Geological development of the Sørvestsnaget Basin, SW Barents Sea, from ocean bottom seismic, surface seismic and potential field data

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The study integrates seismic wide-angle data from Ocean Bottom Seismographs (OBS), multichannel reflection seismics (MCS), and gravity- and aeromagnetic data, acquired along a 195 km profile from the Lofoten Basin, across the Sørvestsnaget Basin and the Veslemøy High. The study also includes OBS and MCS data from a 77 km long crossing profile, and available data from boreholes have been utilized. The MCS data generally provide the best imaging of the shallow to intermediate deep sedimentary levels (down to ca. 5 km), whereas the OBS- and gravity data are mainly used to constrain the geometries and velocity/density of the deeper sedimentary section, the crystalline crust and upper mantle layers. In the Lofoten Basin, an approximately 6 km wedge of Cenozoic sediments overlies ca. 6 km thick `normal` oceanic crust. The continent-ocean-transition crossed by the profile occurs over a ca. 20 km wide zone, where a pronounced landward thickening of the crust is associated with the presence of igneous intrusions. Interpretational models with large amounts of salt in the Sørvestsnaget Basin have been tested, but none of the datasets used supported the presence of these. The modelling suggests that an interface at 7-8 km depth, which originally was interpreted as the base Cretaceous level, rather represents mid-Cretaceous levels in the Sørvestsnaget Basin, and that the base Cretaceous section is located as deep as 9-10 km here. A deeper interface (11-12 km) is interpreted as the mid-Jurassic level, based on similarities with observations in the Tromsø Basin. The depth to the crystalline basement is estimated to be approximately 17 km which implies the presence of a ca. 5 km thick section of late Paleozoic to early Mesozoic sedimentary strata in the basin. Beneath the westernmost part of the Veslemøy High igneous intrusions are thought to be present at both upper and lower crystalline crustal levels, i.e. at about 8 and 15 km depth, respectively. Igneous rocks are also inferred to be present locally at ca. 6 km depth, beneath the base Cretaceous interface further east on the high. The depth to the Moho is estimated to be ca. 28 km beneath the Veslemøy High.

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Introduction

The Sørvestsnaget Basin (Gabrielsen et al., 1990) is located in the southwestern part of the Norwegian sector of the Barents Sea (Fig. 1a,b). This deep Cretaceous - Cenozoic basin separates the Barents Sea shelf from the Lofoten Basin to the west, and is one of the least explored areas of the Norwegian continental shelf. Following the 1996 announcement of the "Barents Sea Project" by the Norwegian authorities, however, an approximately 4670 km^2 area ("Seismic Area A"; Fig. 1a) in the Sørvestsnaget Basin, was awarded to a group of companies 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 a set of 4 seismic lines with long record length (17 s), a regional high resolution aeromagnetic survey covering the "seismic area", and 2 ocean bottom seismograph (OBS) profiles (Fig. 1b).

The evaluation of the 3D seismic data was concluded in 1999, by the selection of production license PL 221 (part of Seismic Area A; Fig. 1a) by Norsk Hydro, Statoil and TotalFinaElf. Well 7216/11-1S was subsequently drilled by Production License 221 during the summer of 2000 to test a Cenozoic structural closure. The well was spudded in water depths of 361 mMSL (mean sea level) and terminated at a total measured depth of 4215 mMSL (true vertical depth is 3709 mMSL due to a deviated well path) in rocks of Early Palaeocene (Danian) age. The well did not encounter hydrocarbons, but provides new, stratigraphic information for the Cenozoic succession (Ryseth et al., subm.).

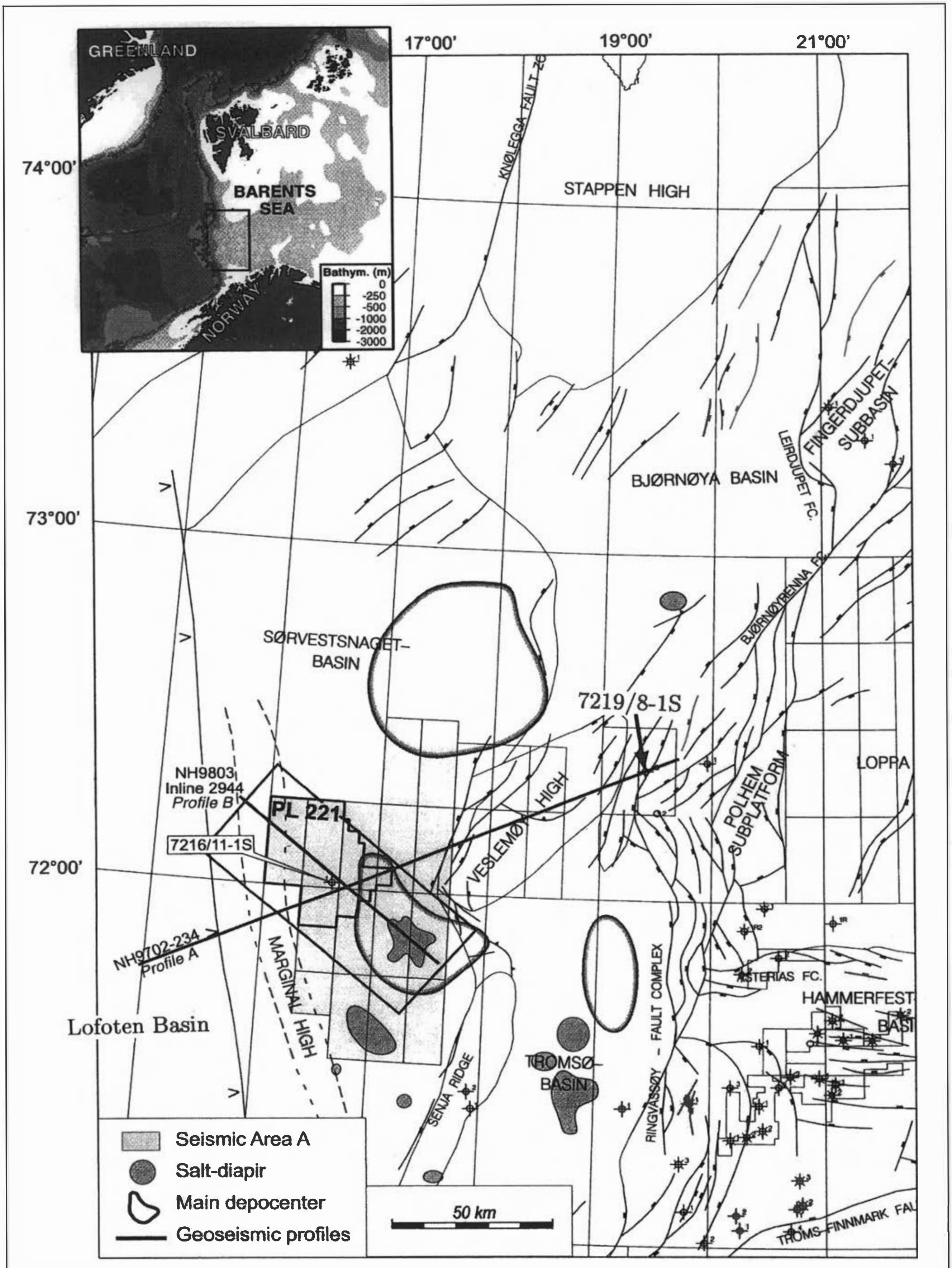

Fig. 1a. Location of profiles A and B on the structural element map of the south-western Barents Sea (Gabrielsen et al., 1990). The main depocenters represent areas of largest sedimentary thickness.

The present study is based on the integration of OBS data with MCS-, gravity- and aeromagnetic data, and is essentially directed towards unravelling the nature of the deeper, sub-Cenozoic sedimentary succession and the structure of the crystalline crust. Particular targets for study are the determination of the depth to the Base Cretaceous horizon, the existence of possible salt layers, depths to crystalline basement and to the Moho. Particularly, an improved definition of the Base Cretaceous level is considered important for evaluating the hydrocarbon source rock potential in the area.

Geological framework

The continental margin of the western Barents Sea and Svalbard (Fig. 1a) developed by transtensional movements between Eurasia and Greenland during the Paleogene period, with final continental separation between 35 and 25 Ma due to a shift in relative movements between the plates (e.g. Talwani & Eldholm, 1977; Myhre et al., 1982; Eldholm et al., 1987; Faleide et al., 1991, 1993a, 1996; Vaagnes, 1997). The margin comprises three main structural segments; 1) a southern shear margin segment, the Senja Fracture Zone; 2) a central volcanic rift segment, the Vestbakken volcanic province; and 3) a northern shear and subsequently rift margin along the Hornsund Fault Zone.

The southwestern Barents Sea is a province of particularly deep Cretaceous and Cenozoic basins, including the Harstad-, Tromsø-, Bjørnøya- and Sørvestsnaget basins (Gabrielsen et al., 1990; Faleide et al., 1993a,b). The basins are flanked and partly separated by the Senja Ridge and the Veslemøy High. The highs are 'basement supported' and appear to have been formed during several tectonic phases. The present signature of the structures is largely related to Late Cretaceous and Early Cenozoic subsidence and salt mobilization in the adjacent basins (Faleide et al., 1993a,b; Breivik et al., 1998). Moderate compressive or strike-slip related stress may have been involved in the Late Cretaceous structuring, but both highs are separated from the Sørvestsnaget Basin by clear west-stepping extensional faults (Gabrielsen et al., 1990; Faleide et al., 1993b; Breivik et al., 1998). The entire province of deep basins and structural highs is bounded to the west by the Senja Fracture Zone. Farther southwest the Lofoten Basin and the Cenozoic oceanic crust is covered by as much as 5-7 km of mainly Neogene sediments (Faleide et al., 1993a,b). The transition from oceanic to continental crust is assumed to occur over a 10 - 20 km wide zone (Faleide et al., 1993b; Breivik et al., 1998), which encompasses a "marginal high" along the western margin of the Sørvestsnaget Basin (Knutsen & Larsen, 1997).

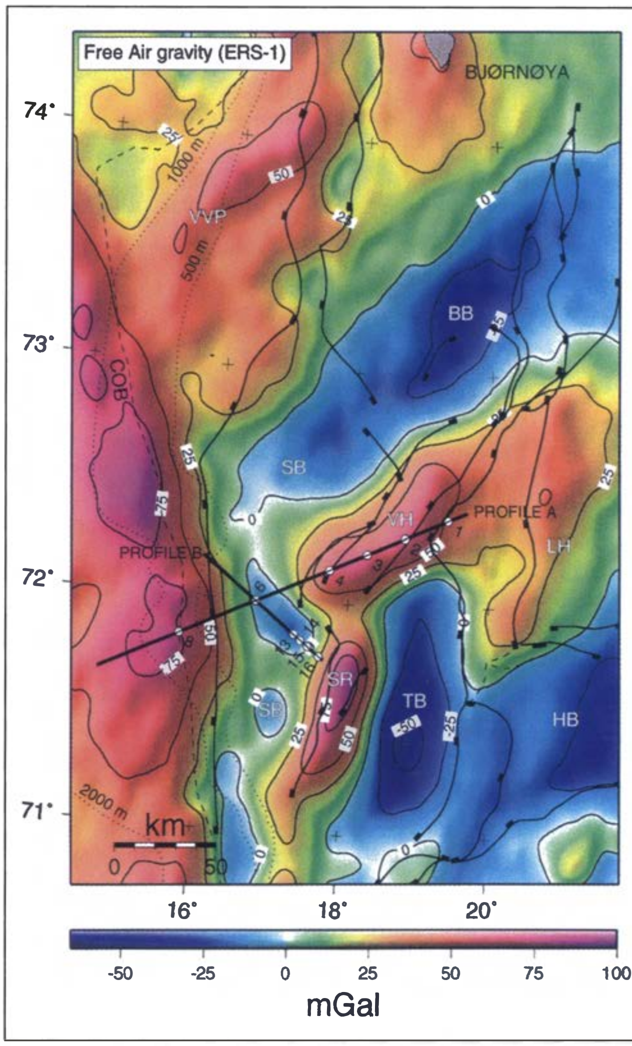

Fig. 1b. Free-air gravity map illuminated from the west-northwest, based on ERS-1 satellite data. OBS locations and bathymetry are also indicated. BB: Bjørnøya Basin, COB: Continent-ocean boundary, HB: Hammerfest Basin, LH: Loppa High, SB: Sørvestsnaget Basin, SR: Senja Ridge, TB: Tromsø Basin, VH: Veslemøy High, VVP: Vestbakken Volcanic Province. Regional faults are from Faleide et al. (1993b), COB from Breivik et al. (1999), ERS-1 grid from Andersen & Knudsen (1998).

Mapping of the Sørvestsnaget Basin by use of 2D surface seismic and gravity data (Breivik et al., 1998) shows the existence of two main Late Devonian - Cenozoic depocentres (Fig. 1a,b), located to the north and south of the Veslemøy High, respectively. Gravity models constrained by seismic data indicate that the Base Cretaceous/Middle Jurassic level may be as deep as 14 - 17 km in these depocentres, with an average burial depth of about 12 km throughout most of the area.

