Early Tertiary sedimentation and salt tectonics in the Nordkapp Basin, southern Barents Sea

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Detailed seismic interpretation of the early Tertiary sediments in the Nordkapp Basin (southern Barents Sea) has revealed the nature of sedimentation within a basin strongly influenced by salt diapirism. Two phases of reactivation of salt movement have been defined, and are thought to reflect reactivation of older fault regimes in the Barents Sea during the earliest phase of sea-floor spreading in the Norwegian–Greenland Sea. Earliest Palaeocene deposition was characterized by sediment gravity flows along the eastern basin margin and along intrabasinal highs. During a relative sea-level rise in mid/late Palaeocene, hemipelagic deposition prevailed in the Nordkapp Basin. Late Palaeocene/early Eocene sedimentation was dominated by progradation from the Finnmark Platform into the Nordkapp Basin.

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The Barents Sea covers an intracratonic basin with Devonian to Quaternary sediments over a basement of Caledonian and pre-Caledonian rocks. The geological history and tectonic framework of the area are described in a number of publications (Faleide et al. 1984; Gabrielsen et al. 1990; Rønnevik & Jakobsen 1984; Vorren et al. 1986, 1991). Here only a brief summary focusing on the Nordkapp Basin will be given.

A regional rift episode during Late Devonian to Early Carboniferous time affected the Barents Sea, Bjørnøya and Svalbard. During this time period the Nordkapp Basin and a number of other N–S to NE–SW-trending basins were formed. The Nordkapp Basin is more than 300 km long and 30–80 km wide, with a general NE–SW trend, the eastern part having a more E–W orientation. The basin is defined at base Cretaceous level (Gabrielsen et al. 1990). At the Palaeozoic level, the southwestern part of the basin is a half graben, while the central part is a graben (Jensen & Sørensen 1992). Shallow flat-lying platforms with only minor post-Palaeozoic relief surround the Nordkapp Basin and the basin is characterized by numerous salt structures.

Geometrically, the salt structures in the basin are walls, irregular massifs and diapirs, all piercing to Quaternary level. Understanding the origin and movement-history of these salt structures is important in the hydrocarbon exploration of the Nordkapp Basin.

The Pre-salt history of the Nordkapp Basin is not known in detail, but a Devonian–Early Carboniferous development with rifting and clastic sedimentation has been suggested. Halokinesis is believed to have started in the early Triassic and was reactivated in Tertiary time.

The main objective of this study is to elucidate the early Tertiary sedimentary regime of the southwestern Nordkapp Basin (Fig. 1). The early Tertiary sedimentation in the Nordkapp Basin is highly affected by the latest phase of salt diapirism. Evaluation of the complex interplay between salt movement and sedimentation is therefore an important aspect in deducing the early Tertiary evolution of the Nordkapp Basin.

Material and methods

The seismic data used in this study are provided by IKU Petroleum Research (Fig. 2).

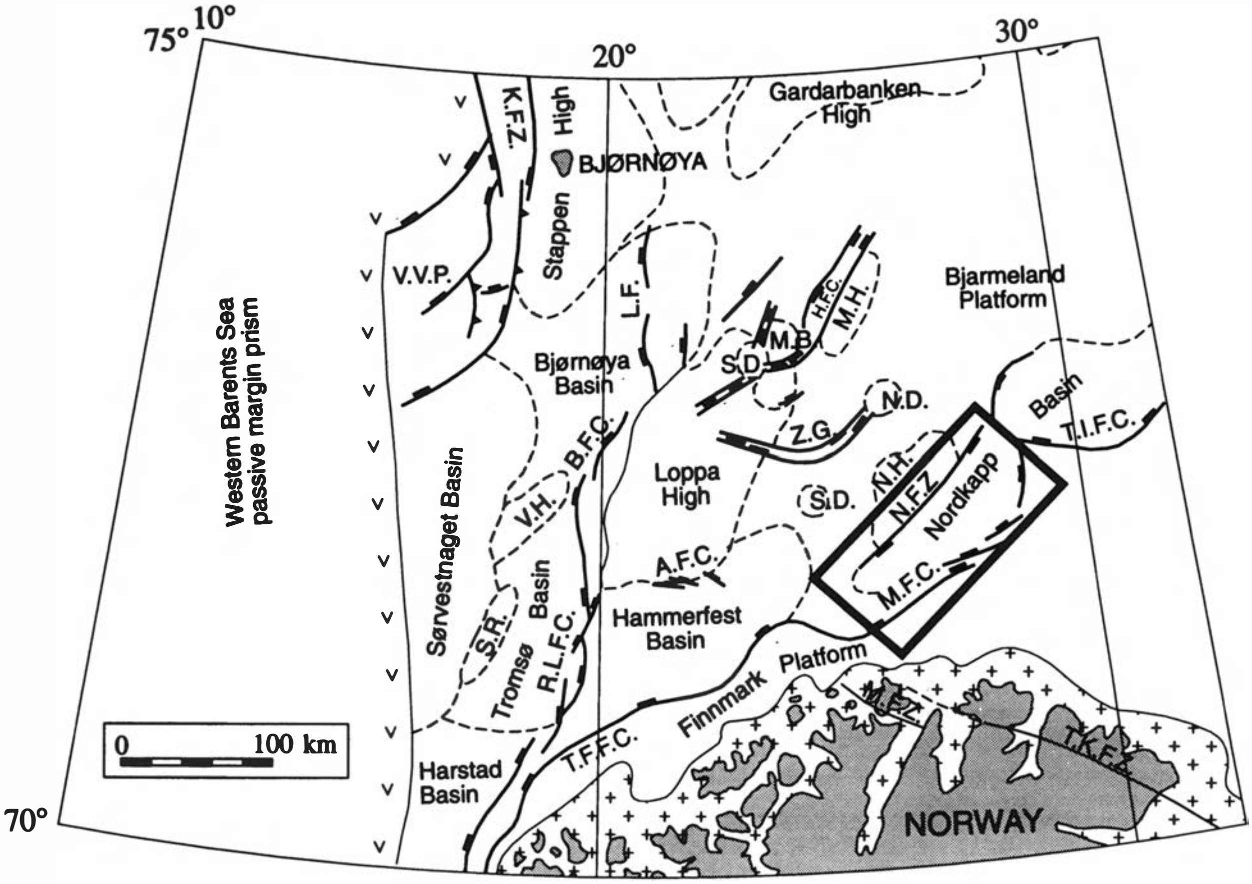
Seismic lines collected by the Norwegian Petroleum directorate (NPD) in 1985 and 1986 have been made available from Statoil A/S. Additionally, selected lines from other surveys have been used to improve maps, make regional correlations and to illustrate key problems of the Tertiary stratigraphy in the Nordkapp Basin. These are: lines D14-84 and 7150-74 presented in Figs. 7, 8 and 3 respectively.

The IKU lines include air-gun (digital data) and sparker (analogue) data. The digital data penetrate down to 2.5 sec. TWT. The analogue data penetrate down to 1.0 sec. TWT. The NPD data are digital and penetrate down to 6.0 sec. TWT. Well information has not been available from the area.

The fundamental procedures and techniques of seismic sequence stratigraphy outlined by Vail et al. (1977) and Vail (1987) were applied to delineate the bounding unconformities and other surfaces within the Tertiary package in the Nordkapp Basin. Delineation of erosional truncation surfaces and various onlap, downlap and toplap surfaces was a fundamental step in developing a valid stratigraphic framework in the Nordkapp Basin.

