, N-7465 Trondheim, Norway*
[f]*IC Future AS, Buveien 6, N-9406 Harstad, Norway*

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Abstract

The Nordkapp Basin is a Late Palaeozoic rift basin characterised by numerous salt diapirs. The salt was deposited in the Late Carboniferous–Early Permian and has been remobilised several times. Upper Palaeozoic and Mesozoic sediments filled in the basin and were uplifted by salt diapirism in the Early/Middle Triassic, Late Jurassic, Late Cretaceous and Tertiary. Regional uplift and erosion in the Early Tertiary and extensive glacial erosion in the Late Pliocene/Pleistocene removed up to 1200 m of the Mesozoic and Cenozoic strata and left them heavily tilted and truncated around the salt diapirs, only covered by a thin sheet of glacial sediments.

During much of the Triassic and Jurassic the Nordkapp Basin was a large marine embayment, open to the ocean in the southwest. This allowed deposition of potential hydrocarbon source rocks in anoxic basins during transgressive periods in the Triassic and Late Jurassic. Coastal processes improved the reservoir quality of Upper Triassic to Middle Jurassic sands during regressive periods. One exploration well within the basin and three wells surrounding the basin have produced oil shows, but no commercial discoveries have been made so far. During the review period of the present paper, an exploration well encountered oil and gas in Triassic sandstones in the southwestern segment of the basin. This is the first direct indication of a mature, oil-producing source rock in the Nordkapp Basin and will be important for future exploration of the basin.

Keywords: Barents Sea; Mesozoic stratigraphy; Depositional history

1. Introduction

The Nordkapp Basin is a 300 km long north–eastward-trending basin located in the southwestern Barents Sea (Fig. 1). The geological history and tectonic framework of the Nordkapp Basin are described and discussed in several publications (Dengo & Røssland, 1992; Gabrielsen, Færseth, Jensen, Kalheim, & Riis, 1990; Gabrielsen, Kløvjan, & Stølan, 1992; Henriksen & Vorren, 1996; Jensen & Sørensen, 1992; Koyi, Talbot, & Tørudbakken, 1995; Nilsen, Vendeville, & Johansen, 1994; Nilsen, Vendeville, & Johansen, 1995; Rønnevik & Jacobsen, 1984; Talbot, Koyi, & Clark, 1993; Vendeville, Nilsen, & Johansen, 1994; Yu & Lerche, 1993).

Exploration for petroleum in the Nordkapp Basin started in the 1980s. The Norwegian Petroleum Directorate (NPD) has estimated that approximately 6% of the undiscovered petroleum resources in the Barents Sea could be found in the Nordkapp Basin, with the greatest expectations to Triassic, Jurassic and possible Cretaceous reservoirs (NPD, 1996). Statoil and Exxon Mobil now lead the exploration for these resources as operators for two licences in the southwestern segment of the Nordkapp Basin. Only two exploration wells in the southwestern basin segment and three wells on structures along the margins have so far been drilled in the area (Jensen & Sørensen, 1992). Statoil drilled the last well in the fall 2000 and encountered oil and gas in Triassic sandstones, thus demonstrating the

* Corresponding author.
E-mail address: tom.bugge@hydro.com (T. Bugge).
[1] Previous address: IKU Petroleum Research (now SINTEF Petroleum Research), N-7465 Trondheim, Norway.

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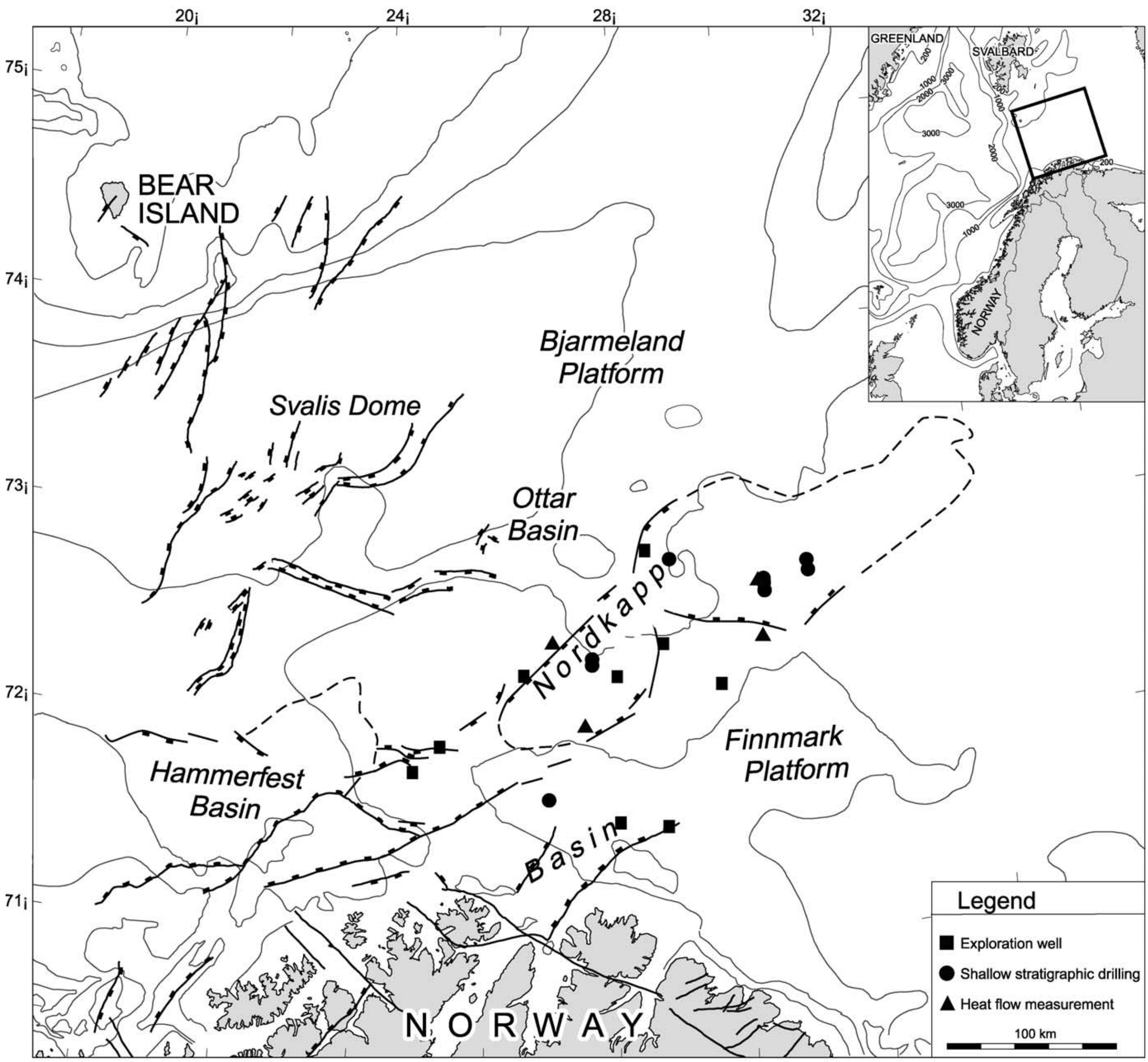


Fig. 1. The Nordkapp Basin is a Devonian–Carboniferous rift basin in the southwestern Barents Sea. It consists of two sub-basins and is heavily influenced by salt diapirism.

presence of a mature source rock in the Nordkapp Basin. Only limited information is released to date (NPD, 2001).

The primary play model in the basin is related to salt traps, especially to reservoirs sealed by salt overhangs, and this model was proved by the last well (Carstens, 2001). However, other structural and stratigraphic traps are also recognised within the basin.

In addition to the two exploration wells, 12 shallow stratigraphic boreholes have been drilled by IKU Petroleum Research within the Nordkapp Basin. This paper presents the results from the shallow boreholes as a contribution to the understanding of the geology and exploration potential of the basin.

2. Methods and data

Late phase diapirism has uplifted and folded the Mesozoic strata above salt diapirs (Nilsen et al., 1995), and later erosion has left these strata truncated and exposed at shallow levels beneath the base Quaternary unconformity. This permits the coring of substantial parts of the Mesozoic sedimentary succession in shallow stratigraphic boreholes. Rise

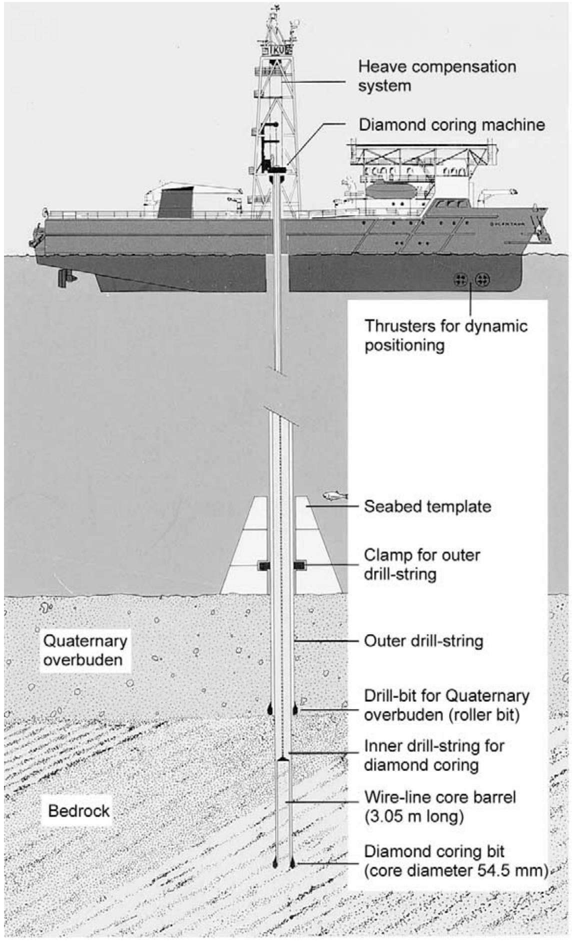


Fig. 2. Shallow stratigraphic drilling is performed from a dynamically positioned drill ship (Rise & Sættem, 1994). A diamond coring machine rides on top of the heave-compensated outer drill string, which acts as a riser in the water column and as a casing below seabed. Continuous coring is performed, and the cores are retrieved in 3 m lengths by a wireline system.

and Sættem (1994) have described the shallow stratigraphic drilling method. Using a small drillship, continuous cores with a diameter of 54.4 mm are retrieved in 3-m lengths by a wireline system (Fig. 2).

Approximately 1500 km of high-resolution seismic data were acquired in order to find the best borehole locations (Fig. 3). Single channel sparker and air-gun data were acquired along all lines, while multi-channel data (2.5 s recording, 2 ms sampling rate, 12.5 m shot point interval/ group length) were acquired along 700 km of this grid. The seismic data were later integrated with the borehole data in order to interpret the seismic facies and to correlate cores with the conventional seismic data.

The Quaternary overburden varied in thickness from 20 to 40 m at the 12 drill sites, and the holes were drilled from 15 to 100 m into the bedrock. A total of 590 m of Mesozoic core were obtained with an average core recovery of 93% (Table 1). Eleven of the 12 coreholes were drilled on the flanks of salt diapirs, with three coreholes in the southwestern segment of the basin and nine in the central/ eastern segment (Fig. 3). Only corehole 7230/05-U-09 was drilled outside the diapir area, with the objective of dating the youngest sedimentary rocks preserved in this part of the basin. The recovered cores range in age from Middle Triassic (Anisian) to Late Cretaceous (Cenomanian). Approximately 50% of the sedimentary succession in the basin has been cored.

Spectral gamma-ray intensity and horizontal sound velocity were measured shortly after retrieval of the cores. Onshore analysis included sedimentology, biostratigraphy and organic geochemistry. Heat flow data were obtained in four boreholes by recording temperatures at different depths and measuring thermal conductivity in situ and on the recovered cores (Table 2).

3. Geological setting of the Nordkapp Basin

The Nordkapp Basin is an ENE–WSW oriented, dog-leg shaped fault-related Late Palaeozoic rift basin (Gabrielsen et al., 1990; Rønnevik & Jacobsen, 1984). It is characterised by numerous salt diapirs and pillow-like salt structures along the margins (Fig. 4) (Gabrielsen et al., 1990, 1992; Nilsen et al., 1995). The initial basin was probably formed by regional extension during the Late Devonian–Early Carboniferous, judging from seismic tie from Finnmark Platform wells. The initial sediment fill is believed to consist of coaly alluvial siliciclastics of the Billefjorden Group (e.g. Bugge et al., 1995). They probably correlate with the lower part of Unit 2 of Nøttvedt et al. (1993) and represent pre-salt infill of the basin. Renewed and regional rifting in mid Carboniferous was associated with a climatic change to arid conditions. The sediments deposited during this rift phase are correlated with the conglomerates of the Landnørdingsvika Formation on Bjørnøya (Bear Island) and with the evaporites of the Ebbadalen Formation (Bashkirian) on Spitsbergen. They are expected to consist of coarse-grained red beds along the basin margins and to pass into carbonates and evaporites along the basin axis (Nøttvedt et al., 1993).

As suggested by Rønnevik (1981) and Faleide, Gudlaugsson, and Jacquart (1984), the evaporites could represent the lower of two salt units in the Nordkapp Basin, tentatively of Bashkirian–Kasimovian and Asselian age (e.g. 7229/8-1 well). Evaporites were deposited over an area wider than the present Nordkapp Basin, and seismic data indicate that the Ottar Basin (Breivik, Gudlaugsson, & Faleide, 1995), the southern part of the Bjarmeland Platform, the eastern part of the Loppa High, large parts of the Finnmark Platform and the Maud, Hammerfest, and Tromsø basins contain evaporites. Based on volumetric calculations, the original salt thickness in the Nordkapp Basin is estimated to have been in the range 2000–2500 m in the southwestern segment of the basin and about 4000 m in the central/eastern segment (Bergendahl, 1989; Jensen & Sørensen, 1992).

