Cenozoic stratigraphy and evolution of the Sørvestsnaget Basin, southwestern Barents Sea

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The Sørvestsnaget Basin is a major Cenozoic depocentre in the southwest Barents Sea. A relatively complete Paleocene - Middle Eocene succession is seen, including deposits of Early Paleocene (Danian) - Early Eocene, and Middle Eocene age. Deep marine conditions persisted throughout the Early Paleocene - Late Eocene, with emplacement of significant sandy submarine fans during the Middle Eocene. Deposits of Late Eocene - Late Miocene age are condensed, with several stratigraphic breaks. Significant marine shallowing took place at the Eocene - Oligocene boundary, and shallow marine conditions persisted throughout the Oligocene - Miocene. A thick wedge of Upper Pliocene - Pleistocene glacial erosion products truncates the older Cenozoic strata.

The Sørvestsnaget Basin is bounded to the west by the oceanic Lofoten Basin, and it's Cenozoic evolution is consequently affected by the opening of the Norwegian - Greenland Sea. The new well data, however, do not support earlier notions of widespread uplift in the Sørvestsnaget Basin associated with Early Eocene crustal break-up. However, a phase of differential subsidence and uplift between the Sørvestsnaget Basin and the flanking Veslemøy High/Senja Ridge occurred in the Early - Middle Eocene, and marine shallowing at the Eocene - Oligocene boundary may be coeval with a phase of tectonism induced by the plate tectonic movements.

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Introduction

Hydrocarbon exploration in the Barents Sea commenced in 1979 (5th Norwegian licensing round). Prior to the year 2000, 53 exploration wells had been drilled, proving total hydrocarbon resources of about 288×10^6 Sm^3 oil equivalents (Knutsen et al. 2000), of which approximately 90% occur in the Hammerfest Basin (Fig. 1). However, most of the wells drilled have failed to prove significant hydrocarbons, and all the discoveries are so far considered to be non-commercial or only marginally commercial. This lack of success is commonly attributed to the Neogene to Recent regional uplift and erosion, which has led to the removal of up to 500 - 2000 m of rocks over large areas (e.g. Riis & Fjeldskar 1992; Doré & Jensen 1996; Knutsen et. al. 2000), causing leakage from former hydrocarbon accumulations.

Thick and relatively complete Cenozoic successions occur along the western margin of the Barents Sea (Fig. 1a), particularly in the Sørvestsnaget Basin (Knutsen & Larsen 1997), in the Vestbakken Volcanic Province (Rasmussen et al. 1995; Eidvin et al. 1998; Knutsen et al. 2000), and also further north along the margin between the Stappen High and Svalbard (Grogan et al. 1999). Well 7316/5-1 (Vestbakken Volcanic Province; Fig.1b) penetrated approximately 3,5 km of Cenozoic strata, and proved the existence of a minor gas accumulation in Middle Eocene sandstones (Knutsen et al. 2000). Although non-commercial, the discovery documented the existence of a Cenozoic hydrocarbon play.

Following the 1996 announcement of the "Barents Sea Project" by the Norwegian authorities, approximately 14.5 blocks (app. 4670 km^2), defined as "Seismic Area A" (Fig.1b) were awarded to a group consisting of Elf, Mobil, Saga, Statoil and Norsk Hydro (operator) in 1997. Subsequently, about 5700 km of 2D seismic data (survey NH9702) and 2000 km^2 of 3D seismic data (survey NH9803) were acquired during 1997 and 1998, along with 4 deep seismic lines, a regional high resolution aeromagnetic survey, and 2 ocean bottom seismographs (OBS). The evaluation of the seismic area was concluded in 1999, by the selection of production license PL 221 (Fig.1b) by Norsk Hydro, Statoil and Total/Fina/Elf.

Well 7216/11-1S was drilled during the summer of 2000 to test the Cenozoic hydrocarbon play of the Sør-

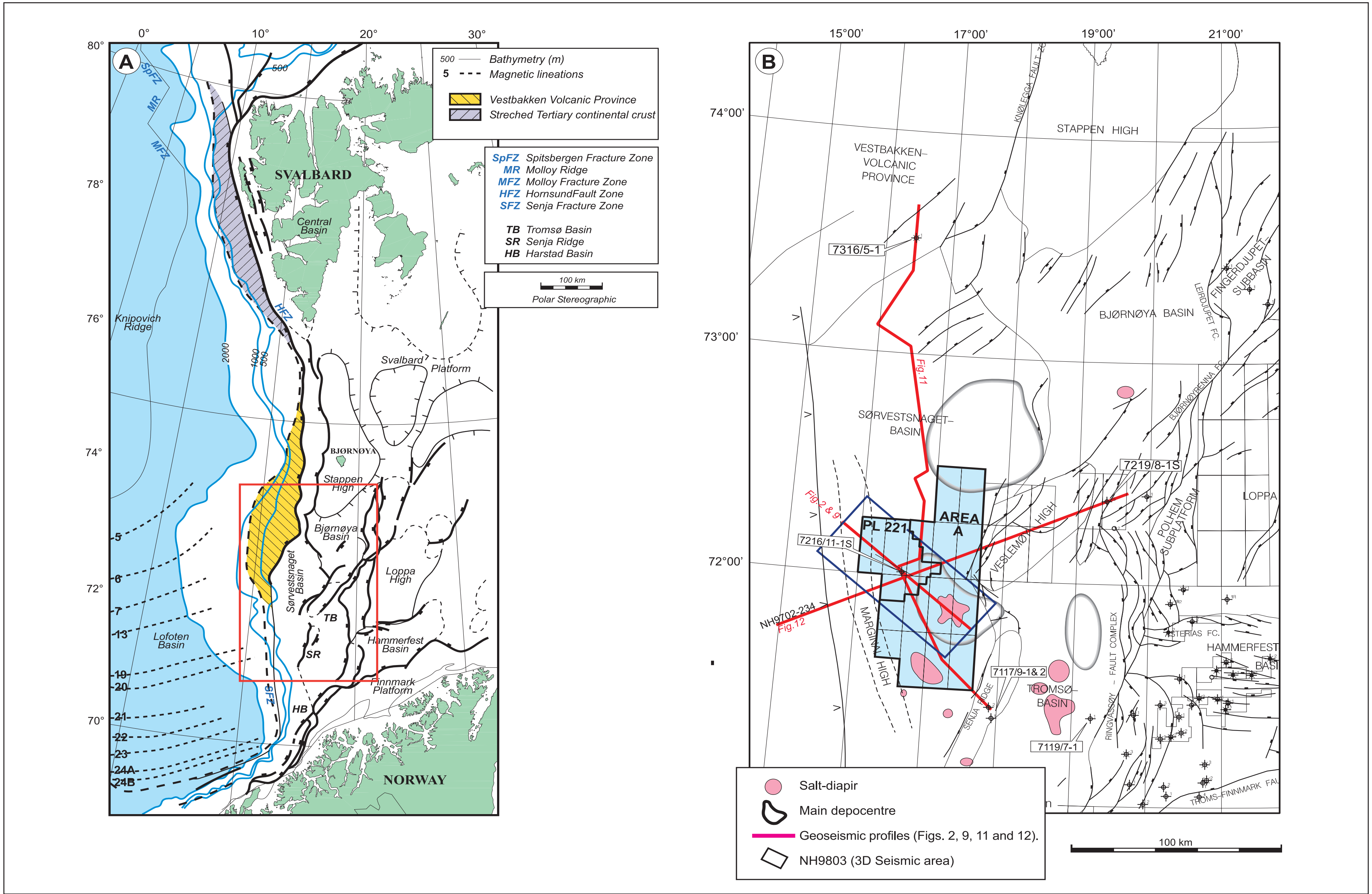

Fig.1. A Main structural and plate tectonic features of the western Barents Sea - Svalbard margin. The margin comprises three main segments including the Senja Fracure Zone and the Hornsund Fault Zone, separated by a central rift segment (Vestbakken Volcanic Province). Modified from Faleide et al. (1996). B. Location map and main structural features of the southwest Barents Sea. The indicated-depocentres (from Breivik et al. 1998) reflect the Late Cretaceous - Cenozoic setting. Also shown are the locations of seismic and geoseismic sections shown in Figs. 2, 9, 11,and 12, and the wells shown in Figs.10 and 12.

vestsnaget Basin. The well was spudded in water depths of 361 mMSL (mean sea level) and terminated at a total depth of 4215 mMSL (true vertical depth is 3709 mMSL due to a deviated well path) in rocks of Early Paleocene (Danian) age. Although dry, the well proved the existence of significant Middle Eocene reservoir sandstones, and provided new stratigraphic information from an unexplored part of the Norwegian shelf. The aim of this study is to assess the Cenozoic evolution of the Sørvestsnaget Basin on the basis of the new data, with emphasis on stratigraphy, sedimentology and structural development.

Geological setting

The Barents Sea area has undergone several phases of tectonism and sedimentation since the Devonian, eventually leading to crustal break-up and sea floor spreading in the north Atlantic rift. At least five phases of basin development are widely recognizable throughout the area, i) Late Devonian - middle Carboniferous rifting, ii) Late Carboniferous - Permian carbonate platform development, iii) Triassic - Cretaceous siliciclastic shelf development, iv) Early Cenozoic crustal break-up, and v) Late Cenozoic passive margin development (Nøttvedt et al.1992).

The present continental margin of the western Barents Sea and Svalbard (Fig.1a) extends about 1000 km in a broadly NNW direction. It comprises three major structural segments, including a southern, sheared margin along the Senja Fracture Zone, a central volcanic rift segment (Vestbakken Volcanic Province; see Gabrielsen et al. 1990), and a northern, sheared and subsequently rifted margin along the Hornsund Fault Zone. The NNW-oriented zone (collectively referred to as the "de Geer zone" by Harland, 1969) also includes the Trolle Land fault zone of North Greenland (see Peel and Sønderholm, 1991 and papers therein; Breivik et al. 1998). Furthermore, it may link with the Proterozoic

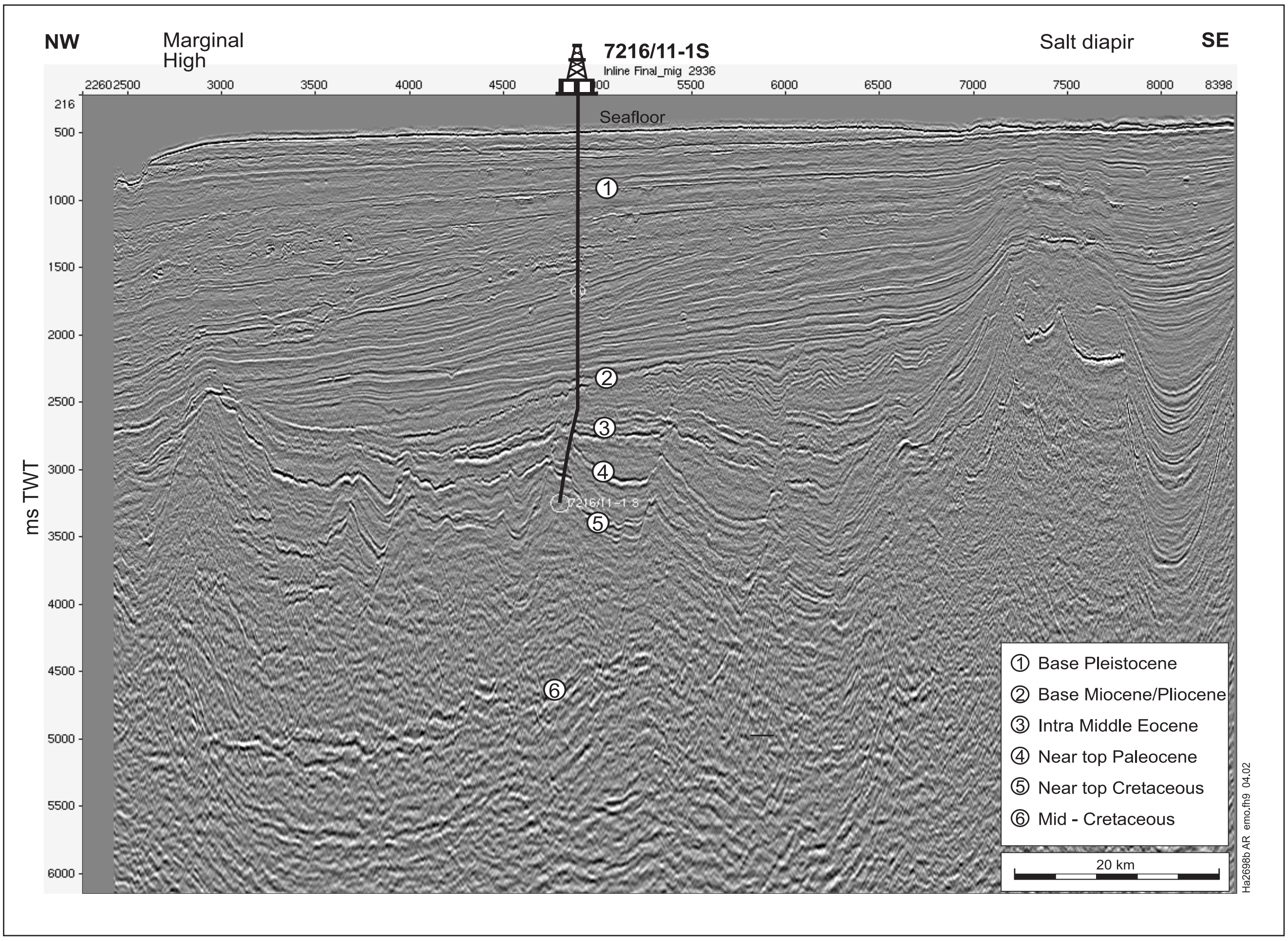

Fig. 2. Seismic section across the study area. The identified reflectors illustrate the pre-drill stratigraphy inferred for the well. Below the Base Miocene/Pliocene reflector, a succession of Palaeogene strata was prognosed above a thick interval of assumed Late Cretaceous age. A domal, partly fault-bounded structure is present at the Middle Eocene level and a deeper horst-like structure is present at the Paleocene - Early Eocene level. The Middle Eocene and Paleocene - Early Eocene structures formed the main reservoir targets for the well. Significant sandstones were only present in the Middle Eocene. For location, see Fig. 1b. A geoseismic representation of the cross-section, based on new stratigraphic data, is shown in Fig. 9.