Seismic stratigraphy

The Tertiary package in the Nordkapp Basin can be subdivided into four units, designated a1, a2, a3 and a4



ABBREVIATIONS:

A.F.C.	Asterias Fault Complex	N.D.	Nordvarg Dome
B.F.C.	Bjørnøyrenna Fault Complex	N.F.Z.	Nysleppen Fault Zone
B.F.Z.	Billefjorden Fault Zone	N.H.	Nordsel High
H.F.C.	Hoop Fault Complex	R.L.F.C.	Ringvassøy - Loppa Fault Complex
K.F.Z.	Knølegga Fault Complex	S.D.	Samson Dome, Svalis Dome
L.F.	Leirdjupet Fault	S.R.	Senja Ridge
L.F.Z.	Lomfjorden Fault Zone	T.F.F.C.	Troms Finnmark Fault Zone
M.B.	Maud Basin	T.I.F.C.	Thor Iversen Fault Complex
M.F.C.	Måsøy Fault Complex	T.K.F.Z.	Trollfjord - Komagelv Fault Zone
M.F.Z.	Magerøy Fault Zone	V.H.	Veslemøy High
M.H.	Mercurius High	V.V.P.	Vestbanken Volcanic Province

Fig. 1. Location map of the study area. Nomenclature of structural elements is according to Gabrielsen et al. (1990).

(Fig. 3). These units represent different phases in the sedimentary evolution of the basin. Additionally, a series of complex fills, designated Na3–Na6, are found between the salt diapirs in the northern part of the study area (Fig. 4).

An upper regional unconformity (URU), probably of fluvial origin, but reshaped by glacial processes in the late Cenozoic (Vorren et al. 1986, 1991), defines the base of the glacigenic sediments on the Barents Sea shelf and truncates all older units in the area.

The thickness of the Tertiary sediments in the Nordkapp Basin varies from 0.5 sec. TWT in the southern part to a thin cover in the northern part (Fig. 5a). Tertiary sediments are missing in the northeastern Nordkapp Basin. In the southwest the thickness increases towards the transition to the Hammerfest Basin, where it thins over the ridge between the two basins before thickening again in to the Hammerfest Basin (Knutsen & Vorren 1991). The Tertiary sediments are thickest along the axis of the rim synclines close to the salt diapirs (Fig. 5a), indicating syn-sedimentary salt movement.

The base Tertiary reflection is a marked unconformity, defining a major sequence boundary. In the central parts of the basin, the base Tertiary reflection is essentially a non-faulted, high-amplitude reflection. The shape of the Tertiary basin is, however, strongly affected by salt tectonism in that this basal reflection is frequently bent up and broken by salt diapirism (Figs. 3 and 5b). The few faults that influence the Tertiary sediments in central parts of the basin are largely related to this episode of tectonism. The Tertiary sediments are also disturbed by movement along the larger fault complexes which border the basin (Figs. 3 and 5b).

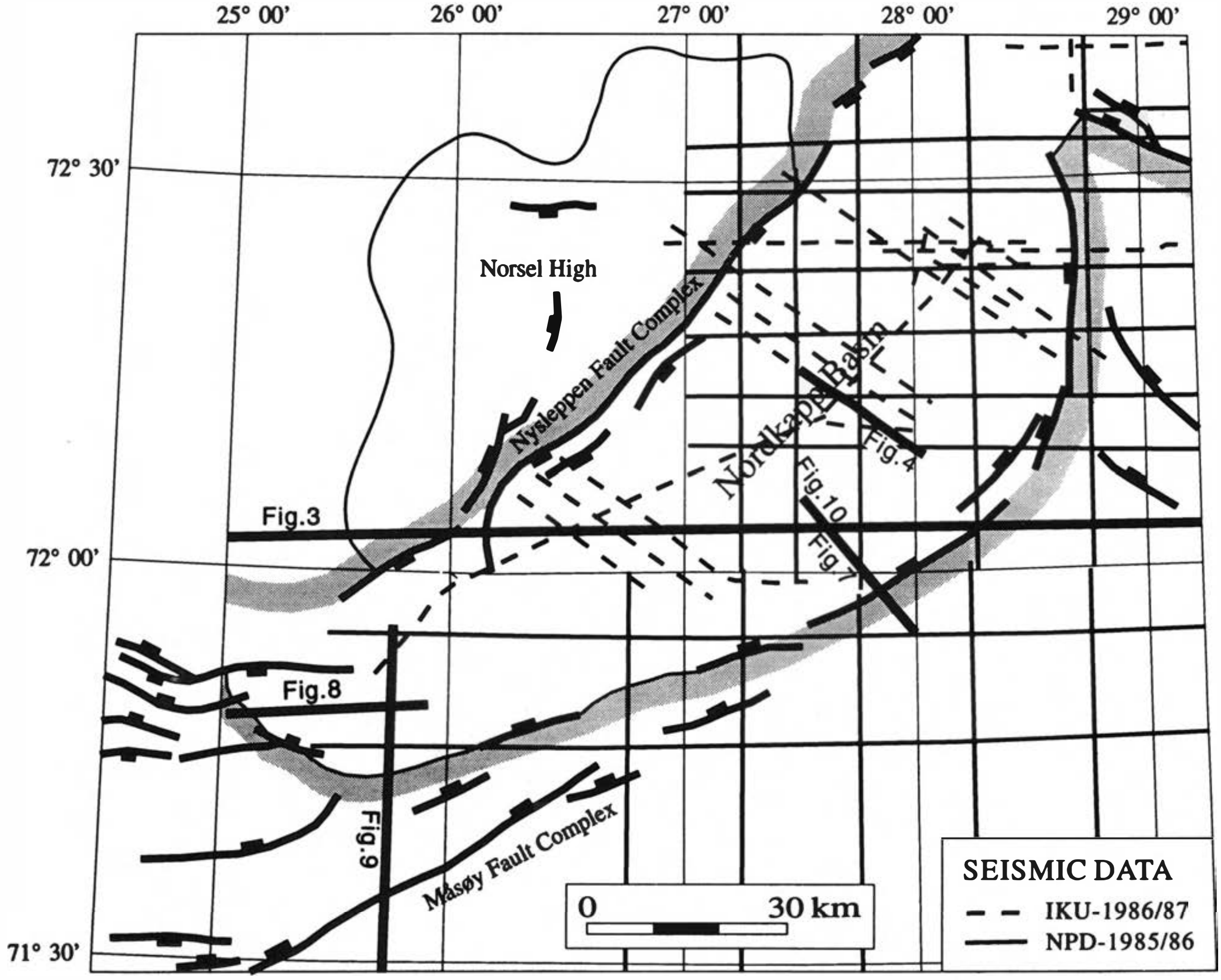


Fig. 2. Seismic database used for this study. The thick lines indicate the location of the profiles illustrated in subsequent figures by corresponding numbers.