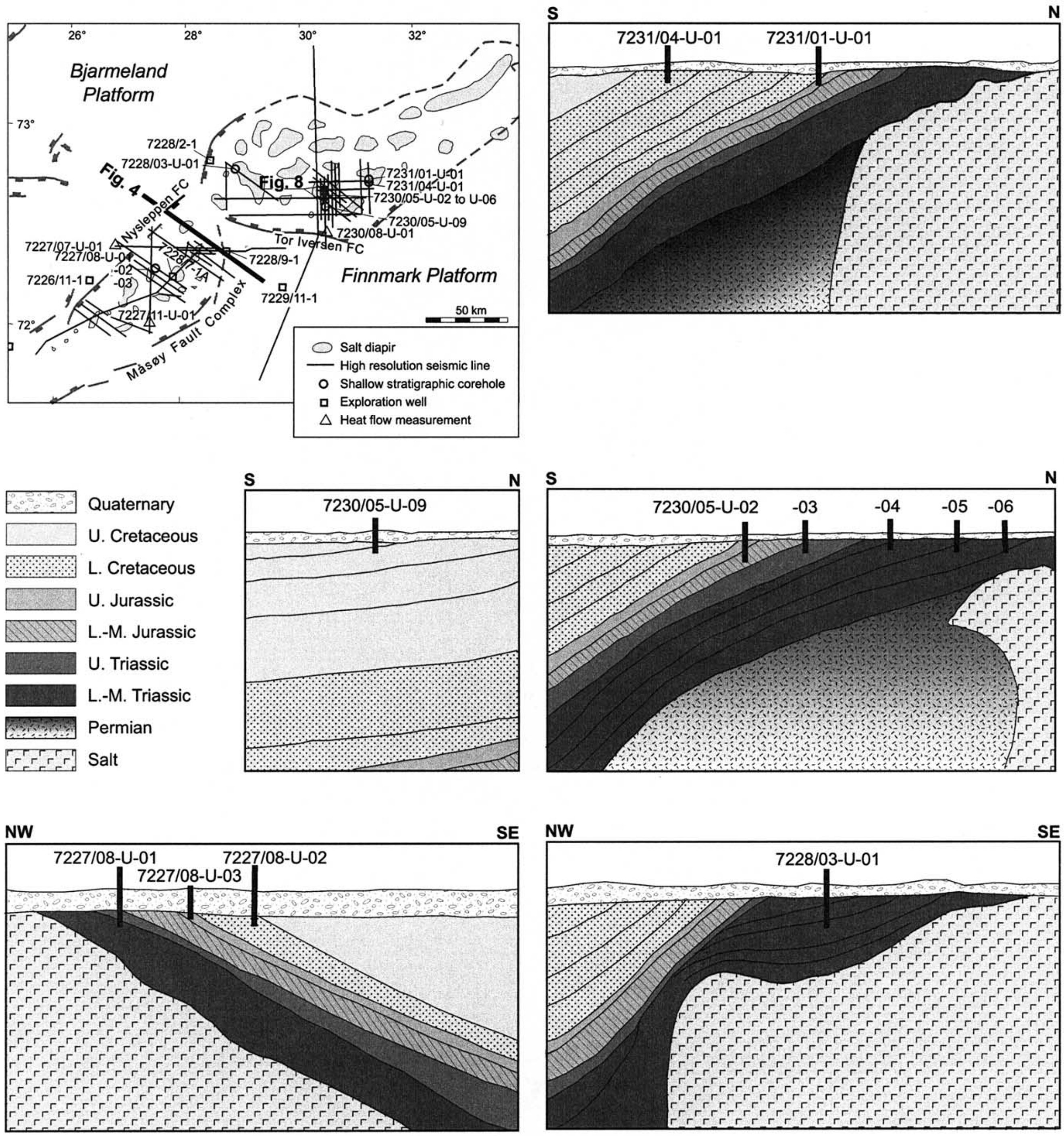


Fig. 3. Continuous coring at 12 locations resulted in 590 m of core from the Mesozoic succession in the Nordkapp Basin. Coring was performed up to 130 m below seabed with an average core recovery of 93%.

The Permian succession above the salt is believed to comprise mainly cool-water carbonates, siliciclastics and some chert as seen on Spitsbergen, Bjørnøya (Stemmerik, 1995, 2000; Stemmerik & Worsley, 1989), the Svalis Dome to the west (Nilsson, Mangerud, & Mørk, 1996) and the Finnmark Platform to the south (Bugge et al., 1995) (Fig. 1).

During the Early and Middle Triassic, approximately at the end of the Anisian, an overall westward and northwestward prograding coastline characterised the Barents Shelf. Sediments were supplied from the south (van Veen et al., 1993) and east from the Fedynsky Arch/Central Barents High in the Central Barents Sea (Gading, 1994; Mørk, 1999). Dominantly shallow marine conditions prevailed during this period. Thickness variations of the Triassic

Table 1
Technical data of the boreholes

Borehole number	Geographic co-ordinates		Water depth (m)	Quaternary overburden (m)	Penetr. in bedrock (m)	Total penetr. below seabed (m)	Core length (m)	Core recovery (%)
7228/03-U-01	72°49′03.7″N	28°52′14.8″E	294	41.0	47.7	88.7	47.5	99.8
7227/08-U-01	72°19′08.9″N	27°33′21.3″E	277	30.0	41.6	71.6	36.5	87.7
7227/08-U-02	71°19′01.8″N	27°33′57.3″E	279	37.8	15.3	47.1	9.3	93.6
7227/08-U-03	72°19′05.7″N	27°33′37.6″E	282	31.6	21.5	53.1	21.8	100.0
7231/01-U-01	72°45′12.5″N	31°07′30.2″E	278	36.3	56.5	92.8	55.7	98.6
7231/04-U-01	72°44′16.3″N	31°07′28.9″E	280	37.7	59.7	97.4	58.0	97.3
7230/05-U-02	72°40′51.1″N	30°22′29.5″E	286	28.7	97.3	126.0	95.1	97.7
7230/05-U-03	72°41′10.1″N	30°22′26.7″E	288	27.0	88.5	115.5	78.1	88.2
7230/05-U-04	72°41′39.7″N	30°22′26.6″E	282	23.6	55.2	78.8	54.5	98.8
7230/05-U-05	72°42′06.0″N	30°22′31.6″E	286	23.3	26.4	49.7	24.2	91.4
7230/05-U-06	72°42′21.2″N	30°22′28.9″E	285	24.6	71.7	96.3	68.0	94.9
7230/05-U-09	72°37′22.4″N	30°22′31.4″E	294	20.0	55.1	75.1	42.7	77.5
Sum/average					636.1		591.4	93.0

succession in the Nordkapp Basin indicate that increased subsidence occurred in the Spathian and Anisian (Nybakken & Berg, 1993). This is interpreted to have been caused by salt movements and to have been the result of initial diapirism and lateral flow to salt pillows.

Several later episodes of salt reactivation are postulated from Jurassic to Recent time. However, the most pronounced episode responsible for the present-day geometries probably occurred in the Tertiary. Most authors argue for salt rise due to buoyancy and density contrast, while Nilsen et al. (1995) suggested that regional tectonics was the driving force. Henriksen and Vorren (1996) dated the last major reactivation of the salt to the Early Eocene. Nilsen et al. (1995) related the last diapirism to mid Tertiary compression, which could explain the diapir geometries and the folded strata above the salt structures, a common phenomenon observed in many salt basins.

The Nordkapp Basin was subsequently uplifted and deeply eroded in Pliocene–Pleistocene times (Eidvin, Jansen, & Riis, 1993; Nyland, Jensen, Skagen, Skarpnes, & Vorren, 1992; Riis & Jensen, 1992). The area then subsided and was overlain by a thin cover (20–50 m) of Quaternary sediments. The sea floor is now below 300–400 m of water. Total Cenozoic erosion in the Nordkapp Basin area is estimated to be in the order of 500–1200 m (Nardin & Røssland, 1993; Nyland et al., 1992). The erosion removed any Tertiary strata originally present, except for Palaeocene and possibly some Lower Eocene sediments in the southwestern part of the basin (Henriksen & Vorren, 1996). The Tertiary diapirism and Late Tertiary erosion exposed outcrops of Mesozoic rocks around the salt diapirs below the Base Quaternary unconformity and enabled these rocks to be reached by the shallow stratigraphic drilling as described in this paper.

4. Stratigraphy

The regional Mesozoic stratigraphy of the Barents Sea has been discussed in numerous articles (Johansen et al., 1993; Mørk et al., 1993; Olaussen, Dalland, Gloppen, & Johannesen, 1984; Smelror, 1994; van Veen et al., 1993; Vigran, Mangerud, Mørk, Bugge, & Weitschat, 1998). A formal lithostratigraphy for the Barents Sea was defined by Worsley, Johansen, and Kristensen (1988). Based on published data and shallow stratigraphic coreholes in the Nordkapp Basin and in the Troms III area in the southwesternmost part of the Barents Sea, a generalised stratigraphy from different parts of the Barents Shelf area is presented in Fig. 5.

4.1. The cored section

Three of the 12 shallow stratigraphic drilling sites in the Nordkapp Basin were located in the southwestern segment of the basin and nine in the central/eastern segment (Fig. 3). Borehole 7228/03-U-01 was drilled in the western part of

Table 2
Heat flow values measured in shallow boreholes. Borehole 7230/05-U-05 was drilled in the Quaternary sediments above a salt diapir. The other holes were located in rim synclines inside the Nordkapp Basin and are interpreted not to be influenced by the higher thermal conductivity in the salt diapirs. Heat flow was calculated from measured temperatures and thermal conductivity of the actual sediments

Borehole number	Geographic co-ordinates		Water depth (m)	Heat flow (mW/m^2)	Temperature gradient (°C/km)
7227/07-U-01	72°25′34.7″N	27°00′31.8″E	278	49.4	31.1
7227/11-U-01	72°01′15.8″N	27°29′59.3″E	280	45.9	22.8
7230/08-U-01	72°25′45.6″N	30°22′34.4″E	283	54.2	35.6
7230/05-U-05	72°42′07.1″N	30°22′32.1″E	286	104	69.3

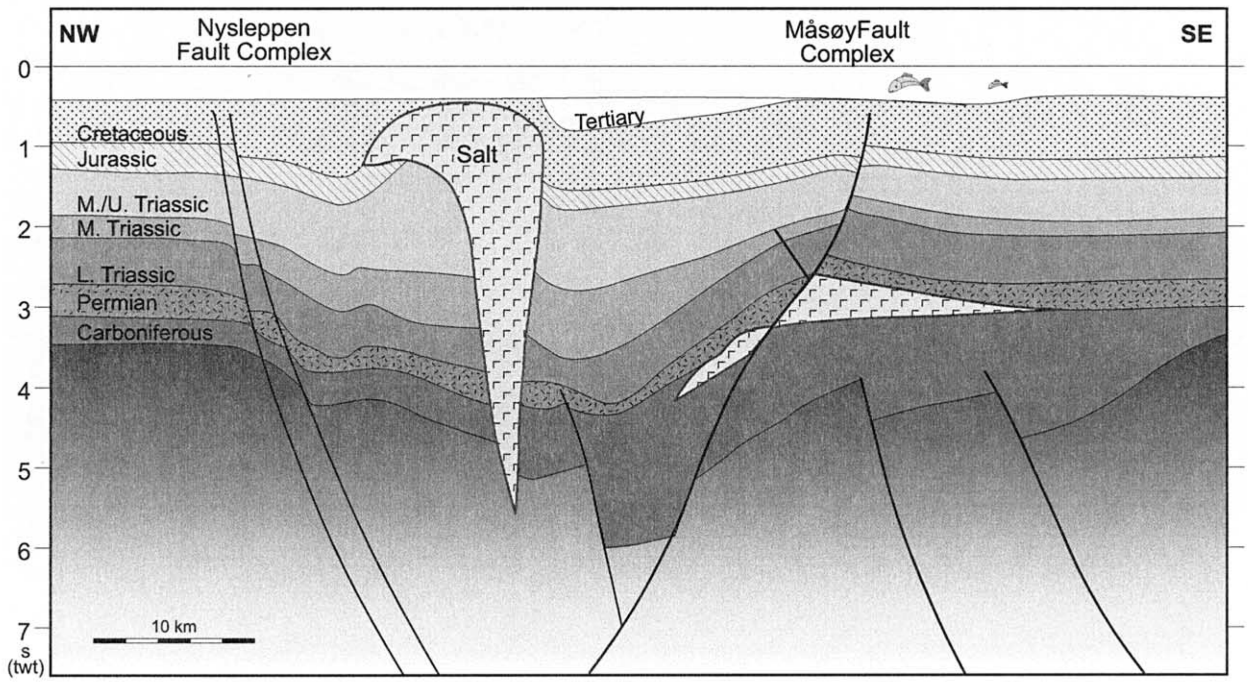


Fig. 4. Geoseismic section through the Nordkapp Basin showing a typical mushroom-shaped salt diapir and a salt pillow on the flank of the basin. Thickening of the Lower–Middle Triassic succession is the result of initial salt movement. Cenozoic erosion removed in the order of 1200 m of Mesozoic and Cenozoic sediments. See Fig. 3 for location of the line.

the central/eastern segment and comprised shallow marine sediments of Middle Triassic (Anisian) age that are assigned to the Kobbe Formation (Figs. 6 and 7). These sediments were probably sourced from a local high above a salt pillow to the west, which later collapsed and moved into a salt diapir rising to the east of the drill site (Fig. 3).