Bothnia - Senja shear zone to the south (Doré et al. 1997), testifying to its long-lived existence as a tectonic lineament, even prior to the Caledonian orogeny.

The Cenozoic evolution of the Senja Fracture Zone (southern sheared margin) is closely linked to the opening of the Norwegian - Greenland Sea (e.g. Talwani & Eldholm 1977; Myhre et al. 1982; Eldholm et al. 1987; Faleide et al. 1991, 1993a, 1996; Vågnes 1997; Skogseid et al. 2000). Vågnes (1997) inferred three main phases, in accordance with the plate tectonic history; 1) continent - continent transform prior to crustal break-up (Early Eocene, magnetic anomaly 24A, Fig.1a), 2) ocean - continent transform as the Atlantic spreading ridge propagated northwards along the shear zone (Eocene - earliest Oligocene), and eventually 3) a passive continental margin with no shear movement as the spreading ridge shifted still further to the north. Since the Oligocene, oceanic crust is developed along the entire continental margin between Norway and Svalbard, leading to subsidence of a passive margin and deposition of a thick Neogene sedimentary wedge coincident with wide-spread uplift and erosion of Svalbard and the Barents shelf to the east (e.g. Nøttvedt et al. 1988; Vorren et al. 1991; Faleide et al. 1996).

The southwest Barents Sea area (Fig.1a), including the Sørvestsnaget Basin (app. 71°-73°N, 15°-18°E) and the nearby Bjørnøya, Tromsø and Harstad basins, is a province of particularly deep Cretaceous and Cenozoic basins. Gabrielsen et al. (1990) suggested that the Sørvestsnaget Basin has experienced significant subsidence since the Early Cretaceous, providing accommodation space for a substantial thickness of Cretaceous and Cenozoic sediments. Breivik et al. (1998) noted that the Sørvestsnaget-, Bjørnøya- and Tromsø basins show equal rates of Early Cretaceous subsidence, with the Sørvestsnaget Basin subsequently showing more pronounced Late Cretaceous and Cenozoic subsidence than the Tromsø- and Bjørnøya basins, indicating a temporal, westward migration of the tectonic activity, towards the transform margin. Faleide et al. (1993b) noted that the basin has been affected by major tectonism during the early Cenozoic break-up ("Tertiary marginal basin"), involving repetitive phases of vertical motion, erosion and sedimentation. Particularly, Early Eocene uplift concurrent with crustal break-up, and the development of a regional break-up unconformity, has been inferred (Sættem et al. 1994; Vågnes 1997).

The Senja Fracture Zone (see above) separates the Lofoten Basin (Fig.1a), which contains ca. 5 - 7 km of mainly Neogene sediments (Faleide et al. 1993b) above the oceanic crust, from the Sørvestsnaget Basin. The transition from oceanic to continental crust occurs over a ca. 20 km wide zone (Faleide et al. 1993b; Breivik et al. 1998; Mjelde et al. 2002), and encompasses a marginal high (Fig.1b) along the western margin of the Sørvestsnaget Basin. This marginal high is characterized by truncation of Palaeogene strata, as inferred from seismic data (Brekke & Riis 1987; Faleide et al. 1993a,b; Knutsen & Larsen 1997; Vågnes 1997; Brevik et al. 1998). It probably originated during the Late Paleocene - Early Eocene opening of the Norway - Greenland Sea, and may have been re-activated/ uplifted in the Early - Middle Oligocene, possibly by transpressional tectonics induced by a change in the location of spreading poles between the Greenland and Eurasian plates (Knutsen & Larsen 1997). Geophysical modelling of ocean bottom seismic data (OBS) and potential field data (Mjelde et al. 2002) indicate that igneous intrusions are present at about 9,5 km along the marginal high, suggesting that the initial uplift was in part related to magmatism during break-up. There is, however, no evidence for magmatic underplating of the crust, as was the case for the outer high of the Vøring Basin to the south, which formed by contemporary (?) massive flood basalt extrusion during crustal break-up (Skogseid et al. 1992, 2000).

To the north, the Vestbakken Volcanic Province (Fig.1a) with Early Eocene and Pliocene magmatism (see Faleide et al. 1988; Mørk & Duncan 1993; Sættem et al. 1994; Rasmussen et al. 1995) is separated from the Sørvestsnaget Basin by a zone of NE-trending normal faults. This fault zone shows significant Paleocene rotational faulting (Sættem et al.,1994; Breivik et al. 1998), and is linked to the NNE-oriented Knølegga Fault Zone (Fig.1b) to the northeast, separating the Vestbakken Volcanic Province from the Stappen High. The Stappen High was uplifted during the Cenozoic due to shearing along the Hornsund Fault Complex (Gabrielsen et al. 1990).

To the east/northeast, the Sørvestsnaget Basin is separated from the Bjørnøya Basin by a Cenozoic normal fault system ("Tertiary hinge-line" of Faleide et al. 1988). To the east and southeast, the Sørvestsnaget Basin is bounded, and partly separated from the Tromsø Basin, by the Veslemøy High and the Senja Ridge (Fig.1b). The highs are basement-supported and have been active during several tectonic phases, but became positive features during Late Cretaceous and Early Cenozoic faulting and salt mobilization in the adjacent basins (Faleide et al. 1993b; Breivik et al. 1998). Some limited compressive strike-slip movement may have been involved in the Late Cretaceous structuring, although both highs are separated from the Sørvestsnaget Basin by west-stepping normal faults (Gabrielsen et al. 1990; Faleide et al. 1993a,b; Breivik et al. 1998). The southern boundary with the Harstad Basin is poorly defined, but possibly marked by NE-trending faults at the southern extension of the Senja Ridge.

Geophysical mapping of the Sørvestsnaget Basin (Breivik et al., 1998) shows the existence of two main depocentres (Fig.1b), located to the north and south of the Veslemøy High, respectively. Large-scale salt diapirism of inferred Middle - Late Eocene age is seen in the southern area, and also in the Tromsø Basin to the east (Knutsen & Larsen, 1997). Breivik et al. (1998) related the subsidence of the southern depocentre to salt movement, and inferred extensive Late Cretaceous - Early Paleocene pull-apart faulting to account for the northern depocentre.

Due to the extreme Cretaceous and Cenozoic subsidence, little is known about the pre-Cretaceous stratigraphy of the Sørvestsnaget Basin. Ocean bottom seismographs and potential field data (Mjelde et al. 2002) indicate that crystalline basement is present at about 17 km underneath most of the basin. The presence of salt diapirs and related structures in the southern part of the basin also show that the area probably commenced as a sedimentary basin in Late Palaeozoic times (e.g. Knutsen & Larsen 1997), eventually becoming part of a Carboniferous - Permian sag basin which may have included the entire Barents Sea (Gudlaugsson et al. 1998).

Gravity models constrained by seismic data indicate that the Base Cretaceous/Middle Jurassic level may be as deep as 14 - 17 km in the basins' two depocentres (Fig.1b), with an average burial depth of about 12 km throughout most of the area (Mjelde et al. 2002). This implies that about 5 km of Upper Palaeozoic - Lower Mesozoic strata are present. Furthermore, the Base Cretaceous surface may be buried to about 9 - 10 km, whereas the mid-Cretaceous level may be buried to about 7 - 8 km (Mjelde et al. 2002).

Cenozoic deposits are widespread throughout the Barents Sea. A mudrock-dominated Palaeogene succession (Sotbakken Group) has been related to a deep marine shelf environment, whereas a marine to glacial marine setting has been suggested for the Neogene deposits (Nordland Group) (Dalland et al. 1988; Nøttvedt et al. 1988). In the Hammerfest Basin to the east, Palaeogene marine mudrocks rest unconformably on Cretaceous strata, with a marked Maastrichtian - Danian depositional break (Dalland et al. 1988; Knutsen et al. 1992; Faleide et al. 1993b). Furthermore, these deposits are truncated and separated from Pleistocene strata by a regional unconformity (upper regional unconformity, URU; e.g. Vorren & Kristoffersen 1986). Oligocene and Neogene strata are preserved to the west (Eidvin et al. 1993, 1998). Nøttvedt et al. (1988) inferred that broad subsidence in the Barents Sea and continental shelf of northern Greenland produced a large epeiric, marine basin during the Paleocene. This epicontinental setting, however, terminated in the Early Eocene due to rifting and volcanism associated with crustal break-up. Glaciations probably have affected the area since the Late Pliocene, manifested by the deposition of the thick clastic wedge (Sættem et al. 1994; Faleide et al. 1996).

The Cenozoic stratigraphy of the Sørvestsnaget Basin has previously been investigated from reflection seismic data (see also Fig. 2). Knutsen and Larsen (1997) documented the existence of significant Palaeogene and Neogene seismic units, separated by a major unconformity of inferred intra-Miocene age. Below the unconformity Knutsen & Larsen (1997) indicated the existence of significant Paleocene - Middle Eocene deposits, possibly extending into the Early Oligocene - ?Early Miocene. The Neogene succession above the unconformity forms the west-dipping wedge of Neogene - Quaternary erosion products from the uplifted Barents shelf to the east. Breivik et al. (1998) inferred a maximum thickness of about 4 km for the Cenozoic succession in the northeast part of the Sørvestsnaget Basin, with the Palaeogene succession being the thickest unit (app. 3 km). In the forthcoming sections, the stratigraphic observations from well 7216/11-1S will be tied to the adjoining areas, particularly the Vestbakken Volcanic Province and the intrabasinal highs (Senja Ridge and Veslemøy High).

Study area

The study area (Fig.1b) is located in the axial to western part of the Sørvestsnaget Basin, to the northwest of the southern salt-related depocentre, between the Veslemøy High and the western, marginal high. Reflection-seismic data across the well site and the main part of the basin are shown in Figure 2. The cross-section includes the transition to the Lofoten Basin and the western marginal high (app. CDP 3000; Fig. 2), and a major salt diapir to the southeast (app. CDP 7500; Fig. 2) of the well. The upper part of the section (Fig. 2) is characterized by a major wedge of west-dipping reflectors (down to about 2230 ms at the well trajectory), representing the Neogene clastic wedge of the western Barents Sea (e.g. Eidvin et al. 1993, 1998).

Below the wedge, several strong reflections of inferred Paleocene - Eocene age at about 2500 - 3500 ms. reveal a series of rotated fault blocks between the marginal high and the salt diapir (CDP 3000 - 7000, Fig. 2), probably formed by extensional faulting during crustal break-up. The well was drilled into an identified faulted anticline at the intra-mid-Eocene level and further into a rotated Paleocene - Eocene fault block to test the prospectivity of the Paleocene interval. The well's total depth point (TD) is dated as Early Paleocene, and there is no clear definition of the Cretaceous/Cenozoic boundary. However, a reflection band at about 5000 ms in the western part of the cross-section may correspond to a mid-Cretaceous (intra-Albian?) level, as a thick succession of Late Cretaceous age is inferred in the area (see above; Breivik et al. 1998). The well provides a unique data set as regards the Cenozoic stratigraphy and evolution of the Sørvestsnaget Basin, which will be discussed in detail below.

Database

Approximately 36000 km of 2D reflection seismic data have been acquired along the western margin of the Barents Sea, all of which have been made available. The primary seismic database, however, is the NH9702 and NH9803 surveys. The 2D survey NH 9702 comprises 5752 km of reflection seismic data, including four deep seismic lines, and covers the seismic area in a line spacing of 1 x 2 km. The 3D seismic data set (NH9803) of 2000 km^2 covers PL 221 (Fig.1b). The seismic data are used to analyse structural and stratal patterns. Three geoseismic sections are constructed, to examine and compare the Cenozoic stratigraphy of the Sørvestsnaget Basin to the Senja Ridge, Veslemøy High and Vestbakken Volcanic Province. The data quality of the 2D data varies from good in the north to poor to the south, whereas the 3D data are generally of good quality.

Two cores were cut in well 7216/11-1S, at 2964 - 2972,4 mMSL and 4206 - 4214 mMSL, and a sedimentological description and interpretation is given. Lithological data reported during drilling are used to derive a lithological coloumn for the Cenozoic. Furthermore, the drilled section from 1006 - 4215 mMSL has been analysed for biostratigraphy by a combination of quantitative palynology and semi-quantitative micropaleontology from core chips, sidewall cores and ditch cuttings. The biostratigraphic data are used to date the Cenozoic sequences and the main stratigraphic breaks, and are also used to correlate Well 7216/11-1S to other wells in the area, based on published accounts (Eidvin et al. 1993, 1998) and Norsk Hydro *in house* data. Depths are generally referred to mean sea level (mMSL), except for wireline log sections shown in Figures 5 and 8, which are referred to the rig's Kelly Bushing (mRKB), 24m above sea level. The assigned stratigraphic ages follow the timescale of Hardenbol et al. (1998), and the lithostratigraphic nomenclature follows Dalland et al. (1988).