Unit a1

Immediately above the base Tertiary reflection a depositional system of complex chaotic mounds is found on the basin margin east and south in the southwestern Nordkapp Basin (Figs. 6a and 7). Mapping of the complex mounds reveals two large lobes separated by an area where erosion of the surface defined by the base Tertiary reflection possibly can be indicated (Fig. 6a). Unit a1 is generally thin with an average thickness between 10 and 50 ms TWT. In the northeastern corner of the basin,

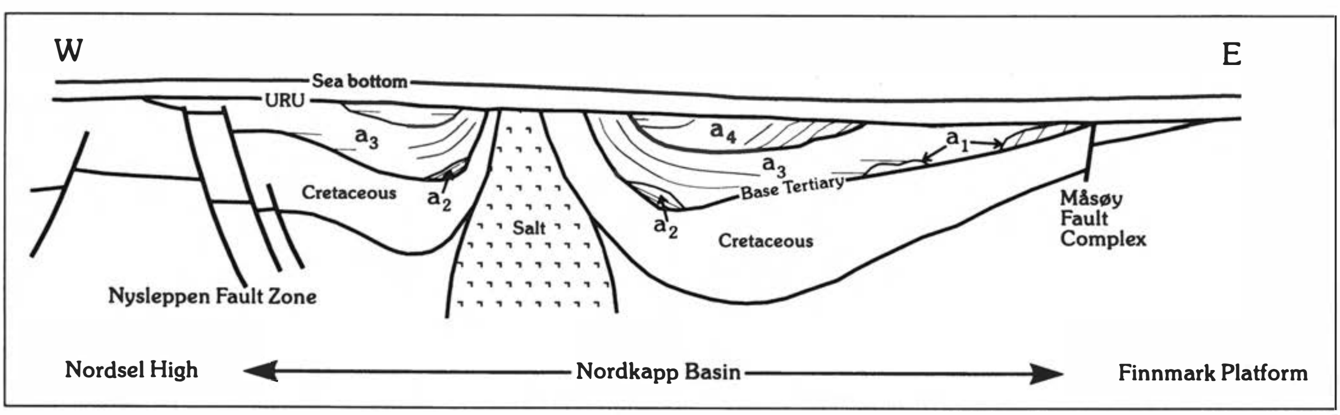


Fig. 3. Schematic cross-section of the Tertiary package in the Nordkapp Basin. On the eastern slopes of the basin a mounded complex (unit a1) is deposited. A similar unit (a2) is found on the flanks of the salt diapirs. An acoustically semi-transparent unit (a3) overlies, and onlaps the mounded complexes on the basin margin. The youngest unit (unit a4) is defined at the base by a downlap surface, thus marking a flooding surface. A regional unconformity (URU) truncates all other sedimentary units on the shelf and defines the base of a thin Quaternary cover. See Fig. 2 for location of profile.

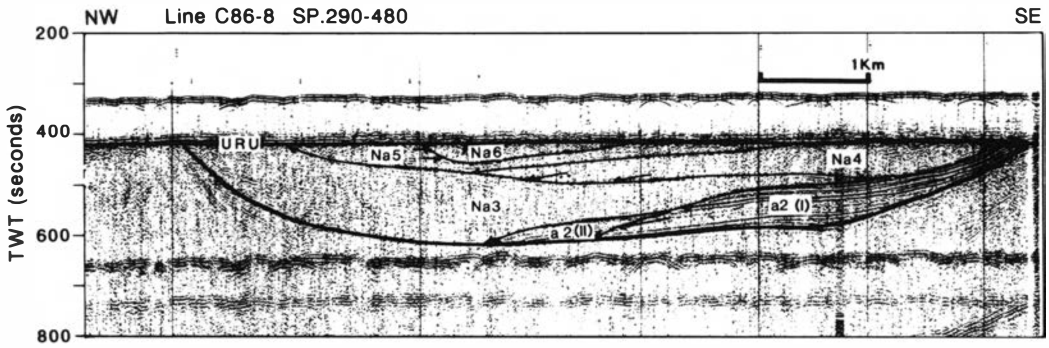


Fig. 4. Segment of seismic profile, line C86-8 s.p. 290-480, illustrating the sequential division in central parts of the northern study area. See Fig. 2 for location of profile.

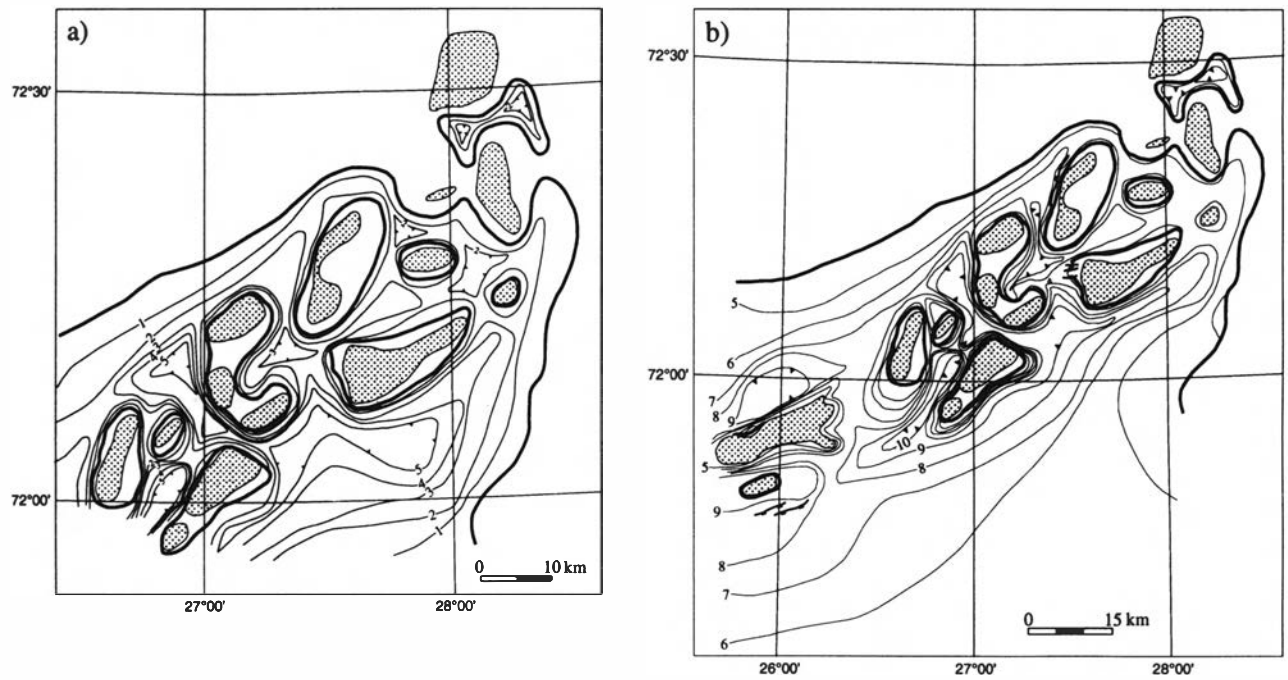


Fig. 5. (a) Isopach map showing the total Tertiary thickness in the southwestern Nordkapp Basin. Contour interval 100 ms TWT. Note the thickness increase close to the salt diapirs. (b) Isochrone map of the base Tertiary reflection in the southwestern Nordkapp Basin. Contour interval 100 ms TWT, measured from sea level. Dotted areas represent salt piercing to Quaternary level.

however, accumulations of more than 100 ms TWT thick occur.

Most of the mounds have a chaotic or semi-transparent internal reflection pattern, but in some cases the internal reflections form a seismic downlap configuration at the lower boundary (Fig. 7). These reflections have a considerably steeper dip than the lower boundary, and are considered to indicate progradation.

Unit a2

At the flanks of the diapirs unit a2 forms fan-like bodies with parallel, more or less continuous internal reflections, variously showing onlap, downlap and draping configuration against the base Tertiary reflection. Unit a2 forms fills at the slopes of the salt diapirs, thus resembling a type of slope front fill, or, alternatively, smaller fan-bodies at the diapir slopes (Figs. 4 and 6b).

The maximum thickness of unit a2 does not exceed 80 ms TWT in any part of the study area. Internal reflections seem to diverge slightly in the direction from the salt diapirs (Fig. 4). This diverging pattern is hardly of primary origin, but rather is due to compression of the strata near the salt diapirs as a consequence of the Tertiary halokinesis.