Due to the extreme thickness of Cretaceous and Cenozoic strata, little is known about the pre-Cretaceous stratigraphic evolution of the Sørvestsnaget Basin. However, the presence of salt-related structures in the southern part of the basin shows that the area probably

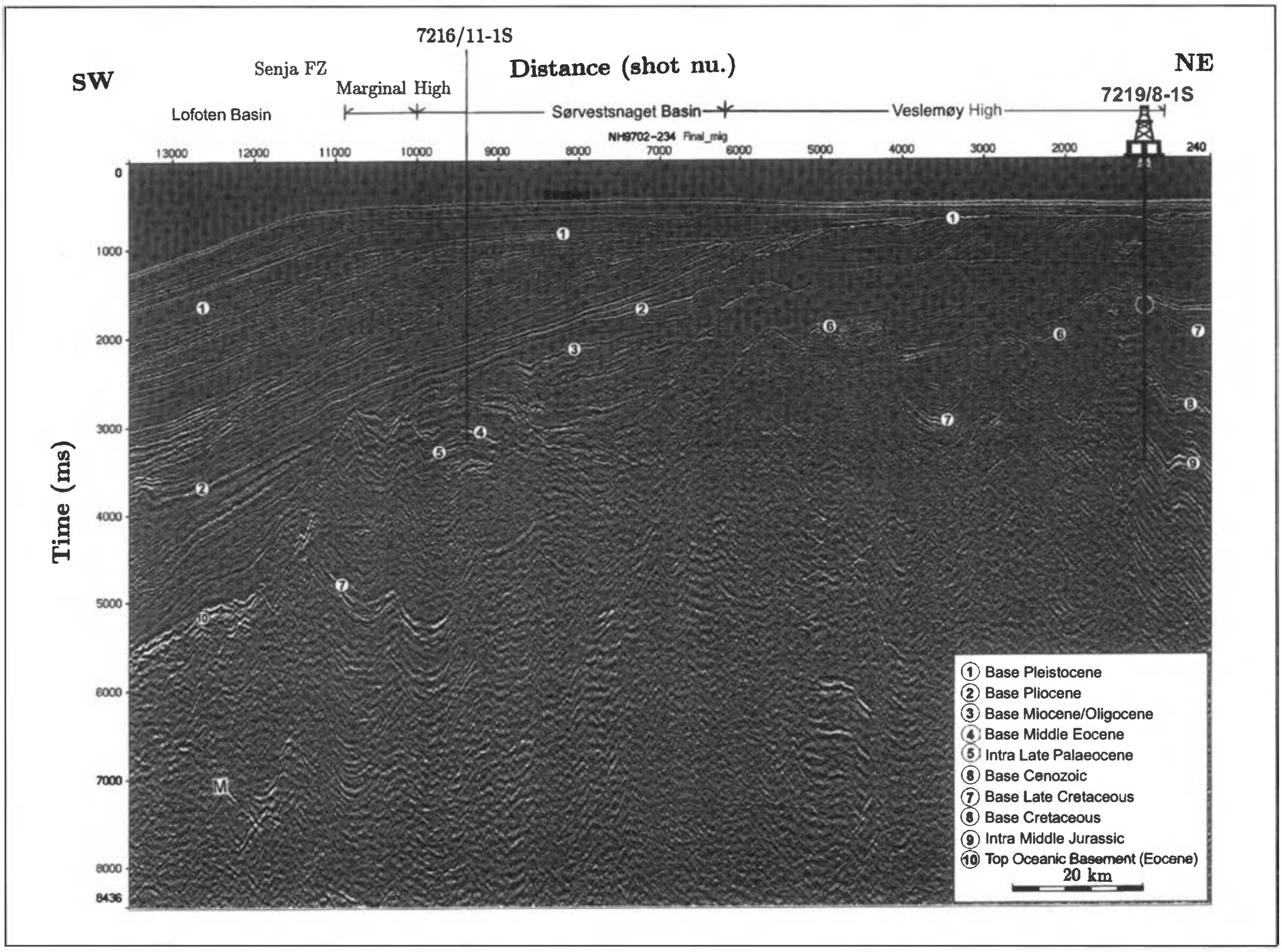

Fig. 2. Seismic reflection profile NH9702-234 with interpretation tied to results from wells 7216/11-1S and 7219/8-1S. M: Moho.

commenced as a sedimentary basin in Late Palaeozoic times (e.g. Knutsen & Larsen, 1997; Gudlaugsson et al., 1998; Fig. 1a). Large-scale salt diapirism of inferred Middle - Late Eocene age is seen in the southern depocentre (Fig. 1b), indicating that salt-mobilization may have triggered or amplified the subsidence in this part of the basin (Breivik et al., 1998).

Triassic and Jurassic strata are widespread throughout the Barents Sea (e.g. Dalland et al., 1988; Gabrielsen et al., 1990; Nøttvedt et al., 1992; Grogan et al., 1999). Their distribution and thickness in the Sørvestsnaget Basin are uncertain, although it is assumed that they are present below the Base Cretaceous horizon throughout the area. Interpretation of 2D surface seismic data and gravity modelling have shown that the Sørvestsnaget Basin may contain up to 9 km of Late Jurassic - Early Cretaceous deposits and up to 6 km of Late Cretaceous deposits in the northern depocentre, the latter possibly reflecting contemporary (Late Cretaceous - Early Palaeocene) pull-apart faulting in this part of the basin (Breivik et al., 1998).

The Cenozoic stratigraphy of the Sørvestsnaget Basin has been described as being composed of two main seismic units of Palaeogene and Neogene age, respectively (Knutsen & Larsen, 1997). Measured depths from well 7216/11-1S (Table 1) are largely in agreement with these observations. The well penetrated about 1370 m of Danian - Late Oligocene strata, below ca. 100 m of Miocene and a very thick Pliocene-Pleistocene succession (Faleide et al., 1996).

Interpretation of reflection seismic data, profile A

The reflection seismic data of line NH9702-234 (along OBS profile A) cover the inner part of the Lofoten Basin (app. CDP 13000 - 11500), the Sørvestsnaget Basin (app. CDP 11500 - 6000) and the Veslemøy High (app. CDP 6000 - 500; Fig. 2). The following interpretation is consistent with the 3D dataset covering the entire 'seismic area' (Fig. 1a). The top of the oceanic crust in the Lofoten Basin is seen by the strong southwest-dipping reflections at about 5000 ms, representing lavas of inferred Early to Middle Eocene age. Above the oceanic basement, a sedimentary unit of probable Middle Eocene - Miocene age can de seen, terminating northeastwards (at ca. CDP 11500) against a large fault escarpment marked by the Senja Fracture Zone at the western termination of the Sørvestsnaget Basin. Furthermore, a thick west-dipping wedge of Late Pliocene - Pleistocene age (see Eidvin et al., 1998) can be followed from the Lofoten Basin and across the Sørvestsnaget basin, but is severely truncated by a regional unconformity (denoted 1 in Fig. 2 or URU: upper regional unconformity, e.g. by Vorren & Kristoffersen, 1986) across the Veslemøy High.

In the Sørvestsnaget Basin, the Cenozoic stratigraphy is recorded in well 7216/11-1S (Fig. 1a, Table 1). The Danian age assigned to the well's total depth at about 3240 ms (corresponding to a true vertical depth of 3709 m below mean sea level) does, however, not allow for a clear definition of the base of the Cenozoic section. It is, however, inferred from other wells that the Cretaceous/Cenozoic boundary is present immediately below the 3709 m TD. Strong reflections at about 3000 - 3500 ms in the Sørvestsnaget Basin (Fig. 2) correspond to reflective levels within the Palaeocene - Early Eocene sequence.

A band of strong east-dipping reflections occurs at about 5000 ms at CDP 11000 - 10000 (western Sørvestsnaget Basin), possibly climbing to the east across a major basinal fault. Although these reflections may represent the Base Cretaceous horizon, regional seismic correlations and published data (e.g. Breivik et al., 1998) would indicate a mid-Cretaceous age. The actual Base Cretaceous/top Middle Jurassic level may be defined at about 7000 ms in the western part of the Sørvestsnaget Basin (CDP 11000 - 10000; Fig. 2), rising to the east similar to the inferred mid-Cretaceous reflector. Such a deep interpretation is also indicated by Gabrielsen et al. (1990; their Figs. 7 and 13). Further southwestwards, at ca. CDP 12000, the Moho interface

	True vertical depth (mMSL)	Two-way time (ms)
Sea Floor	361	480
Base Pleistocene	743	890
Base Pliocene	2240	2230
Base Miocene	2337	2304
Base Oligocene	2431	2372
Top Early Eocene	2951	2750
Top Paleocene	3069	2832
Total Depth	3709	3240

Table I: Time-depth relations for different horizons in well 7216/11-1S. The well was terminated in mudrocks of probable Early Palaeocene (Danian) age.

Survey	Survey type	Acquisition year	Acquisition	Processing	Line density	Total km
Amarok integ.	2D	1970-1996	Varying	Amarok	Varying	
NH9702	2D	1997	Austin Expl.	ARK Gephys.	2-4 km	5733
NH9803	3D	1998	Austin Expl.	ARK Gephys	400m	

Table II: Description of the different gravity datasets used.

Data set	Line spacing	Tie-in spacing	Navigation	Sensor flying height	Instrument	Total noise envelope
HRAMS97-1 (1997-98)	1 km	5 km	GPS	225 m	Cesium magnetometer	0.1 – 0.05 nT
NGU-data (1969-71)	Ca 4 km, but variable	Not used systematically	Loran C Decca	300 m	Proton magnetometer	2-7 nT

Table III: Acquisitional comparison between the HRAMS97-1 aeromagnetic dataset and older datasets.

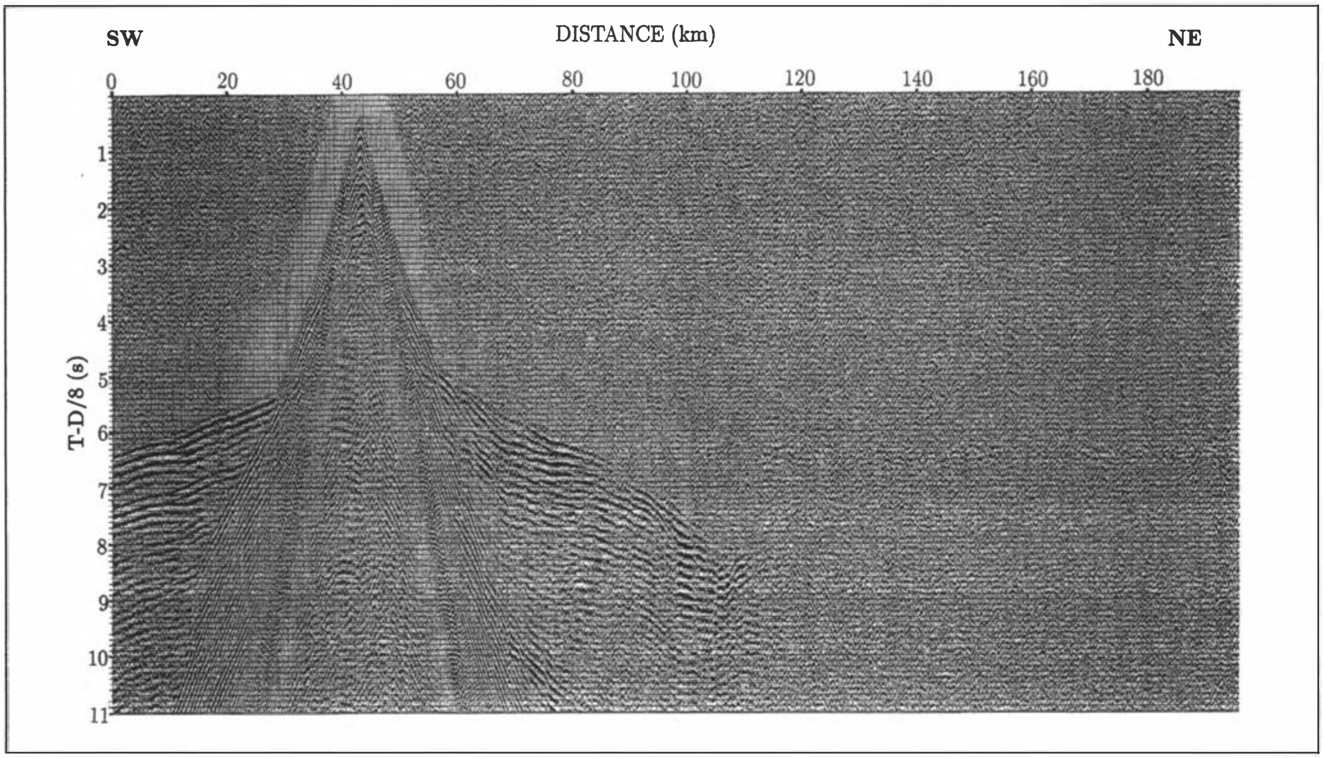

Fig. 3. Vertical component data from OBS 8 in profile A. 4-14 Hz band-pass filtered, and plotted with 8 km/s reduction velocity.

is inferred at about 7000 ms, dipping downwards to about 8000 ms at CDP 11000.

On the Veslemøy High, the Middle Jurassic to Cenozoic stratigraphy is derived from well 7219/8-1S (Fig. 2). East-dipping reflections at about 3000 - 3500 ms near the well correspond to the top of the sandy Early - Middle Jurassic Stø Formation (Dalland et al., 1988), which is capped by thick Middle - Late Jurassic shales. The Base Cretaceous level is at about 2500 - 3000 ms near the well, but seems to step significantly down, to about 4000 ms and deeper, on fault blocks further to the west. The well data demonstrate that mainly Early Cretaceous deposits are present on the Veslemøy High, as is also suggested by Gabrielsen et al. (1990). The Cretaceous/Cenozoic boundary on the high is seen at about 1500 - 2000 ms, and is reported to represent a significant Campanian/Maastrichtian - Early Palaeocene depositional break. However, significant Late Palaeocene - Early Eocene rocks covered the high, but were later significantly eroded in Pliocene - Pleistocene time (ca. 800 ms, Fig. 2). Due to the complex fault-pattern across the Veslemøy High and at the boundary to the Sørvestsnaget Basin, the seismic reflector ties between the two areas at Palaeogene and deeper levels are problematic.