The three cores 7227/ 08-U-01, -02 and -03 were drilled in the central part of the southwestern basin segment (Fig. 3). The older core 7227/08-U-01 sampled Upper Triassic coastal plain red bed deposits belonging to the uppermost part of the Snadd Formation, unconformably and transgressively overlain by shallow marine sediments assigned to the Fruholmen Formation (Fig. 6). This unit is abruptly and unconformably overlain by fluvial coarse-grained sandstones and conglomerates of Early Jurassic age. These sediments are transgressively and unconformably overlain by fine- to medium-grained glauconitic, shallow marine sandstones. Both the fluvial and shallow marine sandstones are assigned to the Stø Formation (Figs. 6 and 7). Organic rich Hekkingen Formation claystones of Late Jurassic age were sampled in core -03, while shallow and open marine siltstones of Middle Albian age were sampled in core -02.

The most complete section was sampled in the five boreholes 7230/05-U-02 to -06 in the central/eastern segment of the Nordkapp Basin (Fig. 3). Cores 7230/05-U-06 and -05 comprise regressive and transgressive units of Anisian inner shelf to paralic deposits, equivalent to the Kobbe Formation in the west. Core -04 sampled marine shales and coastal plain sediments of Ladinian age, equivalent to the lower part of the Snadd Formation. In core -03, Upper Triassic coastal plain red beds from the uppermost part of the Snadd Formation are unconformably overlain by delta front coarse-grained sandstones of the Fruholmen Formation, and finally unconformably overlain by Lower Jurassic (Toarcian) shallow marine sandstones (delta front) of the Stø Formation. In core -02, deltaic sediments containing both coarsening upward sandstone mouth bar complexes and fining upward sandstone distributary channel complexes associated with pedogenic features of the Stø Formation are abruptly and transgressively overlain by bioturbated, glauconitic sandstones of the Stø Formation and finally by silty shales of the Fuglen Formation. The lower deltaic parts of the Stø Formation in core -03 and -02 are correlated to the middle Stø Formation unit of Gjelberg, Dreyer, Høie, Tjelland, and Lilleng (1987), while the upper shallow marine glauconitic part with phosphorites is assigned to the upper Stø Formation unit. The Fuglen Formation is abruptly overlain by Upper Jurassic black shales of the Hekkingen Formation.

Core 7230/05-U-09 was drilled 5 km to the south of these locations (Fig. 3) and comprises sandstones and siltstones of Albian to Cenomanian age, assigned to the Kolmule Formation. The two cores 7231/01-U-01 and 7231/04-U-01 were drilled 30 km further to the northeast (Fig. 3). They comprise the upper part of the Hekkingen Formation shales with overlying Lower Cretaceous limestones of the Knurr Formation/Klippfisk Formation and siltstones of the Kolje Formation. The younger of the two cores sampled inner shelf to shoreface and lagoonal siltstones of Late Albian

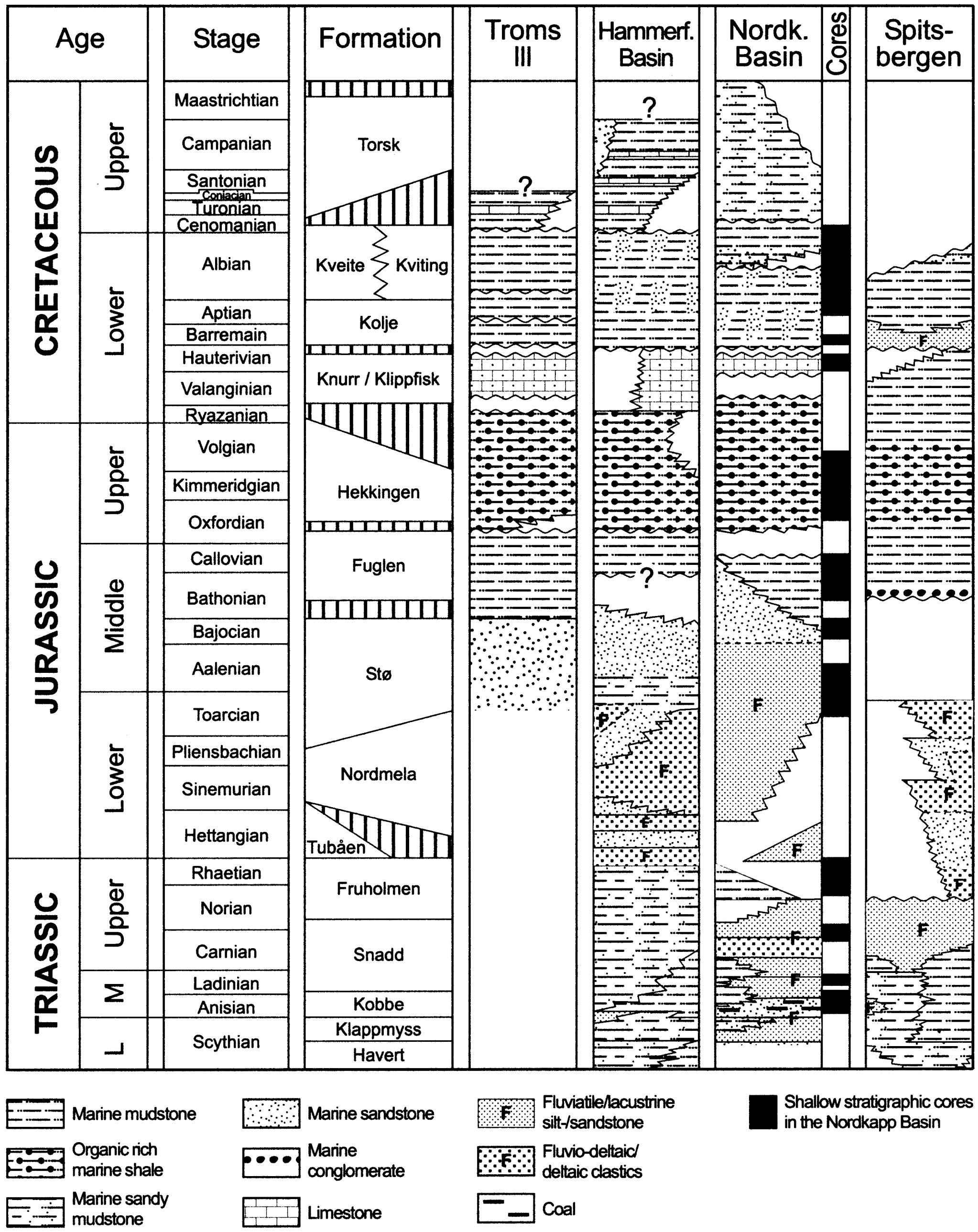


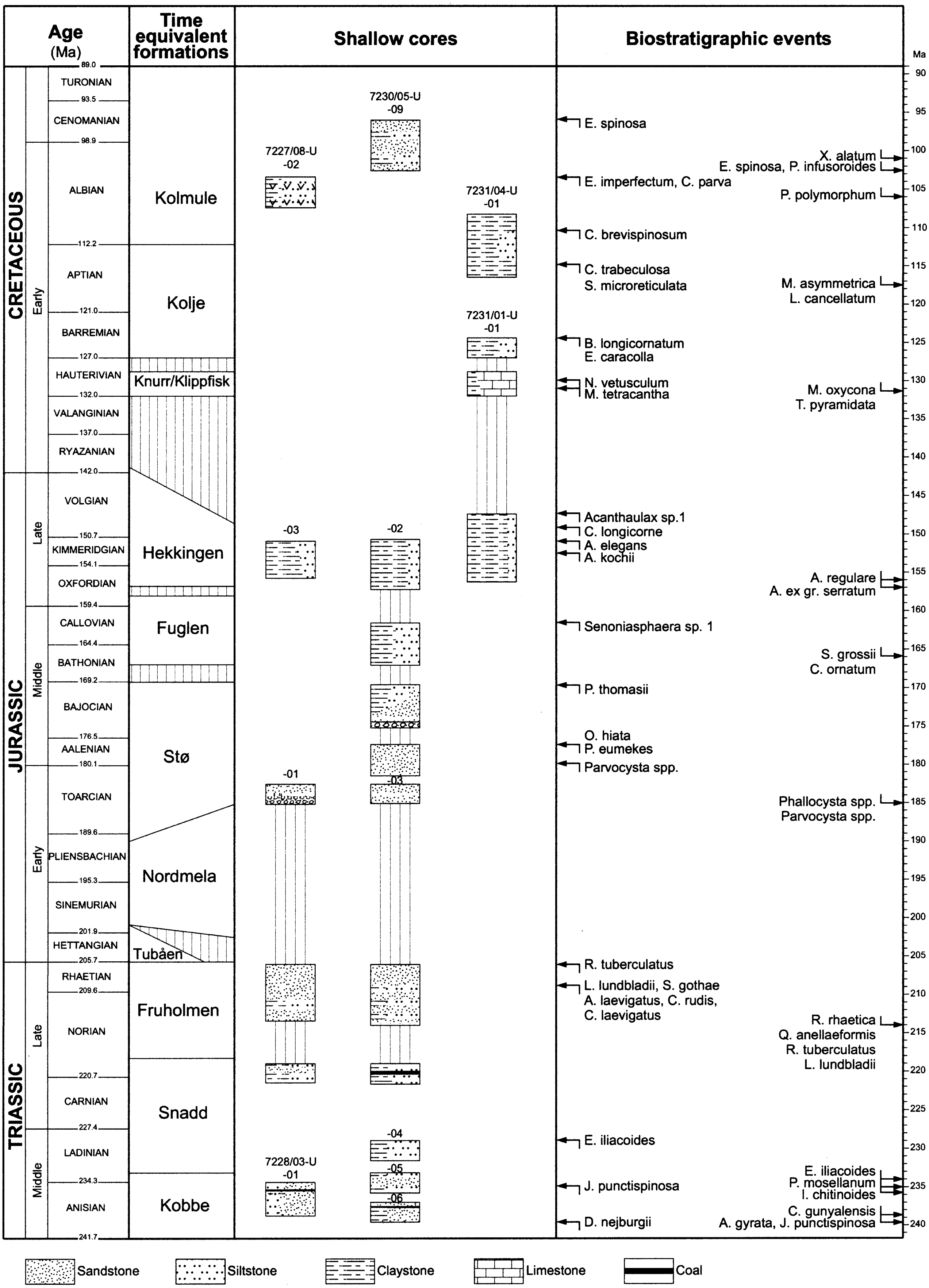
Fig. 5. Regional stratigraphy of the Barents Shelf and Spitsbergen. The cored intervals in the Nordkapp Basin are shown. Formation definition by Worsley et al. (1988). The Klippfisk Formation was defined by Smelror, Mørk, Monteil, Rutledge, and Leereveld. (1998).

to Early Cenomanian age, belonging to the Kolje and Kolmule Formations.

4.2. Stratigraphic synthesis of the Nordkapp Basin

The following synthesis places most emphasis on the central/eastern segment of the basin, where more than half of the Middle Triassic–Upper Jurassic succession was sampled in the five cores assigned 7230/05-U-02 to -06 (Fig. 9). It is noteworthy that the apex of the underlying salt diapir migrated northward during its evolution. Middle Triassic strata were originally deposited on a north-dipping palaeo-slope which changed gradually to the present southerly dip. The earlier apex of the diapir was located below drill site 7230/05-U-03 (Fig. 8). The overlying succession was deposited when the rim syncline had a weak expression at the surface. The relatively steep present dip (12–15°) is the result of both salt reactivation during the Early Tertiary and later subsidence.

Six different sedimentary facies groups, related to different depositional environments, are identified in the cored Mesozoic succession. In order to abbreviate the text, facies


Age (Ma)
Time equivalent formations
Shallow cores
Biostratigraphic events
Ma
CRETACEOUS
JURASSIC
TRIASSIC
Early
Late
Middle
Early
Late
Middle
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
RYAZANIAN
VOLGIAN
KIMMERIDGIAN
OXFORDIAN
CALLOVIAN
BATHONIAN
BAJOCIAN
AALENIAN
TOARCIAN
PLIENSBACHIAN
SINEMURIAN
HETTANGIAN
RHAETIAN
NORIAN
CARNIAN
LADINIAN
ANISIAN
89.0
93.5
98.9
112.2
121.0
127.0
132.0
137.0
142.0
150.7
154.1
159.4
164.4
169.2
176.5
180.1
189.6
195.3
201.9
205.7
209.6
220.7
227.4
234.3
241.7
Kolmule
Kolje
Knurr/Klippfisk
Hekkingen
Fuglen
Stø
Nordmela
Tubåen
Fruholmen
Snadd
Kobbe
7230/05-U -09
7227/08-U -02
7231/04-U -01
7231/01-U -01
-03
-02
-01
-03
7228/03-U -01
-04
-05
-06
E. spinosa
E. imperfectum, C. parva
C. brevispinosum
C. trabeculosa
S. microreticulata
B. longicornatum
E. caracolla
N. vetusculum
M. tetracantha
Acanthaulax sp.1
C. longicorne
A. elegans
A. kochii
Senoniasphaera sp. 1
P. thomasii
O. hiata
P. eumekes
Parvocysta spp.
R. tuberculatus
L. lundbladii, S. gothae
A. laevigatus, C. rudis,
C. laevigatus
E. iliacoides
J. punctispinosa
D. nejburgii
X. alatum
E. spinosa, P. infusoroides
P. polymorphum
M. asymmetrica
L. cancellatum
M. oxycona
T. pyramidata
A. regulare
A. ex gr. serratum
S. grossii
C. ornatum
Phallocysta spp.
Parvocysta spp.
R. rhaetica
Q. anellaeformis
R. tuberculatus
L. lundbladii
E. iliacoides
P. mosellanum
I. chitinoides
C. gunyalensis
A. gyrata, J. punctispinosa
90
95
100
105
110
115
120
125
130
135
140
145
150
155
160
165
170
175
180
185
190
195
200
205
210
215
220
225
230
235
240
Sandstone
Siltstone
Claystone
Limestone
Coal

groups are initially defined (Table 3) and illustrated with core photographs (Fig. 9). The facies development of the cored succession is shown in Fig. 10.