In the northern part of the study area an unconformity has been identified within unit a2 (Fig. 4) separating it into an upper and a lower part, each of which displays identical internal reflection patterns. On seismic dip-profiles, the boundary between the upper and lower parts is delineated by an erosional truncation of internal reflections in the lower part of the unit. On a strike-oriented cross-section, the erosive boundary between the upper and lower parts shows gentle 'U'-shaped forms, which can be interpreted as channels. The boundary relationships between the upper and lower parts of the unit show lateral variations. Internal reflections in the upper part of the unit do in some cases show low-angle onlap at the lower boundary. In other parts of the basin it appears that the sediments in the upper part of unit a2 lie conformably on the boundary surface, draping older

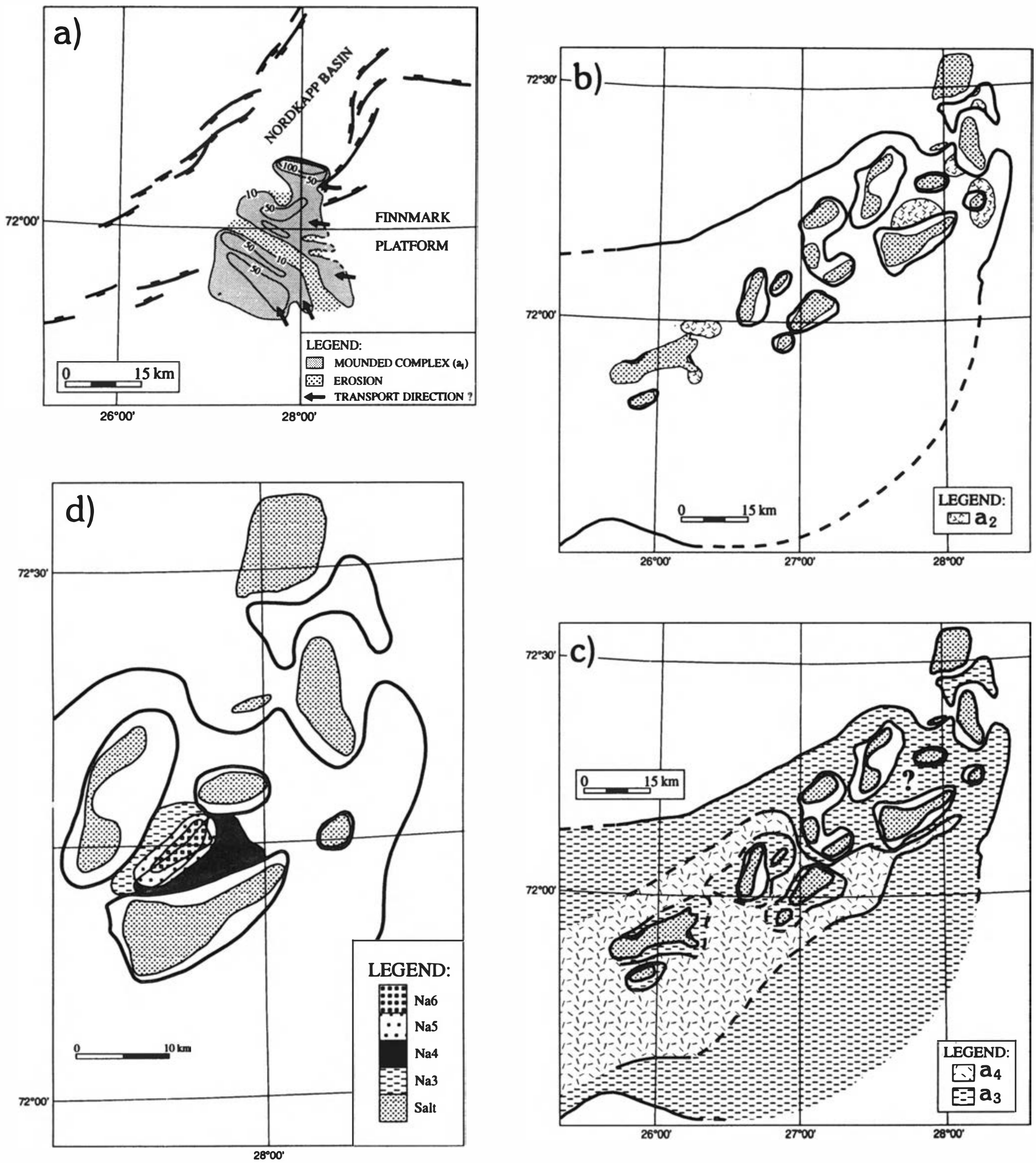


Fig. 6. Distribution of the individual Cenozoic subunits in the Nordkapp Basin. (a) Mounded complex (unit a1) at the eastern basin flank. (b) The slope fills (unit a2). (c) Units a3 and a4. Note that the sediments that underlie sequence a4 are mainly unit a3. (d) Detailed map of the northern part of the study area, showing the distribution of the complex basin-filling subunits Na3, Na4, Na5 and Na6.

relief. It may be argued that the upper and lower parts of the unit should have been divided into two individual units (cf. Mitchum et al. 1977), but the upper and lower parts of this unit are probably genetically related, and are considered to belong to the same depositional system and are therefore presented as a single unit.

Unit a3

This unit was deposited over the entire study area (Fig. 6c) and varies in thickness from 50 ms TWT in the northern part to 300 ms in the south. In central parts of the study area unit a3 is almost acoustically transparent,