Cenozoic stratigraphy and facies of well 7216/11-1S

Time-stratigraphic breaks

Figure 3 summarises the lithology and stratigraphy of well 7216/11-1S, along with a number of seismic ties to the well. The drilled section comprises two main units

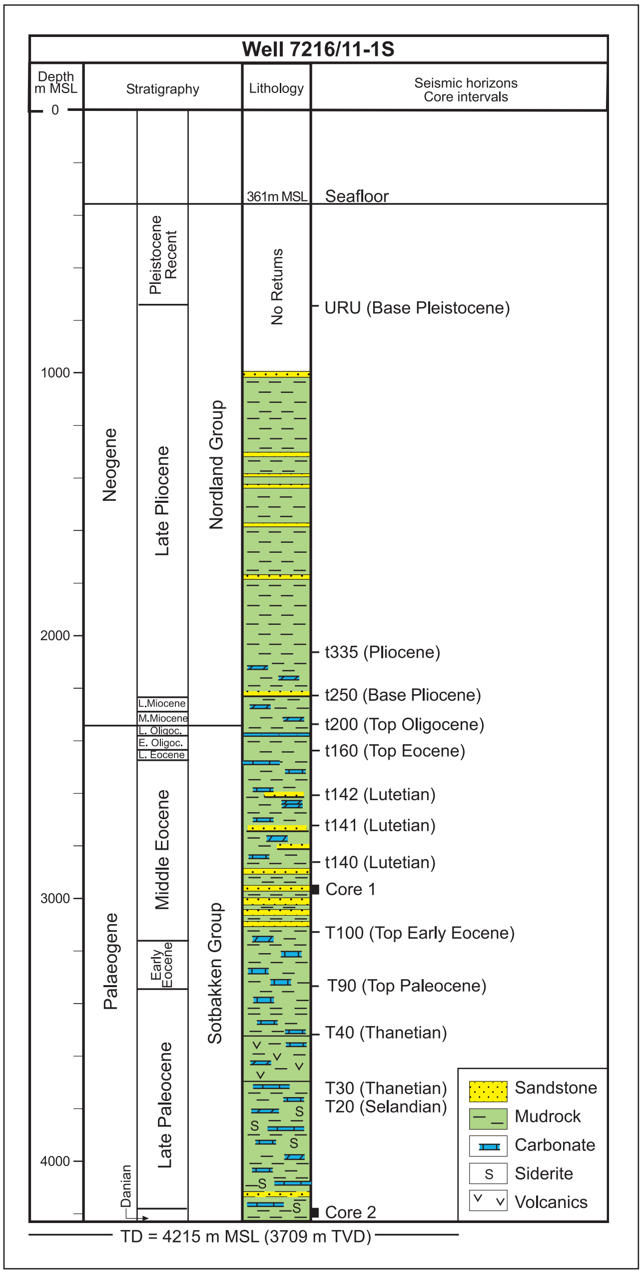

Fig. 3. Stratigraphic and lithological summary of well 7216/11-1S, Sørvestsnaget Basin. Depths are not corrected for the inclined well path. Due to well deviation, the true vertical thicknesses of the Nordland and Sotbakken groups are 1976 m and 1372 m, respectively. The total depth point (TD) is located in strata of Early Paleocene (Danian) age.

of Palaeogene and Neogene age, corresponding to the Sotbakken and Nordland lithostratigraphic groups (Dalland et al. 1988), respectively. There is biostratigraphic evidence for a total of 6 time-stratigraphic breaks in the Early Eocene - Pliocene interval, 4 of which occur in a condensed interval of Late Eocene - Miocene age. Furthermore, a basal Pleistocene unconformity (URU, Fig. 3) has also been defined from the seismic data. The time-stratigraphic breaks are important for understanding the stratigraphy, and will be outlined in some detail.

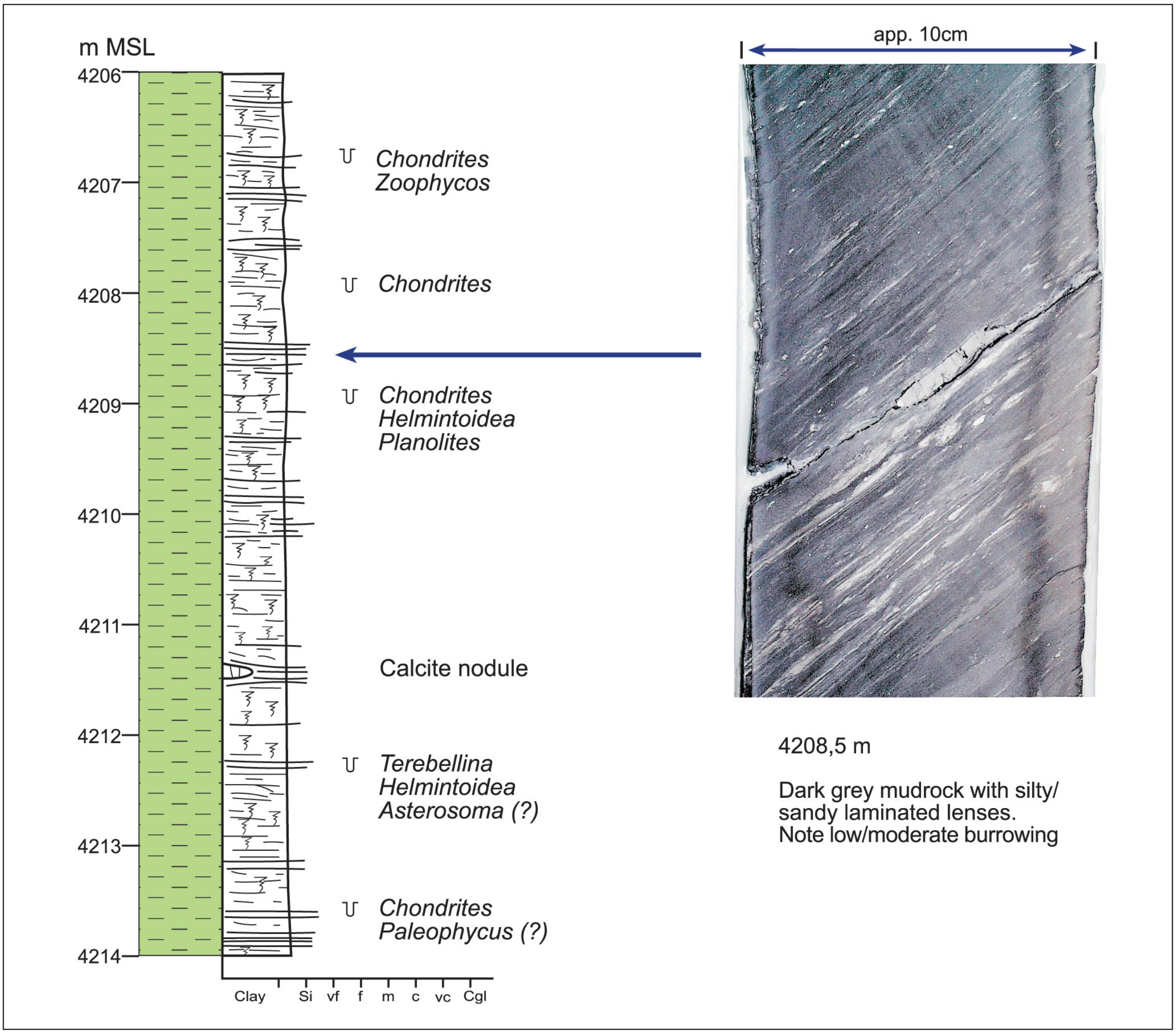

Fig. 4. Graphic description of Core 2: Danian sandy mudrocks, well 7216/11-1S. The sedimentary facies of laminated black mudrock with sandy streaks and lamina is related to deposition in a deep marine (bathyal) setting affected by bottom currents. The dip of the lamination seen in the photograph is due to structural dip and well deviation. See Figure 3 for the stratigraphic position of the core.

A break of approximately 3.5 Ma is identified at the Early - Middle Eocene boundary (49 Ma sensu Hardenbol et al. 1998), as strata of Late Ypresian age are missing from the section. Seismic data (Fig. 2, see also Fig. 9 below) indicate that this break may be caused by a normal fault at the well trajectory. However, erosion associated with this break can be inferred from seismic data (T100 re-flector in Fig. 3, see also below), where truncation of underlying deposits can be seen, particularly towards the eastern basin margin. Furthermore, deposits of Middle Eocene age seem to on-lap this boundary from the east. The origin of this break and its possible relation to the opening of the Norwegian - Greenland Sea will be discussed in the forthcoming paragraphs, as widespread Early Eocene uplift during crustal break-up has been inferred for the Sørvestsnaget Basin (e.g. Sættem et al. 1994; Vågnes 1997).

The Middle - Upper Eocene succession is apparently complete. However, a minor time-stratigraphic break (0.5 Ma or less) is present at the Late Eocene - Early Oligocene boundary (33.7 Ma, Hardenbol et al., 1998). The seismic data also show truncation of inferred Upper Eocene strata below this surface (t160, Fig. 3). A more significant break is recognized at the Early - Late Oligocene boundary (28.5 Ma), with a possible duration of less than 4 Ma. This unconformity has no clear seismic definition, as the Oligocene succession is thin (app. 100 m) and apparently condensed.

The most significant time-stratigraphic break is recorded at the Oligocene - Miocene boundary. Deposits of Early- to (earliest) Middle Miocene age are not present in the section, with Middle Miocene (Serravallian) strata resting on Upper Oligocene (Chattian) deposits.

A break of about 13 Ma is therefore suggested at this level. A time-stratigraphic break of less than 2 Ma is further seen at the Middle - Late Miocene boundary (11.2 Ma), dividing the Miocene interval into two stratigraphic units.

A break of about 2 Ma is also indicated at the Miocene - Late Pliocene boundary (base of the Neogene wedge), the Lower Pliocene being mainly missing. The erosive character of the basal Pliocene surface (t250, Fig. 3) is clear from the seismic data. Truncation of successively older strata is evident towards the eastern basin margin (see below). Furthermore, deposits of Late Paleocene - Miocene age are truncated below this surface across the marginal high to the west.

Paleocene - Early Eocene (3166 - 4215 mMSL)

Above a thin unit of Danian deposits (see below) the Paleocene - Lower Eocene section comprise deposits of Late Paleocene (Selandian - Thanetian) and Early Eocene (Ypresian) age. The biostratigraphic data indicate a complete Upper Paleocene - Lower Eocene succession. Agglutinated foraminifera occur throughout, associated with pyritised diatoms and radiolaria. The section also contains abundant reworked microfossils of Late Cretaceous (mainly Campanian) age.

Figure 4 shows a graphic log of a bottom hole core (core #2; Fig. 3), below the Danian - Selandian boundary at 4186 mMSL. The cored section comprises a dominant background lithology of dark grey, laminated mudrock, with streaks and lenses of siltstone and very fine-grained sandstone occurring throughout. The silty/sandy lamina are usually planar, with sporadic small-scale cross-lamination. Bioturbation is generally weak, but comprises a suite of small traces, including *Chondrites, Helmintopsis* and *Terebellina.*

A unit (3796 - 4186 mMSL) of Late Paleocene (Selandian) age overlies the Danian interval (Fig. 3). These deposits are dominated by greyish mudrocks, with traces of very fine- to fine-grained sandstone. Furthermore, stringers of limestone and dolomite occur throughout, and the section is also characterized by abundant siderite. The remaining Late Paleocene interval (3346 - 3796 mMSL) is of Thanetian age. Varicoloured, grey, greenish to blackish mudrocks dominate throughout, associated with limestone/dolomite stringers and traces of very fine to fine-grained sandstone. Notably, volcanic, tuffaceous fragments occur relatively frequently at this level (particularly at 3531 - 3701 mMSL, see Fig. 3). Lower Eocene (Ypresian) deposits (3166 - 3346 mMSL) are totally dominated by light to dark grey mudrocks with carbonate-cemented stringers.

The completely fine-grained nature of the Paleocene - Lower Eocene succession is indicative of deposition in a generally low-energy marine environment. Furthermore, the microfaunal evidence (agglutinated benthic foraminifera, pyritised diatoms, lack of open marine planktonic foraminifera) is indicative of a poorly oxygenated deep marine shelf or bathyal environment. Based on the presence of reworked (Campanian) palynomorphs, significant sediment contribution from a Late Cretaceous source area can be assumed. The observed volcanic material is older than the tuffaceous Tare Formation (Early Eocene) on the mid-Norwegian shelf, and may reflect Late Paleocene volcanic activity in the area, i.e. prior to the crustal break-up.

The inferred, deep marine setting is further supported by the facies seen in the cored section (Fig. 4). The dominance of dark mudrocks testifies to deposition by suspension fall-out in an oxygen-depleted subaqueous environment, as can also be inferred from the observed burrowing traces *(Chondrites, Helmintopsis)*. The frequent occurrence of planar- to cross-laminated silty-sandy lamina sets and lenses (Fig. 4) indicates weak, but time-persistent agitation of the bottom sediment by currents. The agitation may be due to periodic storms introducing coarser clastic material from shallow marine environments, or may reflect the more continuous activity of oceanic currents on the deep marine bottom sediment.

Middle Eocene (2486 - 3166 mMSL)

Middle Eocene (Lutetian - Bartonian) strata rest with a possibly faulted stratigraphic break on Lower Eocene deposits. The biostratigraphic data show a continuous succession, dominated by agglutinated foraminifera and pyritised diatoms, but lacking calcareous microfossils. Grey to dark grey mudrocks with limestone/dolomite stringers and scattered traces of very fine- to fine-grained sandstones dominate throughout (see Fig. 3), with the notable exception of a significant sandstone unit (2888 - 3102 mMSL) within the Lutetian interval (2546 - 3166 mMSL; see Fig. 3). This is the only significant reservoir sandstone penetrated by the well and contains abundant reworked Early Jurassic palynomorphs.