4.2.1. Anisian unit (Kobbe Formation equivalent)

The cored part of this unit represents an overall regressive development from a shallow, storm-influenced shelf to a coastal plain environment during the Early–Middle Anisian, and a transgressive development from a coastal plain to an open marine shelf environment in the Late Anisian.

On seismic data (Fig. 8), the lowermost part of the unit exhibits weak, parallel reflections, which represent the lower and most marine part of core 7230/05-U-06. The upper part of the unit is characterised by strong, parallel reflections prograding from south to north.

In core 7230/05-U-06 (87 m below seabed), a storm-influenced inner shelf/lower shoreface unit with a phosphorite conglomerate lag is unconformably overlain by a restricted estuarine or marine, poorly bioturbated (*Diplocraterion*) crossbedded sandstone with a conglomerate of siderite pebbles at its base. This sandstone is overlain by a few metres of transgressive, marginal marine sandstone, which in turn is regressively overlain by lagoonal shales, tidal channels and tidal flat complexes (Fig. 9c,d) and coastal plain successions with coals. The unit exhibits an overall regressive character. Core 7228/03-U-01 in the central basin segment is slightly younger than core 7230/05-U-06 and comprises more open marine environments. It consists of repeated fining-upwards units in an overall regressive setting, culminating in a coastal plain environment (Fig. 9b) that was later transgressed by inner shelf to shoreface silt-/sandstones. In the younger Anisian core 7230/05-U-05, a lower unit of coastal plain and tidal flat association is unconformably overlain by medium-grained, coarsening upward shoreface sandstone with an intra-clast siderite-dominated lag at its base. Open marine shelf deposits with distal storm beds/lenses are encountered abruptly above the sandstone. The cored unit shows an overall transgressive development.

4.2.2. Ladinian–Norian unit (Snadd Formation equivalent)

Core 7230/05-U-04 of Ladinian age comprises a lower unit with three coarsening upward successions dominated by low-density *Chondrites* bioturbated shales overlain by silty shales. The successions contain dm thick hummocky sandstone beds with local wave ripples representing transition zone to lower shoreface depositional setting (Fig. 9g,h). These are overlain by a silty shale-dominated middle shelf unit, which is unconformably overlain by a greenish, calcareous soil unit. Shallow marine, bioturbated sandy siltstone deposits with some cocquina/intra-clast siderite represent a transgressive lag with an overall regressive development. On seismic data, the lower and most marine part of the Ladinian–Norian unit exhibits no significant reflections (Fig. 8). The coastal plain unit at 45.5–48 m in core 7230/05-U-04 gives strong and continuous seismic reflections, and the overlying open marine interval appears to generate frequent semi-continuous, parallel reflections.

There is a non-cored interval of approximately 90 m between cores 7230/05-U-04 and -03 (Fig. 10). From seismic facies interpretation we suggest that most of this interval represents a regressive development from the shelf environment of the upper part of core -04 to the paralic environments seen in the lower 14 m of core -03 (Fig. 9a). The upper part of these strata is distinct with a dusky red coloration caused by exposure and pedogenesis. Similar red coloured sediments are characteristic of the uppermost part of the Snadd Formation (Worsley et al., 1988) and of the upper part of the DeGeerdalen Formation on Hopen (e.g. Iversen Formation of Smith, Harland, and Hughes (1975), which was assigned to the DeGeerdalen Formation by Worsley and Heintz (1977)). None of the pedogenic sediments are accurately dated, but in core -03 they are overlain by well-dated mid Norian marine sediments. In a regional context we suggest a Late Carnian–Early Norian age for the red-coloured pedogenic strata.

4.2.3. Norian–Rhaetian unit (Fruholmen Formation equivalent)

On seismic data, this sandstone-dominated unit appears to generate more discontinuous sub-parallel reflections than the underlying, more marine influenced Middle Triassic unit. The upper boundary, which represents the Triassic/Jurassic transition, is represented by a relatively strong and partly truncational seismic reflector (Fig. 8). Local progradational patterns separated by horizons possibly representing flooding events can be observed on the seismic data within the uppermost Triassic succession. Biostratigraphical data document that most of the Lower Jurassic succession (~20 million years) is missing, and Toarcian shallow marine sandstone and shales in the upper part of core 7230/05-U-03 occur immediately above the unconformity.

Core 7230/05-U-03 (Fig. 7b) contains braided river delta front sandstones. Fining upward sandstones with faint trough and planar cross laminations are interpreted as distributary channel deposits, while coarsening upwards sandstones, sometimes with planar laminae, are interpreted as mouth bar sandstones (Fig. 9e). These are interbedded with a few metres thick siltstone beds that represent bayfill deposits. Loading/ball-and-pillow structures and other synsedimentary deformation structures indicate periods of rapid deposition. The approximately 90 m thick unit represents prominent reservoir-quality sandstones.

The basal unconformity of the sandstone represents an

Fig. 6. Chronogram of the cores, with main biostratigraphic events.

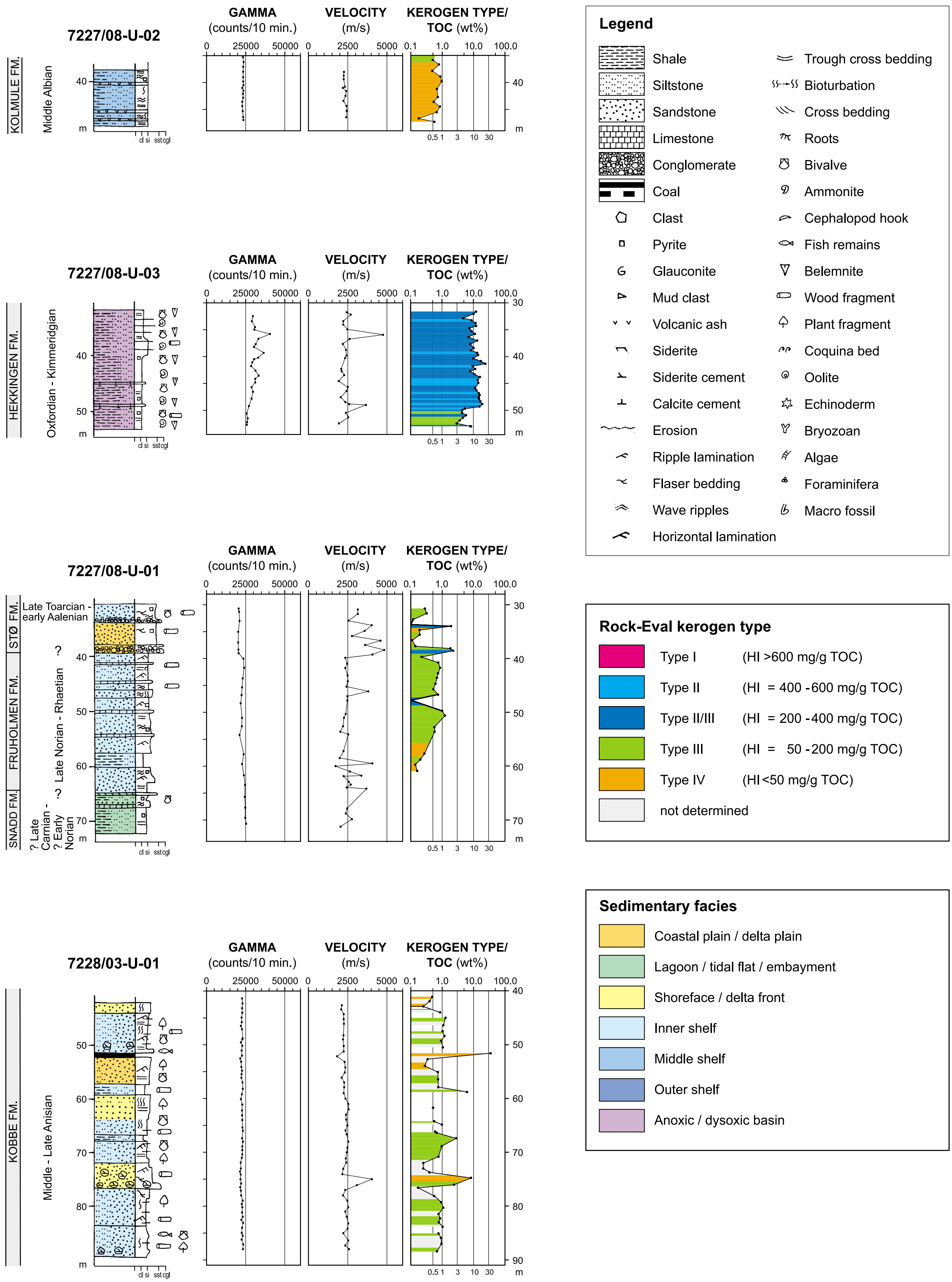


Fig. 7. Sedimentological logs with facies interpretations. Gamma, sound velocity and TOC/kerogen type logs are based on core measurements.

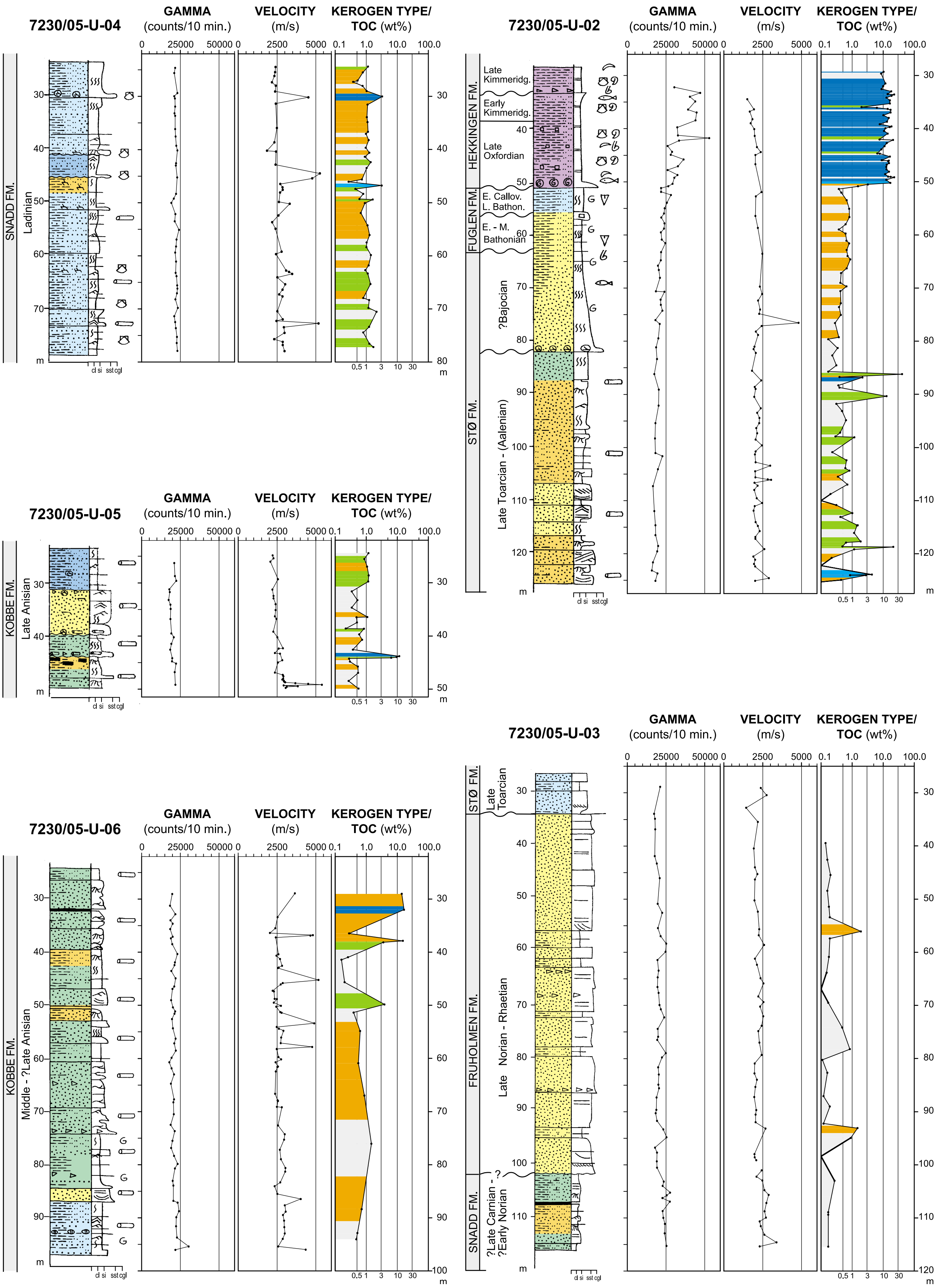


Fig. 7. (*continued*)