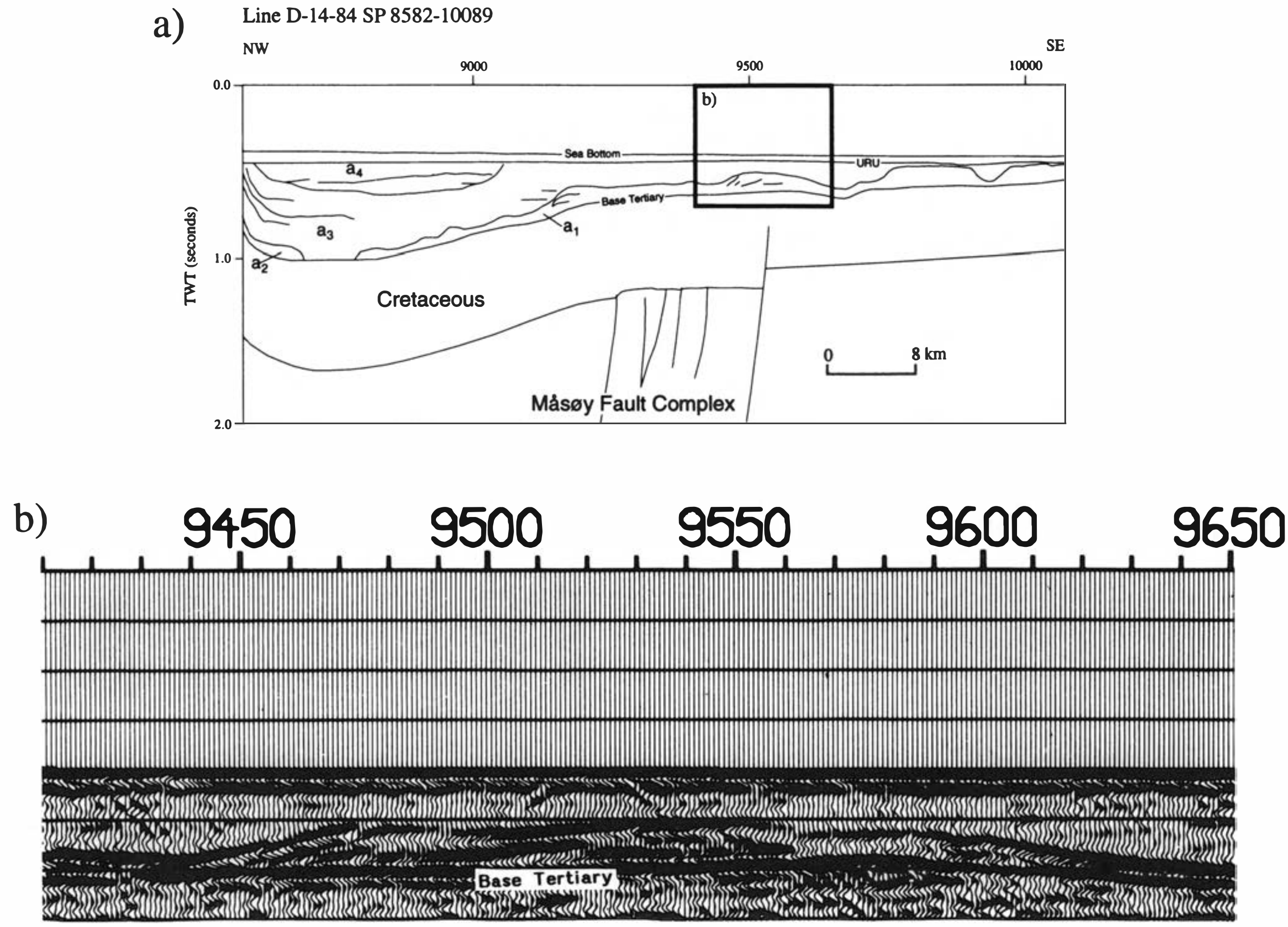


Fig. 7. Segment of seismic profile, line D14-84 s.p. 8600-10089, showing example of mounding close to the base of the Tertiary sequence. The mounds form a complex of ridges and lows which defines unit a1. (b) Enlarged segment of line D14-84. Note the internal reflections in unit a1, indicating progradation. See Fig. 2 for location of profile.

with only a few, weakly developed, subparallel internal reflections. Along the basin slope and over the platform areas internal reflections are seen. Unit a3 is here recognized by subparallel, more or less continuous internal reflections that onlap the lower boundary (Fig. 7a). It also occurs between the mounds represented by the upper boundary of unit a1, where a bidirectional onlap geometry can be observed. In these areas unit a3 shows a well-developed, aggrading stacking pattern.

Towards the salt diapirs the internal reflections are bent up, but onlap is not observed. The unit therefore blankets the central parts of the basin (Fig. 7).

Unit a4

The unit is present over most of the study area, but is confined to the rim synclines that developed around the salt diapirs (Fig. 6c). The thickness of the unit varies from 50 ms TWT in the north to about 200 ms in the south. The upper part of the unit is truncated by URU, which results in thinning over the platform areas. Unit a4 may have had a much larger distribution, but evidence of this is removed by later erosion.

A number of clinoforms prograding from the Finnmark Platform downlap the lower boundary of unit a4 (Figs. 8 and 9). These show decreasing amplitude in downdip direction, and grade into flat-lying, subparallel reflections towards the basin centre. Where the lower boundary is bent up by salt diapirism the internal reflections onlap the lower boundary (Fig. 10).

Subunits Na3–Na6

Between the salt diapirs in the northern part of the study area, a complex pattern of basin fills has been identified (Figs. 4 and 6d). These subunits, labelled Na3–Na6, form realtively thin (50–80 ms TWT) fills between the salt diapirs. The internal reflections in the subunits all show a similar pattern, with subparallel reflections onlapping the lower boundary. Correlation to the other depostitional systems in the Nordkapp Basin is not possible. It is possible that Na3–Na6 might be a poorly expressed stratigraphical equivalent to units a2 and a4.

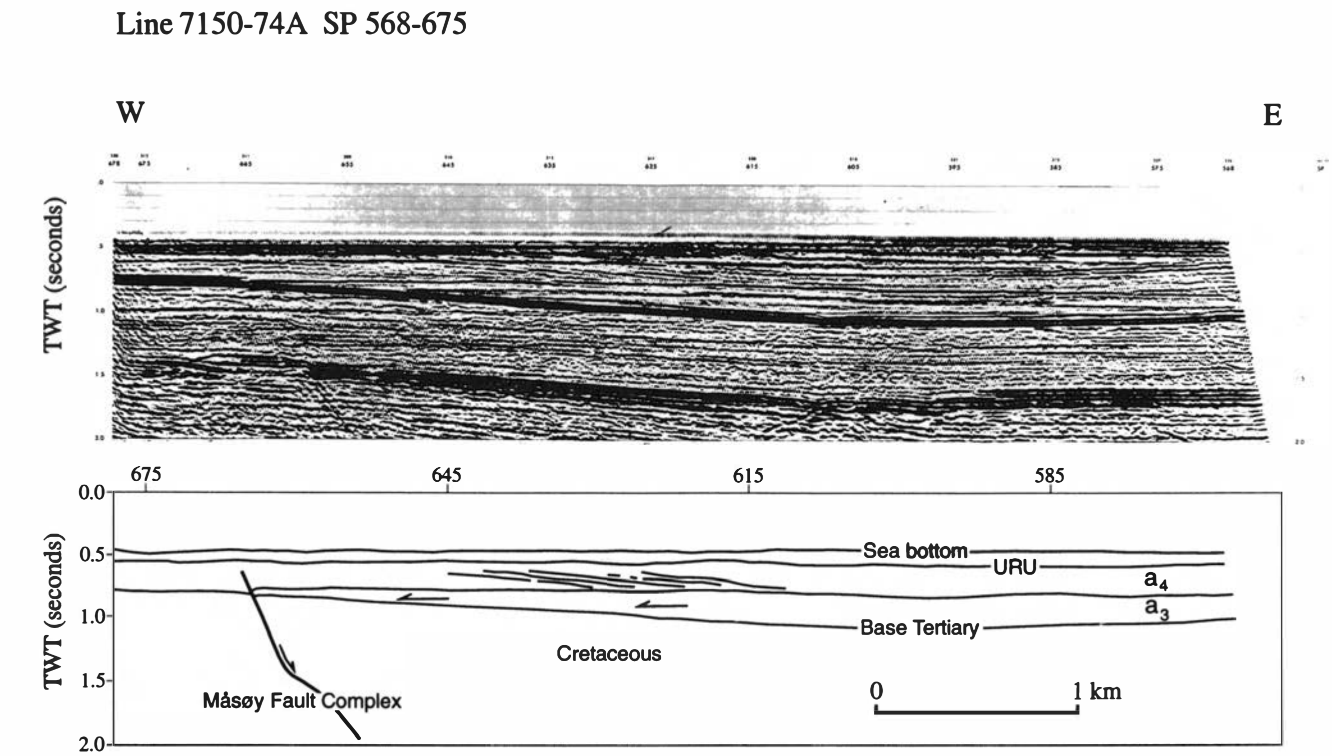


Fig. 8. Segment of seismic profile, line 7150-74A s.p. 568-678. Prograding clinoforms built out from the platform areas in the west. Note that these oblique reflections tend to 'flatten out' towards the basin and grade into subparallel, horizontal reflections. See Fig. 2 for location of profile.

Age and regional correlations

Dating the Cenozoic reflections and units in the Nordkapp Basin is problematic,because of the lack of well data from the area. Our age suggestions of the Cenozoic reflections and units in the Nordkapp Basin are therefore based on correlations to earlier work further west in the Barents Sea, and regional considerations about the sedimentary evolution in the region (Fig. 11).

The base Tertiary unconformity and the acoustically semi-transparent unit a3 in the Nordkapp Basin can be traced westwards into the Hammerfest and Tromsø Basins, where the unit is penetrated by several commercial wells.