OBS data acquisition and processing

The OBS-data (Fig. 1b) were acquired in the period 15-20 July, 1998, by the Institute of Solid Earth Physics (IFJ), University of Bergen (UoB), cooperating with the Institute for Seismology and Volcanology (ISV), Hokkaido University, Sapporo, by use of the vessel R/V Haakon Mosby, UoB. The IFJ seismic air-gun source (4.800 cu.inch.) was fired every 200 m, and the data were recorded by use of the ISV analogue and digital OBSs. The OBSs record the seismic wave-field by use of three orthogonally mounted (three-component) geophones. The vertical component detects dominantly compressional energy (P-waves), whereas shear energy (S-waves) is mainly constrained to the horizontal components. Six OBSs were deployed along profile A, whereas five OBSs were used along profile B (Fig. 1b).

The data were digitized to 60 s and tied to the navigation at ISV, and further processing has been performed at IFJ. Figs. 3-5 show the data from two OBS vertical components and one OBS horizontal component along profile A, and Figs. 6-7 show the data for one vertical and one horizontal component along profile B. The data have been band-pass filtered (4-14 Hz) and the vertical time-scale reduced (T-D/8) in order to enhance the resolution of the arrivals. The data have been plotted by use of a 4 s Automatic Gain Control (AGC) window. The quality of the vertical component data (P-waves) is considered as good to very good, whereas the quality of the horizontal component data (S-waves) can be classified as moderate to good.

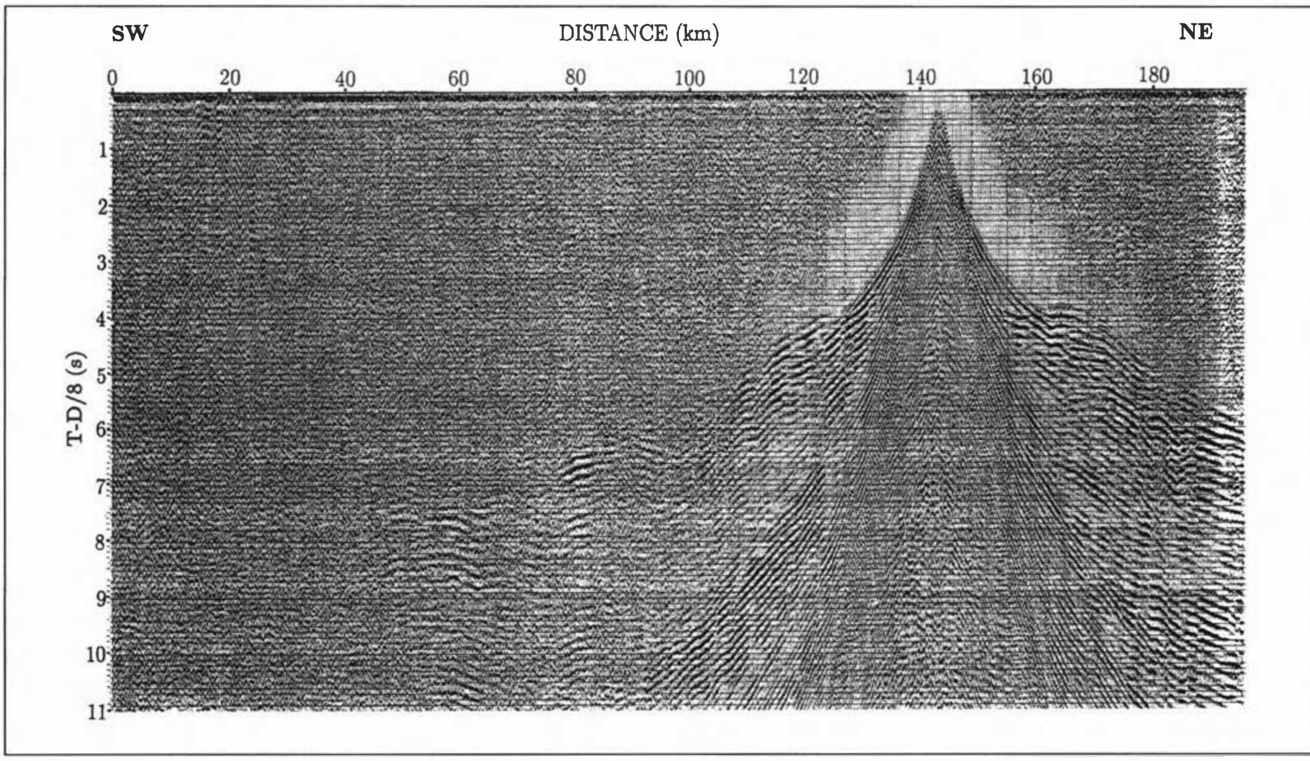

Fig. 4. Vertical component data from OBS 3 in profile A. 4-14 Hz band-pass filtered, and plotted with 8 km/s reduction velocity.

OBS modelling

P-wave modelling of profile A

In regional OBS-surveys the large OBS-spacing used (10-30 km) gives poor resolution for the uppermost 2-3 km. Before starting the modelling of the OBS-data, an initial shallow model derived from the interpretation of existing reflection data is generally made. For profile A, the interpretation of 8 interfaces from the seafloor to the assumed base Cretaceous horizon was provided by Norsk Hydro, and as an initial velocity model the MCS stacking velocities were used. The interpretation of the MCS data was based on a preliminary processed version of line NH9702-234. Several interpretational models were tested, including some incorporating layers of salt at intermediate as well as deeper stratigraphical levels. In the SW part of the profile the deepest interpreted interface is assumed to represent the top of oceanic crust in all models.

The modelling of the OBS-data has been performed both by forward (ray-tracing) and inverse modelling, using software developed by Zelt & Smith (1992). The modelling is performed by successive adjustments of horizons and velocities from the seafloor to the Moho. Figs. 8-9 show the fit between the interpreted arrivals (hatched lines) for the OBSs shown in Figs. 3-4 and the arrivals calculated from the model (solid lines), as well as the ray-paths through the OBS-model.

The final integrated velocity model for profile A confirms the geometry of all interpreted reflectors from the reflection data (Fig. 10). The OBS-modelling provides an independent estimate of the velocities, but the mean velocities for the different layers are quite similar to the starting velocities. The velocities derived from the OBS-data are ca. 5 % higher than the initial velocities for the Tertiary layers, and ca. 5 % lower for the Cretaceous layer.

All interfaces and velocities deeper than the assumed base Cretaceous horizon and the structure of the oceanic crust are solely based on the OBS-data. The velocity-model suggests that normal oceanic crust is found below a large sedimentary wedge beneath the first 50 km of the profile. The top of oceanic crust (2A) is observed as a strong reflection. The next arrivals on the OBS-data indicate velocities in the range 6.5-7.9 km/s, and are suggested to represent oceanic layer 3 (plutonic complex) overlying Moho.

Beneath the continental part of the profile (from ca. 60 km), the OBS-data suggest that the deepest sedimentary rocks can be modelled as one layer with relatively high velocities, i.e. in the range 5.4 to 5.8 km/s.

The OBS-data suggest the presence of high-velocity (6.0 km/s) igneous intrusions at about 9 km depth between 60 and 70 km. Similar high-velocities are observed at 140-150 km in the Veslemøy High region, and are also in that area interpreted as igneous in origin. A dipping reflector is inferred within the deepest sedi-

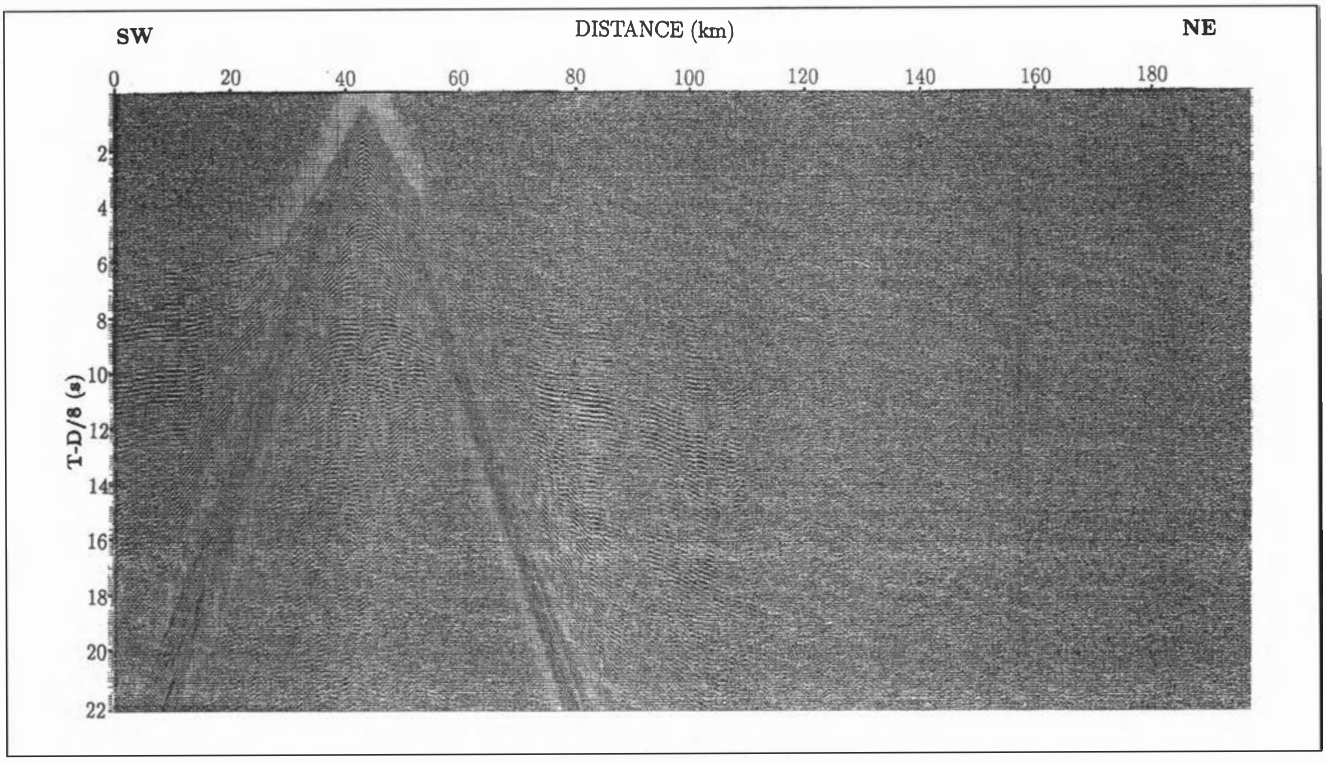

Fig. 5. Horizontal component data from OBS 8 in profile A. 4-14 Hz band- pass filtered, and plotted with 8 km/s reduction velocity.

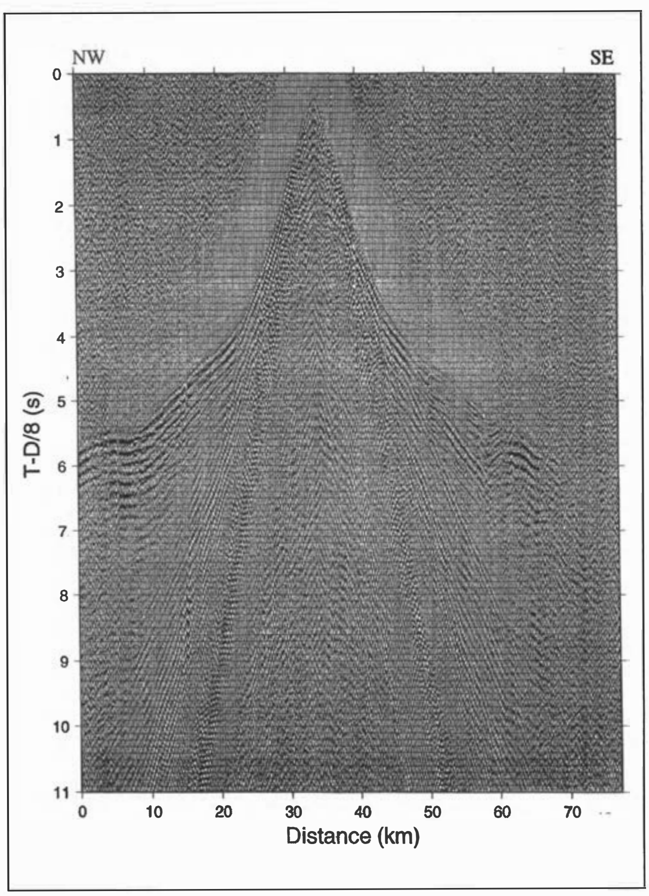

Fig. 6. Vertical component data from OBS 6 in profile B. 4-14 Hz band-pass filtered, and plotted with 8 km/s reduction velocity.