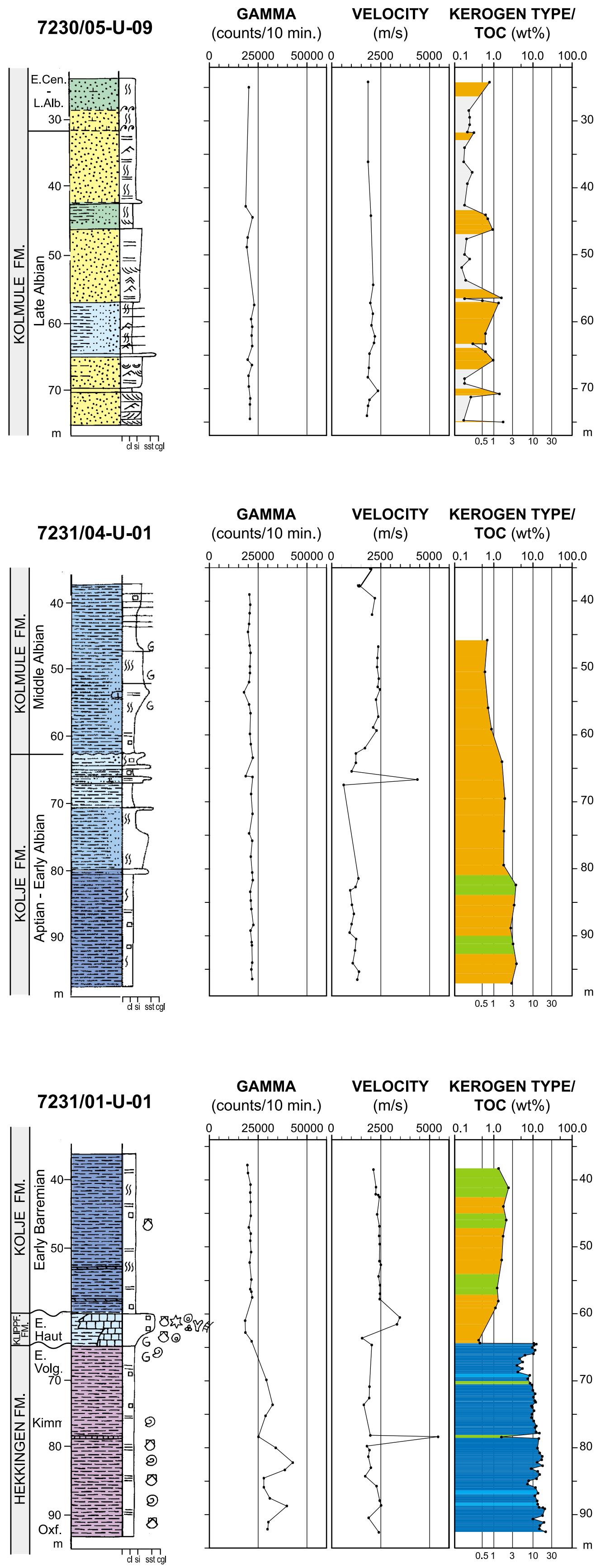


Fig. 7. (*continued*)

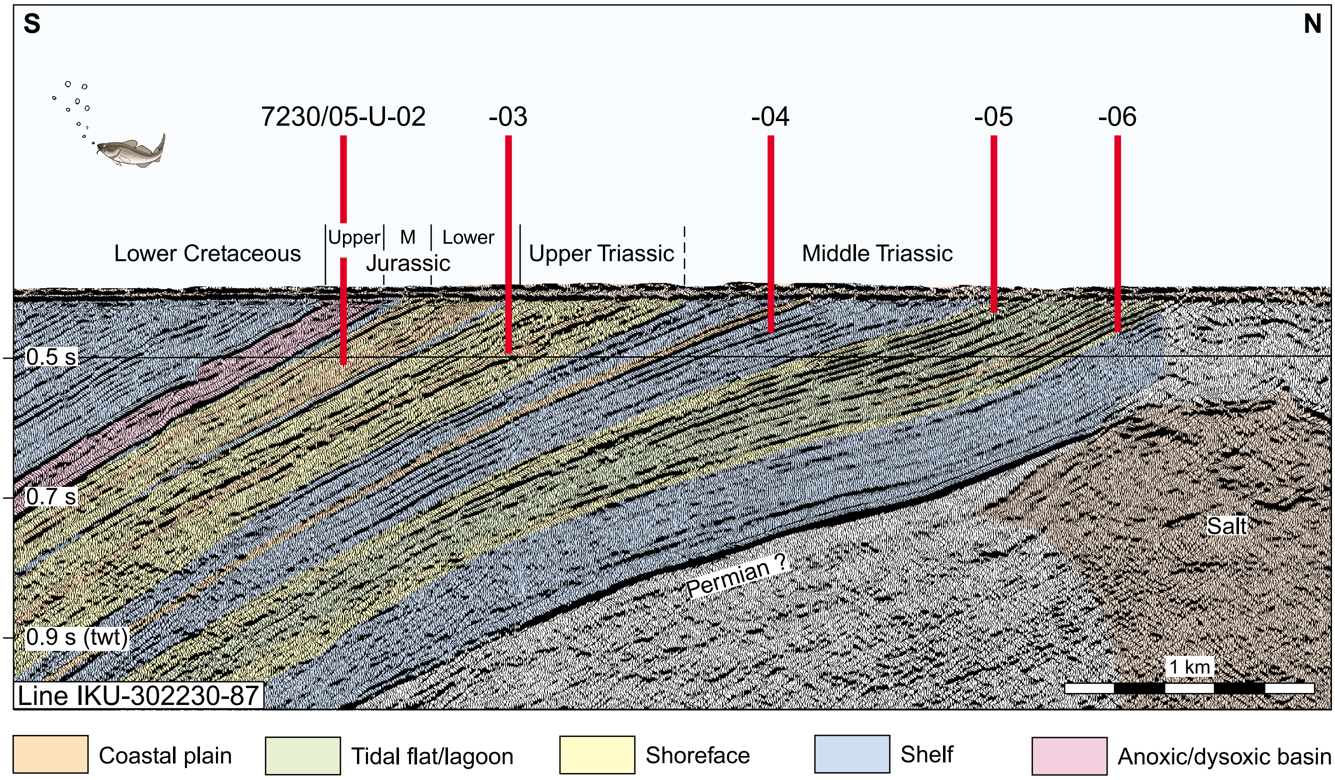


Fig. 8. Seismic cross-section through the Triassic–Lower Cretaceous section in the central/eastern segment of the basin (see Fig. 3). The seismic expression of sedimentary facies recognised in the cores is indicated in transparent colours.

abrupt facies change from the underlying fine-grained pedogenic sediments developed during prolonged sub-aerial exposure. The seismic data at this level show onlap features, and the boundary most likely represents a sequence boundary onto which the overlying transgressive sediments onlap. Core 7227/08-U-01, in the southwestern Nordkapp Basin, contains Norian–Rhaetian storm-influenced prodelta siltstones which are time-equivalent to the delta front deposits. The Fruholmen Formation sediments in this core represent a coarse-grained braided-river type delta prograding into a fine-grained prodelta basin where the sandstone-dominated facies has high reservoir potential.

4.2.4. Hettangian–Lower Toarcian unit (Tubåen and Nordmela Formation equivalents)

Sedimentary rocks from this stratigraphic interval are not preserved in any of the boreholes in this study (cf. the hiatus in the upper part of core 7230/05-U-03 that spans from Rhaetian to Late Toarcian, Fig. 6). Eastward thinning and facies changes to more continentally influenced environments are identified in the same formations in the Hammerfest Basin (Fig. 5) (Gjelberg et al., 1987; Olaussen et al., 1984), and the recorded hiatus in the Nordkapp Basin is interpreted to be caused by sub-aerial exposure and erosion.

4.2.5. Toarcian–Bajocian unit (Stø Formation equivalent)

Sandstones equivalent to the Stø Formation are presented in the uppermost part of cores 7230/05-U-03 and 7227/08-U-01 (Fig. 7a) and in core 7230/05-U-02 (Fig. 7b). The seismic expression is different from that of the underlying Fruholmen Formation equivalent in having more continuous and slightly more parallel reflections (Fig. 8). Based on the three cores the Stø Formation is sub-divided in two main facies groups: a lower unit containing both coarsening upward and fining upward sandstones with soils representing deltaic sandstones; including facies that have not previously been included in the Stø Formation. The upper unit consists of strongly bioturbated, glauconitic and phosphoritic sandstones representing lower to middle shoreface sandstones, which are typical for the Stø Formation in the type area. The lowermost part of the formation occurs in core 7230/05-U-03 where it consists of storm-deposited inner shelf/lower shoreface sandstones. The lower 40 m of core 7230/05-U-02 consist of fining upward sequences of medium- to fine-grained sandstones with fossil plant roots, interpreted to be part of a delta plain environment with sand deposition in distributary channels and mouth bar complexes. The transition from coarsening upward silty sandstones to medium-grained sandstones is interpreted to represent the development from a prodelta to a delta front environment. Siltstones interbedded with up to 5 cm thick, very fine to fine-grained sandstone beds with *Diplocraterion* burrows are interpreted to represent lagoonal/bay fill sediments (Fig. 9f).

A time equivalent interval, comprising 6 m of fluvial, fining upward coarse-grained, calcite-cemented sandstone, with a polymict conglomerate at the base, was cored in the upper part of borehole 7227/08-U-01 (Fig. 7a), located in the southwestern basin segment. These sediments are correlated with Stø unit 2 of Gjelberg et al. (1987). Core 7230/05-U-02 displays an overall regressive trend for this unit of the Stø Formation.

A 4 m thick unit of intensely bioturbated, glauconitic, very fine to fine-grained, silty lower shoreface/inner shelf sandstones above 86 m depth in core 7230/05-U-02 (Fig. 7b) is interpreted as a transgressive unit. An unconformity or hiatus separates this sandstone from an overlying 10 cm thick brown phosphoritic hardground bed at 82 m (interpreted as an omission surface), followed by 17 m of intensely bioturbated fining upward, glauconite-rich, medium to very fine-grained muddy sandstones of Bajocian age. These are interpreted to represent transgressive, middle–lower shoreface to inner shelf deposits. The phosphorite conglomerate contains reworked Upper Toarcian to Lower Aalenian fossils (palynomorphs), and may represent a lateral equivalent to parts of the phosphorite conglomerate of the Brentskardhaugen Bed on Central Spitsbergen (Bäckström & Nagy, 1985). Similar glauconitic and phosphoritic sandstones are widespread in Stø unit 3 (Gjelberg et al., 1987).

The feldspar content drops from 20–30% in the underlying Triassic sandstones to approximately zero in the Jurassic sandstones, while the quartz content increases. This mineralogical shift was reported by Bergan and Knarud (1993) to occur at the boundary between the Snadd and Fruholmen Formations (i.e. within the Triassic), however, our data indicate that it appears later, i.e. at the Triassic/Jurassic contact. This abrupt change may in part be explained by reworking of Upper Triassic sediments in the Early Jurassic, as is evident from common redeposition of Upper Triassic fossils. It also coincides with a climatic change from a semi-arid environment characterised by caliche development in the Carnian–Norian, to more humid conditions in the Early Jurassic, favourable for the development of coals.

The sandstones of the Fruholmen and Stø Formations represent one of the best reservoir rocks in the Nordkapp Basin, see Section 5 later.

4.2.6. Upper Bathonian–Lower Callovian unit (Fuglen Formation equivalent)

The Fuglen Formation is represented by an approximately 15 m thick interval in core 7230/05-U-02 (Fig. 7b) consisting of grey, silty, bioturbated shales with some glauconite-rich horizons. It contains belemnite rostra and cephalopod hooks and is interpreted to be deposited in a well-oxidised middle shelf environment. A thin pyrite-cemented bed marks the base of the unit. The abundance of authigenic minerals indicates slow and condensed deposition with average rate of deposition of three metres per million years.

As this unit is rather thin, only the lower and upper boundaries are detected on seismic data. Any internal character is below seismic resolution.

4.2.7. Upper Oxfordian–Lower Volgian unit (Hekkingen Formation)

The Hekkingen Formation is an organic-rich shale, and is the most widespread hydrocarbon source rock in the Barents Sea (Leith et al., 1993). The formation is approximately 50 m thick at sub-crop position on the flanks of the salt diapirs, but thickens to approximately 125 m in the rim synclines between the diapirs. A hummocky and partly chaotic seismic pattern is probably the result of ductile deformation of the shale as a result of reactivation of the salt diapirs. From the thickness variations it is inferred that the rim synclines formed topographic lows during deposition of the shale.

Marked hiatuses occur at the base and the top of the Hekkingen Formation shale. In well 7230/05-U-02 the Hekkingen Formation rests with a sharp and erosive contact on the underlying grey Fuglen Formation (Fig. 7b) with a 10 cm thick lag of rip-up clasts from the Fuglen Formation, associated with undifferentiated greenish glauconitised shale clasts. The unconformity most likely represents a submarine hiatus where erosion was followed by glauconitisation processes. As the glauconitisation requires a low Eh associated with very slow rate of deposition, the process most likely took place during the major transgression that took place with the onset of the deposition of the Hekkingen Formation. Biostratigraphic data indicate an unconformity spanning most of Callovian to Middle Oxfordian time (Smelror & Below, 1993).