Based on the datings in the Hammerfest Basin, it is clear that the base Tertiary reflection represents a time-transgressive surface. The longest stratigraphic break is on the Loppa High (Fig. 1) (Carnian–late Palaeocene in

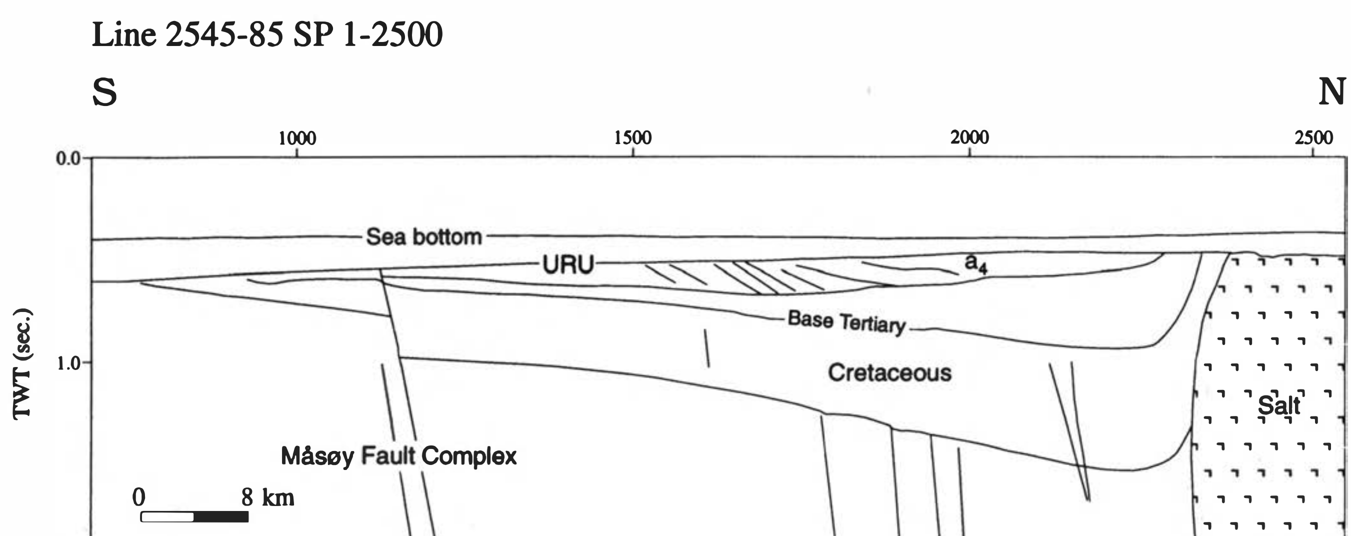


Fig. 9. Line drawing of seismic profile, line 2545-85 s.p. 1-2000. Clinoforms prograding from the Finnmark Platform in the south. The relation between the fault-offset of base Tertiary – and pre-Tertiary – reflections over the Måsøy Fault Complex shows that the Nordkapp Basin underwent less subsidence during the Cenozoic than during the Mesozoic. See Fig. 2 for location of profile.

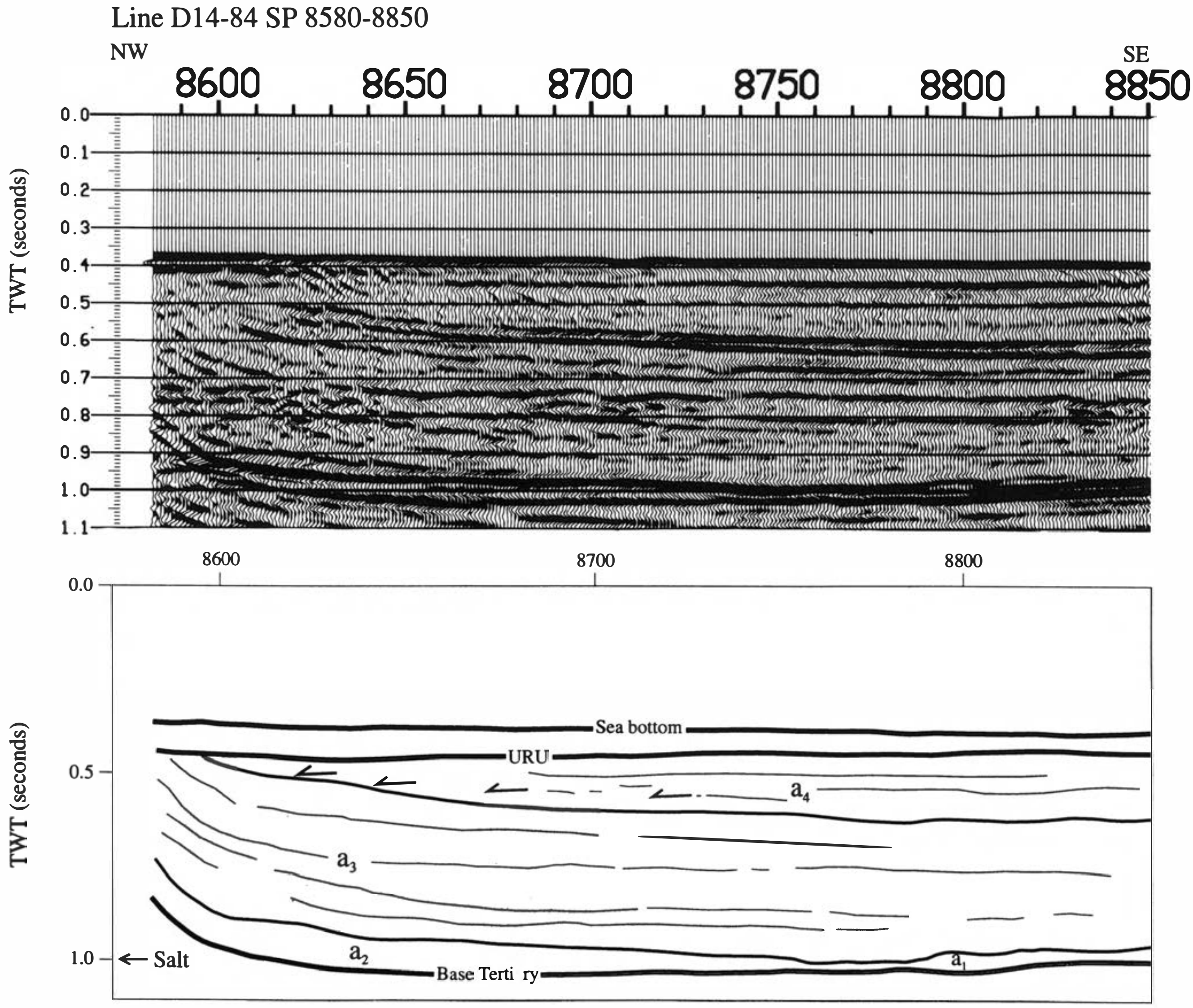


Fig. 10. Enlarged segment of seismic profile, line D14-84 s.p. 8580-8850. (a) Uninterpreted and (b) interpreted version of line; onlap configurations at lower boundary of unit a4 towards the salt diapirs are indicated by arrows. See Fig. 2 for location of profile.

well 7120/2-1), a bit shorter in the Hammerfest Basin (Campanian–late Palaeocene in well 7121/4-1) and least in the Tromsø Basin (Maastrichtian/late Campanian–early Palaeocene in well 7119/7-1) (Knutsen & Vorren 1991).

From the well data in the Hammerfest Basin and the Tromsø Basin, the correlative sediments to unit a3 are assumed to have an age of mid/late Palaeocene, in places the upper parts are dated to early Eocene (Knutsen & Vorren 1991). Units al and a2 are probably of approximately the same age and were deposited immediately before unit a3 (Fig. 11).