Figure 5a shows the stratigraphy, log response and lithology of the sandy Middle Eocene interval. The 214 m thick (135 m true vertical thickness) reservoir unit comprises sharply bounded (blocky GR-response) sandstone beds of variable thickness (maximum 16 m), intercalated with the background mudrocks. The total sandstone content of the interval is about 30%. The seismic cross-section (Fig. 5b) shows the sandstone as a unit of increased amplitudes within a more opaque seismic background. Furthermore, the sandy interval appears rather deformed, with an irregular base, occasionally forming laterally discontinuous lenses of sandstone within the associated mudrock. The reflection

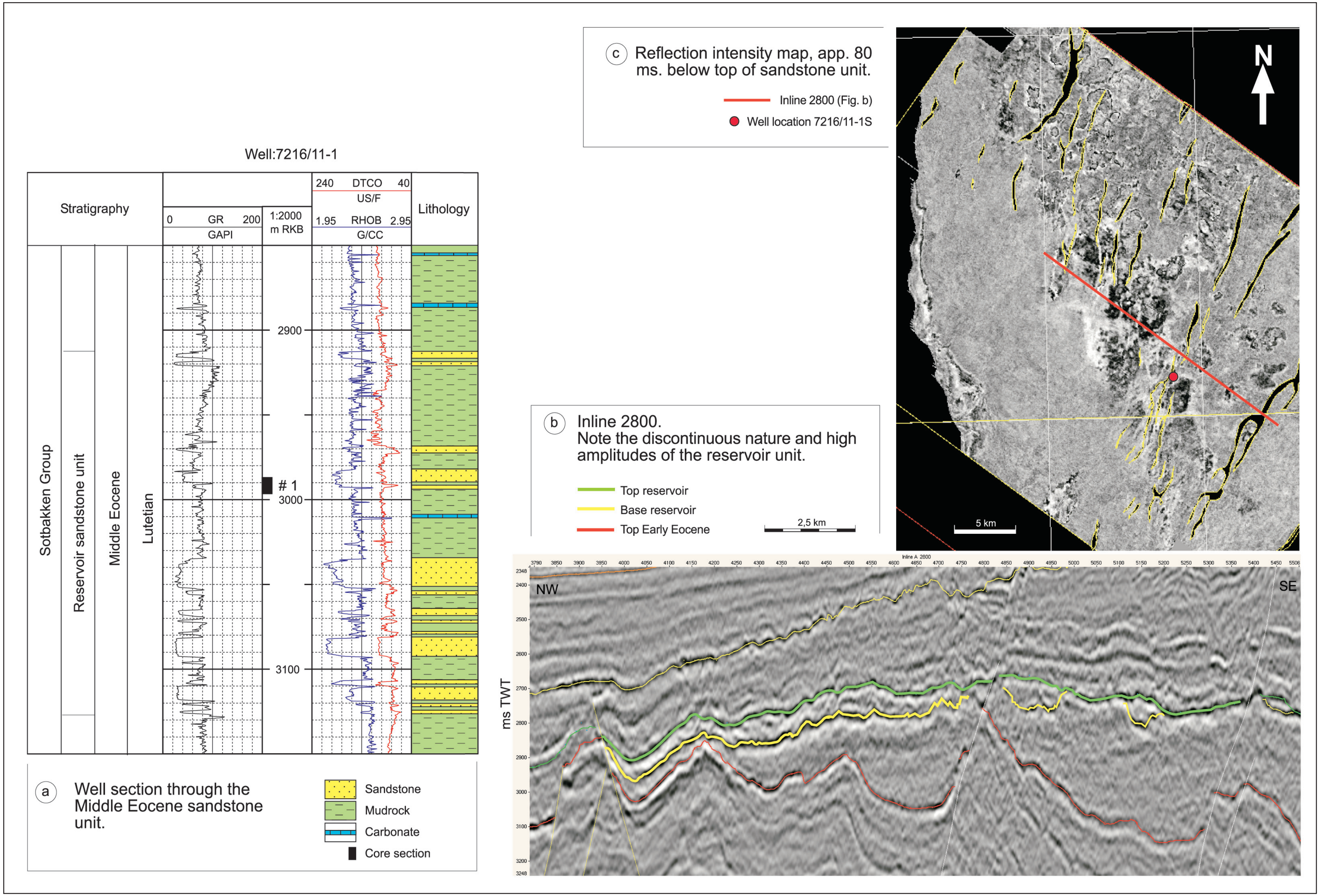

Fig. 5. Lithology and seismic characterization of the Middle Eocene sandstones. a) Wireline log signature, b) reflection seismic definition, c) reflection intensity map obtained 80 ms below the interpreted top reservoir seismic reflection. Note that the measured depth for the wireline data (mRKB) refers to the rig's Kelly Bushing, 24 m above sea level (mMSL).

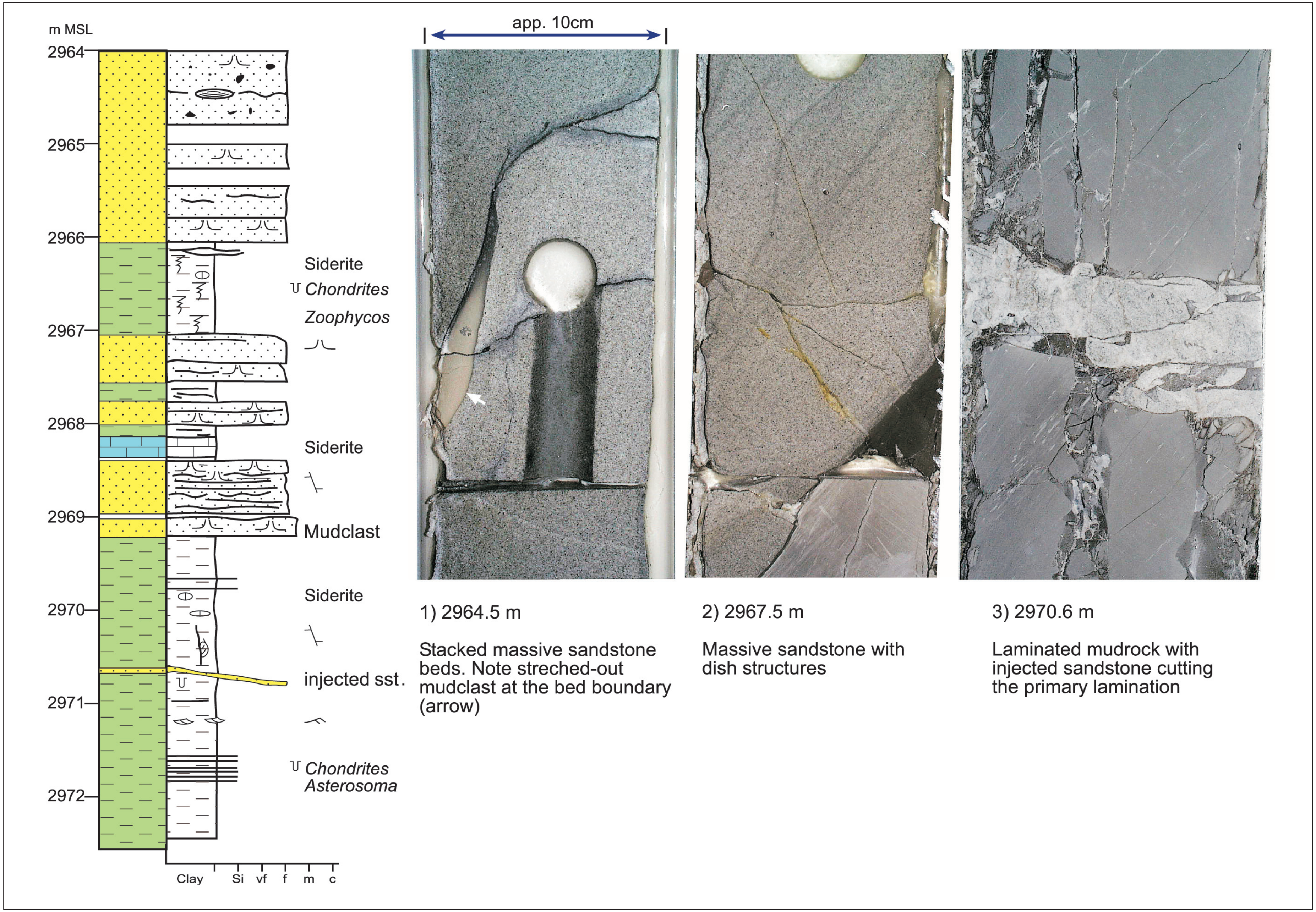

Fig. 6. Graphic description of Core 1: Middle Eocene sandstones and associated mudrocks, well 7216/11-1S. See also Figure 3 for the stratigraphic position of the core.

intensity map (Fig. 5c) shows a NNW-oriented high-intensity belt (sandstone) pinching out rather abruptly to the west. A number of possible mud diapirs can also be observed (Fig. 5b,c) within the inferred sandstone belt.

A cored section (Fig. 6; core #1 in Fig. 3), cut about 70 m below the top of the reservoir sandstone unit, comprises a lower interval of intercalated mudrocks and sandstones (2966,1 - 2972,4 m), overlain by a thicker sandstone unit (2964 - 2966,1 m). The lower interval comprises three fine-grained sandstone beds, each with sharp upper and lower boundaries. The basal bed contains abundant cm-size mudclasts showing some planar lamination above. Otherwise, the sandstone beds show a massive texture, associated with dish structures (Fig. 6: 2967,5 m) and soft sediment deformation features, particularly convolute laminations. The associated mudrocks are light grey, with a well-defined lamination. Furthermore, thin silty to sandy lamina and lenses occur, particularly in the section below 2970,2 m. A thin injected sand layer cuts through the primary lamination (Fig. 6: 2970,6 m). Sideritic nodules and lamina occur at irregular intervals, locally forming dm-thick units (Fig. 6: 2968,2 m). Bioturbation is weak throughout, and comprises scattered traces of *Chondrites* and possible *Zoophycos.*

The overlying sandstones (above 2966,1 m, Fig. 6) show a sharp basal contact with the subjacent mudrock, with the basal boundary being rather parallel to the lamination seen in the underlying deposits. Internally, the unit comprises stacked and amalgamated dm-thick beds of fine-grained sandstone. Bed contacts are usually sharp and occasionally draped by stretched-out mudclasts (Fig. 6: 2964,5 m). The overall sandstone texture is rather massive and occasionally associated with parallel lamination and dish structures.

The biostratigraphic data indicate a deep, oxygen-depleted marine depositional environment (diverse assemblage of agglutinated foraminifera, pyritised diatoms, no calcareous microfossils) for the Middle Eocene. The integration of core data, wireline logs and seismic attributes further indicate that the sandstone emplacement occurred by gravity-driven deposition in a submarine fan/channel environment.

The bedded and amalgamated nature of the cored sandstones, the invariably sharp upper and lower bed boundaries, and the lithofacies types (mainly massive sandstones associated with dish structures) are related to vertical stacking of sandy, high-density turbidites (e.g. Kneller & Branney 1995; Stow & Johansson 2000). The massive sandstone facies was rapidly deposited from sandy, turbid flows, whereas the associated dishes formed during subsequent water escape. The mudclasts at the base of individual beds indicate erosion of the underlying basin plain deposits by sediment rip-up. This may indicate a possible channelised setting, with the rapid westerly termination of the high seismic amplitudes suggesting confinement of the submarine fan in the axial part of the basin. The reworking of Early Jurassic palynomorphs suggests that the sandstones may have been sourced by erosion of the Nordmela and Stø formations, which are known reservoir-quality sandstones, particularly in the Hammerfest Basin to the east.

The observed ichnofacies of *Chondrites* and possible *Zoophycos* is rather characteristic of deep marine settings colonized by epibenthic and endobenthic organisms (Pemberton et al. 1992). Moreover, this ichnofacies can indicate a slight oxygen depletion within the bottom sediment, and also quiet conditions well below wave base, in good agreement with the interpretation based on the agglutinated foraminifera (see above). The injected sandstone layer at 2970,6 m is most likely sourced from an underlying or lateral sand accumulation. This indicates some large-scale deformation of the entire unit.

The seismic observations (Fig. 5) can tentatively be related to large-scale soft-sediment deformation following emplacement of the sandy submarine fan on a soft, water-saturated substrate. Particularly, deformed sandstone lenses and the possible diapirs inferred from the seismic data (Fig. 5b,c) can be related to diapirism induced by sediment loading and density contrasts between the newly accumulated sand and the surrounding muddy basin-floor sediment. The deformed nature of some of the cored sandstone beds (particularly 2967 - 2970,2 m; Fig. 6) and the existence of injected sandstones in the associated mudrock testifies to significant post-depositional soft-sediment deformation, as is to be expected if large-scale diapirism has occurred.

Finally, it is noted that the assemblage of agglutinated foraminifera in the Middle Eocene and the Paleocene - Lower Eocene successions described above, are almost identical, and reflect rather similar, deep marine (bathyal) conditions throughout Paleocene - Middle Eocene time.

Late Eocene (2444 - 2486 mMSL)

A thin and condensed Upper Eocene (Priabonian) section is identified. The lithology comprises varicoloured grey, green, and brown to blackish mudrocks associated with minor limestones. Furthermore, micropaleontological analysis shows a marked reduction of agglutinated foraminifera at this level. The microfauna comprises abundant siliceous diatoms and radiolarians, whereas calcareous, benthic foraminifera are absent.