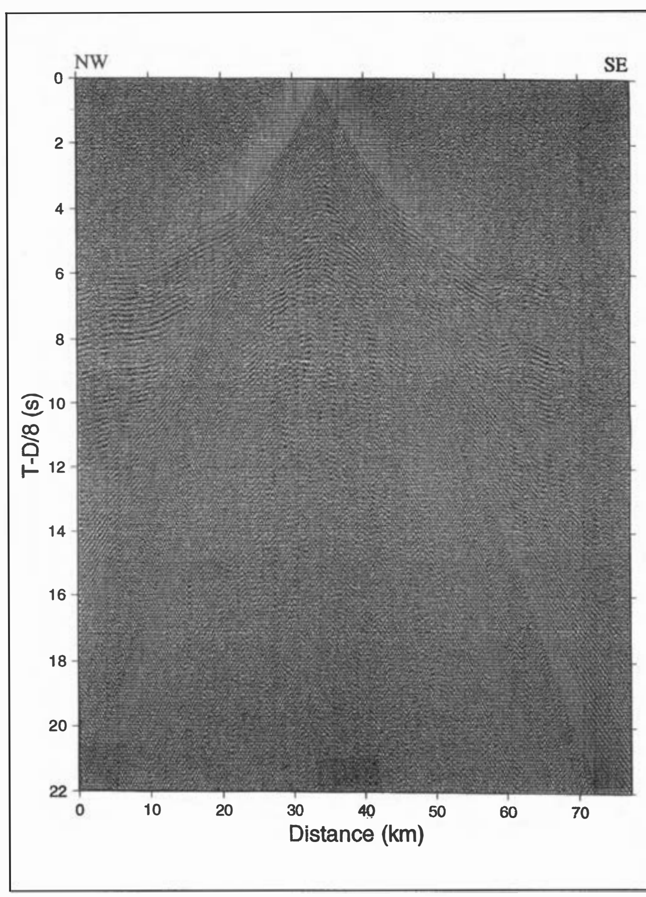

Fig. 7. Horizontal component data from OBS 6 in profile B. 4-14 Hz bandpass filtered, and plotted with 8 km/s reduction velocity.

mentary layer at 85-100 km (Fig. 8). This reflection may be caused by an intrusion or a fault zone.

The top of the crystalline crust is shown by velocities in the range from 6.1 to 6.6 km/s. In the Sørvestsnaget Basin, 80-90 km, the depth to this interface is ca. 17 km, shallowing abruptly to ca. 8 km beneath the Veslemøy High, 120-140 km. Further northeastwards it again deepens to 12-13 km. The velocities in the basement beneath the Veslemøy High are found to be ca. 6.7 km/s, possibly suggesting the presence of a large proportion of mafic intrusions or a highly metamorphosed basement block. The large distance from the continent-ocean transition suggests that the high-velocity anomaly is associated with old intra-basement bodies, not the opening of the Atlantic.

The lower crustal velocities reflect a similar structural setting as the upper crystalline crust. Beneath the Veslemøy High velocities in the lower crust (7.4 km/s) may again indicate the presence of mafic components.

The depth to Moho is inferred to increase steeply from ca. 13.5 km beneath the oceanic part of the profile to 27-28 km beneath the continental part. The upper mantle velocity is estimated to 7.9 km/s. Some poorly constrained horizontal to landward-dipping reflections are inferred within the upper mantle (Fig. 8). Such reflections are commonly observed in OBS-data (e.g Mjelde et al., 1997) and are generally suggested to represent major shear-zones, or in some cases off-line reflections.

S-wave modelling of profile A

Accurate use of S-waves in marine seismics implies that the recorders must be located at the seafloor, since S-waves do not propagate in water. Several surveys have shown that the horizontal components of the OBSs generally detect high amplitude S-waves (e.g Mjelde & Sellevoll, 1993).

The modelling of the S-waves, interpreted from the two horizontal components, has been based on the P-wave model discussed above using the same forward modelling scheme. The travel-time modelling of the S-waves consists of obtaining the S-wave velocities in each layer, expressed as the Vp/Vs-ratio, as well as the identification of interfaces for P-S conversions. In the modelling it is assumed that the structural interfaces are the same for both P- and S-waves. This procedure is considered valid since the quality of the P-waves generally is superior to that of the S-waves (Digranes et al., 1996). The fit between the observed (interpreted) and calculated travel-time curves for one OBS, as well as the ray-paths through the model, is presented in Fig. 11, and the obtained Vp/Vs-ratios for each layer are indicated in Fig. 10.

Water	1.03
Pleistocene / Pliocene	2.05
Paleocene – Early Eocene	2.20
Salt	2.15
Upper Cretaceous	2.35
Lower Cretaceous	2.40
Triassic / Jurassic	2.48
Late Paleozoic sediments	2.62
Upper crystalline basement	2.75
Lower crust	2.82
Oceanic layer 2	2.80
Oceanic layer 3a	2.85
Oceanic layer 3B	2.95
Oceanic mantle	3.18
Continental mantle	3.22

Table IV: Densities (g/cm³) used in the gravity modelling of profile A, based on well logs and Ludwig et al. (1970).

S-waves are interpreted as those arrivals that appear strongly on the horizontal components and weakly on the vertical component (Digranes et al., 1996). The S-wave arrivals can generally be divided into two types; direct S-waves (P-S converted on the way down; PSS-waves), and P-S waves converted on the way up (PPS-waves). The modelling indicates that P-S conversions occur at all interfaces, the dominant being URU, Base Eocene, Intra Paleocene, Base Tertiary, 'Base Cretaceous', the lower sedimentary interface, and top crystalline basement, each with 8-15% of the conversions.

The Vp/Vs-ratio within the Tertiary sequence is found to decrease with depth; 5.1, 2.4, 2.06, 1.88, 1.88, 1.88 (Fig. 10). The decrease is mainly a function of increased degree of consolidation and reduction in porosity with depth (Mjelde & Sellevoll, 1993). The Vp/Vs-ratio in consolidated (sedimentary) rocks is often referred to as an indicator of lithology; a pure sandstone corresponds to a ratio of about 1.6 and a pure shale to a ratio of 1.9-3.5 (e.g. Neidell, 1985). Thus, the Vp/Vs-ratio increase, 1.78 to 1.88, from southwest to northeast within the Cretaceous sequence may either be interpreted as an increase in the shale content or a decrease in the thickness of the overburden.

The Vp/Vs-ratio within the two deepest sedimentary layers remains relatively high; 1.78 and 1.82, indicating that the content of sandstone is relatively low. The Vp/Vs-ratio in salt is not well known, but values in the order of 2.0 have been reported (Raymer & Kendall, 1998). Hence the modelling of the S-waves along profile A does not support a model with large volumes of salt.

The Vp/Vs-ratio is found to be slightly higher in the oceanic crust than in the continental crystalline crust; 1.78 vs 1.73 (i.e. the oceanic crust is more mafic). The

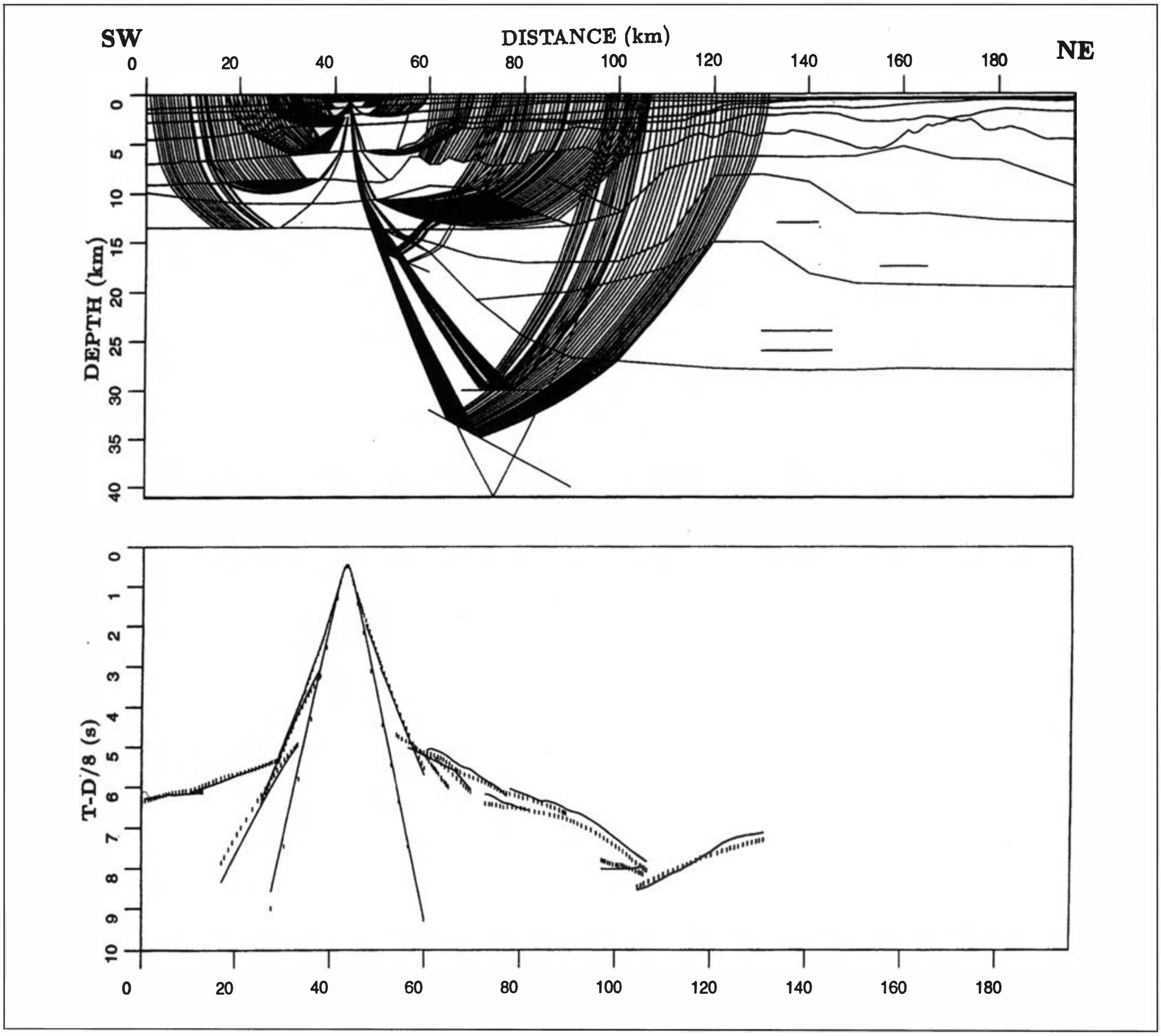

Fig. 8. Above: Vertical component ray-paths for OBS 8 in profile A. Below: Interpreted (hatched lines) and calculated travel-time curves for the same OBS.

value for the oceanic crust corresponds well with the results from the oceanic part of the Vøring Plateau (Mjelde et al., subm.), whereas 1.73 suggests granitic-granodioritic composition of the continental crust. The area with high P-wave velocity does not correspond to an anomaly in the Vp/Vs-ratio, which may suggest that the P-wave anomaly consists of several high-velocity intrusions of limited thickness.

P-wave modelling of profile B

The initial model was based on inline 2944 from a 3D seismic survey recorded in the Sørvestsnaget Basin in 1998, and the interpretation was provided by Norsk Hydro. The same 8 reflectors as in profile A were drawn, as well as one deeper reflector and a salt pillow. The proposed Base Cretaceous horizon and the deepest reflector, presumably mid Jurassic in age, had to be extrapolated to the SE as they were not interpretable in this area (Fig. 13).

The two-way time interpretation was converted to depth by using the interval velocities estimated from the modelling of profile A. From the northwest, the model covers the outer high bordering the continent-ocean transition, passes through the Sørvestsnaget Basin, and stops close to the western flank of the Senja Ridge in the SE (Fig. 1a).

During the initial modelling the velocities were adjusted to fit the interpreted arrivals on all OBSs. The fit between the interpreted arrivals for one OBS and the arrivals calculated from the model demonstrates the quality of the modelling and illustrates the ray-paths through the OBS-model (Fig. 12).