The internal reflection pattern in unit a4 has similarities to a depositional system (dated to late Palaeocene–early Eocene) described in the Hammerfest Basin by Knutsen & Vorren (1991). Unit a4 may thus be a remnant of an early Eocene sedimentary unit in the Nordkapp Basin (Fig. 11).

Sedimentary environment

Unit a1, complex/chaotic mounds

The base Tertiary unconformity is interpreted to have formed during a fall in the relative sea level. This relative sea-level fall has possibly led to subaerial exposure and erosion of highs bordering the basin. The erosional products prograded over the platform areas and were deposited in the deeper marine area as the complex mounded facies of unit a1 (Fig. 7).

A sediment gravity flow model can be used in the interpretation of the basinward part of unit a1. The initiation of the depostitional system is a function of the interaction between eustasy, basin subsidence and sediment supply (Van Wagoner et al. 1988). Considering the amount of sediment contained in the lobes (Fig. 6a), the mass flow processes have remobilized significant volumes of sediments from the adjoining platform areas, and

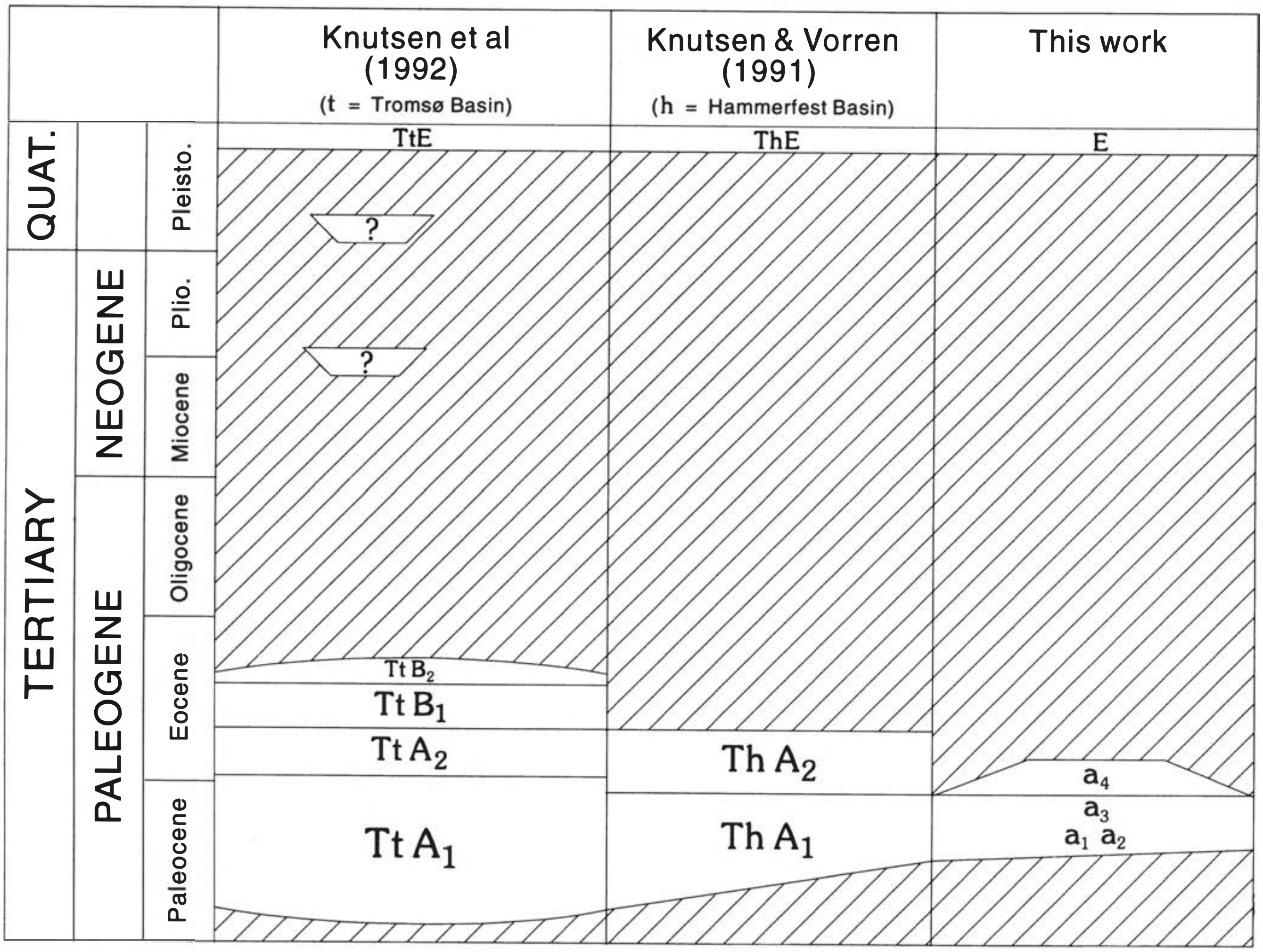


Fig. 11. Correlation diagram of the Cenozoic seismic stratigraphic units in the southern Barents Sea.

transported them downslope to the basin slope and plain. It is probable that some sedimentary system, possibly deltaic, and/or a river acted as a source for the gravity flow system.

The distribution of the complex mounds, east and south of the Nordkapp Basin respectively (Fig. 6), indicates that ther must have been at least two, possibly more, source systems acting simultaneously. Most of these proximal features have been removed by later erosion, leaving mainly the distal portion of the system.

A lowering of the sea level over the basin flanks and adjoining shelf areas would in itself lead to increased erosion and sediment transport into the basin. The sudden release of sediment gravity flows could also be caused by the combined effect of sea-level fall and some other triggering mechanism, such as tectonic movements. Remobilization of salt in deeper parts of the basin could also cause a significant increase in the slope gradient and thereby cause slumping and mass movements on the upper slopes of the basin margin. The available data in the area are, however, not adequate to test this hypothesis.

Unit a2, slope front fills

The deposition of unit a2 has led to the formation of a series of parallel reflections, which variously onlap, downlap and drape the topography of the base Tertiary reflection. The relatively high amplitude of the internal reflections indicates varying depositional energy (Beaudry & Moore 1985; Badley 1985). Minor unconformities within the unit indicate that the sediments were deposited in pulses, creating a stacked pattern of process-related subunits (Fig. 4).

Unit a2 is found exclusively on the flanks of the salt diapirs. It is thus most likely that these sediments are derived from the salt diapir highs within the basin. This implies that the salt diapirs were reactivated in the early Tertiary, giving rise to small intra-basinal highs in the Nordkapp Basin. Thesee highs were subjected to erosion, and the erosional products accumulated as slope front fills at the flanks of salt diapirs. Subaerial exposure of the intrabasinal highs is possible, but not necessary, in that, given a shallow marine environment, subaqueous remobilization processes are quite adequate to create such mass movement (Peres 1993).

The unconformity surface between subunits a2(I) and a2(II) (Fig. 4) could be interpreted as erosional channels that transported sediment. Alternatively, the internal truncation surface that subdivides unit a2 could be a slide surface related to slumping. Continued upward movement of salt would have increased slope gradients towards the salt diapirs; oversteepening of the slopes may have triggered slumps and mass movements along the diapir highs.

Which of these two depositional models for unit a2 is the correct one is difficult to decide upon because the top of the salt diapirs and parts of the unit have been removed by later erosion. In both cases the sediments which comprise unit a2 are probably sediment gravity flows. Indeed, the salt movements involved during the deposition and/or deformation of unit a2 are probably the same as those suggested to have triggered the mass movements during deposition of unit a1.