The persistence of a similar foraminiferal microfauna to that of the Middle Eocene indicates an equally deep, oxygen-depleted, bathyal marine setting for the Late

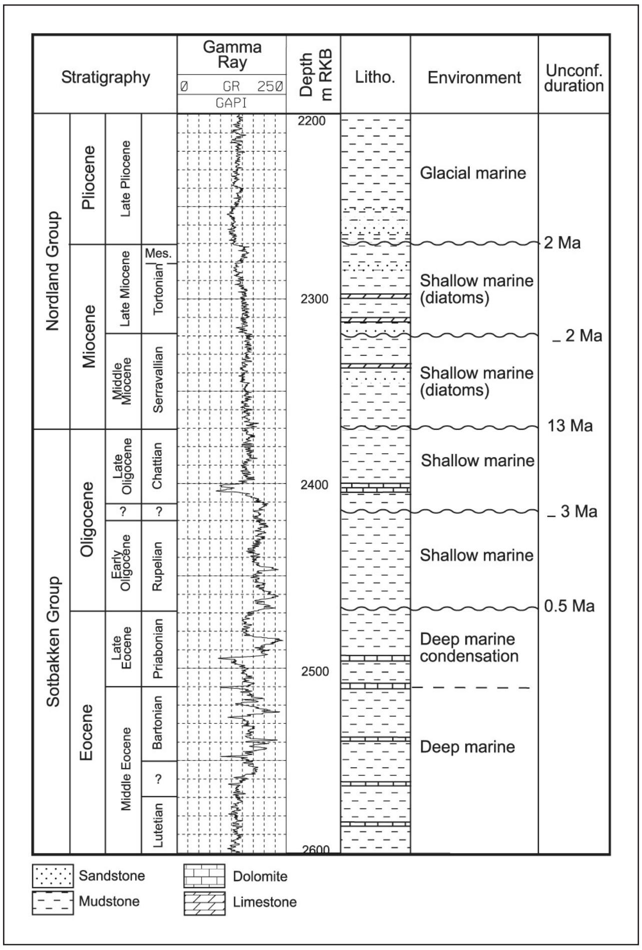

Fig. 7. Stratigraphy, lithology and depositional environments of Late Eocene - Late Miocene strata, well 7216/11-1S. The measured depths (mRKB) refer to the rig's Kelly Bushing, 24m above mean sea level.

Eocene. The fine-grained nature of the Upper Eocene interval would generally testify to deposition by settling of suspended fines in a low-energy environment. However, the near disappearance of agglutinated foraminifera most likely records significant marine shallowing during the latest Eocene (i.e. at the Eocene - Oligocene boundary). These shallow marine conditions persisted through the Oligocene - Miocene as well (see below).

Oligocene - Miocene (2246 - 2444 mMSL)

The Oligocene (2346 - 2444 mMSL) to Miocene (2246 - 2346 mMSL) succession is condensed, and consists of 4 unconformity-bounded units (see also Fig. 3). The micropaleontological data show this interval to contain siliceous diatoms and radiolaria, with no calcareous forms, and with only a few agglutinated foraminifera. Lower Oligocene (Rupelian) deposits (see Fig. 7) are entirely fine-grained, consisting of generally grey/dark grey mudrocks. The Upper Oligocene (Chattian) interval (Fig. 7) comprises grey to brown mudrocks associated with a significant limestone (cemented) bed. The Middle - Upper Miocene succession comprises silty mudrocks and scattered fine-grained sand-stones, associated with dolomite-cemented stringers.

As shown in Figure 8, Oligocene - Miocene strata onlap the Eocene - Oligocene boundary towards the western marginal high of the Sørvestsnaget Basin, testifying to the unconformable nature of the basal Oligocene surface. Furthermore, the Upper Miocene unit is apparently truncated by the basal Pliocene surface, bringing tilted Paleocene - Eocene strata into contact with Pliocene strata across the marginal high.

The Oligocene - Miocene succession was probably deposited in a shallow marine environment. On-lap of these strata towards the western marginal high (Fig. 8) is a clear indication that the high formed a topographic element or at least a submarine high during deposition. The marginal high, therefore, was re-activated at the Eocene - Oligocene boundary. Subsequently, Oligocene - Miocene deposits seem to have filled-in a more shallow marine basin confined to the west, and separated from age-equivalent deposits in the Lofoten Basin, by the marginal high. This aspect is further discussed below.

Late Pliocene - Pleistocene (361 - 2246 mMSL)

The position of the basal Pleistocene boundary at about 743 mMSL (Fig. 3) is tied from the seismic data. The first samples at 1006 mMSL are dated as Late Pliocene on the basis of biostratigraphy. The entire section down to 2246 mMSL contains calcareous benthonic foraminifera and reworked Cenozoic and Mesozoic palynomorphs and microfossils (e.g. *Inoceramus* prisms). The influx of *Operculodinium centrocarpum* (a warmer-dwelling dinoflagellate cyst) at 2204 mMSL near the base of the succession is also noted as it may compare to similar warm-dwelling assemblage described from ODP site 986 offshore western Svalbard (Channell et al. 1996; Smelror 1996). Reworked microfossils within this unit show a mixture of different sources, but mainly from Cretaceous sediments. The lithology is dominated by grey clays and claystones with minor beds of fine- to very coarse sand. On the seismic data (Figs. 2, 8), the Pliocene interval is characterized by westward dipping clinoforms. Deep incisions occur within the clinoforms (Fig. 8), apparently truncating deposits of Eocene - Paleocene age in the vicinity of the marginal high.

A Late Pliocene - Pleistocene age for the Neogene wedge is in general agreement with other studies of the western Barents Sea (Eidvin et al. 1993, 1998; Sættem et al. 1994; Channell et al. 1996; Faleide et al. 1996). Furthermore, a glacio-marine depositional environment can be inferred from the available micropaleontological data, in good agreement with previous studies of the

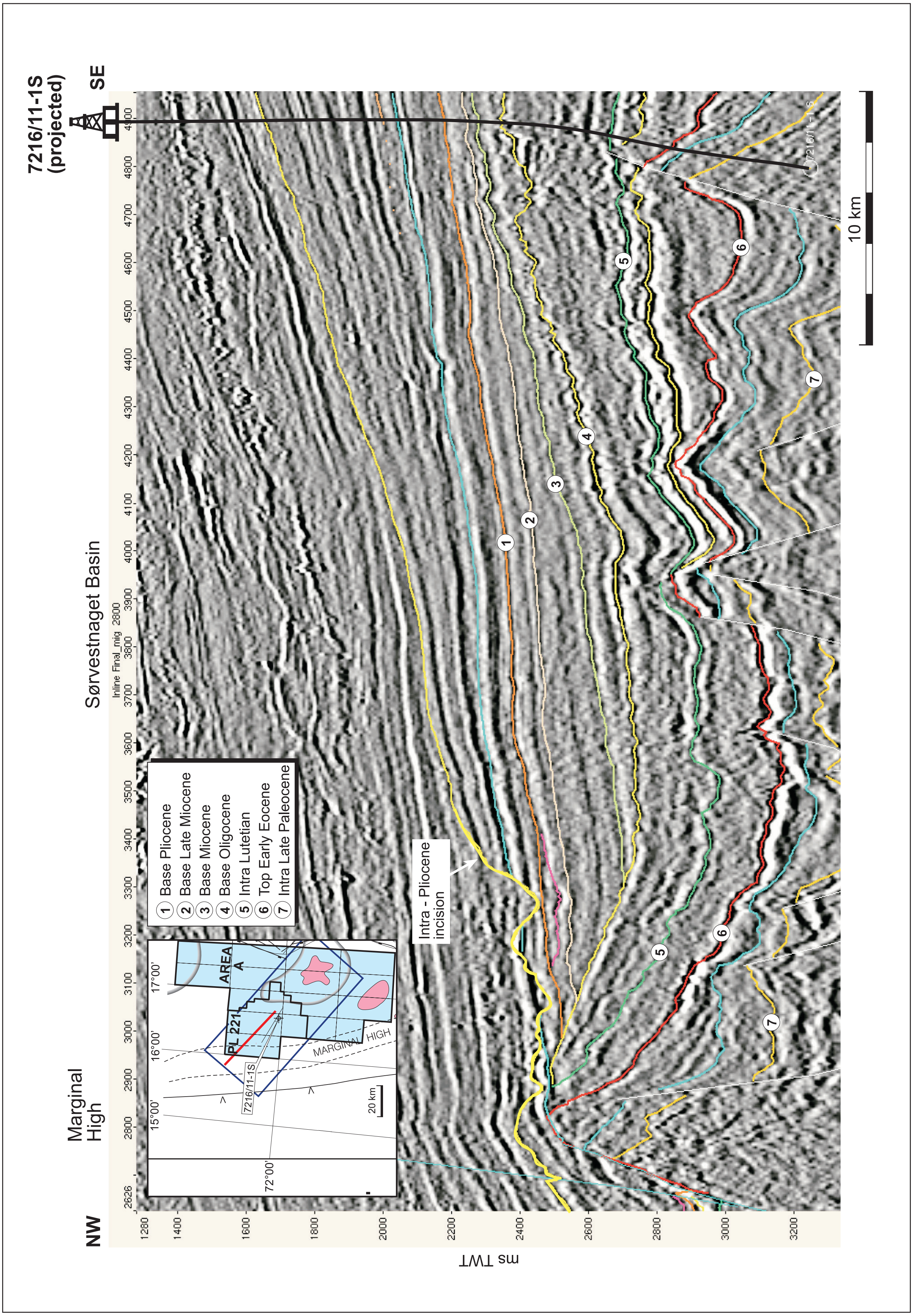

Fig. 8. Seismic section showing on-lap of Oligocene - Miocene strata on the Early Oligocene (Base Oligocene) unconformity towards the western marginal high of the Sørvestsnaget Basin.

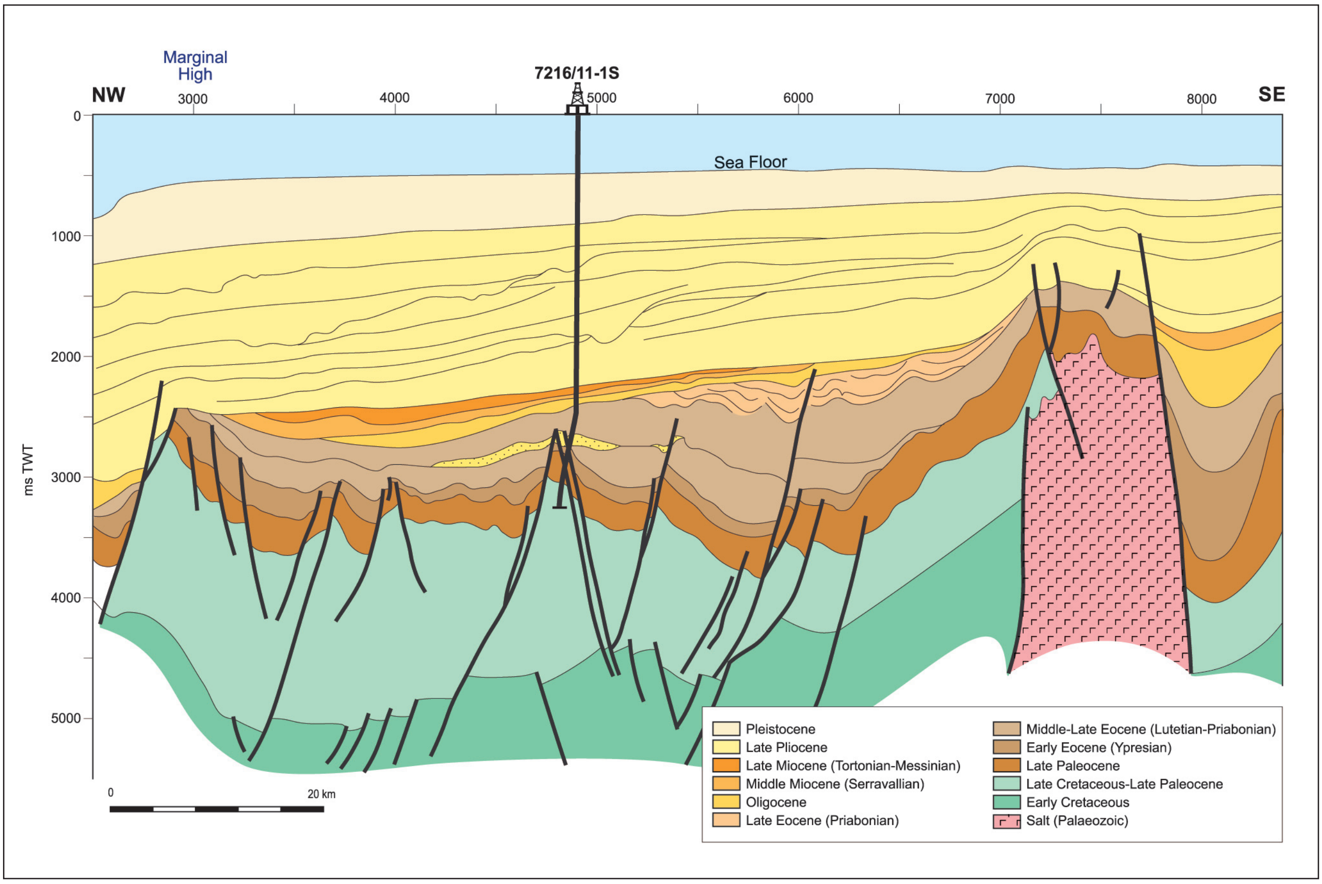

Fig. 9. Geoseismic representation of inline NH9803-2936 (Fig. 2) in the Sørvestsnaget Basin.The stratigraphic interpretation is based on data from well 7216/11-1S. For location, see Fig.1b.

clastic wedge (e.g. Sættem et al. 1994; Faleide et al. 1996). The clinoforms are related to progradation of glacial deltas supplied from the uplifted shelf to the east, whereas the incisions probably represent feeder channels cut during glacio-eustatic sea level falls.

The warm-dwelling dinocysts near the base of the succession may reflect a mid-Pliocene (app. 3 Ma) global warming prior to the onset of the Svalbard - Barents Sea ice sheet (Knies et al. 2002), or alternatively, record re-sedimentation of older Pliocene deposits within the clastic wedge. However, the dinocysts may also record periods of warmer water influx from the North Atlantic Current during the Late Pliocene (see Smelror, 1996 for further discussion).