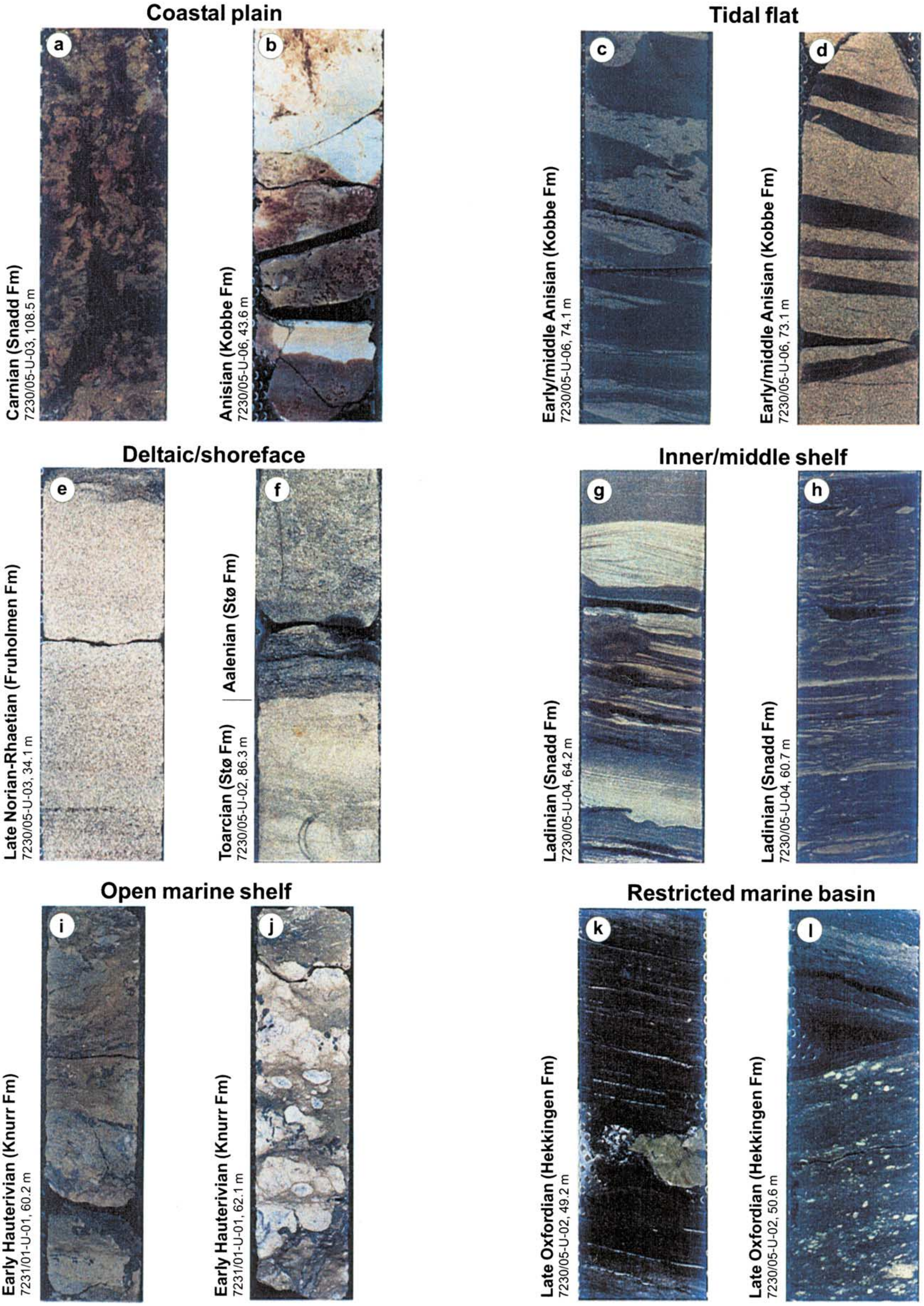
The Hekkingen Formation consists of black shales, typically splitting into paper-thick sheets referred to as paper shale. Laminae enriched in silt and skeletal fragments may represent distal turbidites and are developed into a faint coarsening upward unit in the lower part of the formation, terminated by a dark-grey shale-clast conglomerate, 1–2 cm thick, at 33 m in core 7230/05-U-02. Pyrite laminae and concretions are also common throughout the formation. In core 7227/08-U-03 laminae enriched in skeletal fragments also develop into coarsening upward units. Here, the unit below contains abundant calcite concretions, often displaying cone-in-cone structure. The upper boundary of the Hekkingen Formation was cored in well 7231/01-U-01 (Fig. 7c), where calcareous shales of Hauterivian age (Knurr/Klippfisk Formation equivalent), with glauconite concentrated near the base, rest unconformably on black shales. The hiatus on top of the formation spans from Early Volgian to the Early Hauterivian. The core penetrated the Upper Oxfordian to Lower Volgian part of the Hekkingen Formation. Among many calcite concretions a siderite concretion occurs at approximately 77 m, probably reflecting dysoxic conditions. Common, fairly well preserved ammonites allow a detailed stratigraphic resolution of the Upper Oxfordian–Lower

Table 3
The six different sedimentary facies defined in the cored Mesozoic succession. See core photographs of the same facies in Fig. 9

Depositional environment	Lithology	Description
Coastal plain/Delta plain (Fig. 9a,b)	Reddish brown to greenish shales with coals/roots and fining upward very fine and fine-grained sandstones	Lithology varies from shales to sandy shales with ripple-laminated sandstone beds. Root structures and coal beds in the shales. Siderite concretions and calcitic/sideritic pisolites in the reddish brown shales. Soil development and lack of bioturbation in the uppermost part of fining upward sandstones.
Shallow subtidal/tidal channels/tidal flat (Fig. 9c,d)	Lenticular to flaser bedded sandstone	Coarsening upward units: regressive shallow subtidal to shore line deposits, grading upwards from lenticular to flaser bedding. Wave and current ripples. Low to medium intensity ichnofabrics including *Rhizocorallium*, *Planolites*, *Teichichnus* and *Palaeophycus*. Fining upward units: Common in the overall coarsening upward subtidal unit. Flaser bedded, sometimes with climbing ripples and well developed reactivation surfaces with mudclast conglomerate beds at the base. Bioturbation is normally sparse. Root structures in uppermost parts.
Shoreface environment (Fig. 9e,f)	Coarsening upward fine to coarse-grained sandstone	Marine trace fossils and palynomorphs. High energy, regressive development. Lower part: Horizontal lamination and wave ripples. Middle part: trough crossbedded, often rich in plant debris. Upper part: occasional root structures, trough crossbedding, horizontal lamination and low angle tabular crossbedded beds.
Inner–outer shelf (Fig. 9g,h)	Greyish silty shales	Moderate to strong bioturbation including *Chondrites*, *Teichichnus*, *Helminthopsis*, *Rhizocorallium* and *Planolites*. Local bivalves. Scattered to abundant calcite and siderite concretions. Glauconite and phosphorite occur as distinct beds or scattered. Fine-grained sandstone beds are turbidites. Wave ripple laminae and hummocky bedding represent inner shelf/lower shoreface environment. Silty shales represent shallow, inner storm-influenced shelf environment.
Open marine shelf (Fig. 9i,j)	Carbonate mudstone to wackestone	Approximately 5 m thick. Buchiid and inoceramid bivalves, belemnites, crinoids, bryozoa, foraminifers and ammonite fragments are common. Lower part: Fully bioturbated greyish green glauconitic calcareous shale with nodular wackestone and packstones. Upper part: nodular wackestone with thin greyish green shale partings with the same biotic content as below. Slow sedimentation below storm wave base.
Restricted marine basin (Fig. 9k,l)	Black to dark brownish grey shale	Type II and II/III kerogen and high gamma radiation. 7–23% TOC in lower part (paper shales), 4–14% in the upper part. Thin siltstone to skeletal laminae. Cone-in cone and septarian type calcite concretions/beds often in high gamma radiation zones. Pyrite concretions/laminae. Bioturbation absent to very rare. Benthic fauna suggesting restricted (?dysoxic) conditions together with high planctonic fossil content suggests stratified water body with anoxic to dysoxic bottom conditions.

Volgian in the present data set (Wierzbowski & Smelror, 1993).

The Hekkingen Formation is recorded to contain 4–23 wt% total organic carbon (TOC). Worsley et al. (1988) differentiated the Hekkingen Formation into a lower, highly radioactive Alge Member and an upper, less radioactive Krill Member. Spectral gamma measurements on the core samples from the Nordkapp Basin, in combination with biostratigraphic data, suggest that most of the cored Hekkingen Formation sections belong to the Alge Member (Fig. 9k,l). TOC contents in these sections vary from 7 to 23 wt%. The Krill Member probably occurs only in core 7231/01-U-01 where the Upper Kimmeridgian–Lower Volgian section above 78.3 m has generally lower total gamma-ray readings, slightly lower TOC contents (4–14 wt%) and locally siderite concretions suggesting less oxygen-depleted conditions than in the underlying section (7–21 wt% TOC).


Coastal plain
a
Carnian (Snadd Fm)
7230/05-U-03, 108.5 m
b
Anisian (Kobbe Fm)
7230/05-U-06, 43.6 m
Tidal flat
c
Early/middle Anisian (Kobbe Fm)
7230/05-U-06, 74.1 m
d
Early/middle Anisian (Kobbe Fm)
7230/05-U-06, 73.1 m
Deltaic/shoreface
e
Late Norian-Rhaetian (Fruholmen Fm)
7230/05-U-03, 34.1 m
f
Aalenian (Stø Fm)
Toarcian (Stø Fm)
7230/05-U-02, 86.3 m
Inner/middle shelf
g
Ladinian (Snadd Fm)
7230/05-U-04, 64.2 m
h
Ladinian (Snadd Fm)
7230/05-U-04, 60.7 m
Open marine shelf
i
Early Hauterivian (Knurr Fm)
7231/01-U-01, 60.2 m
j
Early Hauterivian (Knurr Fm)
7231/01-U-01, 62.1 m
Restricted marine basin
k
Late Oxfordian (Hekkingen Fm)
7230/05-U-02, 49.2 m
l
Late Oxfordian (Hekkingen Fm)
7230/05-U-02, 50.6 m

4.2.8. Lower Hauterivian unit (Knurr Formation/Klippfisk Formation equivalent)

A 4.5 m thick, condensed unit of limestone and carbonate-rich claystone in core 7231/01-U-01 (Fig. 9i,j) rests unconformably above of the Hekkingen Formation shales (shown before). The lower part of the unit consists of strongly bioturbated greyish green glauconitic calcareous shale with nodular wackestone and packstones. Buchiid and inoceramid bivalves, belemnites, crinoids, bryozoa, foraminifera and ammonite fragments are common. It is abruptly overlain by a nodular wackestone containing thin greyish green shale partings with the same biotic content as the underlying unit.

As stated before, the hiatus at the base of the calcareous shale spans from the Early Volgian to Early Hauterivian, and a hiatus on top spans the Late Hauterivian. The limestone unit was probably deposited on structural highs defining areas developing into shallow marine and condensed carbonate platform environment below storm wave base, and has been referred to as the Klippfisk Formation by Smelror, Mørk, Monteil, Rutledge, and Leereveld (1998).

4.2.9. Barremian–Lower Albian unit (Kolje Formation equivalent)

The Kolje Formation equivalent is represented in core 7231/01-U-01 by 25 m of open marine claystone. The transition from the Knurr Formation equivalent to the overlying dark grey claystone of the Kolje Formation represents an unconformity and regional sequence boundary which is recognised over larger parts of the western Barents Shelf (Århus, 1991; Smelror et al., 1998). The oldest transgressive dark grey shales of the Kolje Formation equivalent are of Early Barremian age and were deposited in an outer shelf environment.

There is a non-cored interval of about 100 m up to core 7231/04-U-01. The lower 35 m of this core consist of dark grey claystones that represent a regression from outer to inner shelf environment. The top of the shale unit is located at 62.5 m depth in core 7231/04-U-01 and is dated as being close to the Early–Middle Albian boundary. In contrast to the organic rich black to dark grey shales of the Hekkingen Formation equivalent, the dark grey claystones of the Kolje Formation equivalent contain relatively hydrogen-lean organic matter (type III and type IV kerogen) and have therefore no significant petroleum generation potential despite their fair to good organic richness (1.1–3.8 wt% TOC).

4.2.10. Middle Albian–Cenomanian unit (Kolmule Formation equivalent)

The upper 25 m of core 7231/04-U-01 consist of Middle Albian dark grey shales interpreted as middle shelf deposits. Core 7230/05-U-09 of Late Albian to Early Cenomanian age contains sandier lithologies and is interpreted to consist of regressively stacked inner shelf to shoreface and lagoonal sandstones.

5. Source potential and thermal maturity

The Hekkingen Formation, with its TOC content of 4–21 wt%, is the only potential source rock represented in the cored sections. The organic matter is of mixed marine–terrestrial origin, with typical hydrogen index values of between 200 and 430 mg/g TOC (kerogen types II and II/III). Thin beds containing type-III kerogen occur locally, possibly suggesting short periods of lesser oxygen deficiency or increased input of terrigenous material. The organic matter is thermally immature, as indicated e.g. by mean vitrinite reflectance (R_m) values of 0.25–0.32%, hopane isomerisation ratios (22S/(22R + S), extended hopanes) of 14–58% and sterane isomerisation ratios (20S/(20S + R), C29 steranes) of 3–15%.

Despite their low maturity, the rocks contain appreciable concentrations of thermally immature bitumen, and results from maturation (hydrous pyrolysis) experiments on two samples with similar hydrogen index (300 and 345 mg/g TOC) but different TOC content (11.9 and 22.9 wt%) suggest that at least the most organic rich intervals of the Hekkingen Formation shales are able to generate and expel liquid hydrocarbons.

The biomarker ratios suggest maximum burial temperatures of about 80–113 °C, using kinetic models by Ritter, Aareskjold, and Schou (1993a) and Ritter, Myhr, Aareskjold, and Schou (1993b) and a heating rate of 2.5 °C/Ma. It is uncertain at which point of the complex burial and uplift history these temperatures have been reached, and they may therefore not necessarily be related to the latest burial phase.

At present, the shales are at 1500–1800 m depth in the Nordkapp Basin, while the samples in the cores were taken at less than 60 m below seabed. At the time of maximum burial the difference could have been in the order of 1000 m. The shale may thus be more thermally mature in the sub-basin centres than on the flanks where the cores were taken, and a rough estimate using biomarker isomerisation ratios and a geothermal gradient of 30 °C/km suggests that the formation could have reached at least early oil-window maturity in the deepest part of the basin.