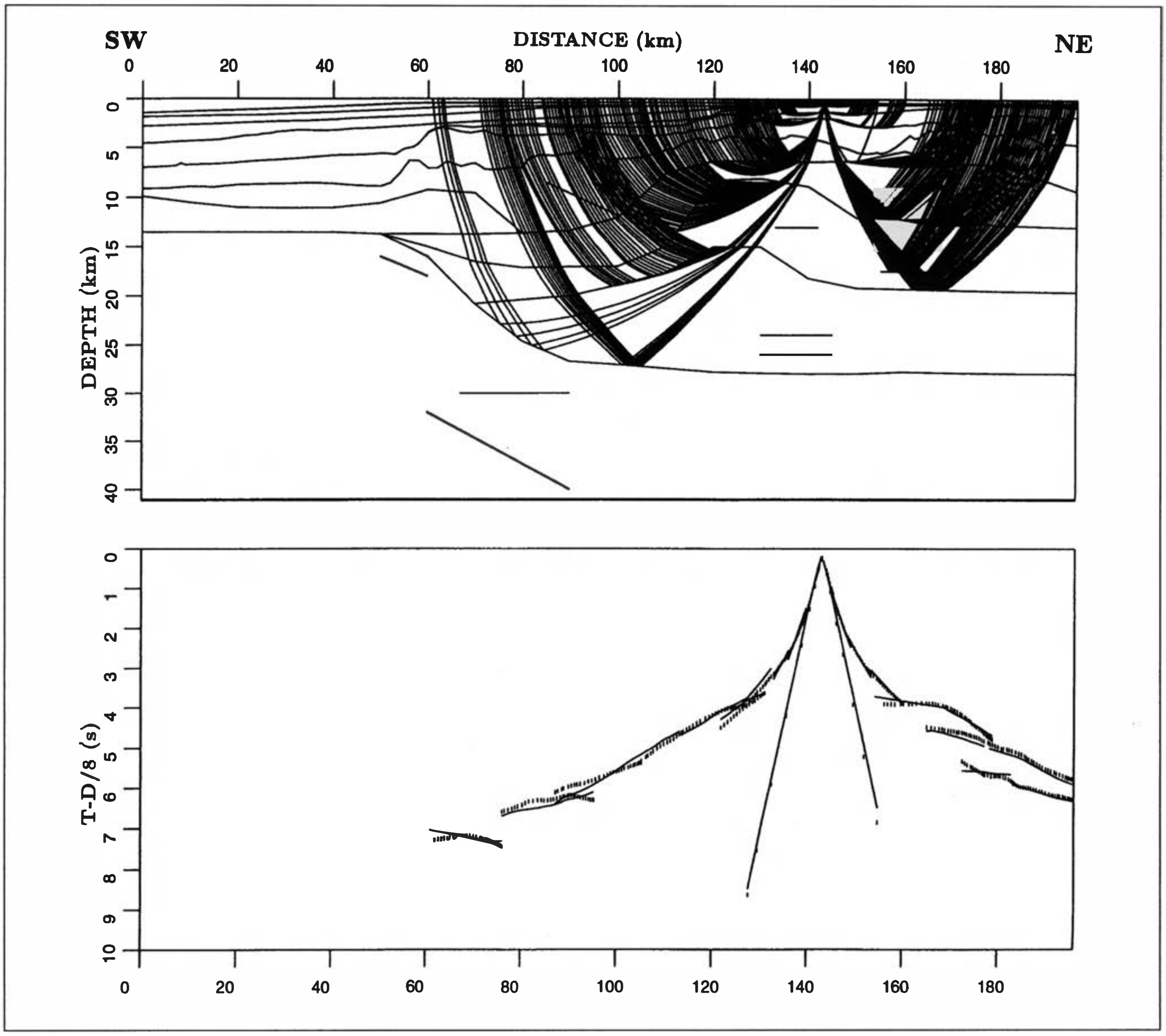

Fig. 9. Above: Vertical component ray-paths for OBS 3 in profile A. Below: Interpreted (hatched lines) and calculated travel-time curves for the same OBS.

On OBS 6 a high-amplitude, high-velocity arrival can be seen at the NW end of the profile (Fig. 6). It was not possible to reproduce this arrival without introducing a body with seismic velocities ranging from 5.3 to 5.8 km/s at 5-7 km depth. With respect to the likelihood of significant igneous activity at break-up time, we believe this body to represent an igneous unit with a minimum thickness of 200 m.

The deepest interpreted horizon (possibly Middle Jurassic), turns out to be an important velocity interface in the modelling on most OBSs along the profile. In the NW part of the seismic reflection profile this horizon has high continuity and high amplitude, whereas the interpretation is more ambiguous along the remaining part of the profile. A velocity of 6.0 km/s below the proposed Middle Jurassic horizon is required to obtain a good fit to the observed arrivals.

Arrivals in the SE part of the OBS-profile are dominated by higher seismic velocity than the surrounding sedimentary rocks and a salt body is a likely explanation. Complex ray-paths are found through the salt lens, and there are also indications of some internal reflections. In the modelling different depths to the top of the structure, as well as different internal velocities were tested. A reasonable fit on all OBSs was obtained by keeping our initial geometry, but by lowering the velocity to 3.9 km/s (pure salt has a velocity of approx. 4.5 km/s). This velocity is not well resolved due to complex ray-paths close to the edges of the pillow. The base of the structure was placed at a strong reflector seen in the MCS data. To the SE side of the pillow there is a narrow syncline most likely created in response to the salt movement. An alternative interpretation would be that the lens consists of a volume of sedimentary rocks pushed up by salt movements just below. The amount

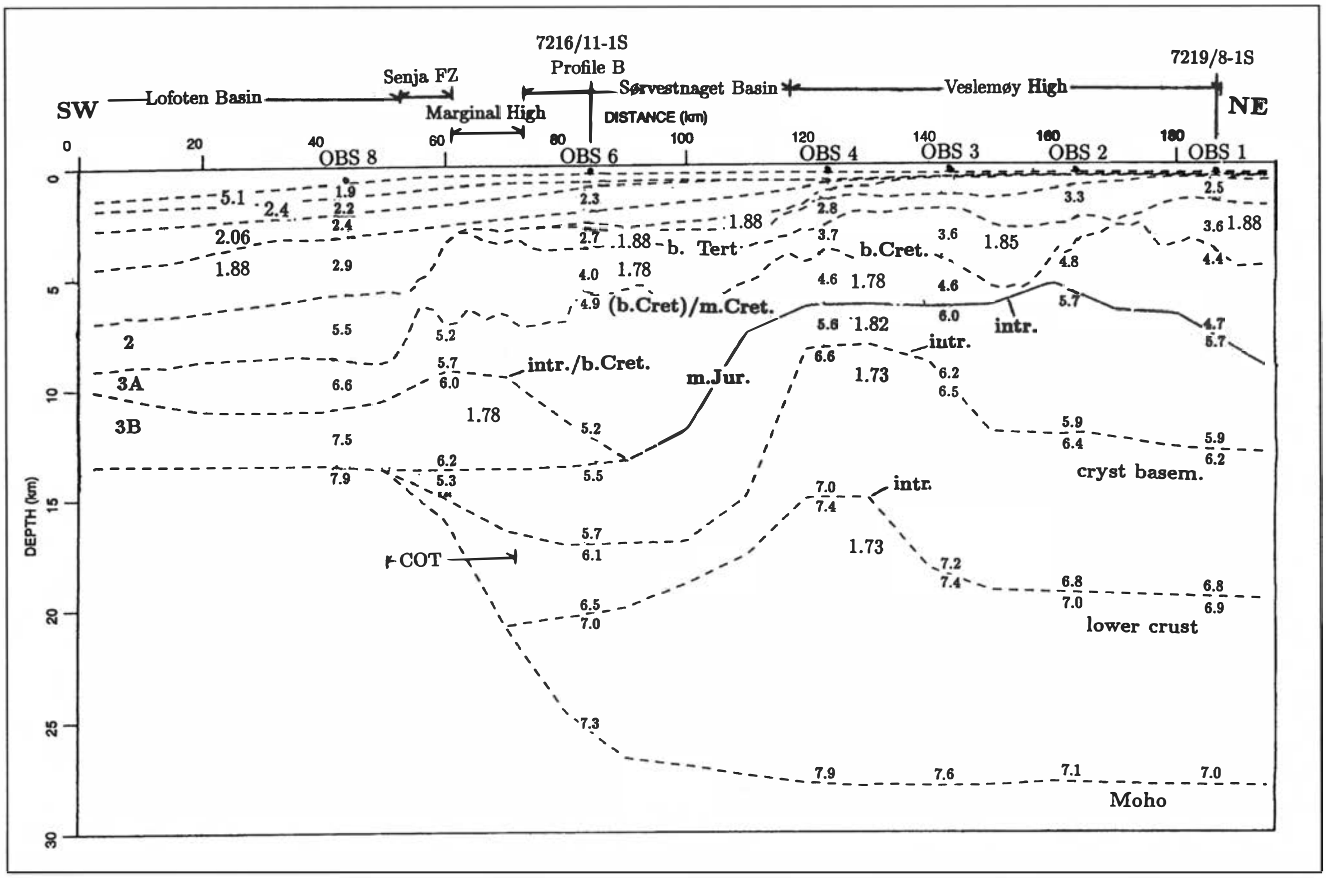

Fig. 10. Final crustal model based on integration of MCS- and OBS-data for profile A. The suggested ages on interfaces represent our preferred interpretation based also on the integration with gravity modelling. In the Sørvestsnaget basin the initial base Cretaceous interpreted from MCS-data is interpreted as mid Cretaceous based on the integration of all datasets. Undulations in the mid-Cretaceous - base Cretaceous interface represent fault blocks. The top of local intrusive bodies are indicated. COT: Continent- ocean-transition. Small numbers: P-wave velocities, large numbers: Vp/Vs-ratios.

of salt involved would then be unconstrained by the seismic data, as the velocity contrast to the surrounding sedimentary units is low at that depth. In our judgement, the present data cannot distinguish between these models.

S-wave modelling of profile B

The initial model was made by combining the velocity-depth model from the P-wave modelling of profile B, with the Vp/Vs-ratio for each layer obtained from the crossing profile A. The S-waves were then modelled by the same procedure as for profile A (Fig. 14).

The Vp/Vs-ratio determined for profile B agrees with that of profile A down to the proposed Base Cretaceous horizon. Below that, the ratio had to be decreased by ca. 0.1, which could suggest increased content of sandstone.

The main P-S converting interface along this profile is the Base Pliocene horizon representing about 33%. Other significant convertors were the URU, Intra Pliocene and Base Tertiary interfaces.

Uncertainty in OBS-modelling

Ambiguities inherent in interpretation represent the main source of uncertainty in models derived from all types of seismic data. During the modelling of the profiles presented in this paper, the uncertainty of each interpreted branch of the travel-time curves has been kept constant at 50 ms, although the uncertainty locally may be up to 100 ms (e.g. Figs. 8,9). Qualitative estimates of the resolution can be made from inspections of the ray-diagrams; the resolution is best in those parts of the models that are covered by many rays from several OBSs. Based on this and comparisons with similar surveys in other areas (e.g. Mjelde et al., 1992), the uncertainty in the depth to the crystalline basement, lower crust and Moho is estimated to ± 1 km in the areas where the coverage of rays is very good (between 130 and 170 km on profile A), and ± 2 km where the coverage is poorer (10-130 km on profile A). These interfaces are not seen in profile B, due to its limited range of offsets. Close to the ends of the profiles, deep interfaces are unresolved.

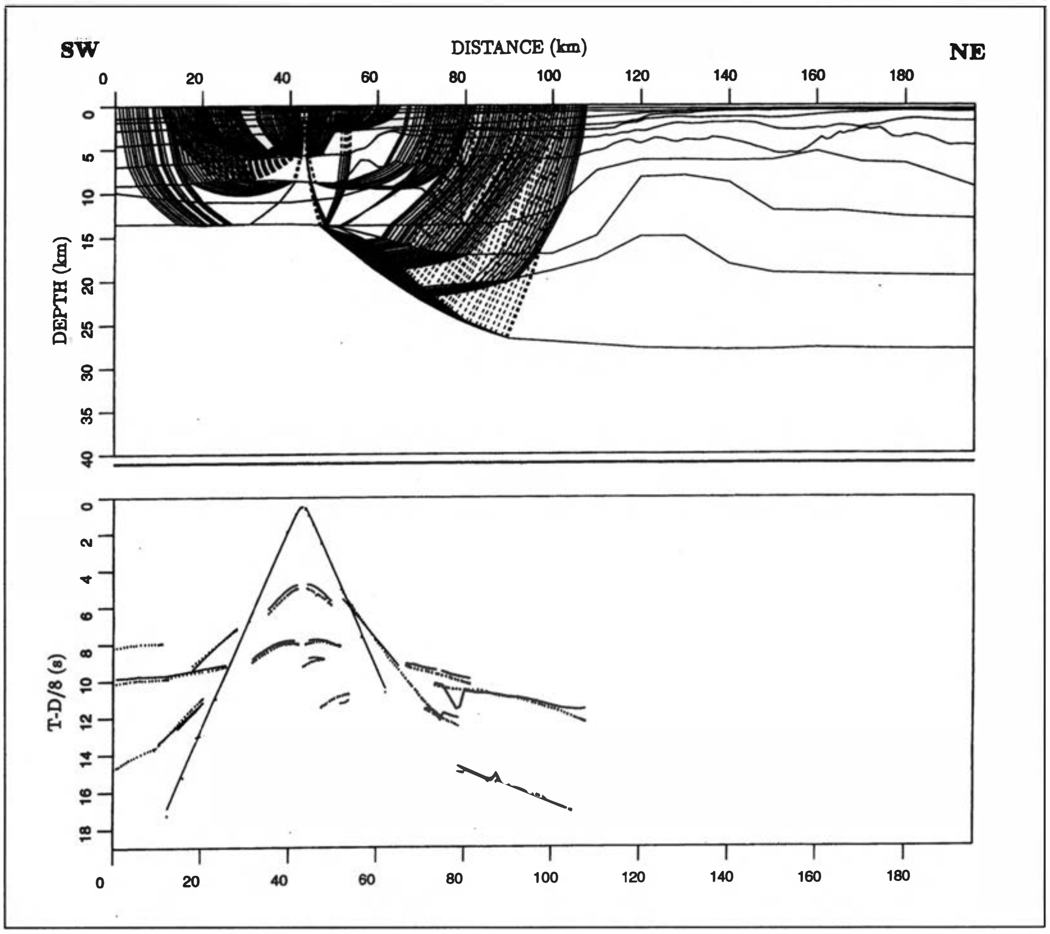

Fig. 11. Above: Horizontal component ray-paths for OBS 8 in profile A. Below: Interpreted (hatched lines) and calculated travel-time curves for the same OBS.