Regional correlation of Cenozoic strata

Sørvestsnaget Basin

In the following sections, the stratigraphic observations from the well are tied to a regional stratigraphic framework through well correlations and geoseismic profiles. A geoseismic representation of the Sørvestsnaget Basin in the vicinity of well 7216/11-1S (Fig. 9) illustrates the local stratigraphy of the area, from the marginal high to the west, through the drilled structure in the central part of the basin, terminating in a salt-influenced area to the east.

The Cretaceous - Cenozoic boundary has not been clearly identified, but is probably present more or less immediately below the well's total depth point, judging from the Danian age of these deposits (see also correlation to well 7316/5-1 below). However, Upper Paleocene - Lower Eocene (Thanetian - Ypresian) strata can be followed from the marginal high, across the central part of the basin. They are apparently truncated by the Early - Middle Eocene unconformity to the east, towards the salt diapir. There is no significant thickness contrast between the marginal high and the central part of the Sørvestsnaget Basin at this level, although some growth faulting can be inferred in the western part of the profile, particularly at the Early Eocene level, testifying to syn-sedimentary extensional faulting related to the contemporary crustal break-up. Furthermore, a substantial increase in thickness in the rim syncline to the east of the diapir indicates salt movement at this time.

The Middle Eocene (Lutetian - Bartonian) deposits show the maximum thickness of Palaeogene deposits

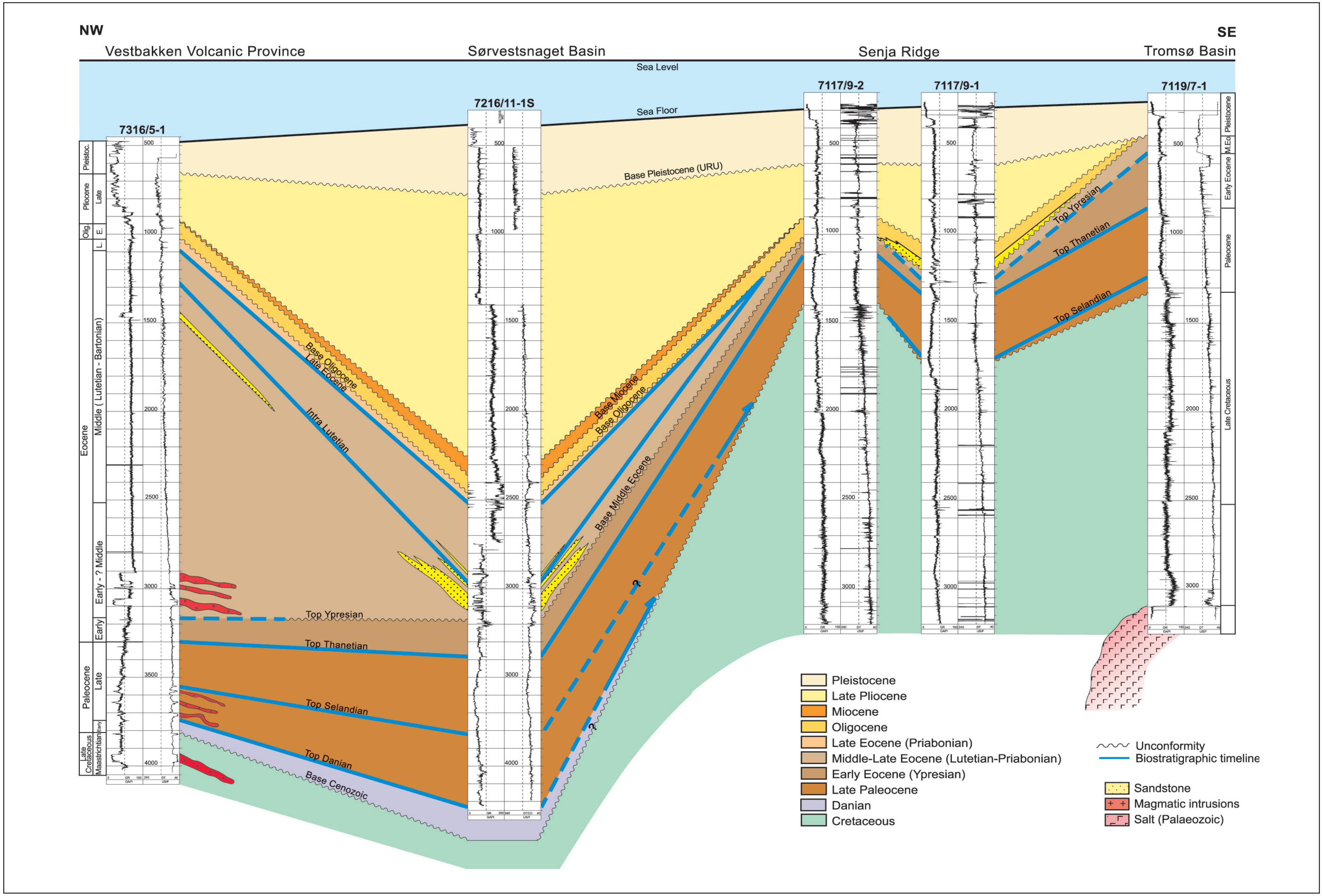

Fig. 10. Well-correlation of Cenozoic strata, Vestbakken Volcanic Province, Sørvestsnaget Basin, Senja Ridge and Tromsø Basin. Log traces are Gamma Ray (API) (left curve) and Sonic log (microseconds/feet) (right curve). Datum is set at mean sea level. For location of the wells, see Fig.1b.

along the transect, forming a depocentre in the central part of the basin, where they are also capped by the thickest Upper Eocene (Priabonian) deposits. The sandy, Lutetian submarine fan unit is positioned rather axially in the basin, but apparently not within the area of maximum Middle Eocene thickness. The Middle Eocene succession shows apparent thinning on to the marginal high to the west. This thinning is only partly controlled by truncation by the identified Oligocene - Pliocene unconformities, so that incipient uplift or reduced subsidence rates of the marginal high may be inferred during the Middle Eocene. Middle Eocene deposits are apparently truncated by the Oligocene - Pliocene unconformity near the salt diapir. Middle and Upper Eocene deposits (in Fig. 9) are not separated in the rim syncline, but the thickening of the inferred Middle Eocene interval in the syncline testifies to continuing growth of the salt.

As shown above, Oligocene - Miocene strata on-lap the marginal high from the east. Hence, the high was probably established as a bathymetric feature by the Oligocene. The main phase of uplift of the marginal high may have occurred during the Late Eocene - earliest Oligocene, concurrent with the recorded shallowing in the Sørvestsnaget Basin. The Oligocene - Miocene interval is truncated below the Upper Pliocene wedge to the east. However, the successions reappear in the rim syncline of the salt. The Upper Pliocene and Pleistocene units form a thick wedge of westwards dipping strata across the basin. Notice particulary the truncation of Paleocene - Miocene strata below the basal Pliocene unconformity, testifying to substantial Pliocene erosion of the marginal high. Also, the deformation of Pliocene deposits above the salt indicates rather recent salt movement.

Senja Ridge - Vestbakken Volcanic Province

Figure 10 shows a correlation of Cenozoic strata in five wells from the Vestbakken Volcanic Province through the Sørvestsnaget Basin and the Senja Ridge, to the Tromsø Basin. A composite geo-seismic profile through the same area (not including the Tromsø Basin, see Fig. 11) and a geoseismic representation of the 2D seismic line NH-9709-234 (Veslemøy High to Lofoten Basin; see Fig.12) shows the Cenozoic stratigraphy of the Sørvestsnaget Basin compared to the adjacent basins and highs.

A thin unit of Lower Paleocene (Danian) mudrocks is seen in the Vestbakken area (well 7316/5-1; Fig. 10), apparently resting conformably on Upper Cretaceous (Late Maastrichtian) mudrocks. Danian deposits are also present in the Sørvestsnaget Basin (see above), but disappear by apparent on-lap of strata towards the Senja Ridge. The geoseismic data (Fig. 11) give no indication about the lateral continuity of the Danian interval and it is possible that the Vestbakken Volcanic Province and the Sørvestsnaget Basin were structurally separated by a barrier in the fault zone between these two domains. Danian deposits are generally absent throughout the Barents Sea (c.f. Dalland et al. 1988), but the present data show that Early Paleocene basins existed in the western Barents Sea.

Significant (300 - 400 m thick) Upper Paleocene (Selandian - Thanetian) strata (mainly mudrocks) can be correlated throughout the whole section. Apparently, however, deposits of Selandian age are better developed in the Vestbakken area and the Sørvestsnaget Basin than on the Senja Ridge/Tromsø Basin, where they are either thin or absent. It is inferred that Selandian strata in part on-lap the Senja Ridge from the west. Thanetian deposits rest unconformably on Upper Cretaceous mudrocks on the Senja Ridge. On the basis of biostratigraphy and log patterns they seem to form a laterally continuous facies, particularly in the section from the Sørvestsnaget Basin, Senja Ridge and Tromsø Basin and also throughout the rest of the Barents Sea (c.f. Dalland et al. 1988). These observations support the idea of a widespread Late Paleocene epeirogenic sea in the Barents Sea region (Nøttvedt et al. 1988).

Lower Eocene (Ypresian) mudrocks can be correlated through all the wells (Fig. 10). On the Senja Ridge (well 7117/9-2) the entire Eocene succession is apparently truncated below Lower Oligocene mudrocks, testifying to a significant break below the basal Oligocene unconformity on the ridge. Further to the east, however, the thickness of Ypresian deposits increases in the Tromsø Basin, and the erosive break below the Oligocene succession is apparently less pronounced.

Figure 11 shows extensional faulting of the Paleocene - Lower Eocene succession along the entire transect from the Senja Ridge to the Vestbakken Volcanic Province, probably reflecting rift-related tectonism during crustal break-up (as is also seen in Fig. 9). However, lateral continuity of Paleocene - Lower Eocene successions can be inferred between the Vestbakken province and the Sørvestsnaget Basin, testifying to the widespread nature of the Late Paleocene - Early Eocene marine basin.

Middle Eocene deposits reach an extreme thickness (app. 2 km) in the Vestbakken area. The succession in well 7316/5-1 (Fig. 10) is totally dominated by mudrocks, however, with a notable sandstone unit in its upper part. This sandy unit is age-equivalent to the Lutetian sandstones in the Sørvestsnaget Basin. Furthermore, sedimentological studies of cores from well 7316/5-1 (John Gjelberg, 2000 pers. comm.) indicate that the sandstone unit was emplaced as a submarine fan (similar to the reservoir sandstones in well 7216/11-1S). A thin unit of Upper Eocene (Priabonian) mud-

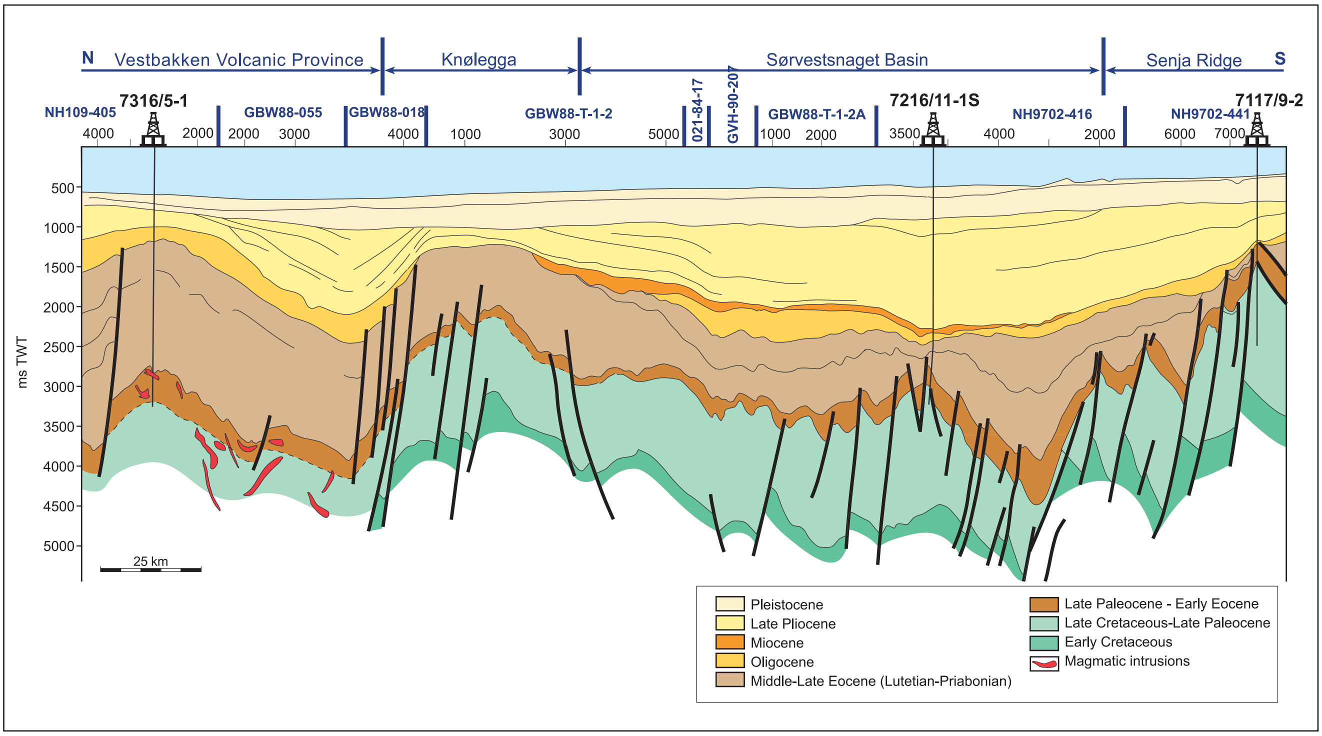

Fig. 11. Geoseismic cross-section, Vestbakken Volcanic Province, Sørvestsnaget Basin and the Senja Ridge. For location, see Fig. 1b.

rocks can be correlated between wells 7316/5-1 and 7216/11-1S. Middle- and Upper Eocene strata are, however, severely truncated below the basal Oligocene unconformity across the Senja Ridge, and eventually by the basal Pleistocene boundary even further to the east.