As discussed in Section 8 later, we also suggest that organic rich sediments with source rock potential were deposited in local sub-basins formed by salt movements in the Nordkapp Basin. The most likely intervals coincide with the first mobilisation of the salt in Late Spathian to Anisian time, but could also occur higher in the Triassic succession. These sediments would be more mature than those of the Hekkingen Formation.

Fig. 9. Core photographs showing examples of the six different sedimentary facies defined in the cored succession. See also description of the facies in Table 3.

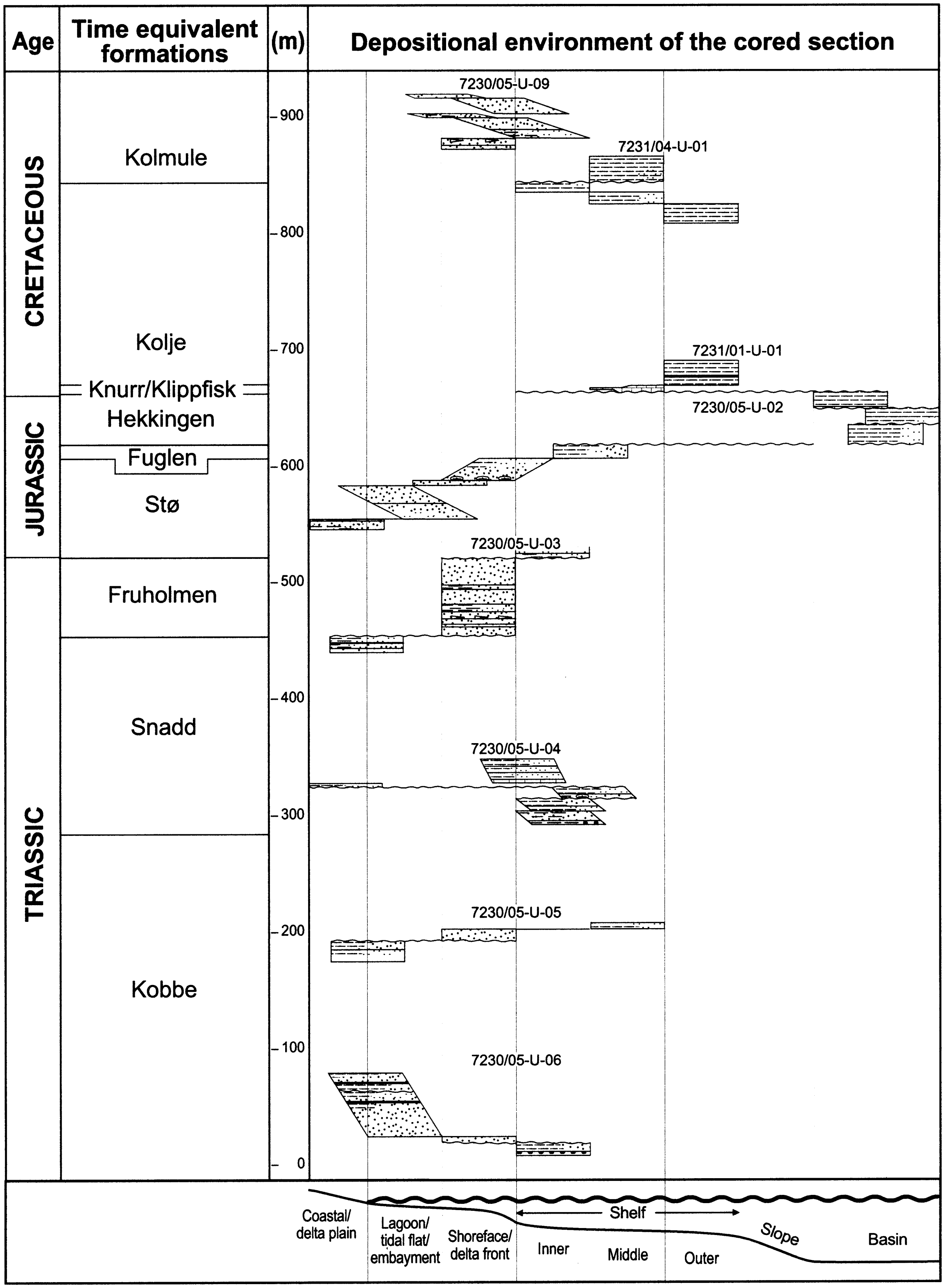


Fig. 10. Interpreted depositional environments of the cored succession in the central/eastern segment of the Nordkapp Basin. The vertical axis shows true stratigraphic thickness, in contrast to the linear time scale of Fig. 6.

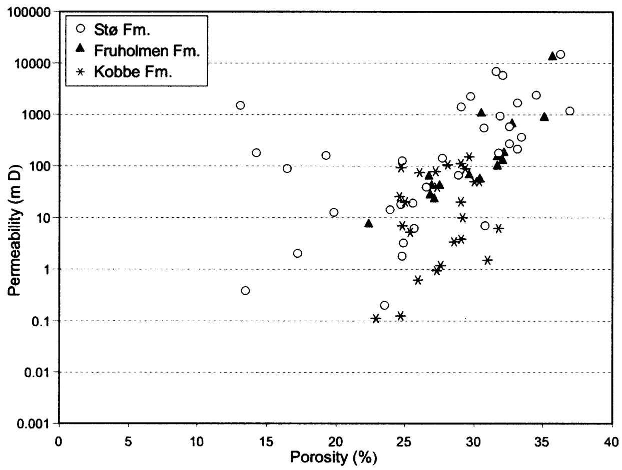


Fig. 11. Porosity and permeability measured on core plugs of the three most prominent cored reservoir units, the Stø, Fruholmen and Kobbe Formations.

6. Reservoir potential

Key reservoir parameters such as porosity/permeability and net/gross values (*N*/*G*) have been extracted from the core data. The most prolific reservoir intervals are recognised in the Stø and Fruholmen Formations and partly in the Kobbe Formation. The Stø Formation shows *N*/*G* values in the order of 0.9–1.0, porosities of up to 35% and permeabilities of 10 mD to more than 1 Darcy (Fig. 11, Table 4). The Fruholmen Formation sandstones have the same order of porosity and *N*/*G*, but slightly lower permeabilities (dominantly 10–100 mD). The Kobbe Formation sandstones show *N*/*G* values of 0.3–0.5, permeabilities of 1–100 mD and porosities of 25–30%.

7. T–R sequences

Many of the global second order sequence boundaries (Haq, Hardenbol, & Vail, 1988) can be recognised in the cored succession of the Nordkapp Basin. They are represented by the unconformity between the Snadd and Fruholmen Formations where the lower Norian succession is missing (Fig. 6), the break between the Fuglen and Hekkingen Formations where the Upper Callovian to mid-Oxfordian sediments are missing, the break between the Hekkingen and Klippfisk Formations where the upper part of the Volgian and the lowermost Hauterivian are missing, and the break between the cored Cenomanian sediments and the overlying Tertiary sediments in the southwestern part of the basin.

The development seen in the shallow cores resembles the T–R sequence development model as described by Embry (1993, 1995). In outer shelf/basinal setting, the sequence boundary is represented by an abrupt shallowing event (e.g. Alge to Krill Member transition, core 7231/01-U-01), sometimes marked by an intra-formational lag (e.g. Early/Late Kimmeridgian boundary at 33 m in core 7230/05-U-02) followed by condensed T–R development a few metres thick. In shelf settings, the basal boundary is marked by a sudden increase in grain size where coarser grained shallower water facies directly overly finer grained more distal facies. This coarser grained facies, typically a few metres thick, is overlain by a T–R development consisting of a lower shaly unit which again is overlain by a coarsening upward, regressive unit. Examples of these T–R sequences are shown in core 7230/05-U-06 above 87 m and in core 7231/04-U-01 above 80 m.

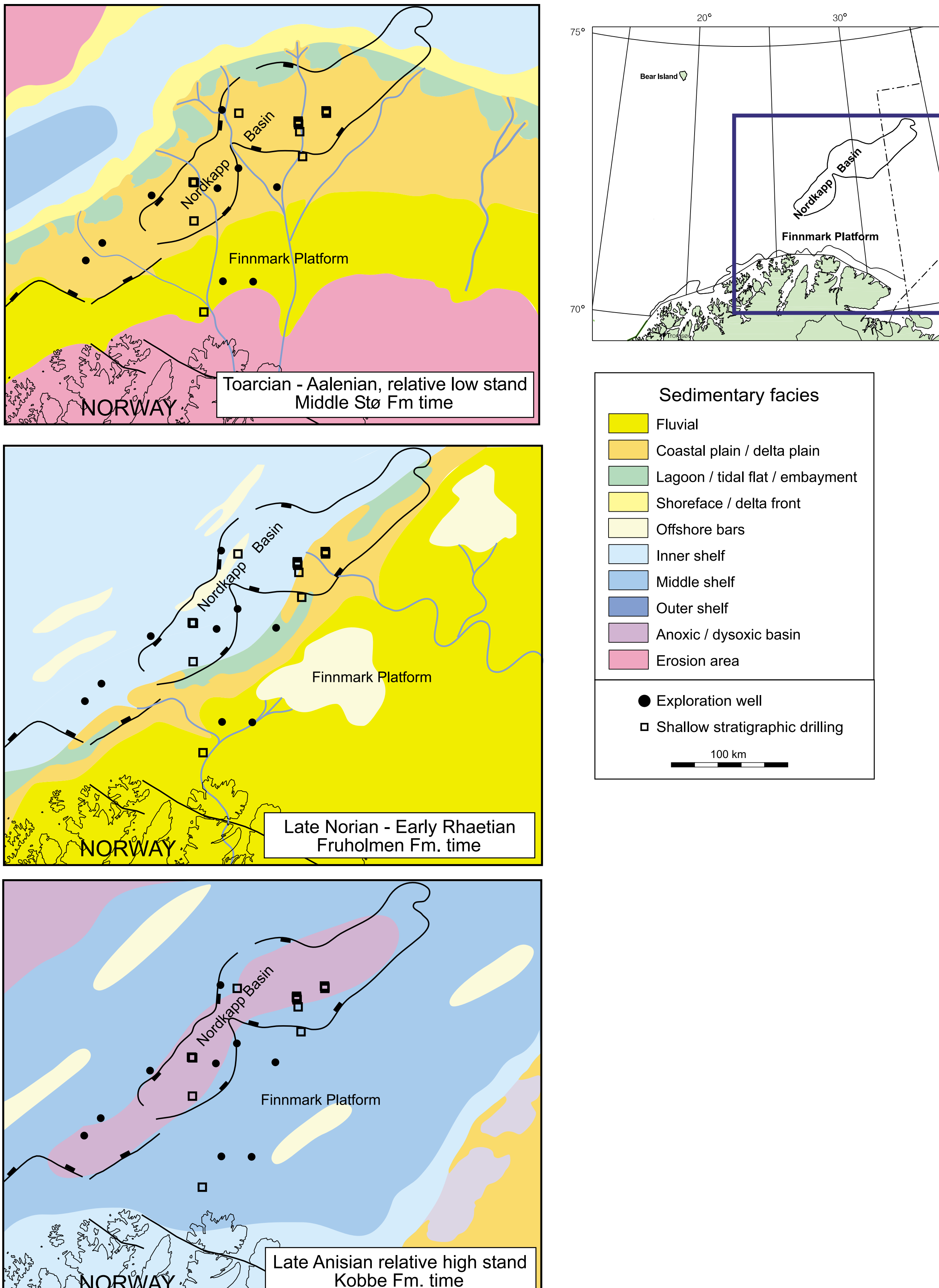
In general, these sequences are characterised by an abrupt facies change above the sequence boundary, sometimes with a conglomerate lag, including clasts derived from the immediately underlying beds, followed by a transgressive–regressive development in the overlying part of the T–R sequence. We interpret them as representing third order depositional sequences. In the Nordkapp Basin, they seem to be caused by semi-regional tectonic events interacting with local uplift/subsidence caused by salt movements.

8. Palaeogeography and regional facies variations

We briefly resume that the Nordkapp Basin was formed

Table 4
Reservoir properties of the three most prominent reservoir units in the cored succession

Core	Formation	Net/gross (*N*/*G*)	Average porosity (%)	Permeability (mD)	
				Range	Average
7227/08-U-01	Stø III	1	13	0.04–180	105
7230/05-U-02	Stø III	1	27	0.4–1200	225
7227/08-U-01	Stø II	1	9	14–1520	405
7230/05-U-02 and -03	Stø II	0.9	27	0.04–15 100	1560
7230/05-U-03	Fruholmen	0.9	29	0.04–14 500	1070
7227/08-U-01	Fruholmen	0.3	8	0.04	0.04
7230/05-U-05	Kobbe	0.5	28	0.04–105	47
7230/05-U-06	Kobbe	0.5	25	0.04–50	10
7228/03-U-01	Kobbe	0.3	26	0.7–150	48



Nordkapp Basin
Finnmark Platform
NORWAY
Toarcian - Aalenian, relative low stand
Middle Stø Fm time
Late Norian - Early Rhaetian
Fruholmen Fm. time
Late Anisian relative high stand
Kobbe Fm. time
20°
30°
75°
70°
Bear Island
Sedimentary facies
Fluvial
Coastal plain / delta plain
Lagoon / tidal flat / embayment
Shoreface / delta front
Offshore bars
Inner shelf
Middle shelf
Outer shelf
Anoxic / dysoxic basin
Erosion area
Exploration well
Shallow stratigraphic drilling
100 km

by rifting in the Late Devonian to Early Carboniferous and was filled by sediments of Late Palaeozoic, Mesozoic and Cenozoic age. The salt was probably first mobilised in Spathian time (Early Triassic) and movement culminated in the Ladinian (Middle Triassic). Later remobilisation probably occurred in the Tertiary. Minor but important salt movements also took place in the more quiet periods and many such events are locally expressed as unconformities in the shallow cores. Erosion during the (?)Eocene and Pliocene/Pleistocene removed up to 1200 m of the sediments from the area. Today, only a thin blanket of mainly Late Weichselian till, a few 10s of metres thick, covers the Mesozoic sediments and the Lower Tertiary remnants in the southwest.