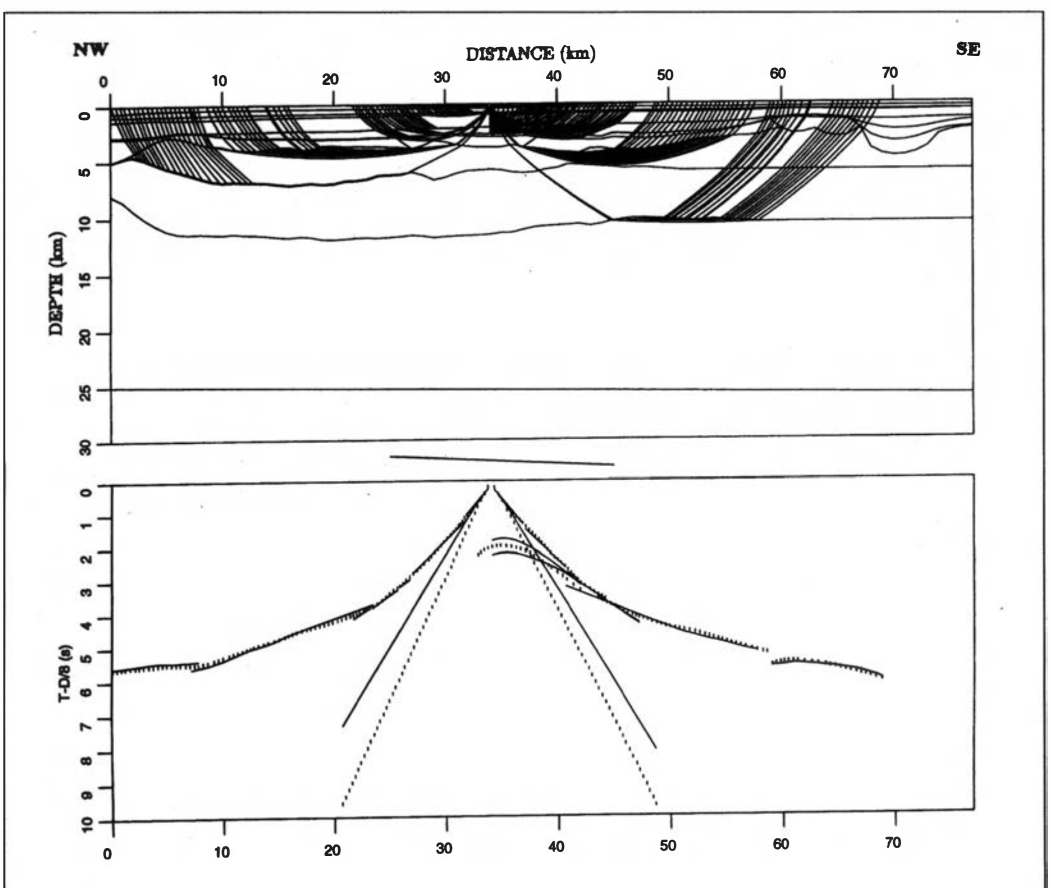

Fig. 12. Above: Vertical component ray-paths for OBS 6 in profile B. Below: Interpreted (hatched lines) and calculated travel-time curves for the same OBS.

We estimate the uncertainty in the Vp/Vs-ratio to be ± 0.07 for all layers. This is in accord with modelling of larger datasets off mid-Norway, where the uncertainty was estimated to be ± 0.05 on data of slightly higher quality (Digranes et al., 1996).

Potential field data

Gravity data (Table II)

In addition to processing performed by ARK Geophysics, UK, a complete interpretation/quality control processing based on processed line data and grids was performed by Norsk Hydro using the Oasis Montaj from Geosoft Inc. software.

For interpretation purposes it is useful to perform regional-residual separation of the gravity data. Large-scale structural and deep basement elements give rise to very long wavelength anomalies referred to as the regional com- ponents. Superimposed on these components are the residual component, smaller localised perturbations attributed to smaller structures and lithology changes within the sedimentary section.

For this study regional-residual separation was performed both on the Bouguer and on the free air gravity data, due to uncertainty in the quality of the Bouguer correction. The actual separation of the regional and residual fields was carried out by applying low/high-pass filters in the wave number domain. Filter algorithms/parameters and cut-off wavelengths were based upon testing and spectral analysis.

Aeromagnetic data acquisition and processing (Table III)

The new HRAMS97-1 data set has been compiled with older Geological Survey of Norway (NGU) aeromagnetic data sets and data compiled by Atlantic Geoscience Center (Geological Survey of Canada). The processing and quality control of the HRAMS97-1 data have been described in detail by Skilbrei et al. (1998).

The HRAMS97-1 survey was operated by NGU on behalf of Norsk Hydro. The data were acquired during the period 16th September to 26th October, 1997, and during the period 17th April to 15th June, 1998.

The old NGU data have been compiled into grids by digitising the contour lines, then merging these values

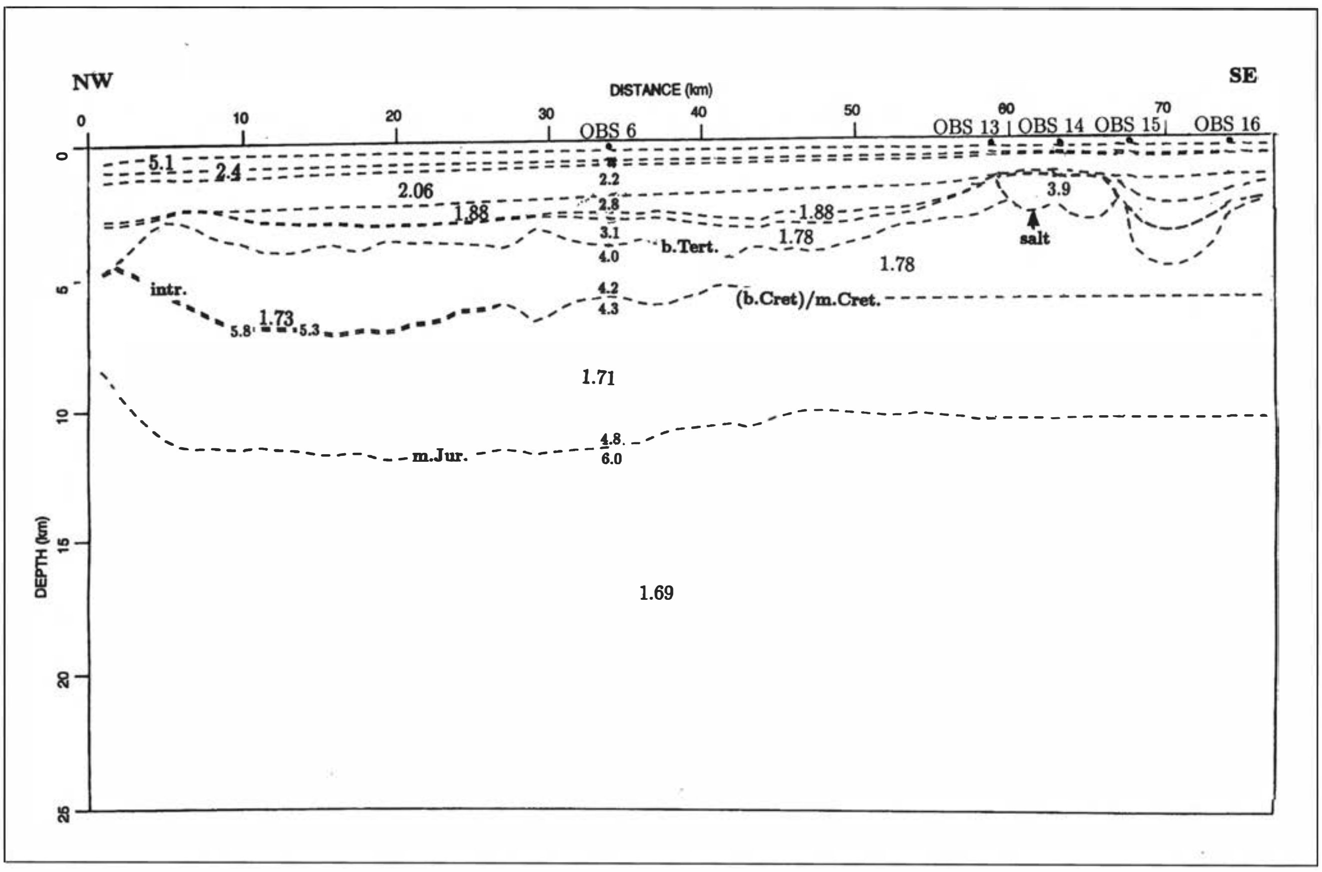

Fig. 13. Final OBS-model for profile B. The dating of interfaces represents our preferred interpretation based on the integration of the MCS- and OBS- data, tied to profile A. The initial base Cretaceous interpreted from MCS-data is interpreted as mid-Cretaceous based on the integration of all datasets. An intrusion at mid Cretaceous levels, as well as a shallower salt-pillow, are also indicated. Small numbers: P-wave velocities, large numbers: Vp/Vs-ratios.

with the data from the land areas along the coast. The data set consists of a 500 x 500 m grid.

Gravity and Magnetic modelling

The results from the MCS and OBS integration together with interpreted horizons from 2D and 3D seismic data were used as input for the modelling of the potential field data along NH9702-234 (OBS profile A; Fig. 15). The densities used in the modelling are listed in Table IV.

The large negative gravity anomaly from the Sørvestsnaget Basin is interpreted and modelled to be caused by a combination of the increased depth to the Moho surface compared to the oceanic side, and increased depth to the basement. The magnetic and gravity anomaly over the Veslemøy High is modelled to be structurally defined. Both the sedimentary units and base- ment are shallow over an intra crustal high-density and high susceptibility body. The depth to the magnetic 'body' is modelled to be 8-9 km. No gravity and magnetic modelling was performed along OBS profile B because the location of the profile is along a gravity minimum trend without significant anomalies.

Integration of interpretations and discussion

Interpretation of MSC data and modelling of OBS and potential field data represent different geophysical approaches to obtain geological information. The MCS technique provides in general the best resolution of intermediate to shallow sedimentary levels (above ca. 5 km depth), whereas revealing information on the deepest sedimentary rocks, as well as the crystalline crust and upper mantle, often rely exclusively on the other two methods. Of these, the OBS-method is considered the more accurate, since it provides both a direct measurement of the seismic velocity, and the depth to the corresponding layers. However, in potential field modelling there is a trade-off between modelled density/susceptibility and the depth to corresponding gravity/magnetic anomalies. The cost of acquiring an OBS profile is, however, several times higher than for the equivalent gravity profile. The potential field data provide means for extending the information from the OBS-data into 3 dimensions. The data analysis presented in the previous paragraphs demonstrates that the different methods very often provide similar results, giving increased credibility to the geological interpretations, but also that there are significant differences that need discussion.

Referring to the model for profile A there is a general consistency between the velocity and gravity models for the oceanic part of the profile (Fig. 10). Here, a 6 km thick wedge of Cenozoic sediments overlies a ca. 6 km thick crystalline crust, which can be considered 'normal' oceanic crust (White et al., 1992).

Across the Sørvestsnaget Basin (55 to ca. 115 km), and the Veslemøy High (115-190 km) the interpretation and the different modelling approaches generally agree in describing the uppermost 2-4 km (Cenozoic) sedimentary succession.

Furthermore, the modelling provides similar results concerning the depth to the base Cretaceous horizon on the Veslemøy High; i.e. 4-5 km, which also corresponds with drilling results. In the Sørvestsnaget Basin the velocity and gravity models indicate that the base Cretaceous horizon may be located quite deep. The modelled OBS-velocities beneath the mid-Cretaceous interface is modelled to vary from 4.2 to 4.9 km/s, which is similar to mid-Cretaceous velocities found for rocks at similar depths in the Vøring Basin. Here, as in the SW Barents Sea, pre-Cretaceous velocities from OBS-data are generally found to exceed 5 km/s (Mjelde et al., 1992; 1998). As the mid-Cretaceous horizon shows some faulting that is not directly related to the extensional faulting in the early Tertiary, it could represent a horizon that may be used to limit the onset of the latest Mesozoic tectonism and subsequent basin development. This should not be confused with the onset of the late Middle Jurassic - Early Cretaceous major rift episode, e.g. documented in the Hammerfest Basin (Worsley et al., 1988). Furthermore, Breivik et al. (1998) pointed out an episode of extensional faulting on the NW end of the Veslemøy High within the Cretaceous, which does not affect the basins farther east. Also the Wandel Sea Basin on Greenland (at that time located directly to the north) suggests that a mid-Cretaceous rift episode occurred (Håkanson & Stemmerik, 1989), which strengthens our preferred suggestion of a mid Cretaceous age for the interface at 7-8 km in the Sørvestsnaget Basin.