Figure 11 indicates that the large thickness of Middle Eocene deposits in the Vestbakken area is due to differential subsidence between the Sørvestsnaget Basin and the Vestbakken Volcanic Province, most likely accommodated by normal down to the northwest faulting in the fault zone separating the two areas. Also, hangingwall thickening of Middle Eocene strata on faulted blocks on the northwest flank of the Senja Ridge can be seen, testifying to localized Middle Eocene extensional faulting.

A thin Oligocene interval can be correlated along the transect (Fig. 10) from the Vestbakken Volcanic Province, through the Sørvestsnaget Basin and across the Senja Ridge. As noted above, shallow marine mudrocks were deposited in the Sørvestsnaget Basin. However, a unit (app. 30 m thick) of glauconitic sandstones occurs above the Oligocene boundary in the eastern part of the Senja Ridge (well 7117/9-1), probably reflecting deposition in a more nearshore setting. Miocene, shallow marine deposits are most substantial in the Sørvestsnaget Basin. In the Vestbakken area and on the Senja Ridge Miocene strata were apparently removed by erosion below the basal Pliocene unconformity.

The Oligocene - Miocene succession in the Sørvestsnaget Basin is apparently confined to the north by the fault zone at the transition to the Vestbakken Volcanic Province ("Knølegga", Fig. 11, Fig. 1b). Inspection of reflection seismic data also shows on-lap of Oligocene - Miocene strata on the composite basal Oligocene/Miocene unconformity towards the northern limit of the Sørvestsnaget Basin, similar to the on-lap seen towards the western marginal high (Figs. 8, 9). Accordingly, a bathymetrical high or positive structural feature may have been located in the fault zone between the Sørvestsnaget Basin and the Vestbakken area during the Oligocene - Miocene, possibly linked to the western marginal high of the Sørvestsnaget Basin.

The Upper Pliocene wedge is most significant and apparently best preserved in the Sørvestsnaget Basin (Figs. 11, 12). Significant thinning and truncation below the basal Pleistocene unconformity occur on the Senja Ridge, leading to complete erosion to the east (Tromsø Basin, see Fig. 10). Furthermore, Pliocene deposits are severely truncated below the Pleistocene unconformity across the fault zone between the Sørvestsnaget Basin and the Vestbakken Volcanic Province, possibly indicating very recent uplift in this area (see Fig. 11). The biostratigraphy and the seismic data support a Late Pliocene age for the deposits above the basal Pliocene unconformity throughout the correlated section (Fig. 10). It is also noted that the Pliocene succession is dominantly sandy in the Vestbakken area (Knutsen & Larsen 1996), in contrast to the mudrock-dominated succession in the Sørvestsnaget Basin and on the Senja Ridge. Finally, about 150 - 300 m of Pleistocene

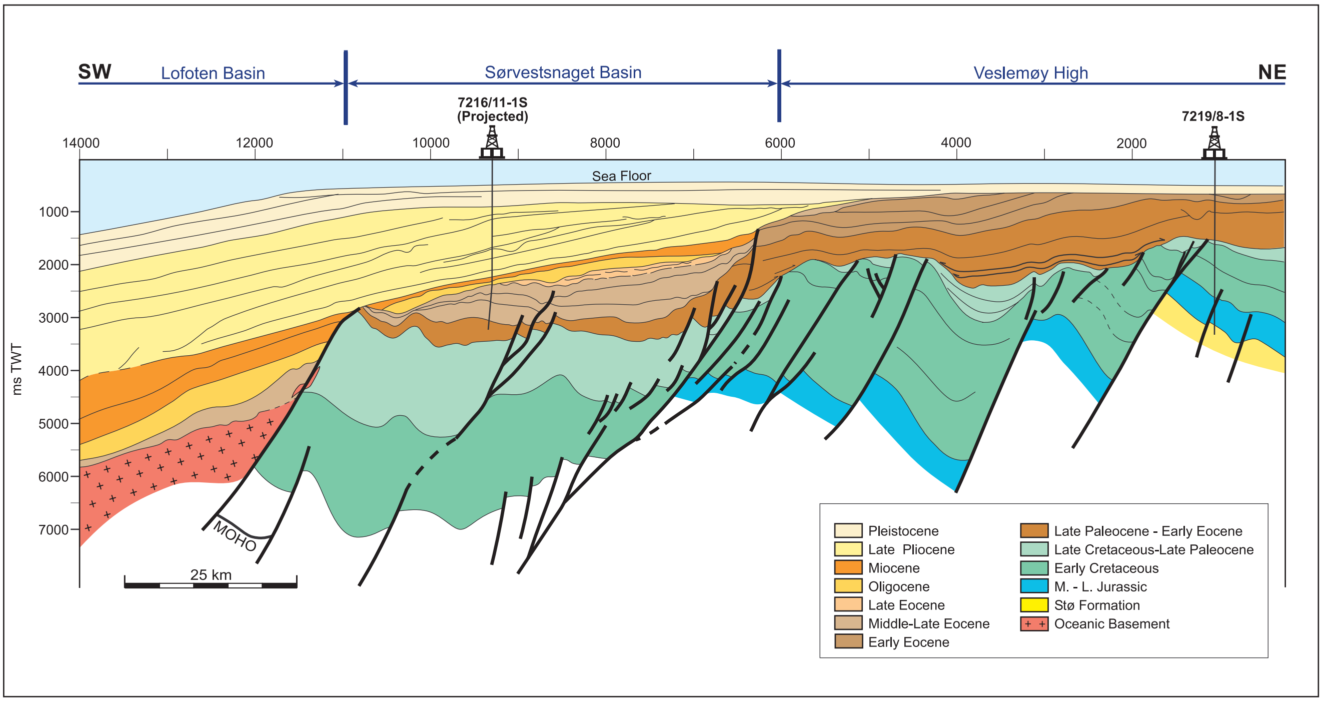

Fig. 12. Geoseismic cross-section, Lofoten Basin, Sørvestsnaget Basin and Veslemøy High. The Cretaceous time-thickness and the Moho location at about 7000 ms. below the outer part of the marginal high are inferred from regional seismic interpretation supported by ocean bottom seismographs (OBS), gravity and magnetic field data (Mjelde et al. 2002). For location see Fig. 1b.

glacial erosion products rest unconformably on the older Cenozoic strata throughout the investigated area.

Sørvestsnaget Basin - Veslemøy High

The geoseismic profile from the Lofoten Basin to the Veslemøy High (Fig. 12) crosses the Sørvestsnaget Basin (and the transect shown in Fig. 11) immediately to the south of well 7216/11-1S. A thick Lower Cretaceous succession is present on the Veslemøy High and in the Sørvestsnaget Basin, indicative of a large, continuous, Early Cretaceous basin that also included the Tromsø-, Bjørnøya- and Harstad basins. In contrast, the most prominent Upper Cretaceous succession is apparently confined to the Sørvestsnaget Basin, confirming the Late Cretaceous - Cenozoic separation of the Sørvestsnaget Basin from the remaining deep basins in the area (see also Faleide et al. 1993a,b; Breivik et al. 1998). Comparison of stratigraphic data in the Sørvestsnaget Basin and the Veslemøy High reveal two important contrasts at the Palaeogene level.

Firstly, biostratigraphic dating of the Palaeogene succession in well 7219/8-1S on the Veslemøy High (see Fig. 12) gives a Late Paleocene (Thanetian) - Early Eocene age for the entire interval of approximately 990 m (well 7219/8-1S), unconformably overlying Upper Cretaceous (Campanian) and older deposits. The corresponding Paleocene - Early Eocene thickness seen in well 7216/11-1S is about 760 m (true vertical thickness). Hence, at the Paleocene level, the Sørvestsnaget Basin differs from the Veslemøy High by containing an apparently thinner but stratigraphically more complete Paleocene - Early Eocene (Danian - Ypresian) package. Essentially, the Danian - Selandian succession seen in the Sørvestsnaget Basin appears to on-lap the basal Cenozoic unconformity towards the Veslemøy High. Locally on the high (e.g. between CDP 2000 and 4000; Fig. 12) older Paleocene strata may be present in smaller sub-basins as defined by the relief of the basal Cenozoic unconformity.

Secondly, the Sørvestsnaget Basin (and the Vestbakken area) is characterized by its thick unit of Middle Eocene strata. The seismic data show on-lap of Middle Eocene deposits onto the Early - Middle Eocene unconformity, particularly towards the fault zone separating the Veslemøy High from the Sørvestsnaget Basin (Fig. 12). These stratal patterns are indicative of differential tectonic activity between the Veslemøy High and the Sørvestsnaget Basin during the Early - Middle Eocene (see below).

At the Late Palaeogene - Neogene level, the existence of Oligocene - Miocene deposits distinguishes the Sørvestsnaget Basin from the Veslemøy High (see Fig. 12). Furthermore, the Upper Pliocene wedge is well developed in the Lofoten and Sørvestsnaget basins. The Cenozoic stratigraphy of the Lofoten Basin is not discussed in any detail. However, a significant sedimentary unit can be defined below the Pliocene succession (Fig. 12), resting on inferred oceanic crust. Since the crust itself started to form during the Early Eocene, the pre-Pliocene sediments are of probable Middle Eocene - Late Miocene age (Fig. 12).

Cenozoic subsidence and uplift of the Sørvestsnaget Basin

Based on the information shown in Figure 12, and the stratigraphic and sedimentologic data presented above, the tectonostratigraphic evolution of the Sørvestsnaget Basin and the Veslemøy High is shown in Figure 13. Above Upper Cretaceous strata, Danian - Selandian marine shelf deposits are present in the Sørvestsnaget Basin (Fig. 13a), onlapping the Veslemøy High from the west. A similar onlap of Danian - Selandian deposits can be inferred between the Sørvestsnaget Basin and the Senja Ridge (Fig. 10). Accordingly, it appears that the Sørvestsnaget Basin, as well as the Vestbakken Volcanic Province (see Fig. 10), were established sedimentary basins during the Danian - Selandian, and that the Veslemøy High and the Senja Ridge formed contemporary, bathymetrical (submarine) highs. However, subsequent transgression/subsidence caused the establishment of a widespread deep marine (bathyal) environment during the Late Paleocene and Early Eocene (Fig. 13a), with deposition of mainly marine, offshore mudrocks (epeirogenic basin of Nøttvedt et al. 1988).

The Early Eocene onset of sea floor spreading along the Senja Fracture Zone (see above) triggered significant extensional faulting in the area (Figs. 9, 12). Sættem et al. (1994) argued that significant footwall uplift occurred in the Sørvestsnaget Basin during the Early Eocene due to crustal break-up. Furthermore, Vågnes (1997) considered the actual amount of uplift along the Senja Fracture Zone during the Eocene - Oligocene ocean - continent transform stage and early passive margin stage. Heat conduction from the hotter oceanic lithosphere combined with viscous coupling across the plate boundary can lead to significant uplift of continental crust. Vågnes (1997) inferred that up to 1 km of Paleocene deposits were eroded from the marginal high during the Eocene - Oligocene, and noted that the uplift/erosion might occupy a 50 - 60 km wide zone, gradually decreasing to zero to the east of the transform. Vågnes (1997) predicted that such uplift would produce a major break-up unconformity over large parts of the Sørvestsnaget Basin.

This interpretation is not supported by the data gathered from well 7216/11-1S. The biostratigraphic data presented above show a limited, possibly fault-induced break (app. 3,5 Ma) in the well at the Early - Middle Eocene boundary. On-lap of Middle Eocene strata towards the Veslemøy High (Fig.12) provides evidence for a regional unconformity during the Early - Middle Eocene, with the Veslemøy High forming a contemporary bathymetric high adjacent to the Sørvestsnaget Basin (Fig. 13b). However, the uplift in this case is away from the transform margin and to the east of the Sørvestsnaget Basin, in strong contrast to earlier predictions of widespread uplift along the transform margin. It is also noted that the recorded break in well 7216/11-1S is in the Late Ypresian, whereas an Early Ypresian age is related to magnetic anomaly 24 marking the onset of crustal break-up in the Norwegian - Greenland sea (e.g. Skogseid et al. 2000; Mosar et al. 2002). The inferred Early - Middle Eocene structuring between the Veslemøy High and the Sørvestsnaget Basin is probably younger than the actual break-up, and could perhaps record more localised relative uplift of the structural high.

By early Middle Eocene (Lutetian) time, deep marine, bathyal conditions again persisted in the Sørvestsnaget Basin and in the Vestbakken Volcanic Province to the north (Fig.13b; Fig 12), testifying to subsidence along the transform margin. Of particular relevance is the deposition of sandy submarine fans in the axial part of the Sørvestsnaget Basin and in the Vestbakken area. Provided that the Sørvestsnaget Basin was uplifted in the Late Ypresian, the deep marine nature of the deposits immediately above and below the unconformity would indicate a much smaller magnitude of the uplift than previously predicted, with rather rapid collapse and renewed subsidence of the uplifted areas.

The end-Eocene shallowing in the Sørvestsnaget Basin was followed by deposition of condensed, shallow marine, fine-grained sediment during the Oligocene - Miocene, more or less contemporary with the passage of the spreading ridge along the western basin margin (Fig. 13c; Fig. 8). The western marginal high was uplifted at this stage, as recorded by on-lap of strata on to the high. The main Oligocene - Miocene depocentre was probably located in the oceanic Lofoten Basin, with the marginal high forming a partial barrier towards the Sørvestsnaget Basin. The actual extent of the Oligocene - Miocene strata to the east of the Sørvestnaget Basin is masked by Late Neogene uplift and erosion, although a unit of Oligocene sandstones and mudrocks is present on the Senja Ridge and in the western part of the Tromsø Basin (Fig. 10).