Unit a3, aggrading complex

The relatively transparent pattern of the unit, with only few internal reflections in the central part of the basin, indicates deposition in a relatively calm marine environment distal to the coast (Mitchum et al. 1977; Badley 1985). Such reflection configuration often represents sediments that consist of silt and clay (cf. Schlee & Hinz, 1987). This is also corroborated by well data from the correlative sediments in the Hammerfest Basin where hemipelagic sediments were encountered (Knutsen & Vorren 1991). Towards the basin flanks and over the platforms the internal reflections become stronger, indicating that the deposition here occurred in shallower conditions.

As described, unit a3 can be correlated to sediments in the Hammerfest- and Tromsø Basins. The URU truncates the upper part of unit a3 which probably had a much larger distribution, possibly covering most of the southwestern Barents Sea.

The onlapping configuration against the basin slope indicates rising relative sea level during deposition of the unit. Moreover, the bi-directional onlap of unit a3 between the mounds which represent the upper boundary of unit a1 indicates a gradual filling of palaeorelief in the basin.

However, where the base Tertiary reflection is bent up by the salt diapirs no onlap of a3 internal reflections is observed, likewise no onlap is observed against the upper boundary of unit a2. It is, however, observed that internal reflections are bent up and pressed together against the salt diapirs. This upbending of internal reflections over the salt diapirs, we interpret to be a result of post-depositional deformation of originally subhorizontal layers. Altthough upward movement of salt gave rise to highs within the basin during deposition of unit a2, this indicates that the salt diapirs had a pause in their upward movement during deposition of unit a3, or, alternatively, that the sedimentation rates exceeded the rate of salt movement.

Unit a4, progradational infill

The observation that the internal reflections of unit a3 are bent up by the salt diapirs, while the internal reflections of unit a4 onlap the diapir highs, indicates that significant movement of salt and basin subsidence occurred at the unit a3/a4 transition.

The increased basin subsidence recorded by the deposition of a4 may thus be the result of a complex interplay between large tectonic movements, sedimentary input and reactivation of salt movement. A likely order of events is that large-scale tectonic movements, related to the opening of the Norwegian–Greenland Sea, caused reactivation of major fault systems around the Nordkapp Basin (Gabrielsen & Færseth 1988). This tectonic phase also reactivated the upward movement of salt and caused compression and relative uplift of the basin flanks; uplift of the basin flanks caused increased sedimentary input to the basin.

Compared to the inferred low energetic sedimentation of unit a3, the progradational character of unit a4 indicates a significant increase in depositional energy and sedimentary input to the basin.

The highly progradational pattern of the earliest a4 sedimentation indicates a decrease in accommodation rate around the flanks of the basin. Conversely, the lateral gradation to a subparallel, flat-lying reflection pattern in the central part of the basin is interpreted to represent an increase in accommodation. The inferred accommodation development may reflect a progressive increase in basin subsidence during the late stage of outbuilding. However, the onlapping configuration of internal reflections towards diapir highs suggests that most of the subsidence occurred before the deposition of unit a4.

Na3, Na4, Na5 and Na6, complex fills

A complex interplay among tectonics, sedimentary input and movement of salt is also inferred to explain the development of subunits Na3, Na4, Na5 and Na6 in the northern part of the study area. Since internal reflections in units Na3–Na6 seem to onlap the lower boundary, the most likely stratigraphical equivalents to these subunits are units a2 and a4. However, if the salt diapirs in this area were active during most of the early Tertiary, type a2 and a4 deposition may have occurred simultaneous to deposition of unit a3 in other parts of the basin.

The development of more units in the northern part of the study area may thus not represent major changes in the sedimentary facies, but rather reflects differential movement of salt diapirs, causing displacement of the axes of the rim synclines in relation to the basin and to each other.

Conclusion

The early Tertiary depositional history of the Nordkapp Basin can be reconstructed as represented in Fig. 12.

In an early phase, unit a1 was deposited as a sedimentary unit over the platform areas to the east. Reactivation of the salt diapirs led to subsidence of the rim synclines and relative uplift of the basin margin. Because of the increased gradients of the basin flanks, parts of unit a1 were remobilized by mass movement and deposited in the deeper parts of the basin as complex chaotic mounds.

From unit a1 to unit a2 the salt diapirs continued their upward movement coeval with further basin subsidence. This gave rise to highs over the salt diapirs. These highs were subjected to shallow marine and/or subaerial erosion. The erosional products accumulated on the flanks of the diapir highs as unit a2.

During deposition of unit a3 the salt movement appears to have been negligible. Hemipelagic sediments drape central parts of the basin and onlap the basin flanks.

At the transition to unit a4 there was a major reactivation of salt movement and basin subsidence in the Nordkapp Basin. This has accomplished the upbending of internal reflections in unit a3 over the salt diapirs and resulted in the formation of secondary basins in the rim synclines. Renewed salt movement was probably related to reactivation of the major basin margin fault systems. Reactivation of faults also led to uplift and erosion of the surrounding areas, thereby increasing sedimentary input to the Nordkapp Basin.

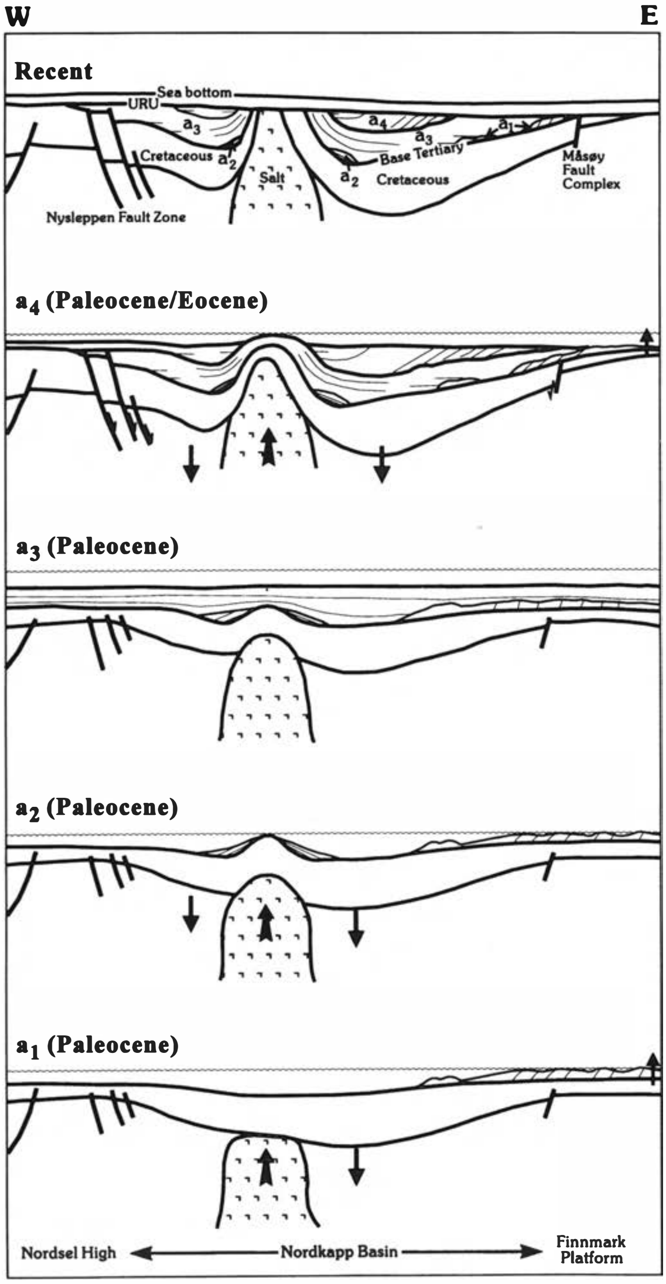


Fig. 12. Schematic backstripped profile across the Nordkapp basin. See Fig. 2 for location of profile (same line as Fig. 3).

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