Beneath the marginal high (55-70 km), a strong high-velocity refractor (6.0 km/s) is observed in the OBS-data at ca. 9.5 km depth. Based on its similarity with intrusions on the mid-Norway margin, we interpret the refractor as intrusive rocks emplaced during the latest rifting / break-up. A similar, although somewhat shallower refractor is observed in the same area along profile B (Fig. 13). No prominent reflections can be observed from this level in the MCS data. Although sills that are 100-200 m thick often can be seen both as strong reflections in MCS data and as high amplitude reflections/refractions in OBS-data, it is not unusual to observe them only in OBS-data in areas of high structural complexity (e.g. Mjelde et al., 1998). One possible interpretation to such observations is a strong component of steeply inclined intrusions (dykes), which can-

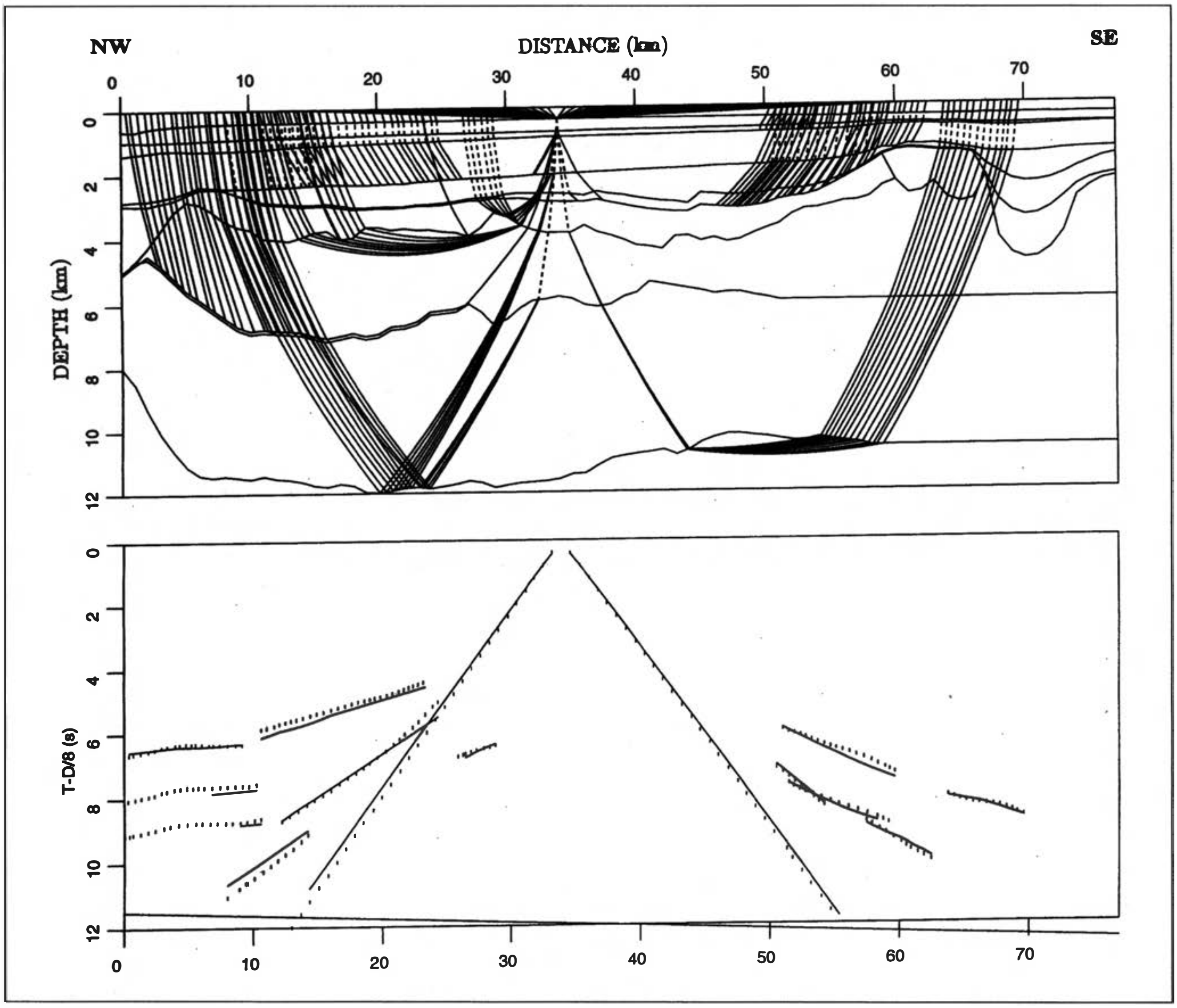

Fig. 14. Above: Horizontal component ray-paths for OBS 6 in profile B. Below: Interpreted (hatched lines) and calculated travel-time curves for the same OBS.

not be imaged on near vertical incidence MCS data. If the intrusion is a sill, destructive interference between the reflection from the top and the base of the sill will occur for a certain thickness depending on the frequency content of the seismic signal. Intrusions similar to the one described here are often inferred to intrude near the base Cretaceous level on the mid-Norway margin (e.g. Raum et al., 2002).

The deepest reflector used in the modelling of OBS profile B (single, bright reflector at 11-12 km depth) has a similar character to the Middle Jurassic observed in the Tromsø Basin (Faleide et al., 1993a), and the depth agrees well with the estimates previously made from gravity models (Breivik et al., 1998). These models also indicated shallowing of the horizon towards the margin, similar to what is observed here. The corresponding refractor along profile A is located slightly deeper, at 12-13 km. The velocity beneath this interface is found to be 6.0 km/s at the cross-point between the profiles, which most likely indicates that parts of the marginal high intrusions (associated with the opening of the Atlantic) extend to the central part of the Sørvestsnaget Basin. It is important to emphasize that the intrusive 'body' indicated in Fig. 10, most likely represents a mixture of intrusions and sedimentary rocks. The percentage of igneous rocks is not possible to estimate from the present data.

If our interpretation of the mid Cretaceous to mid Jurassic levels is correct, the Late Jurassic-Early Cretaceous subsidence is less than in the Tromsø Basin, while the Late Cretaceous subsidence there is larger. Furthermore, profile A indicates a depth of 17 km to crystalline basement within central parts of the Sørvestsnaget Basin, which leaves a ca. 5 km thick section of late Paleozoic to early Mesozoic sedimentary strata in place. This compares to a 3 km thickness of Triassic and

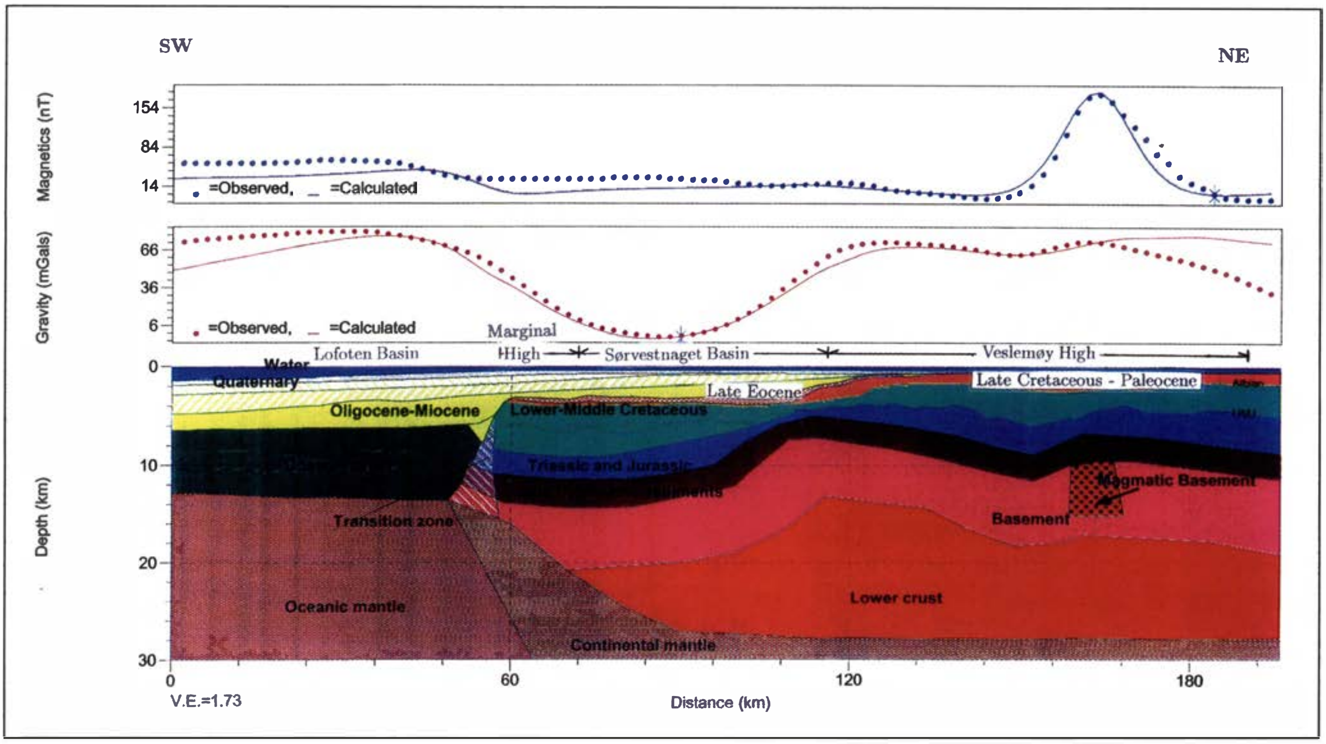

Fig. 15. Gravity and magnetic modelling along profile A.

Early-Middle Jurassic sedimentary rocks drilled in well 7120/9-2 in the Hammerfest Basin, plus typically a 1 km thick Permian section recognized on seismic lines in the area. Late Carboniferous deposition is dominated by evaporites, which appear to be mostly mobilized in the Sørvestsnaget Basin, though a significant clastic fraction may still be present.

Within the Veslemøy High the interface interpreted as mid Jurrassic in the Sørvestsnaget Basin climbs to ca. 7 km depth (profile A). In the area 150-170 km it shallows even further to ca. 6 km. Since the velocity beneath increases significantly to 5.8-6.0 km/s and the interface cuts through the sedimentary strata, it is concluded that this 'high' most likely represents a local intrusion, i.e. that the interface here is located shallower than mid-Jurassic. There are no obvious observations in the MCS data supporting this interpretation, which also was the case for the marginal high intrusions. However, a clear magnetic anomaly is present in this part of the area. This anomaly has been modelled as an intrusion within the upper crystalline basement, but the uncertainty in magnetic modelling implies that it could be located 2-3 km shallower.

The three deepest interfaces (crystalline basement, top lower crust and Moho) can generally be inferred only from OBS and gravity data. On two locations, however, clear, but short, reflections from these levels can be observed in the MCS data (Fig. 2); beneath the marginal high at ca. 7 s twt, corresponding to the continent-ocean-transition where the Moho, basement and mid-Jurassic interfaces merge, and at 120-140 km (4700) at ca. 5.8 s twt, where the top of the intrusive lower crust (inferred from the OBS data) can be seen.

For the top of the crystalline basement, however, there appears to be significant deviations between the OBS and gravity models. The models agree in the western part of the Veslemøy High, where the basement is located at ca. 8 km, but the OBS model is ca. 3 km deeper in the Sørvestsnaget Basin (17 vs 14 km), and in the eastern part of the Veslemøy High (13 vs 10 km). It is suggested that these differences can be mainly related to the fact that lateral density variations within units have not been considered in the gravity modelling. The high-velocity anomaly both at upper basement and lower crustal depths beneath the western part of the Veslemøy High, interpreted as intrusions, may correspond to a body with higher density than compared to the surrounding rocks. Modelling of OBS and gravity data from the north-eastern Barents Sea has shown that lateral density variations within the crust may be significant, and that gravity anomalies in that area generally not follow basement highs and lows (Breivik et al., 2002). There is, however, a first order correlation between main structural elements and gravity data in the south-western Barents Sea (Fig. 2).

Regional gravity modelling taking the thermal regime into account (Breivik et al., 1999) is conformable with the measurements of low heat flow in the area (less than 50 mWm^{-2}; Sundvor et al., 2000). These studies imply a temperature of ca. 200°C at the top of the basement (17 km) in the Sørvestsnaget Basin. Temperature measurements in the well 7216/11-1S, however, indicate a somewhat higher gradient of 35°C/km (Zwach et al., 2002). By correcting for the general decrease in thermal gradient with depth (e.g. Rybach, 1987; Chapman and Furlong, 1992) and extrapolating the temperature model of Zwach et al. (2002) to 17 km depth to crystalline basement, we infer a temperature of 400-500°C there. This temperature regime implies low-grade greenschist facies metamorphism for the deepest sedimentary rocks in the Sørvestsnaget Basin (Winkler, 1979; Spear, 1995). Laboratory measurements on greenstones at 4 kbar have indicated P-wave velocities and densities in the range of 5.7-5.9 and 2.69-2.72, which is consistent with the relatively low velocities and densities found at these depths in our modelling. It must be emphasized, however, that metamorphism implies complex processes strongly dependent on the distribution of mineral assemblages, as well as fluid content and composition (e.g. Spear, 1995). Attempts to relate geophysical observations to temperatures and metamorphic grade should thus be made with caution.

It appears that the marginal high is related to uplift of at least the whole upper crust during early development of the continental margin. Whether the uplift influences the entire crust cannot be resolved with the present data. Several explanations for this uplift are possible, including the preservation of early thermal uplift due to fusion with oceanic crust combined with subsequent flexural support (Vågnes, 1997), massive magmatic intrusions in the crust, or possible magmatic underplating below the crust. Compression can probably be ruled out as the early margin development is transtensional (Eldholm et al., 1987). The OBS profiles do not detect the presence of massive magmatic underplating of the crust at the margin. Magmatic intrusions in the deep sedimentary section have been recognized in both profiles modelled here, though judging from the MCS and gravity data the volume of these rocks is probably restricted. We thus propose that the margin uplift is caused by a combination of a preserved early thermal uplift caused by lateral heat transport from the oceanic crust, as well as the presence of crustal intrusions emplaced during the latest rifting / break-up. The present modelling restricts the continent-ocean-transition to a ca. 20 km wide zone (from 50 to 70 km along profile A). Southwest of 50 km 'normal' oceanic crust is inferred, whereas the area northeast of 70 km is influenced by the marginal high intrusions to a small degree only.

Summary and conclusions

One dip-profile extending from the Lofoten Basin, across the Sørvestsnaget Basin and along the Veslemøy High, SW Barents Sea margin, has been investigated with OBS, MCS, gravity and aeromagnetic data. The sedimentary part of the model has been verified by a shorter, transverse profile. The modelling of the OBS-data consisted of travel-time inversion and ray-tracing of both the vertical (P-waves) and horizontal (S-waves) components.