Several unconformities occur within the shallow marine Oligocene - Miocene package (Fig. 7),. These unconformities seem to coincide, at least partly, with possible phases of compression and inversion (mainly Oligocene) of the intrabasinal highs, particularly the Senja Ridge, the Veslemøy High and the Stappen High (Gabrielsen et al. 1990; Rasmussen et al. 1995). Doré & Lundin (1996) pointed out that Cenozoic phases of compression and inversion are common within the northeast Atlantic realm of Cretaceous - Cenozoic basins, with important phases of structuring occurring

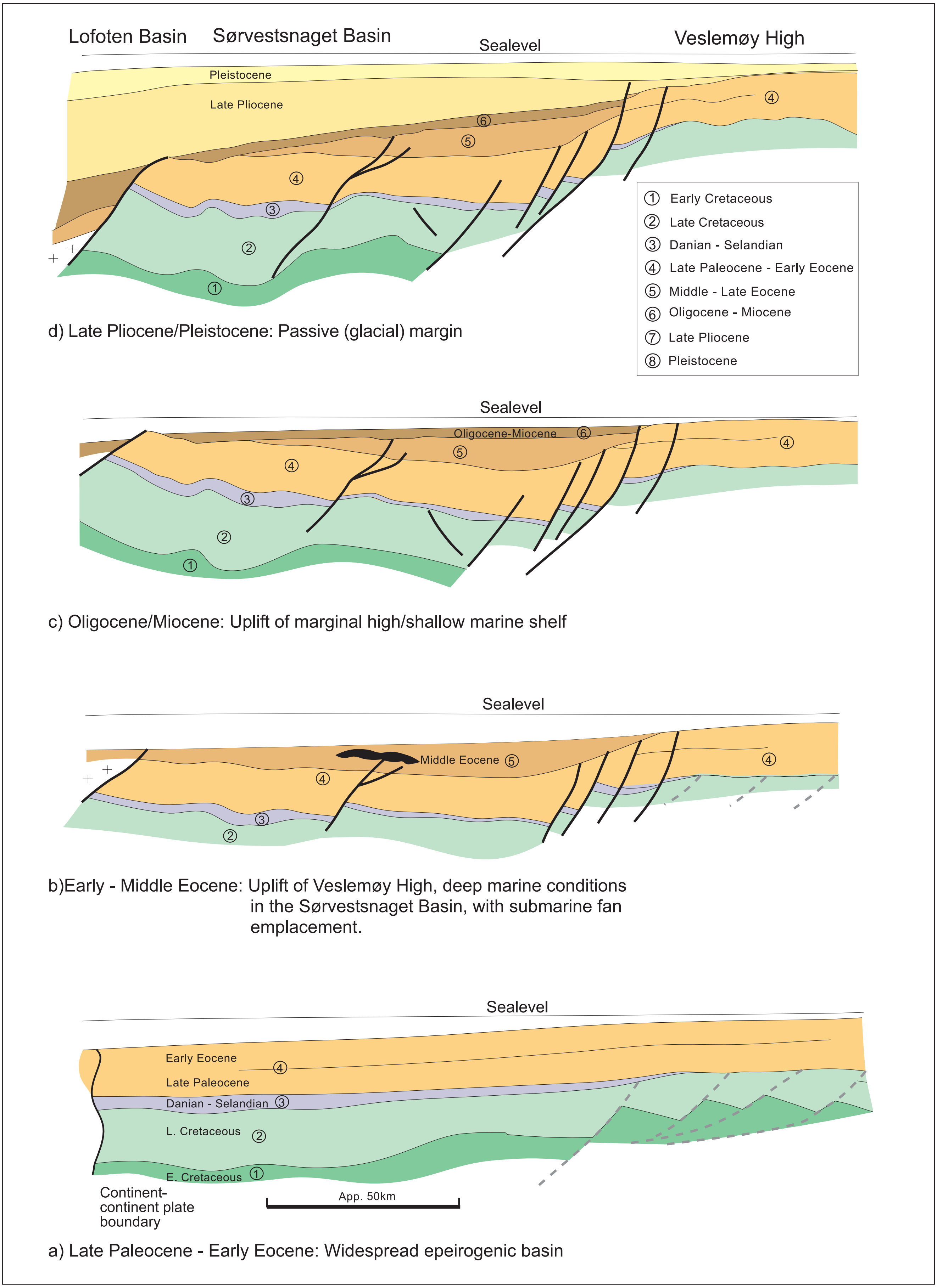

Fig. 13. Tectonostratigraphic model for the evolution of the Sørvestsnaget Basin and the Veslemøy High.

during the Oligocene and Miocene. These phases may relate to plate tectonic changes in the northeast Atlantic, as well as to major Alpine deformation phases (Doré & Lundin, 1996). Accordingly, the basal Oligocene unconformity can possibly be related to the Early Oligocene (magnetic anomaly 13) reorganization of spreading poles. Faleide (1993b) noted that significant uplift of the intrabasinal highs can be attributed to this plate tectonic event, and Knutsen & Larsen (1997) related a phase of uplift of the marginal high (Sørvestsnaget Basin) to the same event. Possibly, the observed change from a rather deep marine Paleocene - Late Eocene setting to a shallower marine Oligocene - Miocene environment in the Sørvestsnaget Basin can be related to this phase of structuring.

The recorded 13 Ma stratigraphic break at the Early - Middle Miocene unconformity (Fig. 7) is apparently equivalent in age to a similar unconformity in the North Sea and the Møre Basin, reflecting widespread erosion followed by marine condensation (Martinsen et al. 1999). The regional extent of the Early - Middle Miocene unconformity implies that its genesis is not just due to tectonic activity along the Senja Fracture Zone. The remaining unconformities of intra-Oligocene and Middle - Late Miocene age (see Fig. 7) in the Sørvestsnaget Basin cannot be related to any particular tectonic event. These breaks have, however, formed during a period of globally low sea level (Hardenbol et al. 1998), and may be controlled by eustatic changes.

The final stage of margin development (Fig. 13d) is represented by the Upper Pliocene - Pleistocene wedge, which essentially records subsidence along a passive continental margin where the oceanic and continental crusts are locked across the continent-ocean boundary. The unconformable nature of the basal Late Pliocene surface (Fig. 7) probably reflects the filling of available accommodation space in the Sørvestsnaget Basin during the Late Miocene - Pliocene, with Late Pliocene erosion being enhanced by glacially induced sea level falls and glacial erosion. Sættem et al. (1994) argued that the unconformity at the base of the Upper Pliocene wedge formed due to regional uplift and concurrent sea level falls during the Pliocene. Subsequently, however, the western Barents Sea, including the Vestbakken Volcanic Province, the Sørvestsnaget Basin, the Senja Ridge and westernmost part of the Tromsø Basin subsided to accommodate the prograding wedge, which was supplied from the uplifted Barents shelf still further to the east.

Cenozoic basins and sediment source areas

There is an apparent consensus in the literature that major structural highs such as the Stappen- and Loppa highs were uplifted during the Palaeogene, and that they have acted as sediment sources for the Sørvestsnaget and Tromsø basins. Knutsen et al. (1992) observed clinoforms prograding off the Loppa High, supplying sediment to the Tromsø Basin, whereas Faleide et al. (1993a,b) noted that the Stappen High acted as a source area for thick Eocene successions in the Vestbakken Volcanic Province and in the northern part of the Sørvestsnaget Basin. The Stappen High may have been uplifted some 1 - 2 km (3.5 km on Bjørnøya) due to Early Eocene tectonism and volcanism (Faleide et al. 1993b). Rasmussen et al. (1995) noted in particular the continuous westwards progradation of shorelines from the Stappen High during Middle and Late Eocene times, forming a likely source for the Middle Eocene sandstones seen in the Sørvestsnaget Basin and the Vestbakken Volcanic Province (Fig. 10). The existence of a reworked Early Jurassic microflora in the Middle Eocene sandstones (see above) seems most supportive of a local (intrabasinal) source.

Riis (1996) suggested that about 1000 - 1200 m of uplift occurred in northern Fennoscandia during the Late Cretaceous - Palaeogene. This uplifted area would form a suitable source of coarse clastic sediment to the flanking sedimentary basins, a relationship that has recently been demonstrated for the Danian Ormen Lange submarine fan in the Møre Basin (Gjelberg et al. 2001). By analogy, sediment derived from the Fennoscandian hinterland may have sourced the Middle Eocene sandstones in the Sørvestsnaget Basin. These sediments would, however, have to bypass the more proximal Harstad- and Tromsø basins and the Senja Ridge (see Fig. 1a). Based on the observed subsidence of the Sørvestsnaget Basin during the Middle Eocene, such a paleogeographic model seems possible, even if significant sediment volumes were trapped in the more proximal areas.

Supply of sandy sediment from a westerly source such as the Greenland landmass has been inferred for the Late Cretaceous of the Vøring Basin (e.g. Morton & Grant, 1998), and might be considered for the pre-drift and early drift phase of the western Barents Sea margin as well. Plate reconstructions for the Middle Eocene (Lutetian) time interval (e.g. Torsvik et al. 2001), reflecting the configuration of landmasses during the emplacement of submarine fan sandstones in the Sørvestsnaget Basin, as well as in the Vestbakken Volcanic Province, show that the Greenland hinterland was separated from the southwest Barents Sea by a broad shelf offshore northeast Greenland, bounded to the south by the Jan Mayen Fracture Zone and to the north by the northward extension of the Senja Fracture Zone (see Larsen 1984, 1990). Geophysical studies of the northeast Greenland shelf (Larsen 1984, 1990) show that the transition to oceanic crust is at magnetic anomaly 24 (Early Eocene). This is coeval with the continent-ocean boundary along the Lofoten margin (e.g. Faleide et al.

1996; Fig. 1a), placing the eastern parts of the northeast Greenland shelf along the western margin of the Harstad- and Sørvestsnaget basins prior to the onset of sea floor spreading.

The northeast Greenland shelf comprises a series of Palaeozoic - Mesozoic (Permian - Jurassic) fault-bounded basins, below a thick package of Cretaceous - Cenozoic sediments. Larsen (1990) suggested that the Cenozoic succession on the shelf would include a relatively continuous Paleocene - Oligocene interval, capped by a Neogene wedge. Accordingly, the northeast Greenland shelf shows important similarities with the southwest Barents Sea margin. The indication of significant Palaeogene deposition on the Greeland shelf would generally seem to limit the potential supply of sandy sediment from the Greenland landmass to the southwest Barents Sea, as such sediments would most likely be trapped on the shelf. Other sources of clastic sediment, particularly uplifted areas of the Barents Sea, would consequently seem more likely.

Conclusions

The Sørvestsnaget Basin comprises a rather complete succession of Cenozoic deposits as recorded by well 7216/11-1S. Deposition commenced in the Early Paleocene (Danian), and was succeeded by continuous deposition throughout the Late Paleocene and Early Eocene. The data from well 7216/11-1S do not support previous interpretations of a widespread Early Eocene breakup unconformity in the Sørvestsnaget basin. Limited Late Ypresian uplift of the basin cannot be completely excluded, although the most significant Early - Middle Eocene uplift seems to occur to the east, on the Veslemøy High and the Senja Ridge.

Furthermore, the Sørvestsnaget Basin subsided during the Middle Eocene, as recorded by a significant Lutetian - Bartonian succession, that can also be correlated to the Vestbakken Volcanic Province to the north. The Upper Eocene - Upper Miocene succession is thin and condensed, with four significant stratigraphic breaks. The most significant unconformity (13 Ma) is recorded at the Oligocene - Miocene boundary, time-equivalent to a similar break in the Møre Basin and the North Sea. The Paleocene - Miocene succession is truncated by an Upper Pliocene - Pleistocene glacial sedimentary wedge, comprising material eroded off the uplifted Barents Sea to the east.

Deep marine, bathyal conditions persisted in the Sørvestsnaget Basin until the Late Eocene. During the Middle Eocene (Lutetian) significant sandy submarine fan sandstones were deposited in the axial part of the basin. Correlation of strata towards the Vestbakken Volcanic Province shows that age-equivalent submarine fan sandstones were emplaced also further to the north. The Middle Eocene fan deposits form the most significant reservoir sandstones in the Sørvestsnaget Basin and in the Vestbakken Volcanic Province, and were most likely eroded and resedimented locally from Jurassic sandstones on the uplifted Stappen High to the northeast.

A significant shallowing phase took place at the Late Eocene - Early Oligocene boundary, and more shallow marine conditions persisted throughout the Oligocene - Miocene. It is speculated that the end-Eocene shallowing can be related to a reorganization of spreading poles during the Early Oligocene, and consequently, be genetically linked to recorded phases of compression and deformation in the area. The Oligocene - Miocene interval in the Sørvestsnaget Basin is generally dominated by mudrocks. However, Lower Oligocene sandstones occur locally above the basal Oligocene unconformity on the Senja Ridge. These sandstones may have accumulated in a more nearshore environment and may form an additional reservoir sandstone in the southwest Barents Sea.

The western marginal high of the Sørvestsnaget Basin may have been active during the Middle Eocene, judging from thinning of mid-Eocene strata on to the high. Furthermore, onlap of Oligocene - Miocene strata towards the high indicates that it was uplifted in the Late Eocene - Early Oligocene, forming a barrier between the Sørvestsnaget and Lofoten basins through the Oligocene - Miocene. Similar stratal patterns at the structural boundary zone between the Sørvestsnaget Basin and the Vestbakken Volcanic Province indicate the existence of an Oligocene - Miocene structural barrier in this area, which may have been linked to the marginal high.

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