The Anisian unit is time equivalent to the Kobbe Formation (Worsley et al., 1988) in the Hammerfest Basin (Fig. 5), where it is generally mud-rich and represents a marine environment in contrast to the paralic, inner shelf sandy Anisian sediments in the Nordkapp Basin. In a palaeogeographic sense, exemplified during sea level lowstand, the Nordkapp Basin was situated in a coastal plain/delta plain setting with a NE–SW-directed coastline to the west, touching the eastern margin of the Hammerfest Basin (Rasmussen, Kristensen, van Veen, Stølan, & Vail, 1993). It is likely that syndepositional salt movements and sediment loading caused formation of local basins with banks and islands in the present Nordkapp Basin area, which became part of a larger embayment connected to the open sea via the Hammerfest Basin to the southwest. Erosion of the islands may have resulted in deposition of local shorelines and banks associated with the islands, sometimes with deposition of lacustrian sediments in the depressions.

Fig. 12 shows a tentative palaeogeographic reconstruction of high sea level conditions in the Late Anisian. The broad and flat coastal plain areas were transgressed and the shoreline may have migrated hundreds of kilometres eastwards. The Nordkapp Basin area was probably part of an intra-platform basin with an irregular topography caused by synsedimentary salt movements. Many of the abrupt changes in facies stacking patterns, i.e. flooding surfaces and sequence boundaries, may be due to synsedimentary salt movements resulting in sudden local relative sea level rises or falls, rather than the regional sea level changes. Organic rich material was probably deposited in local basins with oxygen-poor bottom water related to salt withdrawal and may represent potential hydrocarbon source rocks. At the same time organic-rich mud was deposited further west, as recorded at the Svalis Dome (Bugge & Fanavoll, 1995; Isaksen & Bohacs, 1995).

A regional flooding event has been identified near the Anisian–Ladinian transition over large tracts of the Barents Sea. It was dated as latest Anisian on the western Bjarmeland Platform/Loppa High (van Veen et al., 1993) and on the Svalis Dome (Bugge & Fanavoll, 1995; Vigran et al., 1998). The transgression recorded in core -05 in the Nordkapp Basin probably reflects a slightly earlier and smaller Late Anisian event that also has been described from the Bjarmeland Platform by van Veen et al. (1993) and the Svalis Dome by Bugge and Fanavoll (1995) and Mørk and Elvebakk (1999).

The cored Ladinian–Lower Norian unit from the Nordkapp Basin is time-equivalent to the Snadd Formation in the Hammerfest Basin (Worsley et al., 1988). Although approximately 90 m in the middle of the unit were not cored, we suggest an overall regressive development from dysoxic storm-influenced shelf environments in the lower, Ladinian part to continental red beds in the uppermost Late Carnian–Early Norian part. Potential hydrocarbon source rocks may have accumulated in local depressions, perhaps under anoxic conditions, elsewhere in the Nordkapp Basin, as is recorded in the Ladinian part of the Botneheia Formation in Spitsbergen. Salt movement is indicated by soil development directly on shelf deposits in core 7230/05-U-04. This evolution contrasts the significantly thicker and more open marine development seen in the Hammerfest Basin area. The dusky red soil sediments in the lower parts of cores 7230/05-U-03 and 7227/08-U-01 are similar to those described by Worsley et al. (1988) in the uppermost part of the Snadd Formation. They also have striking similarities with semi-arid continental red bed development as is observed in the uppermost part of the De Geerdalen Formation on the island of Hopen, Svalbard.

The Norian–Rhaetian unit is time-equivalent to the Fruholmen Formation of Worsley et al. (1988). Paralic conditions existed in the northeastern half of the Nordkapp Basin and further southwestward, while more open marine facies occurred in the northwestern part of the basin. In core 7230/05-U-03 the Fruholmen Formation consists of approximately 90 m of medium- to very coarse-grained braided river delta front deposits with thin bay-fill shales, lying unconformably on paralic deposits of the Snadd Formation. In core 7227/08-U-01 the 26 m thick Fruholmen Formation equivalent comprises prodelta sandy siltstones with a few metres thick medium-grained sandstone. This contrast underlines the significant facies variations within the Nordkapp Basin in the latest Triassic. The development in the Nordkapp Basin resembles what is observed on Svalbard. Here, the Carnian to Early Norian De Geerdalen Formation (partly equivalent to the Snadd Formation) is separated by an unconformity from mid-late Norian sediments of the Wilhelmøya Formation (Mørk et al., 1993).

Hettangian–Lower Toarcian sediments seem to be absent

Fig. 12. Palaeogeographic reconstructions based on exploration wells and shallow stratigraphic drillings in the Nordkapp Basin area.

in the investigated parts of the Nordkapp Basin. The areas east of the Hammerfest Basin were probably uplifted during this period, possibly forming a land area with little or no sediment deposition. However, minor amounts of fluvial sediments, time equivalents to the Tubåen/Nordmela Formations, may have been deposited in rim synclines in the Nordkapp Basin.

The Toarcian–Bajocian unit (*Stø Formation equivalent*) in the Nordkapp Basin has a different development to that in the type area of the Stø Formation (Gjelberg et al., 1987; Olaussen et al., 1984). This is particularly the case for the lower part, which is represented by delta front and delta plain sediments (mouth bars and distributary channels and associated bay fill and delta plain deposits) in the Nordkapp Basin. A palaeogeographical map of the lower deltaic sediments of the Stø Formation (Stø unit 2) during low sea level is illustrated in Fig. 12. The Nordkapp Basin was located in a sandy coastal/delta plain setting with flood plain deposits towards south and by open marine conditions towards north. This lower part of the formation may represent a lateral marine time-equivalent to the fluvial and estuarine sandstones recorded between 1522 and 1406 m in well 7125/1-1 (well B of Bergan & Knarud, 1993). This well was drilled in a basinal position relative to well 7124/3-1 (well A of Bergan & Knarud, 1993) where the Stø Formation represents fluvial deposits. It is correlated to the Stø unit 2 of Gjelberg et al. (1987). The upper part of the Stø Formation is represented by strongly bioturbated, glauconitic and phosphoritic middle to lower shoreface sandstones, equivalent to Stø unit 3 of Gjelberg et al. (1987). In a palaeogeographical sense, the shoreface condition in the Nordkapp Basin extended southward to a shoreline located on the Finnmark Platform.

The Upper Bathonian–Lower Callovian unit (*Fuglen Formation equivalent*) was deposited during a period when the Nordkapp Basin area was a stable marine shelf with partly condensed sedimentation, however, more continuous sedimentation than in the central Hammerfest Basin. The development from the underlying Stø Formation equivalent is similar to that seen in the Troms III area southwest of the Hammerfest Basin (Smelror, Mørk, Mørk, Løseth, & Weiss, 2001), but different from that in the central Hammerfest Basin where an abrupt lithological change marks a hiatus that spans the Bathonian stage (Fig. 5).

Upper Oxfordian–Lower Volgian shales of the Hekkingen Formation were deposited over most of the southwestern Barents Sea. In the Late Oxfordian–Early Volgian, the Nordkapp Basin was deeper than the surrounding platform areas. The basin itself comprised several smaller sub-basins between the salt diapirs. This is indicated by the doubling of the thickness from the flanks of the diapirs to the centres of the sub-basins. The environment was restricted and the bottom water conditions anoxic to dysoxic, while the shallow water layers were oxygenated. Most of the Hekkingen Formation in the area comprises the older Alge Member, which is dominated by organic-rich paper shales exhibiting high gamma-ray signatures. Only 13 m of the Krill Member were cored in 7231/01-U-01, where these rocks are characterised by less organic-rich and less radioactive claystones deposited in a dysoxic environment. A thicker development of the Krill Member is expected in the synclines.

The Lower Hauterivian unit (*Knurr Formation/Klippfisk Formation equivalent*) in core 7231/01-U-01 has also been encountered in other shallow stratigraphic cores from a wide area. Examples include the northern Bjarmeland Platform (7430/10-U-01), the northern and western margin of the Bjørnøya Basin (7320/03-U-01 and 7425/09-U-01) (Smelror et al., 1998), and a location off Mid Norway (IKU82-7, Århus, Birkelund, & Smelror, 1989; Århus, Kelly, Collins, & Sandy, 1990). All the cores in this study (correlated with the Knurr Formation) represent a bivalve-dominated carbonate platform with slow sedimentation rate. This differs from the type area of the formation in the central Hammerfest Basin, where the basinal setting gave a less punctuated history of sedimentation, with a higher clastic content and a relatively low carbonate content (Worsley et al., 1988). Thus, the Lower Hauterivian unit compares more closely in lithology with the platform carbonates of the Klippfisk Formation (Smelror et al., 1998).

Barremian–Lower Albian unit (*Kolje Formation equivalent*). After deposition of the Knurr Formation equivalent the platform areas were probably partly exposed and eroded, resulting in the above-mentioned Early Hauterivian–Early Barremian hiatus between the Knurr and Kolje Formations. This unconformity coincides with extensive volcanism and intrusive activity on Svalbard, which caused heating and consequently uplift of the Svalbard area (Gjelberg & Steel, 1995). The uplift and erosion were followed by a large-scale and multi-episode progradation of shoreline from northeast towards southwest during the Barremian–Cenomanian time. The Fennoscandian Shield may have been transgressed during this time as the Barremian–Cenomanian clinoforms onlap the underlying succession on the Finnmark Platform. The transgression in the Early Barremian led to deposition of open marine claystones (core 7231/01-U-01). The regressive trend observed in core 7231/04-U-01 (Aptian–Early Albian age) represents the upper part of a sedimentary wedge that prograded into the Nordkapp Basin from the northeast. The wedge spans an age range from Barremian to Early Albian, and the sequence exhibits clinoforms downlapping the underlying Knurr/Klippfisk Formation. On seismic data, the wedge pinches out to the south and west.

Middle Albian–Lower Cenomanian unit (*Kolmule Formation equivalent*). A lithological change from grey claystone to darker grey shale at 62.5 m in core 7231/04-U-01 is interpreted to have resulted from a relative rise in sea level that caused drowning of the Aptian–Lower Albian clastic wedge described before. A new progradation from the northeast resulted in deposition of an up to 1000 m thick unit of Middle–Late Albian age. This wedge extends farther to the south and west than the underlying Barremian–Lower Albian wedge. The Late Albian–Cenomanian shoreface sandstones probably represent the final stage of this large-scale progradation when the shoreline finally migrated towards southwest across the Bjarmeland Platform/Nordkapp Basin.

9. Conclusions

From the Early Triassic to Late Cretaceous, the palaeoenvironment of the Nordkapp Basin area shifted between marine basin and shelf to coastal and delta plain settings. The coastline was periodically situated to the west of the Nordkapp Basin, but at times the basin subsided and formed a large embayment communicating with the open sea via the Hammerfest Basin in the southwest. This occurred in periods during Early–Middle Triassic, Early–Late Jurassic and probably during Early Tertiary. These developments were associated with salt movements that formed local depocentres and highs within the basin.

The oldest cored rocks are of Anisian age and represent an overall shallowing from inner shelf to coastal plain environment. Salt diapirism may have formed local highs that acted as local sediment sources.

The initial salt movements formed local, restricted subbasins during the Spathian and Anisian in the Nordkapp Basin. This may have been favourable for the deposition of organic rich sediments with hydrocarbon source-rock potential. The Spathian and Anisian sediments are source rocks for hydrocarbons further west and northwest in the Barents Sea.

The Ladinian is characterised by open marine shales, which are correlated with the Snadd Formation. Distinct dusky red clayey pedogenic rocks of Late Carnian/Early Norian age are overlain by coarse-grained, feldspar-rich, deltaic sandstones of Norian–Rhaetian age (Fruholmen Formation equivalent). At the Triassic/Jurassic boundary there is a transition to more mature sandstones, equivalent to the Stø Formation. These sandstones were deposited in an inner shelf environment, developing through delta front/prodelta environment up to tidal plain with distributary channels and mouth bar complexes. Coastal processes in the great embayment that covered the Nordkapp Basin in the Middle Jurassic probably enhanced the sorting of this sand and improved its potential as a reservoir for hydrocarbons.

During the Middle and Late Jurassic there was a general transgressive trend from deposition of the deltaic sandstones of the Stø Formation to the organic rich, anoxic to dysoxic shales of the Hekkingen Formation. These potential hydrocarbon source rocks are generally oil-prone, but thermally immature at the core sites.

The Hekkingen Formation shales are unconformably overlain by a thin, condensed limestone unit (Klippfisk Formation) of Early Hauterivian age, which is typical for platform settings over a wider area. Two sedimentary wedges transgressed the Nordkapp Basin from the northeast in the Early Cretaceous. They are dated as Barremian–Lower Albian and Middle–Upper Albian.

The youngest pre-Quaternary sediments that are still preserved in the eastern segment of the Nordkapp Basin are dated as Early Cenomanian. Palaeocene/Eocene sediments are probably present in the southwestern part of the basin. All younger sediments were removed during the Cenozoic erosion.

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