The modelling reveals the presence of a ca. 6 km thick wedge of Cenozoic sedimentary strata on top of a ca. 6 km thick oceanic crust in the Lofoten Basin, implying a Moho depth of ca. 13 km. The continent-ocean-transition occurs over a ca. 20 km wide zone, and is accompanied by significant margin uplift. We propose that the margin uplift is caused by a combination of a preserved tectonic uplift induced during the shear margin formation, as well as the presence of crustal intrusions emplaced during the latest rifting / break-up.

The depth to the base of the Tertiary rocks is estimated to 3-4 km in the Sørvestsnaget Basin and 2-3 km on the Veslemøy High, in agreement with drilling results. The depth to the base Cretaceous is estimated to 4-5 km on the Veslemøy High, and as deep as 9-10 km in the Sørvestsnaget Basin. An interface here at 7-8 km, initially interpreted as the base Cretaceous based on MCS-data, is by the present integrated results inferred to be related to the onset of a tectonic episode initiated in the mid-Cretaceous. The deepest sedimentary interface in the basin, at 11-12 km depth, has a similar character to the middle Jurassic observed in the Tromsø Basin, and is interpreted accordingly. The presence of large amounts of salt is not indicated in any of the datasets used, but a pillow of salt is defined in the southeastern part of the shortest profile.

Our interpretation of the mid Cretaceous to mid Jurassic levels imply that the Late Jurassic-Early Cretaceous subsidence in the Sørvestsnaget Basin is less than in the Tromsø Basin, while the Late Cretaceous subsidence is larger. A 17 km depth to the crystalline basement is inferred in the basin, leaving a ca. 5 km thick section of late Paleozoic to early Mesozoic sedimentary layers in place. The depth to the crystalline basement is ca. 8 km in the western part of the Veslemøy High, and ca. 13 km along the northeastern part of the high. The local high corresponds to a high in the lower crust, as well as increased velocities (0.3-0.4 km/s) both in the upper and lower crust. This increase in P-wave velocity is interpreted to reflect the presence of Caledonian or Precambrian magmatic intrusions. The anomaly is not seen in the Vp/Vs-ratio, which probably indicates that the anomaly consists of several high-velocity intrusions of limited thickness.

On the central part of the Veslemøy High a similar high-velocity anomaly is observed locally at ca. 6 km depth. A significant magnetic anomaly is observed in the same area, and we interpret the anomaly as Caledonian or Precambrian magmatic intrusions.

The Vp/Vs-ratio is found to decrease with depth in the sedimentary layers from ca. 5 to ca. 1.8, mainly as a function of increased compaction and reduced porosity. The Vp/Vs-ratios suggest a domination of shaly rocks. No indications of sand-dominated layers are modelled, although the modelling of the shortest profile indicates lower Vp/Vs-ratios (ca. 1.7) beneath mid-Cretaceous, which could suggest higher content of sandstone.

The Moho depth increases rapidly across the continent-ocean-transition to ca. 28 km beneath the Veslemøy High. The upper mantle velocity is estimated to ca. 7.9 km/s.

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References

Andersen, O.B. & Knudsen, P. 1998: Global marine gravity field from ERS-1 and Geosat geodetic mission altimetry. *Journal of Geophysical Research 103*, 8.129-8.139.

Breivik, A.J., Faleide, J.I. & Gudlaugsson, S.T. 1998: Southwestern Barents Sea margin: late Mesozoic sedimentary basins and crustal extension. *Tectonophysics 293*, 21-44.

Breivik, A.J., Verhoef, J. & Faleide, J.I. 1999: Effects of thermal contrasts on gravity modeling at passive margins: Results from the western Barents Sea. *Journal of Geophysical Research 104*, 15.293-15.311.

Breivik, A.J., Mjelde, R., Grogan, P., Shimamura, H., Murai, Y., Nishimura, Y. & Kuwano, A. 2002: A possible Caledonide arm through the Barents Sea imaged by OBS data. *Tectonophysics 355*, 67-97.

Chapman, D.S., & Furlong, K.P. 1992: Thermal state of the continental crust. In Fountain, D.M., Arculus, R. & Kay, R.W. (Eds.): *Continental lower crust, Elsevier*, 179-199.

Dalland, A., Worsley, D. & Ofstad, K. 1988: A lithostratigraphic scheme for the Mesozoic and Cenozoic succession offshore mid- and northern Norway. *Norwegian Petroleum Directorate Bulletin 4*, 1-65.

Digranes, P., Mjelde, R., Kodaira, S., Shimamura, H., Kanazawa, T., Shiobara, H. & Berg, E.W. 1996: Modelling Shear waves in OBS data from the Vøring Basin (Northern Norway) by 2-D Ray-tracing. *Pure and Applied Geophysics 4*, 611-629.

Eidvin, T.E., Goll, R.M., Grogan, P., Smelror, M. & Ulleberg, K. 1998: The Pleistocene to Middle Eocene stratigraphy and geological evolution of the western Barents Sea continental margin at well site 7316/5-1 (Bjørnøya West area). *Norsk Geologisk Tidsskrift 78*, 99-123.

Eldholm, O., Faleide, J.I. & Myhre, A.M. 1987: Continent-ocean transition at the western Barents Sea/Svalbard continental margin. *Geology 15*, 1118-1122.

Faleide, J.I., Gudlaugsson, S.T., Eldholm, O., Myhre, A.M., & Jackson, H.R. 1991: Deep seismic transect across the sheared western Barents Sea - Svalbard continental margin. *Tectonophysics 189*, 73 - 89.

Faleide, J.I., Vaagnes, E. & Gudlaugsson, S.T. 1993a: Late Mesozoic-Cenozoic evolution of the southwestern Barents Sea. *In* Parker, J.R. (Ed.): *Petroleum Geology of Northwest Europe: Proceedings of the 4th conference*, 933-950. Geological Society, London.

Faleide, J.I., Vaagnes, E. & Gudlaugsson, S.T. 1993b: Late Mesozoic-Cenozoic evolution of the south-western Barents Sea in a regional rift-shear tectonic setting. *Marine and Petroleum Geology 10*, 186-214.

Faleide, J.I., Solheim, A., Fiedler, A., Hjelmestuen, B.O., Andersen, E.S. & Vanneste, K. 1996: Late Cenozoic evolution of the western Barent Sea - Svalbard continental margin. *Global Planetary Change 12*, 53-74.

Gabrielsen, R.H., Førseth, R.B., Jensen, L.N., Kalheim, J.E. & Riis, F. 1990: Structural elements of the Norwegian continental shelf. Part I: The Barents Sea region. *Norwegian Petroleum Directorate Bulletin 6*, 1-33.

Grogan, P., Østvedt, O., Ghazi, A.-M., Larsen, G.B., Fotland, B., Nyberg, K., Dahlgren, S. & Eidvin, T. 1999: Structural elements and petroleum geology of the Norwegian sector of the northern Barents Sea. *In* Fleet, D.J. & Boldy, S.A.R. (Eds.): *Petroleum Geology of Northwest Europe; Proceedings of the 5th Conference*, 247-259. Geological Society, London.

Gudlaugsson, S.T., Faleide, J.I., Johansen, S.E., & Breivik, A.J. 1998: Late Palaeozoic structural development of the southwestern Barents Sea. *Marine and Petroleum Geology 15*, 73-102.

Håkanson, E. & Stemmerik, L. 1989: Wandel Sea Basin - a new synthesis of the late Paleozoic to Tertiary accumulation in North Greenland. *Geology 17*, 683-686.

Knutsen, S.-M. & Larsen, K.I. 1997: The Late Mesozoic and Cenozoic evolution of the Sørvestsnaget Basin: a tectonostratigraphic mirror for regional events along the southwestern Barents Sea margin. *Marine and Petroleum Geology 14*, 27-54.

Ludwig, J.W., Nafe, J.E. & Drake, L. 1970: Seismic refraction. *In* Maxell, A. (Ed.): *The Sea*, vol. 4, 53-84. Wiley-Interscience, New York.

Mjelde, R., Sellevoll, M.A., Shimamura, H., Iwasaki, T. & Kanazawa, T. 1992: A crustal study off Lofoten, N. Norway by use of 3-C ocean bottom seismographs. *Tectonophysics 212*, 269-288.

Mjelde, R., Sellevoll, M.A., Shimamura, H., Iwasaki, T. & Kanazawa, T. 1993: Crustal structure under Lofoten, N. Norway, from vertical incidence and wide-angle data. *Geophysical Journal International 114*, 116-126.

Mjelde, R., Kodaira, S., Shimamura, H., Kanazawa, T., Shiobara, H., Berg, E.W. & Riise, O. 1997: Crustal structure of the central part of the Vøring Basin, mid-Norway margin, from ocean bottom seismographs. *Tectonophysics 277*, 235-257.

Mjelde, R., Digranes, P., Shimamura, H., Shiobara, H. Kodaira, S., Brekke, H., Egebjerg, T., Sørenes, N. & Thorbjørnsen, T. 1998: Crustal structure of the northern part of the Vøring Basin, mid-Norway margin, from wide-angle seismic and gravity data. *Tectonophysics 293*, 175-205.

Mjelde, R., Raum, T., Digranes, P., Shimamura, H., Shiobara, H. & Kodaira, S., Submitted: S-wave structure of the Vøring Margin, mid-Norway margin, from OBS-data. *Tectonophysics.*

Mjelde, R. & Sellevoll, M.A. 1993: Possible shallow crustal anisotropy off Lofoten, Norway, inferred from three-component ocean-bottom seismographs. *Geophysical Journal International 115*, 159-167.

Myhre, A.M., Eldholm, O. & Sundvor, E. 1982: The margin between-Senja and Spitsbergen fracture zones: Implications from plate tectonics. *Tectonophysics 89*, 33-50.

Neidell, N.S. 1985: Land application of S waves. *Geophysics: The leading edge of exploration*, 32-44.

Nøttvedt, A., Cecchi, M., Gjelberg, J., Kristensen, S.E., Lønøy, A., Rasmussen, A., Rasmussen, E., Skott, P.H., & van Veen, P. 1992: Svalbard - Barents Sea correlation: a short review. *In* Vorren, T.O., Bergsager, E., Dahl-Stamnes, -.A., Holter, E., Johnsen, B., Lie, E. & Lund, T.B. (eds.): *Arctic Geology and Petroleum Potential, Norwegian Petroleum Society Special Publication 2*, 363-375.

Raum, T., Mjelde, R., Digranes, P., Shimamura, H., Shiobara, H., Kodaira, S., Haatvedt, G., Sørenes, N. & Thorbjørnsen, T. 2002: Crustal structure of the southern part of the Vøring basin, mid-Norway margin, from wide-angle seismic and gravity data. *Tectonophysics 355*, 99-126.

Raymer, D.G. & Kendall, J.M. 1998: Seismic anisotropy in salt structures due to preferred crystal orientation, *Revue de l'Institut Francais du Petrole 53*, 585-594.

Rybach, L. 1987: A petrological model of the lower continental crust derived from seismic velocities and from radioactive heat production. *Annales Geophysicae 4*, 403-408.

Ryseth, A.E., Opsal, J.G., Sundsbø, G. & Charnock, M., Submitted: Cenozoic stratigraphy and evolution of the Sørvestsnaget Basin, southwestern Barents Sea. *Norsk Geologisk Tidsskrift.*

Skilbrei, J.R., Rønning, S. & Kihle, O. 1998: Acquisition and processing report HRAMS97-1. Southwestern Barents sea high resolution aeromagnetic survey 97-98 (Area A). *NGU report*, 98.132, 10 pp.

Spear, F.S. 1995: Metamorphic Phase Equilibrium and Pressure-Temperature Time Paths. *Mineralogical Society of America, Washington D.C.* pp 799.

Sundvor, E., Eldholm, O., Gladczenko, P. & Planke, S. 2000: Norwegian-Greenland Sea thermal field. In Nøttvedt, A. (ed.): *Dynamics of the Norwegian Margin. Geological Society Special Publication 167*, 397-410.

Talwani, M. & Eldholm, O. 1977: Evolution of the Norwegian - Greenland Sea. *Geological Society of America Bulletin 88*, 969 - 999.

Vorren, T.O. & Kristoffersen, Y. 1986: Late Quaternary glaciations in the southwest Barents Sea. *Boreas 15*, 51-59.

Vågnes, E. 1997: Uplift at thermo-mechanically coupled ocean-continent transforms: Modeled at the Senja Fracture Zone, southwestern Barents Sea. *Geo-Marine Letters 17*, 100 - 109.

White, R.S., KcKenzie, D. & O`Nions, R.K. 1992: Oceanic crustal thickness from seismic measurements and rare earth element inversions. *Journal of Geophysical Research 97*, 19683-19715.

Winkler, H.G.F. 1979: Petrogenesis of Metamorphic rocks. Springer-Verlag, pp 348.

Worsley, D., Johansen, R. & Kristensen, S.E. 1988: The Mesozoic and Cenozoic succession of Tromsøflaket. *In* Dalland, A., Worsley, D., & Ofstad, K. (eds.): *A lithostratigraphic scheme for the Mesozoic and Cenozoic succession offshore mid- and northern Norway. Norwegian Petroleum Directorate Bulletin 4*, 42-65.

Zelt, C.A. & Smith, R.B. 1992: Seismic traveltime inversion for 2-D crustal velocity structure. *Geophysical Journal International 108*, 16-34.

Zwach, C., Wilhelms, A. & Augustson, J.H. 2002: Vitrinite reflectance responses in a fast subsiding basin. *The 8th Norwegian Meeting in Organic Geochemistry, Sundvollen 6-7/7, 2002.*